DEGREE PROJECT

Solar Photovoltaic Fire Risks

FE-analysis of fire exposed solar photovoltaic systems and comparison of current legislation and recommendations from different countries

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Fire Protecting Engineering Master Level

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Preface

This thesis is the final work of the Master Programme in Fire Engineering at Lulea University of Technology. The work includes 2x30 credits and was concluded in September 2019. Initially Elin has been responsible for collecting and analysing legislation and recommendations from different countries and Greta has been responsible for the computer simulations. The continuous work has been distributed equally.

First, we would like to thank our supervisors Alexandra Byström for her great support and guidance throughout the project. We have really appreciated her knowledge and advice on how to plan and perform the work. We would also like to thank Ulf Wickström for all his support and guidance with TASEF.

Secondly, we would like to thank our work employers Brandprojektering AB and Briab - Brand & Riskingenjörerna AB for giving us a peaceful and inspiring place to finalize our thesis at. The opportunity to have an office to sit and work at, and great colleagues to discuss different issues with has contributed to an efficient and creative work.

Finally, we would like to thank our friends and family for all their help and support throughout this process.

Västerås, Sweden. 2019-09-02.

Elin Bergroth

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Abstract

The global use of energy increases every day and to meet the growing demand, energy sources are constantly being developed to become more efficient and reliable. During the last decade, the global solar photovoltaics (PV) capacity has increased every year and in 2017, solar PV was the global leading power source of renewable energy. However, hazards and risks regarding fire have been connected to the installation and use of solar PV systems. An Italian study showed an increase of fires in solar PV systems following the increase of installed PV systems. A German report estimated that integrated solar PV systems have 20 times higher fire risk than non-integrated systems. The fire risks of solar PV systems are related to their electrical components, the fact that they produce power as long as a light source is shining and the changed fire dynamic of e.g. roofs when systems are installed. To reduce risks and create standards, several countries have legislated and published recommendations of installation and maintenance of solar PV systems. However, the regulations and recommendations vary greatly between countries and a comparison has therefore been performed in this thesis with the purpose of identifying differences. Legislation and other recommendations from four countries as well as European guidelines have been investigated and compared to see how solar PV systems are regulated. The difference between non-integrated and integrated solar PV systems has been examined as well as the fire risks connected to each system. Furthermore, the impact of solar PV systems during a fire rescue operation have been investigated. Finally, computer simulations have been performed to see what temperatures can be expected at the presence of a solar PV system at a façade.

The result shows a great difference in the level of details in the regulations and recommendations. Some countries have more general requirements while others are very specific in distances between PV systems and fire walls etc. The only requirement found in every countries' regulations or guidelines is of informative signage. The requirements regarding placement of solar PV systems is also similar between the countries. Such requirements can refer to clear pathways between panels for fire fighter access and distances between modules and smoke/heat exhaust ventilation. The regulations and recommendations found are mostly for non-integrated solar PV system wherefore a suggested further work is to investigate the need for specific regulations regarding integrated systems. Another conclusion is that reports regarding integrated systems are rather common but very few experiments have been performed. A commonly mentioned aspect of fire investigations regarding PV systems is the need for professional planning and installation of the systems. Since the development of solar PV systems is highly increasing, investigations have found that low-quality components and installation faults have led to fires.

The computer simulations were performed using the computer code TASEF with a model representing a wall structure of an integrated PV-system. Two different fire scenarios were investigated where the first scenario represented fire exposure on the solar panel and the other scenario fire exposure within the void (created between the PV and insulation of the wall). The design fires used were the ISO 834-curve and a constant temperature of 800 °C.

The temperatures received in the computer simulation did not vary much between different design fires or the simulated fire scenarios. The highest temperatures were measured in the cavity of the model (between the timber studs and the insulation) and reached between 792 and 937 °C after 60 minutes.

The conclusions of this thesis indicate that the legislation of safety regarding solar PV system is not developing as rapidly as the development of the systems themselves. The difference and specific risks regarding non integrated and integrated PV systems also need to be further investigated, as the current state of the literature is largely unexplored.

Sammanfattning

Den globala energianvändningen ökar varje dag och för att möta den växande efterfrågan utvecklas ständigt energikällor för att bli mer effektiva och pålitliga. Under det senaste decenniet har den globala solenergikapaciteten ökat varje år och 2017 var solenergi den globalt ledande kraftkällan för förnybar energi. Brandrisker har dock visats sig ha en koppling till installation och användning av solceller. En italiensk studie visade en ökning av bränder i solcellsanläggningar samtidigt som det ökade antalet installerade solcellsanläggningar. En tysk rapport uppskattade att integrerade solpaneler har 20 gånger högre brandrisk än icke-integrerade system. Brandriskerna för solcellsanläggningar är relaterade till deras elektriska komponenter, det faktum att de producerar ström så länge som en ljuskälla lyser och den förändrade branddynamiken hos t.ex. tak när solpaneler installeras. För att minska riskerna och skapa standarder har flera länder lagstiftat och publicerat rekommendationer om installation och underhåll av solceller. Reglerna och rekommendationerna varierar dock mycket mellan länder och en jämförelse har därför gjorts i denna avhandling med syftet att identifiera skillnader. Lagstiftning och andra rekommendationer från fyra länder samt europeiska riktlinjer har undersökts och jämförts för att se hur solcellsanläggningar regleras. Skillnaden mellan icke-integrerade och integrerade solpaneler har granskats såväl som brandriskerna för varje system. Dessutom har effekterna av solcellsanläggningar under en räddningstjänstsinsats undersökts. Slutligen har datorsimuleringar genomförts för att se vilka temperaturer som kan förväntas.

Resultatet visar en stor skillnad i nivån på detaljer i regler och rekommendationer. Vissa länder har mer allmänna krav medan andra är mycket specifika i t.ex. avstånd mellan solpaneler och brandväggar/brandcellsgränser. Det enda krav som finns i varje lands regelverk eller riktlinjer är krav på informativ skyltning. Kraven på placering av solcellsanläggningar är också relativt lika mellan länderna. Sådana krav kan vara fri passage mellan paneler och avstånd mellan moduler och rök-/värmeutloppsventilation. De föreskrifter och rekommendationer som hittats är mestadels för icke-integrerat PV-system, varför ett föreslaget ytterligare arbete är att undersöka behovet av specifika regler för integrerade system. En annan slutsats är att rapporter om integrerade system är ganska vanliga men att få experiment har utförts. En vanligtvis nämnd aspekt i brandundersökningar avseende PV-system är behovet av professionell planering och installation av systemen. Undersökningar har funnit att komponenter av låg kvalitet och installationsfel har lett till bränder.

Datorsimuleringarna utfördes med hjälp av TASEF med en modell motsvarande en väggkonstruktion med en integrerad solpanel. Två olika brandscenarion undersöktes, ett scenario där modellen utsätts för utvändig brand och ett scenario där branden placerades inuti hålrummet mellan solpanelen och isoleringen. Brandkurvorna som användes var ISO 834-kurvan och en konstant temperatur på 800 °C.

Temperaturerna från simuleringarna varierade inte så mycket mellan de olika brandkurvorna eller scenarierna. De högsta temperaturerna mättes i hålrummet i modellen (mellan träreglarna och isoleringen) och nådde mellan 792 och 937 °C efter 60 minuter.

Slutsatserna från denna avhandling indikerar att lagstiftningen om säkerhet beträffande solcellssystem inte utvecklas lika snabbt som utvecklingen av själva systemen. Skillnaden och specifika risker med avseende på icke integrerade och integrerade solcellssystem behöver också undersökas, eftersom det nuvarande läget i litteraturen till stor del är outforskat.

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Nomenclature

A_f = floor area (m^2)

A_t = total surface area (m^2)

A_{tot} = total surface area of enclosure (m^2)

A_v = total surface area of vertical openings on all walls (m^2)

O = opening factor ($\mathrm{m}^{1/2}$)

T = temperature of intrest (K or °C)

T_0 = refrence temperature (K or °C)

T_g = absolute surrounding gas temperature (K or °C)

T_{HC} = temperature of interest with the hydrocarbon curve (°C)

T_{ISO} = temperature of interest with the standard time − temperature curve (°C)

T_{max} = gas temperature at the end of the heating phase (K or °C)

T_s = absolute surface temperature (K or °C)

b = thermal property parameter ($\mathrm{J/(m^2 s^{1/2} K)}$)

c = specific heat capacity($\mathrm{J/kg * K}$)

e = specific volumetric enthalpy ($\mathrm{kJ/m^3}$)

h_{eq} = weighted average of window heights (m)

l_i = latent heat at various temperatures($\mathrm{J/m^3}$)

t = time (min)

t_{max} = duration of the heating phase (h)

q = heat flux boundary (Ws)

$q_{t,d}$ = fire load density related to the total surface area ($\mathrm{MJ/m^2}$)

β = convective heat transfer coefficient ($\mathrm{W/m^2\ K}$)

Γ = expansion coefficient (−)

γ = convective heat transfer power (−)

ε = resultant emissivity (−)

λ = thermal conductivity (W/mK)

ρ = density($\mathrm{kg/m^3}$)

σ = stefan − bolzmann constant ($\mathrm{W/m^2\ K^4}$)

Abbreviations

PV	Photovoltaic
BAPV	Building Additive Photovoltaic
BIPV	Building Integrated Photovoltaic
MSB	Swedish Civil Contingencies Agency (Myndigheten för samhällsskydd och beredskap)
TASEF	Computer code for Temperature Analysis if Structures Exposed to Fire
PBA	The Planning and Building Act
BBR	Boverket's Building Regulations (Boverkets Byggregler)
FEM	Finite Element Method
AC	Alternating Current
DC	Direct Current

1 Introduction

The following section describes the background to the subjects investigated in this master thesis. Further it presents the aim, objectives, and limitations to the work.

1.1 Background

The global use of energy increases every day and to meet the growing demand, energy sources are constantly being developed to become more efficient and reliable. Frequently used fossil fuel-based energy sources are finite and cause environmental pollution. Therefore, clean and renewable energy sources using wind, water and the sun are highly demanded. Solar radiation can with thermal technologies be converted into heat energy or, with the use of the photovoltaic effect, into electricity (Solanki, 2015).

During the last decade, the global solar photovoltaics (PV) capacity has increased every year, see Figure 1. This due to that it in both residential, commercial, and utility projects often are the most competitive option for electricity generation. However, for solar PV to become a major electricity source worldwide, several improvements and development are required. For example, policies and regulatory frameworks are still in many countries incomplete and inadequate (REN21, 2020).

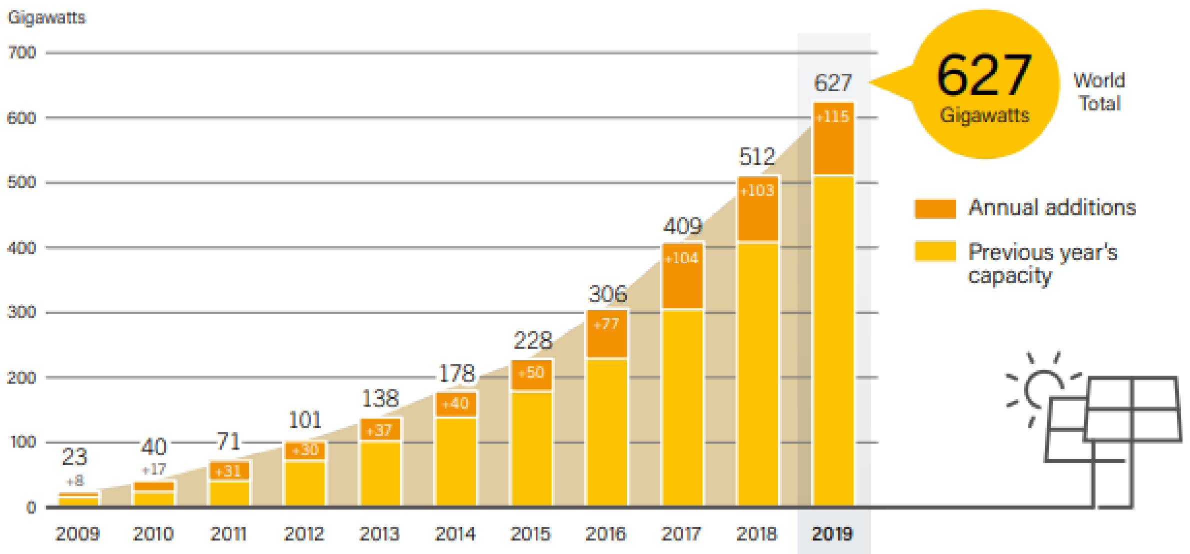


Figure 1: Solar PV Global Capacity and Annual Additions during the years 2009-2019 (REN21, 2020).

In Sweden, a similar increase can be seen for installed solar PV capacity, see Figure 2. The market for grid-connected solar PV systems has grown rapidly in recent years, mostly due to the introduction of a direct capital subsidy system in 2006. Simplified rules for micro producers, growing interest from utilities and a high popularity among the public are also factors contributing to the increase (Lindahl , 2017).

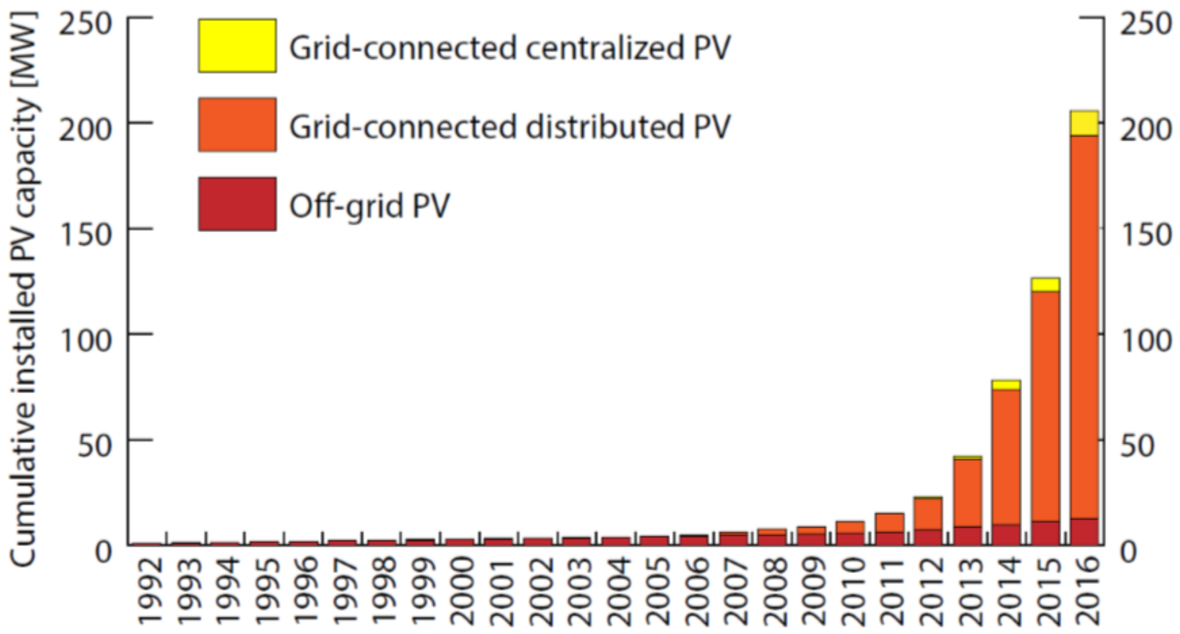


Figure 2: Solar PV capacity installed in Sweden during the years 1992-2016 (Lindahl, 2017).

Statistics Sweden reported of an even larger increase of solar PV capacity in 2018. At the end of the year, the total installed solar PV capacity was 411.06 MW which was an increase of almost 78 % from 2017 (230.99 MW). The number of solar PV systems increased with 10 188 in 2018 where the majority of these systems were installed on single-family houses (Energimyndigheten, 2019).

The Swedish production of solar energy is currently less than the energy production from hydro and nuclear power. Although, the Swedish market is ready to invest in renewable energy. A national plan of wind power usage already exists, but a similar plan for solar energy does not. A benefit of using solar PV systems is that they can be installed on existing buildings and be integrated in facades and rooftops. The areal efficiency of solar PV systems is also higher than for both wind and hydropower. A more negative aspect to consider regarding solar PV systems is that their efficiency reduces at lower temperatures and especially during the winter months (Greenmatch, 2018).

Since solar PV systems produce electrical current, they are a source to risks and hazards associated with electrical compounds. Solar PV systems generates a high amount of direct current and entails several kinds of risks regarding fire safety. According to the project Electrical safety in domestic housing started in 2017, at least 8 people die in electrical fires every year in Sweden. The emergency services respond to approximately 1 800 electricity-related fires every year where 280 of these fires are due to electrical failure in electrical products (Elsäkerhetsverket, 2018).

An Italian study found a significant increase of fires in solar PV installations connected to the large increase of installed solar PV systems. They estimated an amount of 1250 fires per million installed solar PV systems per year. Further they state that the fast and large increase of solar PV systems on the market has lead to that many installations have been performed by unauthorised or personnel lacking experience (Fiorentini et.al, 2017)

A German report estimated on the other hand 30 fires per million solar PV installations per year. The fires included here are fires originated in the solar PV installation and that contributed to damage on the buildings. They also state that integrated solar PV systems have 20 times higher fire risk than additive solar PV systems. (Laukamp et.al, 2013)

The UK had in the beginning of 2017 installed approximately one million solar PV systems. The same year, the Building Research Establishment (BRE), collected information regarding fires in solar PV systems and refers to the work in a report (Pester & Woodman, 2017). They found a total of 42 fires caused by the solar PV installations. Where 17 of these fires were categorized as severe since they spread from the ignition place and demanded large extinguishing operations.

Solar PV systems consist of combustible materials which can contribute to rapid fire spread and the panels can obstruct firefighting efforts. Since the solar panels continue to produce power as long as the sun is shining, they can cause great danger if firefighters need to extinguish a fire nearby. The firefighters can then be subject to electrical shock due to the energized panels. The panels can also fall down, block key points and pathways on roofs or potentially produce toxic fumes when heated (Stolen et al. 2018).

Solar PV systems are often attached to roofs on top of buildings. Considerations must then be taken regarding how the panels should be treated in relation to the fire safety requirements of roof covering. It is also important to separate non integrated and integrated solar PV systems since they may affect the fire spread differently (Boverket, 2018).

Steemann, Kristensen, Merci & Jomaas concluded through experimental tests that solar PV panels can have a significant contribution in roof fires. Since the panels change the fire dynamic surroundings of the roof construction where they are mounted, the solar PV panels also stimulate the fire spread over the roof (Steemann, Kristensen et al., 2017).

It is important to consider the air gap created between the facades or the roof when dealing with fire spread, as it creates a rapid fire spread. Also the risks of; fire spread between fire compartments, within the fire walls, on the associated surface and falling parts to injury people have to be considered (Boverket, 2018).

