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Fire risk of building-integrated photovoltaics in facades

Masterproject Research

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Chapter 1

Introduction

1.1 Introduction

On the 14th of June 2017, the world shockingly witnessed the fire of the Grenfell Tower in London. The 67 meter high residential building was renovated years earlier with a very combustible cladding. Before the firefighters could extinguish the fire that had started in one of the apartments, the fire had already reached the facade and expanded to the roof of the building. The extremely combustible facade materials, in combination with the British stay-put strategy, resulted in 72 casualties. Three years later, the Dutch ATGB published a report for the Dutch government containing recommendations and conclusions for the Dutch Building Code resulting from the Grenfell fire. They concluded, among other conclusions, that the NEN should improve the Dutch Building Code and their fire standards for facade materials and that in the mean time, the Dutch Practical Guidelines should allow for a better examination on the possible expansion of a fire by the facade [1].

Climate change is an important factor that influences the design of building characteristics such as facades in an attempt to renovate (or newly build) green buildings. These buildings should use less energy or even produce the same amount of energy that is being used (zero energy buildings). A popular innovation to attain to this goal is the use of photovoltaic systems. A distinction is being made between building attached photovoltaic systems (BAPV) and building-integrated photovoltaic systems (BIPV). Especially BIPV systems, which are part of the construction, could potentially introduce additional risks for fire safety. Recently, BIPV systems are not only applied to roofs, but also to facades. There is however little knowledge on the fire safety of BIPV-systems.

The BRE Group (a group of UK based scientists, engineers and researchers who aim to improve the built environment) published a governmental report in 2018 with investigations on PV related fires in the UK. A total of 80 incidents with buildings with BIPV/BAPV systems were analyzed, and they concluded that 72% of the fires were directly caused by the PV system and another 20% involved the PV system (without directly causing the fire). They did not find casualties caused by a PV fire, but they did found injuries such as smoke inhalation, minor burns, shock and anxiety and minor knee injury [2]. The Dutch equivalent organisation for applied research, TNO, produced a similar report about the Netherlands in 2019 [3]. The researchers concluded that BIPV systems form the highest risk, since the Dutch Building Code has no requirements yet on the combustibility of the materials directly behind the PV panels (insulation and foil). This is no issue for BAPV systems, since they are placed on incombustible roof tiles [3]. In Germany, researchers concluded that between 2005 and 2012, there were 50 times more fire that involved photovoltaics and in the period 2011-2013 50% photovoltaics caused already 50% of the fires [4]. In the United States photovoltaics caused seven (out of 240 Walmart stores) fires on roofs [4]. Overall, it can be concluded that not only the Issues related to the fire safety of the PV panel itself should be investigated, but the entire system is very relevant.

For a fire to start, an ignition source is needed. Since PV systems are part of an electrical installation, various systems errors such as faulty connectors, lightning, hot spots and arcing could take place which could produce a spark [5]. BIPV systems, in comparison with BAPV systems, have a smaller air gap in between the PV panels and the outer layer of the building. This means that less ventilation can take place and the air behind the PV panels can heat up even more. Not only are high temperatures sub-optimal for the production of solar energy, it also decreases the amount of energy that is needed to start a fire [6]. Additionally, BIPV systems (which are combustible in itself, though the mass is low) often adjoin combustible materials such as wood, insulation material or a waterproofing foil [5]. Furthermore, in case of a fire, smoke and flames could quickly spread over the facade or roof, and they can enter the building. Extinguishing the burning photovoltaic elements is also a concern, because of electric shocks (the photovoltaic modules keep on producing energy as long as solar energy is falling on the panels) and toxic gasses [7].

The prescriptive building code is not up-to-date regarding BIPV systems, since it only looks at the consequences (effects) of a fire and not at the risks that are introduced when adding a BIPV-system. Especially in the case of BIPV facades, since their application is relatively new, there is a lack of knowledge on the risks related to fire safety. This means that a facade can theoretically attain to the building code, but in practice could have an unacceptable failure probability. Currently, the two public-law related fire safety goals are: firstly personal safety of building occupants and the emergency services, and secondly the safety of neighbouring plots and buildings of third parties. To review whether a facade is safe, instead of an effect-based, a risk-based approach should be taken. The two public law related fire safety goals are however too abstract to be practically applicable for determining the risk of a facade fire due to a BIPV system. Therefore they should be divided over several risk subsystems:

1. Constrain the start of a fire
2. Constrain the development of a fire (includes fire classes for external separation construction)
3. Constrain the fire spread to the compartment where the fire is taking place
4. Constrain the smoke propagation outside the (sub)compartment where the fire is taking place.
5. Maintain the supporting structure of the building
6. Maintain escape and fire attacking routes
7. Constrain the expansion of a fire to neighbouring plots and buildings

Especially the first three risk subsystems are important for determining the failure probability of a BIPV-facade fire. BIPV-systems add an ignition source in the facade and they potentially increase the amount and severity of fire trajectories and possibility of short cutting compartments due to combustible materials and additional cavities where smoke and fire can spread. The risk of a fire is determined by the probability of the start of a fire and the impact (consequences) of a fire. This leads to the following research question: to what extent is the overall failure probability, as defined by the risk subsystems, increased by adding a BIPV-system to the facade? Additionally: What are the requirements and solutions for a safe implementation of BIPV-facade system?

In order to assess the failure probability of a BIPV-facade, chapter 2 investigates the designs of BIPV-facades that are currently applied in buildings. This is needed to determine the fire trajectories and the failure situation in case of a fire. Next, the different fire safety threats of a BIPV-facade for the risk subsystems will be analyzed by means of a literature review. Additionally, in chapter 4, a survey will be conducted that looks at the failure probability of a BIPV-fire (risk subsystem 2 and 3) and partly about the probability of the start of a fire (risk subsystem 1). In chapter 4 the overall failure probability of BIPV-facade will be established as well. Finally, in chapter 5 solutions and requirements will be suggested to decrease the overall fire safety risk of a BIPV-facade.

Figure 1.1: Residential building with BIPV facade in Bremen (Germany) [8]

List of Abbreviations

ATGB	Adviescomissie Toepassing en Gelijkwaardigheid Bouwvoorschriften, Advising Committee for the application of the Building Code
AVG	Average value
BAPV	Building Attached Photovoltaic
BIPV	Building Integrated Photovoltaic
EVA	Ethylene-vinyl acetate copolymer, encapsulant material for a photovoltaic cell
Fire resistant	Degree of fire resistance of a building material, according to fire resistance tests specified by EN EN 13501-2
Fire retardant	Response of a building material to fire, according to the fire classes specified by EN 135101-1
NEN	Dutch Standardisation Organisation
$P(f)$	Failure probability
$P(f\|fi)$	Failure probability under the condition of a fire
$P(fi)$	Probability of the start of a fire
SD	Standard deviation

Chapter 2

Technical overview BIPV-facades

2.1 Photovoltaics

A photovoltaic cell consists of a layer of glass, a layer of encapsulant, the actual (silicon) photovoltaics, another layer of encapsulant and a backsheet material (figure 2.1). The encapsulant materials protect the photovoltaics and ensure adhesion to the other layers. Ethylene-vinyl acetate copolymer (EVA) is a material that is often used as an encapsulant. Photovoltaics are a semiconductor material in which different types of homojunction cells can be used, with different efficiencies. Silicon is often used PV cell material, with an efficiency of around 25% [9].

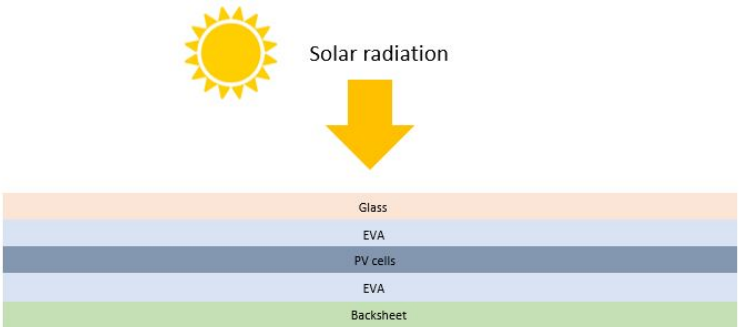


Figure 2.1: Photovoltaic cell

2.2 BIPV facade designs

There are various ways in which photovoltaics can be integrated in facades. According to NEN-EN 50583-1, vertically mounted PV-systems can be divided into two groups: category C and category D [4]. Category C refers to systems which are mounted on the exterior wall and which are not accessible from inside the building. Double skin facades, solar cladding and solar curtain walls belong to this category. Alternatively, PV-systems that are accessible from within the building belong to category D. These systems are mounted within window frames. This means that the photovoltaics are not continous. PV-systems in category C often have an air cavity between the pv-modules and the partition construction.

From the solar energy falling onto the PV-system, around 20% is converted into energy, 10% is directly reflected and around 70% gets transformed into heat [10]. From this heat, roughly 10% of the heat transfers back to the outside air via convection and radiation, and 90% gets transmitted to the cavity [11]. A normal operating cell temperature (NOCT) is defined to determine average operating conditions of photovoltaics. This is established at a solar irradiance of 800 W/m^2, ambient temperature of 20 degrees Celsius and and a wind speed of 1 m/s [12]. However, this approach is used for a rack of photovoltaics under 45 degrees (BAPV). A BIPV system at a different angle has a different solar irradiance and heat accumulation in the cavity. The solar irradiance (diffuse and direct sunlight) is dependent on the sun elevation and azimuth angle, the orientation of the building and the presence of other buildings. While photovoltaics on roofs often have an unobstructed solar exposure, facades are more likely to be (partly) shaded by the presence of other buildings or trees. The total solar irradiance on a South oriented vertical plane is at the most (21st of June, ideal conditions) 600 W/m^2 direct sunlight and 65 W/m^2 diffuse sunlight in the Netherlands [13]. This is lower for other days in the year and different facade orientations. This means that the efficiency of facade PV-panels are lower in comparison with a roof configuration. As a result, the PV-panels will also accumulate less heat. The facade solar irradiances can be much higher in warmer climates. Martinez-Rubio et al., (2016) developed a model to determine the solar irradiances of facades in cities with high buildings [14]. Their case study from a building in the south of Spain reached solar energy of 1760 kWh/m^2. Especially the higher floors of the building were able to obtain a higher solar irradiance. This shows how the geographical location of a building largely influences the facade solar irradiance.

The higher the solar energy, the higher the temperature behind the PV-modules. According to research from 2006, a minimum temperature in the air gap behind the PV array occurs when the ratio between the length of the array and the hydraulic diameter is 20 [15]. Consequently, the longer the air duct, the bigger the gap should be between BIPV system and the facade to allow for optimal ventilation. When the air gap is larger, the velocity of the airflow will be reduced. This is however counteracted by a lower rise in temperature within the cavity. The findings apply to all inclinations, thus also for facade systems [15].

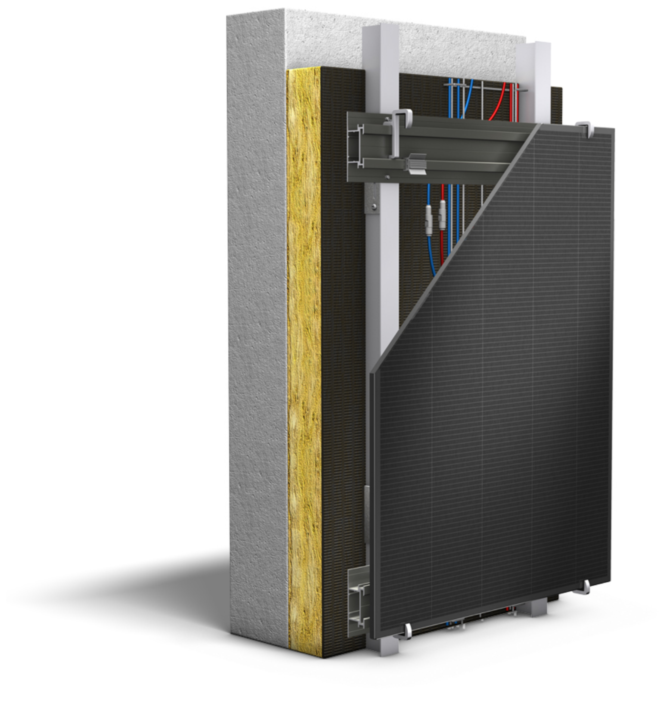


Figure 2.2: Example of a BIPV system build-up [8]

2.3 Fire trajectories and failure situation

As described in the previous section, there are two major categories of BIPV-facades according to European standards. Figure 4.3 shows the fire trajectories for these two categories [4]. Fire can spread by means of radiation, convection and conduction. Radiation from flashover spreads the fire through the windows and air cavity of a double-skin facade, igniting the PV-modules. Convection spreads the heat through the cavity of a double-skin facade, introducing an additional fire trajectory in comparison with category D facades. Conduction can play a role in the mounting system of a BIPV-facade, as these PV-modules are often attached to the facade with aluminium structures. Aluminium starts melting at temperatures of 600 degrees Celsius. However, at 200 degrees Celsius, aluminium has lost already 50% of it's structural strength [16]. This is dangerous, since a loss of strength could mean that photovoltaics get detached from the facade. Direct fire trajectories are covered in European codes, but some other trajectories that are introduced with a BIPV-facade fire are not. Examples are the introduction of a fire source in the facade, and the increased temperature of in the cavity of a facade in the case of a compartment fire. Even if the facade is compliant with the European fire resistance for facades, the continuous exposure to heat can easily ignite the BIPV-facade. PV-panels can be considered thermally light in the case of a fire. Since they contain little mass, they can easily transfer energy (heat). Another example of a trajectory that is not covered in European codes is a fire that originates from the facade, which introduces not only a larger risk for the start of a fire, but also new trajectories.

