Fire Safety of Building Integrated PhotoVoltaics (BIPV):

A risk-based design support tool for designing façades with BIPV

Fire Safety of Building-Integrated Photovoltaics (BIPV)

A risk-based design support tool for designing façades with BIPV

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Abstract

Building-integrated photovoltaic (BIPV) façade systems introduce high-voltage ignition sources, carrying DC currents up to 1000 V, directly into façade structures, a hazard unprecedented in conventional façades. Despite this, the regulatory framework in the Netherlands falls short in adequately addressing the fire safety risks posed by BIPV façade systems, with no short-term tendency for improval. Currently, the applicable fire safety regulations do not address the unique electrical characteristics of BIPV systems, considering them equal to conventional construction materials. The testing methods fail to account for the distinct ignition scenarios these systems present, resulting in fire classifications for façades that are not adequately representative. Furthermore, there is no statutory quality system in place to guarantee an acceptable level of safety.

Through the execution of a fault tree analysis, several foundational findings were identified regarding the fire risks of BIPV façade systems. The most common failure modes are electric arcs and hot-spots. In addition to the inherent risks of façades and the chimney effect, BIPV façade systems introduce further risks. They expose combustible materials to new ignition sources, contain components within cavities that may not be designed to operate at high temperatures, present inspection and maintenance challenges, cable penetrations which can facilitate fire spread and heavyweight BIPV modules can pose a risk of injury or blocking pathways if they fall.

A wide variety of measures have been identified to tackle the fire risks of BIPV system. To narrow it down, it is most effective to first focus on preventing the ignition of fire. This can primarily be achieved by proper design and installation of electrical systems, validating them through quality schemes, and performing periodic maintenance with infrared (IR) inspections. While quality installation by accredited installers (InstallQ) minimizes errors, it doesn't eliminate them entirely. Therefore, independent quality inspections (SCOPE12) are crucial for added safety and reliability.

Subsequently, to limit the development of fire, it is essential to always employ a glass/glass or glass/copper BIPV module (fire class B: NEN-EN 13501-1), and use a protective fire barrier (fire class A2/A1: NEN-EN 13501-1) in the cavity. Additionally, segmenting BIPV façades and cavities that span multiple fire compartments through physical barriers or well-performing cavity barriers is necessary. Utilizing smart detailing around façade openings and BIPV cavities, ensuring modules are easily removable from the façade, and implementing well-performing cable penetrations through the façade are also critical steps.

As these measures require an integrated approach, it is emphasized that the architect, façade designer, BIPV manufacturer and electrical installer should closely collaborate to design the electrical configuration of the BIPV system and adequately implement the effects of the system on the detailing, particularly in the façade (e.g. component placement in façade, cable penetrations, etc.).

To improve the spread of knowledge, a design support tool has been developed. This tool provides a framework that highlights critical fire safety considerations through 23 risk parameters on building, façade and product level, enabling users to conduct risk assessments and offering specific measures based on design input. User feedback confirmed the tool's potential in raising awareness among designers about BIPV challenges, facilitating informed decision-making, and integrating fire safety from the outset.

The design support tool does not provide a guaranteed 'fire safe' solution; fire safety should always be assessed in its unique context, especially due to the electro-technical characteristics of BIPV systems. The tool is a preliminary setup that lays a solid framework but requires further refinement through empirical research and end-use testing. It is particularly relevant in the current pre-normative state, guiding designers through fire safety complexities and potentially supporting future regulatory developments.

Keywords: BIPV façade systems, fire safety, fire risks, pre-normative, regulatory gap, fault tree analysis, design support tool, building context, risk parameters, design measures, risk awareness

Contents

1

Introduction

1.1 Background

According to the International Energy Agency (IEA) (2022), between 2019 and 2022, the construction sector experienced a relative reduction in global energy consumption from 36% to 34% and a decrease in global energy-related CO_2 emissions from 39% to 37%. However, when these numbers of energy consumption within the construction sector are presented by pre-eminent research institutions, the numbers are presented in relative figures to other sectors, signifying reduction. The apparent success in improving efficiency is only a partial truth, despite the substantial efforts within the industry to lower overall energy consumption and CO_2 emissions. The reality is that these statistics are somewhat deceptive, as actual consumption and emissions have not decreased but have instead risen, reaching all-time highs in 2022 (International Energy Agency, 2022). Additionally, the impact of the COVID-19 pandemic is not always mentioned, which has distorted energy usage patterns and emissions, complicating efforts to accurately assess and address the sector's environmental impact. Ultimately, the IEA currently concludes that the construction sector is falling short of the necessary trajectory to achieve decarbonization by the targeted year of 2050.

Therefore, it is crucial to establish sustainable buildings and to provide energy-focused upgrades to existing building stock which are aimed at enhancing energy conservation, efficiency improvements, and the reduction of CO_2 emissions (IEA PVPS Task 15, 2019a). This involves designing and constructing buildings with the goal of ensuring they generate as much, or more, energy over their entire lifespan as they consume. This process begins with minimizing energy usage through efficient design and technology integration. Subsequently, the focus shifts to implementing renewable energy technologies, such as solar, wind, and hydro power, to meet the remaining energy requirements sustainably.

In alignment with these efforts, the utilization of energy from photovoltaic (PV) systems is increasingly becoming a popular energy supply for buildings (Pillai et al., 2022). While these systems are available in many different configurations, the predominant application of PV technology in the built environment is categorized as building-attached photovoltaics (BAPV) systems, where standard PV panels are attached to the surfaces of walls or roofs of buildings. However, BAPV systems come with inherent limitations that restrict their global implementation, especially in dense urban environments (Kumar et al., 2019). These systems are often hindered by their robust nature, limiting their implementation possibilities. Additionally, their clunky shapes often do not harmonize with the architectural expression of the building. Luckily, PV technologies have advanced in recent years from standard unitized panels to more flexible applications. These so called building integrated photovoltaic (BIPV) modules convert external walls, roofs, windows and other building components (Figure 1) into assets that are able to generate energy and provide building-related functionalities such as weather protection, noise reduction, thermal insulation, aesthetics appearance, etc. (Pillai et al., 2022).

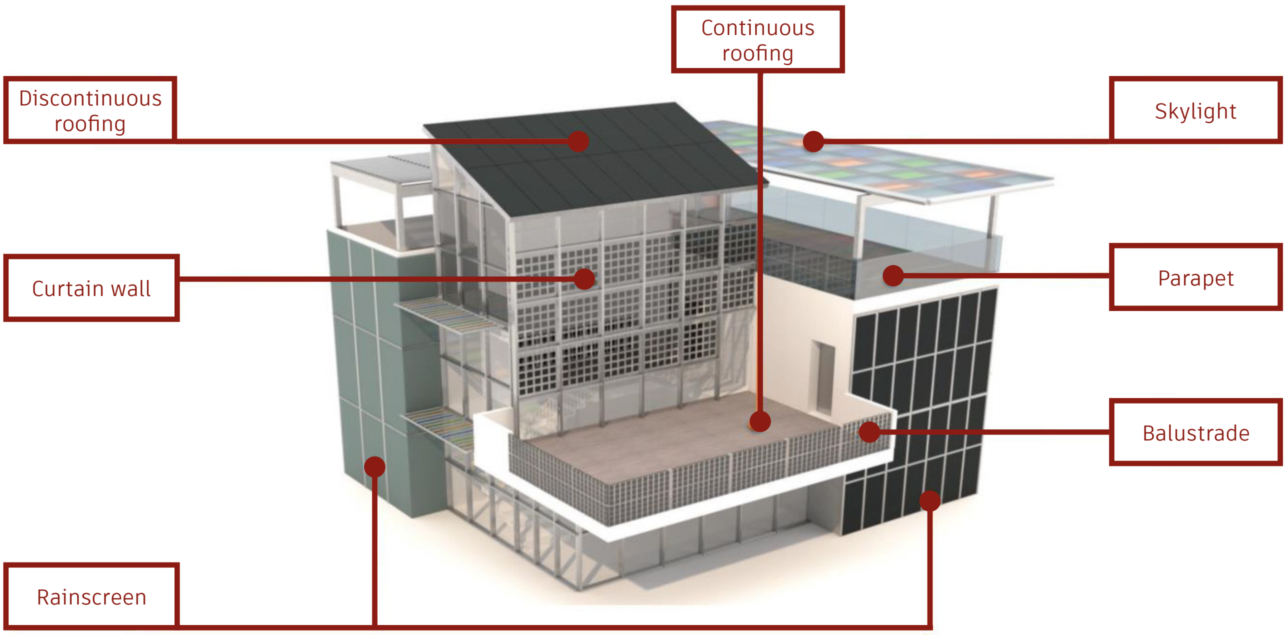


Figure 1: BIPV application examples. Source: Solarnova (2023)

According to REN21's 2023 report, various countries worldwide are currently actively employing BIPV strategies. For instance, in 2022, China announced its goal to deploy 50 GW of rooftop and building-integrated photovoltaic (BIPV) systems by the end of 2025 (Hall, 2022). Comparing that to China's total PV capacity increase of 106 GW in 2022 (REN21, 2023) signifies that BIPV will become a predominant strategy. Similarly, the Seoul metropolitan government in the Republic of Korea initiated a rebate program during the same period, offering coverage for up to 80% of the expenses associated with acquiring and installing BIPV systems (Bellini, 2022). Aligning with these governmental strategies, a market research conducted by Research and Markets (2023) underscores the significant potential of BIPV, projecting an annual compound growth rate of 21.4% until 2030. This growth is anticipated to elevate the market value from 17.7 billion USD to 83.3 billion USD. Not only Research and Markets (2023) projects these high market growth figures, but several other market research entities also anticipate growth within the same range (Allied Market Research, 2021; Grand View Research, 2023; Transparency Market Research, 2022), proving the substantial growth anticipated for the BIPV market.

Figure 2 provides insight on the development of all PV systems (not only BIPV and/or BAPV) and showcases the rising energy supply of PV systems on a global scale. However, for solar photovoltaic (PV) to establish itself as a primary global electricity source, significant improvements and developments are necessary to enhance efficiency, storage capabilities, and overall infrastructure resilience (REN21, 2023).

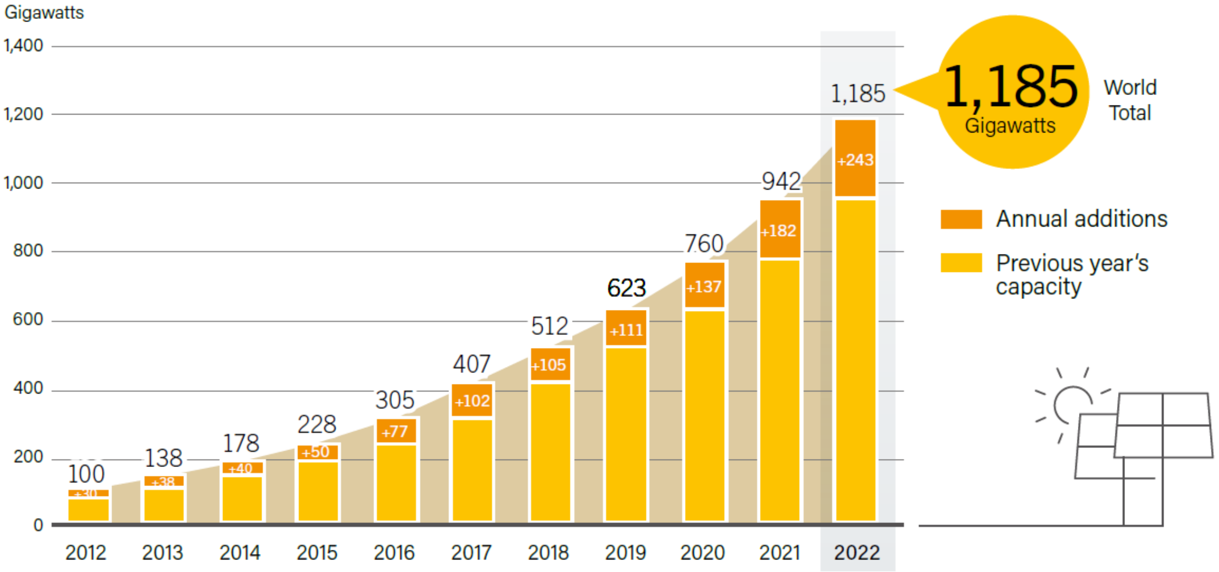


Figure 2: Global solar PV capacity and annual additions, 2012-2022. Source: REN21 (2023)

One notable obstacle in the expansion of PV energy lies in the substantial space demands of large-scale solar parks with PV panels and in the limitations on land acquisition, especially within urban areas (REN21, 2023). Fortunately, within this context, BIPV emerges as an innovative solution as it provides new opportunities to produce energy on-site, supporting the argument of behind-the-meter" energy production (Yang et al., 2022) and limiting the need for large-scale PV plants (Zhang et al., 2018). There are several advantages of generating energy on-site, as opposed to off-site:

Relieve strain electrical grid | On-site BIPV systems help alleviate strain on an already overloaded electrical grid by decentralizing energy production and reducing reliance on centralized power plants, thus enhancing grid resilience and stability (Zhang et al., 2018).

Maintain local ecosystem | Large-scale solar parks disrupt local ecosystems and habitats, negatively impacting biodiversity and the aesthetic value of the natural environment (Zhang et al., 2018).

Minimized Energy Transmission Losses | On-site PV systems minimize inefficiencies by producing and using electricity on-site, reducing energy transmission losses and costs associated with centralized off-site systems (Yang et al., 2022).

Moreover, BIPV have emerged as a promising choice for on-site energy generation for buildings over conventional BAPV. This due to several advantages, which all contribute to the establishment of energy-efficient buildings (Figure 3):

Enhanced Aesthetics | BIPV seamlessly integrates with architectural elements, preserving and enhancing the visual appeal of buildings without causing interruptions (Mangherini et al., 2023; Pillai et al., 2022).

Utilization Flexibility | BIPV's flexibility allows extensive deployment on various surfaces, ensuring adaptability to diverse architectural contexts (Mangherini et al., 2023; Pillai et al., 2022).

Provide Building Functionalities | BIPV serves a dual function, functioning both as a building envelope and a clean energy generator. Additionally, the replacement of traditional components results in a reduced need for materials in the overall construction of the building (Mangherini et al., 2023; Pillai et al., 2022).

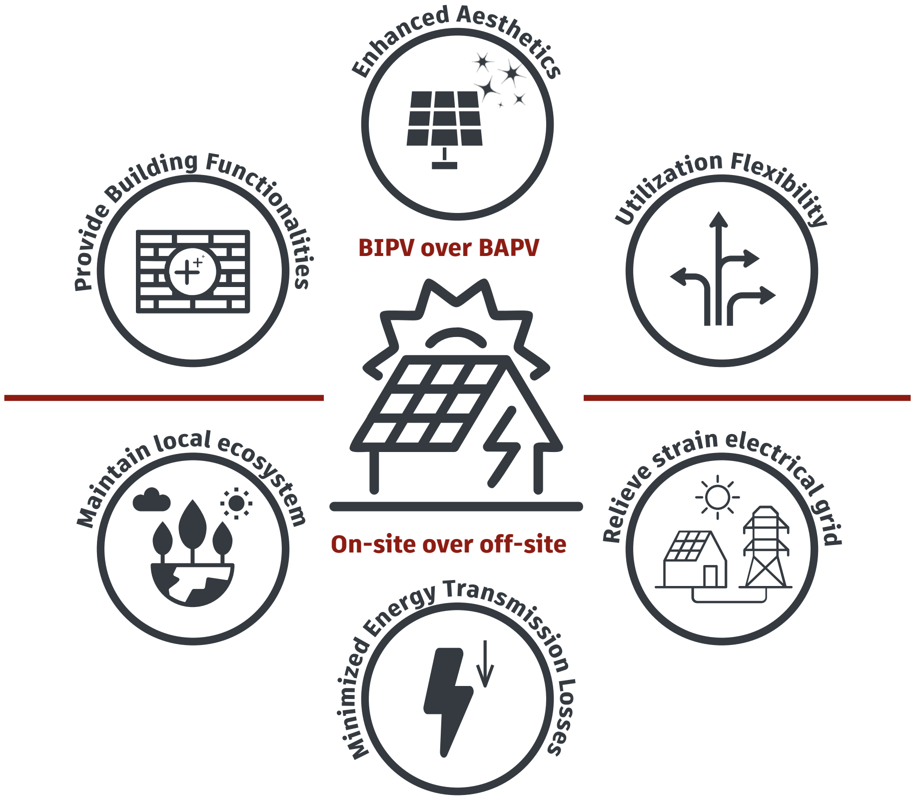


Figure 3: BIPV advantages over BAPV and off-site energy generation. Own work

As BIPV systems are employed on residential, commercial, and industrial structures, it is essential that they do not compromise the safety, well-being, comfort, accessibility, or sustainability of building occupants (Yang et al., 2022). Despite the projected rapid growth in the BIPV market, the absence of explicit and comprehensive safety requirements tailored for these systems poses significant challenges, particularly regarding fire safety, which slows deployment and fails to ensure occupant safety (Bonomo et al., 2018). Currently, there is a lack in supporting fire safety building codes and performance criteria specifically tailored for BIPV systems, aimed at ensuring the safety of building occupants (Yang et al., 2023). Furthermore, the current testing methods fall short in ensuring proper implementation of BIPV as these systems undergo testing under conditions identical to those of conventional setups, neglecting to account for their distinctive electrical properties and newly introduced ignition scenarios (Aram et al., 2021). Therefore, the current fire classes for these systems don't represent their true fire performance. Additionally, there is no statutory quality systems which could oblige installation companies to utilize products that meet specific standards and to set requirements for the competency levels of installation staff (IEA PVPS Task 15, 2023). Therefore, addressing these gaps is critical to achieve fire safety and resilience in buildings with BIPV systems, ensuring overall building safety and occupant protection.

1.2 Problem statement

To achieve fire safety and resilience in the built environment, fire hazards related to buildings are addressed through fire safety regulations and standards. These guidelines provide measures and strategies to minimize the loss of human life and property damage (Kodur et al., 2019). The prescribed design strategies and evaluation methods vary based on the building's context. Traditional standards and regulations were primarily designed for buildings with conventional components, leading to a lack of specific fire safety guidelines for "green" technologies (Meacham & McNamee, 2020). BIPV systems are recognized as critical "green" building components as they provide both functional and electro-technical attributes, thereby falling under two distinct fire safety domains: electricity production components and building components (Bonomo et al., 2018). Unlike conventional building components, BIPV systems introduce new fire hazards, such as fire ignition sources, increased fire propagation, impacting occupancy evacuations and fire department response (Yang et al., 2023).

Despite the high criticality of BIPV systems, existing fire safety codes and standards lack comprehensive provisions for their diverse applications, posing challenges to ensuring their fire safety verification (Aram et al., 2021). Moreover, conforming to the requirements outlined in current building codes, regulations, and standard fire test methods does not adequately address the unique considerations associated with BIPV systems. Aram et al. (2021) argue that achieving comprehensive fire safety provision requirements further studies into the specific impact of BIPV fires on overall building fire safety. While there are several electro-technical norms designed for PV modules aimed at preventing the ignition of fire, these norms do not address the broader context of PV systems integrated into building envelopes. This gap highlights the necessity for a more inclusive approach to fire safety that considers the evolving landscape of "green" building technologies like BIPV systems (Meacham & McNamee, 2020).

Regarding BIPV systems, there is limited literature addressing the fire hazards and risks associated with these systems and how to prevent and mitigate them properly. Existing studies on BIPV systems mostly centers around performance and feasibility, with little focus or acknowledgment to fire safety aspects. This disparity is concerning, as the fire safety of a product influences its overall feasibility and should be a crucial aspect of any comprehensive analysis.

This issue, previously also observed for BAPV systems, has seen improvements as NEN commissions in the Netherlands have been set up to address fire safety of BAPV systems. Unfortunately, for BIPV systems, in both façades and roofs, there remains a lack of comprehensive focus on fire safety standards due to relative smaller size of the BIPV segment and especially façades, which are even smaller. Although fire safety concerns related to BIPV in façades and roofs, such as fire spread via cavities and new ignition sources, are acknowledged in fire spread codes, there is no specific standard yet, and it remains a point of attention for further studies. However, although currently relatively small, several studies predict that the façade segment will grow relative to the roof segment (Pillai et al., 2022), as solely roof systems will not be able to provide sufficient energy to meet the NZEB standards (Kong et al., 2023), highlighting the increasing criticality of BIPV façade systems. In the Netherlands, the BENG 3 standards specify that, for example, 40% of energy for residential buildings and 30% for office buildings must come from renewable sources (Nieman, 2021). This is particularly relevant in dense urbanized areas, where the roof area relative to the building volume is low (Shakbunko et al., 2018).

Considering this pre-normative phase of façade BIPV fire safety (Yang et al., 2022), which fails to link fire risks of specific BIPV systems to design considerations within a building context, comprehensive guidance is needed to help designers efficiently integrate strategies and measures. This ensures proper fire safety within diverse building contexts and enables a tailored approach without standardized regulations. Meacham & McNamee (2020) emphasize that prevention and mitigation costs are typically higher when addressed later in the design process, highlighting the added value of integrating fire safety considerations early on in the design process.

In conclusion, the current regulatory and research landscape reveals a significant gap in fire safety provisions for BIPV façade systems. Existing standards and testing methods are insufficient for addressing the unique fire hazards posed by these systems. Comprehensive guidelines and standards specifically tailored to BIPV façades are essential to ensure their safe integration into buildings. Addressing this gap will enhance the fire safety and resilience of buildings with BIPV systems, ultimately protecting occupants and property while supporting the broader adoption of sustainable building technologies.