Solar PV system installation, fire safety and extinguishing operations are not regulated in the current national Swedish legislation/regulations. To give guidance, the Swedish Civil Contingencies Agency (MSB) has developed advice regarding extinguishing operations in solar PV facilities (Myndigheten för samhällsskydd och beredskap, 2014a) and a map of risks in the event of fire in solar PV systems (Myndigheten för samhällsskydd och beredskap, 2014b). The National Board of Housing, Building and Planning (Boverket) has also developed advice on how to interpret requirements in the Planning and Building act, and Boverket's Building Regulations regarding solar PV systems (Boverket, 2018).

1.2 Aim

The purpose of this thesis is to examine the need for specific fire protection legislations and regulations regarding solar PV systems. How solar photovoltaic (PV) systems affect fire ignition and fire spread when attached to roof and/or facades will also be investigated.

1.3 Objectives

To achieve the purpose of this thesis, current legislations and regulations regarding fire protection connected to solar PV systems in Sweden and other countries will be investigated and compared. The difference between non-integrated and integrated solar PV systems and how they affect ignition and fire spread will also be examined. Lastly, an analysis of heat transfer during fire connected to solar PV systems will be performed using the Finite Element Method (FEM) in computer simulations.

1.3.1 Questions to be answered

The aim and objectives are fulfilled by answering the following problem statements:

- Legislations and regulations
  - How is fire safety regarding solar PV systems regulated in different countries? Are there any differences/similarities?
  - Do the legislations and regulations in Sweden fulfill safety regarding solar PV systems?
- Non integrated solar PV systems
  - What parts of the solar PV system can ignite and cause a fire?
  - How do non integrated solar PV systems contribute to fire spread?
- Integrated solar PV systems
  - Are integrated PV systems regulated different from non integrated?
  - How do integrated solar PV systems contribute to fire spread?
- How do solar PV systems affect a fire rescue operation? What requirements are important in order to secure a safe environment for fire rescue personnel?
- Heat transfer queries
  - What temperatures can be expected on the inside of the facade if a solar PV system is ignited? and What temperatures can be expected between the facade and the solar PV system if the solar panel ignites?

1.4 Limitations

The study does not comprise analyses regarding energy storage systems, e.g. batteries, connected to the solar PV systems and their impact on fire spread and fire safety. PV power plants, also known as solar parks, are not addressed in this thesis. The solar PV systems examined are systems attached to or integrated in buildings.

The examined legislations and regulations are limited to Sweden, Germany, USA and Dubai. Regulations required from European organisations are also investigated. The study focuses on preventive measures and extinguishing operating techniques are only briefly mentioned.

The study is limited to heat transfer perpendicular to the roof surface and only exposed on one side. The computer code Temperature Analysis of Structures Exposed to Fire (TASEF) is used to conduct computer simulations for a fire between the solar panels and the roof surface.

2 Methodology

This section describes the methods used to fulfil the aim of the thesis.

2.1 Selection of Method

Two research methods were used to evaluate data and literature for this thesis. The methods used are qualitative and quantitative research. A qualitative research method is based on expressions through words, non-standardised data and analysis conducted through the use of conceptualisation. The quantitative research method is based on derived numbers, results in numerical and standardised data and analysis conducted through the use of diagrams and statistic (s. 482) (Saunders, Lewis, & Thornhill, 2009).

The main method used was qualitative research as a great number of literatures was studied. However, some analyses were performed using diagrams and statistics. The research method used for the numerical calculations and computer simulations are based on a quantitative data since a large amount of standardized data were examined.

2.2 Literature Studies

The literature study included to review published material about solar PV systems and legislation regarding fire safety. As well as the theory behind thermal conduction and fire risks with respect to the solar PV system. The literature study consists of books, scientific articles, reports, regulations, standards, and legislations. The literature was studied in respect to the problem statements.

The digital scientific archive (DiVA) was used to search for previously thesis regarding solar panels and Google was the primary search tool to find scientific articles and reports. Regulations, standards, and legislation was found on relevant authorities' websites. Articles, reports and handbooks was examined through access to the Luleå University Library.

To achieve a wide collection of information, countries different from Sweden regarding size, amount of installed solar PV systems and developed regulations regarding fire safety were examined. The choice of countries was also based on the accessible regulations, legislations, and guidelines. Regulations and guidelines for Europe, Sweden and the USA were found on the relevant authority website for each country. For Germany and Dubai, the guidelines and relevant articles were provided by the supervisor of this thesis. The timeframe of this thesis also limited the amount of countries examined.

3 Solar Photovoltaic Systems and Fire Risks

The following section describes the technical properties of solar PV modules and fire risks connected to solar PV systems. Thereafter, current legislation and regulations regarding solar PV systems are presented for different countries. Finally, the theoretical background of the FEM calculations in TASEF are presented.

3.1 Technical Specifications

The construction of a typical solar PV system and its components are presented in the following section. The two most common solar PV systems, Building Applied Photovoltaics (BAPV) and Building Integrated Photovoltaics (BIPV) are presented and described further.

3.1.1 Solar photovoltaic (PV) system construction

The solar panels of a solar PV system absorb sunlight and generates direct current (DC) through the photovoltaic effect. An inverter thereafter converts the DC into usable alternating current (AC). The electricity can then be used to power electronic devices. Excess electricity produced by the solar PV system can be fed to an electrical grid system. The whole process is shown in Figure 3 (Richardson, 2018).

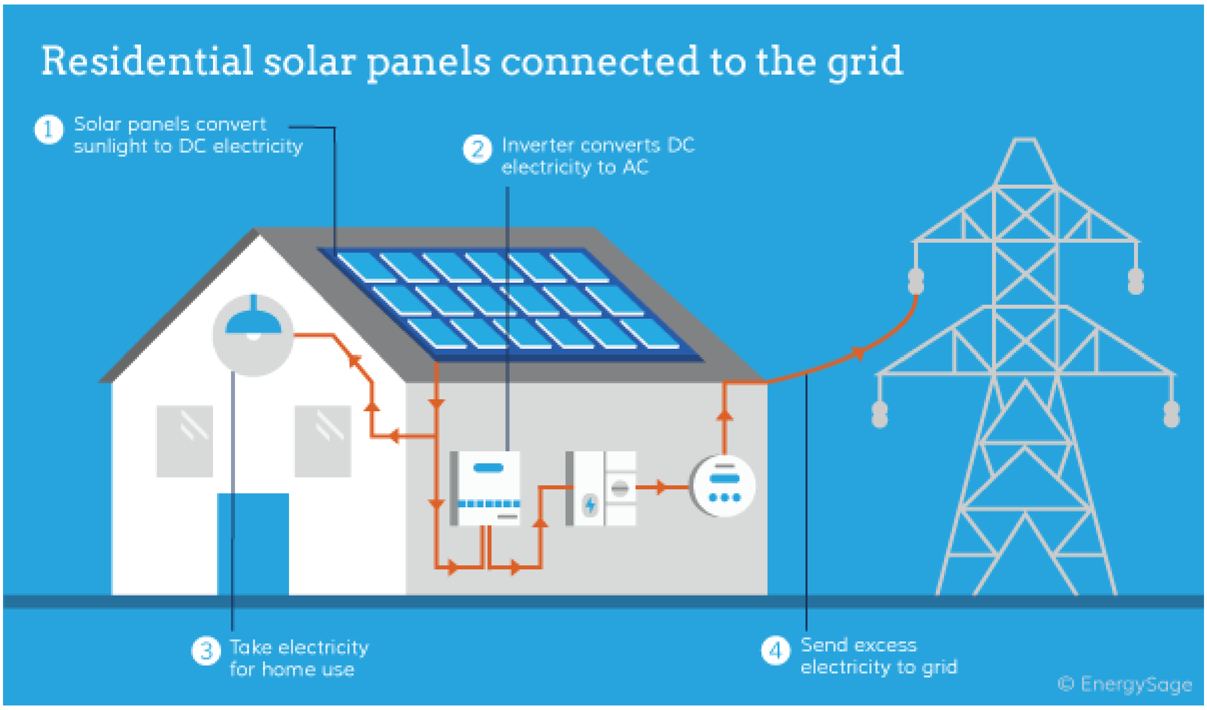


Figure 3: The different steps when producing electricity with solar PV systems (Richardson, 2018).

The electric properties of the PV modules are controlled by its active devices. The active devices are the solar cells. A solar panel consists of multiple solar cells in circuits and multiple solar panels forms a PV system, see Figure 4. To understand how solar panels produce electricity, the single cell properties need to be examined. The cell consists of two layers with different doping, where the base layers often consist of a semiconductor material. The top base layer, the emitter, doped with phosphorus donor atoms, provides free electrons as charge carriers. The bottom layer, the base, is doped with boron acceptor atoms, which provides as "free ways" regarded as free charge carriers. The top layer is called the n-type and the bottom layer is called the p-type. When electricity is produced, photons from the sunlight sets the two layers (n- and p-type) in contact. Immediately the n-type is positive of charge and the p-type is negative of charge. This results in a strong electricity force in the junction of the layers, which is associated to a diffusion voltage (Wirth, Weiß & Wiesmeier, 2016).

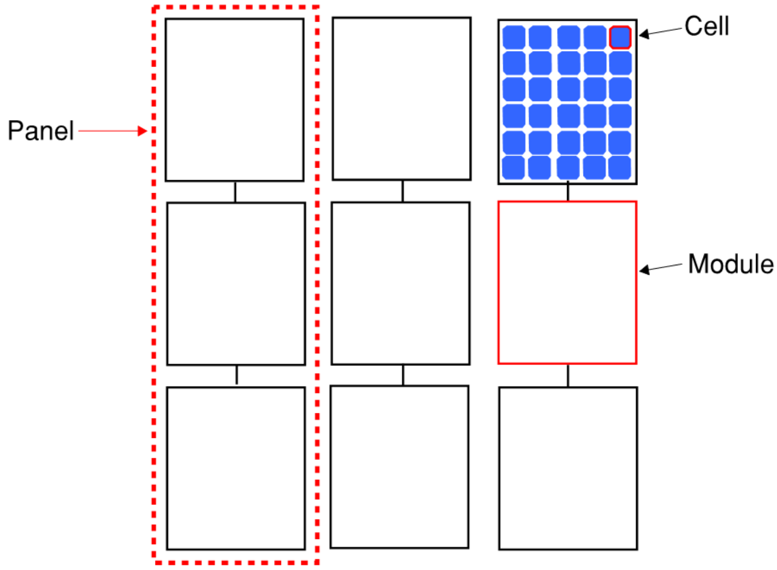


Figure 4: Description of the difference between solar cell, module and panel.

In order to connect the solar panels to the electrical system an inverter is needed. The inverter converts the direct current (DC) from the solar panel to alternating current (AC) (Sommerfeldt, Klintberg, Muyingo & Kristoffersson, 2016).

Solar panels can be divided into first-, second-, and third generation. The first generation includes the traditional types and is most conventionally used. These solar panels are made of monocrystalline silicon (Mnon-SI) or polysilicon (Poly-SI). The second generation is different types of thin film solar cells. These are used for PV power stations, building-integrated systems or smaller power systems. The third generation is still in the research or development phase and some of them may generate electricity using organic material or other inorganic substances (Bagher, Abadi Vahid, & Mohsen, 2015).

3.1.2 Building Applied Photovoltaics (BAPV)

According to the CFPA-E (2018b), PV systems are either building integrated systems or building additive (or attached) systems. Building Additive PV (BAPV) systems are attached to the building envelope. The solar panels are fixed in parallel to the building envelope or at an angle adjacent to the roof or facade. Figure 5 presents examples of different BAPV systems installed on either the roof of the building or the facade.

The mounting system of a BAPV system often consists of a supporting frame. The PV modules can thereby be anchored to the frame. The frame is anchored to the adjacent building components and supports the loads of the PV modules (Confederation of Fire Protection Associations, Europe [CFPA-E], 2018b).

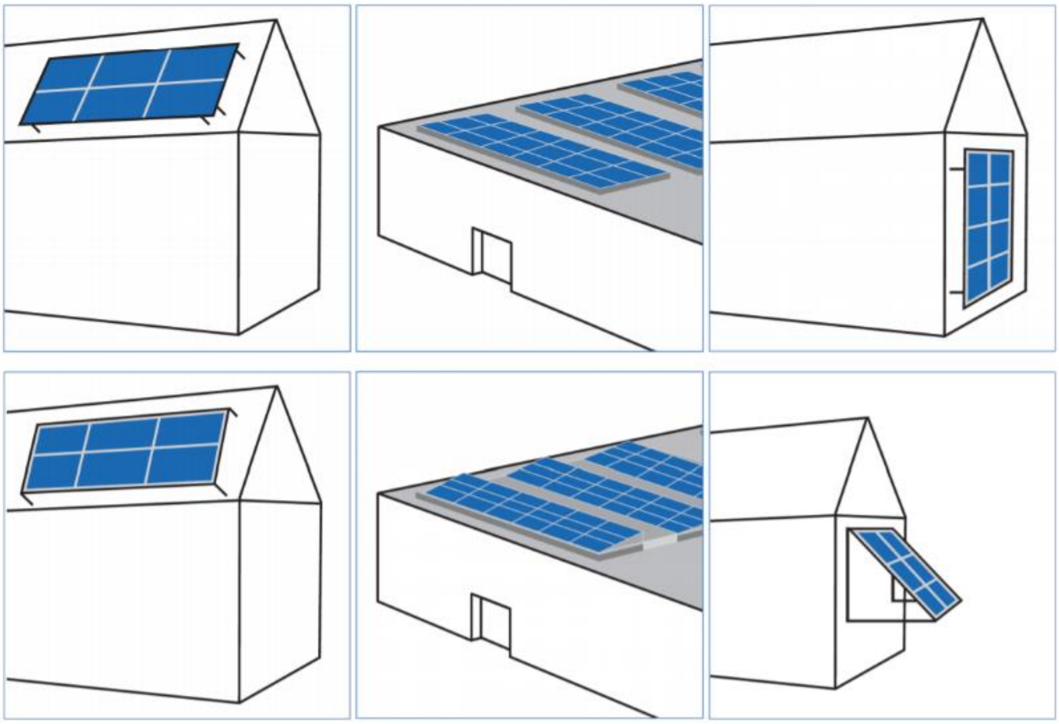


Figure 5: Examples of additive PV:s (CFPA-E 2018b).

In Sweden, BAPV systems are the most commonly installed solar PV system. Roof-mounted systems installed by private persons or companies stands for almost the entire grid-connected PV capacity. In 2016, the grid connected capacity was around fifteen times higher than the off-grid capacity and still growing. Privately owned systems for small houses represent about 32 % of the grid connected capacity. 62 % is built on company, agriculture or public buildings and the final 6 % are PV parks (The International Energy Agency [IEA], 2016).

3.1.3 Building Integrated Photovoltaics (BIPV)

Building Integrated PV (BIPV) systems form a part of the building envelope, meaning that they are integrated into the roof or the facade. Figure 6 presents examples of BIPV systems installed on the roof and facade of the building. Unlike BAPV systems, the BIPV system must meet the function of electricity and at least one of the construction functions, such as weather protection, thermal protection or electromagnetic shielding (CFPA-E 2018b).

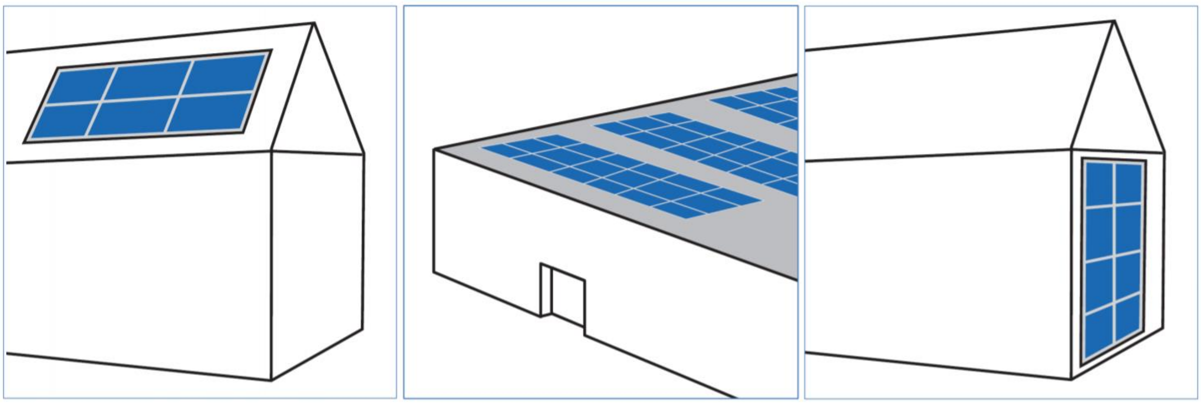


Figure 6: Examples of building integrated PV systems (CFPA-E 2018b).

The International Energy Agency [IEA] (2018) investigated and compared different international standards to develop a definition of BIPV systems. They separated the terms BIPV module and BIPV system. The following definitions were found as a conclusion:

A BIPV module is a PV module and a construction product together, designed to be a component of the building. A BIPV product is the smallest (electrically or mechanically) non-divisible photovoltaic unit in a BIPV system which retains building-related functionality. If the BIPV product is dismounted it would have to be replaced by an appropriate construction product.

A BIPV system is a photovoltaic system in which the PV modules satisfy the definition above for BIPV products. It includes the electrical components needed to connect the PV modules to external AC or DC circuits and the mechanical mounting systems needed to integrate the BIPV products into the building.

BIPV systems have a wider variety than BAPV systems. BIPV systems can be applied to curved surfaces, be custom-made, be different colours or transparent and integrated into windows. They can also be made from flexible material. In Europe, there are currently around 200 different products on the market and the installed capacity is expected to surpass 11 GW in 2020 (SolarPowerEurope, 2019).

BIPV systems are often developed to replace another part of the building envelope, e.g. the roof or the facade. The modules and panels are therefore often designed to replicate the replaced material. As seen in Figure 7, the PV cells can be integrated in both roof tiles and shingles (Pohjonen, 2016)

Figure 7: BIPV systems in roof materials. Picture (Solkompaniet, 2016).

An example of a building with a unique BIPV system is Copenhagen International School, see Figure 8. It was the largest BIPV system on a facade when it was put into use in January 2017. The facade in covered by 12 000 solar PV modules and has an installed effect of 720 kW (Stridh, 2018)

Figure 8: BIPV systems in the facade of Copenhagen International School (Stridh, 2018).