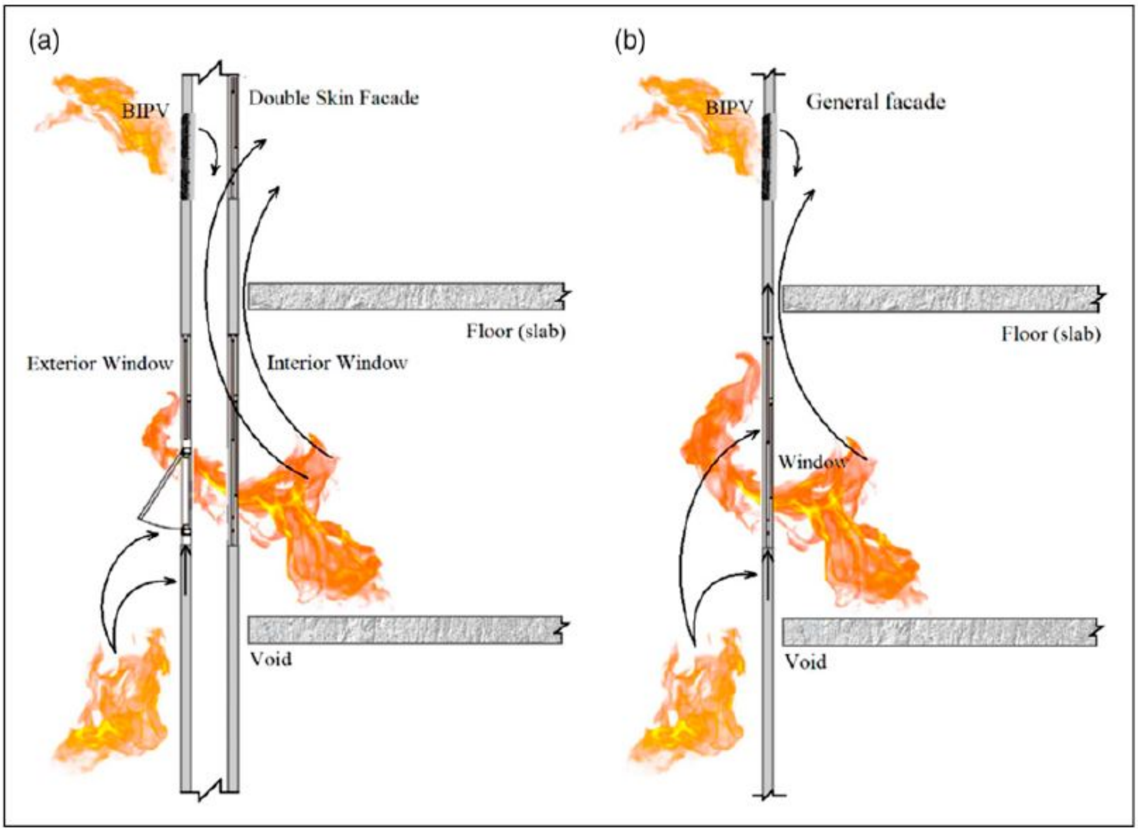


Figure 2.3: Potential fire scenarios for BIPV-facades. (a) category C. (b) category D [4]

Chapter 3

Risk subsystems BIPV-facade

3.1 Introduction

BIPV systems are complex technological systems that add fire safety risks to building facades, which are currently not completely covered by the Building Code. This chapter gives an overview of the risk-subsystems that are threatened by the implementation of a BIPV-facades. The analysis is based on the supplementary risks in comparison with a 'normal' facade.

3.2 Risk subsystem 1: constrain the start of a fire

A fire in a building can start either within the building (compartment), or in the facade. The first risk is not considered here, as this is the same for a building with or without BIPV-systems. Thus, only the additional risk of the start of a fire in the BIPV-facade is questioned here. Research from TNO concluded that one third of the building fires with a PV system, was caused by BIPV systems. Contradictory, according to damage insurance experts, around 80-90% of all fires is caused by BIPV systems. This discrepancy might by explained by the fact that BIPV systems are relatively new and sometimes it is difficult to find the cause of the fire. Experts however agree on the fact that most PV fires are caused due to wiring and faulty connectors. Especially cross-mating, where connectors of different brand are connected, could lead to a potential ignition source [3]. Other electronic causes for the start of a fire are arcing and hot spots [7]. Arcing takes place when the electric current jumps between two connectors through the air, releasing a lot of heat to the environment. Hot spots are localized overheating spots on a photovoltaic. If a single photovoltaic is producing less energy than the previous cell in the series, because it is in a shadow or because something is covering the cell, the cell starts acting as a resistor. This means that only the same amount of energy that was transferred by the faulty cell is conducted. The remaining energy (that was produced by the previous cell) will then be released in the form of heat [17]. An environmental factor that could cause the start of a fire, is the hitting of the photovoltaic by a lightning stroke [4].

Since BIPV-facade systems have a smaller cavity in comparison with BAPV systems, temperatures within the cavity become higher. Research shows that the efficiency of PV cells drops by 0.5% for each temperature increase in degrees Celsius [6]. This is especially problematic for BIPV systems, since air gaps can reach temperatures of 85 degrees Celsius with an ambient temperature of 40 degrees Celsius (which is more than 30 degrees Celsius higher in comparison with a BAPV structure) [18]. According to safety standards, J-boxes (containing the direct to alternating current converters) should be able to operate with temperatures up to 85 degrees Celsius [11]. However, measurements from Taiwan on a summer day (ambient outdoor temperature of 27 degrees Celsius) demonstrated temperatures of 110 degrees Celsius within the J-box [11]. This exceedance of the J-box safe operating temperature increases the risk of ignition in the J-box.

3.3 Risk subsystem 2: constrain the development of a fire

A BIPV-facade always contains combustible materials, as the photovoltaics themselves are already combustible. It is however important to note that the mass of a photovoltaic is small in comparison with other (combustible) materials in the facade (chapter 2). Research shows that the encapsulant of PV modules (such as ethylene-vinyl acetate copolymer (EVA)), used for lamination of PV modules, is the most combustible part of PV module [4]. The back sheet of a PV module, protecting the module against moisture, is also a critical part of the module when it comes to combustibility [4]. A BIPV-facade should, just like a normal facade attain to fire classes of external separation constructions. This is also applies to the combustibility of PV-modules. However, the amount of heat that is being released by an external flame during a facade fire is much higher than the temperatures that are being applied when determining a fire class of a material [19]. As a result, a fire can burn through the non-combustible backside protection layer and quickly reach the combustible part of the PV-modules which accelerates the development of the fire. This is also problematic, since there is a relationship between heat flux and ignition time. With an increase in heat flux from 28 kW/m^2 to 45 kW/m^2 (the heat flux of an external flame even exceeds 45 kW/m^2), ignition time already decreases from 913 seconds to 83 seconds [20]. This shows that in the case of a flash-over room fire, the PV-facade can quickly ignite.

3.4 Risk subsystem 3: constrain the expansion of a fire to one compartment

Decreasing the risk subsystem 3 is important because the overall risk of a BIPV-system is smaller if the fire cannot extend over compartments. Not only the combustibility, but also the flame spread and heat and smoke generation are important factors for the fire behaviour of BIPV systems. Even if a fire is not started at the BIPV system, when it reaches the facade the flames can use the combustible materials as a shortcut to higher floors of the building. The same thing could happen if something at street-level (for instance a car or an external trash container) starts a fire that spreads by the facade [7].

When BIPV systems are applied to a facade, several additional fire trajectories are introduced in comparison with a traditional facade: a fire source in the facade and an air cavity (gap) behind the photovoltaics. This means that flames and smoke can spread through the PV cavity, from the photovoltaics to within the building and from a fire within the building to the facade (shortcutting compartments) [4]. This increases the speed of fire spread and it introduces toxic smoke from the photovoltaics into the building, which can threaten building occupants. Especially the role of the PV cavity is not taken into account when establishing the fire class of photovoltaics.

Full-scale fire tests (three stories) on combustible facade systems revealed that facade systems could get exposed to heat flux levels over 100 kW/m^2 and maximum temperatures of 1000 degrees Celsius [21]. This is problematic, since existing tests on the fire resistance of a facade consider lower heat flux levels and lower temperatures. Furthermore, most full-scale facade tests only consider an internal post-flashover situation with flames coming out of the windows and not the fire behaviour of a fire that started in the facade [22]. For that reason, a full-scale fire test (three stories) on the fire spread of combustible facade cladding by means of an external ignition source on the ground floor was performed by Srivastava et al., (2020). They observed a fire spread from the ground floor to the third floor of only 3 minutes and temperatures over 300 degrees Celsius on the first floor within 5 minutes. They were able to conclude that the severity of a fire with an external ignition source was actually higher than the severity of a fire with an internal ignition source, since flash over on the ground floor in the first situation occurred 16 minutes earlier [21]. This demonstrates that the fire trajectory coming from a fire in the facade could actually contain an equally or even worse failure probability for risk subsystem 3.

3.5 Other relevant risk subsystems

A BIPV-facade also decreases fire safety because it affects the escape and attacking routes. As long as the photovoltaics are exposed to sunlight, they produce energy. This is threatening for firefighters who could potentially get an electric shock when extinguishing the fire [23]. It is therefore essential for firefighters to first switch off the converter (to decrease the voltage), which should ideally be reachable easily. If the converter cannot be switched off, it it more difficult to safely suppress the fire with water. Additionally, the photovoltaics could fall off the facade if the high temperatures melt the suspension system. Falling parts increase the risk for both the building occupants who need to flee from the fire, and firefighters. When a BIPV-facade fire reaches high temperatures, combustion products and fine particles from the photovoltaics rise within a cloud of smoke. These (possible harmful) photovoltaic particles can then spread around a radius of kilometers around the fire (figure 3.1 [24]). This damage to the environment is also an important incentive to make sure that a BIPV-facade fire cannot extend over various compartments. Though it should be noted that this is mostly an issue for large(r) (industrial) buildings with roof-covered photovoltaics and not for small residential BIPV-systems.

Figure 3.1: Spread of (toxic) combustion products and fine particles of PV-fire for large industrial fires [24]

Threat	**Specific cause**	**Risk sub-system 1: start of a fire**	**Risk sub-system 2: development of a fire**	**Risk sub-system 3: expansion of a fire**	**Other risk subsystems**
Cross-mating	Electronics	x			
Arcing	Electronics	x			
Hot spots	Electronics	x			
Lightning stroke	Environmental	x			
Cavity temperature	Construction	x	x		
Combustible materials	Construction		x		
Direct contact to indoors	Construction			x	
Shortcutting compartments	Construction			x	
Electric shock	Electronics				x
Toxic smoke and spread of glass particles	Electronics				x
Falling parts	Construction				x

Table 3.1: Overview fire safety threats BIPV-facade

Chapter 4

Failure risk building with BIPV-façade

4.1 Introduction

The previous chapter showed how various factors influence the increased failure probability of the relevant risk subsystem of a BIPV-facade. Because of the complex behaviour of a fire, simulations and experiments cannot give a complete answer on the failure probability. This chapter tries to quantify the failure probability by asking a panel of experts to judge various situations on fire safety.

4.2 Methods

4.2.1 Method survey

Chapter 2 looked into different BIPV-facade designs that are currently being used. A facade of category C is most likely to form the highest risk, since the photovoltaic panels are connected and the air cavity can increase the likelihood of a fire spreading along the facade. Two different scenarios are worth considering: a fire in a compartment, that can spread along the combustible facade as an additional fire trajectory and a fire within the PV-system that can enter a building. A third source of fire would be an external fire that ignites the facade from outside. This source is not considered, since the assumption made that the overall fire class of the facade is sufficient. Thus, this leaves two possible fire sources: a compartment fire and a fire within the facade. The question remains which of these two scenarios have the highest probabilities (and thus risks) of occurring. Next to the different scenarios, the type of construction and combustibility of the materials in the facade is worth discussing. For the type of construction, a thermal heavy and a thermal light construction were chosen (figure 4.1 and figure 4.2). A thermal heavy construction means that a lot of heat from a fire can be accumulated in the construction looking from the inside (by using for instance concrete), while the thermal light construction transfers heat (by using for instance a wooden frame construction). Thermal heavy and thermal light in this context is only related to the amount of heat that can be accumulated in the case of a fire. This is different than from a building physics perspective, since a building physics perspective looks at fluctuations over a longer period of time. In comparison, the fire resistance perspective takes a fire into account, which deals with extreme temperatures in short time periods. Additionally, two types of insulation material of the facade were considered: combustible and non-combustible insulation. This results in the following options: thermal heavy construction with non-combustible insulation, thermal heavy construction with combustible insulation, thermal light construction with non-combustible insulation and a thermal light construction with combustible insulation. All four designs are judged on the fire resistance (in minutes available safe time) in the case of a photovoltaic fire or in the case of a compartment fire (figure 4.3). The fire resistance is divided over four different options: less than 5 minutes, 5-15 minutes, 15-30 minutes, 30-60 minutes and more than 60 minutes. The entire survey can be found in Appendix A.

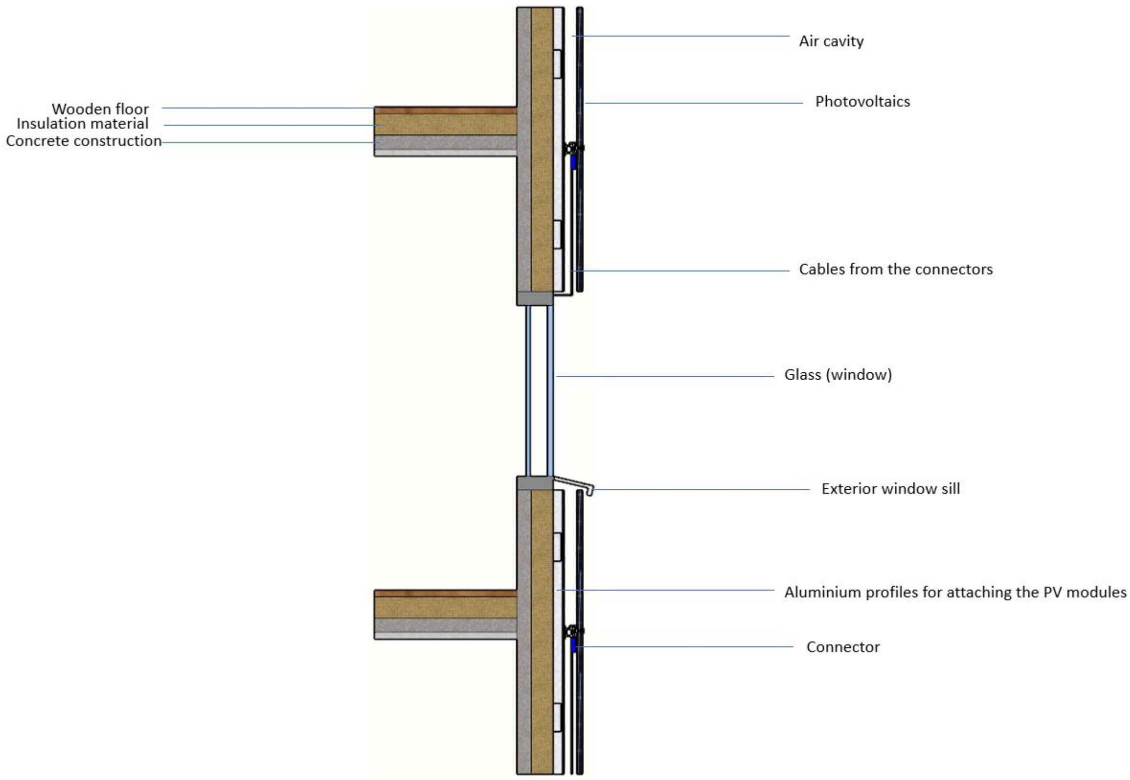


Figure 4.1: Thermal heavy construction: concrete floors and facade with either combustible or non-combustible insulation (from inside to outside)