1.3 Research objective

1.3.1 Main objective

The underlying objective of this study is to achieve fire resilient buildings equipped with BIPV systems in their façades, addressing the pre-normative state of the regulatory framework in the Netherlands, which currently fails to provide adequate guidelines for this. Achieving such a goal hinges on two critical factors: conducting in-depth research on the fire safety of BIPV systems to establish clear strategies for achieving fire resilience, and raising awareness within the industry to ensure that this knowledge is effectively implemented (Figure 4). This thesis is set up to address both of these key aspects. It provides preliminary insights into the fire safety of BIPV systems in façades and outlines critical future research directions, providing an initial overview of the current status of research on this topic. Additionally, this thesis will develop a tool that facilitates the spread of this preliminary knowledge to the industry in a quick and accessible manner, enhancing the reach and practical application of the research findings. It achieves a focus by targeting the group arguably most influential in shaping design outcomes, namely designers, ensuring that the tool is both practical and tailored to their specific need, ultimately aimed at enhancing their decision making. The synergy between the design support tool and the body of BIPV fire risk knowledge aims to mutually reinforce each component, fostering the improvement of the fire resilience of buildings equipped with BIPV systems in their façades.

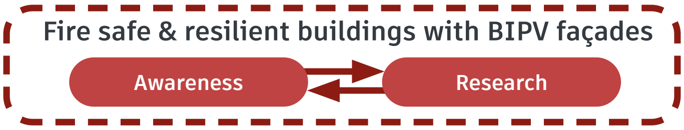


Figure 4: Awareness & research. Own work

1.3.2 Scope and limitations

Recognizing the ambitious nature of developing a comprehensive design support tool for the fire safety of BIPV façade systems, this study acknowledges the inherent limitations due to the current lack of knowledge within the context of BIPV in façades. The complexity of BIPV systems, coupled with the absence of studies addressing fire safety aspects, sometimes necessitated a reliance on educated reasoning rather than on concrete empirical data. Despite these constraints, the study is focussed on providing insights and practical guidelines to ensure safer BIPV implementations in façades. Additionally, while this study does not encompass every aspect of fire safety for BIPV in façades, it focuses on the most critical parameters that impact fire safety. In the tool, these critical issues are highlighted as risk parameters and suggests measures and strategies for prevention and mitigation, establishing itself as a preliminary guide rather than a definitive solution. Importantly, while the full spectrum of potential risks associated with BIPV systems may require more extensive resources and expertise than those available for this thesis, this study aims to contribute valuable foundational knowledge and practical approaches to the field. To further outline specific areas of focus and limitations of this study:

Managing existent risks BIPV systems | This study does not aim to solve the inherent risks associated with BIPV façade systems directly. Instead, it focuses on managing the existing risks associated with these systems through thoughtful design considerations, along with the implementation of specific measures and strategies.

BIPV façades | BIPV systems encompass three primary applications: roofs, façades, and external integrated devices. This study will specifically focus on façades, as there is a significant gap in knowledge and regulatory development for BIPV façades compared to other PV system applications in buildings. Regulatory developments have primarily concentrated on roof applications, particularly BAPV systems, leaving BIPV façades underexplored. Addressing this gap is crucial to advancing the comprehensive integration of BIPV systems in building design and ensuring their safe and efficient deployment.

Additionally, façades present inherent complexities and higher risks that could lead to greater fire hazards, opposed to roof applications (Ju et al., 2017). As façades are integral to a building's aesthetic and structural design, it presents unique challenges for each situation in terms of fire safety that must be addressed. For example, façades inherently increase the possibilities of fire propagation compared to roofs and the proximity to occupied spaces raises concerns about impacts on building occupants.

Within the application category of façades, this study narrows its focus to rainscreen façades, the most commonly employed BIPV façade system type. This targeted approach allows the to explore the particular fire safety challenges associated with rainscreen BIPV systems. By focussing on rainscreen façades, the study provides detailed insights and practical guidelines aimed at enhancing the resilience and safety of these systems, which could also be extrapolated to the other façade system types: curtain wall, window and double façade.

Sustainability | While sustainability is the driving force behind the adoption of BIPV systems, this study will primarily concentrate on addressing the critical aspect of fire safety within the context of building integration. The decision to prioritize fire safety comes from the need to mitigate the inherent fire risks associated with BIPV systems, particularly in façade applications. Although sustainability remains a vital consideration, it will not be the main focus within the framework of the developed tool.

1.4 Research question

1.4.1 Main research question

RQ 1 | Can a risk-based design support tool aid designers of façades in the design process to achieve fire safe and fire resilient designs when integrating building-integrated photovoltaic systems?

1.4.2 Sub research questions

SQ 1 | What are photovoltaics and their main characteristics?

SQ 2 | What are building integrated photovoltaics and their main characteristics?

SQ 3 | What are the fundamental principles behind fire safety engineering in the built environment?

SQ 4 | What are the relevant fire safety standards and codes for façades with BIPV systems in the Netherlands?

SQ 5 | How can classical risk theories contribute to the identification and documentation of the fire risks of BIPV systems in façades?

SQ 6 | What are the fire risks associated with employing BIPV systems in façades?

SQ 7 | How can a designer effectively prevent or mitigate the fire risks associated with BIPV systems in façades?

SQ 8 | Do PV employed in façades pose a higher risk than PV systems employed on roofs?

1.5 Methodology

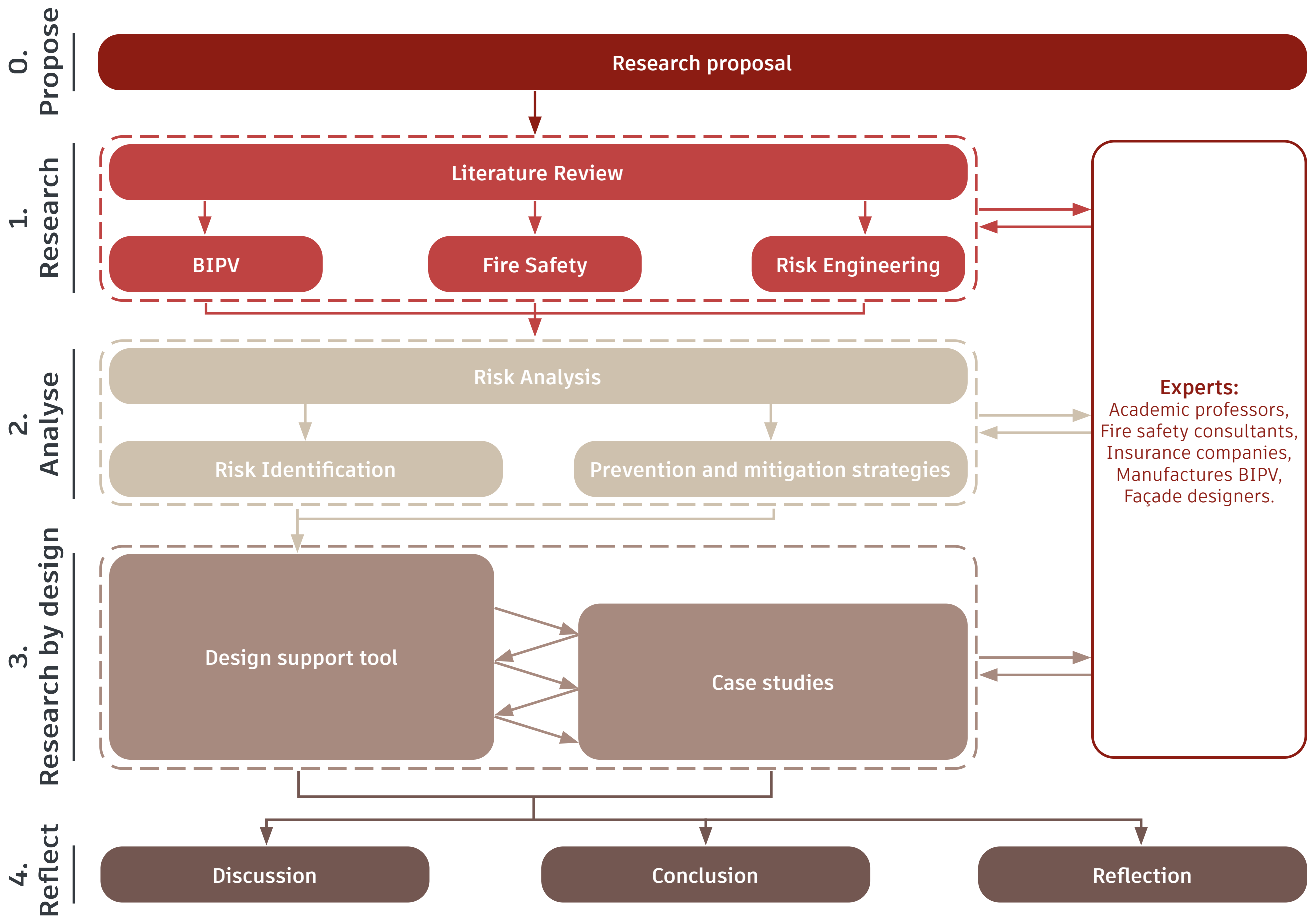


Figure 5: Research methodology. Own work

0. **Preliminary Proposal |** Preliminary research will be conducted in order to find the academic gaps within the topic of fire safety of BIPV. This knowledge will then be utilized to propose the first concept of the graduation plan, consisting of: problem statement, research objective and research questions.

1. **Literature Review |** The literature review consists of thorough research on three main topics to get a grasp on the knowledge required to achieve proper understanding of the relatively unknown fields of work for me. These three topics are: BIPV, fire safety and risk engineering. The information required is retrieved by reviewing and documenting papers and by consulting external experts. The papers are found by using relevant keywords in search engines such as Scopus, Web of Science and Google Scholar. Subsequently, a software tool called Zotero is utilized to categorize all the papers and to systematically take notes.

2. **Risk Analysis |** The knowledge gained from the literature is used to execute a risk analysis. The type of risk analysis is determined through the findings of the literature study and by aligning the objectives of each risk analysis with the primary goal of systematically identifying and assessing potential risks to subsequently be able to formulate preventive and mitigative measures and strategies. This preliminary framework forms the basis for initial strategies, which are further refined through consultations with fire safety experts.

   A qualitative fault tree analysis (FTA) was chosen. A FTA follows a structured methodology, starting with the identification of the most critical top event, the ultimate undesired outcome in the context of fire safety. This top event is broken down into sub-events, such as specific events/conditions, ignition scenarios, and conventional events that could lead to the top event. The fault tree is then constructed by tracing back from the top event through logical gates, identifying all conceivable pathways that could lead to this outcome. Then, the risks for each ignition scenario and component are analysed textually, founded by about BIPV systems in façades.

3. **Design support tool |** The prevention and mitigation strategies found by the risk analysis are translated to a design support tool which aids façade designers in the initial stages of their projects to achieve fire safe and fire resilient designs when integrating BIPV systems. The method of the tool is based on two main documents: "Risicotool brandveiligheid gevels" (DGMR, 2019) and the "Borgingsprotocol" (Nieman & DGMR, 2022). Just like these tools, the design support tool for this thesis will be constructed in Excel. Excel was chosen for its quick development, flexibility in handling data, and low entry data visualization. Its widespread availability and familiarity reduce the learning curve and eliminate the need for additional software.

   The tool aims to provide designers with main considerations for mitigation and prevention strategies, presenting these through risk parameters that originate from design considerations. These parameters are extracted from the literature reviews and through expert consultations, and are fine-tuned for this specific application through educated reasoning. In an attempt to represent the impact of different design considerations, weights are assigned to each risk parameter, allowing designers to roughly evaluate the impact of various design considerations and make improved informed decisions regarding the fire safety in BIPV-integrated façades. These weights are initially based on insights from the two main documents and further refined using case studies. By incorporating case studies, the aim is to generate outputs that align with the assessments of fire safety experts, ensuring that the output of the design support tool aligns with advice given by fire safety experts. Once the concept version of the design support tool is developed, it will undergo a short testing phase where it will be evaluated by selected users. Feedback from these sessions will be incorporated to refine and improve to a definitive version of the tool.

4. **Reflection |** As a final step, a discussion, conclusion and reflection are written on the entire process of this master thesis. This highlights the most important findings, articulates the significance of the study and offers foundational insights to potential future research directions.

1.6 Relevance

1.6.1 Societal relevance

BIPV façade systems are increasingly vital in light of sustainable urban development. As part of the built environment's shift towards 'green' technologies, BIPV systems not only enhance aesthetics and functionality but also address the rising on-site energy demands, thus reducing the reliance on large-scale off-site energy production. However, as the adoption of these systems grows, so does the concern over fire safety. Recent reports indicate a rising number of fire incidents linked to BIPV installations, underscoring the urgent need for improved safety measures and awareness within the sector. This thesis aims to highlight the societal relevance of fire safety in BIPV façade systems, urging the integration of fire risk mitigation strategies to ensure the safety of building occupants and the integrity of structures.

Need for BIPV | The global consensus on reducing energy demand has urged the built environment to employ 'green“ technologies which are clean and energy efficient (Meacham & McNamee, 2020). As energy consumption within buildings is projected to be rising, the imperative to generate on-site energy becomes increasingly vital. By enabling more on-site energy generation, on-site PV systems mitigate the necessity for off-site energy production through large-scale PV plants, thereby relieving strain on overloaded electrical grids, minimizing energy transmission losses, and preserving the integrity of the local ecosystem. On-site BAPV systems have already proven to be highly effective in generating energy, but come with inherent disadvantages which limit the implementation possibilities. BIPV systems have risen as a technological solution designed to address these limitations of on-site BAPV and provide advantages such as: enhanced aesthetics, utilization flexibility and building functionalities. Additionally,

BIPV fires | As more BIPV systems are being installed in the Netherlands, also more cases of fires caused by these systems are being reported. TNO (2019) investigated 23 PV related fire accidents in 2018 in residential buildings out of 170.000 systems placed on residential buildings. Cancelliere (2016) underscores an investigation conducted by the Italian National Firefighters Brigade, revealing that out of 590,000 installed PV systems, 1,600 fires were associated with these systems. While these numbers may seem relatively low, it is important to note that these are an underrepresentation due to several reasons: a lack of clarity on the actual cause of fires in many cases, a lack of proper investigation and administration on the fire causes or the unavailability of data due to ongoing investigations by authorities (TNO, 2019).

Notably, no fires have been identified with BIPV façade systems. This absence may be due to the smaller number of façade installations, better integration methods, or other yet-to-be-identified factors. However, as the façade segment grows rapidly, the risk of fires increases. Despite the current lack of façade-related fires, it is clear that BIPV systems, in general, pose potential risks to the safety and well-being of building occupants (Bonomo et al., 2018). Given the frequency of fires linked to BIPV systems of all types, comprehensive measures must be quickly implemented to ensure the safety and security of individuals and properties.

(BIPV) fire risk awareness | This thesis aims to raise awareness and consciousness among designers about the critical importance of fire safety, especially in the context of incorporating innovative green systems like BIPV into building designs. Despite its importance and the impact that measures can have on the design, fire safety is often overlooked in the design process. Thus, this research aims to shed light on the unique fire risks introduced by BIPV systems and advocate for proactive measures to mitigate these risks. By providing a deeper understanding of fire safety principles and encouraging adherence to regulatory standards, this thesis seeks to empower designers to make informed decisions that prioritize the safety of occupants and the resilience of buildings against fire incidents.

1.6.2 Academic relevance

In summary, this thesis offers academic contributions by advancing fire safety knowledge, developing guidelines, validating fire safety codes, integrating risk engineering principles, and advocating for a holistic approach and early stage approach to designing fire resilient façades with BIPV. By addressing key gaps in existing literature and providing practical recommendations, the thesis enhances our understanding of fire safety in the built environment and contributes to the development of safer and more sustainable building practices.

Bridging knowledge gaps | There is a substantial gap in academic research on fire safe and fire resilient façades incorporating BIPV systems. This thesis utilizes the existing knowledge from BAPV, the currently limited research of BIPV, and general fire safety principles for buildings and façades. The goal is to adapt this knowledge to the context of BIPV on façades, proposing measures and strategies to enhance fire safety. This approach not only seeks to bridge the gap between academic insights and practical application but also aims to elevate the standard of fire safety practices within BIPV installations, thereby advancing both theoretical and practical understanding in this area of building technology.

Guideline development | Guidelines for designing fire resilient façades with BIPV systems are currently lacking as a basis for the pre-normative phase of BIPV fire safety. This thesis aims to bridge this gap by synthesizing existing knowledge from architecture, engineering, and fire science to offer practical, preliminary recommendations for designers, clients, developers, and other stakeholders involved in the design and construction of BIPV façade systems. Although the thesis does not focus on empirically validating these proposed guidelines, it provides a foundational framework that integrates multidisciplinary insights, thereby supporting the development of safer BIPV installations.

Holistic approach | This study adopts an holistic approach to the fire safety of BIPV façade systems, expanding beyond a mere product-focused analysis to encompass the broader contexts of building and façade design. This enhances the understanding of how BIPV systems interact with various architectural and fire safety considerations. Such an approach is relatively new in existing literature and offers valuable insights into the complex interplay between fire safety measures, BIPV technologies, and overall building design.

Early-stage integration | Emphasizing the potential benefits of incorporating fire safety considerations early in the design process, this thesis advocates for a proactive rather than reactive approach to building safety. By developing a design support tool, the thesis enables the integration of fire safety measures from the initial stages of a design project. This proactive approach not only aims to enhance the overall safety and resilience of buildings but also ensures that fire safety is a fundamental component of the design process, leading to more efficient and effective implementation of safety measures.

Validation of regulatory framework | By assessing the existing fire safety codes and standards' effectiveness in addressing BIPV systems, the research attempts to validate or identify shortcomings in current regulatory frameworks. However, since this is not a primary objective of the study, the analysis will be more exploratory in nature rather than comprehensive.

Risk engineering integration | This thesis leverages principles and methods from the field of risk engineering, known for its proven effectiveness in various sectors. By applying these established techniques, the study aims to enhance the evaluation and management of fire safety risks associated with BIPV systems, demonstrating their valuable applicability in this context.

1.7 Outline of the report

Chapter 2 | In this chapter, the basics of PV systems are explored (SQ 1) and the characteristics of BIPV systems without delving into their fire characteristics (SQ2).

Chapter 3 | This chapter focuses on the fundamental principles behind fire safety engineering (SQ 3) and the regulatory framework of fire safety of BIPV façade systems in the Netherlands (SQ 4), focussing on applicable regulations and highlighting the shortcomings.

Chapter 4 | This chapter explores the fire risks associated with BIPV façade systems. It utilizes risk analysis from classical risk engineering practices (SQ 5) to identify these fire risks (SQ 6) and compares them to those of roof systems (SQ 8). Finally, it presents preventive or mitigative measures to address these risks (SQ 7), ultimately presenting the foundational knowledge needed to develop the design support tool.

Chapter 5 | This chapter serves as a proof of concept, aiming to answer the main research question (RQ 1). It presents the proposal for a design support tool, detailing its setup and highlighting key developments.

Discussion & conclusion | This chapter provides an overview of all findings, critically examines the results, and addresses any limitations. Additionally, all the research questions are answered comprehensively, offering insights based on the study's outcomes.

Future recommendations & reflection | This chapter provides future recommendations for the design support tool, further research on fire safety in BIPV façades and the regulatory framework for fire safety in BIPV façades. At last, the reflection focuses on the methods and results, the relationship between research and design, method adjustments and the personal process.

2

BIPV Façade Systems

2.1 Photovoltaics

Building-integrated photovoltaics (BIPV) systems, while sharing similarities with conventional photovoltaic (PV) systems, are uniquely integrated into building structures, presenting additional considerations and challenges. To effectively grasp the complexity of BIPV, a foundational understanding in PV technology is essential. Understanding PV systems' principles, such as cell generations and module configurations, offers insights into the underlying technology that forms the basis of BIPV systems. By comprehending how PV cells convert solar energy into electricity and how modules are configured to optimize power output, it becomes easier to understand BIPV integration.

2.1.1 Introduction to photovoltaics

In the early 19th century, the first observations were made about the sun's sunlight capability of generating electrical energy. Edmond Becquerel first identified this phenomenon in 1839, naming it the photovoltaic effect, and PV cells were designed to utilize this effect (Tala-Ighil, 2015). Subsequently, entire PV systems were designed around the PV cell. Roger Messenger & Amir Abtahi (2017) state that PV cells usually generate less than 5 W, which is insufficient for practical usage. Therefore, PV modules were created by connecting multiple PV cells into specific patterns, known as series-parallel configurations, to produce enough power for practical usage. The power output of these modules vary from typically 300 to 400 watts, depending on the intended use. Modules can be linked together in either parallel or series to produce even more power in the range of several hundred watts to kilowatts. Figure 6 and Figure 7 show how cells are arranged into modules, and modules are arranged into strings.