3.1.4 Material in solar PV systems

The structure of the solar panel is shown in Figure 9. The top part om the solar panel consist of the metal frame and the glass, thereafter a film of ethylene-vinyl acetate (EVA), the cells and another EVA-film and finally the back film. (Bagher, Abadi Vahid, & Mohsen, 2015). Ethylene-vinyl acetate is a form of plastic. (Britsh Plastic Federation, n.d)

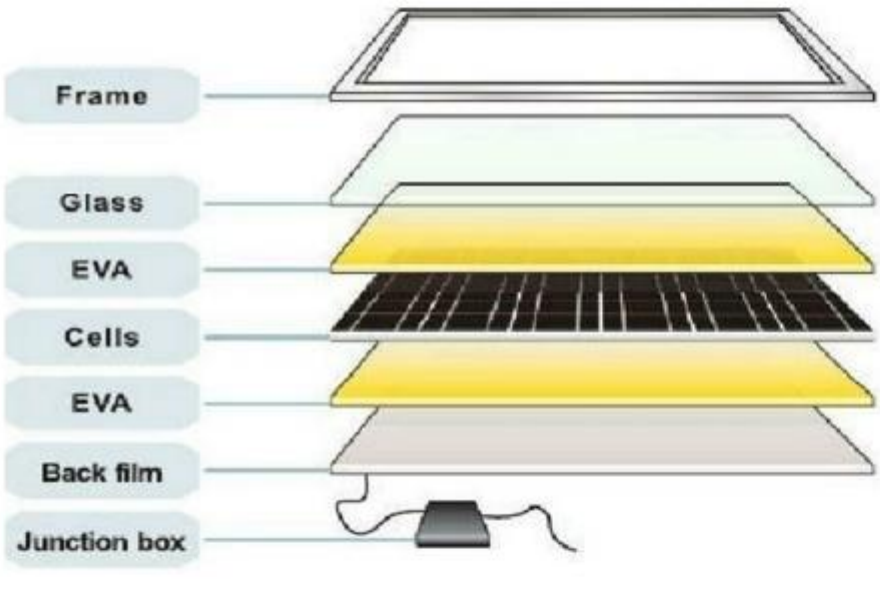


Figure 9. Solar panel structure, retrieved from Types of Solar Cells and Application(Bagher, Abadi Vahid, & Mohsen, 2015).

3.2 Fire risks related to solar PV systems

In an article from the Society of Fire Protection Engineers (SFPE) it is stated that solar PV systems come with specific risks. One associated risk is that the panels and their mounting system have a great impact on the combustibility of the roof system. As some solar panels include a backing of highly combustible plastic, the combustibility of the roof system increases when panels are mounted (SFPE, 2014).

When solar PV systems are installed on an existing building, they may increase the fire risk of that building. Depending on the components and their location, the solar PV systems can interfere with smoke ventilation systems and prevent the fire gases from exit the building. The systems can also be an obstacle during cooling and fire extinguishing operations. The risk of flame spread can also increase when solar PV systems are installed due to the presence of wiring and rapidity of fire development (Dubai Electricity & Water Authority [DEWA], 2015).

Laukamp et al. published in 2013 an investigation of heat damages and fires of solar PV systems. A statistical analysis of fire incidents in Germany between 1995-2012 showed that solar PV systems were involved in 400 incidents. In 180 of these incidents, a solar PV system caused the fire. The authors found that the number of incidents depending on the mounting type of the solar PV systems correlated to the fraction of each system on the current German market. However, BIPV systems deviated since they were the mounting type in 11% of the incidents but only represented 1% of the market. Table 1 presents the number of incidents depending on the mounting type of the solar PV system.

Table 1: Number of incidents depending on the placement of the PV system.

Mounting type of solar PV system	**Number of incidents**
Roof, stand off[1]	92
Roof, integrated	20
Façade	2
Flat roof/rack	27
Field	39

1. Stand off roof systems - solar panels are mounted on the roof and the roof are often hard roofing.

3.2.1 Electrical components

The work of Laukamp et al. (2013) examined the 180 fires caused by a solar PV system further and the location of the components originated the fires. Figure 10 presents the different system sections and the number of incidents each section had. The AC-section in the diagram includes all components from inverter output terminals to the point of coupling to the grid. The DC-section includes all components from string connectors at the modules to inverter input terminals.

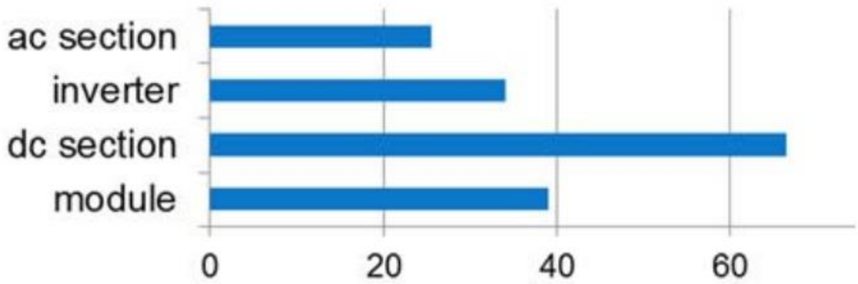


Figure 10: Distribution of system section where the fire originated (Laukamp et al., 2013).

As shown in Figure 10, the majority of the fires originated within the DC-section, which includes string, array cabling and array junction boxes. Thereafter the main system comprising of modules and inverters, accounts for roughly half of the fire incidents. Inverters are almost as often as the modules found as the critical component to start the fire.

Laukamp et al. (2013) also performed an investigation identifying the specific component causing the fire. Except for the inverter, a high number of fires were found in the module junction box. The number of fires in the module junction box was motivated by a combination of product defects and the deficient manufacturing quality. Incidents in other components were equally distributed and the authors concluded that all sorts of connections in a solar PV system are sensitive. The authors found that there are two "hot-spots" with an abnormal fire risk, product defect and installation errors. The distribution of 110 identified causes of fire are presented in Figure 11.

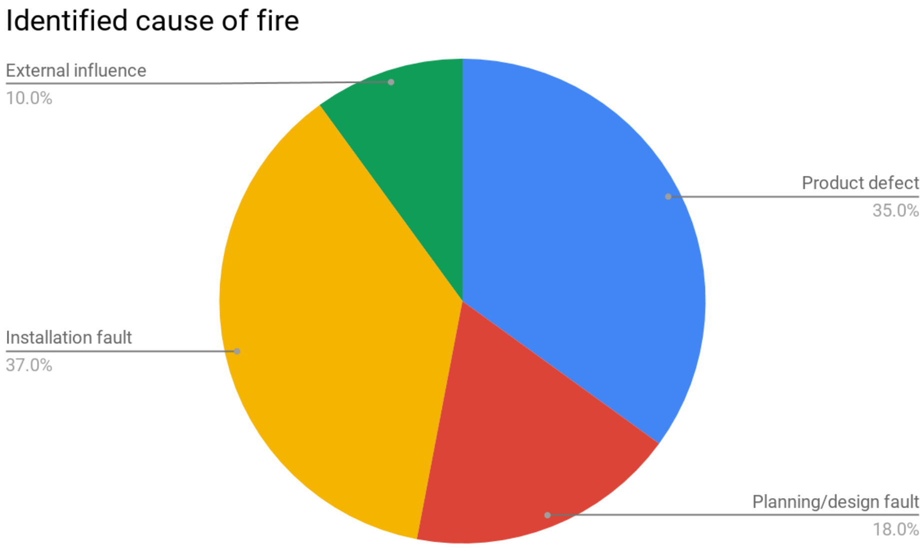


Figure 11: Distribution of identified incidents of fire.

Further, Laukamp et al. (2013) examined DC-switches, due to the high number of incidents found, and due to many inspectors reported overheated switches. A site where a fire had originated within a DC-switch was examined to further investigate this problem. A total of 15 switches was installed within the facility, eight switches were found, where two of these had charred terminals and six of them were still functioning. The suppliers of the damaged switchers were contacted. It was informed that hundreds of product replacement has been made due to charred terminals. It was also reported that one manufacturer was aware of the problem and had changed the design to replace the faston terminals by screws. Initially the fire investigator identified the DC-switch as the cause of the fire, but the final cause of the fire was lack of maintenance.

According to Laukamp et al. (2013) errors that occur in solar PV system have increased with the number of installed solar PV system. The most incidents occur during installation or under the first year of operation. This indicates that the cause of the most fire incidents are product defects and poor workmanship. A more detailed table of defects that caused fires in the solar PV systems are presented in Appendix A.

A reason for a fire origin in a solar PV system is faults in the construction. Khorshed Alam et al. published in 2015 a paper stating ground fault, line-to-line fault and arc fault as the major reasons behind electrical fires in solar PV systems (Khorshed et al. 2015).

Ground fault

All noncurrent carrying (NCC) metals/conducting part (e. g. module frame, mounting racks etc.) of a solar PV system are connected together to the ground or earth. If an electrical connection is established between the current carrying connectors (CCC's) and the NCC conductors due to fault, there would otherwise be a potential risk of electric shock hazard. Proper grounding during installation is therefore an essential part to provide adequate personnel and system safety. Potential reasons for ground fault are cable insulation damage during installation, ground fault within the PV modules, insulation damage of cables due to chewing done by rodents and accidental short circuit inside the PV combiner box. A ground fault within a solar PV system is important to detect, otherwise it can generate a DC arc within the fault and cause a fire hazard (Khorshed et al. 2015).

Line-to-line fault

If a short circuit occurs between two different parts of a solar PV system with different voltage potential, a line-to-line fault may occur (RISE, 2018). The chance of detecting a line-to-line fault depends on the illumination at the time the fault occurs. If there is low illumination (e.g. during night), the current through the affected strings is too small to melt the over current protection devices (OCPDs). The fault can therefore remain undetected and may cause a fire due to high fault current through the PV modules (Khorshed et al. 2015).

Arc fault

Since a solar PV system is assembled by several electrical components, it contains many junction points. The PV system delivers continuous DC as long as the module is exposed to a light source e.g. the sun. DC generates a high voltage which can create arcs more easily than a regular electrical installations with 230 volt AC. This affects the junction points and cables of a PV system. Since the PV systems are placed outside, the components are exposed to different weather conditions over a long time e.g. wind, water, temperature changes and UV-radiation. Most of the solar PV systems are also connected by quick connections to reduce the risk of misconnections and facilitate the assembly. However, if quick connections from different producers are connected together, this can lead to bad connections over time (RISE, 2018).

A critical component regarding fire safety of a solar PV system is the combiner box. It is located before the inverter, where the DC current is inverted to AC, and is the place where numerous wires from the panels are connected. Due to its location before the inverter, it is subject to considerable voltage and may cause electrical arcs. The arcs can thereafter ignite the roof assemble and a fire can spread under the solar PV panels. To reduce the risks of ignition of the electrical components, micro-inverters can be attached to the solar PV panels where the inverter convert voltage from DC to AC (SFPE, 2014).

Sepanski et al (2015) also state that defective and prematurely aged contacts of components are a source of risks. In the long term, these defects lead to overheating and can cause schoring or electric arc. If the components are placed on a combustible material, a fire can occur and lead to devastating consequences. The authors also discuss that electric arc detectors can reduce risks but that more research is needed since they currently do not have great detection reliability or a low tendency to fault activation. (Sepanski et al, 2015).

Cables

To prevent fires from occurring in PV systems with cables as the ignition source, Allianz (2019) has stated some general recommendations. They state that the cables used in PV modules should be suitable for outdoor applications since severe weather conditions and sunlight increases the aging process. Further they state that the cables should be flame resistant and fixed, loose cables should not be allowed. Regarding the routing of the cables, positive and negative wirings can be routed in separate conduits to minimize the risk of arcing. The cables should neither be routed over sharp edges or comprise fire compartments of the building. If the routing e.g. penetrates a fire wall, the openings need to be protected in accordance with applicable fire wall standards. If combustible materials are present at the roof, direct contact with the materials and cables/connectors should be avoided. Finally, the main DC cables from the PV panels to the inverter should be routed along the exterior of the building (Allianz, 2019).

The organization responsible for standardisation in the field of electricity in Sweden, SEK Svensk Elstandard, developed a guidance with advice and regulations for the electrical installation of solar PV modules (SEK Svensk Elstandard, 2019). They state similar advice as Allianz above but also includes that special considerations should be made when PV modules are installed on agriculture buildings. Since the risk for rodent is higher cables can be protected by using steel reinforcement or strategic placing.

3.2.2 Fire dynamics

When a solar PV system is installed on a roof, the fire dynamic of the roof changes. In laboratory-based fire tests of roof coverings without solar PV systems (UL 790, 2004) (ASTM E108, 2011), the maximum fire spread allowed is approximately 1.9 to 3.7 m^2, depending on the roof rating (American classification). However, real roof fires have ended in fire damage on roof areas between 93 to 17,000 m^2 when solar PV systems have been mounted on the roof (SFPE, 2014). This wide disparity identifies a concern that the FM Global Research Campus in West Glocester, USA, has examined. A test was conducted with ASTM E108 (2011) test apparatus, where the solar PV panels were placed on a, in the USA commonly used, roof assembly. The roof assembly held the highest fire resistance class (Class A, which includes concrete and clay roof tiles). The test was considered failed when one of the following three criteria occurred:

- Fire spread laterally to both edges of the sample
- Material continues to burn after falling to the floor
- Fire spread across the 4 m length of the assembly within 90 seconds.

The associated test failed in all three criterias (SFPE, 2014).

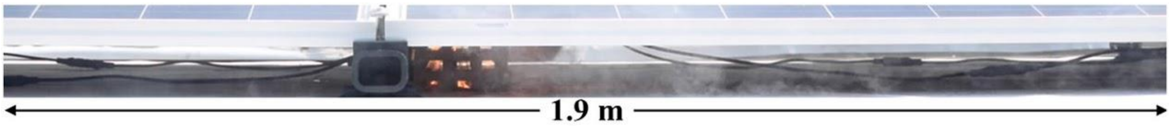
Research on mounted solar panels on roofs have been conducted at the Underwriters Laboratories, Northbrook. The research has shown that when mounting a PV panel on a roof, the fire dynamics on that roof assembly changes. This regardless of the materials used in the construction of the solar PV panel. Even tests performed with a cement panel simulating the presence of a solar PV panel have demonstrated an increased fire spread across the roof assembly (SFPE, 2014).

SFPE (2014) also discuss three main consideration that affects the fire spread along a roof:

- In a typical roof fire the flame is vertical when not affected by wind. When such flame spreads under solar panels, the flame is redirected much closer to the roof surface and almost parallel to the roof. This results in an increased incident heat flux to the roof surface, often above the roof materials critical heat flux.
- Even though the fire classification of a roof is an effective way to assessing the fire performance of a roof, even assemblies containing non-combustible materials will contribute with some fuel to the fire spread. However, this is not the case when solar PV panels are mounted on a metal roof assembly.
- Fire spread is likely to continue up and down at the back of the solar panel and beneath the roof assembly. This due to the bottom of the panel may include some combustible materials in forms of polyester-based materials in the encapsulants and back sheets.

Steemann Kristensen, Merci & Jomaas (2017) showed that when PV panels are installed on top of roofs, the fire dynamic of the roof construction largely changes. The received heat flux to the roof surface significant increases when compared to a baseline test without the reflection from the PV panel. The incoming heat flux to the roof also behaves contrary to the basic view factor theory. The highest heat flux was shown under the most elevated part of the panel. This was explained by two flame related reasons. The first corresponds to that the flame is spreading upwards and deflects to the more elevated part of the panel. This results in an increased amount of radiation from the flame towards the surface. The deflected flame also contributes to the second reason, the non-homogeneous surface temperature of the PV panel. This contributes to a non-homogeneous emission from the heated PV panel.

Full-scale experiments confirm the change in fire dynamic as the lab-scale studies focusing on the re-radiation described above. A PV array consisted of six PV panels on a flat roof construction was examined. The experiments showed that a fire underneath the PV array propagated quickly, see Figure 12. This since the PV panels reflect an additional contribution of heat to the fire. The experiments also indicate that the geometry of the PV installations can have a significant influence on the propagation. Combustible construction materials can become fuel loads and contribute to a hazardous scenario if a fire ignites underneath the PV installation (Steemann & Jomaas, 2018).



(a) Time: 6 min 56 s (frame 5 of 60), no ignition of membrane

(b) Time: 6 min 56 s (frame 6 of 60), ignited material drops on right side of wood crib, below edge of PV panel

(c) Time: 6 min 56 s (frame 7 of 60), ignited material continues to burn before it hits the membrane

(d) Time: 6 min 56 s (frame 8 of 60), the falling, burning material ignites the roofing membrane

(e) Time: 7 min 6 s, the fire is self-sustained

(f) Time: 7 min 21s, the fire propagates towards the right side

(g) Time: 7 min 27 s, the fire propagates further towards the right side

(h) Time: 7 min 53 s, the fire ignites the cables underneath the panels

Figure 12: Fire development between the roof and the solar panels (Steemann & Jomaas, 2018)

Steemann & Jomaas (2018) examined a typical roof construction of a warehouse where the roof membrane consisted of expanded polystyrene (EPS) and BROOF (t2) classified polyvinylchloride (PVC-based). A mitigation layer of either 30 mm mineral wool or 40 mm polyisocyanurate (PIR) was placed between the roof membrane and the PV panel. This to establish whether or not ignition of the EPS could be avoided. After one hour, the EPS had not been ignited, for both the experiment with the PIR insulation and the mineral wool. After one hour and three minutes, the mechanical properties of the PIR insulation failed and the EPS was ignited.

3.2.3 Examples of real fires with solar PV systems

This section presents real examples of fires where solar panels were installed on the roof of the buildings.

Vestby, Norway

A 10 000 m^2 freezers warehouse was in April 2017 subject to a fire (Brannmannen, 2017). The fire originated in a truck located in the freezer area and the fire spread to the roof. The fire continued for seven days and was believed to be extinguished but restarted after two days in the stored groceries and continued to spread within the building. The greatest risk except for ammonium, fire spread to other warehouses or residential buildings was the solar panels. The fire in the solar panels was tried to be extinguished 30 times by helicopters that dropped 3000 liters of water each time. This method proved to be very effective to reduce the flames and limit the fire spread. However, the fire was not fully extinguished and finally it was decided to tear down the building to completely stop the fire spread (Brannmannen, 2017).

The conclusions from the fire brigade was that the fire was difficult to extinguish and the greatest risks considered was the solar panels since no fire personnel were allowed to be on the roof. The height of the building and the structural damage on the roof construction also contributed to difficulties in the extinguishing work (Brannmannen, 2017).

Exeter, UK

In May 2013 the three storey hotel Teign Valley Golf Club was destroyed by a fire. The fire originated in the wooden-framed extension used to get from the golf course to the hotel. Thirty firefighters fought to extinguish the fire. The fire fighters could not reach the roof or enter the building as solar panels were installed on the roof, which meant that the building had live electricity. Therefore the fire spread more rapidly then they could handle and this resulted in that the entire building was destroyed (BBC, 2013).

Sweden

In Sweden, fires have occurred in buildings containing solar PV systems. Of the reported fires not all originated within the solar panels, in some fires the building only had solar PV systems installed. It is difficult to know exactly have many fires that are associated to solar PV systems since the statistics about accidents and fires do not include that. When the fire brigade report what have happened at a fire or accident, solar PV systems cannot be chosen as a cause of fire. (MSB, 2019a).

Table 2 presents three different fires in Sweden including solar PV systems. The cause of the fires as well as their consequences are stated.