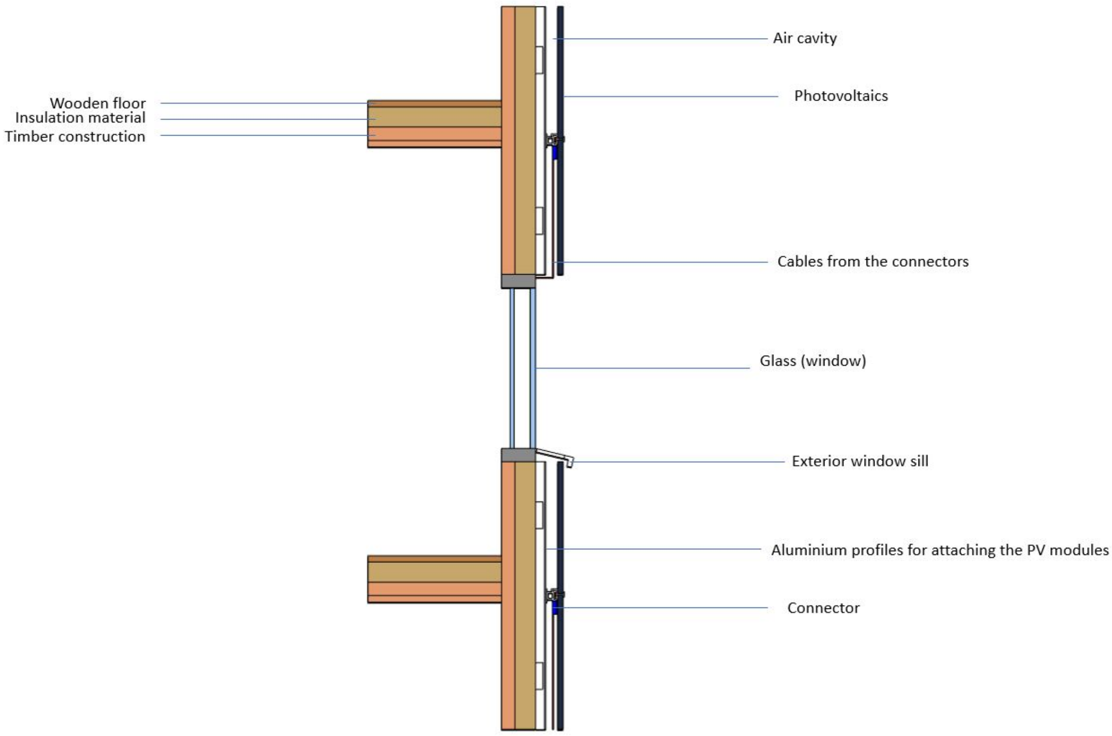
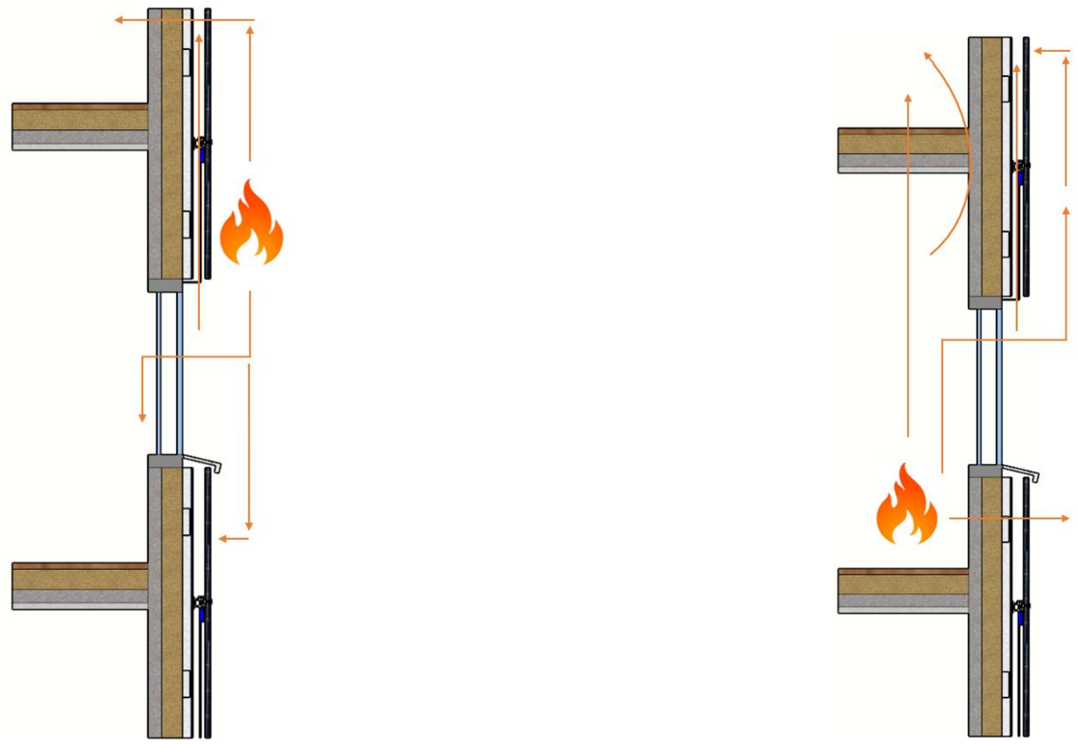


Figure 4.2: Thermal light construction: timber floors and facade with either combustible or non-combustible insulation (from inside to outside)



(a) Fire scenario 1: fire in the facade

(b) Fire scenario 2: fire in a compartment

Figure 4.3: Fire scenarios

4.2.2 Method failure probability analysis

The method to determine the failure probability of a building is based on the risk subsystems and the failure probability of each system. Each failure probability can be determined by comparing the AST (available safe time in minutes) with the RST (required safe time in minutes), where AST should be larger than RST. The AST is based on the building characteristics, while the RST is determined by the fire characteristics (thermal load, building specific). In the survey, the failure probability of compartments (risk subsystem 3) is questioned. The fire resistance of this risk subsystem consists of the direct and the flanking fire trajectories (alongside the facade). The flanking trajectory via the facade, cannot have a lower fire resistance (in minutes available safe time) than the direct trajectory because then the overall failure probability is not achieved. If the inner walls and floors have an available safe time of 60 minutes, the facade should have an even larger available safe time to reach equal failure probabilities as a building without BIPV-facades. This is because a facade can have a failure probability (just like the inner separation construction) based on the fire trajectories, but there is also the additional risk of including an extra source for a potential fire.

The questions that are asked in the survey do not make a distinction between the direct and the flanking fire trajectories, but respondents are informed about the additional (flanking) fire trajectories of a BIPV-facade. This means that each question attempts to inquire the total available safe time for the given construction and materials. The required safe time is based on the fire curve of a natural fire, specified to the building function (office, retail or residential) by stochastic boundary conditions [25]. For this analysis, a residential building is calculated. The stochastic boundary conditions are shown in table 4.1. These stochastic boundary conditions correspond to an RST of 54 minutes SFC (with a standard deviation of 13.4) equivalent fire duration for a residential compartment of 70 m^2 [25]. This is the RST for the compartment fire. For the facade fire, the area is smaller and the fire load is also smaller than for a compartment fire, thus an estimated guess of 5.5 minutes RST SFC (with a standard deviation of 1.34) is assumed [25].

Stochastic boundary conditions	**Average value for a residential compartment fire**
Fire load density q $[MJ/m^2]$	780
Time constant fire spread tc [s]	300
Rate of heat release density RHR $[kW/m^2]$	250
Stoichiometric constant r [kg/kg]	1.27
Heat of combustion Hc [MJ/kg]	17.5
Opening factor Aopen [-] **(glass failure of daylightopenings)**	0.8

Table 4.1: Stochastic boundary conditions for a natural residential fire [25]

The AST of each question will be calculated with an average value and a standard deviation. First, the range of answering options is brought back to one number. Thus, the range 0-5 minutes corresponds to 2.5 minutes, 5-15 minutes corresponds to 10 minutes, 15-30 minutes corresponds to 22.5 minutes, the range 30-60 minutes corresponds to 45 minutes and finally more than 60 minutes is defined as 75 minutes. For each average option, the probability is the total number of answers divided over the total number of answers. Additionally, respondents that refrained from choosing an answer, are considered to find each option equally likely. Thus, the probability of each multiple choice option can be calculated by equation 4.1. Next, the probability of each option is multiplied with the corresponding average option to get to an average. These numbers are added to come to an average AST for that question. This approach leads to an average AST and average standard deviation for each of the eight questions.

$$P(a) = \frac{\frac{n_{answer(a)}+n_{noanswer}}{n_{answeroptions}}}{n_{respondents}} \tag{4.1}$$

where,
P(a): probability option a
$n_{answer(a)}$: amount of answers for multiple choice answer option a
$n_{noanswer}$: amount of respondents who refrained from answering any option
$n_{answeroptions}$: amount of multiple choice options
$n_{respondents}$: amount of respondents to the survey

When both the RST and AST are known, the cumulative failure probability AST-RST can be determined. The failure probability for AST-RST is calculated for -60 to 72 minutes, resulting in a graph with the cumulative failure probabilities. The average value (in minutes) of this calculation is the probability that AST-RST is more than 50%. Additionally, when AST-RST is more than zero minutes, the success rate can be calculated. The failure probability is then 1-success rate.

The eight questions from the survey considered two separate fire scenarios: a fire in a compartment and a fire in the facade. These are two different scenarios, but in order to be able to conclude something on the entire failure probability of a BIPV-facade, the failure probabilities of the two scenarios should be combined. In general, the failure probability can be determined by multiplying the probability of failure (given a fire) with the probabilities of the start of a fire (equation 4.2). In this case, the failure probability P(f) is then the failure probability of the compartment and the failure probability of the facade (equation 4.3). The probabilities of the start of a fire (P(fi)) can be estimated at $4 * 10^{-4}$ for a compartment fire. Because the exact probability of the start of a fire in the facade is unknown due to missing information, the probability of the start of a fire per square meter of facade is assumed to be equal to the probability of the start of a fire per square meter of compartment. However, as was mentioned earlier, the area of one facade is smaller than the floor area of one compartment, thus the probabilities are also smaller. If the assumption is made that the residential compartment is $70m^2$ and the facade is 7m x 3m, the probabilities of the start of a facade fire are 21/70 of the compartment fire (equation 4.4). Thus, the overall probabilities of fire is 91/70 times bigger when a BIPV-facade is introduced (equation 4.5).

$$P(f) = P(f|fi)_{comp} * P(fi)_{comp} \tag{4.2}$$

$$P(f) = P(f|fi)_{comp} * P(fi)_{comp} + P(f|fi)_{fac} * P(fi)_{fac} \tag{4.3}$$

$$P(fi)_{fac} = \frac{21}{70} * P(fi)_{comp} \tag{4.4}$$

$$P(f) = (P(f|fi)_{comp} + P(f|fi)_{fac} * \frac{21}{70}) * P(fi)_{comp} \tag{4.5}$$

where,
P(f): failure probability
$P(f|fi)_{comp}$: failure probability under the condition of a compartment fire
$P(fi)_{comp}$: probability of the start of a compartment fire
$P(f|fi)_{fac}$: failure probability under the condition of a facade fire

$P(fi)_{fac}$: probability of the start of a facade fire

By applying equation 4.5, the overall failure probability of the BIPV-facade of risk subsystem 3 can be calculated for each situation (thermal heavy, thermal light, combustible insulation and non-combustible insulation).

Finally, it is important to note the prescriptive building code only focuses on limiting the maximum effects, without taking the probabilities into account. Thus, in order for the calculations to match the building code, the calculations will also be done with considering only the effects. Equation 4.6 shows only taking the consequences of a fire into account, without looking at the probability of the start of a fire, as described in the prescriptive building code. When combining equation 4.6 with equation 4.4, the equation for the failure probability according to the Dutch building code follows (equation 4.7). The failure probability according to the method of the Dutch building code will be calculated as well for the four different situations (thermal heavy, thermal light, combustible insulation and non-combustible insulation).

$$P(fi)_{comp} + P(fi)_{fac} = 1 \tag{4.6}$$

$$P(f)_{bd} = (P(f|fi)_{comp} + P(f|fi)_{fac} * \frac{21}{70}) * \frac{70}{91} \tag{4.7}$$

where,
$P(f)_{bd}$: failure probability according to the prescriptive building code
$P(f|fi)_{comp}$: failure probability under the condition of a compartment fire
$P(fi)_{comp}$: probability of the start of a compartment fire
$P(f|fi)_{fac}$: failure probability under the condition of a facade fire
$P(fi)_{fac}$: probability of the start of a facade fire

4.3 Results

The responses from the survey revealed both quantitative and qualitative results, which will be discussed in this section. First, the quantitative results will be discussed as calculated by the method in the previous section. Next, the qualitative results will be analyzed.

4.3.1 Quantitative results

This section shows the results for the AST-RST failure probabilities and the combined failure probabilities for the different scenarios of the survey: a fire in the facade and a fire in the compartment (figure 4.3. Important to note is that there is no fire stop present in the cavity behind the photovoltaics. The results are calculated according to the method specified in the previous section. A total of 72 responses where received on the survey questions. The answers per survey question can be found in appendix B (table B.1). Not all respondents answered all questions. Those missing answers were dealt with as was described in the method. From the respondents 64% are currently employed in an engineering firm. The other 36% are spread out over more than 10 different employers, such as the National Institution for Public Safety, the fire brigade, suppliers for building materials, the government, certification institutions, non-profit organisations, a university, a branch organisation, VVE and contractors.

Table4.2 shows the average available safe time (as calculated from the survey results), the average required safe time and the corresponding failure probability of each of the four constructions and two types of fire scenarios. The complete calculations can be found in Appendix B. The first thing that is important to note are the large standard deviations of the average available safe time. This indicates a large spread in the answers that respondents gave to the questions. This means that either the respondents felt like they lacked knowledge to give an estimation of the available safe time or that vital information was missing to be able to answer the question. The large standard deviation also shows that even though there were a lot of experts among the respondents, currently the estimation on the safety of BIPV-facade is too dependent on the personal judgement of the advisor and cannot be estimated based on an existing framework. For both the compartment fire and the facade fire, the average available safe time is higher for non-combustible insulation in comparison with combustible insulation. This difference is not found between thermal light and thermal heavy, meaning that either the respondents valued the combustibility of the insulation materials as more important or they cannot properly estimate the impact of heat accumulation in a construction during a fire.