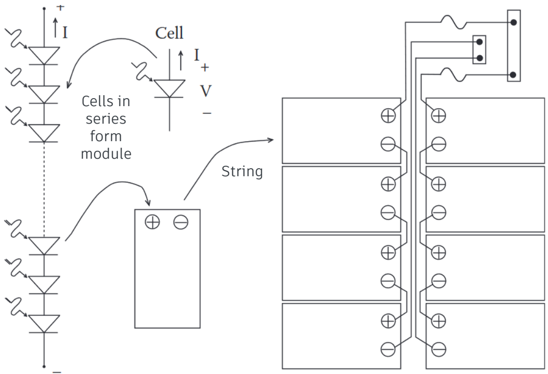


Figure 6: Cells, modules, and strings. Source: Roger Messenger & Amir Abtahi (2017)

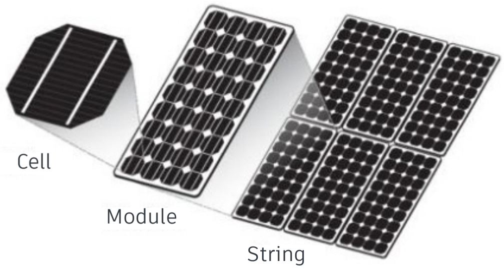


Figure 7: Cell, module and string. Source: Nabipour Afrouzi et al. (2013)

2.1.2 Photovoltaic systems

A PV system comprises a PV module or string, coupled with an ac/dc converter and various electrical and mechanical components necessary for electricity generation (Nabipour Afrouzi et al., 2013). The ac/dc inverter is crucial as pv modules or strings generate direct current (DC), while homes and appliances typically operate on alternating current (AC) power. Also, as PV cells generate energy exclusively when exposed to sunlight., PV systems can be engineered with energy storage systems (Roger Messenger & Amir Abtahi, 2017). This ensures that the generated energy can be stored and utilized during periods when sunlight is not available, enhancing the overall efficiency and reliability of the system. These systems come in various configurations to meet diverse energy needs:

Stand-alone PV systems | These systems operate independently from the utility grid and are also known as off-grid systems. They are common in remote areas or off-grid buildings (Roger Messenger & Amir Abtahi, 2017). However, since such areas are scarce in the Netherlands, these systems are seldom applied.

Grid-connected utility-interactive PV systems | These systems are designed to contribute excess energy to the grid or draw upon the grid as a backup during periods of insufficient PV generation (Roger Messenger & Amir Abtahi, 2017). This type of system is widely employed in the Netherlands, as it allows for efficient use of renewable energy while ensuring reliable access to electricity, particularly in urban areas with established grid infrastructure.

Battery-backup grid-connected PV systems | These are hybrid systems connected to the grid and include batteries to store excess energy generated by the PV modules/strings. During periods of low PV generation or grid outages, the system can draw on the stored energy in the batteries to continue powering the loads. These systems are most commonly found where power outages are frequent or where a reliable power supply is critical (Roger Messenger & Amir Abtahi, 2017). However, since power outages are rare in the Netherlands, these systems are currently rarely applied. Nevertheless, the planned reduction of the financial stimulus offered through 'saldering' will most likely boost the adoption of battery systems.

2.1.3 Photovoltaic cells

A solar cell, also referred to as a photovoltaic (PV) cell, is an electronic device that directly converts solar energy into electricity through the photovoltaic effect. As such, these sub-devices serve as the main components of PV modules (Suman et al., 2020). Figure 8 provides an overview of the components of a PV cell. The emitter (n-region) releases electrons when sunlight interacts with the semiconductor, forming the basis for electric current generation. The substrate (p-region) works with the emitter to create a potential difference, enabling electron movement and contributing to energy conversion efficiency. The anti-reflective coating optimizes light absorption by reducing reflection, while the electrical contacts facilitate the collection and transfer of the generated electric current for external use.

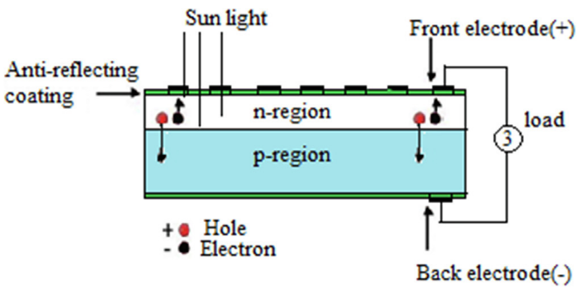


Figure 8: Elements of PV cell. Source: Suman et al. (2020)

2.1.4 Generations of photovoltaic cells

Numerous advancements have been made since the PV cell technology was discovered in 1839, shaping the evolution of PV cells into four distinct generations. The categorization of these generations is based on the materials utilized in the fabrication process (Suman et al., 2020).

First generation | includes the first PV cells created: silicon-based PV cells (Radziemska, 2003). These PV cells are characterized by materials constructed from thick crystalline layers of Si silicon. This generation of cell is widely employed due to their relatively high efficiency, making them the most used cells and holding a dominant 91% market share in 2020 (Pastuszak & Węgierek, 2022). However, this generation has reached technical maturity concerning both manufacturing processes and performance, temporarily halting further improvements to the technology (Wu et al., 2020). Within the first generation, there are several types of PV-cells, such as (Suman et al., 2020):

- Monocrystalline silicon (m-Si)
- Polycrystalline silicon (p-Si)
- Multicrystalline silicon (mc-Si)
- Gallium arsenide (GaAs)

Figure 9: Monocrystalline silicon solar cell. Source: Adam (2013)

Second generation | introduces thin-film PV cell technology as a less expensive alternative to crystalline silicon cells (Lee & Ebong, 2017). The materials used enhance mechanical properties, making them suitable for flexible applications and cheaper than silicon-based cells. However, they have reduced cell efficiency (Pastuszak & Węgierek, 2022). This led to lower market acceptance, reflected by a 9% market share in 2020 (Wu et al., 2020). Several types of PV-cells within this generation are (Suman et al., 2020):

- Copper indium gallium selenide (CIGS)
- Cadmium telluride/cadmium sulfide (CdTe/CdS)

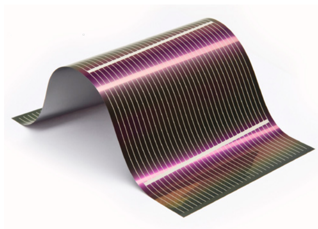


Figure 10: Copper indium gallium selenide solar cell. Source: SolarFeeds Editorial Team (2019)

- Microcrystalline silicon (μc-Si)
- Amorphous silicon (a-Si)

Third generation | PV cells utilize more recently developed chemical compounds or organic nanomaterials (Mangherini et al., 2023) and show high potential in achieving higher efficiencies, stable performance and lower production costs. However, these solutions have not yet attained widespread manufacturing as there are still several challenges to overcome (Shah et al., 2023). Nevertheless, these cells show a promising trajectory for future integration. Some of the of the most commonly researched emerging technologies (Suman et al., 2020):
- Organic materials (OSC)
- Multi-junction (MJ)
- Perovskites (PSC)
- Dye-sensitized (DSSC)
- Quantum dots (QD)

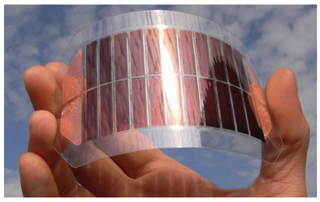


Figure 11: Copper indium gallium selenide solar cell. Source: SolarFeeds Editorial Team (2019)

Fourth generation | PV cells are also known as hybrid solar cells due to their ability to integrate both organic and inorganic materials (Rehman et al., 2023). They merge the cost-effectiveness and adaptability of polymer thin films from the first and second generations with the stability of organic nanostructures from the third generation (Wu et al., 2020). These devices hold the potential to shape the future landscape of PV technology as they combine the best performing properties of the technologies from previous generations (Pastuszak & Węgierek, 2022). But, compared to the third generation, there are even more challenges to overcome in order to achieve worldwide production (Rehman et al., 2023). Some of the commonly researched technologies (Suman et al., 2020):
- Graphene-Based
- Metal nanoparticles and metal oxides
- Carbon nanotube

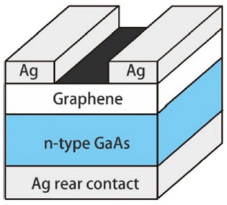


Figure 12: Graphene/GaAs HJ solar cell schematic. Source: Rehman et al. (2023)

Figure 13 shows an overview of the best research cell efficiencies in laboratory conditions. While many cells demonstrate potentially high efficiencies, achieving these efficiencies in real-world conditions remains challenging as highlighted in the previous paragraphs. Factors such as material stability, manufacturing costs, and environmental durability must be addressed before these high-efficiency cells can be widely adopted.

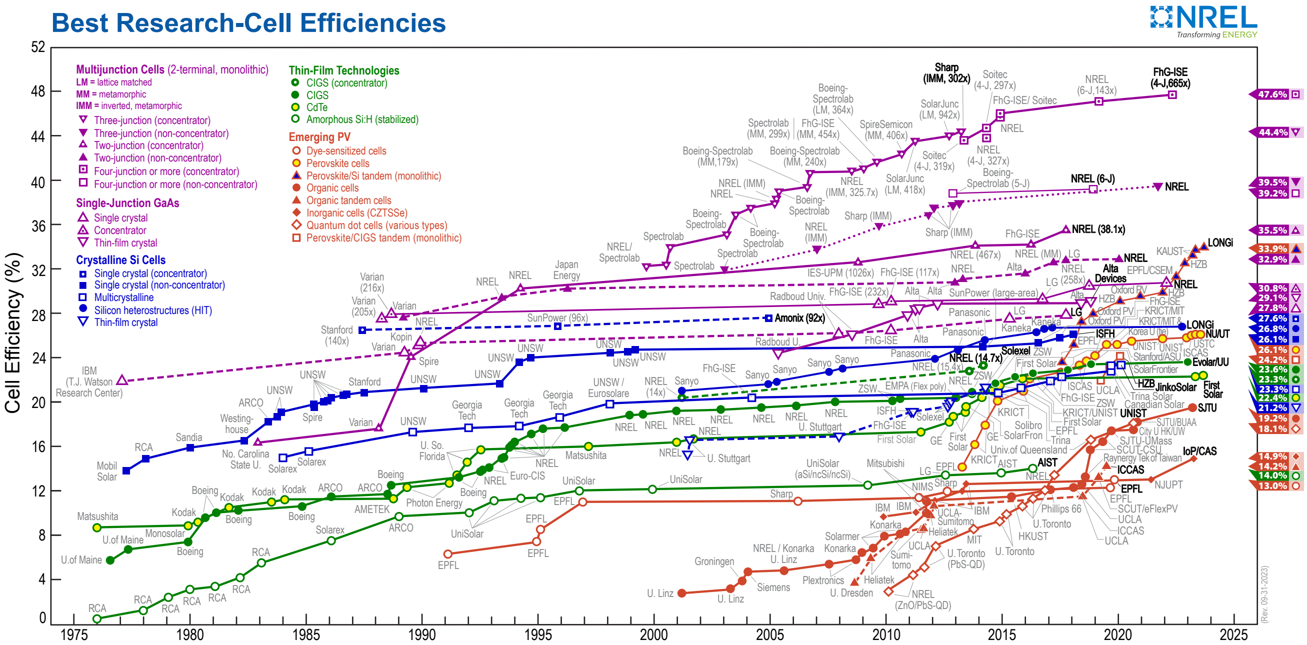


Figure 13: Best Research-Cell Efficiency. Source: NREL (2024)

2.2 Building-integrated photovoltaic systems

The goal of this chapter is to provide a comprehensive understanding of BIPV systems, exploring their technology, applications, and implications within the context of renewable energy integration and architectural design. By delving into the principles, components, and classifications of BIPV systems, insights are gained into the multifaceted nature of these systems. By understanding the technical and practical considerations associated with BIPV systems, the fire risk tool can be designed around these findings and ultimately form the foundation of the tool.

2.2.1 Building-integrated photovoltaics introduction

Building integrated photovoltaics (BIPV) consist of PV modules specifically designed to be incorporated directly into elements of a building. Recognizing the transformative potential of BIPV in the renewable energy landscape and the construction sector, the International Energy Agency Photovoltaic Power Systems Programme (IEA PVPS) established Task 15. The overall objective of Task 15 is to establish a framework that fosters the development of Building Integrated Photovoltaic (BIPV) products, aiming to accelerate their penetration and deployment in the market. IEA PVPS Task 15 (2018) provides a comprehensive overview of existing BIPV definitions, acknowledging the many variations that emerge from diverse codes, standards, and regulations worldwide. Ultimately, two distinct all-encompassing definitions were proposed for a BIPV module and a BIPV system to segregate areas of responsibility, recognizing that the system manufacturer typically differs from the one designing or installing the system.

> *"A **BIPV module** is a PV module and a construction product together, designed to be a component of the building. A BIPV product is the smallest (electrically and mechanically) non-divisible photovoltaic unit in a BIPV system which retains building-related functionality. If the BIPV product is dismounted, it would have to be replaced by an appropriate construction product.*
>
> *A **BIPV system** is a photovoltaic system in which the PV modules satisfy the definition above for BIPV products. It includes the electrical components needed to connect the PV modules to external AC or DC circuits and the mechanical mounting systems needed to integrate the BIPV products into the building"*
>
> *- IEA PVPS Task 15 (2018) -*

These definitions are mainly derived from EN 50583-1 for PV modules and EN 50583-2 for PV systems. As mentioned in the definition above by IEA PVPS Task 15 (2018), BIPV systems influence building-related functionalities, transforming the structure into a source of renewable energy. The integration of PV modules within the building components not only generates electricity but also contributes to the overall architectural and functional aspects of the building. Figure 14 showcases an overview of the functional requirements of a BIPV as prescribed by the NEN-EN 50583-1. IEA PVPS Task 15 (2021) simplifies the organization of BIPV market advancements by introducing a hierarchical approach that categorizes BIPV technologies into five levels. However, in contrast to the categorisation of PV systems, BIPV are considered to be construction elements and are therefore categorized differently. The breakdown of BIPV categories is based on a functional breakdown of parts related to the building envelope:

Application category | Classifying applications based on integration type, slope, and accessibility criteria, derived from IEC 63092 and NEN-EN 50583.

System | A technological construction unit which is substantiated by its integration within the building envelope.

Module | The technological solution for the multifunctional active element defined by specific characteristics and construction technology features.

Component | Each part of the PV module which can offer various technical alternatives to better align with the building's requirements.

Material | The fundamental material forming a component which influences its characteristics and performance.

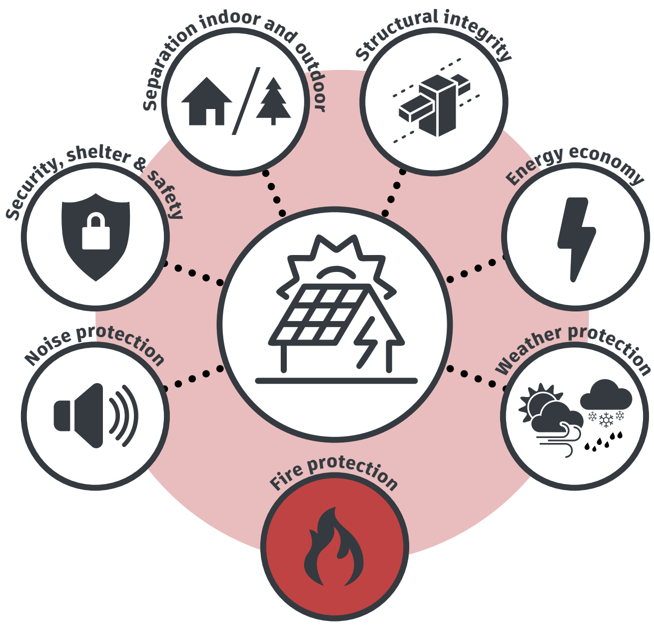


Figure 14: Functional requirements BIPV. Own work

2.2.2 Building-integrated photovoltaics: application categories

The application categories originate from NEN-EN 50583-1 and NEN-EN 50583-2. Five different categories (Table 1) are defined according to combinations of the following criteria:

Building system integration | Is the BIPV module integrated into the building's envelope? If so, in which specific part of the envelope: roof or façade?

Accessible from within building | Is the BIPV module accessible from within the building? A system is considered to be "inaccessible" when there is another building product present, which prevents the interior surface of the module to be touched from the inside of the building, or prevents large pieces to fall onto adjacent accessible areas within the building.

Slope of PV | Is the BIPV module installed on a sloped surface? A slope is defined as being between 0 and 75 degrees relative to the horizontal plane, while a non-sloped surface is considered to be between 75 and 90 degrees relative to the horizontal plane

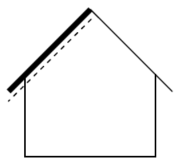
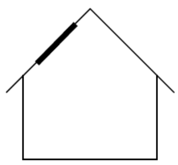
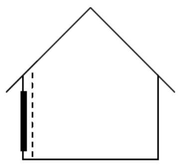
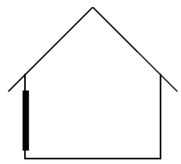
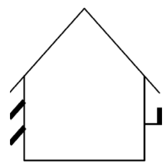
Mounting Category	Category A	Category B	Category C	Category D	Category E
Building System Integration	Roof	Roof	Façade	Façade	External
Accessible from Within Building	No	Yes	No	Yes	No
Slope of PV	0° ≤ angle ≤ 75°	0° ≤ angle ≤ 75°	75° ≤ angle ≤ 90°	75° ≤ angle ≤ 90°	0° ≤ angle ≤ 90°
Reference Image					
BIPV Example Systems	Discontinuous roofing Continuous roofing	Atriums Skylights	Rain screen/ ventilated façade Double skin façade	Window Curtain wall	Parapet Balustrade Canopy Solar shading

Table 1: Application categories. Source: NEN-EN 50583-1. Own edit

2.2.3 Building-integrated photovoltaics: systems

BIPV systems are categorized based on the integration in the building envelope (IEA PVPS Task 15, 2021):

Roof | Serves as the top cover. It offers protection and separates the indoor and outdoor environments (application categories A and B).

External integrated devices | Components and systems within the building envelope that exclusively interact with the outdoor environment (application category E).

Façade | Constitutes the vertical (or inclined) outer surface, serving as an architectural display and acting as a boundary between indoor and outdoor (application categories C and D).

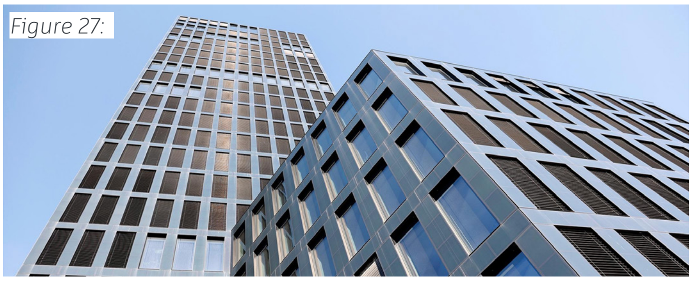


Figure 27:

Figure 28:

Grosspeter tower
Basel, Switzerland

Rainscreen façade (Ventilated)

Source: SolAR (2022)

Figure 31:

Figure 32:

The Pulse of Amsterdam, Netherlands

Rainscreen façade (Ventilated)

Source: MVSA-architects (2020)

Figure 33:

Figure 34:

Glassbel office
Klaipeda, Lithuania

Double skin façade (BIPV + transparent)

Source: Onyx Solar (2018)

Figure 29:

Figure 30:

Balenciaga Store
Miami, USA

Curtain wall

Source: David_OS (2018)

Figure 35:

Figure 36:

Murdoch University
R&D Greenhouse
Perth, Australia

Window

Source: ClearVue (2021)

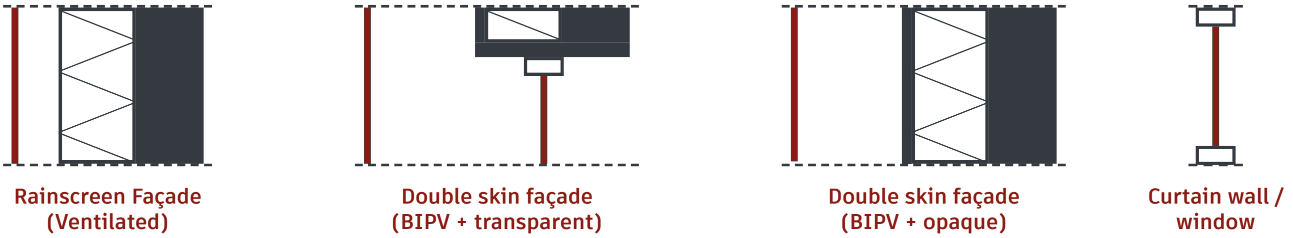


Figure 15: BIPV façade system typologies. Own work

Figure 15 highlights the main BIPV façade typologies:

Rainscreen façade (Ventilated) | This system features an outer BIPV layer separated from the inner structure by a ventilated cavity. The cavity allows for air circulation, which helps with temperature regulation but can also contribute to fire spread if not properly managed.

Double skin façade (BIPV + Transparent / opaque) | This façade incorporates a transparent BIPV layer with a large air gap between the BIPV and the inner building skin, , which can be either transparent or opaque This cavity can be naturally ventilated, but is more often regulated, connecting it with the building's HVAC system. This regulated space can heavily impact fire safety by facilitating the spread of smoke and flames through the building.

Curtain wall / window systems | These systems integrate BIPV modules within the building's glazing or curtain wall. Unlike the other systems, there is no cavity. However, with the BIPV module directly adjacent to the interior, fire scenarios can directly impact indoor environments

2.2.4 Building-integrated photovoltaics: modules

BIPV modules are available in diverse forms and dimensions, customized to fit almost any possible envelope application. Considering module characteristics and applications, IEA PVPS Task 15 (2021) prescribes a classification of BIPV products accessible in the market. Due to the wide variety of BIPV modules, several characteristics categories for technical design are proposed to aid in making informed decisions based on project requirements and objectives (Table 2).

Characteristics categories	Options	Description
Transparency	Opaque	Does not transmit visible light.
	Translucent	Transmits diffuse light; objects not seen distinctly
	Semi-translucent	Transmits diffuse light with partial view obstruction
	Transparent	Transmits visible light without significant scattering; objects seen clearly.
	Semi-transparent	Transmits visible light with partial view obstruction.
Planarity	Flat	Designed in a single planar surface.
	Curved	Not designed in a single planar surface.
Mechanical rigidity	Flexible	Can bend under load; fits curved or flat surfaces.
	Rigid	Cannot bend under load; retains shape once produced.
Size	Large	Surpasses 2.6 m in any dimension or exceeds 2.1 m in both dimensions.
	Shingle	Measures less than 0.9 m in both dimensions.
	Regular	Does not fit within the classifications of large or shingle.
Thermal insulation	Insulated	Has a U-value (thermal transmittance) lower than 2,7 W/m^{2}K.
	Non-Insulated	Has a U-value (thermal transmittance) more than or equal to 2,7 W/m^{2}K.
Standardization level	Standard	Conventional PV module, not specifically developed for any application.
	Customized	Non-standard PV module, developed for specific applications.