Table 2: Errors that have caused the fire ignition and its consequences

Incident	**Cause**	**Consequences**
Fire in the solar panels (Tjugofyra7, 2016).	Poor workmanship during installation, as the DC-cabling was mounted together and in a tube. The DC-cables was probably damaged due to weather and sharp metal edges that caused insulation damage. As the insulation was damaged a connection between DC-cables was created (Tjugofyra7, 2016).	A short circuit in the DC-cables and an electrical arc. From the electric arc, the temperature reached 2000 - 3000 C which resulted in melted material such as the aluminium constructions, protective glass, copper cable and the steel sheets on the roof. This resulted in more electrical arcs and the arcs stopped when the solar panel have melted and the connection between the plus and minus sides of the module were broken. The temperature under the steel sheet was so high that the fire occurred inside the building (Tjugofyra7, 2016).
Solar PV system overheated boiler during power failure (Tjugofyra7, 2017).	During power failure the solar PV system still produced DC electricity into the boiler. The boiler had two independently protections. Where the overheating protection system should when temperatures are above 93°C disconnect the solar PV system, which in this case did not occur (Tjugofyra7, 2017).	Smoke production in the isolation around the immersion heater to the boiler (Tjugofyra7, 2017).
Fire within the cables in a PV system (Schultz, 2018).	The cabling in the distribution box caught fire (Schultz, 2018).	Smoke production from the solar panels (Schultz, 2018).

4 Legislation and regulations

Legislation and regulations regarding solar PV systems can either be found in international standards and guidelines or in national legislations. The following section presents different regulations, guidelines and standards for fire safety regarding both preventive measures and fire brigade operations of solar PV systems.

4.1 International Regulations

The International Electrotechnical Commission, IEC develops international standards and conformity assessment for all electrical, electronic and related technologies. In 2016, a new standard IEC 61730 of PV module safety qualification was published, part 1 (2016a) and part 2 (2016b). Part 1 provides requirements for construction and Part 2 requirements for testing.

4.1.1 European Union

National organisations working with fire prevention, protection, safety and security in Europe are working together in an association called The Confederation of Fire Protection Associations Europe (CFPA-E). CFPA-E develops common guidelines regarding fire protection, natural hazards and security. Their aim is to achieve similar interpretation in European countries and to give examples of acceptable solutions, concepts and models (the Confederation of Fire Protection Associations Europe [CFPA-E], 2018a).

The CFPA-E has developed a guideline (CFPA-E, 2018b) regarding recommendations of PV systems and on loss prevention. The following sections presents a compilation of the recommendations in the guideline considered most relevant to the study.

Recommendations regarding electrical components

The guideline initially state that solar PV systems and its components should conform to generally recognized rules for electrical installations. Nine European standards regarding electrical installations are listed including recommendations that PV systems should be protected against lightning and overvoltage.

The guideline further states that components with combustible elements such as cables, are not allowed to pass over compartments/fire walls. If that could not be achieved, the cables must be installed in fire-resistant cable ducts or shafts, see Figure 13.

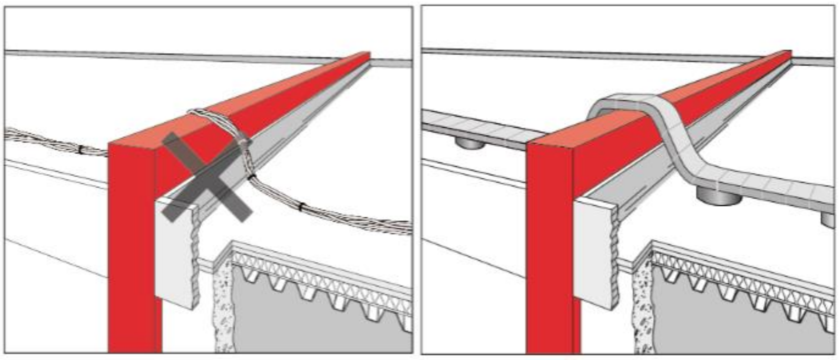


Figure 13: Cables passing a fire wall should be fire protected (CFPA-E, 2018b).

Further, the guideline suggests that fire brigades should be able to disconnect the power from the PV modules. A “Fireman's switch” should be located in a nearby and easily accessible location. This in order to isolate the power supply from the PV modules.

Recommendations regarding placing, roof access and signage

The guideline presents the following recommendations regarding placement of the solar PV modules, required roof access and signage

- Solar PV systems installed on roofs should be placed with a minimum distance of 2.5 meters on each side to a compartment/fire wall. The distance may however be reduced if the potential for a fire to spread across the compartment boundary is assessed by a fire consult.
- Continuous installation areas and rows of solar PV panels should be divided into sufficient width in order to provide access for fire fighting operation and maintenances. The PV system should not exceed a width of 40m and the distance between PV systems should be at least 5m.
- If smoke and/or heat exhaust ventilation systems are installed on the roof, the PV system must be kept on a sufficient distance from the ventilation. These requirements are from the manufacturing industry according to wind tunnel tests. An example of sufficient distances is presented in the guideline.
- If solar PV systems are mounted on the facades, the requirements of the associated building regulations in terms of fire spread along the facade applies. Solar PV system on the facade should meet the same requirements as the rest of the facade.
- Buildings with solar PV systems should be provided with informative signage. The signs should be situated at the
    - Origin of the electrical installation,
    - Metering position (if remote from the origin); and
    - Distribution board to which the supply from the inverter is connected.
- Signage should be provided to direct fire rescue personnel to the location of the “Fireman's switch”.

4.2 National Regulations

The following section describes national legislation and regulation.

4.2.1 Germany

According to the Renewables 2020 Global Status Report from REN21, Germany is the country in Europe having the largest installed solar PV capacity (REN21, 2020). Figure 14 presents a diagram of the global solar PV capacity between 2009-2019. Germany has, according to the diagram, always been a large part of the market.

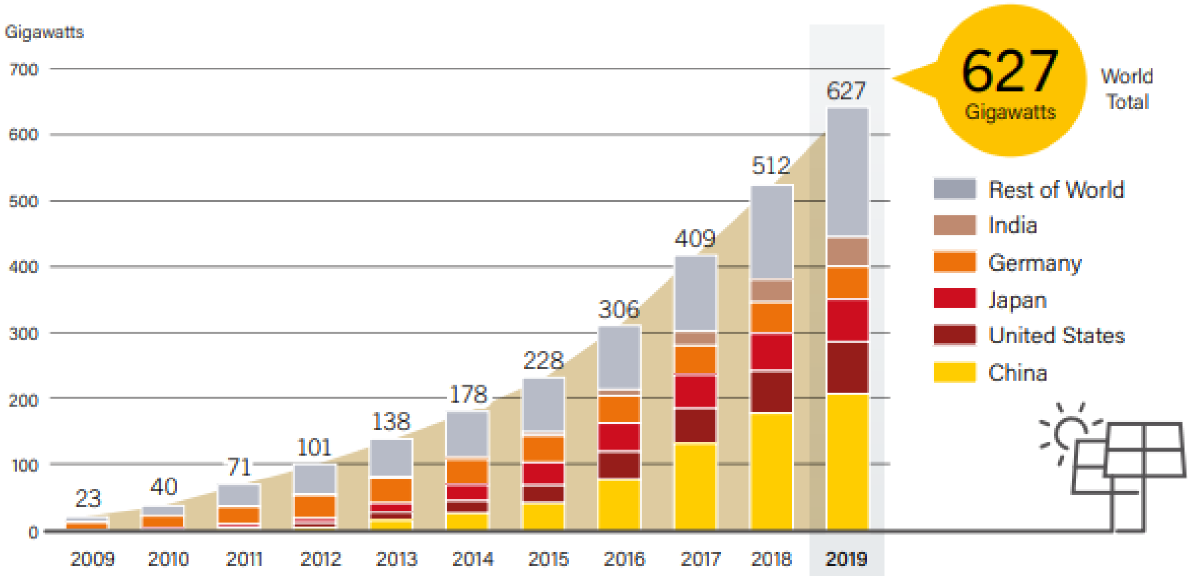


Figure 14: Solar PV global capacity, by country or region, 2009-2019, (REN21, 2020).

The legal framework German Renewable Energy Act (EEG) includes the current standards and requirements for the components of solar PV systems in Germany. Sepanski et al. (2015) present in their report a list of the most important standards and series of standards in reference to PV systems from the EEG. The list contains standards for both configuration, requirements on PV modules, PV inverters, mounting system and DC components. A total of approximately 50 standards and guidelines are listed and briefly described.

The information accessible for this work regarding German regulations has been a guideline for fire protection regarding solar PV systems. Experts, planners, installers, associations and the fire brigade developed a guideline (Expertenkommission, 2011) for installers and planners regarding the fire safety of solar PV systems. The information in the guideline is based on structural and fire safety standards and recommendations. The following section presents a compilation of the guideline and the information considered most relevant to the study.

Recommendations regarding electrical components

- DC - cabling over 1 meter should be fire protected or mounted outside of the building.
    - Installation in the entrance and in one or two storey building should be avoided.
    - When installing cabling outside the following is required:
        - Waterproofed cabling.
        - DC-cabling must be visible for the fire brigade.

    - DC-cabling is not allowed in emergency exits or in the fire brigade access.
    - When solar panels are in operations, no damage on the cabling insulation are allowed.
- Inverters are to be installed outdoors or directly at the entrance of the building, so that only AC cables are installed inside the building.
  - Inverters installed outside should:
    - Not to be placed in the rescue route.
    - Be accessible for the fire brigade.
    - Be waterproof.
    - Comply with the associated conditions on the installation site.
  - Inverters are recommended to be placed on a non combustible material with an additional 10 cm on each side.
  - The inverter should not be placed near combustible materials.
- The DC disconnector is to be placed in the area of the building's main fuse.

Sepanksi et al. (2015) mention in their guideline that a rapid shutdown for PV systems is not generally required. However, it can be an optional solution if structural measures e.g. safe routing of cables or cables and inverter placed outdoors are not regarded as sufficient. The authors also state that despite the potential presence of a switch-off device, rescue personnel often need to assume that the system is de-energized. This since emergency teams work under time pressure and the time is very critical when rescuing people are prioritized. A safe switch-off is very time consuming and can therefore not be guaranteed.

Regarding extinguishing methods, Sepanksi et al. (2015) state that if a distance of 5 m with full jet and 1 m with spray jet is maintained, hazardous electric currents via the extinguishing water will not be a danger to the rescue workers.

Recommendations regarding placing, roof access and signage

The guideline presents the following recommendations regarding placement of PV systems, how to provide roof access and proper signage:

- If PV systems are installed on hard roof[1] or the modules do not meet the requirements of hard roofing, structures should be in accordance with §32 MBO[2]. A minimum distance from the PV system to the middle of the fire wall is recommended to be 1.25 meter.
- Roof integrated PV systems that meets the requirements of hard roofing can be build up to the overhang of the fire wall.
- Cable penetrations through fire walls must be in accordance with MLAR[3].

If the above distances are not fulfilled, a reduced distance can be permitted if a fire protection assessment is considered.

[1] Hard roofing means that the roof must be fire resistant against sparks and radiation (Expertenkommission, 2011).
[2] MBO - (Musterbauordnung) New Model Building Code issued by the German construction minister conference (Kathage, 2016).
[3] MLAR - A building code that regulates the fire protection for pipelines and electrical installations issued by the German construction minister conference (Düker, n.d.).

Solar panels placed on roofs need to be accessible for the fire brigade. The following section presents different scenarios and the associated recommendations.

When placed on pitched roofs or roofs occupied on both sides, clear access pathway with a width or 1 meter should be provided. Also, an accessible opening with a clear width of 90 cm and a height of 120 cm is to be provided. See example in Figure 15.

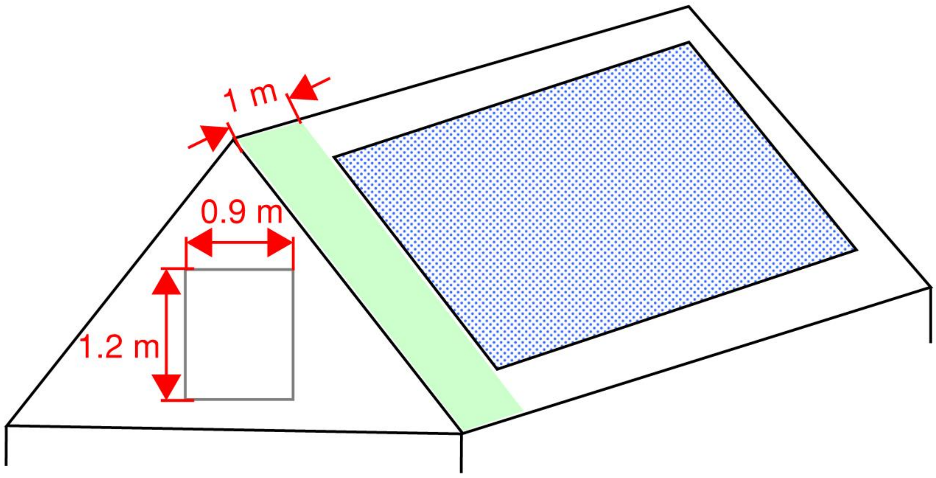


Figure 15: Roof access on pitched roofs or roofs occupied on both sides.

To access flat roofs or pent roofs without access through openings or windows and a floor space of 40 x 40 meter without fire walls. The roof access can be created with a clear access pathway with a width of 1 meter. PV systems with a width up to 20 meters are recommended to have a clear access pathway of 1 meter. See example in Figure 16.

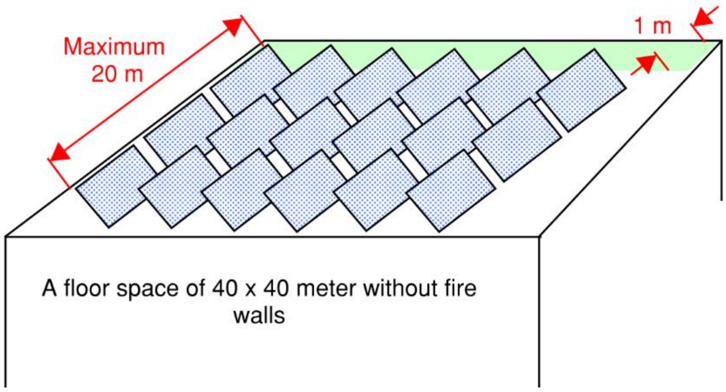


Figure 16: Access on flat roofs or pent roof without access through openings or windows and a floor space of 40 x 40 meter without fire walls.

Large flat roofs with PV systems up to 40 x 40 meter should have access around each PV system with a clear access pathway of 1 meter so that the safety for the fire fighters can be maintained. For other roof constructions it is recommended to consult a fire consult. See example in Figure 17.

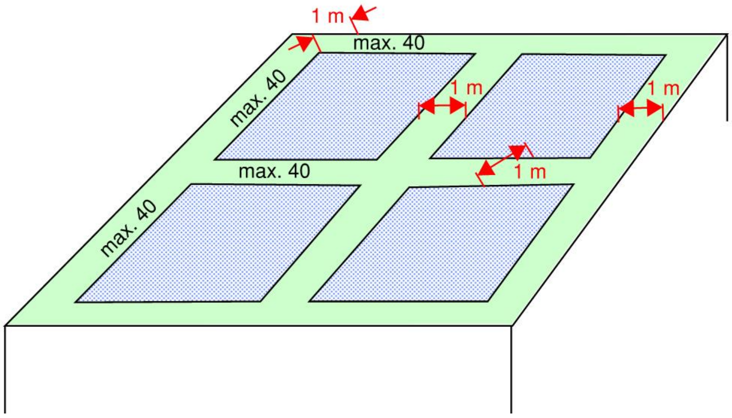


Figure 17: Access on large flat roofs with PV systems up to 40 x 40 meter.

Fire brigade operations of PV systems are based on the same principles as firefighting in other low-voltage electrical installations. However, in order to achieve a safe environment for fire fighters the following recommendations for organizations, structural and technical means can be considered.

- Signage of PV systems are to be located at the service connection box and the house distribution.
- Plans for emergency services regarding PV systems and additional information should be placed near the existing fire plans.

4.2.2 Sweden

In Sweden, there are no current legislation and regulations regarding solar PV system. However, the safety in case of fire of construction works are regulated through mandatory provisions and general recommendations in Boverket's building regulations (BBR). Guidelines have been developed to achieve a similar interpretation of how solar PV systems should be installed and what safety requirements should be present. The following section presents a compilation of requirements found in acts and guidelines relevant to the study.

Requirements regarding electrical components

Roof covering is defined as the protection of the building against the external climate. Regarding PV systems installed on roofs, it is important to separate integrated PV systems and non integrated PV systems. Non integrated PV systems do not take part of the actual roof covering and do not need to fulfill the requirements for roof covering. Although, buildings with non integrated PV systems still have to meet the requirements for general fire protection, described in Chapter 3, 8 § of the Planning and Building Act (Boverket, 2018c).

Since photovoltaic systems are not regulated in detail in the swedish planning and building ordinance (PBF), a guiding level of requirements can be retrieved from a similar situation that is more regulated. The most similar requirements regarding roof covering are presented in Boverkets building regulations, BBR chapter 5:62. The fire protection level BROOF(t2) is there suggested as a guiding level of the fire protecting level. However, other differences can be discussed and thereafter reduce the fire protection level (Boverket, 2018c).

The general recommendations in BBR Ch. 5:62 state that combustible roof covering can be used on combustible roofing underlay if the distance to a nearby building is at least 8 meters or if the building is a residential house with one or two apartments.

Requirements for non-integrated and integrated PV systems in the facades are discussed similar to roof covering. The basic requirements are described in Chapter 3, 8 § of the Planning and Building Act and the requirements are presented in BBR Chapter 5:551. The fire protection level of the facade is depending on the building class Br0, Br1, Br2 or Br3 where the building class 0 have the highest level of protection (Boverket, 2018c).

The general recommendations in BBR Ch. 5:55 state that the cladding should only produce a limited amount of heat and smoke during fire. For facades in building class Br1 this means that cladding tested according to SS-EN 13501-2 should be designed to fulfil the requirements of the fire technical class EI60, EI120 or EI240 depending on the dimensioning fire load. To prevent fire spread inside the outer wall, the facade can be designed with non-combustible material (A2-s1, d0). However, combustible cladding can be used at special considerations. The outer walls should also be designed so that the risk of falling building components are reduced. To fulfil the requirements, the facade system can be tested according to SP FIRE 105.

Facades for buildings in class Br2 and Br3 should be designed to limit fire spread along the facade surface. The cladding should fulfil the requirements for class D-s2,d2 which includes combustible material.

Recommendations from the Swedish civil contingencies agency

The Swedish Civil Contingencies Agency (MSB) has developed a guidance (Myndigheten för samhällsskydd och beredskap, 2019) for rescue service operations when PV systems are present. The guidance state risks regarding PV systems, both connected to fire and personnel. Practical examples of typical fires involving PV systems are also presented in the guidance with suggestions for how to perform a rescue operation.

For extinguishing operations where PV systems are installed, a certain safety distance (both vertical and horizontal) is required depending on what extinguishing agent that is used, see Table 3. Furthermore, neither foam or saltwater should be used as extinguishing agent (MSB, 2019b). Foam increases the conductivity of water and should therefore not be used where PV systems are installed (Sepanski et al, 2015).