Construction	**Fire**	**Average AST (min)**	**Standard deviation AST (min)**	**Average RST (min)**	**Standard deviation RST (min)**	**P(f|fi) bijAST-RST = 0 (min)**
Thermal heavy, non-combustible insulation	Compartment	34.01	26.47	54	13.4	0.75
Thermal heavy, combustible insulation	Compartment	25.19	26.92	54	13.4	0.83
Thermal light, non-combustible insulation	Compartment	29	26.37	54	13.4	0.80
Thermal light, combustible insulation	Compartment	24.38	27.12	54	13.4	0.84
Thermal heavy, non-combustible insulation	Facade	30.16	26.31	5.5	1.34	0.17
Thermal heavy, combustible insulation	Facade	24.53	27.08	5.5	1.34	0.24
Thermal light, non-combustible insulation	Facade	28.2	26.44	5.5	1.34	0.20
Thermal light, combustible insulation	Facade	23.17	27.44	5.5	1.34	0.26

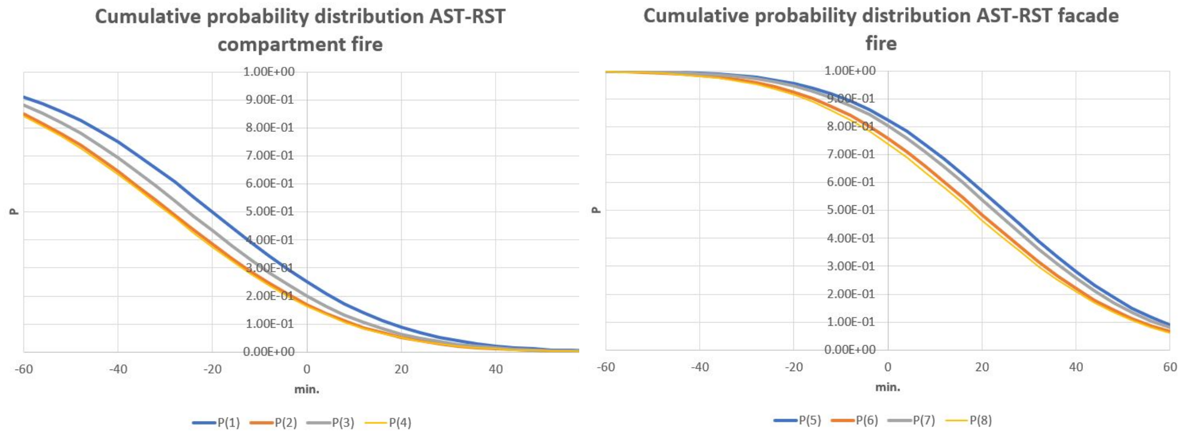
Table 4.2: Available safe time and required safe time for each type of construction and fire scenario, based on survey results

In reality, there are not two different scenarios, but the failure probability and probability of the start of a fire of the facade, comes in addition to the compartment failure probability and probability of the start of a fire in the compartment. Table 4.3 shows the results from the failure probabilities according to equation 4.5 (P(f)) and equation 4.7 ($P(f)_{bd}$). As expected, since the failure probabilities in the case of a fire are close for all types of constructions, the overall probabilities of failure (P(f)) are in the same order of magnitude. This also applies to the probability of failure when the probability of a fire starting is not taken into account (Dutch Building Code).

Construction	$\mathbf{P(f\|fi)_{comp}}$	$\mathbf{P(f\|fi)_{fac}}$	$\mathbf{P(fi)_{comp}}$	$\mathbf{P(f)}$	$\mathbf{P(f)_{bd}}$
Thermal heavy, non-combustible insulation	0.75	0.17	0.0004	$3.2 \cdot 10^{-4}$	0.62
Thermal heavy, combustible insulation	0.83	0.24	0.0004	$3.6 \cdot 10^{-4}$	0.69
Thermal light, non-combustible insulation	0.80	0.20	0.0004	$3.4 \cdot 10^{-4}$	0.66
Thermal light, combustible insulation	0.84	0.26	0.0004	$3.7 \cdot 10^{-4}$	0.71

Table 4.3: Failure probabilities according to survey results and calculations

The failure probabilities based on AST-RST=0 are very high for the compartment fire and relatively low for the facade fire. Figure 4.4 shows the cumulative probability distribution for the two types of fires. P(1) to p(8) corresponds to the eight different questions and the constructions and types of fire as shown in table 4.2. It can be seen that for both fire scenarios, the failure probabilities are close to each other. Additionally, the low failure probability of the facade fire can be noticed. The reason why this is so low for the facade fire, is that the RST (based on the fire load in BIPV facade) is lower than the fire load of a compartment fire. However, the danger with a BIPV-facade is not necessarily the fire load of the photovoltaics itself, but that cannot be displayed in this graph.



(a) Cumulative probability distribution for a compartment fire

(b) Cumulative probability distribution for a facade fire

Figure 4.4: Cumulative probability distributions for two types of fire scenarios and 4 types of constructions

4.3.2 Qualitative results

The respondents of the survey were able to add comments to each multiple-choice question and to the final answer box where they were asked in an open question if they had any ideas on the improvement of fire safety of BIPV-facades. This section shortly summarizes the main ideas from the qualitative part of the survey.

Firstly, the combustibility of the solar panels themselves are important, because they determine the amount of fuel that can start burning. The amount of fuel determines if the fire can expand and how fast the fire can spread. If the fire was started because of a short circuit, there will be a constant release of energy because the solar panels keep producing energy as long as solar radiation is falling onto the panels. If the insulation material in the facade is combustible, this will contribute to the fuel of the fire, as well as radiate heat through the facade. The solar panels themselves might not have sufficient fire load for a long enough duration for fire spread, but combustible materials in the facade will. In the case of PUR insulation, a lot of energy will be released during a fire, which could break window glass, making it easier for a fire to expand into a different compartment. Together with the chimney effect, that could increase the temperature even more, the fire can spread quickly. In principle, the fire will mostly expand upwards. However, when an aluminium construction is used, that will eventually loose strength, (burning) solar panels could start falling down. Additionally, if EPS insulation is used or the solar panels contain plastics, the fire could also spread downwards because of burning droplets. Most respondents felt that thermal heavy or thermal light constructions did not matter much, as long as the available safe time was the same. One respondent did mention that for thermal light constructions, the temperature criterion will be exceeded much faster, which is problematic. The entrance of a fire into another compartment not only depends on the amount of fuel and the cavity, but also on the characteristics of the windows. If the windows are less than 60 minutes fire resistant, they will be the weakest link in the construction, through which a compartment fire can expand to the combustible facade panels. One respondent estimated breaking of the glass within eight minutes, after which the solar panels and the possible combustible materials in the facade could start burning. The fire can then reach upper compartments either directly by flames or by radiation. The fire resistance of the glass and the frame is thus not only important for keeping the fire within a compartment, but also for preventing a facade fire to enter the building. The distance between solar panels and windows, and the opening factor of the windows influences the fire resistance as well. Finally, one respondent mentioned that a fire within a burning photovoltaic could not only spread alongside the facade, but it could also spread via cables which penetrate the facade to indoors. To summarize, the combustibility of the photovoltaics and the insulation materials determine the fire load and the velocity of expansion in the case of a fire. Entrance into another compartment is then mainly determined by fire characteristics of the windows.

Next to threats, solutions were also proposed to improve the fire safety of BIPV-facades. First, the combustibility of the solar panels should be minimized by preventing the use of plastics and using only glass-glass panels. Next to that, fire retardant panels, such as CEM panels, could be placed directly behind the photovoltaics as an extra layer. Alongside of that, non-combustible insulation materials such as rockwool should be used. The electric parts of the photovoltaic should be placed outside of the facade or within a fire retardant box. Electric failure could be prevented by using micro-inventors, which prevent arcing by using alternating current instead of direct current. The solar panels should be attached to the wall without the use of aluminium, to make sure they cannot fall down quickly in the case of a fire. Though, one person mentioned that an automatic folding away system could potentially also be a solution. Next, almost all respondents agreed that the facade system should be divided into compartments as well, which align with the indoor compartments. Firestops could be used to prevent fire spread in the cavity, in addition to alternating photovoltaics with non-combustible cladding. Finally, the fire resistance of the windows and window frames should be improved upon to decrease the ease of flames from the burning facade entering another compartment.

Chapter 5

Solutions and system requirements for fire safety threats BIPV-façade

5.1 Introduction

The previous chapters revealed the complicated fire safety practices of introducing BIPV-systems to a building. The fact that PV-systems contain electronics, is often the main cause of the start of a fire due to either malfunctioning or errors in installation. This research however also revealed that facade and building characteristics can contribute to the overall failure probability of various risk subsystems. This chapter looks into possible solution and system requirements for improving fire safety of a BIPV-facade.

5.2 Threats to risk subsystem 1 and 2

5.2.1 Electronic errors

Since photovoltaics are part of an electronic system, there is always a risk of electronic errors such as arcing and hot spots. If the occurrence of these errors can be prevented, the failure probability of risk subsystem 1 could be drastically decreased. Hot spots could take place when there is unequal power generation of in series connected photovoltaics, due to for instance dust or shade [26]. Thus, a first step in preventing hot spots is making sure that there is frequent cleaning of the photovoltaic facade. This slows down the aging of the panels and prevents unequal power generation. Additionally, the geographical location of the facade should be taken into account by looking at shade on the panels from other buildings and trees. A third method to prevent hot spots is to apply bypass diodes to the configuration of the photovoltaic system. When a single PV-panel is blocking the current (due to dust, shade, being broken, etc.), the bypass diode is able to bypass the nonperforming cell and keep on passing the current through the system [26]. To prevent arcing from starting a fire, fault detection methods could be applied. Currently, various methods are possible to apply fault diagnosis for PV systems: physical analysis, Fast Fourier Transform, time domain analysis, wavelet detection and artificial intelligence methods [26]. These methods make use of different signals (such as heat, noise or electromagnetic radiation) to determine the acceptable range of each signal. Above a certain signal threshold, a DC arc takes place and the fault diagnosis method can detect the fault before it can develop into a fire. Advantages differ per method, but in general they can achieve high accuracy in detecting DC arcs and thus also improving efficiency of the PV system. The disadvantage is often the increased costs of the PV-system and the complexity of the model [26].

5.2.2 Installation errors

Analysis of PV-related fires revealed that faulty installation is often the case for the start of a PV-fire. Currently, there are no requirements for the correct installation of PV-systems. Manufactures of photovoltaics often provide a manual with all the specifications needed for safe installation and implementation. However, there is no monitoring that indeed checks if each installation is performed as it should. A first step in decreasing the failure probability of risk subsystem 1 is to create mandatory regulations for the installation of photovoltaics. The risk of placing electronics in a facade-element that could possibly produce a spark remains, but certification ensures that preventable fire hazards are limited.

5.2.3 Combustible materials

Photovoltaics are inherently combustible, but it is possible to use different material compositions to make sure that a fire either from within the PV-system or from an external cause cannot easily ignite the entire system. The backsheet of the panel is important to protect the more combustible layers of the panel from a fire. Backsheet materials that are currently being used are: FEVE (fluoroethylene vinyl ether), PVDF (polyvinylidene fluoride), PET (polyethylene-vinyl acetate) and PVF (polyvinyl fluoride) [27]. Aluminium and glass backsheets could also be applied. However, an aluminium backsheet is highly conductivity and since PV-systems produce electricity, this material is less applied. Nair et al., ([28]) concluded that a backsheet of three layers (thickness of 325 micrometer) consisting of PVF/PET/PVF achieved the best fire resistance. However, this was mainly due to the fact that this backsheet had the highest thickness of all three configurations that were tested. Other research on the combustibility of backsheet configurations showed the lowest flame propagation speed and damaged zone for a PET backsheet with a total thickness of 325 micrometer [29]. Ideally, fire tests should take place that consider all design parameters of the backsheet: thickness of the entire backsheet, type of materials and the amount of layers.

An example of a (more) fire-retardant BIPV design was suggested in research from Huang et al., ([11]. Instead of mounting the junction-box directly on the back substrate of the photovoltaic (exposed to a potential fire), they placed the junction-box (and all wires) between double transparent tempered glass and hidden in the peripheral frame of the BIPV module. A fire test (up to 810 degrees Celsius heat in an oven for 12 minutes) revealed that the J-box would start burning and falling from the back of a normal BIPV module, while the J-box of the 'hidden' J-box was still intact without any damage [11].

5.2.4 Cavity temperatures

One of the main conclusions of researchers on BIPV-facades is that the temperature in the cavity of double-skin PV-facade can increase to very high values. This means that only very little energy is needed to start a fire. Thus, one of the system requirements would be to cool down the cavity. One way of decreasing the cavity temperature is by increasing ventilation. According to research from 2006, a minimum temperature in the air gap behind the PV array occurs when the ratio between the length of the array and the hydraulic diameter is 20 [15]. Consequently, the longer the air duct, the bigger the gap should be between BIPV system and the facade to allow for optimal ventilation. When the air gap is larger, the velocity of the airflow will be reduced. This is however counteracted by a lower rise in temperature within the cavity. The findings apply to all inclinations, thus also for facade systems [15]. Next to the influence of the length and width of the cavity, there might also be an influence of the resistance of any obstructions within the cavity created by the construction of the BIPV facade. The facade design includes attachments of the PV cells to the facade itself, and other cavity obstructions such as nets to prevent insects from flying in or birds creating nests in the cavity. According to simulations from Brinkworth et. al ([15]) these obstructions would not lead to a higher temperature in the cavity. As an explanation they give the fact that even though the added resistance decreases the airflow-rate by a third, the turbulent mixing of the air also doubles the heat transfer coefficient and thus the overall air temperature decreases. Tonui et al., ([30]) even on purpose placed obstructions in the cavity to enhance natural ventilation. Two options were considered: placing a suspended vertical metal sheet in the cavity (TMS sheet) and placing various parallel horizontal 'fins' in the cavity at the opposite wall of the channel (figure 5.1). Especially the 'fin' system was able to decrease the cavity temperatures effectively by 10 degrees Celsius, while the TMS system decreased the temperature by 2 degrees Celsius. Both systems function optimally if the cavity length is less than 6m [30]. Finally, another factor influencing the ventilation of a cavity is determined by the total amount of temperature decrease. If the air outlet is placed in a region with negative wind pressures, natural ventilation is enhanced [31]. It is however important to note that ventilation of the cavity is contradictory with the application of a firestop. Without a fire, the air cavity should be open to allow for optimal flow. This can only be achieved without firestops, or a firestop that only comes into place when a fire has started (for instance with material that expands into the cavity due to heat release of the fire).