Table 2: Categorization options BIPV modules based on characteristics. Source: IEA PVPS Task 15 (2021) . Own edit

2.2.5 Building-integrated photovoltaics: components

The BIPV module is designed with improvements compared to a regular PV module to achieve enhanced constructional performance (IEA PVPS Task 15, 2021). Each component of the BIPV module is adjusted to align with the building's requirements. The components are often the same for PV and BIPV modules, but differ in materiality and performance. An overview of the characteristic components of a BIPV module:

PV cell | The fundamental unit of a (BI)PV module, the PV cell converts solar radiation into electricity through the photovoltaic effect.

BIPV encapsulant | This protective layer serves multiple functions, including shielding PV cells and metallization from environmental stresses (such as moisture and UV exposure), providing adhesion between laminate layers, ensuring electrical insulation, and facilitating the transmission of irradiation for wavelengths relevant to photovoltaics.

BIPV front cover | Composed of one or more transparent layers, the front cover forms the face of the PV module. This component not only ensures transparency for incoming light, but also safeguards the PV cells and circuitry structurally and acts as a barrier that prevents the ingress of moisture and oxygen.

BIPV back cover | Composed of one or more (transparent) layers, the back cover serves as the rear layer of a photovoltaic module. It offers environmental protection and electrical insulation for PV cells and circuitry. Moreover, it can provide additional construction-related performance requirements such as mechanical strength and fire safety.

Junction box | An enclosed or protected section of a photovoltaic module where circuits are electrically connected. It's often designed as a separate element, contributing to the safety and reliability of the electrical connections.

Bypass diode | Installed in the junction box in parallel to the string of cells in a PV module, the bypass diode facilitates the diversion of current, bypassing shaded or malfunctioning cells. This preventive measure mitigates power loss in suboptimal conditions.

System bypass diode | Installed in the junction box in parallel across one or more PV modules, the system bypass diode facilitates the diversion of current, bypassing shaded or malfunctioning PV modules. This preventive measure mitigates power loss in suboptimal conditions.

Frame | Designed to withstand environmental stresses and impacts, ensuring the overall integrity of the PV module within the context of its installation on a building or other structures.

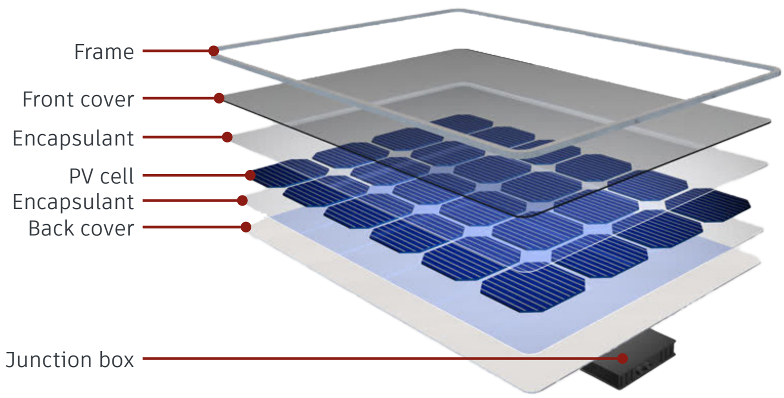


Figure 16: (BI)PV module components . Source: Sauer (2021). Own edit

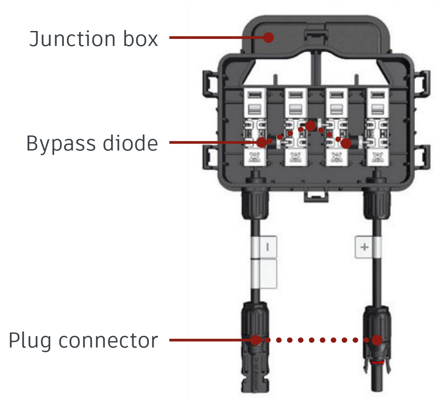


Figure 17: Junction box. Source: De Rooij (2023). Own edit

Additional to the BIPV module, there are also other standard electrical components in BIPV systems:

Inverter | An inverter is the central component in BIPV systems. It converts the DC electricity generated by the PV modules into AC electricity that can be used to power household appliances and fed into the grid. Two main types of inverters are: string inverter and micro-inverter.

- **String inverter** are typically used in configurations where multiple PV modules are connected in series to form a string. This type of inverter is installed indoors and is capable of handling high voltage DC inputs from the entire string, converting it into AC. While cost-effective and simple, string inverters can be less efficient under shaded conditions, as shading on one module affects the entire string's performance.

- **Micro-inverter** are small inverters mounted on the back of each individual PV module. They convert the DC electricity from each module into AC right at the module level, which increases the overall system efficiency, particularly in cases of shading or module mismatch. Although more expensive and complex to install, micro-inverters offer better performance monitoring and higher overall energy yield.

Wiring | Wiring in BIPV systems includes both AC and DC wires. DC wires carry the direct current electricity generated by the PV modules to the inverter, while AC wires transmit the alternating current electricity from the inverter to household appliances and the electrical grid.

Plug connectors | A plug connector is an electrical component used to connect electrical components and wiring together. It typically consists of male and female parts that securely fit together to establish an electrical connection. Plug connectors must ensure a secure, weather-resistant connection to maintain system performance and safety

Mounting system | The mounting system attaches the BIPV modules to the façade. It consists of a variety of components, including rails, clamps, and brackets, that are used to support and position the modules. The mounting system ensures the structural integrity of the BIPV modules and withstands environmental loads such as wind. Typical connections between the BIPV module and the mounting structures are secured with bolts, clamps or glue.

Figure 18: Growatt string inverter. Source: Volt Zonnepanelen (2024)

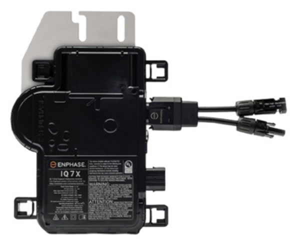


Figure 19: Enphase micro-inverter. Source: Volt Zonnepanelen (2024)

Figure 20: Wiring and plug connector. Source: Volt Zonnepanelen (2024)

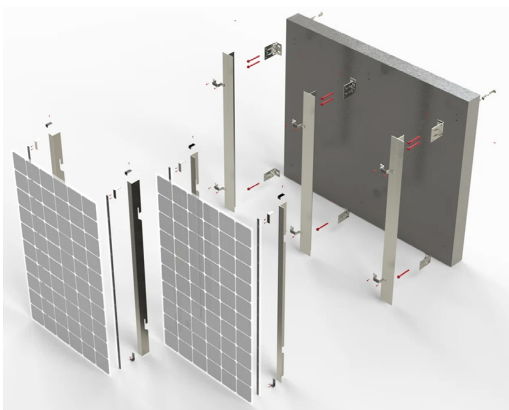


Figure 21: Mounting system. Source: AGS (2023)

Additional to the standard components in a BIPV systems, there are also some optional components which can be utilized dependant on the electrical configuration requirements:

Arc-fault circuit interrupter (AFCI) | An arc fault circuit interrupter (AFCI) is a circuit breaker that interrupts the circuit when it detects electrical arcs, preventing serial arcs. Note that an AFCI can only detect parallel arcs, it cannot prevent them. AFCIs are typically integrated into modern inverters by default, but there also exist inverters without them. Take note that AFCIs are not always activated when installed.

Optimiser | PV optimisers are electronic devices that are typically installed at the module level, between a PV module and a string inverter. They perform a similar function to micro-inverters, optimizing the performance of each module by maximizing power output and minimizing losses due to shading or mismatch. However, opposed to micro-inverters, optimisers deliver an DC output. PV optimisers work by tracking the maximum power point (MPP) of each module and adjusting the voltage and current to ensure maximum energy production.

Combiner Box | A combiner box serves as a central hub where multiple strings of PV modules are combined into a single output which can be routed to the string inverter for conversion into AC electricity. It consolidates the DC outputs from individual strings, ensuring that voltage levels are appropriately matched. The total output current is the sum of the current from all strings. Additionally, combiner boxes typically include overcurrent protection devices, such as fuses or circuit breakers, to safeguard against electrical faults and overloads.

Figure 22: SIEMENS AFCI. Source: Nokovich (2019)

Figure 23: SolarEdge optimizer. Source: Volt Zonnepanelen (2024)

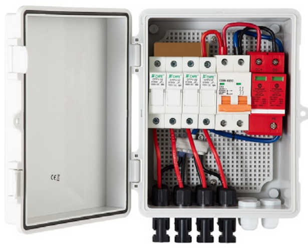


Figure 24: ECO-WORTHY combiner box. Source: UBuy France (2023)

2.2.6 Building-integrated photovoltaics: future trends

BIPV systems are continuously evolving, with significant improvements anticipated in the coming years. One of the primary areas of focus for BIPV module development is enhancing cell efficiency, which directly relates to the type of PV cell technology employed. Increasing the efficiency of PV cells is crucial for maximizing energy generation and making BIPV systems more viable and attractive for widespread adoption. Although advancements in PV cell efficiency do not significantly impact fire safety, they are essential for the overall performance and sustainability of BIPV systems. After having interviewed BIPV manufactures, like CombiSolar and Soltech, it also became apparent that the trust in the development of new cell technologies is very low within the market. The expectation is that most of the new cell technologies will fail. Consequently, the sector has shifted its focus towards optimizing other key parameters of the modules, responding directly to other sector demands:

Life time expectancy | According to manufacturers, glass/glass BIPV façade modules typically have a longer life expectancy of approximately 50 years, surpassing that of glass/polymer PV modules, which typically have a life expectancy of 30-35 years. The increased durability of glass/glass modules not only improves economic viability but also enhances fire safety by reducing the likelihood of material degradation that could pose fire risks over time.

Adjustable size | Modern façades exhibit a wide diversity in shape and dimensions, often tailored to the requirements of architects and designers. Unlike standardized BAPV modules, BIPV modules are often custom-engineered to fit precise specifications outlined by architects and façade designers. This customization has become increasingly prevalent with advancements allowing PV cells to be divided into halves or quarters, directly influencing the possible sizes of

BIPV modules. Custom sizes must be carefully designed to maintain structural integrity and fire resistance, ensuring modifications do not introduce vulnerabilities that compromise fire safety.

Coloured or textured finishing | To integrate BIPV seamlessly into building façades, customized glass modules have been heavily developed within the sector. These modules offer architects and designers design freedom by concealing PV cells behind coloured patterns. However, this camouflage may lead to a reduction in energy production due to irradiance mismatch, necessitating careful optimization to ensure energy efficiency without compromising reliability or durability. Techniques such as anti-reflection coatings on solar cells, coloured or semi-transparent PV-active layers, special solar interlayer filters, coloured polymeric encapsulant films and modified front glass are used to achieve aesthetic appeal (IEA PVPS Task 15, 2019b).

No data has been found which elaborates on the impact of these techniques on the fire performance of BIPV modules. However, through reasoning, the following can be argued. Most of these techniques, except for modified front glass, affect the interlayers of the BIPV module. While these interlayer modifications might influence the overall fire performance of the module, their impact is primarily mitigated by the protective function of the front and back sheets in the event of a fire. Conversely, modified front glass techniques deserve particular attention because, depending on the method used, an added outer layer or foil could potentially be combustible. Therefore, ensuring that these modifications do not compromise the fire safety of BIPV modules is essential for their safe integration into building façades.

Figure 25: Soltech factory. Thorpark Gent, Belgium. Source: De Koning (2024)

Figure 26: Kameleon Solar: Titaan. Den Haag, Netherlands. Source: De Koning (2024)

3

BIPV Façade Fire Safety Regulations

3.1 Regulatory framework fire safety BIPV façades

The façade of a building is a critical element in ensuring its fire safety, particularly in the context of the growing developments of mid and high-rise structures in the Netherlands. Therefore, understanding and adhering to the regulatory requirements outlined in the Bbl, and related standards and codes, is of importance for designers. This chapter will delve into the essential aspects of façade design concerning fire safety. By examining the relevant regulations and standards, the goal is to provide a comprehensive overview of the regulatory framework and its shortcomings for constructing fire-safe façades, focussing on fire classification, fire tests, and fire spread, particularly focusing on regulations within the Netherlands.

3.1.1 Fire safety principles in the built environment

Fire safety in the built environment is a multifaceted domain aimed at protecting against fire hazards. Given the many factors involved, an integrated approach across disciplines is essential to ensure the safety of lives and property. Derived from public law, the primary objectives are (Ruud van Herpen, 2023):

1 | Limiting loss of life in the event of a fire situation.
2 | Limiting fire spread to neighbouring properties in the event of a fire situation.

To achieve these objectives, fire safety principles are structured to sub-objectives, or so-called risk subsystems. These risk subsystems should be focussed on in the sequence presented below, as this is considered to be the most effective order for fire protection (Ruud van Herpen, 2023):

1 | Prevent the ignition of a fire
2 | Limit the development of a fire
3 | Limit the spread of fire within the building
4 | Limit spread of smoke within the building
5 | Maintain the structural integrity of the building
6 | Maintain the escape and access routes
7 | Limit the spread of fire and consequences for the surroundings

In addition to the public law objectives, it is crucial to consider private law wishes that encompass the intrinsic, emotional, and cultural values of the built environment:

Intrinsic Value | The inherent worth of the property, based on its utility, features, and condition, influencing its market price and replacement cost.

Emotional Value | The sentimental importance of a property to its owners and occupants, often derived from personal experiences, memories, and attachments, making its loss deeply personal and impactful.

Cultural Value | The cultural importance of a building or area, particularly those that contribute to the heritage and identity of a community, preserving historical narratives.

Integrating these private law considerations ensures a holistic approach to fire safety, aligning with both the practical requirements of public safety and the broader needs of preserving the emotional and cultural fabric of the built environment.

For extra information about the basic principles of fire safety in the Netherlands, refer to Appendix IV

3.1.2 Regulatory framework fire safety façades in the Netherlands: fire classification

The only two requirements from the Bbl specifically for façades revolves around limiting the fire growth across the outside pane (DGMR, 2019). The first requirement is a minimum fire class rating, ensuring that the materials used can adequately resist fire for a specified duration. The second is the requirement on the 'Weerstand tegen BrandDoorslag en BrandOverslag' (WBDBO), which addresses the prevention of fire spread through pathways that include the façade and/or cavity, also indirectly referring to minimal fire classes.

Regarding the fire class, the Bbl prescribes that at the outer layer of the façade construction should comply to a fire class as shown in Table 3, which is determined according NEN-EN 13501-1. This code defines one main material characteristic: reaction to fire, along with two sub-characteristics: smoke generation and burning droplets. For instance, a material classified as B-s1-do can be roughly translated as a material with limited contribution to fire, limited combustibility, barely any smoke production, and no droplet formation. Table 4 provides simplified definitions for the classifications of material characteristics according to the code.

New building	
Bbl artikel 4.2.7	
Façade height < 2.5 m	B (if highest floor > 5m)
Façade height > 13 m	B
*1 Façade height > 30 m	A2 (sleeping function with reduced self-reliance), B (other functions)
*1 Façade height > 50 m	A2 (sleeping function), B (other functions)
Façade adjacent to extra protected escape route	B (cell function), C (other functions)
Façade adjacent to protected escape route	B (cell function), C (sleeping function), D (other functions)
Façade part (other)	D
Exception: doors, windows, window frames	D
Bbl artikel 4.2.8	
Façade between openings of two fire compartments	B (condition WBDBO / NEN 6068)
Façade between openings of protected sub fire compartments and fire compartments	B (condition WBDBO / NEN 6068)
*1 Expected to be implemented in Bbl • Classes A2/B/C/D according NEN-EN 13501-1	

Table 3: Summary of minimal fire classes from "Besluit bouwwerken leefomgeving (Bbl)". Sources: DGMR (2019) & Denkers (2023) . Own edit

Euro classification	**Fire behaviour of the material**		**Smoke production**		**Droplet forming**	
A1	No contribution	Non-combustible	S1	Barely	D0	None
A2	Almost no contribution	Almost non-combustible	S2	Average	D1	Some
B	Limited contribution	Limited combustibility	S3	Big	D2	Quite a lot
C	Big contribution	Combustible				
D	High contribution	Easily combustible				
E	Very high contribution	Highly combustible				
F	Dangerous contribution	Very highly combustible				

Table 4: Fire class definitions from "Besluit bouwwerken leefomgeving (Bbl)". Source: NEN-EN 13501-1 . Own edit

Laboratory tests are conducted by independent companies following codes to determine the fire class (Table 5). The Single Burning Item (SBI) test is frequently used to test reaction to fire of specific building materials, as it aligns with the specified fire classes outlined in the Bbl (Table 3): A2, B, C, or D. This test simulates a typical fire scenario by subjecting a corner fragment of the material or façade setup, measuring 100 x 50 x 150 cm, to a 30 kW burner. For determining fire classes E or F, the small flame test suffices. However, for fire class A1, tests according to NEN-EN ISO 1182 or NEN-EN ISO 1716 are currently mandatory, as neither the SBI nor small flame test suffice.

Test name	**Applicable fire classes**
Non-Combustibility test (NEN-EN ISO 1182)	A1, A2
Heat of Combustion test (NEN-EN ISO 1716)	A1, A2
Single Burning Item (SBI) test (NEN-EN 13823)	A2, B, C, D
Small Flame test (NEN-EN ISO 11925-2)	B, C, D, E, F

Table 5: Current fire test used in the Netherlands for determining fire classes of building products. Own work

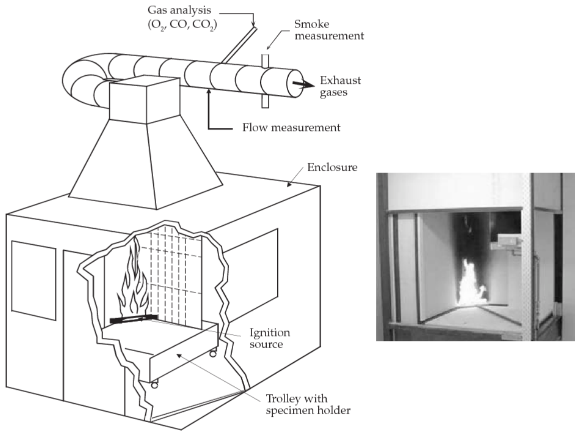


Figure 37: SBI-test setup.
Source: van Mierlo (2005)

Additional to the current regulations for the fire class of outer materials in façades, two new rules are expected to be implemented in the Bbl in the near future which specify higher requirement for façades above 50 meters in buildings where people sleep (e.g. residences, hotels) or for façades above 30 meters in buildings where less self-reliant or impaired individuals sleep (e.g. hospitals, childcare, elderly care), and where the stairwells are not effectively shielded from a façade fire. The requirement is to comply to one of these options: (De Kort, 2024):

1 | Ensure that the façade meets fire class A2.
2 | A portion of the façade construction must comply with option 1 and shield more combustible materials with fire-resistant cladding that meets EI15 standards.
3 | Test the façade construction with a large scale fire test (Table 6) and ensure compliance with a specific class according NPR 6999.

Considering the shortcomings of the SBI-test, which are critical for high-risk buildings, the new Bbl regulations regarding higher fire classes for high-risk buildings will address these issues. Large-scale fire tests (Table 6) can determine the fire class of a façade according to criteria in the upcoming NPR 6999, as they address most SBI-test shortcomings. Previously, large-scale tests were rarely used due to no direction from the Bbl, as well as the time and high costs involved Alternative methods involved combining the SBI-test with expert opinion, as an alternative to execute an SBI test for every configuration ,or relying solely on expert opinion. These methods consider the fire behaviour of individual components, acknowledge the SBI-test's limitations, and implement the principle of equivalence (DGMR, 2018). However, as expert opinions can vary significantly in reliability due to differences in expertise, it is generally more reliable to depend on fire tests for accurate assessments.