Table 3: Error that have caused the fire ignition and its consequences

Extinguishing agent	**Safety distance [m]**
Freshwater, closed water beam	10
Freshwater, scattered water beam	3
Powder	1.5
CO_2	1.5

To reduce the risks during a rescue operation involving PV systems, the current circuit should be broken at as many places as possible in the system. The danger for being exposed to electrical shock occurs when a person becomes a part of the electrical circuit. This can occur either when the person is in contact with both the positive and negative side of the circuit or between the positive and ground. Depending on which kind and location of an emergency switch, the risk reduces at different parts of the system. If there is a risk for falling objects, for example if PV panels are placed at a facade, a safety block should be established (MSB, 2019b).

In Sweden there are no existing requirements for signage of solar PV systems, therefore the signage is based on general requirements of warning signs from ELSÄK-FS 2008:2. The signage and its instruction should comply with the following:

- Signage should clearly define that the building contains safety/disconnected inverters
- Signage should be placed in close proximity to the solar panels, inverters and at the main centre which than the fire brigade can operate from. Additional information including technical specification and a map of the solar PV installation comprising the location of components and cablage between solar panels and inverters. Also, contact information to a person with knowledge of the solar PV installation, such as the installer or a property manager should be included in the information.

Recommendations from the Swedish fire brigades

In Sweden each municipality has its own rescue service, where the main responsibility of the rescue services is to strengthen the society's ability to prevent and provide against accidents (Sveriges Kommuner och Landsting, 2018). As mentioned above, there are no established laws, ordinances, mandatory provisions, regulations or general recommendations in Sweden specific regarding solar PV systems. Based on the recommendations from MSB and each rescue service own interpretation, several rescue services have developed their own advice to prevent and facilitate fire rescue operations.

Advice from nine different rescue services have been examined and a compilation of these is presented in Appendix B. A summary of the advice is presented below:

- Inverters should be placed near solar PV panels. This way, DC cables become as short as possible.
- The DC inverter should be placed as close as possible to the solar panels. With such inverter that the fire rescue can switch off the DC cabling. Ideally, each solar panel should be provided with inverters directly at, or inside the panel. The inverter should also disconnect the DC automatically if other power supply of the building is broken. The inverter should be manual and not be able to automatically return to the initial position.
- Control device for the DC inverters are to be placed at the entrance of the building, or alternatively in connection with the fire defence table. If the building has an automatic fire alarm, the control device should be placed at the control panel. Instructive signage should be placed in close connection with the control device.
- The firefighter switch, means that an inverter to the DC cabling is placed as close as possible to the PV panels. A control device to these inverters should be placed in the access pathway. If the facility has an automatic fire alarm with diverts to the rescue service, the inverter should switch off when the alarm is activated.
- Exposed DC cables should be placed clearly visible and labelled.
- Avoid placing solar PV panels in near proximity to the storage location for flammable and/or explosive goods.
- If possible, the whole roof area should not be covered by solar panels. Rescue services must be able to provide holes in the roof construction for ventilation of fire gases.
    - If the building is divided into different fire compartments, it should be possible to provide holes in the roof construction for ventilation of fire gases in all fire compartments.

- Contact information to a person with knowledge of the solar PV system should be accessible in connection with the building, preferably at the entrance at fire panel. A suitable contact person may be an installer, property manager or an expert on the facility.
- At larger facilities, information should be in the near to the control panel (if the building is provided with an automatic fire alarm) or at the entrance of the building. The information must include a technical specification of the solar PV system and a drawing overviewing the cable routing. It is important that the drawing illustrates which parts that still have power after the inverters has been used.

4.2.3 USA

The National Fire Protection Association (NFPA) is a global codes and standards organization based in the USA. NFPA delivers information and knowledge regarding fire, electrical and related hazards (the National Fire Protection Association [NFPA], 2019). Solar PV systems are addressed in five different codes and standards developed by NFPA. The NFPA 1, Fire Code (NFPA, 2017a) primarily provides requirements for firefighter safety during extinguishing operations. It also regulates and emphasis marking and access to the PV systems. Additional requirements on the solar PV systems is found in the NFPA 70 National Electrical Code (NFPA, 2016), NFPA 70B Recommended Practice for Electrical Equipment Maintenance (NFPA, 2018) and NFPA 70E Standard for Electrical Safety in the Workplace (NFPA, 2017b) . Finally, NFPA 5000 Building Construction and Safety Code (NFPA, 2017c) addresses requirements for solar PV system. The following section presents a summary of the requirements in the above mentioned codes considered most relevant to the study.

Requirements for electrical components

NFPA 70 National Electrical Code provide for detailed requirements regarding the electrical components of the solar PV system. It states that PV systems shall be permitted to supply a building or other structure in addition to any other electrical supply system. According to the code, all installation of equipment and associated wiring and interconnections shall be performed only by qualified personnel. The code further state requirements regarding the following subjects:

- circuits (maximum voltage, sizing and current),
- overcurrent protection (device ratings),
- arc-fault circuit protection,
- rapid shutdown (controlled conductors, limits, array boundary, initiation devices, equipment),
- disconnecting means (location, marking, maximum numbers of disconnects, ratings, type of disconnect),
- wiring methods (permitted methods, identification, grouping, marking, labeling, component interconnections, connectors),
- grounding and bonding (grounding configurations, fault protection, detection, isolation methods, equipment),
- marking (modules, identification of power sources, rapid shut-down),
- connections to other sources; and
- energy storage systems.

NFPA 70B Recommended Practice for Electrical Equipment Maintenance provide for requirements regarding maintenance of the solar PV system. The code states that maintenance programs should be planned at the time the system is installed. Attention should be given to the system after significant weather or environmental events due to its sensibility to weather and climate changes. Further, the code states that all maintenance should be performed only by qualified personnel. Detailed requirements regarding energy monitoring, array cleaning, emergency response, power quality, marking and labeling are also provided in the code.

Requirements for placing, roof access and signage

For building-mounted PV systems, NFPA 1 Fire Code states the following:

1. Marking
   a. Buildings with PV systems shall be permanently marked with labels depending on the rapid shutdown type. The code describes further what design (colors, text, text sizes) and information (diagram of the building, location of PV system) shall be on the label. It also presents where the labels shall be located and requires name and emergency telephone number to the company currently servicing the PV system on a label next to the main disconnect.
2. Roof Access
   a. Emergency access, pathways to specific areas, smoke ventilation areas and emergency egress shall be provided on the roof. All pathways shall be located in areas with minimal interference of vent pipes, conduit, or mechanical equipment.
   b. For one- and two-family dwellings and townhouses not less than two 36 in. (914mm) wide pathways, from gutter to ridge, on separate roof planes shall be provided on all buildings. On a roof plane with a PV array, a pathway shall be provided on either the same roof plane, an adjacent roof plane or straddling the same and adjacent roof planes.
   c. Other buildings than one- and two-family dwellings and townhouses shall allow for roof access as described above if they are similar to one- and two-family dwellings and townhouses. Otherwise, perimeter pathways shall be provided as presented in Table 4.

Table 4: Building lenght and pathway.

Building length or width along either axis	**Perimeter pathway**
≤ 250 ft (76.2m)	4 ft (1219mm)
> 250 ft (76.2m)	6 ft (1829mm)

Other pathways (width 48 in. (1219mm) or greater) shall be provided to fire fighters between array sections, to and around all ventilation hatches and roof standpipes. Pathways shall be provided at intervals no greater than 150 ft (46m). Non-gravity operated smoke and heat vents shall be provided with a 48 in. (1219mm) or greater pathway. The code describes further different options for providing pathways between array sections depending on present vents and skylights.

NFPA 5000 Building Construction and Safety Code provide for fire protection requirements as well as wind design and earthquake design. The code states that roof-mounted PV systems and the roof assemble they are mounted on should comply with the requirements of either:

1. ANSI/FM 4478, Approval Standard for Rigid Photovoltaic Modules
2. UL 1703, Standard for Flat-Plate Photovoltaic Modules and Panels, and UL 2703, Standard for Safety for Mounting Systems, Mounting Devices, Clamping/Retention Devices, and Ground Lugs for Use with Flat-Plate Photovoltaic Modules and Panels.

Recommendations from Los Angeles Fire Department

Los Angeles Fire Department (2014) has developed a recommendation for installation of PV systems. The following section presents a summary of the recommendations of what is considered most relevant to the study.

Recommendations for the roof access points:

1. Roof access points shall be located in areas that do not require the placement of ground ladders over openings such as windows or doors.
2. Located at load bearing walls where the access point does not conflict with overhead obstructions such as tree limbs, wires, or signs

Residential Systems (Single Family Dwelling/Duplex):

1. Access:
   a. Panels/modules shall be located in a manner that provides 3-foot-wide clear access pathways (3' clear width measured from the load bearing wall to the PV panel) to the ridge on all sides of each roof slope where panels/modules are located.
   b. Access pathway clear width shall not include any eaves or overhangs.
   c. Panels/modules shall be located no closer than 18-inches to a hip or valley if placed on both sides of the hip or valley.
   d. Where panels/modules are located on only one side of a hip or valley that is of equal length, the panels may be placed directly adjacent to the hip or valley.
   e. Roof slopes less than two units vertical in 12 units horizontal (2:12), panels/modules shall be located in a manner that provides a minimum 3-foot-wide clear access pathway (3' clear width measured from the load bearing wall to the PV panel) around the perimeter edges of the roof.

2. Dead Ends:
   a. Where there are two or more access pathways, the clear pathways shall be arranged so there are no dead ends greater than 25-feet in length.
   b. If any access pathway leading to a dead end is greater than 25-feet in distance, it shall continue on to the next access pathway.
   c. At no time shall any access pathway cause a person's travel distance to exceed 150-feet before arriving at another required access pathway.

The guideline (2014) also presents requirements regarding inverters, PV signage, location of PV relative to smoke ventilation in residential building, residential housing and commercial buildings. The commercial buildings and residential housing are also regulated, such:

1. Access: A minimum 6-foot-wide clear perimeter is required around the edges of the roof.
2. Pathways: Shall be established in the design of the solar installation and meet the following requirements:
   A. Located over structurally supported members.
   B. Center line axis pathways shall be provided in both axes of the roof. Centerline axis pathways shall run on structurally supported members or over the next closest structurally supported member nearest to the centerline of the roof.
   C. A minimum of 4-feet clear straight line pathway shall be provided from the access path to skylights and/or ventilation hatches.
   D. A minimum of 4-feet clear straight line pathway shall be provided from the access path to roof standpipes.
   E. A minimum of 4-feet clearance around roof access hatches with at least one 4-foot clear straight line pathway to parapet or roof edge.

4.2.4 Dubai

Dubai Electricity and Water Authority has published recommendations for DRRG (Distributed Renewable Resources Generation) solar PV systems. The recommendations are based on the IEC 61730-2 standard which includes the fire test (MST 23) for PV modules. With this small-scale test, the fire resistance of the PV modules is tested. The tested modules are serving as a roof covering material or are mounted onto a building over an existing roof. The modules are thereafter classified after their fire resistance where building integrated modules demands a higher class than building mounted modules. When using a PV module in place of a classified roofing material or mounted above an existing classified roofing material, the module needs to comply with both a spread-of-flame test and a burning brand test. These tests are performed to ensure that the modules are not easily flammable, afford the measurable degree of fire protection to the roof deck, do not slip from position, and are not expected to produce flying brands (Dubai Electricity & Water Authority [DEWA], 2015).

The design and installation criteria are divided into five parts: Basic requirements, Prevention of fire propagation from PV plant to inside the building, Minimum distance from smoke exhaust systems and openings on rooftops, Emergency disconnection and wiring penetrations of PV plants and Labeling and marking. The following section presents a compilation of the recommendations considered most relevant to the study.

Recommendations regarding electrical components

For emergency disconnection, a manual disconnector shall be placed on the DC side if the inverters are inside the building and at the AC side (recommended) if inverters are placed outside the building. If an external placement is not possible, a proper fire-compartment area can be used inside the building. Figure 18 present a comparison of these scenarios. Cables from PV modules to the disconnector passing on the inside of the building should be placed in a channel with a fire-rate protection of at least 30 min. The manual call point should be placed close to an external access as well as in a plain, well-lit and free of hindrance place.

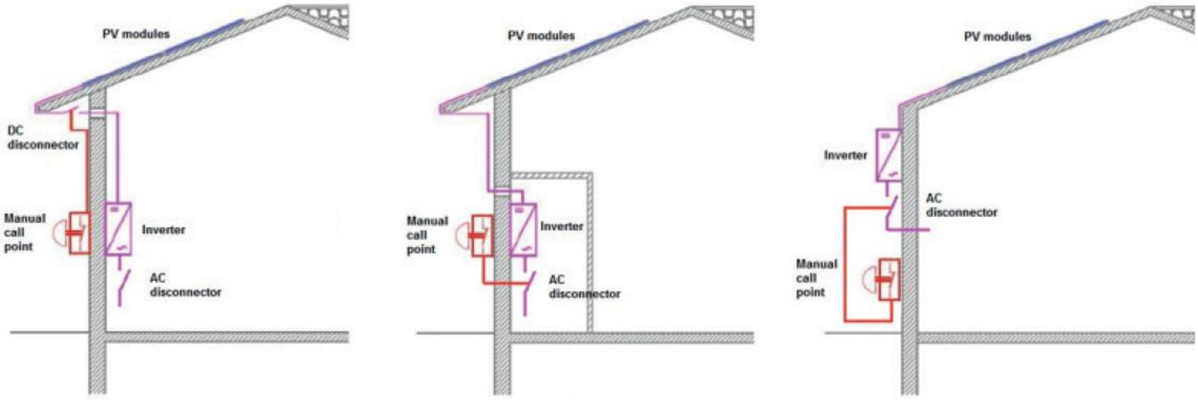


Figure 18: Manual call point locations.

If a BIPV system is installed in an unsatisfying fire compartment area the manual call point should also disconnect or short-circuit separate each module or group of modules. If this is not possible, an arc fault circuit interrupter should be installed and disconnect the DC side of a solar PV system if it detects a failure.

Recommendations regarding placing, roof access and signage

The basic requirements state that the PV modules shall fulfil applicable standards, rules and codes. The prevention of fire propagation can be achieved by ensuring that the roof where the PV module is attached is made of non-combustible material. If this is not possible, a layer of a non-combustible material (minimum fire-rating: 30 min) can be placed between the module and the roof. A risk assessment document shall also be submitted to the Civil Defence for approval.

PV modules or equipment connected to the module shall not cover any ventilation system and be placed at a minimum distance of 1 meter (top view) from the perimeter of any smoke exhaust systems. From other openings, e.g. chimneys and skylights, the modules shall be placed outside a distance of 0.5 meter (top view). The elevation from the roof to the PV modules shall be minimum 50 mm.

Regarding labelling and marking, warning signs shall be placed in any area where accessible PV modules, components and wirings are located. The signs should be a minimum size of 200 x 200 mm and be UV resistant. A simplified site plan with the position on PV modules, cables and disconnectors should be placed near the main energy meter or at each manual call point, see Figure 19 for an example.

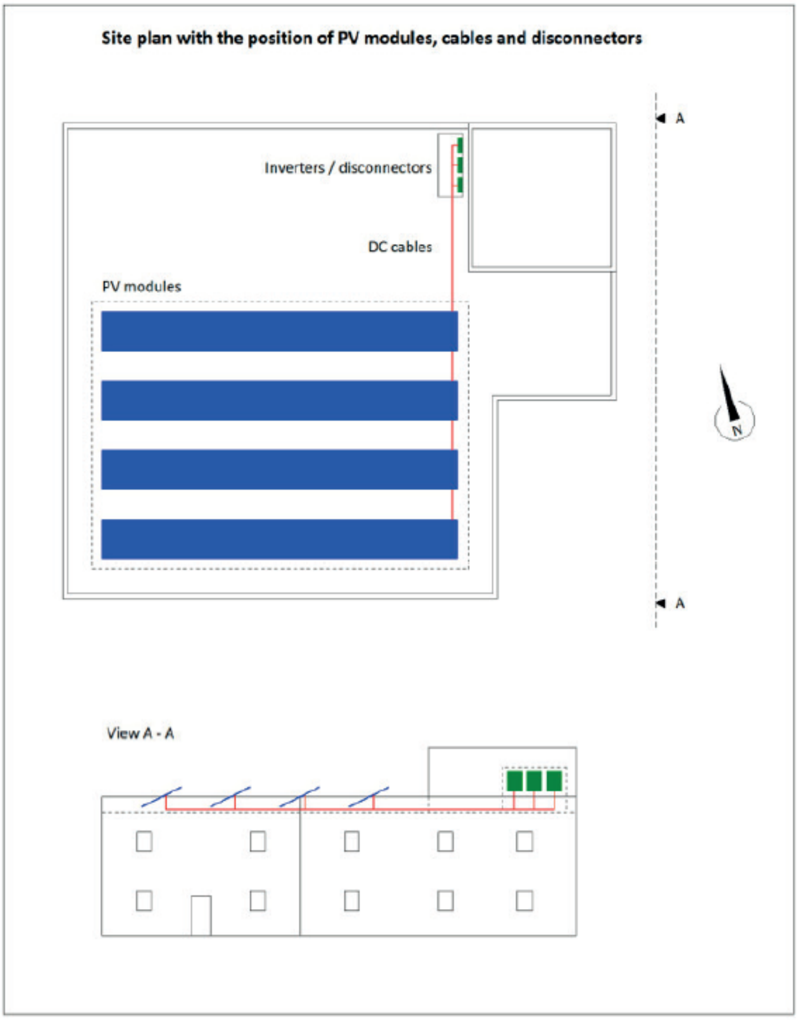


Figure 19: Example of simplified site plan.

4.3 Standards for testing PV modules

The Building Research Establishment (BRE) National Solar Centre published 2017 a literature review of standards relevant to fire safety connected to solar PV installations. A total of 87 standards related to fire and solar PV systems are listed in the report (BRE, 2017). Some of the most relevant standards connected to testing of solar PV modules are presented below.

IEC 61730

IEC 61730 is an international standard developed by the International Electrotechnical Commission consisting of two parts. Part one, IEC 61730-1, specifies and describes the fundamental construction requirements for PV modules and part two, IEC 61730-2 the requirements of testing. The standard assess requirements to prevent electrical shock, fire hazards and personal injury due to mechanical and environmental stresses. The standard refers to ISO 11925-2 considering ignition which is a test standard used in the european classification on construction parts. ISO 11925-2 where the test sample are being exposed to a 20 mm long flame for 15 or 30 seconds and thereafter classified. To examine the fire protection of the module from external fire sources, the standard refers to national or local regulations and requirements (IEC, 2016a-b).

EN 13501-5

EN 13501-5 is a standard used to test and classify roof coverings (European Committee for Standardization [CEN], 2016). The standard refers to four test methods described in CEN/TS 1187.

CEN/TS 1187

CEN/TS 1187 describes four different test methods of external fire exposure to roof covering. The technical specification does not mention PV module specific however, according to e.g. BBR, BIPV modules should fulfill the same requirements as for roof covering. BAPV modules on the other hand, do not necessarily contribute to the building envelope and do therefore not assess to this standard (CEN, 2012).