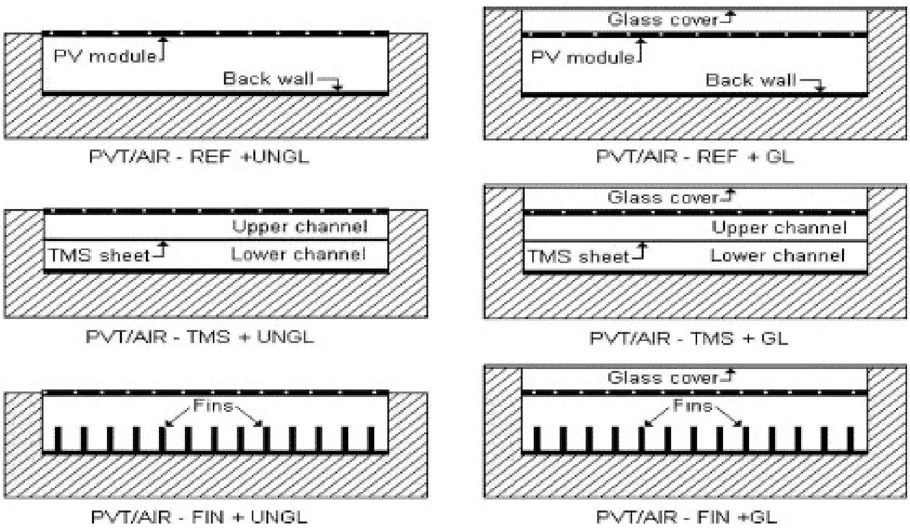


Figure 5.1: Experimental study on the use of obstructions in the cavity to enhance natural ventilation [30]

Ventilation of the cavity behind the PV-system can also be increased with an active system. Research from Ritzen et al., ([18]) suggests to make use of the buildings' mechanical ventilation system to actively increase ventilation behind the BIPV-system. The air outlet of the mechanical ventilation system can be placed just before the natural ventilation outlet 5.2. The cool air from inside the building can then cool down the hot air in the cavity during summer [18]. This experiment was conducted with a BIPV-roof, thus the effects might be different with a BIPV-facade, since buoyancy forces are stronger in a facade.

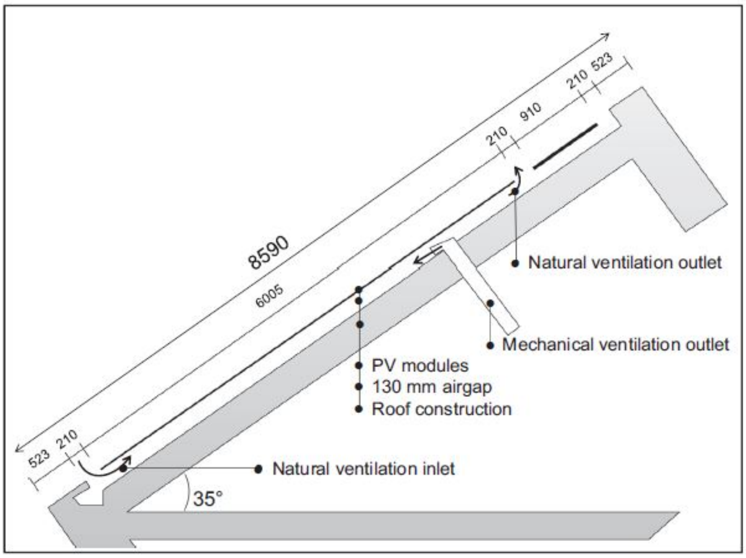


Figure 5.2: Field test of using the HVAC system to cool down the photovoltaic cavity [18]

While ventilation techniques usually make use of (passive) buoyancy forces, another method to remove heat from the PV-system is by applying phase changing materials. Hasan et al., ([6]) performed experimental research on phase changing materials as a method of cooling down PV-systems. They compared five different PCM's with melting points between 20 and 30 degrees Celsius. When these melting points are reached, the PCM is going into a phase change and absorbs heat from the direct environment. As a result, the PV-cells as well as the cavity decrease in temperature. The PCM's are attached on the backside of the PV-cells in aluminium containers. Important parameters for the heat removal are the thermal mass of the PCM and the insulation of the entire PV/PCM system. The PCM $CaCL_2{\cdot}6H_2O$ (pure salt hydrate, melting point at 29.17 degrees Celsius, heat of fusion of 213.12 kJ/kg) was the most successful, as it was capable of decreasing the temperature by 10 decrease Celsius for 5 hours, with a solar irradiance of 1000 W/m^2. Similarly, Biwole et al., ([32]) designed a numerical model to predict the performance of a PV/PCM system (5.3). By using the PCM RT25, they were able to keep the temperature of the system below 40 degrees Celsius for 80 minutes, while exposed to a solar irradiance of 1000 W/m^2. In comparison, the system without the PCM exceeded the temperature of 40 degrees Celsius already after 5 minutes with the same solar irradiance exposure [32]. Additionally, a case-study from South-Korea concluded that the higher the width of the PCM container, the greater the heat removal [33]. Their experiment contained a PV/PCM system on a vertical wall. They established an optimal width of the PCM container of 50-70mm in the South-Korean climate, though it is important to note that this width is optimized on energy generation of the PV-panels and not on temperature decrease of the PV cells [33]. Since there are various phase changing materials available, depending on the orientation of the building, the climate (outdoor temperatures), the PCM characteristics (melting point, specific heat capacity and thermal conductivity) and the PCM container design (width of the container and overall conductivity) a choice can be made for optimal cooling of the PV-system by a PCM.

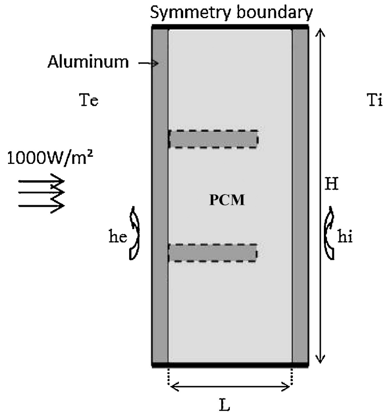


Figure 5.3: Numerical model of a PV/PCM system [32]

5.3 Threats to risk subsystem 3

5.3.1 Extending over fire compartments

All risk subsystems are related. If a fire can be contained within a compartment, the overall failure probability of a BIPV-facaade decreases. If however the fire can easily spread, the high probability of the start of a fire in the facade increases the overall risk. To prevent spread along the facade by the photovoltaics, the original fire compartments should stay in place. This could be done by applying the requirements from NEN 6068, which would mean a distance of 1m horizontal between each block of photovoltaics and applying a firestop in the facade to prevent vertical spread of flames and smoke [19]. This also makes sure that there are no burning photovoltaics near escape routes in the case of a fire. A permanent firestop for each facade compartment is sub-optimal, because it decreases ventilation in the air cavity of the photovoltaic system. A firestop that only closes off the cavity in the case of a fire, and does not block ventilation in the normal situation would be ideal.

To prevent the spread from inside the building to the combustible BIPV facade, a sprinkler system could be applied inside the building. Statistics on US building fires related to exterior walls between 2007 and 2011, demonstrated that compartment sprinkler systems have a significant effect on reducing the risk of the spread of a fire from inside to the facade of high-rise buildings [22]. Additionally, the use of external sprinklers could also be applied to prevent the facade fire from extending over fire compartments, though no data on the effectiveness of this method is known.

5.4 Thinking beyond risk subsystems

The risk subsystems are designed to form lines of defense for the main public goals of personal safety and (to a lesser extent) safety of neighbouring plots and buildings. For the solutions of fire safety threats of a BIPV-facade, the previous sections in this chapters looked at decreasing the failure probability of each specific risk subsystem. However, with the main public safety goals in mind, it is also possible to look beyond risk subsystems when looking at fire safety for buildings with BIPV-facades. If an acceptable failure probability of one risk subsystem cannot be achieved, a lower failure probability of another risk subsystem could be a solution to still achieve an overall acceptable failure probability. If for instance the probability of a facade fire cannot be contained (risk subsystem 1), but the fire cannot extend beyond the compartment (risk subsystem 3), the overall failure probability could be acceptable. The same applies to making sure that even if a fire is started, it cannot develop and thus spreads slower. Alternatively, a choice could also be to accept that a fire in a BIPV-facade building spreads faster than without the BIPV-facade. In order to still accomplish personal safety in such a building, quicker evacuation in case of fire could be a solution. Of course, this decreases the fire resilience of a building. And a decreased fire resilience of a building that tried to be sustainable by using photovoltaic systems, is not very sustainable.

Chapter 6

Conclusion

Photovoltaic systems are no longer just suitable for roof configurations, but they can also be applied to facades. However, BIPV-facade systems introduce new fire sources and fire trajectories. Thus, there is a need for a new fire safety determination method.

Risk subsystem 1 (constrain the start of a fire) and risk subsystem 3 (constrain the spread of a fire to other compartments) are especially threatened by BIPV-facade systems. Electronic errors and installation faults are often the cause for the start of a fire. Together with combustible materials in the PV-panels and the surrounding materials and high cavity temperatures, a fire could potentially spread very fast. Current fire tests on the fire resistance do not take realistic situations into account and there is a need for more full-scale fire tests to determine fire behaviour of BIPV-systems.

Since there is only a limited amount of literature available on fire safety of BIPV-systems, and since simulations cannot fully evaluate the complex issues, a survey with experts was conducted. The results show that the failure probability of a compartment increases strongly when a compartment fire can extend via combustible PV-panels and a cavity.The level of risk of the facade fire was more difficult to quantify, since the low fire load decreased the failure probabilities. The highest failure risks were determined for combustible insulation, since this contributes to both the speed of expansion and to the fire load. Thus, even though the RST of a facade fire might be low, the surrounding factors make it still an unacceptable risk. Respondents agreed that BIPV-systems increase the failure probability of a compartment, though the extend is also dependent on the use of combustible materials in the facade and the fire resistance of the window and window frames. Even though the responses showed an increase in the overall failure probability, there was also a large spread in the answers. This means that even experts in the topic experienced difficulties in correctly estimating the situation. Consequently, a need is expressed for a uniform testing method for the failure probability of BIPV facades, because individual expert judgement has shown to not be consistent enough to account for the fire safety level of BIPV-systems.

Solutions to fire safety threats of BIPV-facades can be applied in various area's. A higher failure probability of one risk subsystem could potentially be counteracted by a higher level of safety on other risk subsystems. Even though the Dutch building code does not take the start of a fire into account, this probability could be decreased by demanding mandatory regulations for safe installation of photovoltaics. Electronic errors could be prevented by frequent cleaning of PV-panels, applying bypass diodes or even by applying fault detection methods. As was already mentioned by respondents of the survey, combustible materials in the cavity and facade should be minimized to prevent a fast fire spread and to decrease the fire load. This means non-combustible insulation, fire retardant back sheet layers and a fire retardant junction-box for the electronics. Additionally, decreasing cavity temperatures is important to increase the amount of energy that is needed to develop a fire from a spark. This can be done by designing for optimal natural ventilation, adding PCM's or even applying an active cooling system. Decreasing cavity temperatures not only increases fire safety, but it can also be an interesting incentive for building owners because it increases the efficiency of solar energy generation. Solutions for decreasing the threat to risk subsystem 3 focus on making sure that the fire cannot expand over the (original) compartment boundaries. Firestops could be a good solution, though they are conflicting with natural ventilation flow. Thus, they should preferably only come into place in the case of high temperatures (fire). Alternatively, PV cladding and non-combustible cladding could be alternated, sprinkler systems could be applied and special care should be taken on the fire resistance of windows and window frames as the weak link of the facade.

This report confirmed the hypothesis that a building with a BIPV-facade system increases overall failure probabilities beyond the already existing failure probabilities of an existing building. Though the exact increase in failure probabilities remains difficult to quantify, literature research and expert judgement demonstrated that fire classes of PV materials cannot fully guarantee a safe building and that there is a need for uniform classification methods. Future research with full-scale tests can extent knowledge on the fire safety of BIPV-facade systems, which is needed to define updated classification methods and norms.

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Appendix A

Survey questions

Fire risk of building-integrated photovoltaics in facades (2)

Welkom

Welkom bij deze enquête. Deze enquête maakt onderdeel uit van een onderzoek naar de brandrisico's die geïntroduceerd worden bij het gebruiken van gebouw-geïntegreerde PV-modules in de gevel. Omdat het erg lastig is om branddoor- en overslag te simuleren, is er besloten om een inschatting te maken van de faalkans op basis van een expertpanel. U wordt per situatie gevraagd een inschatting te maken over de brandwerendheid van een gevel met gebouw-geïntegreerde PV-modules. De details vormen een versimpelde weergave van de realiteit en dienen ter illustratie van de mogelijke uitbreidingsroutes van een brand. Voel u vrij om toelichting te geven op de antwoorden. Mocht u aanvullende ideeën hebben over dit onderwerp, ben ik te bereiken via: t.j.w.junggeburth@student.tue.nl. Hartelijk dank voor deelname aan deze enquête!

* 1. Wat is uw achtergrond?

◯ Werkzaam bij een ingenieursbureau

◯ Werkzaam bij de overheid

◯ Werkzaam bij een toetsingsinstelling

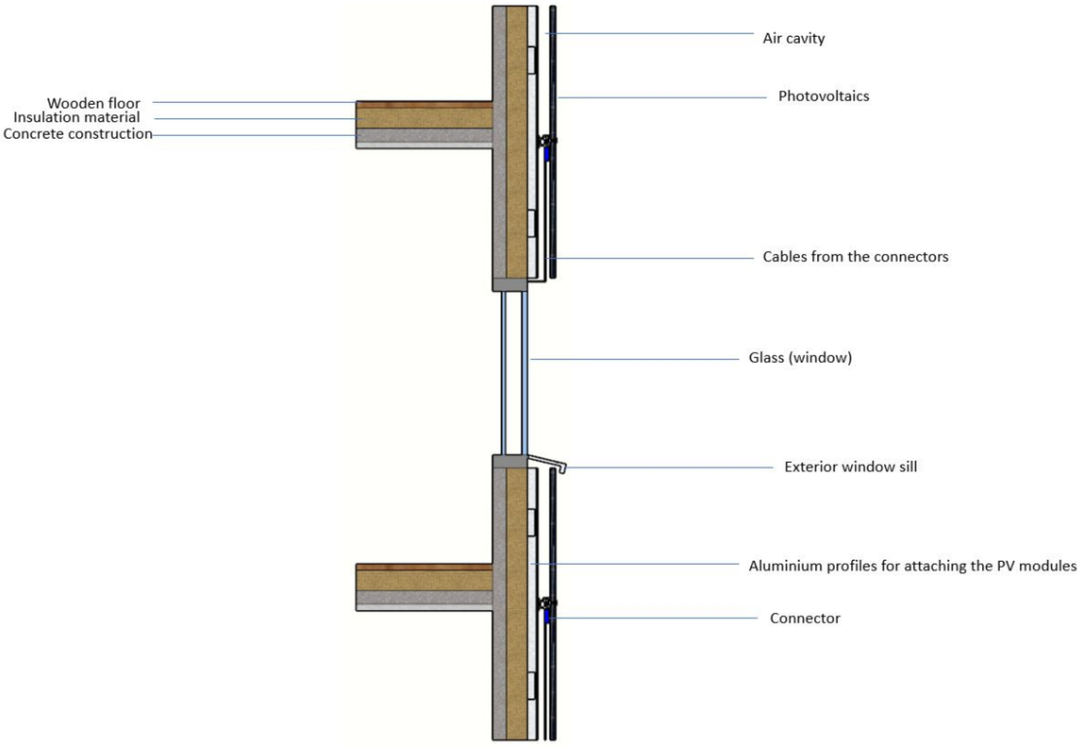
◯ Werkzaam bij een leverancier voor de bouw