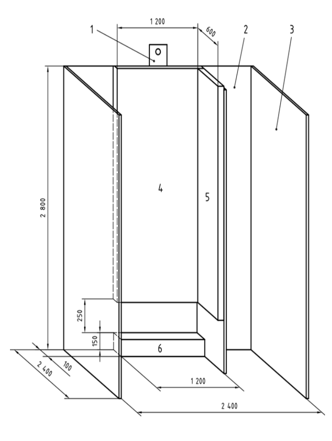
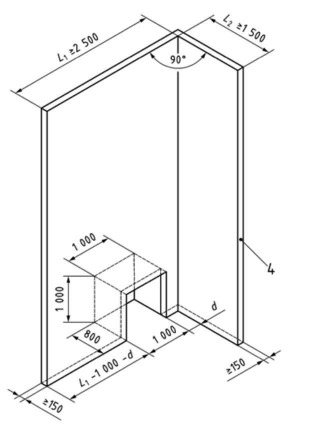
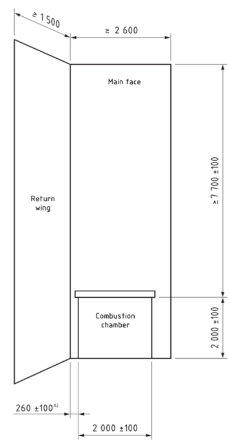
			
Test method	**ISO 13785-1**	**DIN 4102-20**	**BS 8414**
Height:	2.5 meter	5.5 meter	9.5 meter
Flame source:	~100 KW	~ 320 kW	~ 3 MW
Cost estimation:	+ -	+	+ +
Execution time:	+ -	+	+ +

Table 6: Overview of mid-large scale fire tests NPR 6999. Sources: van Mierlo, personal communication (march 2024)

3.1.3 Regulatory framework fire safety façades in the Netherlands: fire spread

In addition to reaction to fire, the Bbl also sets indirect requirements for the façade construction regarding “weerstand tegen branddoorslag en brandoverslag (WBDBO)” according NEN 6068 and NEN 6069. These standards set requirements for the minimal time it should take for a fire to spread from one fire compartment to another (sub)compartment, through “branddoorslag“ (=internal fire spread) and “brandoverslag“ (=external fire spread) (Table 7). The following concepts are implemented in the code (Veek & Janse, 2005):

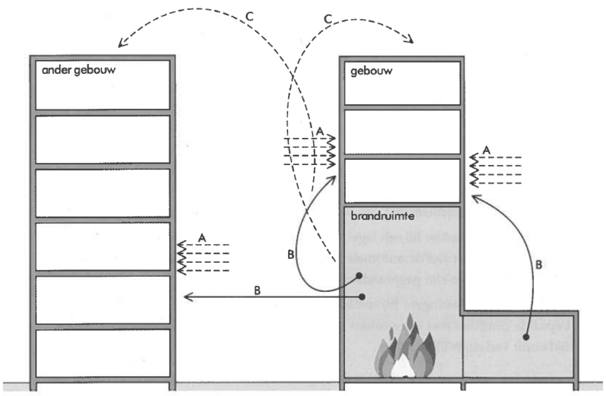
Situation (from):	Situation (to):	New buildings
Fire compartment	Fire compartment	60 min
Fire compartment	Confined space via which an extra protected escape route is situated.	60 min
Fire compartment	Confined space via which a protected escape route is situated.	30 min
Protected sub-compartment	Another room within the same fire compartment requiring additional protection (e.g. patient rooms in hospitals, hotel rooms, prison cells)	30 min

Table 7: WBDBO minimal requirements . Source: Rijksoverheid (2024)

Weerstand tegen brandoverslag (WBO) | “Brandoverslag” is the spread of fire from a fire compartment to another (sub)compartment or (extra) protected escape route, exclusively via the outdoor air. This can occur via: radiation, outward spreading flames and flying fire (Figure 38). The WBO is as a minimal threshold in minutes.

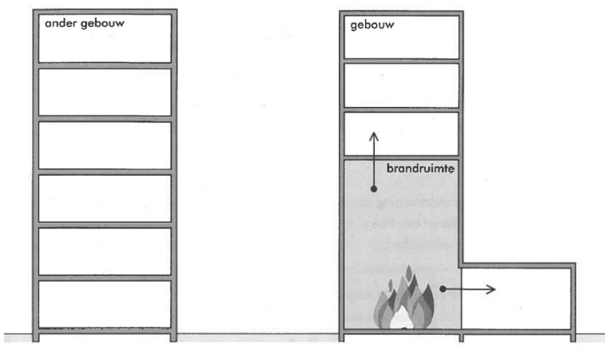
Weerstand tegen branddoorslag (WBD) | “Branddoorslag“ is the spread of fire from a fire compartment to another (sub)compartment or (extra) protected escape route through one or a series of construction elements and not through outdoor air (Figure 39). This occurs when the separating element fails, allows flames or hot gases to pass through, or when the non-heated side reaches a threshold temperature. The WBD is as a minimal threshold in minutes.

Weerstand tegen branddoorslag en brandoverslag (WBDBO) | The shortest time a fire takes to spread from one compartment to another (sub)compartment or (extra) protected escape route, considering all WBO and WBD trajectories or combinations of those trajectories.



“Brandoverslag” (through outdoor air):
A. Radiation
B. Outward spreading flames
C. Flying brands

Figure 38: “Brandoverslag“ scenario’s. Source: Veek en Janse (2005)



“Branddoorslag” (to another space and not through outdoor air)

Figure 39: “Branddoorslag“ scenario’s. Source: Veek en Janse (2005)

For façades, the Bbl prescribes regulations concerning the WBDBO which dictate requirements for the fire resistance of façade-floor and façade-wall connections, the potential fire trajectories of fire spread (inside) through the façade construction, and the distances between openings in the façade (DGMR, 2019).

3.1.4 Regulatory framework fire safety BIPV façades in the Netherlands

PV systems are not directly mentioned in the Bbl regarding the topic of fire safety, and especially not BIPV in façades as this is a smaller niche. However, there are several regulations and guidelines that indirectly are applicable to BIPV systems on façades. Additionally, certain codes that are (partially) enforced under the Bbl do address the fire safety aspects of these systems to some extent, providing a regulatory framework that, while not tailored specifically to BIPV, still impacts their implementation and safety protocols. An overview of the relevant regulations and codes**:**

NEN 7250 | As a key standard for PV systems in the Netherlands, NEN 7250 specifies a range of engineering requirements that PV, BAPV, and BIPV modules must adhere to, based on their installation methods. While it includes basic references to fire safety, the code falls short in providing detailed provisions on fire safety characteristics, failing to adequately address the unique challenges associated with BIPV systems in façades. However, some of the shortcomings are acknowledged.

NEN 1010 | This standard currently provides the normative foundation for the quality of materials and electrical components used in PV systems. Also, NEN 1010 covers the prevention of fire originating from short circuits and overheating. Although not specifically tailored for BIPV façades, the norm is also applicable for these systems. It is referenced by the Bbl in various sections to enforce compliance with quality standards. However, the aspect of NEN 1010 that pertain to quality control lacks direct enforcement from the Bbl.

NEN-EN-IEC 62446 | In addition to the delivery and inspection guideline according the NEN 1010, the NEN-EN-IEC 62446 provides additional requirements for the documentation of the installation, the testing before commissioning, and for the initial inspection. However, this code is also not directed by the Bbl.

NPR 8092 | This guideline serves as a document to guide clients and contractors towards ensuring high-quality and sound workmanship, known as "goed en deugelijk werk," upon project delivery. Specifically for BIPV systems on façades, this guideline can become relevant if the BIPV system is found to be installed in a manner that does not comply with the product specifications of its components, providing a regulatory pillar for addressing and rectifying such issues.

NEN 6068 & NEN 6069 | These codes, referred by the Bbl, don't specifically mention PV systems, but the impact of the BIPV systems should be taken into account with the calculations for "branddoorslag" according NEN 6069 and not for "brandoverslag" according NEN 6068.

NPR 6668 | This guideline acts as a supplementary document, providing detailed elaboration on the calculation methods and definitions outlined in NEN 6068. While this document recognizes PV, it does not offer a universal solution for their integration.

3.1.5 Regulatory framework fire safety BIPV façades in the Netherlands: fire class

In the Netherlands, fire safety standards and codes for BIPV systems in façades align with the regulations for façades. As such, BIPV modules must meet the fire classification requirements outlined in NEN-EN 13501-1, adhering to the minimum classes specified in Table 6 . These modules are evaluated using the same testing methods detailed in Table 5, with the SBI test being most commonly used (Figure 40).

(BI)PV modules can also achieve a certified fire class rating under the ANSI/UL 1703 standard, utilizing the UL 790 test method (Figure 41). This standard assesses the module's fire performance and categorizes it into one of three classes: A, B, or C, which aligns with the classification categories of NEN-EN 13501-1 (A1, A2, B, C, D, E, F). However, it's crucial to note a common misconception:

"Equating a fire class from ANSI/UL 1703 (via UL 790) directly with a fire class from NEN-EN 13501-1 is inaccurate, as the UL 790 test method is specifically designed for roof applications. The two standards evaluate different parameters and utilize varying thresholds for their classifications, which can lead to significant differences in fire safety ratings."

Figure 40: SBI-test with PIZ BIPV cladding system.
Source: IEA PVPS Task 15 (2023)

Figure 41: UL 790 test for PV panel on roof.
Source: Cobouw (2020)

Thus, it is wrong to assume that a BIPV module tested as fire class B according UL 790 is automatically suitable for implementation in a façade. Fire class B is indeed a minimal requirement for façades, but it needs to be attained according to NEN-EN 13501-1 standards, not via UL 790. Therefore, it is crucial to consider the fire class when selecting a BIPV module, ensuring compliance with NEN-EN 13501-1 and not with UL 790. The current market standard for BIPV façade modules, as confirmed by manufacturers CombiSolar and Soltech, are rated with fire class B according NEN-EN 13501-1 and fire class A according UL 790.

BIPV modules have not yet been able to achieve fire class A2 or A1 according NEN-EN 13501-1

Like mentioned in the quote, it is important to take into account that BIPV panels have not been able to reach fire class A2 according NEN-EN 13501-1 due to the presence of combustible foils (EVA or PVB), highlighting a crucial limitation in their fire safety classification. This discrepancy is particularly significant as manufacturers sometimes present their product as fire class A, implying fire class A according to UL 790, which can be misinterpreted as fire class A according to NEN-EN 13501-1 by unaware individuals.

However, with the upcoming new performance requirements in the Bbl of fire class A2 and the limitation of BIPV modules not being able to achieve fire class A2, there might be a hurdle for the BIPV modules not being allowed to be implemented anymore in these cases. The NPR 6999 also allows to validate the performance via ISO 13785-1, DIN 4102-20 or BS 8414 with performance criteria which are still to be determined. Thus, it might be possible that BIPV systems are not able to perform according those new criteria. However, it is currently unknown if BIPV systems will be able to meet these new criteria.

3.1.6 Regulatory framework fire safety BIPV façades in the Netherlands: gaps

Even though several codes and the Bbl prescribe standards for the fire safety of BIPV systems, a summary of some of the most critical gaps which are not properly addressed in the Dutch regulatory framework (Ko et al., 2023):

1 | **Test method adequacy |** The effectiveness and adequacy of current standard test methods for ensuring the fire safety of BIPV façade systems can be considered as questionable. There is a lack of published reviews confirming whether the application of existing codes and test methods, developed for conventional building materials, are adequate for assessing BIPV façade systems.

2 | **Lack of specific regulations |** The absence of dedicated codes or regulations addressing the fire risk associated with BIPV façade systems poses an concern. While building codes may be applicable for BIPV systems, such as NEN-EN 13501-1, the lack of specific codes tailored to these systems leaves a gap in ensuring comprehensive fire safety measures. This incomplete coverage highlights the need for a thorough regulatory review to address all aspects of fire safety specific to BIPV systems, ensuring comprehensive protection against fire hazards.

3 | **Fire detection and suppression |** Regulatory reviews should not only focus on structural fire safety but also on effective fire detection, suppression, and firefighting strategies tailored to BIPV façade fires. Currently, this is not the case, signifying a gap in the preparedness and response strategies necessary for handling potential emergencies involving these systems.

Intent	Risk	Related test methods	Related codes
Fire behaviour	Ignitability	· Direct flame (NEN-EN ISO 11925-2) · Radiant heat (**IEC 61730-2**)	NEN-EN 13501-1
	Combustibility	· Non-Combustibility test (NEN-EN ISO 1182)	NEN-EN 13501-1
	Flame spread and smoke production	· Direct flame (NEN-EN ISO 11925-2) · Smoke density tests · SBI test (NEN-EN 13823)	NEN-EN 13501-1
	Heat and smoke production	· Heat of Combustion test (NEN-EN ISO 1716) · Cone calorimeter tests · SBI test (NEN-EN 13823)	NEN-EN 13501-1
	Smoke toxicity	Not addressed	Not addressed
New ignition source in façade		Not addressed	Not addressed
Fire behaviour when electrically active		Not addressed	Not addressed
Fire suppression when electrically active		Not addressed	Not addressed
· Bold texts are codes which specifically adress BIPV systems			

Table 8: Material fire behaviour (reaction to fire tests). Source: Ko et al. (2023). Own edit

Table 8 provides an overview of fire tests and requirements outlined in current standards. Just like conventional building materials, NEN-EN 13501-1 is referred to by the Bbl for assessing the combustibility, heat, and smoke production of BIPV modules (Ko et al., 2023). However, there are several factors which are not addressed in this code and the directed testing methods.

1 | Ignition source | BIPV systems can potentially ignite fires anywhere in the façade where electrical components are installed, introducing internal ignition sources. Current testing methods fail to account for these unique ignition scenarios as they primarily utilize externally applied flames, which only represent external fire sources. Consequently, the unique scenarios are not adequately represented. To address this gap, new testing methods should be developed that specifically target the cavities with sources that represent typical BIPV ignitions where these components are situated, ensuring a more accurate assessment of BIPV façade systems.

2 | Electrically active testing | The current regulations and codes fail to account for the potential alteration in the burning characteristics of BIPV façades when the BIPV system is operational. When BIPV modules are electrically active, the temperature conditions of the module are higher in-situ opposed to when they are tested. Typical product specifications permit BIPV modules to reach a maximum surface temperature of 85°C and the cavity, if applied, to hit 65°C, the implications of these elevated temperatures extend beyond the individual module's performance during tests like the SBI-test. Particularly in applications where combustible materials like insulation or foils may be utilized, the increased temperatures might impact the fire performance of the entire façade construction. Although it is expected that these condition should not severely impact the outcome of the tests, it is still advised for this to be validated via research.

3 | Fire suppression | The issue of fire suppression concerning BIPV modules when electrically active remains unaddressed academically. The potential hazard of applying water-based suppressants to BIPV modules may escalate to electrical shocks (Yang et al., 2022; Olsø et al., 2023), given that BIPV strings can remain active up to 1000 Volts, posing a risk of fatal injury. However, due to the flow rate (m^3/s) of the suppression source, the risk of electric shock might be mitigated as the electrical current is likely to be dispersed or diluted in the water stream. This has been confirmed via interviews with DGMR and Soltech, however within the limits of this thesis, there was an inability to retrieve validating data on this matter. Therefore, further research is necessary to validate this.

4 | Toxic smoke | The risk of toxic smoke is present, yet no testing requirement addresses this concern. Smoke migration from BIPV systems within buildings, particularly critical for BIPV glazing, is possible. However, while toxic gases pose a direct threat to life safety, many countries do not incorporate smoke toxicity considerations into regulations due to a fire by definition always releasing toxic smoke. Nevertheless, it should be noted that the composition of smoke generated by BIPV systems could amplify health risks for occupants and firefighters and should therefore be researched. Although most smoke from exterior BIPV systems will dissipate outside, it can become a significant problem if the smoke enters the building.

In the Netherlands, the SBI test, as directed by NEN-EN 13501-1, is currently the only directed test method used for assessing façade configurations. However, although it is used to evaluate entire (BIPV) façade systems, the SBI test was not originally designed for such assessments. This limitation became particularly evident after the catastrophic Grenfell Tower fire in 2017, highlighting the test's insufficiency in providing a true reflection of overall façade fire performance (DGMR, 2018). In addition to the general shortcomings for BIPV and testing methods, the SBI test has the following shortcomings:

Ventilation | A naturally ventilated cavity in the façade significantly influences fire development. However, the SBI-test fails to consider this aspect as it positions the fire source in the corner against the exterior pane and does not attack a cavity directly. Consequently, the test overlooks specific fire behaviour within a ventilated cavity, limiting its ability to accurately assess fire resistance in such configurations. It is important to note that this limitation may not be critical if there are no ignition sources within the cavity or if the cavity is not accessible to flames from a fire compartment or from the outside. However, the presence of electrical components within the cavity makes this aspect highly relevant and necessitates careful consideration in BIPV fire safety assessments.

Fire source | The SBI-test inadequately addresses the significance of a fire load because it focuses solely on the initial fire phase, represented by a 30 kW burner. For a façade, a small exterior ignition source is not a relevant scenario. Instead, a fully developed compartment fire breaking through a window, with external flames generating several megawatts of thermal power, poses a more realistic threat. Consequently, the SBI-test fails to capture the full potential of fire propagation under these conditions.

Set-up scale | The SBI test fails to account for the importance of set-up scale because it does not replicate end-use conditions accurately, particularly regarding factors such as ventilation, surface airflow, and thermal deformation of the construction elements. Additionally, although adequate for evaluating individual modules, this method falls short in end-use applications, especially due to the test's size limitations. For example, the SBI test allows a maximum protrusion of only 200 mm, which is restrictive for façades incorporating overhangs or cantilevers.

Connections | The dimension of the SBI test are limited, preventing the examination of critical connections to surrounding construction elements such as window/door frames and corners/ transitions to other façade constructions. Since these connections are critical trajectories for fire propagation in façades, the inability to test them poses a limitation.

To address the above-mentioned limitations, the introduction of NPR 6999 in the Netherlands will enhance the testing possibilities. For instance, ISO 13785-1 offers a practical intermediary solution as it bridges the gap between the limited SBI test and the more extensive, costly alternatives such as DIN 4102-20 or BS 8414, thus allowing for a balanced and effective evaluation of fire safety. However, it should be noted that these methods do not represent the unique ignition source of BIPV systems.

3.1.7 Regulatory framework fire safety BIPV façades in the Netherlands: quality installation

In the Netherlands, the quality of installation of BIPV façade systems is not covered by statutory regulations, with no prospect of becoming mandatory soon. Despite this, the industry has developed voluntary schemes like InstallQ and SCOPE12 to address these gaps, as detailed in 4.2.2 Fault tree analysis: ignition scenarios. These schemes indicate a proactive approach within the industry to enhance safety and reliability, emphasizing the importance of quality assurance in the growing market of solar energy integration in buildings.

Insurance companies also play a critical role, often requiring compliance with these voluntary schemes before offering coverage for buildings with BIPV installations. This ensures that PV systems are installed to high standards, reducing the likelihood of fire incidents and mitigating risks.

In Belgium, there is a statutory quality system for the electrical installation of PV systems known as Algemeen Reglement op de Elektrische Installaties (AREI). AREI focuses on ensuring that all electrical installations meet specific safety and performance standards. If a PV system does not comply with these standards, the network operator will not provide electricity to the property.

4

BIPV Façade Fire Risks

4.1 Risk analysis

Delving into the realm of risks and fire safety, this chapter explores the concepts of risk and hazard, as well as the methodologies for risk analysis within the context of BIPV systems. The rationale behind conducting a risk analysis within this research is elaborated on, emphasizing the importance of comprehensively assessing the safety implications of BIPV systems in built environments. Furthermore, this chapter will elaborate on the chosen method for risk analysis, setting the stage for the detailed analysis in the subsequent section.

4.1.1 Risks and fire safety

Risk refers to the potential for loss (injury, damage, detriment, etc.) resulting from exposure to one or multiple hazards (Figure 42). The significance of risk is determined by both the probability of an undesirable event occurring and the severity of its consequences (Reniers en Meyer, 2022). As the definitions of risks and hazards are sometimes used interchangeably, the definition of the concepts should be considered as:

> *"A **hazard** involves the possibility of a human, machine, equipment, process, material, or physical factor to lead to an undesired event that could cause harm to people, the environment, assets, or production. In essence, it signifies a condition or situation that could lead to a loss. For instance, in the context of BIPV systems, the system being a potential ignition source constitutes a hazard."*
>
> *"A **risk** involves the possibility of experiencing loss, such as injury, damage, or detriment, due to exposure to hazards. It quantifies the probability of an undesirable event occurring and the severity of its consequences. In the case of a BIPV system, the risk might entail the probability of the system igniting and causing a degrees of damage to the building or its occupants."*
>
> *- Reniers en Meyer (2022) -*

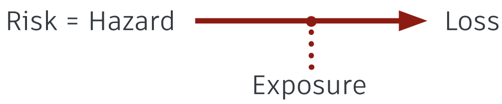


Figure 42: Risk diagram. Source: Reniers en Meyer (2022). Own edit

Risks symbolize a method to address uncertainty (Hagen & Witloks, 2018). We are constantly exposed to risks, willingly or unwillingly, and are not always aware of them. However, we can choose which risks to accept based on personal decisions, underscoring the subjective nature of risk assessment. Understanding existing risks is crucial for making well-informed decisions. In fire safety, engineers address uninformed risks for building users, ensuring measures are in place to mitigate potential hazards and protect occupants and property. For engineers, these are known risks, highlighting the difference in perspective and responsibility between designers and inhabitants (Hagen & Witloks, 2018).

In an attempt to quantify risk, the simple method of assessment relies on the risk neutral function:

Risk = probability * severity

Or in the realm of fire safety, a more detailed risk neutral formula can also be utilized:

Risk = probability of fire occurrence * probability of fire development * severity of potential damage

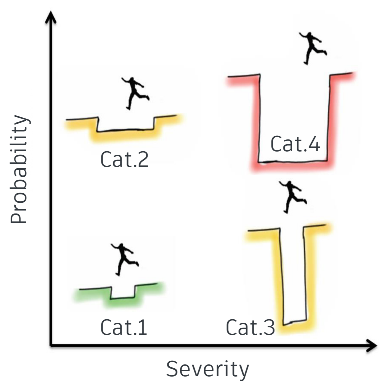


Figure 43: Schematic classification categories risk matrix. Source: Reniers en Meyer (2022). Own edit

Figure 43 showcases the different classification categories resulting from the standard risk function, divided into four categories. Categories 2 and 3 involve balancing the probability against the negative impact of fire, transitioning from unacceptable risks (Cat. 4) to acceptable risks (Cat 1). Organizations often accept higher risks for potential benefits, prompting risk reduction strategies in R2 and R3 situations. Real-world risk assessment lacks clear boundaries where quantitative data is absent.

> *"To provide meaningful insights, it is essential to clearly define and establish the boundaries between these risk categories. Without such definitions, the categorization lacks practical value and can lead to inconsistencies in risk management strategies"*

Achieving zero risk in fire safety is unattainable due to the multifaceted nature of (fire) safety measures. This emphasizes that absolute safety is unreachable and that some level of risk must always be accepted. Instead, the focus should be on minimizing risks to socially acceptable levels, highlighting the subjective nature of risk (Hagen & Witloks, 2018). This necessity to accept a minimum level of risk is universal across all areas, making it a fundamental aspect of risk management.