Test method number one of CEN/TS 1187 evaluate the external fire spread across the roof, the fire spread within the roof and the fire penetration. The roof covering is here only exposed for burning brands (CEN, 2012).

Test method number two evaluate the damaged length on both the roof covering and in the substrate. The roof covering is here exposed to both burning brands and wind.

Test method number three evaluate the external fire spread and fire penetration of the roof covering. The roof covering is here exposed to burning brands, wind and supplementary radiant heat (CEN, 2012).

Test method number four is a two-stage method and evaluate the external fire spread and fire penetration. The roof covering is here exposed to burning brands, wind and supplementary radiant heat (CEN, 2012).

In Sweden, the requirements state that Broof(t2) is the lowest class a combustible material roof covering material should fulfill, see section XX. Broof(t2) corresponds to test method number two of CEN/TS 1187.

UL1703

The American standard UL 1703 covers both BIPV and BAPV modules as well as freestanding modules and components. The complete version of the standard has not been accessible and the information is therefore retrieved from secondary sources. The standard includes burning brand test and spread of flame. The modules can be tested either independent of roof covering or as a mounting system in combination with roof coverings. The module can after the tests be classified in Class A, B or C (Sherwood et. al, 2013).

Research Institute of Sweden (RISE) published 2019 a report regarding energy efficient construction and fire safety (Research Institute of Sweden [RISE], 2019). In the report, they discuss the testing methods described above. They found that the European standards for testing and classification of roof coverings are not direct applicable for solar PV modules. The CEN/TS 1187 test method number one can be used for BIPV modules but for BAPV modules, it does not assess fires in the cavity between the modules and the roof. The test method number two can only test PV modules in a small scale and becomes therefore note representative for larger modules. Test method number three is similar to test number one since a representative BIPV construction can be tested but not air cavity formed with BAPV modules. The test method number four does not allow for a representative PV module construction, neither for BIPV modules or BAPV modules. Further, the authors state that UL 1703 is the mostly compiled standard method for testing the fire properties when combining the roof surface, suspension system and solar PV modules. The European standards does not currently compile for the interaction between different materials present in a solar PV system.

Regarding solar PV systems on facades, the authors state that the PV modules should be treated as any other facade material. A difference with PV modules is that there will be more electrical junctions in the cavity behind the facade/PV module. This will lead to more potential ignition sources in the cavity. The authors state that the regulations concerning fire spread in facades are under development and therefore not clear what requirements should be adapted to solar panels (RISE, 2019).

5 Numerical calculations

Numerical calculations can in many cases help to anticipate expected temperatures in different construction elements during fire. When preventing fires, and the consequences of fires, this can be an important step when choosing the protection level. The following section presents the theoretical background to heat transfer problems.

5.1 Heat transfer

In heat transfer problems it is common to use the Finite Element Method (FEM). Different computer codes are commercially available which are specialized for heat transfer problems or for general purpose. TASEF (Wickström et al., 1990) and SAFIR (Franssen et al., 2000) are specially developed for fire engineering problems and ABAQUS is an example of an advanced general-purpose finite element computer code. TASEF has been used during this thesis work.

TASEF calculates temperature distribution in structural elements exposed to fire. The computer code either calculate two-dimensional or axisymmetric structures and the calculation is based on the finite element method (Wickström et al., 1990).

Each scenario simulated is specified by defining the thermal properties, the time-temperature relationship and the thermal properties for each material varying with temperature. These material properties can be defined by the user to allow for new materials. TASEF also allow for latent heat in the temperature calculation (Wickström et al., 1990).

The thermal conductivity of materials is specified at different temperatures and between two temperatures, the values are assumed to vary linearly. The heat capacity is indirectly set by the specific volumetric enthalpy, e, defined as

$$e = \int_{T_o}^{T} c * \rho * dT + \sum l_i \tag{3.1}$$

where T_0 is the reference temperature (K), T the temperature of interest (K), c the specific heat capacity (J/kg*K), ρ the density (kg/m^3) and l_i the latent heat at various temperatures (J/m^3). The latent heat varies at different temperatures for instance evaporation of water and chemical reactions. Materials with $c * \rho$ constant and independent of temperature the volumetric specific enthalpy is (Wickström et al., 1990):

$$e = c * \rho * T \tag{3.2}$$

The heat transfer models via convection and radiation in internal voids, it also allows for conditions where radiation and gas temperatures are different. The heat transfer across internal voids are calculated depending on different view factors. The heat flux boundary (W/m^2) is defined as

$$\dot{q}'' = \varepsilon\sigma\left(T_g^4 - T_s^4\right) + \beta\left(T_g - T_s\right)^{\gamma} \tag{3.3}$$

where ε is the resultant emissivity (-), σ the Stefan-Boltzmann constant (W/(m^2 K^4)), T_g the absolute surrounding gas temperature (e.g. fire temperature) (K), T_s the absolute surface temperature (K), β the convective heat transfer coefficient (W/(m^2 K)) and γ the convective heat transfer power (Wickström et al., 1990).

5.2 Temperature calculations

The operating temperature of a PV module is important to know since it affects the power output (Olukan & Emiziane, 2014). The photovoltaic efficiency is inversely proportional to the operating temperature (Lee & Tay, 2011). Research has therefore been performed regarding the temperature distribution and thermal analysis of PV modules under normal conditions, not during fire. Any research regarding theoretically calculating the temperature of PV modules during fire has not been found. Below are a summary of articles presenting how to predict temperatures of PV modules and what parameters that affect the temperatures.

Lee & Tay (2011) describes how a finite element thermal analysis can determine the temperature distribution of each layer of a PV module. They include heat losses by convection and radiation in the analysis and determines that the temperature distribution of a solar module across the cells is quite uniform. Since the layers are very thin, the temperature difference in a vertical aspect becomes insignificant. They also state that the convection heat loss coefficient at the module surface affect the temperature of the solar cells.

Olukan & Emziane (2014) presented an analysis of different models used to calculate the temperature of PV modules. They found that the investigated thermal models underestimated the temperatures of the modules. They state that existing simple thermal models should be improved to achieve more accurate predictions of module temperatures.

Mazón et al. (2011) determined the temperature reached by a PV panel and describes a model to account for the heat transfer and convective flow in the air gap between a photovoltaic panel and an adiabatic plate. The PV panel was placed 35° with respect to the horizontal. However, a conclusion of the work was that once a minimum value of the aspect ratio $H/L \approx 0.1$ (H=depth of the channel, L=channel length) has been reached, the effect of the air gap is not very important in the performance of the module.

The procedure to determine the incoming heat flow to the channel requires the simultaneous solution of two heat transfer equations; the heat transfer to the surroundings from the top face of the panel as well as the heat transfer into the air duct. The mass flow rate induced inside the channel is the result of both driving forces and resistant forces. Driving forces are buoyancy-induced by natural convection and wind suction while resistant forces are friction and other hydraulic losses. Finally, the heat transfer inside the duct depends on the heat flow for convection of the PV panel to channel air as well as the heat flow for convection for the adiabatic module. To solve and determine the temperature, EES software was used (Mazón et al. 2011).

6 Fire in solar panels with the Finite Element Method

The following section describes the methodology and the model used in the Finite Element Method (*FEM) calculations.*

6.1 Selection of finite element method computer code

The Finite Element Method (FEM) is common to use for calculation in heat transfer problems. There are two different computer codes based on FEM specially developed for fire engineering problems and heat transfer problem. These are TASEF (Wickström et al., 1990) and SAFIR (Franssen et al., 2000).

During this work, TASEF was the computer code used due to that it is user friendly and most compatible to the heat transfer problems investigated.

6.2 Design fires

The following section describes the design fires used in the simulations. Since there are not many studies in this subject, three arbitrarily time-temperature are chosen.

6.2.1 Nominal time-temperature curves

Standard temperature curve

According to Eurocode 1 (EN 1991-1-2:2012), temperature-time curves are divided into nominal temperature-time curves and natural fire models.

One nominal temperature-time curve is the standard temperature-time curve, also called the ISO 834-curve. According to Eurocode 1 (EN 1991-1-2:2012) it is defined as

$$T_{ISO} = 20 + 345 * \log_{10}(8t + 1) \quad (3.4)$$

where T_{ISO} is the temperature (°C) and t is the time (minutes).

The ISO 834-curve represents the gas temperature development over time during a post-flashover compartment fire. It is identical for all types of scenarios and does not account the variety of thermal exposure caused by different compartment geometries, fuel, fuel loads, opening sizes or thermal properties of the compartment boundaries (Karlsson et al., 2000).

6.2.2 Constant temperature

A constant temperature of 800 °C was used as a design fire in the simulations.

Solar PV systems are often placed outside and at places where people not normally are. Therefore, it is assumed that at fire in a solar PV system is discovered first after approximately 30 minutes. According to the ISO 834-curve, the temperature of a fire after 30 minutes is 800 °C. Based on this scenario, the temperature of 800 °C was used as a design fire in the simulations.

6.3 The Model

A model representing a simplified wall structure of an integrated PV-system was created in TASEF. An illustration of the model used in the simulation is presented in Figure 20.

The material EVA represent the solar panel and is coloured grey with black lines, the timber studs are coloured grey with an x mark, the grey coloured with dots is the PIR insulation and the, the grey coloured is the non-combustible board.

The model has a symmetry around the x – axis and the white area in the centre represent the cut-out, the airtight void in the exterior wall.

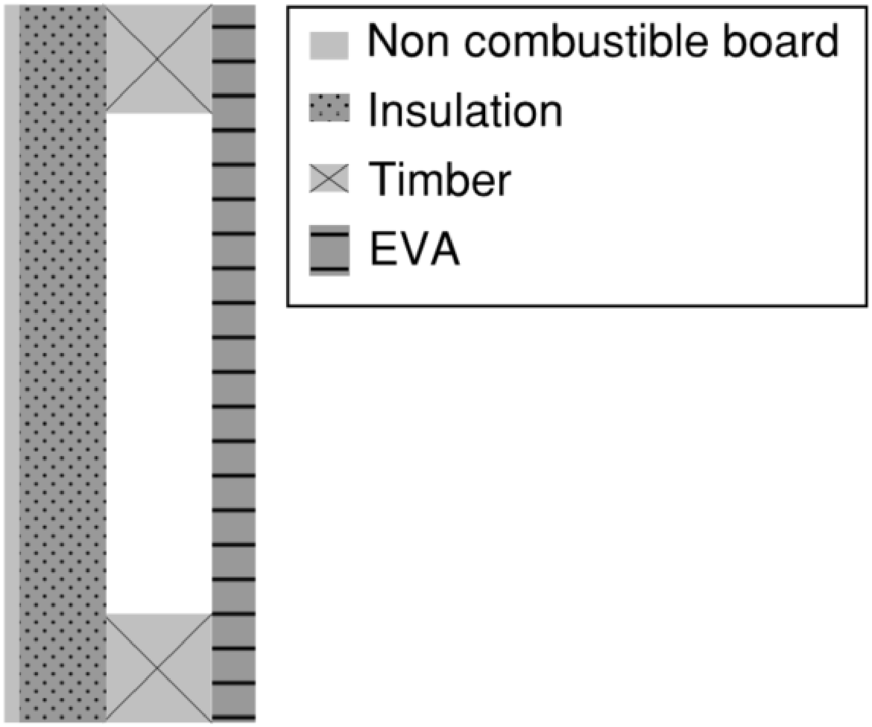


Figure 20: Illustration of the integrated solar panel on the exterior wall.

6.3.1 Material Thermal Properties

The following materials have been used during the computer simulations.

- Gypsum (Wicktröm, 2016)
- PIR insulation (See appendix C),
- EC5 Timber (EN 1995 1-1:2004), and
- Ethylene-vinyl acetate (EVA) (See appendix C).

More details of the material properties are presented in Appendix C.

6.4 Fire Scenarios and boundary conditions

The model was exposed to two different fire scenarios, see Figure 21. In both scenarios the solar PV was assumed to remain intact, and the fire was not assumed to burn through the panel. The scenarios investigated were:

- Fire exposure on the solar panel
- Fire exposure within the void

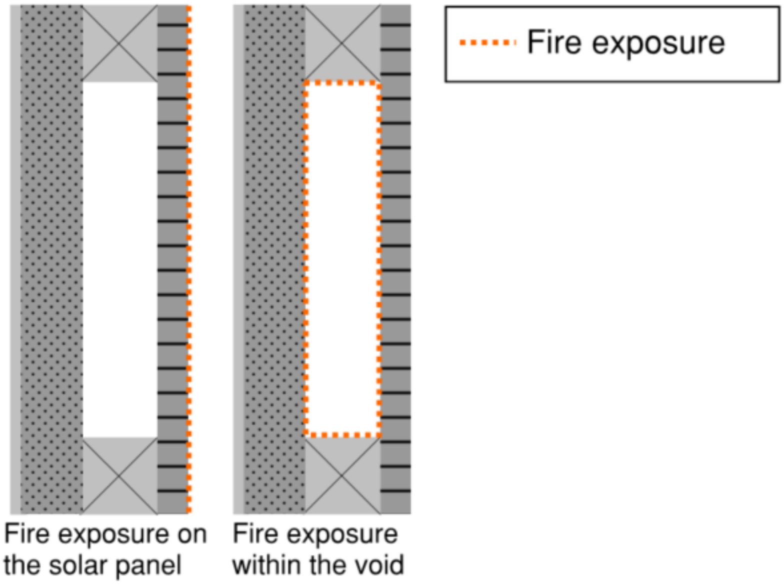


Figure 21: Fire exposure on the solar panel and within the void.

The boundary condition in the models are fire, ambient and void. The boundary conditions are defined as; ε, the resultant emissivity, β, the convective heat transfer coefficient and γ, convective heat transfer power, see Figure 22.

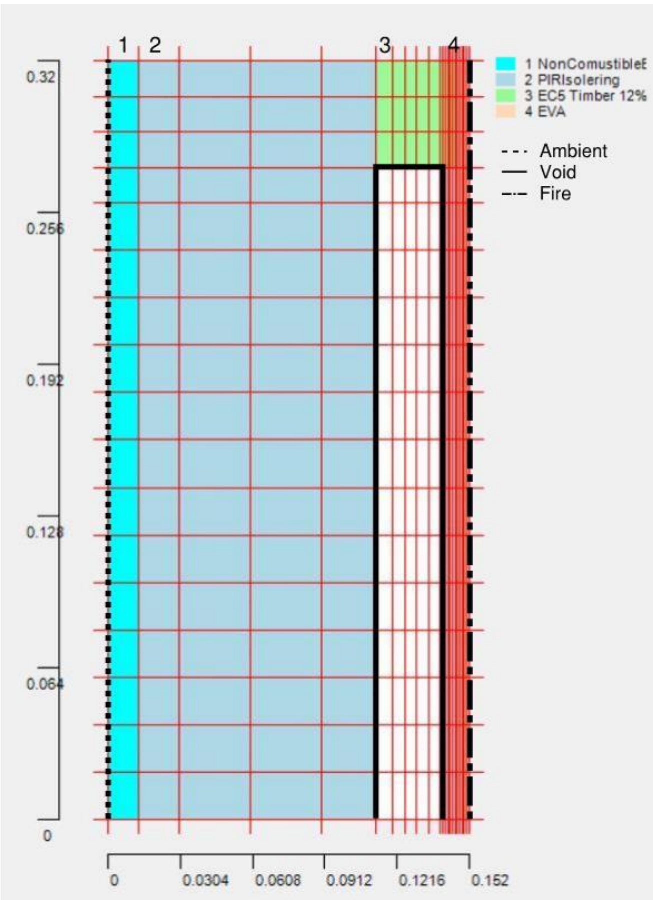


Figure 22: Geometry of the model with grid lines and boundaries.

6.4.1 Fire Scenario 1 – Fire exposure on the solar panel

In Fire Scenario 1 the solar panel is exposed directly to fire, see Figure 21. This scenario simulates a fire starting outside of the solar panel and exposing the panel.

The boundary conditions in Fire Scenario 1 are defined in Table 5 .

Table 5. Boundary conditions for fire, ambient and void.

Material	**ε resultant emissivity [-]** [1]	**β convective heat transfer coefficient [W/m² K]**	**γ convective heat transfer power [-]**
Fire (EVA)	0.9	**35** [2]	1.0
Ambient (Non combustible board)	0.85	4,0	1.0
Void (PIR insulation, EVA, wood)	0.9	4,0	1.0

[1] (Engineering ToolBox, n.d)

[2](EN 1991-1-2:2012)

6.4.2 Fire Scenario 2 – Fire exposure within the void

In Fire Scenario 2 the solar panel is exposed to fire within the void, see Figure 21. This simulates a fire starting at the backside of the solar panel (e.g. the electrical components) and spreads to the construction at which the solar panel is attached to.

The boundary conditions in Fire Scenario 2 are defined in Table 6.

Table 6. Boundary conditions for fire, ambient and void.

Material	**ε resultant emissivity [-]** [1]	**β convective heat transfer coefficient [W/m² K]**	**γ convective heat transfer power [-]**
EVA	0.9	1.0 [2]	1.0
Ambient (Non combustible board)	0.85	35	1.0
Void (ire) (PIR insulation, EVA, wood)	0.9	35	1.0

[1] (Engineering ToolBox, n.d)

[2](EN 1991-1-2:2012)

6.5 Simulation

The simulation time for the fire scenarios was set to 60 minutes. Where output data was set to be created every sixth minute and the remaining data was kept as default.

When the input data was set, the simulations were performed. The output of the temperature distribution was created for all time steps generated.

7 Result

The following section presents the results of the study. A comparison of the current legislation and regulations are presented as well as the temperatures achieved in the FEM-simulations.

7.1 Comparison of legislation and regulations between countries

Table 7 presents a comparison of the information regarding legislation and regulations described in section 3.3. The recommendations in the table are the ones being accessible during this work, other regulations can be present and required. The recommendations are also the ones found in regulations/guidelines specific for solar PV systems. Requirements for e.g. cables and wiring might be regulated in regulations for electrical devices etc.

Table 7: Comparison between the countries recommendations.