◯ Student

◯ Overige (geef nadere toelichting)

Fire risk of building-integrated photovoltaics in facades (2)

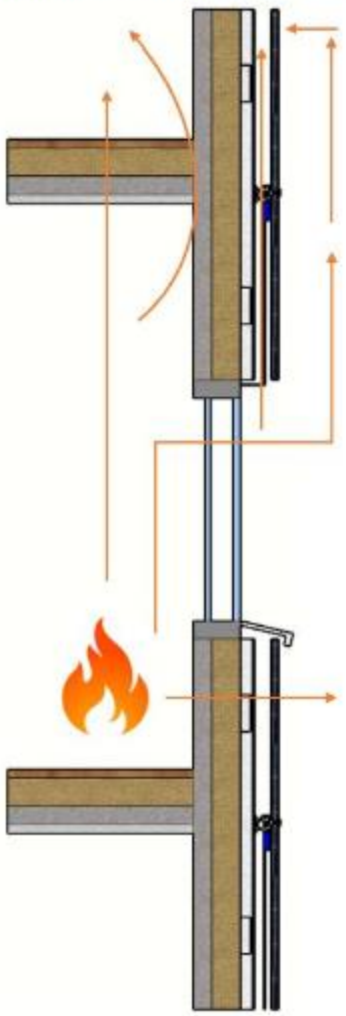
Detail 1: een thermisch dikke gevel



Hierboven ziet u een detail van een **thermisch dikke gevel** met afwisselend PV-modules en ramen. **Thermisch dik** houdt in dat het binnenblad van de gevel alle energie (warmte) kan opnemen, zonder transmissie door het binnenblad heen. De PV-modules zijn aan de gevel bevestigd met een aluminium frame en lopen ononderbroken door over alle brandscheidingen. Tussen het aluminium frame en de PV-modules bevindt zich een spouw waar de bekabeling van de PV-modules loopt. In deze spouw bevindt zich ook een waterkerende folie voor de isolatielaag. De isolatie varieert tussen brandbaar en onbrandbaar (dit is per situatie aangegeven). De spouw is zwak geventileerd (natuurlijke ventilatie) met openingen aan de boven- en onderkant (slechts gedeeltelijk afgedekt door de dorpel) om vocht af te voeren.

Fire risk of building-integrated photovoltaics in facades (2)

Brandwerendheid thermisch dikke gevel en een compartimentbrand



Deze vragen gaan over detail 1 (een **thermisch dikke gevel**). In de afbeelding is een **compartimentbrand** afgebeeld. De brand kan zich verspreiden door middel van stroming, geleiding en straling (oranje pijlen afbeelding).

* 2. Deze vraag gaat over een **thermisch dikke gevel** met **onbrandbare isolatie**. Wat is de brandwerendheid van deze gevel (available safe time)?

- Minder dan 5 minuten
- 5 - 15 minuten
- 15 - 30 minuten
- 30 - 60 minuten
- Meer dan 60 minuten

Toelichting...

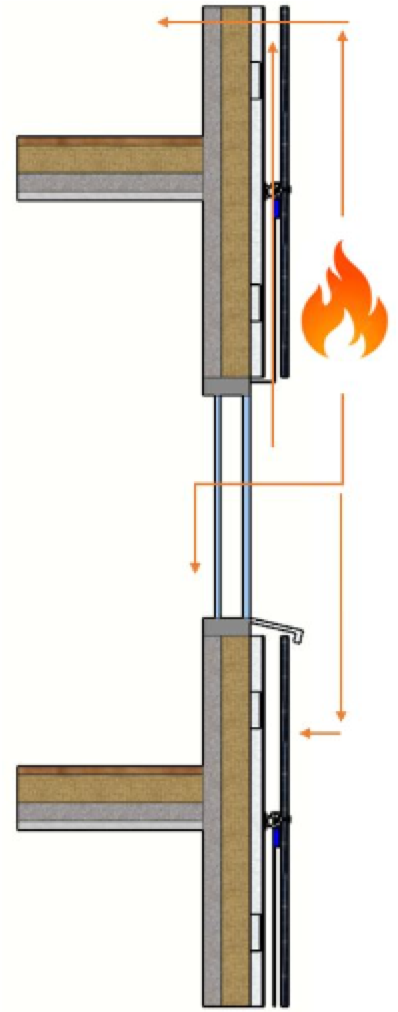
* 3. Deze vraag gaat over een **thermisch dikke gevel** met **brandbare isolatie**. Wat is de brandwerendheid van deze gevel (available safe time)?

- Minder dan 5 minuten
- 5 - 15 minuten
- 15 - 30 minuten
- 30 - 60 minuten
- Meer dan 60 minuten

Toelichting...

Fire risk of building-integrated photovoltaics in facades (2)

Brandwerendheid thermisch dikke gevel en een brand in de gevel



Deze vragen gaan over detail 1 (een **thermisch dikke gevel**). In de afbeelding is een **brand in de gevel** afgebeeld. PV-modules in de gevel houdt in dat er niet alleen een ontstekingsbron wordt geïntroduceerd in de gevel, maar ook dat er brandbaar materiaal in de gevel wordt gebruikt. In deze situatie is er brand ontstaan in de spouw achter de PV-modules, die zich mogelijk kan uitbreiden naar binnen. De brand kan zich verspreiden door middel van stroming, geleiding en straling (oranje pijlen afbeelding).

* 4. Deze vraag gaat over een **thermisch dikke gevel** met **onbrandbare isolatie**. Wat is de brandwerendheid van deze gevel (available safe time)?

- Minder dan 5 minuten
- 5 - 15 minuten
- 15 - 30 minuten
- 30 - 60 minuten
- Meer dan 60 minuten

Toelichting...

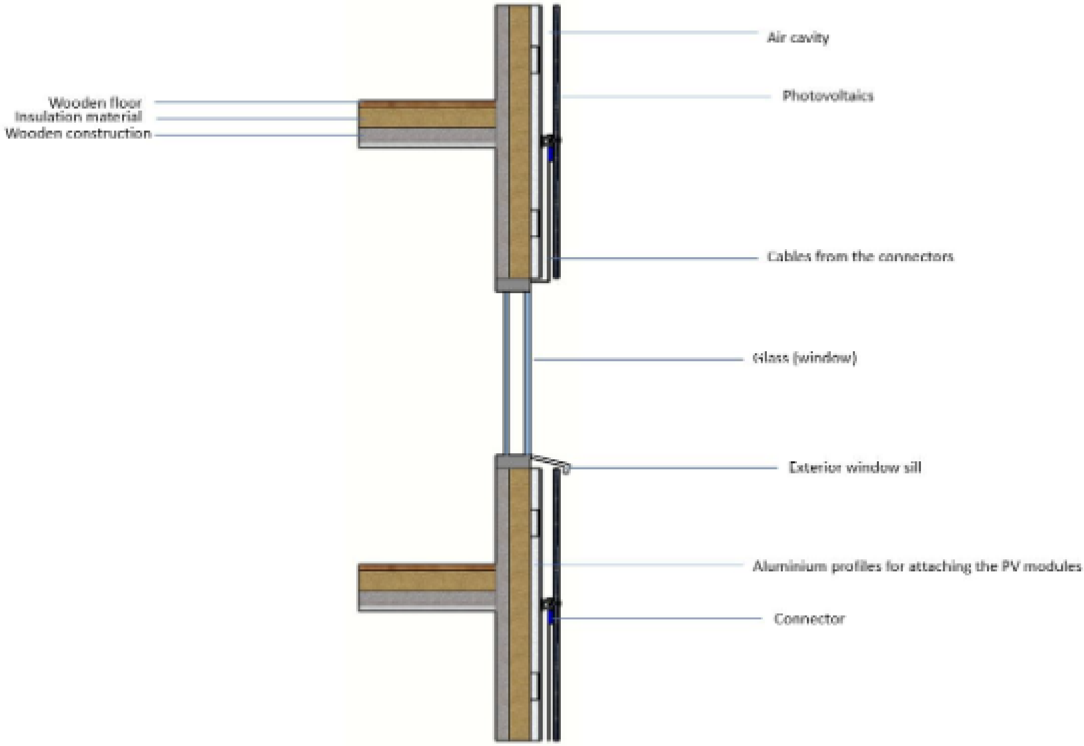
* 5. Deze vraag gaat over een **thermisch dikke gevel** met **brandbare isolatie**. Wat is de brandwerendheid van deze gevel (available safe time)?

- Minder dan 5 minuten
- 5 - 15 minuten
- 15 - 30 minuten
- 30 - 60 minuten
- Meer dan 60 minuten

Toelichting...

Fire risk of building-integrated photovoltaics in facades (2)

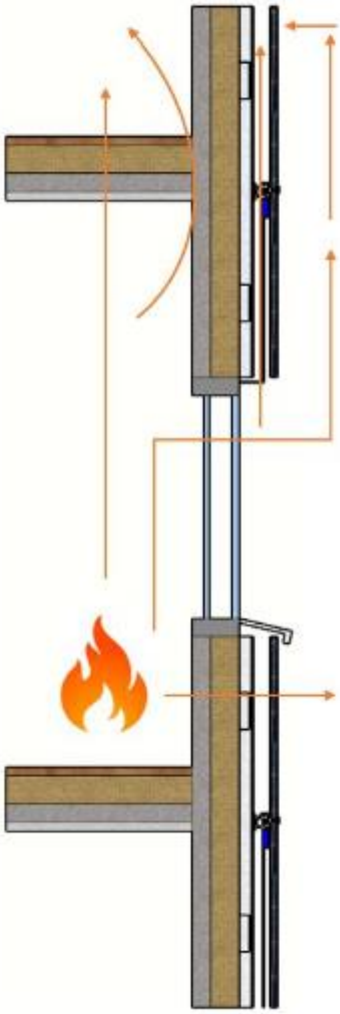
Detail 2: een thermisch dunne gevel



Hierboven ziet u een detail van een **thermisch dunne gevel** met afwisselend PV-modules en ramen. **Thermisch dun** houdt in dat het binnenblad van de gevel geen energie (warmte) kan opnemen, waardoor er warmtetransmissie optreed door het binnenblad. De PV-modules zijn aan de gevel bevestigd met een aluminium frame en lopen ononderbroken door over alle brandscheidingen. Tussen het aluminium frame en de PV-modules bevindt zich een spouw waar de bekabeling van de PV-modules loopt. In deze spouw bevindt zich ook een waterkerende folie voor de isolatielaag. Deze isolatie varieert tussen brandbaar en onbrandbaar (dit is per situatie aangegeven). De spouw is zwak geventileerd (natuurlijke ventilatie) met openingen aan de boven- en onderkant (slechts gedeeltelijk afgedekt door de dorpel) om vocht af te voeren.

Fire risk of building-integrated photovoltaics in facades (2)

Brandwerendheid thermisch dunne gevel en een compartimentbrand



Deze vragen gaan over detail 2 (een **thermisch dunne gevel**). In de afbeelding is een **compartimentbrand** afgebeeld. De brand kan zich verspreiden door middel van stroming, geleiding en straling (oranje pijlen afbeelding).

* 6. Deze vraag gaat over een **thermisch dunne gevel** met **onbrandbare isolatie**. Wat is de brandwerendheid van deze gevel (available safe time)?

- ◯ Minder dan 5 minuten
- ◯ 5 - 15 minuten
- ◯ 15 - 30 minuten
- ◯ 30 - 60 minuten
- ◯ Meer dan 60 minuten

Toelichting...

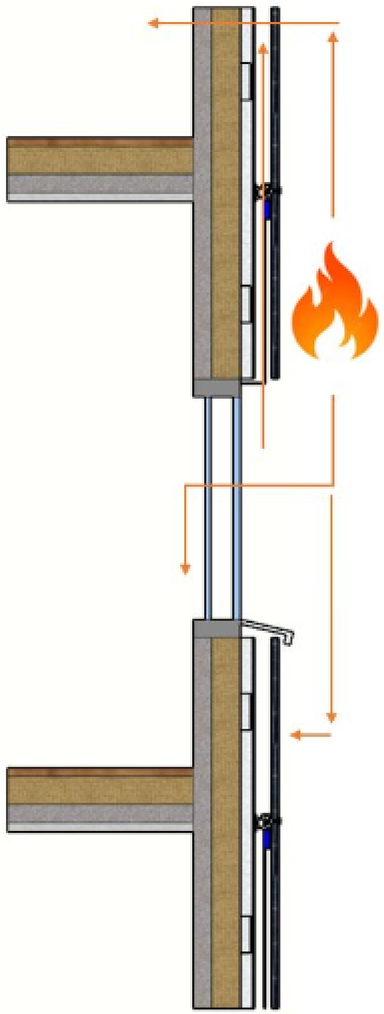
* 7. Deze vraag gaat over een **thermisch dunne gevel** met **brandbare isolatie**. Wat is de brandwerendheid van deze gevel (available safe time)?

- ◯ Minder dan 5 minuten
- ◯ 5 - 15 minuten
- ◯ 15 - 30 minuten
- ◯ 30 - 60 minuten
- ◯ Meer dan 60 minuten

Toelichting...

Fire risk of building-integrated photovoltaics in facades (2)

Brandwerendheid thermisch dunne gevel en een brand in de gevel



Deze vragen gaan over detail 2 (een **thermisch dunne gevel**). In de afbeelding is een **brand in de gevel** afgebeeld. PV-modules in de gevel houdt in dat er niet alleen een ontstekingsbron wordt geïntroduceerd in de gevel, maar ook dat er brandbaar materiaal in de gevel wordt gebruikt. In deze situatie is er brand ontstaan in de spouw achter de PV-modules, die zich mogelijk kan uitbreiden naar binnen. De brand kan zich verspreiden door middel van stroming, geleiding en straling (oranje pijlen afbeelding).

* 8. Deze vraag gaat over een **thermisch dunne gevel** met **onbrandbare isolatie**. Wat is de brandwerendheid van deze gevel (available safe time)?

- Minder dan 5 minuten
- 5 - 15 minuten
- 15 - 30 minuten
- 30 - 60 minuten
- Meer dan 60 minuten

Toelichting...

* 9. Deze vraag gaat over een **thermisch dunne gevel** met **brandbare isolatie**. Wat is de brandwerendheid van deze gevel (available safe time)?

- Minder dan 5 minuten
- 5 - 15 minuten
- 15 - 30 minuten
- 30 - 60 minuten
- Meer dan 60 minuten

Toelichting...