4.1.2 Risk analysis method possibilities

Within the field of risk engineering, risk analysis methods exist to systematically assess risk and mitigate potential hazards. Presently, there are many risk analysis methods available, exceeding a hundred in literature. These methods typically consist of identifying initiating events (causes), potential consequences, safeguards, and recommendations. The primary difference among these techniques lies in their approaches to identifying causes or consequences. Empirical studies highlight the most prominent techniques include hazard and operability studies (HAZOP), failure mode and effects analysis (FMEA), or failure mode, effects and criticality analysis (FMECA), what-if analysis and the risk matrix (Reniers en Meyer, 2022). Figure 44 highlights some of the methods that can be used and for what purpose.

Techniques	Procedure	Advantages	Disadvantages
FMECA	Examine whether components or process can have some failures	Good for equipment, mechanic systems	Little attention given to human factors Does not estimate cost of failure
HAZOP	Use the nodes of industrial plants to search for deviations from designed intent	Improve chemical process and operability	Time-consuming Experienced team leader required
ETA	Structuring cause back to the consequences	Quantitative with graphic tool Good for technology performing	Cannot analyze multiples failures
FTA	Structuring consequence back to the causes	Reveals the main causes of failure Give graphical view	Problem of reliability when data are minimized
RADM	Combining probability and severity of hazard. Determining a risk priority number	Graphical tool. Good relation between probability and severity ranking risks	Inadequate if there are many risks Cannot be used to deduce causes and consequences
PHA	Ask questions about potential failure, fault	Prioritize recommendations	Cannot be used to find details concerning a hazard
What-if	Checks for potential hazards by posing "What-if" questions	Very fast in searching for consequences	Cannot determine causes Very basic
Checklist	Use a list of hazards to record consequences and safety actions	Useful to have an overview of the hazards list	Much time required to find a hazards list
HRA	Evaluates human–machine interface, carry out task analysis.	Can help reducing human errors by improving performance shaping factors	Much time required if there are a lot of personnel

Figure 44: Risk analysis methods Source: Reniers & Meyer (2022)

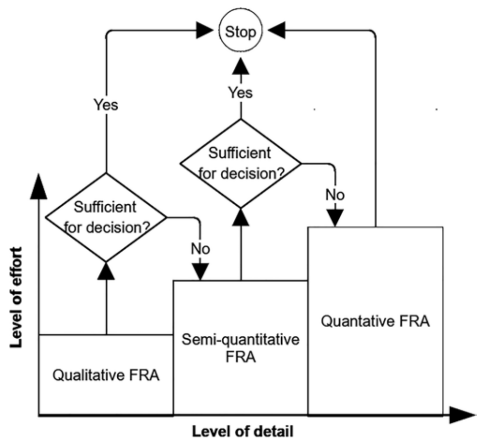


Figure 45: Qualitative and quantitative approach. Source: Reniers en Meyer (2022)

Subsequently, when performing a risk analysis, it can be executed according to different approaches. Depending on the desired level of detail and effort, a decision can be made, as shown in Figure 45

Qualitative approach | Probability and consequences are assessed purely on a qualitative basis, focusing on descriptive analysis rather than numerical data, allowing for a comprehensive understanding of risks without precise quantification.

Quantitative approach | Both probability and consequences are entirely measured numerically, providing precise and quantifiable assessments of risk, which enables statistical analysis and comparisons across different scenarios.

Semi-quantitative / semi-qualitative approach | Probability and consequences are partially quantified within predefined boundaries, balancing qualitative and quantitative approaches, allowing for structured analysis while retaining some subjectivity or uncertainty

4.1.3 Risk analysis method choice

Qualitative RA | A qualitative approach for the risk analysis is employed due to several reasons. Firstly, statistical data on fires in the built environment is scarce, especially for BIPV systems on façades. Given this lack of data, a qualitative approach allows for a thorough risk assessment based on reasoning rather than statistical evidence. Additionally, the primary goal of this study is to comprehensively identify and assess all potential risks associated with BIPV systems. This approach provides the flexibility to explore various risk scenarios and contextual factors without precise quantification, ensuring a comprehensive assessment while acknowledging the limitations of available data

Fault tree analysis | Choosing a suitable risk analysis method is crucial for analysing the diverse contexts in which BIPV systems are implemented. A fault tree analysis (FTA) is employed due to its ability to systematically analyse the interdependencies of specific events, which is essential for fire safety. An FTA systematically traces back potential fire causes through logical gates and events, allowing for the identification of critical pathways and root causes of fire risks. Additionally, FTA offers a structured framework for documenting and visually communicating risk assessment findings, enhancing transparency and facilitating informed decision-making by stakeholders involved in BIPV system design and implementation.

No evaluation criteria | Although methods such as HAZOP, FME(C)A, what-if analysis, or risk matrix could also be suitable, they are tailored for specific contexts and may lack the comprehensive analysis required for examining the interdependencies in fire risks associated with BIPV systems. Unlike these methods, an FTA does not directly apply evaluation criteria (risk = probability * severity) to identify critical events, which might seem like a drawback. Direct application of such criteria allows for straightforward identification of critical events based on their likelihood and severity. However, given the varied nature of fire risks associated with BIPV systems—affected by factors like building design, materials, and environmental conditions—applying evaluation criteria universally is impractical. Thus, while FTA may not directly apply evaluation criteria, its adaptability and ability to analyse interdependencies make it well-suited for assessing the complex fire risks associated with BIPV systems.

Input data sources | The data for the risk analysis will be sourced through expert consultations with DGMR professionals which are specialized in façade fire safety and BAPV systems on roofs. Additionally, academic literature on BIPV fire safety on façades will be reviewed. Given the scarcity of studies specifically focused on BIPV systems on façades, relevant information from research on BIPV and BAPV fire safety on roofs will be adapted and translated to the new context of façades.

4.2 Fault tree analysis

This chapter explores the application of Fault Tree Analysis (FTA) as the chosen method for risk assessment in BIPV façade systems. FTA offers a systematic and structured approach to identifying the underlying events, conditions, and scenarios that could lead to fire incidents. By deconstructing the system into its fundamental components and tracing back to root causes, the FTA provides an understanding of the risk landscape. This method highlights failure modes, explains why BIPV façades present high risks, and identifies critical fire trajectories. Moreover, it informs the development of effective mitigation strategies, laying the foundation for the design support tool.

4.2.1 Fault tree analysis: setup

As prescribed in the previous chapter, the fault tree analysis (FTA) has been selected as the method for conducting the risk analysis. When constructing the FTA tree with events, scenarios, conditions, causes and logical gates, the following rules have been applied:

Rule 1: General event analysis | Given the diverse contexts in which BIPV systems are employed, defining events that apply universally ensures the analysis remains applicable across all applications. This approach identifies risk factors and underlying causes that may vary across specific scenarios, uncovering overarching patterns and trends. By focusing on general events, the analysis provides a foundational knowledge base that can be applied to other divergent situations.

Rule 2: BIPV focus | The FTA focuses solely on "new" scenarios or existing scenarios impacted by BIPV systems. This approach allows for efficient focussing, optimizing risk management efforts. By excluding scenarios unaffected by BIPV systems, the analysis remains relevant and concise, avoiding dilution of focus on risks not directly influenced by the technology. This is assumed to be known knowledge within the field of fire safety.

Table 9 shows an overview of all the different types of symbols which are used in the FTA tree. Subsequently, with these symbols, the FTA tree has been made according the following steps:

1 | **Identifying the top event |** As defined by the standard FTA method, every fault tree starts with identifying the undesired event or outcome that is of concern (Reniers en Meyer, 2022). This event is referred to as the "top event" and represents the ultimate failure or incident that is being analysed.

2 | **Breaking down the top event |** Once the top event had been identified, the fault tree was constructed by systematically breaking it down into sub-events. These sub-events are represented by events/conditions that could lead to the occurrence of the top event, as defined by the standard FTA method (Reniers en Meyer, 2022). To enhance the clarity of this analysis, additional distinctions were incorporated: ignition scenarios, fire trajectories, and standard events or conditions. These categories are further detailed in Table 12.

3 | **Tracing back to root causes |** The fault tree was then constructed by tracing back from the top event through logical gates and events to identify the root causes. This process helped to systematically identify all the potential ways in which the top event could occur.

4 | **Analysis and mitigation |** Once the fault tree was constructed, it could be analysed to identify critical pathways or combinations of events that are most likely to lead to the top event. This information could then be used to prioritize mitigation efforts and develop strategies for reducing the likelihood or severity of the undesired event in the next chapter.

The findings of the FTA will serve as the foundation for developing the risk parameters of the design support tool and the advice on measures. In this chapter, sections will be marked to indicate their relevance to specific risk parameters or measures. For instance, text marked with [12] corresponds to risk parameter 12. An overview of the final risk parameters is shown in Figure 67. Paragraphs marked with [M] indicate that the information is integrated as a measure and not as a risk parameter.

FTA symbol type	Elaboration	Symbol
Top events	The basis of an FTA tree starts with a top event. A top event represents the undesirable outcome or incident being analysed in the fault tree. It is the starting point for tracing back contributing factors and causes	Vertical fire spread over multiple fire compartments
Events/conditions	Events or conditions within the FTA tree are prerequisites for top events, ignition scenarios or fire scenarios to occur.	Fire inside cavity
Ignition scenarios	Ignition scenarios are a specific type of event/condition. This differentiation is added to distinguish between the ignition of fire and the subsequent development of fire, which are defined by fire scenarios. Ignition scenarios focus on identifying events or conditions that lead to the initial ignition of a fire.	**Ignition scenario 1.1:** Fire started from BIPV system itself (outdoors)
Fire trajectory	Fire trajectory encompass the possible trajectories of fire development. They outline the various stages and manifestations of a fire event. However, they exclude factors such as intensity and duration, as these aspects cannot be defined without contextual information.	**Fire scenario A:** Fire spreads from indoor source to BIPV facade
Conventional events/conditions	These events or conditions are assumed to be well-known within the field of fire safety and are not further analysed here to keep the study focused.	"Conventional" flammable facade material (adjacent to cavity)
Causes	Causes in an FTA tree represent the factors or events that directly contribute to the occurrence of an event or condition. They are identified as the root or underlying reasons behind the occurrence of the top event or subsequent events	Soldered points scorched
AND gate	AND gates represent conditions that must all occur simultaneously for the (top) event to happen	AND
OR gate	OR gates represent alternative paths or combinations of conditions that could lead to the (top) event.	OR

Table 9: FTA event types overview. Own work

4.2.2 Fault tree analysis: ignition scenarios

Appendix I provides an overview of all FTA diagrams created for this analysis, as not all are included in the report. Also, for clearer views of the small images, please refer to the appendix.

By integrating BIPV systems into the façade, new fire ignition sources arise that were previously unknown for façades. Unlike conventional façades, which could house electrical systems like mechanical louvres or lighting fixtures, BIPV systems introduce an electrical element with a much higher risk due the multitude of high current electrical connections in the system and by operating on DC current opposed to AC current (Yang et al., 2022). Therefore, the FTA tree commences by examining potential ignition scenarios. This step is important as it establishes the foundational events leading to fire incidents involving BIPV systems.

Recognizing that BIPV components are situated in many different places of a building, ignition scenarios were grouped into three distinct groups (Figure 55). These classifications were roughly determined by the various propagation pathways of a potential fire: fires originating directly from the BIPV systems—whether occurring outdoors, indoors, or within the façade or cavity of the building itself. Subsequently all electrical components were considered as potential sources and linked to the ignition group according to where they could potentially be placed. It is important to clarify that Figure 55 does not imply a hierarchy of criticality among the ignition scenarios; it does not suggest that the scenarios at the top are the most critical.

Appendix I provides an more extensive overview of Figure 55 with added potential causes for each ignition scenario. It should be noted that in reality there are more causes which can lead to a potential ignition scenario, but main causes provided in Appendix I are derived from the extensive study of TUV Rheinland & Fraunhofer-Institut (2018) and through experts consultations.

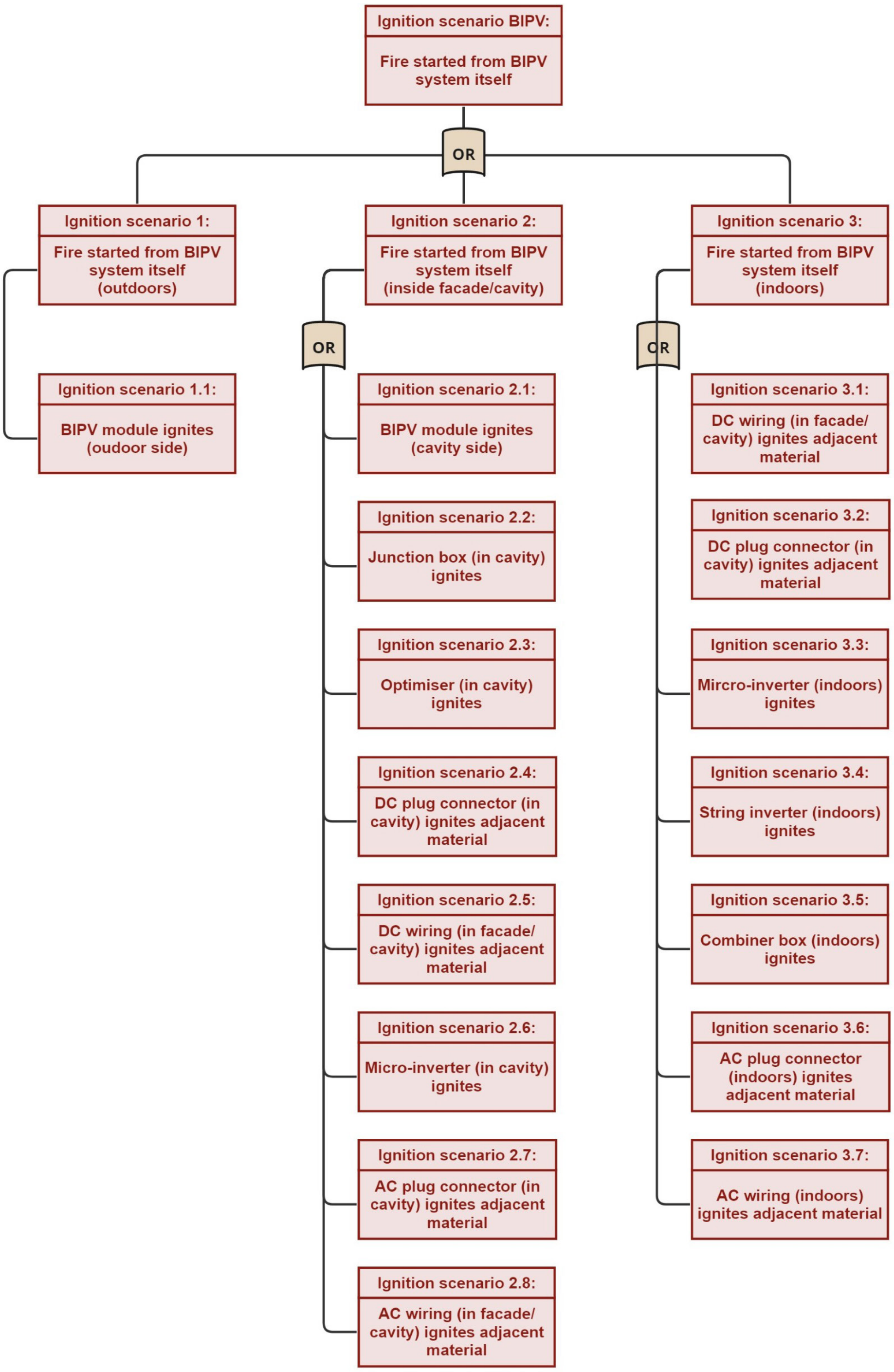


Figure 55: FTA BIPV ignition scenarios (1-3) (Fire started from BIPV system itself). Own work

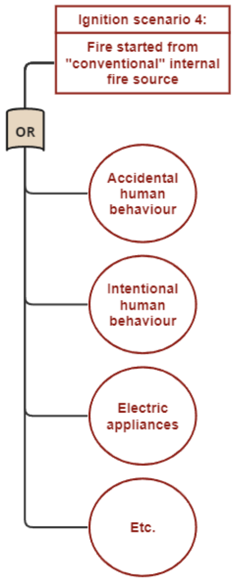


Figure 56: FTA ignition scenario 4 (Fire started from "conventional" internal fire source). Own work

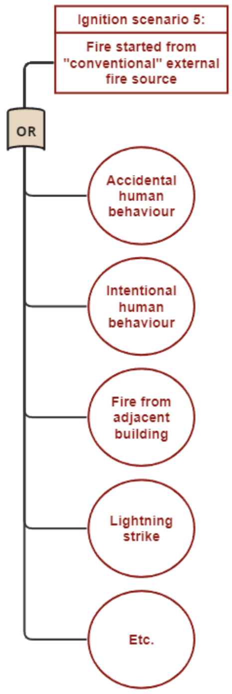


Figure 57: FTA ignition scenario 5 (Fire started from "conventional" external fire source). Own work

Figure 56 shows ignition scenario 4 (Fire started from "conventional" internal fire source) and Figure 57 shows ignition scenario 5 (Fire started from "conventional" external fire source). To maintain the specificity and focus of this risk analysis on BIPV-related scenarios, as implied by rule 2, these particular scenarios will not been explored in extensive detail. Instead, their potential impact is acknowledged and considered within the broader context of the study, ensuring that the analysis remains aligned with its primary objective of examining risks specifically associated with BIPV systems.

4.2.3 Fault tree analysis: ignition scenarios (general)

The TUV Rheinland & Fraunhofer-Institut (2018) study will be frequently referenced in this section, as it represents the most comprehensive research available on PV systems to date. Although the study specifically investigated PV systems on roofs, the electrical operation of PV systems on both roofs and façades is nearly identical. This similarity allows for the extrapolation of risk considerations to BIPV systems on façades.

Some general findings of ignition scenarios of high criticality from the FTA will be now be discussed. These findings concern key ignition scenarios or involve multiple components integral to fire safety in BIPV systems. By focusing on these pivotal areas, the goals is to shed a light on the most pressing risks that significantly impact the safety and functionality of BIPV installations.

Electric arcs [18,20] **|** An arc is an electrical discharge that occurs when a strong current passes through an air gap between two conductors (IEC TR 63226:2021). This discharge can generate intense heat of several 1000 ° C in standard (BI)PV systems. However, an arc does not automatically ignite a fire; the presence of combustible materials nearby is critical. This is especially relevant when electrical components are near combustible materials like foils or insulation, emphasizing the importance of careful material selection and placement.

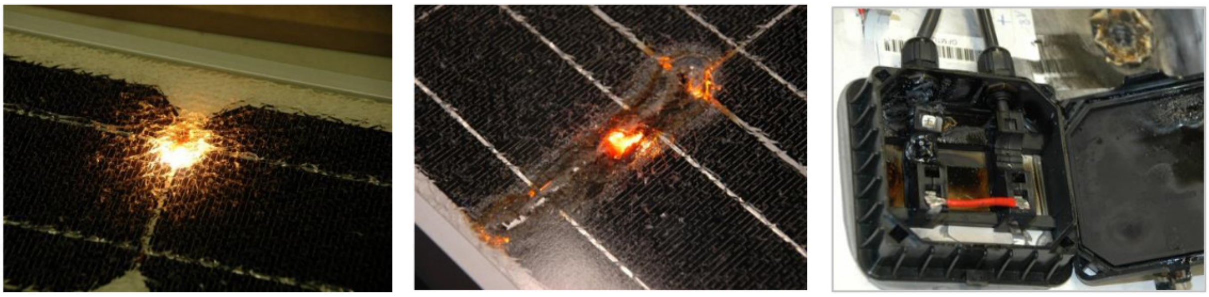


Figure 46: Electric arcs in PV modules. Source: TUV Rheinland & Fraunhofer-Institut (2018)

Electric arcs are the biggest risk for PV systems (Aram et al., 2021), potentially occurring in all electrical connections and components of the system. Both serial and parallel arcs can form throughout a BIPV system (Figure 47). The impact differs between AC and DC circuits; DC arcs are more problematic due to their stability and longer duration, increasing their fire risk. BIPV modules produce DC current, converted to AC by (micro) inverters. Components between the BIPV modules and inverters are DC, posing a higher risk for electric arcs, while post-inverter components are AC, presenting a lower but still significant risk.

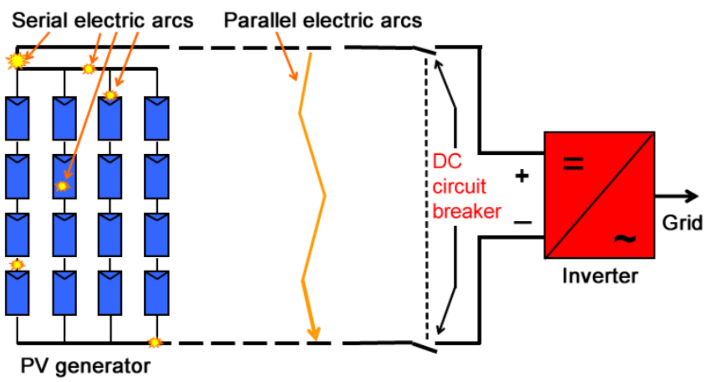


Figure 47: Serial and parallel electric arcs in PV systems. Source: TUV Rheinland & Fraunhofer-Institut (2018)

Voltage levels also affect arc potential. At lower voltages (around 70 volts), arcs are unlikely and harmless. However, at typical BIPV voltages (up to 1000 volts), arcs generate significant energy and heat, increasing their ignition potential.

Factors such as improper installation, product faults, or component deterioration can cause electric arcs (Yang et al., 2023). Thus, BIPV system design and maintenance must prevent arcs, especially near flammable façade materials. NEN 1010 and SCOPE12 guidelines address arc management via installation practices and arc-fault circuit interrupters (AFCIs), but not the presence of combustible materials, necessitating extra caution.