Recommendations regarding electrical components	**CFPA-E**	**Germany**	**USA**	**Sweden**	**Dubai**
Wiring					
Cables passing over/penetrating fire wall should be protected	X*	X*			
DC-cables > 1m should be fire protected /placed outside		X*			
Visible DC-cables outside		X*		X*	
No DC-cables in emergency exits or in the fire brigade access		X*			
DC wiring in enclosed spaces should be protected (metallic conduit)			X*		
Inverter and rapid shutdown					
Inverters placed at the entrance or outside		X*			
Accessible for the fire brigade (inverters)		X*		X*	
Placed on a non-combustible material (inverters)		X*			
Fireman's switch/rapid shutdown	X*		X*	X*	X*
Recommendations regarding placing, roof access and signage (BAPV)	**CFPA-E**	**Germany**	**USA**	**Sweden**	**Dubai**
Roof access and pathways					
Distance between modules and fire wall	X* (2.5m)	X* (1.25m)			
Clear pathway between panels to gain access to fire fighters	X*	X*	X*	X*	
Maximum width of PV system	X* (40m)	X* (40m)			
Minimum distance between solar PV systems	X* (5m)	X* (1m)			

Distance between modules and smoke/heat exhaust ventilation (on roof)	X*		X*	X*	X*
Dead end regulations (pathways)			X*		
Perimeter pathway on the roof		X*	X*		
Elevation between modules and roof					X*
Panels should be placed only on non-combustible roof					X*
Recommendations regarding electrical components	**CFPA-E**	**Germany**	**USA**	**Sweden**	**Dubai**
Marking and labels					
Signage	X*	X*	X*	X*	X*
Special emergency service plans at site		X*		X*	
Contact information at sight to qualified personnel			X*	X*	
Other recommendations	**CFPA-E**	**Germany**	**USA**	**Sweden**	**Dubai**
PV on facade					
PV on facades should meet the same requirements as for a facade material	X*			X*	
Modules					
Tested according to relevant standards			X*		X*
Continuously controls				X	

*Information found in a guideline

7.2 Results - Fire in solar panels with the Finite Element Method

This section presents the results for the two models "fire on solar panel" and "fire within void", from the simulations in TASEF. The models created in TASEF are presented in section 6.3.

7.2.1 Temperatures at the inside of the wall

The following figures presents the temperature distribution when the fire boundary (orange dotted line) is placed on the solar panel and within the void. The temperatures shown in the figures are inside the wall, after 60 minutes simulated with ISO-834 and a constant temperature of 800°C.

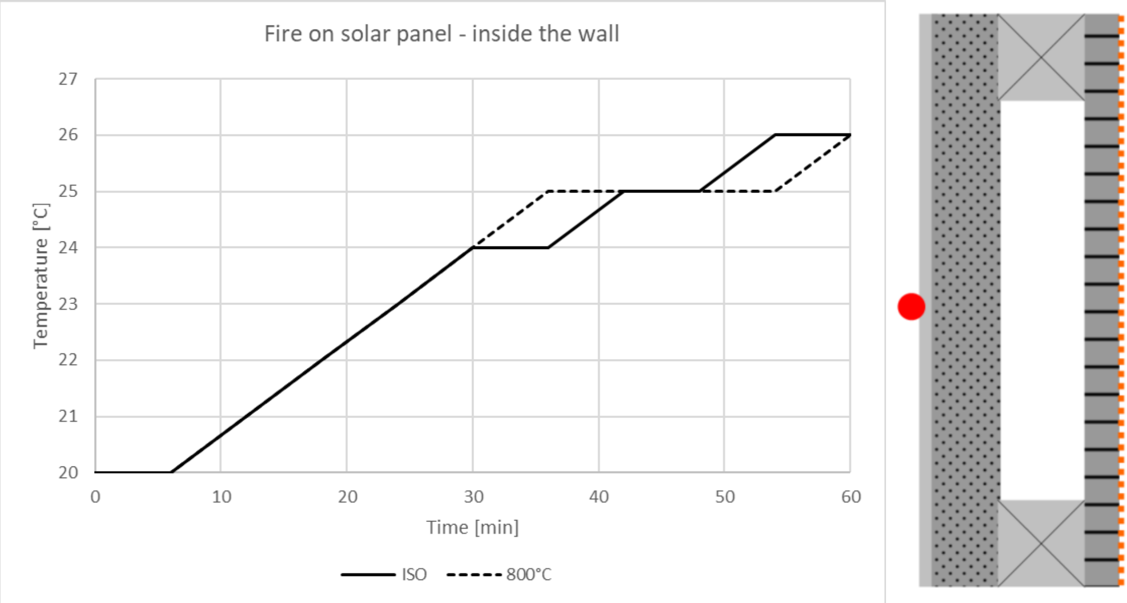


Figure 23: Temperatures inside the wall when the fire boundary is placed on the fire solar panel.

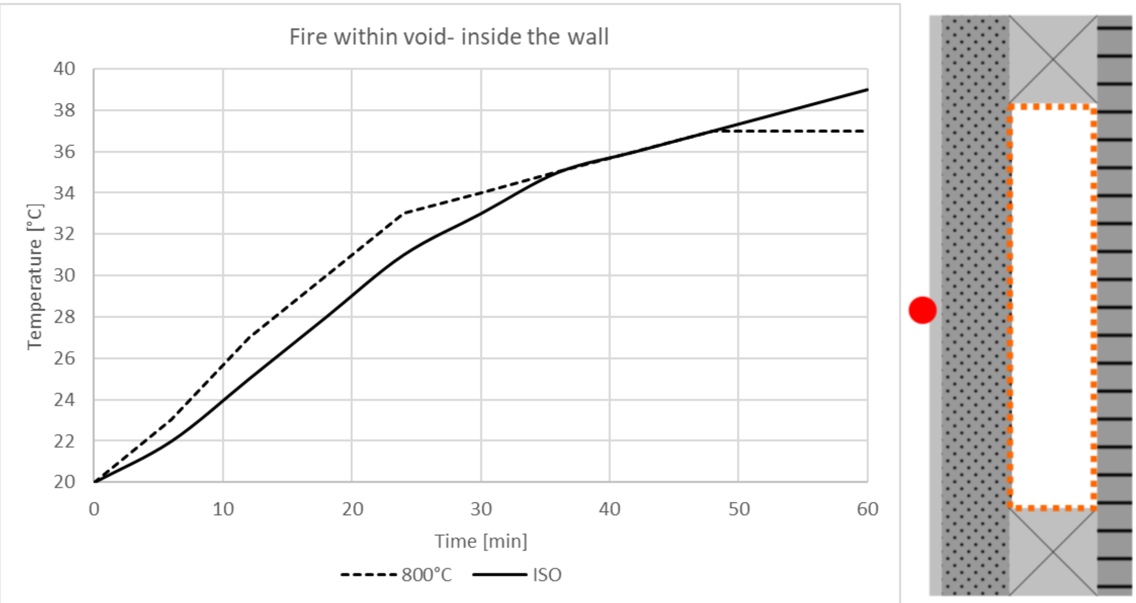


Figure 24: Temperatures inside the wall when the fire boundary is placed within the void.

The following table shows the temperature after 60 minutes between the timber studs and the insulation.

*Table 8:Temperature after 60 minutes **inside the wall.***

Design fires	Fire Sc 1 - Fire exposure on solar panel [°C]	Fire Sc 2 - Fire exposure within void [°C]
ISO 834	26	39
Constant 800 °C	26	37

7.2.2 Temperatures between the timber studs and the insulation

The following figure presents the temperature distribution when the fire boundary is placed on the solar panel and within the void. The shown temperature is between the timber studs and the insulation, after 60 minutes simulated with ISO-834 and a constant temperature of 800°C.

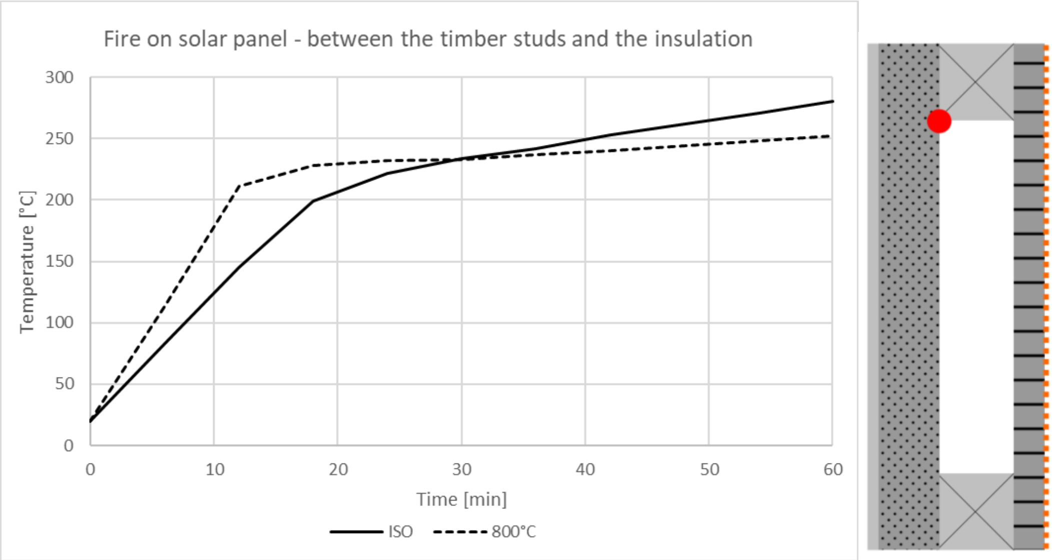


Figure 25: Temperatures between the timber studs and the insulation, when the fire boundary is placed on the fire solar panel.

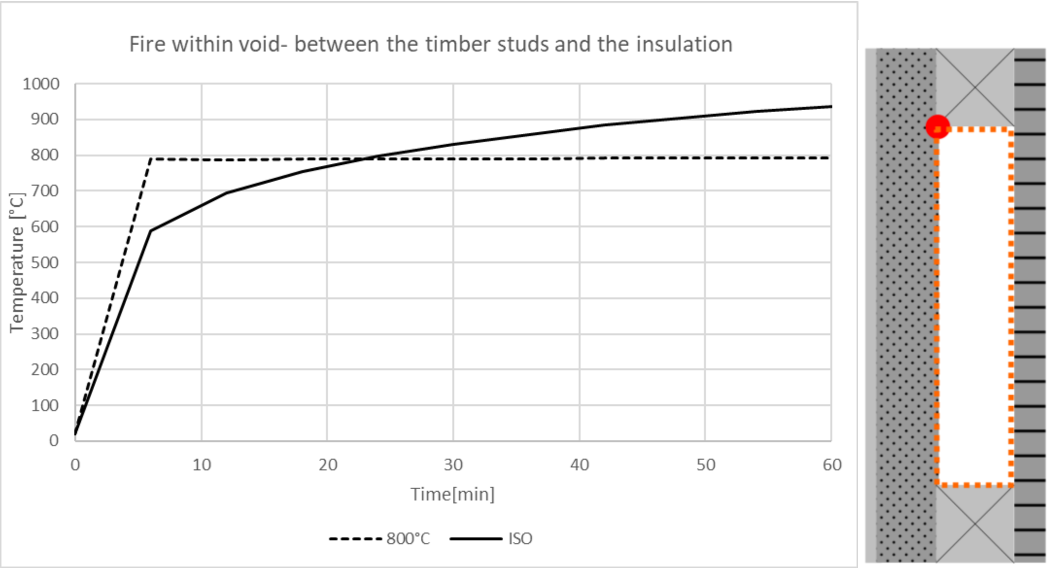


Figure 26: Temperatures between the timber studs and the insulation, when the fire boundary is placed within the void.

The following table shows the temperature after 60 minutes between the timber studs and the insulation.

Table 9:Temperature after 60 minutes ***between the timber studs and the insulation.***

Design fires	Fire Sc 1 - Fire exposure on solar panel [°C]	Fire Sc 2 - Fire exposure within void [°C]
ISO 834	280	937
Constant 800 °C	252	792

8 Analysis and Discussion

The following section presents an analysis of the results. The comparison of current legislations and regulations are discussed as well as the FEM-simulations.

8.1 Legislations and regulations

The following section presents an analysis based on the information presented in section 3.3 and the results in section 4.1. The analysis affects the different recommendations and the current legislation and regulations of the countries.

8.1.1 Recommendations regarding electrical components

Inverters

The guidelines present how and where the inverter should be placed in accordance to the solar panels. The guideline form Germany have thorough recommendation and is suitable to adopt elsewhere when mounting the inverters. The Swedish guideline states that the inverters should be placed as close as possible to the solar panels. The German and Dubai guidelines allows for both indoor and outdoor placement, however with some restrictions. When placing the inverters as close as possible to the solar panels the cables becomes short and less material is used, this may reduce the risk of fire spread through cables. Although according to Laukamp et al. (2013) the inverters have a significant risk of fire to start within them.

Fireman's switch

All of the countries except for Germany recommend having a fireman's switch or a rapid shutdown device present at an accessible place at the solar PV system. This is also a common requirement in the guidelines developed by the Swedish fire services. A rapid shutdown of the power supply between the modules to the inverter can reduce the risk of being exposed to an electrical shock. However, as well as any other component, the shutdown device needs to be of a good quality and has to work perfectly at the time of the fire. Since it often is placed outside it need to withstand aging and all kinds of weather conditions. To reduce the risk for electrical shock due to conductive DC wirings, the inverter should be placed as close to the modules as possible, to reduce the length of cables. The positive and negative cables can also be placed separately with a wide distance between so that a person can never be in contact with both at the same time.

8.1.2 Recommendations regarding placing, roof access and signage

Placing and roof access

The recommendations for placing of solar panels is similar between all investigated guidelines. The main objective of the recommendations is to protect the fire rescue service when approaching and during operation on the roof. Restrictions applies for pathway dimensions and placement of solar panels. Solar panels should not be placed near combustible material or other objects subject to fire spread. The guideline form Germany have the most accurate description on placing and sizing of the solar panels, the guideline is very thorough and is suitable to adopt elsewhere.

An essential part of fire protection is to separate buildings into fire compartments. It then became very important to maintain fire walls and fire compartment boundaries. Germany and CFPA-E recommend having a distance between a solar PV system placed on a roof and the potential fire wall. With the knowledge from section 3.2.2 that a PV array changes the fire dynamic of the roof the fire spread on the roof becomes an important part to consider. As described in the section, a PV array on the roof can contribute to a rapid fire spread, even on a classified roof covering. The terrace house is typical to see in Sweden. A PV array is installed on the whole roof and therefore crossing the fire compartment boundaries established between the compartment. During the last years, several terraced houses have burnt down completely due to deficiencies in the building's fire protection. The deficiencies are often connected to the fire compartment boundaries which have caused fire to spread fast between compartment. At the same time, several terraced houses install PV arrays on the roof to provide electricity. The arrays are often installed throughout the roof. This could be a potential fire hazard since the fire then can spread under the array, crossing the internal fire compartment boundary. It can then lead to greater consequences than necessary.

Informative signage

Signage is the only requirement found in every regulation or guideline. It is a relatively cheap and easy measure to provide knowledge about the installed PV system fast. This can become an essential part of fire extinguishing operations since the rescue service need to know where there are PV systems located and how to assess them. Germany and Sweden even recommend having a specific emergency service plan at site to facilitate a fire rescue operation. USA and Sweden also require accessible contact information at site to qualified personnel which can contribute with more knowledge about risks regarding the PV systems.

The placement for the signage locations is conformity for the investigated guidelines, since the buildings in all countries have similar approach method and therefore the entrance will be the best location to place informative signage.

8.1.3 Other preventive measures to reduce fire risks

Laukamp et al. (2013) investigated 180 fires that were caused by PV system. The majority of the fires (51%) occurred in non-integrated solar panels mounted onto the roof. Only 11% of the fires occurred in roof integrated solar panels. This division may be due to more PV systems are mounted onto the roofs, and when systems are more suitable for facades the deviation may even out.

An aspect often mentioned in investigations regarding fires connected to solar PV systems is the need for professional planning and construction of the systems with high-quality components. 90 % of the fires investigated by Laukam et al. (2013) where caused by either installation fault, planning/design fault or product defect. When installing solar PV systems, it is therefore essential to ensure the use of qualified installation, components etc. The electrical standards and codes provided by both CEN and NFPA address this and can be used during the planning and installation

8.2 Integrated solar PV systems

None of the investigated countries have specific regulations regarding integrated solar PV systems. The market for BIPV systems is currently expanding fast due to the development in technology and the large request for efficient and aesthetic solutions for energy supply. As mentioned, BIPV systems often replace another part of the building envelope e.g. the roof or the facade. A solution is then to make the same requirements for the BIPV system as for the replaced part. Boverket in Sweden recommends this for both BIPV systems on roofs and on facades. However, since solar PV systems on their own can be an ignition source and BIPV systems have a much higher fire risk than BAPV, the overall risk of a fire in the building can increase.

Another aspect of BIPV systems is how the fire rescue service should first of all know that they are installed in the building. As seen in Figure 7, BIPV systems are developed to mimic regular building materials. Since the presence of PV systems affect the operation techniques, it is important that the rescue service personnel get information fast if there are solar PV systems involved.

The Swedish legislation regarding roof covering is based on preventing fire spread from one building to another. Therefore, they only demand a classification of minimum BROOF(t2) when buildings have a distance of 8 meters between them. This could be for example warehouses, malls, barn and other farm buildings. These are buildings that also appears as perfect buildings for PV array installations since they often have large roof areas. However, a Steemann & Jomas (2018) concludes in their experiments, a large PV array installation on a roof can have a significant impact on the propagation of a fire. Adding to this the fact that the legislation accepts a combustible roof membrane on top of a combustible underlayment/decking when building are more than 8 meters apart, this can be a great fire risk.

8.3 Solar PV systems on facades

In two of the examined guidelines (Sweden and CFPA-E), solar PV systems on facade are mentioned. It is then recommended or required that the PV systems on the facade should meet the same requirements as for the associated building regulations. The authors of the report from RISE (2019) also state this, that a PV system on the facade should med the same requirements as the facade itself.

No research or experiments have been found on the subject of PV systems on a facade. However, an assumption can be made that a BAPV system on the facade contributes to the fire spread similarly as a system does on a roof. The experiments from Steemann & Jomaas (2018) showed that there can be hazardous consequences due to the presence of a PV systems during fire. On a facade, there are often no or very little mitigation which allows the fire to spread over large sections, or even the whole building. Due to the fact that flames and hot gases rises, a BAPV system on a facade can therefore contribute to a fire spread upwards the facade.

As mentioned above regarding BIPV systems, Boverket in Sweden recommends the same requirement for BIPV systems in the facade as for the facade itself. However, as mentioned, the requirements for facade material depends in Sweden on the building class of the building. The building classes themselves depend on the need for protection (size of the building, people present during day/night etc.). A combustible material can be used as a facade material for building classes Br2 and Br3. Typical Br2 buildings are multi-compartments buildings with up to three storeys. A BIPV system on a facade in combination with combustible cladding can lead to a rapid fire development and an uncontrolled fire spread. As the PV system is integrated, it is already "inside" the building and can possibly spread to other compartments and the construction.

If a BAPV system in attached on a facade it is also a higher risk of it falling down during fire. People on the ground can then be harmed and rescue service operations can be obstructed due to the risk of falling objects. It is therefore essential that the attachment devices of the PV systems if fire protected and/or secured into the facade.

In the investigation from Laukamp et al. (2013) it is shown that the smallest number of fires occurred in the facades, only 1.1 %. As discussed above this may be since more PV systems are installed onto roofs.

8.4 Numerical calculations

The following section present an analysis and discussion regarding the numerical calculations presented in section 5.2.