Fire risk of building-integrated photovoltaics in facades (2)

Oplossingen risico PV-modules in de gevel

Op de vorige pagina's is u gevraagd te beoordelen wat de brandwerendheid van een gevel met gebouw-geïntegreerde zonnepanelen is bij een thermisch dikke of dunne gevel, bij een brand in een compartiment of in de gevel en bij het gebruik van brandbare of onbrandbare isolatie. Op deze pagina zou ik u willen vragen mee te denken over (bouwkundige) oplossingen waardoor de brandwerendheid van gevels met gebouw-geïntegreerde zonnepanelen verbeterd kan worden.

* 10. Welke (bouwkundige) oplossingen zouden de brandwerendheid van gevels met gebouw-geïntegreerde zonnepanelen kunnen verbeteren en waarom?

Appendix B

Survey results and calculations

Construction	Fire	<5 min	5-15 min	15-30 min	30-60 min	>60 min	No answer
Thermal heavy, non-combustible insulation	Compartment	4	7	8	17	7	29
Thermal heavy, combustible insulation	Compartment	12	15	6	5	5	29
Thermal light, non-combustible insulation	Compartment	3	8	9	7	2	43
Thermal light, combustible insulation	Compartment	9	13	2	5	0	43
Thermal heavy, non-combustible insulation	Facade	4	9	7	9	4	39
Thermal heavy, combustible insulation	Facade	13	12	2	3	3	39
Thermal light, non-combustible insulation	Facade	4	11	5	7	2	43
Thermal light, combustible insulation	Facade	16	7	2	4	0	43

Table B.1: Amount of responses per question and per question option for the survey

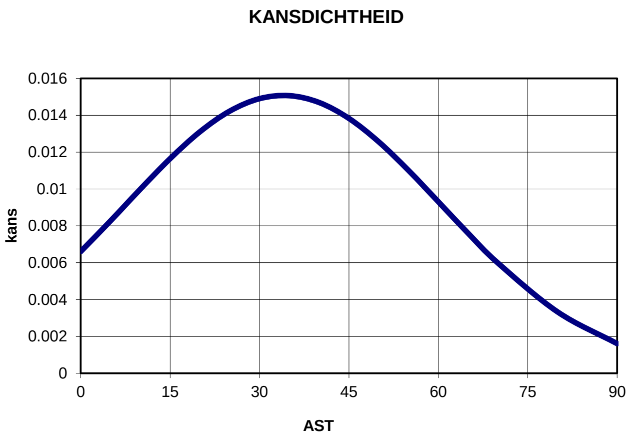
FLANKERENDE BRANDWEERSTAND AST QUESTION 1

(Alle respondenten, ingevuld en niet ingevuld)

AST	kans	gemiddelde		variantie
2.5	0.136111111	0.34027778	-31.5139	993.1252
10	0.177777778	1.77777778	-24.0139	576.6669
22.5	0.191666667	4.3125	-11.5139	132.5696
45	0.316666667	14.25	10.98611	120.6946
75	0.177777778	13.3333333	40.98611	1679.861
[min]	1	**34.0138889**		**700.5835**
		gemiddelde		**variantie**
				26.46854
				standaardafwijking

NORMALE VERDELING

x	f(x)
0	0.006600591
5	0.008265341
10	0.009987139
15	0.011644579
20	0.013101135
25	0.014223172
30	0.014900004
35	0.015061863
40	0.014691747
45	0.013828356
50	0.012559435
55	0.011007078
60	0.009308429
65	0.007595968
70	0.005981254
80	0.003332098
90	0.001609359



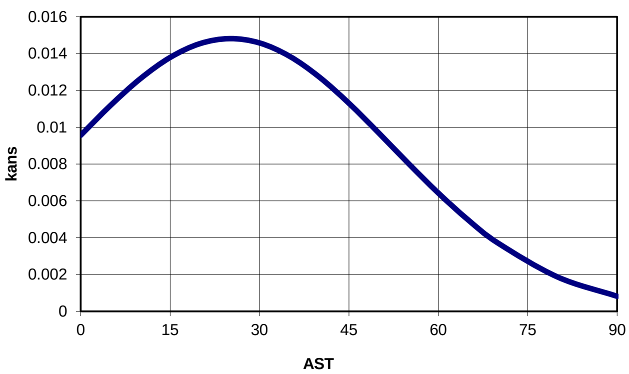
FLANKERENDE BRANDWEERSTAND AST QUESTION 2
(Alle respondenten, ingevuld en niet ingevuld)

AST	kans	gemiddelde		variantie
2.5	0.247222222	0.61805556	-22.6944	515.0378
10	0.288888889	2.88888889	-15.1944	230.8711
22.5	0.163888889	3.6875	-2.69444	7.260031
45	0.15	6.75	19.80556	392.26
75	0.15	11.25	49.80556	2480.593
[min]	1	**25.1944444**		**725.2045**
		gemiddelde		**variantie**
				26.92962
				standaardafwijking

NORMALE VERDELING

x	f(x)
0	0.009563443
5	0.01118325
10	0.012634275
15	0.013789901
20	0.01454121
25	0.014813869
30	0.014580251
35	0.013864048
40	0.012736311
45	0.011303835
50	0.009692516
55	0.008029264
60	0.006426042
65	0.004968667
70	0.003711631
80	0.001867671
90	0.000818747

KANSDICHTHEID

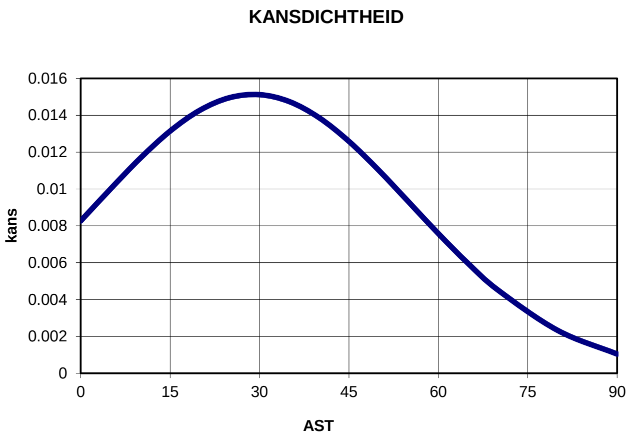


FLANKERENDE BRANDWEERSTAND AST QUESTION 3
(Alle respondenten, ingevuld en niet ingevuld)

AST	kans	gemiddelde		variantie
2.5	0.161111111	0.40277778	-26.5	702.25
10	0.230555556	2.30555556	-19	361
22.5	0.244444444	5.5	-6.5	42.25
45	0.216666667	9.75	16	256
75	0.147222222	11.0416667	46	2116
[min]	1	**29**		**695.5**
		gemiddelde		**variantie**
				26.37233
				standaardafwijking

NORMALE VERDELING

x	f(x)
0	0.00826393
5	0.009998256
10	0.011669466
15	0.013139138
20	0.014271574
25	0.014954298
30	0.015116432
35	0.014740821
40	0.013867021
45	0.012584438
50	0.01101726
55	0.009304703
60	0.007580896
65	0.005958373
70	0.004517768
80	0.00233176
90	0.001042318

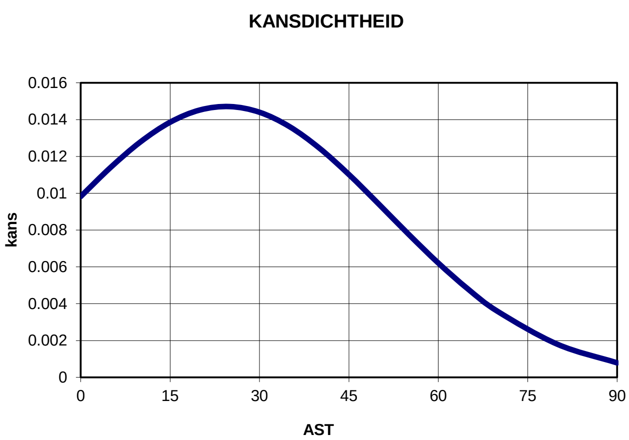


FLANKERENDE BRANDWEERSTAND AST QUESTION 4
(Alle respondenten, ingevuld en niet ingevuld)

AST	kans	gemiddelde		variantie
2.5	0.244444444	0.61111111	-21.8819	478.8195
10	0.3	3	-14.3819	206.8403
22.5	0.147222222	3.3125	-1.88194	3.541715
45	0.188888889	8.5	20.61806	425.1042
75	0.119444444	8.95833333	50.61806	2562.188
[min]	1	**24.3819444**		**735.2987**
		gemiddelde		**variantie**
				27.11639
				standaardafwijking

NORMALE VERDELING

x	f(x)
0	0.009820136
5	0.011395645
10	0.012781871
15	0.013857471
20	0.014521372
25	0.014708398
30	0.014399824
35	0.013626461
40	0.012463586
45	0.01101887
50	0.009415973
55	0.007777274
60	0.006209029
65	0.004791307
70	0.003573703
80	0.001795352
90	0.000787258

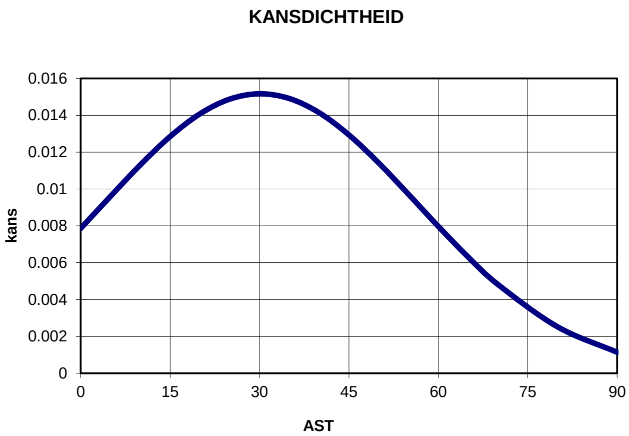


FLANKERENDE BRANDWEERSTAND AST QUESTION 5
(Alle respondenten, ingevuld en niet ingevuld)

AST	kans	gemiddelde		variantie
2.5	0.163888889	0.40972222	-27.6597	765.0602
10	0.233333333	2.33333333	-20.1597	406.4144
22.5	0.205555556	4.625	-7.65972	58.67134
45	0.233333333	10.5	14.84028	220.2338
75	0.163888889	12.2916667	44.84028	2010.651
[min]	1	**30.1597222**		**692.2061**
		gemiddelde		**variantie**
				26.30981
				standaardafwijking

NORMALE VERDELING

x	f(x)
0	0.00786041
5	0.009598748
10	0.011305737
15	0.012843932
20	0.014073818
25	0.014874444
30	0.015162973
35	0.014908805
40	0.014138917
45	0.01293315
50	0.011410569
55	0.009710132
60	0.007969991
65	0.006309651
70	0.00481801
80	0.002520792
90	0.001141473



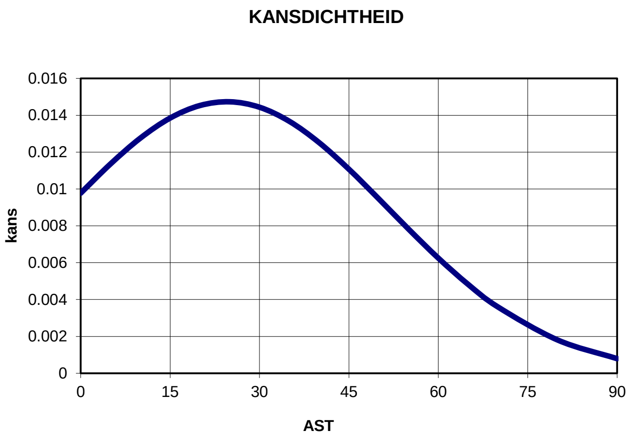
FLANKERENDE BRANDWEERSTAND AST QUESTION 6

(Alle respondenten, ingevuld en niet ingevuld)

AST	kans	gemiddelde		variantie
2.5	0.288888889	0.72222222	-22.0347	485.529
10	0.275	2.75	-14.5347	211.2582
22.5	0.136111111	3.0625	-2.03472	4.140095
45	0.15	6.75	20.46528	418.8276
75	0.15	11.25	50.46528	2546.744
[min]	1	**24.5347222**		**733.2998**
		gemiddelde		**variantie**
				27.07951
				standaardafwijking

NORMALE VERDELING

x	f(x)
0	0.009772755
5	0.011357088
10	0.012755891
15	0.013846768
20	0.014527132
25	0.014730082
30	0.014435249
35	0.013672163
40	0.012515379
45	0.011072473
50	0.009467582
55	0.007823973
60	0.006248984
65	0.004823756
70	0.003598778
80	0.001808323
90	0.000792816

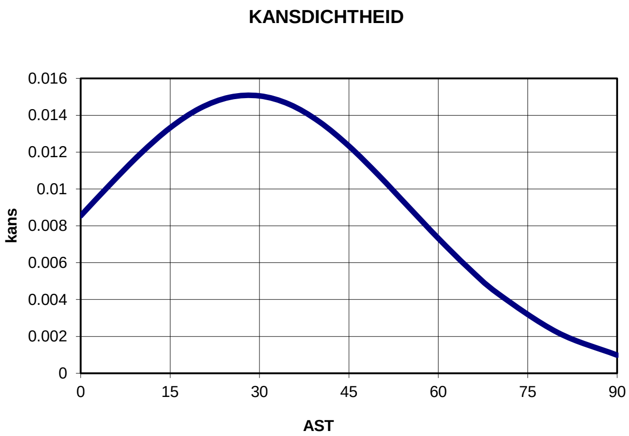


FLANKERENDE BRANDWEERSTAND AST QUESTION 7
(Alle respondenten, ingevuld en niet ingevuld)

AST	kans	gemiddelde		variantie
2.5	0.175	0.4375	-25.7014	660.5614
10	0.272222222	2.72222222	-18.2014	331.2906
22.5	0.188888889	4.25	-5.70139	32.50584
45	0.216666667	9.75	16.79861	282.1933
75	0.147222222	11.0416667	46.79861	2190.11
[min]	1	**28.2013889**		**699.3322**
		gemiddelde		**variantie**
				26.44489
				standaardafwijking

NORMALE VERDELING

x	f(x)
0	0.008543125
5	0.010266472
10	0.011904205
15	0.013318467
20	0.01437748
25	0.014975659
30	0.015050946
35	0.014595411
40	0.01365663
45	0.012329499
50	0.010740437
55	0.009027618
60	0.007321483
65	0.005729275
70	0.004325884
80	0.002215386
90	0.000983383