AFCIs are highly effective in detecting and interrupting serial arcs, but their reliability is not absolute. Frequent false positives, which require manual inspection and resetting by expert personnel, hinder widespread adoption of AFCIs. Despite their efficacy, AFCIs are not mandatory in PV installations in the Netherlands and the EU, unlike in the US. This discrepancy underscores the need for careful consideration and stricter regulations to enhance safety in PV installations

AC / DC current [16] | TUV Rheinland & Fraunhofer-Institut(2018) investigated 210 fire incidents involving PV systems on building roofs (BAPV) and found that the majority of fire accidents originated from the DC section, with the primary components of PV systems (PV modules and inverters) being implicated in half of these incidents (Figure 48). The AC section accounted for the fewest fires. This underscores that DC components collaboratively present a higher fire risk compared to the AC components, which also aligns with the higher risk of DC arcs compared to AC arcs as explained in the previous bulletpoint.

Translating the fire rates of BAPV roof components (Figure 48) to a BIPV façade context, it is likely that there will be an increase in component failures within the façade cavity. This is due to the heightened exposure to elevated temperatures and limited accessibility for maintenance and inspection. Components such as junction boxes, optimisers, micro-inverters, plug connectors, and wiring (AC/DC) are particularly vulnerable under these conditions.

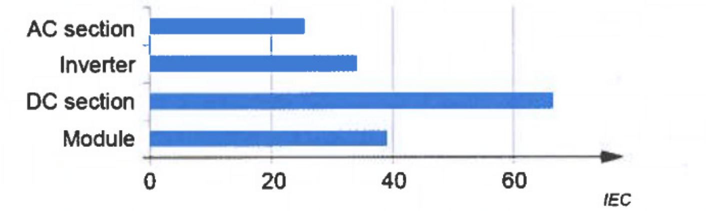


Figure 48: Components where fire started (PV). Source: TUV Rheinland & Fraunhofer-Institut (2018)

Hot-spot [M] | Hot-spot events in BIPV modules are identified as the secondairy major risk in BIPV systems (Cancelliere, 2016). A hot-spot occurs when PV cells experience an excessive increase in temperature due to faults like partial shading, short circuits, and increased ohmic resistance, often caused by material defects, manufacturing faults, or natural degradation (Aram et al., 2021). To mitigate these risks, it is essential to optimize the layout to avoid shading, select high-quality modules, and implement regular IR monitoring and maintenance to detect and address potential hot-spots before they become serious hazards.

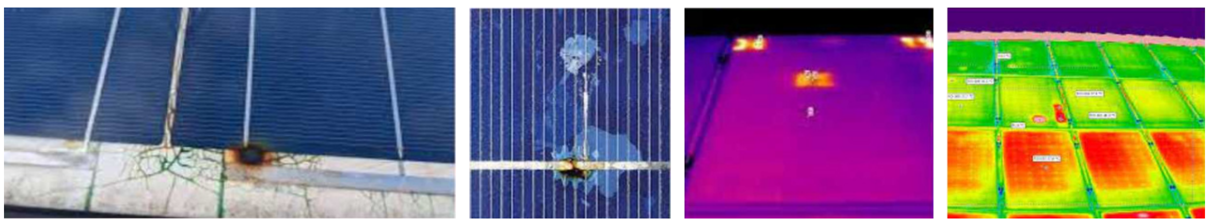
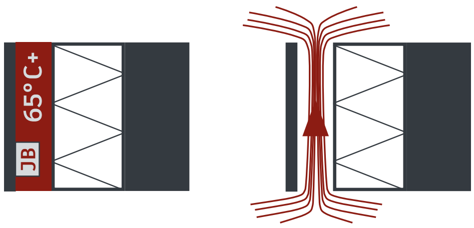


Figure 49: Hot-spot consequences in PV. Source: Sojitra (2023)

Ventilated cavity [19] | Ventilated cavities in façades pose high fire propagation risks due to the chimney effect, which accelerates fire spread in the cavity. These cavities have openings to the outside air, allowing flames to enter and exit, potentially reaching the building's interior at higher levels. The size and placement of these openings are critical for fire spread. Inside the cavity, fire spread is influenced by the material characteristics of the surfaces, the support structure of the outer layer, and the draft within the cavity (DGMR, 2018). More details on this are provided in fire trajectory E in the next sub-chapter.

The risk of fire propagation in ventilated cavities is amplified in façades with BIPV systems due to elevated cavity temperatures. BIPV systems generate heat during energy conversion, with modules reaching surface temperatures up to 85°C and cavity temperatures up to 65°C. In real-world applications, these limits are often exceeded. Increased cavity temperatures pose two main risks in BIPV façades. First, the elevated temperatures strain electrical components, accelerating wear and increasing the risk of electrical failures. Second, higher temperatures reduce BIPV module efficiency by about 2-3% for every 10°C increase.

To mitigate these risks and lower façade cavity temperatures, increasing airflow through the cavity is essential. For example, his can be achieved by maximizing cavity openings to outdoor air or increasing the cavity depth. Reduced cavity temperatures enhance fire safety and improve system performance through better cooling. Therefore, careful design consideration of temperature management and component selection is crucial in BIPV façades.



Derating [M] **|** Optimisers and (micro)-inverters can have a derating option. This function involves operating the component at lower power levels than their maximum capacity when high temperatures are detected, thus reducing the temperature and mitigating the risk of overheating and electrical faults. This precaution ensures the component operates safely within its thermal limits, further enhancing fire safety. However, it limits the energy generation efficiency. Thus, when employing derating components in a façade cavity with elevated temperatures, the energy generation efficiency is significantly affected.

Inspection of components [16] **|** Inspection of components plays a pivotal role in ensuring the safety and longevity of any electrical system. Regular inspections help identify potential issues, such as wear and tear, defects, or improper installations, before they can lead to system failure or hazardous conditions. However, the unique challenge with BIPV systems integrated into façades lies in the accessibility of these components for inspection. Often embedded within the façade structure or located in hard-to-reach areas, these components may not be easily accessible for routine checks. This lack of accessibility complicates maintenance efforts and increases the risk of undetected issues persisting until they contribute to system failure or safety hazards. Therefore, designing systems with inspection, maintenance, and accessibility in mind is crucial.

Replacement of components [16] **|** Components in BIPV systems can fail before the end of their expected lifetime due to various issues such as damage or wear. While manufacturers may claim a 50-year lifespan for BIPV modules, this is not always realistic. In practice, the actual lifespan can be shorter, necessitating replacement before the end of the building façade's lifespan. Smaller electrical components, like junction boxes, typically have a much shorter lifespan, estimated at around 20 years, far less than that of the façade.

Easy removability is crucial for effective maintenance and replacement of components. This is highly dependent on the mounting system used. If the mounting structure and BIPV module are connected with a glued bond, it can make removal extremely challenging, if not impossible, without damaging the module or the façade. Therefore, designing BIPV systems with removable components is essential to ensure they can be maintained and replaced as needed, thus safeguarding the system's functionality and safety over its intended lifespan.

Quality control [23] **|** The Netherlands has quality schemes like SCIOS Scope 12 and InstallQ to ensure the safety and reliability of (BI)PV installations. The main difference between quality of installation scheme InstallQ and quality inspection scheme SCIOS Scope 12 lies in their focus (Table 10). InstallQ adresses the competence and processes of installers from the (e-)design phase through to installation, ensuring high-quality workmanship and adherence to safety standards. SCIOS Scope 12 focuses on the post-installation phase, providing retrospective inspections to verify the safety and performance of the completed systems.

InstallQ | Ensures that certified installation companies and advisors are well-known in relevant regulations and guidelines, applying them safely and effectively in practice. These professionals can provide legally valid documents such as energy labels and tailored advice and can guarantee the quality of installation, replacement, or maintenance of systems. InstallQ regularly evaluates and monitors these companies through inspections by InstallQ inspectors or certifying institutions.

Scope12 | A detailed inspection of PV installations to verify safety and compliance with manufacturer guidelines and applicable standards. This includes for example ensuring proper insulation, adequate fuses and protective equipment to prevent overloads, and regular maintenance to uphold safety throughout the installation's lifespan. Additionally, Scope 12 inspections address points such as reviewing drawings and documents, verifying electrical equipment compliance, conducting visual inspections, measuring current and voltage, and performing thermographic analysis (including drone inspections and data analysis).

While quality installation by accredited installers minimizes installation errors, it does not fully eliminate them, as mistakes can always occur. Therefore, independent quality inspection is of high value, ensuring an additional layer of safety and reliability.

	installQ aantoonbaar beter	SCIOS GECERTIFICEERD SCIOS INSPECTIES SCOPE 8,10 & 12
Scope	Professional competence of installers	Retrospective inspection of existing installations
Systems	BIPV & BAPV	BIPV & BAPV
When relevant	During and before installation	After installation
Initiated By	Techniek Nederland, Holland Solar and Verbond van Verzekeraars	Verbond van Verzekeraars, Holland Solar and various inspection companies, represented by trade organizations such as iKeur and Techniek Nederland.
Regulatory status	Non-statuary	Non-statuary
Accredited companies	*https://www.echteinstallateur.nl/*	*https://www.scios.nl/relatie/*

Table 10: InstallQ and SCOPE12 comparison. Own work

Causes of faults [23, M] | The ignition scenarios presented in Figure 55 (Appendix I) arise from a variety of causes, each contributing to the potential onset of these scenarios. Figure 50 reveals that the majority of incidents investigated in TUV Rheinland & Fraunhofer-Institut (2018) were the result of installation errors or product defects, with planning/design faults and external influences having a lesser impact.

Translating this to a BIPV façade context, it is likely that there will be an increase in product defects due to the difficulty of inspecting components once installed. Conversely, there may be a decrease in installation faults as BIPV façade installations typically are installed by more highly skilled workers than roof systems, leading to better initial setup and fewer errors during installation. This shift underscores the importance of quality control and robust inspection protocols to mitigate the risk of defects that cannot be easily detected post-installation.

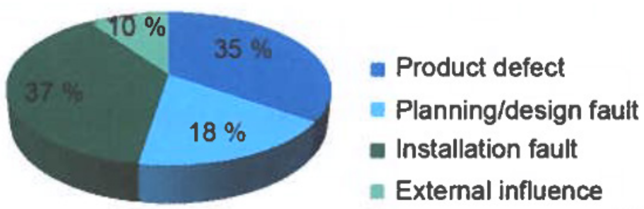


Figure 50: Causes of fire incidents PV. Source: TUV Rheinland & Fraunhofer-Institut (2018)

Animals M **|** Animals can significantly impact BIPV façade systems. Birds, rodents, and insects may nest in or around the modules, bringing in combustible materials in the cavity. They can also chew on cables or block ventilation gaps, leading to overheating. Bird droppings can obscure solar cells, reducing their efficiency. Regular maintenance and protective measures, such as employing cavity opening barriers (e.g. bee beaks) and securing cable pathways, are essential to minimize these risks.

Wind and vibrations M **|** Wind and deformations in façades can cause movements and vibrations. These forces can lead to the loosening of connections and cable transitions, potentially causing electrical faults or system failures. Vibrations might also cause wear and tear on the modules and mounting structures, reducing their lifespan. Regular inspections and robust design considerations, such as securing cable transitions and ensuring strong connections, are essential to mitigate these risks.

4.2.4 Fault tree analysis: ignition scenarios (components)

An overview of the main findings of the ignition scenarios per component as a result of the FTA analysis:

BIPV module [13] **|** BIPV modules vary widely in materials and layers, influencing their functionality, durability, and efficiency. The main types are glass/glass and glass/polymer, with glass/copper being less common (Figure 52).

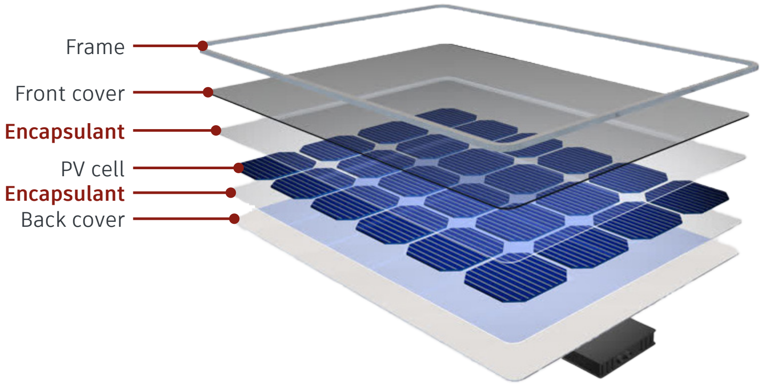


Figure 51: (BI)PV Module components . Source: Sauer (2021). Own edit

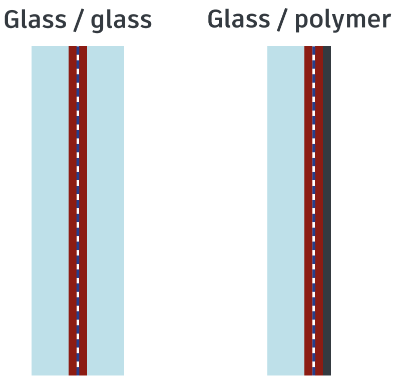


Figure 52: Typical (BI)PV module configurations. Own work

BIPV module config.	Glass / glass	Glass / polymer
Front cover	Glass (non-combustible)	Glass
Encapsulants	PVB or EVA **(combustible)**	PVB or EVA **(combustible)**
Back cover	Glass (non-combustible)	Polymer **(combustible)**
Fire risk	Low	High
Quality	Higher-end	Lower-end
Structural Rigidity	High	Low
Durability	High	Moderate
Main application	Façade	Roof

Table 11: Glass/glass & glass/polymer module characteristics. Own work

The FTA analysis found arcing and hot-spot as significant failure causes within BIPV modules as they have the potential to initiate combustion. Arcing in modules often results from deteriorating connections, but even without visible arcing, poor connections can also lead to fires. Specifically, the ignition can occur through the EVA or PVB foils encapsulated within the module (Figure 51), which are combustible materials. The calorific value of PVB is 30 MJ/kg and that of EVA is 40 MJ/kg (Glass for Europe, 2015). Although these encapsulant layers are relatively thin, ranging from 0.7 mm to 1.0 mm, they can significantly contribute to a fire due to their high calorific values.

While a glass pane is non-combustible, a polymer pane is combustible, which significantly enhances the risk of fire spreading beyond the initial internal hot-spot or arcing incident, where the localized heat can easily compromise the integrity of the polymeric backsheet. Consequently, this can lead to a rapid escalation of the fire, potentially affecting adjacent materials and mounting structures. This works also the other way around. If a fire originates within the cavity and spreads across the backsheet, a polymeric pane fails significantly quicker compared to a glass panes. This would allow the EVA or PVB encapsulant to contribute to the cavity fire. Thus, employing glass/glass (or glass/copper) modules greatly reduces the risk of fire spread both from and to the BIPV modules. Regular inspections and maintenance to check for any signs of damage or degradation in the modules are also crucial in preventing potential fire incidents.

Junction box [20, M] | Junction boxes are always situated on the back of an BIPV module in the cavity of a façade, where they are exposed to considerable risk due to elevated temperatures and the potential for electric arcs, and subsequent fire development.

In traditional BAPV systems on roofs, junction boxes already presented a significant risk of overheating, often caused by the failure of bypass diodes. This risk is further heightened in façade applications, where the ambient temperatures within cavities typically exceed those experienced on roofs. Given their polymeric composition, junction boxes are particularly susceptible to ignition from electric arcs. While the junction box itself contains a limited amount of flammable material, posing a minimal danger individually, the real threat arises from its potential to propagate fire spread to other combustible materials within the façade.

Therefore, the adoption of good joining technologies is crucial to minimize the risks of overheating and electrical arcing. According to TUV Rheinland & Fraunhofer-Institut (2018), it is essential to consider factors such as corrosion resistance, effective heat dissipation, material selection, and overvoltage protection when choosing junction boxes for BIPV modules. For example, employing a bypass diode rated at 15 A, while the junction box can handle 30 A, decreases the likelihood of overheating and subsequent fire hazards.

Optimiser [20] | Optimisers, if applied, are mainly placed in the cavity of the façade behind the BIPV module. These electronic devices are susceptible to electrical faults that can generate arcs. Just like junction boxes, the location in the cavity makes them particularly vulnerable to overheating and electrical faults as they are not designed to operate in high temperature conditions. Thus, if situated near combustible materials in the façades, there is an high change a fire might develop from this arc. This scenario the use of fire-resistant materials around these devices.

DC / AC plug connector [23, M] | Plug connectors are common components in BIPV systems, serving as links between all electrical components. Their widespread use also heightens their risk profile. Factors such as mismatched plug types, low-quality plugs, improper installation, environmental conditions, crimping can lead to scorching and, ultimately, the generation of electric arcs (TUV Rheinland et al., 2018). Thus, ensuring the use of high-quality, heat-resistant connectors and adhering to installation standards of NEN 1010 are essential, especially for DC plug, which pose an higher risk than AC plug. Additionally SCOPE12 cover proper plug installation requirements

DC / AC wiring [23, M] | Electric arcs in wiring can arise due to a variety of factors, including mechanical damage, insulation flaws, and adverse environmental conditions. These arcs may manifest in two forms: serial and parallel. Serial arcs typically occur at loose or faulty connection points, whereas parallel arcs can develop from more severe damage, such as when exposed wires from a damaged cable create a conductive path between the positive and negative terminals (TUV Rheinland et al., 2018). This situation is hazardous as it can lead to high-energy discharges.

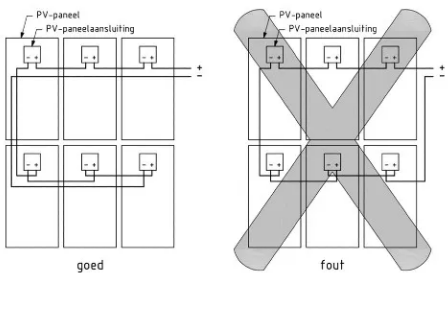


Figure 53: Inductive loop cable management. Source: NPR 5310:2017

An inductive loop can occur in a photovoltaic installation when wires are arranged closely in a loop formation (Figure 53). While under normal operating conditions this does not pose a risk, the danger arises during lightning strikes in the vicinity. As current flows through these wires and lighting strikes in the vicinity of the system, it creates a magnetic field that can induce voltage elsewhere in the circuit. These loops can increase the risk of interference and unintended current paths, which can complicate electrical layouts and increase the potential for arcing if not properly managed. How to deal with this by installation design, is addressed in NEN 1010.

Given these complexities, it is critical that both AC and DC wiring systems are carefully designed, installed, and maintained to minimize the risk of arc formation and ensure system safety. This could include using high-quality or extra insulation, adhering to installation standards NEN 1010, performing an Scope12 inspection and conducting regular inspections, particularly in environments prone to mechanical damage or extreme conditions.

String inverter [17] **|** String inverters, as some of the most intricate components in BIPV systems, encompassing numerous sub-components. This complexity inherently increases the fire risk associated with string inverters. The dense integration of electronic components can lead to higher internal temperatures and potential electrical failures. The risk is compounded by the possibility of component malfunctions or failures, which can initiate electrical arcs or overheating, thus elevating the potential for fire incidents within these systems.

Micro-inverter [17] **|** Micro-inverters can be installed either inside the façade or within interior spaces. The placement significantly influences the risk profile. When installed inside the façade, they are exposed to environmental variables such as temperature fluctuations and moisture, which can affect their performance and safety as they might not be designed for those conditions. Conversely, micro-inverters installed indoors are not exposed to these environmental stresses, reducing this risk. However, regardless of location, ensuring adequate ventilation and protection from direct exposure to elements is crucial to mitigate risks.

Combiner box [M] **|** When combiner boxes are employed in BIPV systems, they are mostly installed indoors. The high number of connections within these boxes increases the likelihood of installation errors, which can lead to loose connections, a precursor to arcing and overheating.

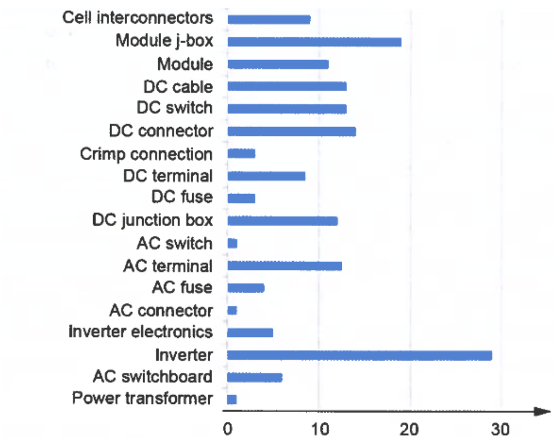


Figure 54: Amount of fire incidents per component PV. Source: TUV Rheinland & Fraunhofer-Institut (2018)

[17] Depending on the required electrical configuration, there are many possibilities for the choice of components and system characteristics. However, these configurations can be broadly categorized into three main types: string inverter, string inverter with optimizer, and micro-inverter. Table 12 provides an overview of the typical characteristics of the main electrical configurations in BIPV systems

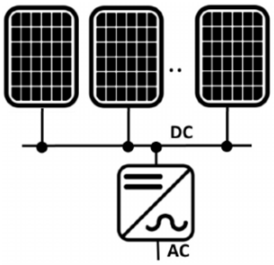
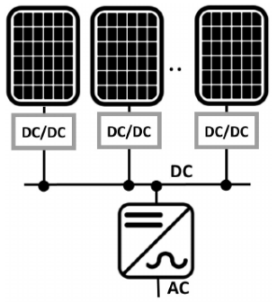
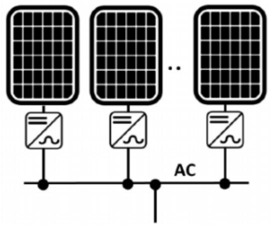
			
Electrical config.	**String inverter**	**String inverter + optimiser**	**Micro-inverter**
Typical components	1 inverter per 10-20 modules	1 inverter per 10-20 modules 1 optimiser per 1 module	1 inverter per 1-2 modules
Typical placement components	String inverter: indoors	String inverter: indoors Optimiser: in façade cavity	Micro-inverter: indoors (or façade cavity)
Voltage in façade	High voltage DC (<1000 V)	High voltage DC (<1000 V)	Low voltage AC (<80 V)
Fire risk	High	Medium	Low
Costs	Low	Medium	High
Efficiency	Medium	High (due to individual module optimization)	High (due to individual module optimization)
Shading Performance	Poor (whole string affected)	Good (only shaded module affected)	Excellent (each module independent)
Flexibility	Low (dependent on string design)	High (independent module control)	Very high (independent module control)
Monitoring	Basic (string level)	Advanced (module level)	Advanced (module level)

Table 12: Characteristics of main electrical configurations BIPV systems. Own work

4.2.5 Fault tree analysis: Vertical fire spread over multiple fire compartments

Preventing vertical fire spread across multiple fire compartments in a building is a primary objective of both the Bbl regulations and fire safety engineering practices (DGMR, 2018). The regulations permit fire to spread across the façade as long as it does not impact other fire compartments within the building. This containment strategy ensures that even if the façade is involved in a fire, the spread is controlled sufficiently to allow occupants time to safely evacuate the building. This approach emphasizes the importance of designing façades and compartmentalization to limit fire propagation vertically, thus safeguarding egress routes and enhancing overall building safety.