To theoretically calculate the temperature distribution of a solar PV module during fire could be a good help when determining the protection level for different construction elements. When considering fire spread between a solar PV module and different construction elements or materials, theoretical calculations could also help or even replace full-scale experiments. However, since there are many different parameters affecting both a fire and the heat transfer in a PV module, the calculations soon become very complex. In order to complete the thesis regarding timeframe and limitations, no further work has therefore been performed regarding temperature calculations.

8.5 Fire in solar panels with the Finite Element Method

In the TASEF analysis the temperature measured at the inside the wall of the solar panel model vary between 26 °C and 39 °C in different design fires or the simulated fire scenarios. The difference between the fire scenarios does not have a great impact of the temperature at the inside of the wall since the temperature in both scenarios are reduced by the insulation material.

The temperatures measured between the timber studs and insulation vary more than between the design fires. In the fire scenario when fire exposure is on the solar panel the temperature between the timber studs and insulation varies between 252 °C (for the constant temperate of 800 °C) and 280 °C (for the ISO-834 curve after 60 minutes). Temperatures between the timber studs and insulation are much higher in the fire scenario when fire exposure is within the void, as the fire exposure are closer to the point of measurement, and temperatures are between 792 °C and 937 °C after 60 minutes. Also note that the measuring point in Figure 26 is not on the "fire curve". The materials do not reach a temperature of 800 °C since the materials adjoining has a cooling effect on the materials at the measuring point.

As the temperature between the timber studs and the insulation reaches temperatures between 792°C (constant temperature 800°C) to 937°C (ISO-834) this could ignite many materials and could possess a high risk if unwanted items are placed inside the cavity. It could also allow the fire to spread more rapidly and over a larger area.

The design fires used in the simulation are standardised and not based on materials normally found in solar panels. This could affect the result and if the fire curves would have been created with a computational fluid dynamics calculation the result may have been different. This due to the calculations would have given varying heat transfer coefficient at the fire boundary. And therefore, create a more credible time-temperature curve.

As mentioned in the theory section, the integrated solar panels are more prone to damage as a result from fire. Therefore, only the integrated model was used in the FEM calculations. The models used where simplified and no previous heat transfer problems were found regarding this subject.

The material properties for the ethylene-vinyl acetate were difficult to find and an engineering assumption was made to create the volumetric specific enthalpy. Another error that may affect the results could be that the material properties and constants. As they may vary more in reality while they were kept constant in the simulations. However, this is a problem to consider for all computer codes.

9 Conclusion

The current Swedish regulations do not fulfil the safety needed when dealing with solar PV system. In order to meet the safety requirements, the recommendations from the guidelines needs to be adopted into the general requirements. Also, the concepts BIPV and BAPV need a more distinct definition in order to update the general requirements. The guidelines investigated show large difference in the number of recommendations and requirements, where USA has the greatest number of requirements. The requirements in USA are also much more detailed than, for example, recommendations in Sweden.

The use of solar PV systems is constantly increasing, and the systems are rapidly developing. However, the legislation of safety regarding PV systems has not yet kept the same developing speed. The demand for more research in the subject is therefore increasing. An example is the reports found regarding integrated PV system. The reports are often focusing on integrated systems on roofs or façades. However, no reports have conducted experiments in the subject.

The heat transfer analyses clearly show a high temperature between the façade and the solar PV system. This also indicated the need for more research in the subject.

9.1 Answers to questions

The following section presents the answers to the questions described in section 1.3.1.

Legislations and regulations

– *How is fire safety regarding solar PV systems regulated in different countries? Are there any differences/similarities?*

Legislations and regulations differ rather much between countries. Some countries have specific regulations for fire safety regarding solar PV systems and some have developed guidelines to address the subject. Informative signage is the only thing required in every country. Other than signage, clear pathways on roofs with installed solar PV systems and some form of rapid shutdown device are often required/recommended.

– *Do the legislations and regulations in Sweden fulfil safety regarding solar PV systems?*

Not currently, the recommendations stated in the guideline should be adapted as general requirements.

Non integrated solar PV systems:

– *What parts of the solar PV system can ignite and cause a fire?*

The electrical components of the system can cause fire due to faults. Electrical arc can thereafter ignite either the combustible part of the PV system or its surrounding materials.

- *How do non integrated solar PV systems contribute to fire spread?*

The solar PV systems change the fire dynamic on the roof and since the heat flux from a flame is reflected back to the roof surface instead of out in the air, the incoming heat to the surface enlarges. The solar PV modules can also contribute with combustible material and components e.g. wiring as fuel to the fire.

Integrated solar PV systems:

– *Are integrated PV systems regulated different from non integrated?*

Since integrated PV systems are a part of the building envelope, recommendations often state that they should fulfil the same requirements as the building part they replaced.

- *How do integrated solar PV systems contribute to fire spread?*

If a fire occurs in an integrated solar PV system, the fire is directly inside the building and can spread further.

- *How do solar PV systems affect a fire rescue operation? What requirements are important in order to secure a safe environment for fire rescue personnel?*

Solar PV systems are conducts high amount of voltage and can contribute to electrical shocks. Modules placed on e.g. the facade can also fall down during a fire in the building. To facilitate a fire rescue operation in a building containing solar PV systems, good accessibility and signage is essential. Fireman's switches or rapid shutdown devices are often required to reduce the risk for electrical shocks. However, the panels still produce DC current as long as it is exposed to a light source. Clear pathways with safety distances to the PV panels is also important to maintain.

Heat transfer queries

- *What temperatures can be expected on the inside of the facade if a solar PV system is ignited? and What temperatures can be expected between the facade and the solar PV system if the solar panel ignites?*

The following tables present the temperatures received in the specific simulations performed in this work. The simulations are based om the scenarios and conditions presented earlier in the report. The result should not be read as temperatures that can be expected in general solar PV system. The result gives an indication of which temperatures that can be expected for the models and scenarios in this work. For other PV system, models and fire scenarios, more simulations need to be performed to be able to calculate what temperatures that can be expected.

Table 10: Temperature at the inside of the wall.

Design fires	Fire exposure on solar panel [°C]	Fire exposure within void [°C]
ISO 834	26	39
Constant 800 °C	26	37

Table 11: Temperature between the facade and the solar PV system.

Design fires	Fire exposure on solar panel [°C]	Fire exposure within void [°C]
ISO 834	280	937
Constant 800 °C	252	792

9.2 Further work

Knowledge about how fires occur and behave in and around solar PV system is mandatory to create appropriate regulations regarding fire safety and fire prevention. Different countries have different knowledge and have been focusing on different aspects regarding fire safety related to solar PV systems. The countries mentioned in this thesis show a great variety in size etc. however China and Japan are two large countries having high amount of installed solar PV systems. It would be very interesting to see what approach they have regarding PV systems, how they are regulated and what difficulties they have experienced.

There is not much research regarding BIPV systems and how they affect the fire spread in a building. Statistical analyses regarding fire incidents in BIPV systems and investigations on what caused the fire would therefore be interesting to see. Small- and full-scale experiments on a roof or facade assembly with BIPV systems instead of the regular material would also gain more knowledge of how the PV system affect a fire. Since there are not much difference in the current legislation regarding BIPV and BAPV it would be interesting to investigate that further. Is there for example a need for other legislation related to BIPV than for BAPV?

The need for numerical calculations to predict the temperature of a PV module during fire could also be interesting to investigate further.

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Appendix A – Defects that caused fires

The following part presents according to Laukamp et al. (2013) errors that have caused the fire ignition. Table A.1 to Table A.4 presents causes where a fire has started or a burn mark have been noticed due to mechanical design, electrical installations errors, poor workmanship and external influences. These errors have been compiled from the 110 incidents reported.

Table A.1: Mechanical design error that have caused the fire ignition due to product defects.

Product	**Defect**
Module	Manufacturing errors, poor designs or series production deficiencies due to poor quality assurance are the underlying cause of these failures.
Inverters	Design flaws, however only anecdotal evidence is available.
Frameless thin-film modules	When mounted too tight to each other, restraints occur, which leads to mechanical tension and glass breakage. Which thereafter led to to electrical arcs.
Mounting rails	Rails mounted tightly next to module junction boxes (j-box) caused shearing forces, which led to damage to the j-box. Which thereafter led to to electrical arcs.
Weather exposed array junction box	Weather exposed array j-boxes (no sun or rain protection) can develop stress on contact components due to high internal air temperatures and humidity from water vapor diffusion. This led to increased contact resistance, which led to electrical arcs.
Array j-boxes and inverters mounted on wooden panels or above non-combustible	Array j-boxes and inverters mounted on wooden panels or above non-combustible material led to a quickly fire spread and damage of building interior.
Array cabling missing retarding seal	Array cabling from the rooftop solar PV was missing retarding seal at the building entrance, which led to an electric arc penetration from the roof into the building, causing heavily damage to the building.

Table A.2: Design error in electrical installations.

Product	**Design errors**
Multiple, bounded laying of cables without current	Overheating of cables led to fire in the cable trunk.

derating	
Underrated cables	Overheating of cables led to charred contacts.
Underrated DC-switch	Overheating of cables led to an electrical arc.
Fuses	*Neglected simultaneous maximum power dissipation from fuses (coincidence factor of 1, different from standard AC loads).* Led to overheating of the cabinet, which led to contact degradation and lastly to fire.
AC-fuse at DC circuit	The fuse did not break the current, which led to an electric arc.
DC wiring routed over sharp metal edge	Caused insulation damage which led to a short circuit and lastly to an electrical arc.
Terminals to connect aluminium conductors	Unsuited terminals used to connect aluminium conductors, led to increased contact resistance and lastly fire.
Cabinets for indoor use	Cabinets for indoor usage used outdoor, caused water penetration, which led to contact degradation, overheating, charred terminal and loss of power.
Cabinets for outdoor use without condensation drainage provided	Water accumulated within the cabinet led to contact corrosion and loss of power.
Inverters installed at unsuitable places	Unsuitable places are for example when exposed to weathering or installed in an unsuitable way. Damage range from defect inverters to barns burnt down.

Table A.3: Poor workmanship and its consequences.

Product	**Consequences**
DC-connector not properly plugged	The plug had molten down which led to the sting being interrupted, in some incidents the building was damaged
DC-connector not at all or poorly crimped	Led to arc and building damage.
Screw terminal not fastened	Arc and generator j-box was destroyed, in one case a

	building was destroyed.
Wire insulation partly inserted into terminal	Resulted in poor contact, overheating and a fire within the cabinet.
Fuse not latched to holder	Led to an electrical arc and damaged on the j-box.
Insufficient or lacking preparation of Aluminium conductors	Led to poor contact, fire and the inverter station was destroyed. Several cases were reported.
Lacking of strain relief of cables	This is a likely cause for contact failure and for fire in the AC-distribution cabinet.
Cross mating of DC-connector parts of different manufacturers	This led to overheating of hundreds of contact pairs in large solar PV system. Which led to an expensive repair.
Module wires were used us handle	Wires were slightly pulled out of the j-box, this led to an electrical arc in the j-box.

Table A.4: External influences and its consequences.

Event	**Consequences**
Rodents and martens eating wire insulation	Led to a short circuit and an electrical arc.
Lightning strike	The bypass diodes were damage (shortened), which ed to a reverse current and a damaged j-box
Craftsman who hidden dc cables drilling long screws in	Led to a short circuit and an electrical arc.

Appendix B – Comparison Swedish fire brigade guidelines

Table B.1 presents the comparison between the Swedish fire brigade guidelines. The X indicates that the associated fire brigade guidelines includes in the table stated recommendation. However, the exact statement may not have been written in the guideline, but the intention is exactly same.

Table B.1: Comparison Swedish fire brigade guidelines

Fire Brigade		**Svedala**[1]	**Eskilstuna**[2]	**Östra Götaland**[3]	**Skåne Nordväst**[4]	**Stor Göteborg**[5]	**Mälardalen**[6]	**Linköping**[7]	**Sörmlands kusten** [8]	**Östra Skaraborg** [9]
Date published		**2018-11-05**	**2018-07-11**	**2016-06-22**	**2016-01-05**	**2018-03-22**	**2017-05-23**	**2017-05-01**	**2017-04-12**	**2015-08-04**
Recommendations										
Design stage	When designing larger PV system, the fire brigade advocates an early consultation with the plant owner. [3]			X			X	X		
Inverters	Inverters should be placed near PV panels. This way, DC cables become as short as possible. [1]	X	X	X	X	X	X	X	X	X
Disconnect inverter	Inverters should be able to disconnect to ensure that the cabling with AC becomes powerless. [5]					X				
DC Power Cables	Exposed DC cables should be placed clearly visible and labelled. [1]	X		X		X	X			X
Safety inverters	The DC inverter should be placed as close as possible to the solar panels. With such inverter that the fire rescue can switch off the DC cabling. Ideally, each solar panel should be provided with inverters directly at, or inside the panel. The inverter should also disconnect the DC automatically if other power supply of the building is broken. The inverter should be manual and not be able to automatically return to the initial position. [1]	X	X		X	X	X	X	X	X

Control device for DC inverters	Control device for the DC inverters are to be placed at the entrance of the building, or alternatively in connection with the fire defence table. If the building has an automatic fire alarm, the control device should be placed at the control panel. Instructive signage should be placed in close connection with the control device. [1]	X	X	X	X	X	X	X	X	X
Indicator light for control device	Indicator light should be placed near the control device to indicate that the power is switched off. [5]					X				
Firefighter switch	The firefighter switch means that an inverter to the DC cabling is placed as close as possible to the PV panels. A control device to these inverters should be placed in the access pathway. If the facility has an automatic fire alarm with diverts to the fire service, the inverter should switch off when the alarm is activated. [3]		X	X	X		X	X	X	X
Informative drawing to the firefighter switches	Drawings should show which parts that becomes powerless and which parts that remain with power after using the firefighter switch. [3]				X		X		X	
Automatic fire alarm	If the building has an automatic fire alarm, if possible, at activation of the fire alarm, a function should be implemented so that all DC inverters break the voltage. [1]	X	X	X	X					
Mounting on non-combustible material	PV panels should be mounted on non-combustible materials to reduce the risk of fire spread from panels to roof/wall construction. [2]		X		X				X	

Mounting on roof	If possible, the whole roof area should not be covered by solar panels. Fire brigade personnel must be able to provide holes in the roof construction for ventilation of fire gases. [1]	X	X	X	X	X	X		X	
Mounting on roofs at fire compartments	If the building is divided into different fire compartments, it should be possible to provide holes in the roof construction for ventilation of fire gases in all fire compartments. [1]	X	X	X	X	X	X		X	
Mounting on roofs with smoke vents	In cases where smoke vents are available, they should be well labelled so that they are easy to find even during winter when snow is on the roof. [1]								X	
Mounting on facade or inclined roof	When solar panels are placed on facades or on inclined roof, the risk of falling panels must be considered. [2]		X							
PV attachment devices	When solar panels or their attachment devices are affected by fire, there is a risk that they will become loose and fall. When installing solar panels on the facade and roof it is important to consider the risks of fire spread and when affected by fire, falling parts or the entire panels. The property requirements in PBF Chapter 3 section 8 regarding safety in the event of fire must be satisfied. For mounting solar panels, this can be done by considering the regulations and general advice described in BBR 5:55 and 5:62. [1]	X				X				
Flammable and / or explosive goods	Avoid placing PV panels near proximity to the storage location for flammable and/or explosive goods. [1]	X	X			X			X	

Informative signage	The building should be clearly marked. Signage with information stating that PV system is installed within the building should be placed at the entrance. If the building is provided with an automatic fire alarm, the signage should also be placed at the control panel. [1]	X	X	X	X	X	X	X	X	X
Contact details	Contact information to a person with knowledge of the PV system should be accessible in connection with the building, preferably at the entrance at fire panel. A suitable contact person may be an installer, property manager or an expert on the facility. [1]	X	X	X		X		X		
Informative support	At larger facilities, information should be in the near to the control panel (if the building is provided with an automatic fire alarm) or at the entrance at the building. The information must include a technical specification of the PV system and a drawing overviewing the cable routing. It is important that the drawing illustrates which parts that still have power after the inverters has been used. [1]	X	X	X	X	X	X	X	X	X
Labelling of cables	Cables and the like should be placed and routed in such way that they are visible and do not risk of being damaged when providing holes in the roof or other work conducted at the roof. It should be easy to see the cable route. Therefore, hidden cables must be marked with the location where they are located. [9]									X

Maintenance	It is not only when the PV system are installed that it will work, it is still important to maintain the system. In order to live up to the Plan and Building Act's (2010:900) requirement for the technical property requirements to be maintained through maintenance during the life of the building and the obligations for owners or holders of extensions and other facilities according to the Act on Protection against Accidents (2003:778). It is in this context important for the property owner to continuously maintain the facility. [4]	X				X				

[4] (Räddningstjänsten Svedala, 2018)
[2] (Räddningstjänsten Eskilstuna, 2018)
[3] (Räddningstjänsten Östra Götaland, 2016)
[4] (Räddningstjänsten Skåne Nordväst, 2016)
[5] (Räddningstjänsten Storgöteborg, 2018)
[6] (Mälardalens Brand- och Räddningsförbund, 2017)
[7] (Linköpings Kommun, 2017)
[8] (Sörmlandskustens räddningstjänst, 2017)
[9] (Räddningstjänsten Östra Skaraborg, 2015)

Appendix C – Material properties, TASEF

The material used in the TASEF models are presented in Table C.1 to Table C.4. The specific volumetric enthalpy is calculated using Eq. 3.2, where he material densities and specific heat are presented in Table C.1.

Table C.1: Ethylene-vinyl acetate, conductivity and specific volumetric enthalpy.

Material	Density [kg/m³]	Specific Heat, c [J/(kg*K)]
Ethylene-vinyl acetate (EVA)	950[1]	1900[2]
PIR insulation	32[3]	1500[3]
Aluminium	2700[4]	910[5]

1. (Britsh Plastic Federation, n.d)
2. (Allan, Pinder, & Dehouche, 2016).
3. (Touma & Jardemyr, 2013).
4. (Prev Home Next, n.d.)
5. (The Engineering Toolbox, n.d.).

The specific volumetric enthalpy for the ethylene-vinyl acetate is estimated with the given specific heat from Table C.1 and multiplied with only the temperatures to achieve a realistic value for the material.

Table C.2: Ethylene-vinyl acetate, conductivity and specific volumetric enthalpy.

Temp[°C]	Conductivity [W/(mK)][1]	Specific Volumetric Enthalpy [kJ/m³]
0	1.2	0
20	1.2	38000
250	0.3	475000
400	0.2	760000
700	0.18	1330000
1200	0.18	2280000

1. (Girardin, Fontaine, Duquesne, Försth and Bourbigot, 2015)

Table C.3: PIR insulation, conductivity and specific volumetric enthalpy.

Temp[°C]	Conductivity [W/(mK)][1]	Specific Volumetric Enthalpy [kJ/m³][2]
0	0.023	1400
1200	0.023	1500

1. (Touma & Jardemyr, 2013).

Table C.4: Non-combustible board, conductivity and specific volumetric enthalpy.

Temp[°C]	Conductivity [W/(mK)]	Specific Volumetric Enthalpy [kJ/m³]
0	0.1	0
1200	0.1	205083