FLANKERENDE BRANDWEERSTAND AST QUESTION 8

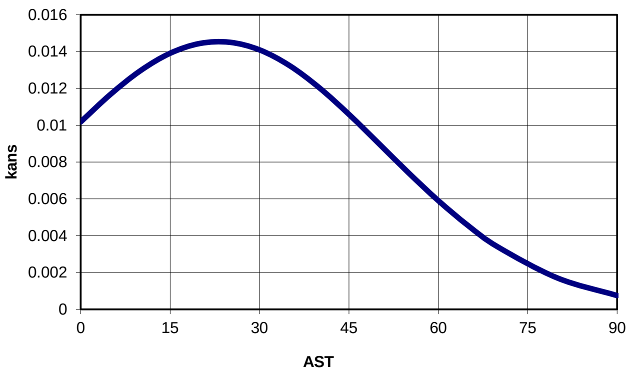
(Alle respondenten, ingevuld en niet ingevuld)

AST	kans	gemiddelde		variantie
2.5	0.341666667	0.85416667	-20.6667	427.1111
10	0.216666667	2.16666667	-13.1667	173.3611
22.5	0.147222222	3.3125	-0.66667	0.444444
45	0.175	7.875	21.83333	476.6944
75	0.119444444	8.95833333	51.83333	2686.694
[min]	1	**23.1666667**		**752.8611**
		gemiddelde		**variantie**
				27.43831
				standaardafwijking

NORMALE VERDELING

x	f(x)
0	0.010180151
5	0.011677851
10	0.012958365
15	0.013909643
20	0.014443097
25	0.014507186
30	0.014095633
35	0.013248433
40	0.012045448
45	0.010594
50	0.009013127
55	0.007417705
60	0.005905302
65	0.004547715
70	0.00338784
80	0.001701836
90	0.00074856

KANSDICHTHEID



BETROUWBAARHEID FLANKERENDE WEG COMPARTIMENTBRAND

SAMENVATTING

AST

VRAAG 1			VRAAG 2	
AVG	SD		AVG	SD
34.01	26.47		25.19	26.92
VAR =	700.6609		VAR =	724.6864

AST-RST

VRAAG 1			VRAAG 2	
AVG	SD		AVG	SD
-19.99	29.66852		-28.81	30.07069

	VRAAG 1				VRAAG 2		
t [min]	SD	BETA	P(1)		SD	BETA	P(2)
-60	29.66852	1.349	9.11E-01		30.07069	1.037	8.50E-01
-56	29.66852	1.214	8.88E-01		30.07069	0.904	8.17E-01
-52	29.66852	1.079	8.60E-01		30.07069	0.771	7.80E-01
-48	29.66852	0.944	8.27E-01		30.07069	0.638	7.38E-01
-44	29.66852	0.809	7.91E-01		30.07069	0.505	6.93E-01
-40	29.66852	0.674	7.50E-01		30.07069	0.372	6.45E-01
-36	29.66852	0.540	7.05E-01		30.07069	0.239	5.94E-01
-32	29.66852	0.405	6.57E-01		30.07069	0.106	5.42E-01
-28	29.66852	0.270	6.06E-01		30.07069	-0.027	4.89E-01
-24	29.66852	0.135	5.54E-01		30.07069	-0.160	4.36E-01
-20	29.66852	0.000	5.00E-01		30.07069	-0.293	3.85E-01
-16	29.66852	-0.134	4.47E-01		30.07069	-0.426	3.35E-01
-12	29.66852	-0.269	3.94E-01		30.07069	-0.559	2.88E-01
-8	29.66852	-0.404	3.43E-01		30.07069	-0.692	2.44E-01
-4	29.66852	-0.539	2.95E-01		30.07069	-0.825	2.05E-01
0	29.66852	-0.674	2.50E-01		30.07069	-0.958	1.69E-01
4	29.66852	-0.809	2.09E-01		30.07069	-1.091	1.38E-01
8	29.66852	-0.943	1.73E-01		30.07069	-1.224	1.10E-01
12	29.66852	-1.078	1.40E-01		30.07069	-1.357	8.74E-02
16	29.66852	-1.213	1.13E-01		30.07069	-1.490	6.81E-02
20	29.66852	-1.348	8.88E-02		30.07069	-1.623	5.23E-02
24	29.66852	-1.483	6.91E-02		30.07069	-1.756	3.95E-02
28	29.66852	-1.618	5.29E-02		30.07069	-1.889	2.94E-02
32	29.66852	-1.752	3.99E-02		30.07069	-2.022	2.16E-02
36	29.66852	-1.887	2.96E-02		30.07069	-2.155	1.56E-02
40	29.66852	-2.022	2.16E-02		30.07069	-2.288	1.11E-02
44	29.66852	-2.157	1.55E-02		30.07069	-2.421	7.73E-03
48	29.66852	-2.292	1.10E-02		30.07069	-2.554	5.32E-03
52	29.66852	-2.426	7.62E-03		30.07069	-2.687	3.60E-03
56	29.66852	-2.561	5.21E-03		30.07069	-2.820	2.40E-03
60	29.66852	-2.696	3.51E-03		30.07069	-2.953	1.57E-03
64	29.66852	-2.831	2.32E-03		30.07069	-3.086	1.01E-03
68	29.66852	-2.966	1.51E-03		30.07069	-3.219	6.42E-04
72	29.66852	-3.101	9.66E-04		30.07069	-3.352	4.01E-04

VRAAG 3

AVG	SD
29	26.37

VAR = 695.3769

VRAAG 4

AVG	SD
24.38	27.12

VAR = 735.4944

VRAAG 3

AVG	SD
-25	29.57933

VRAAG 4

AVG	SD
-29.62	30.24987

VRAAG 3

SD	BETA	P(3)
29.57933	1.183	8.82E-01
29.57933	1.048	8.53E-01
29.57933	0.913	8.19E-01
29.57933	0.778	7.82E-01
29.57933	0.642	7.40E-01
29.57933	0.507	6.94E-01
29.57933	0.372	6.45E-01
29.57933	0.237	5.94E-01
29.57933	0.101	5.40E-01
29.57933	-0.034	4.87E-01
29.57933	-0.169	4.33E-01
29.57933	-0.304	3.80E-01
29.57933	-0.439	3.30E-01
29.57933	-0.575	2.83E-01
29.57933	-0.710	2.39E-01
29.57933	-0.845	1.99E-01
29.57933	-0.980	1.63E-01
29.57933	-1.116	1.32E-01
29.57933	-1.251	1.05E-01
29.57933	-1.386	8.29E-02
29.57933	-1.521	6.41E-02
29.57933	-1.657	4.88E-02
29.57933	-1.792	3.66E-02
29.57933	-1.927	2.70E-02
29.57933	-2.062	1.96E-02
29.57933	-2.197	1.40E-02
29.57933	-2.333	9.83E-03
29.57933	-2.468	6.79E-03
29.57933	-2.603	4.62E-03
29.57933	-2.738	3.09E-03
29.57933	-2.874	2.03E-03
29.57933	-3.009	1.31E-03
29.57933	-3.144	8.33E-04
29.57933	-3.279	5.20E-04

VRAAG 4

SD	BETA	P(4)
30.24987	1.004	8.42E-01
30.24987	0.872	8.08E-01
30.24987	0.740	7.70E-01
30.24987	0.608	7.28E-01
30.24987	0.475	6.83E-01
30.24987	0.343	6.34E-01
30.24987	0.211	5.84E-01
30.24987	0.079	5.31E-01
30.24987	-0.054	4.79E-01
30.24987	-0.186	4.26E-01
30.24987	-0.318	3.75E-01
30.24987	-0.450	3.26E-01
30.24987	-0.582	2.80E-01
30.24987	-0.715	2.37E-01
30.24987	-0.847	1.99E-01
30.24987	-0.979	1.64E-01
30.24987	-1.111	1.33E-01
30.24987	-1.244	1.07E-01
30.24987	-1.376	8.44E-02
30.24987	-1.508	6.58E-02
30.24987	-1.640	5.05E-02
30.24987	-1.773	3.82E-02
30.24987	-1.905	2.84E-02
30.24987	-2.037	2.08E-02
30.24987	-2.169	1.50E-02
30.24987	-2.301	1.07E-02
30.24987	-2.434	7.47E-03
30.24987	-2.566	5.14E-03
30.24987	-2.698	3.49E-03
30.24987	-2.830	2.32E-03
30.24987	-2.963	1.52E-03
30.24987	-3.095	9.84E-04
30.24987	-3.227	6.25E-04
30.24987	-3.359	3.91E-04

RST

THERMISCHE BELASTING

AVG	SD
54	13.4

VAR = 179.56

BETROUWBAARHEID FLANKERENDE WEG GEVELBRAND

SAMENVATTING

AST

VRAAG 5			VRAAG 6	
AVG	SD		AVG	SD
30.16	26.31		24.53	27.08
VAR =	692.2161		VAR =	733.3264

AST-RST

VRAAG 5			VRAAG 6	
AVG	SD		AVG	SD
24.66	26.3441		19.03	27.11313

	VRAAG 5			VRAAG 6		
t [min]	SD	BETA	P(5)	SD	BETA	P(6)
-60	26.34410	3.214	9.99E-01	27.11313	2.915	9.98E-01
-56	26.34410	3.062	9.99E-01	27.11313	2.767	9.97E-01
-52	26.34410	2.910	9.98E-01	27.11313	2.620	9.96E-01
-48	26.34410	2.758	9.97E-01	27.11313	2.472	9.93E-01
-44	26.34410	2.606	9.95E-01	27.11313	2.325	9.90E-01
-40	26.34410	2.454	9.93E-01	27.11313	2.177	9.85E-01
-36	26.34410	2.303	9.89E-01	27.11313	2.030	9.79E-01
-32	26.34410	2.151	9.84E-01	27.11313	1.882	9.70E-01
-28	26.34410	1.999	9.77E-01	27.11313	1.735	9.59E-01
-24	26.34410	1.847	9.68E-01	27.11313	1.587	9.44E-01
-20	26.34410	1.695	9.55E-01	27.11313	1.440	9.25E-01
-16	26.34410	1.543	9.39E-01	27.11313	1.292	9.02E-01
-12	26.34410	1.392	9.18E-01	27.11313	1.144	8.74E-01
-8	26.34410	1.240	8.92E-01	27.11313	0.997	8.41E-01
-4	26.34410	1.088	8.62E-01	27.11313	0.849	8.02E-01
0	26.34410	0.936	8.25E-01	27.11313	0.702	7.59E-01
4	26.34410	0.784	7.84E-01	27.11313	0.554	7.10E-01
8	26.34410	0.632	7.36E-01	27.11313	0.407	6.58E-01
12	26.34410	0.481	6.85E-01	27.11313	0.259	6.02E-01
16	26.34410	0.329	6.29E-01	27.11313	0.112	5.44E-01
20	26.34410	0.177	5.70E-01	27.11313	-0.036	4.86E-01
24	26.34410	0.025	5.10E-01	27.11313	-0.183	4.27E-01
28	26.34410	-0.127	4.50E-01	27.11313	-0.331	3.70E-01
32	26.34410	-0.279	3.90E-01	27.11313	-0.478	3.16E-01
36	26.34410	-0.430	3.33E-01	27.11313	-0.626	2.66E-01
40	26.34410	-0.582	2.80E-01	27.11313	-0.773	2.20E-01
44	26.34410	-0.734	2.31E-01	27.11313	-0.921	1.79E-01
48	26.34410	-0.886	1.88E-01	27.11313	-1.068	1.43E-01
52	26.34410	-1.038	1.50E-01	27.11313	-1.216	1.12E-01
56	26.34410	-1.190	1.17E-01	27.11313	-1.364	8.64E-02
60	26.34410	-1.341	8.99E-02	27.11313	-1.511	6.54E-02
64	26.34410	-1.493	6.77E-02	27.11313	-1.659	4.86E-02
68	26.34410	-1.645	5.00E-02	27.11313	-1.806	3.54E-02
72	26.34410	-1.797	3.62E-02	27.11313	-1.954	2.54E-02

VRAAG 7			VRAAG 8	
AVG	SD		AVG	SD
28.2	26.44		23.17	27.44
VAR =	699.0736		VAR =	752.9536

VRAAG 7			VRAAG 8	
AVG	SD		AVG	SD
22.7	26.47393		17.67	27.4727

VRAAG 7				VRAAG 8		
SD	BETA	P(7)		SD	BETA	P(8)
26.47393	3.124	9.99E-01		27.47270	2.827	9.98E-01
26.47393	2.973	9.99E-01		27.47270	2.682	9.96E-01
26.47393	2.822	9.98E-01		27.47270	2.536	9.94E-01
26.47393	2.671	9.96E-01		27.47270	2.390	9.92E-01
26.47393	2.519	9.94E-01		27.47270	2.245	9.88E-01
26.47393	2.368	9.91E-01		27.47270	2.099	9.82E-01
26.47393	2.217	9.87E-01		27.47270	1.954	9.75E-01
26.47393	2.066	9.81E-01		27.47270	1.808	9.65E-01
26.47393	1.915	9.72E-01		27.47270	1.662	9.52E-01
26.47393	1.764	9.61E-01		27.47270	1.517	9.35E-01
26.47393	1.613	9.47E-01		27.47270	1.371	9.15E-01
26.47393	1.462	9.28E-01		27.47270	1.226	8.90E-01
26.47393	1.311	9.05E-01		27.47270	1.080	8.60E-01
26.47393	1.160	8.77E-01		27.47270	0.934	8.25E-01
26.47393	1.009	8.43E-01		27.47270	0.789	7.85E-01
26.47393	0.857	8.04E-01		27.47270	0.643	7.40E-01
26.47393	0.706	7.60E-01		27.47270	0.498	6.91E-01
26.47393	0.555	7.11E-01		27.47270	0.352	6.38E-01
26.47393	0.404	6.57E-01		27.47270	0.206	5.82E-01
26.47393	0.253	6.00E-01		27.47270	0.061	5.24E-01
26.47393	0.102	5.41E-01		27.47270	-0.085	4.66E-01
26.47393	-0.049	4.80E-01		27.47270	-0.230	4.09E-01
26.47393	-0.200	4.21E-01		27.47270	-0.376	3.53E-01
26.47393	-0.351	3.63E-01		27.47270	-0.522	3.01E-01
26.47393	-0.502	3.08E-01		27.47270	-0.667	2.52E-01
26.47393	-0.653	2.57E-01		27.47270	-0.813	2.08E-01
26.47393	-0.805	2.11E-01		27.47270	-0.958	1.69E-01
26.47393	-0.956	1.70E-01		27.47270	-1.104	1.35E-01
26.47393	-1.107	1.34E-01		27.47270	-1.250	1.06E-01
26.47393	-1.258	1.04E-01		27.47270	-1.395	8.15E-02
26.47393	-1.409	7.94E-02		27.47270	-1.541	6.17E-02
26.47393	-1.560	5.94E-02		27.47270	-1.686	4.59E-02
26.47393	-1.711	4.35E-02		27.47270	-1.832	3.35E-02
26.47393	-1.862	3.13E-02		27.47270	-1.978	2.40E-02

RST

THERMISCHE BELASTING

AVG	SD
5.5	1.34

VAR = 1.7956