Given the complex nature of façade fire scenarios and the variability in potential fire trajectories influenced by the façade's composition and detailing, a focused analysis has been conducted on a standard parapet façade construction with BIPV. Figure 66 shows the analysis where fire trajectories are visualized with red arrows and the potential area from which a ignition scenario can originate, is highlighted with colours as shown in the legend. This approach ensures a basic understanding of the fire behaviour in BIPV façades. Subsequently, insights gained can then be applied to assess and address fire safety in varying façade configurations, ensuring a robust framework for fire prevention and management across different building designs.

> *"Given the fire trajectories detailed in Figure 66, it is essential to recognize that the most effective way to reduce the probability of these trajectories occurring is by preventing the ignition scenarios from developing initially"*

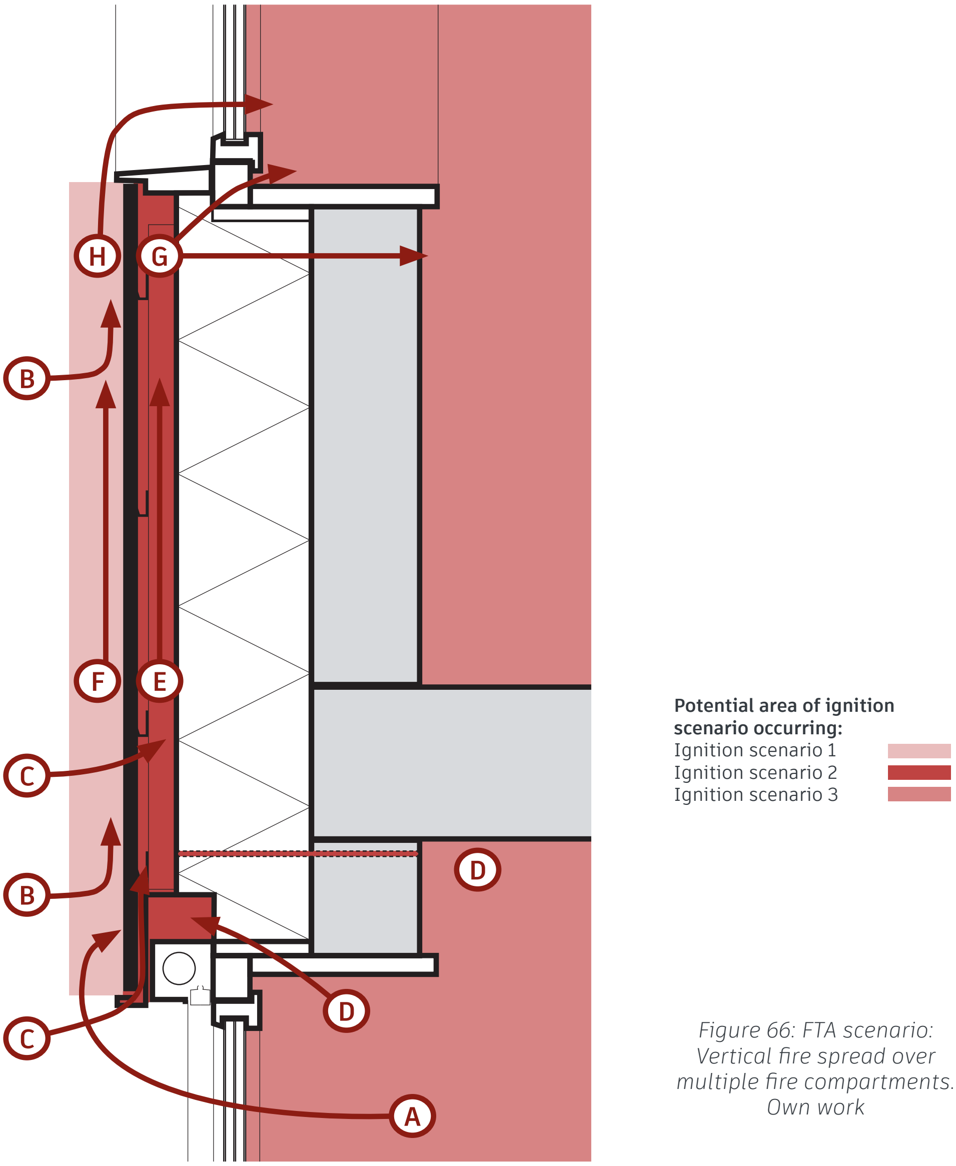


Figure 66: FTA scenario: Vertical fire spread over multiple fire compartments. Own work

FTA 1 is presented in Figure 58. This diagram highlights the interdependencies of the fire trajectories shown in Figure 66 and was developed to personally better understand the relationships between these trajectories. Figure 58 is shown in more detail in Appendix I, where each fire trajectory is also examined in more detail with sub-events and conditions. Given the complex and dynamic nature of fire, there are numerous variations for each trajectory, with each having multiple potential possibilities for the development into other fire trajectories. It is important to understand that this fault tree is primarily an attempt to systematically structure the potential fire scenarios involving BIPV as a means to analyse their impacts. Consequently, this model should be viewed as a conceptual overview, used to explore and hypothesize the complex dynamics of fire scenarios associated with BIPV systems in façades. For this reason, some critical factors influencing fire propagation, such as fire load, exposure time and air/fuel availability, are not individually detailed for each event.

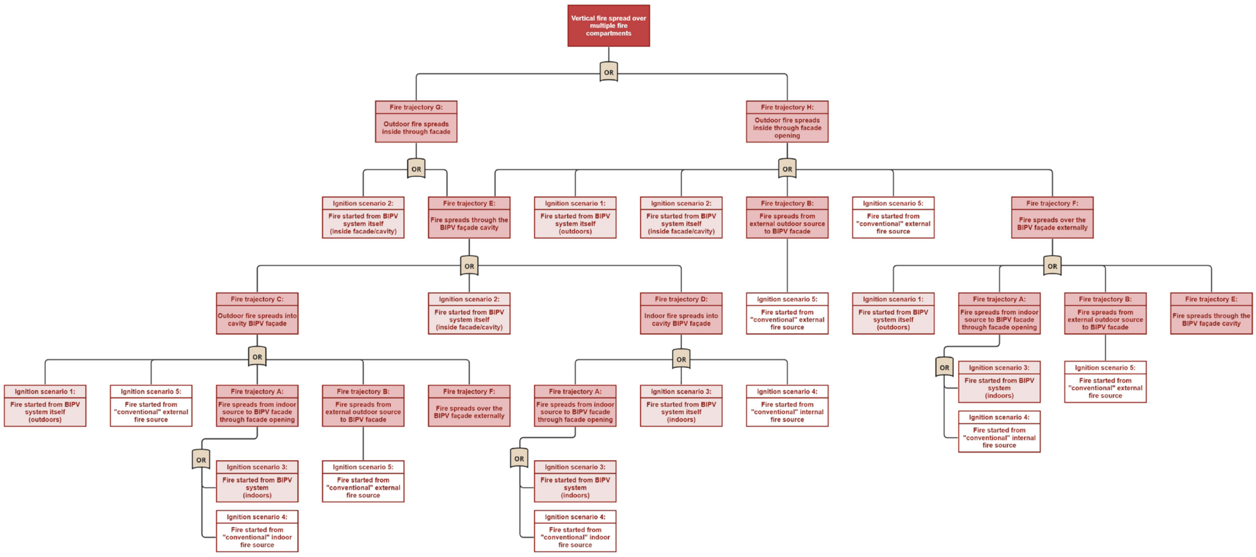
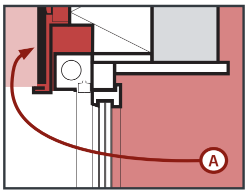


Figure 58: FTA 1: Vertical fire spread over multiple fire compartments (Appendix I). Own work



Fire trajectory A: Fire spreads from an indoor source to the BIPV façade through a façade opening [7] **|** This scenario is highly probable if a fire, originating from conventional sources or the BIPV system itself, ignites indoors and spreads towards a façade opening. In such cases, glass components fail quickly, initiating a "brandoverslag" scenario where the fire leaps from the interior to the exterior. This exposes the façade's exterior materials around the opening to intense heat, particularly above the opening.

BIPV modules have glass front sheets that provide initial protection against small fires, but they will fail under sustained high fire loads, exposing combustible encapsulants. Figure 59 illustrates that small fire loads pose less threat than high fire loads. BIPV modules near openings face an elevated risk of exposure to these high fire loads, increasing the probability of ignition and fire spread across the façade. While it may not always be feasible to avoid placing BIPV modules near openings, designers must strategically place them and consider the impact of subsequent fire trajectories, especially in relation to fire compartments.

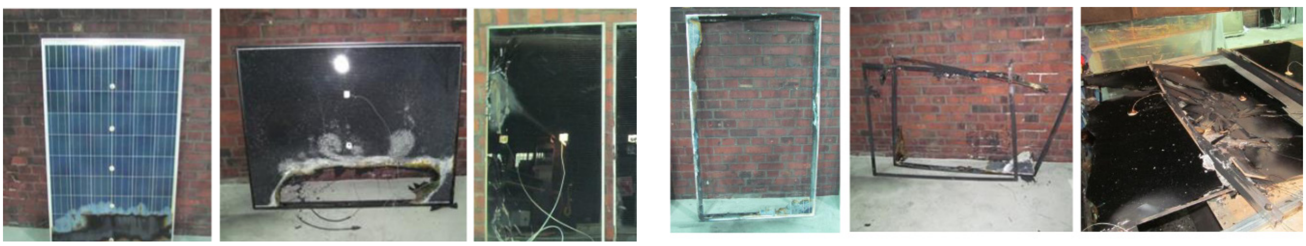
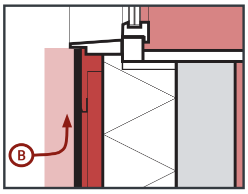


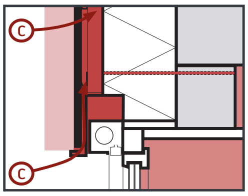
Figure 3-2: Damage from stress with 25 kW burner output, left: c-Si, center: CIS (transversely placed), right: CdTe (transversely placed)

Figure 3-3: Damage from stress with 150 kW burner output, left: c-Si, center: CIS (transversely placed), right: CdTe (transversely placed)

Figure 59: Burner test outputs of 25 kW (left) and 150 kW (right) . Source: TUV Rheinland & Fraunhofer-Institut (2018)



Fire trajectory B: Fire spreads from external outdoor source to BIPV façade [5, 6, 7, 17] **|** Fire spreads from an external outdoor source to a BIPV façade. While this scenario is less common due to the low probability of an external ignition source being significant enough to ignite a BIPV module, it remains essential to consider. Designers should consider the pathways through which an external fire could reach the façade. Strategic placement of BIPV modules is key, such as positioning them away from publicly accessible pathways, balconies, or roof terraces with potential external fire sources, as highlighted in Figure 57.

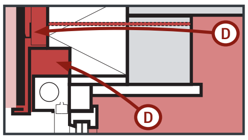


Fire trajectory C: Outdoor fire spreads into cavity BIPV façade [5, 6, 7, 13, M] **|** An outdoor fire can enter the cavity of a façade through various routes, including the penetration of exterior façade materials like BIPV modules or through seams and ventilation openings. This can potentially initiate the critical fire trajectory E, making it essential to address these design considerations.

- To minimize fire penetration through BIPV modules, using glass/glass modules is recommended, as they provide a more robust barrier against fire entry. While these modules can fail under high fire loads, their non-combustible glass surface restricts rapid fire spread.

- It is also crucial to minimize seams between BIPV modules and adjacent materials. Tight, well-sealed joints restrict fire pathways into the cavity, especially around façade openings.

- For ventilation openings, careful design is vital, especially around façades openings. Employing non-combustible materials like steel or stone for flashings at façade openings provides better fire resistance and slows down cavity entry time. Also the placement of the cavity openings in relation to façade openings, such that fire has less direct access to the cavity opening, slows down fire entering the cavity.

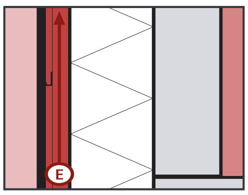


Fire trajectory D: Indoor fire spreads into cavity BIPV façade [7, 22] **|** This scenario is dependant on the overall fire resistance of the façade structure, but most critical at the cable from the BIPV system which penetrate through the façade and at the detailing around and of the window frames of façade openings.

- The fire resistance requirements for the façade's construction should adhere to the standards set forth by NEN 6068 and NEN 6069. However, NEN 6068 does not prohibit non-fire-resistant façades if there is no fire spread to upper, adjacent, or opposite façade openings. For example, this does not imply that no flames are allowed to enter a cavity at all.

- Cable penetrations through the façade are critical points that must match the fire performance characteristics of the façade itself. If the façade becomes less stiff during a fire while the cable penetration remains stiff, gaps can form, allowing fire to spread into a BIPV cavity. Therefore, the fire performance of cable penetrations must align with that of the façade to prevent such vulnerabilities. Simply using cable penetrations with specific fire performance doesn't ensure proper performance

- Detailing around window frames in façade openings also requires careful attention. These elements must be designed to prevent fire spread by minimizing gaps or weak points. Proper sealing and fireproofing around these frames are essential to maintain the façade's integrity as a fire barrier and protect the cavity from internal fires.



Fire trajectory E: Fire spreads through the BIPV façade cavity [19, 20, 21] **|** This trajectory is the most critical for façade fire spread due to the chimney effect, which accelerates fire spread as the cavity draws hot air upward, causing rapid and often invisible fire development (DGMR, 2018). The rate of fire spread within the cavity depends on the material characteristics of the surfaces, the support structure of the outer layer, and the draft within the cavity.

- Regarding the material characteristics within the cavity, one surface is the backsheet of the BIPV module and the other is typically an insulation material or another type of sheet layer. Using only non-combustible materials with a high fire rating of A2/A1 (NEN-EN 13501-1) does significantly reduce, if not prevent, the risk of fire spread throughout a cavity (DGMR, 2018).

A large-scale BIPV façade fire test (SP FIRE 105) performed by Stølen et al. (2024) demonstrated the risks associated with using glass/polymer modules. In this test (Figure 60), a glass/polymer module was mounted on an aluminum structure with a 65 mm cavity, fire breaks, and a non-combustible gypsum board (9.5 mm). Despite the use of non-combustible materials in the cavity, the only combustible element—the glass/polymer module—produced enough fire load for the fire to propagate vertically, compromise the structural integrity of the aluminum mounting structure, surpass the fire break, and reach the top of the façade. This ultimately resulted in the failure of all performance criteria to pass the fire test, highlighting the critical importance of avoiding glass/polymer modules to prevent fire spread in BIPV systems.

Figure 60: Test configuration with BIPV-system installed on the SP FIRE 105 large-scale façade test rig. Source: Stølen et al. (2024)

(a) 15 minutes (b) 25 minutes (c) 30 minutes (d) 36 minutes

Figure 61: Large scale test BIPV façade. Impact falling BIPV modules. Source: Stølen et al. (2024)

The Grenfell Inquiry revealed complex interactions of building materials in cavity fires. Non-combustible insulation materials (A2/A1 per NEN-EN 13501-1) with reflective layers reflect heat across the cavity, increasing the thermal load on the opposing panel. In Grenfell's case, ACM panels ignited faster when paired with such insulation (Luke Bisby et al., 2021). This underscores the importance of avoiding BIPV modules with polymeric backsheets, as they can similarly increase fire risk.

- In the event of a cavity fire, it is highly probable that the structural integrity of the mounting frame will be compromised, leading to the BIPV modules falling. Aluminum mounting frames are the market standard, but steel mounting frames also exist.

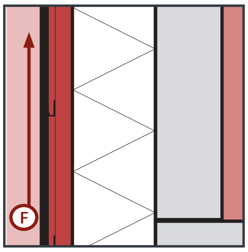
  Aluminium | Aluminum loses 50% of its structural strength at temperatures around 200° C and melts at approximately 600° C. Thus, in the event of a fire, it is highly probable that the structural integrity of the aluminum will be compromised, resulting in BIPV modules falling down (Skejić et al., 2016).

  Steel | Although heavier and more expensive, steel offers significantly better fire resistance than aluminum. Steel retains its structural integrity at higher temperatures as the melting point is around 1400 °C. Consequently, steel mounting frames provide additional time during a fire, potentially preventing or delaying the collapse of BIPV modules (Skejić et al., 2016).

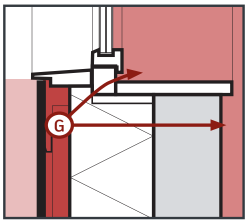
Special attention should be given to the impact of falling BIPV modules on the effectiveness of fire breaks. When these modules fall, they can expose potential pathways for fire to bypass the fire breaks, undermining their function (Stølen et al., 2024). Additionaly, while falling debris is a common occurrence in façade fires, the size and weight of BIPV modules pose an enhanced risk, potentially falling on people, blocking escape routes or causing additional structural damage.

- Another mitigative measure is to limit the draft in the cavity by reducing the size of the cavity openings. However, this is not suitable for BIPV façades, as high temperatures in the cavity are critical for electrical components like junction boxes, wiring, optimizers, and micro-inverters.

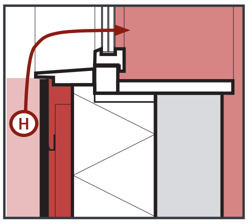
Restricting the draft would raise the temperature further, which is undesirable. Instead, the temperature should be kept as low as possible, and the cavity openings should remain. An alternative approach is to limit the impact of the draft by reducing the cavity length, ensuring only a smaller façade area is at risk. This can be achieved with well-performing fire barriers or by physically disconnecting cavities through design consideration.



Fire trajectory F: Fire spreads over the BIPV façade externally [5, 6, 7, 8] | Once BIPV modules ignite, a fire has the potential to spread fire vertically over external pane of the façade. By itself, this trajectory is not be considered as too big of a risk according to current fire safety practices, as this performs roughly equal as other façade materials with fire class B (NEN-13501-1). However, the inherent fire risk of the building may necessitate enhanced fire safety measures. One strategy could be to interrupt the vertical continuity of BIPV modules, which can help to limit the upward spread of fire. Since this approach is closely linked with the configuration of the façade cavity, decisions regarding the placement and interruption of BIPV modules should be made in conjunction with cavity design considerations.



Fire trajectory G: Outdoor fire spreads inside through the façade [7, 22] | This trajectory is essentially the inverse of fire trajectory D, where the fire direction is reversed but the dynamics remain similar. Consequently, the same considerations outlined for trajectory D are applicable here: adhering to NEN 6068 and NEN 6069 to ensure fire performance of façade, employing proper cable penetrations through the façade and ensuring the performance of detailing around and of the window frames or façade openings.



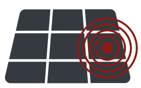
Fire trajectory H: Outdoor fire spreads inside through façade opening [7, 22] | This trajectory is somewhat the inverse of fire trajectory A, where the fire direction is reversed. To minimize this trajectory, it can be drawn upon from other already mentioned consideration: strategic placement of BIPV module in relation to façade openings (fire trajectory A), ensuring the performance of detailing around and of the window frames of façade openings (fire trajectory D), employing non-combustible materials for flashings around ventilated cavity (fire trajectory C).

Through the FTA of a standard parapet situation, the most common BIPV façade type, many findings were highlighted regarding fire-related risks for BIPV façade systems. To summarize the most critical findings:

BIPV façade systems introduce high-voltage ignition sources, carrying DC currents up to 1000 V, directly into façade structures, a hazard unprecedented in conventional façades. Despite this, the current regulatory framework in the Netherlands falls short in adequately addressing the fire safety risks posed by BIPV façade systems

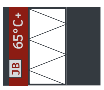
CRITICAL BIPV SYSTEM FAILURE MODES

Electric arc: high-voltage electrical discharge between two or more conductors which can happen at any electrical component or connection in a BIPV system. Often caused by installation faults or component degradation.



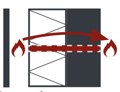
Hot spot: an excessive increase in temperature of PV cells, triggered by faults such as partial shading, short circuits, or increased ohmic resistances.

WHY ARE BIPV FAÇADES OF HIGH RISK?

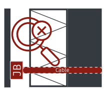


The components within cavities could not be designed to operate at the high temperatures

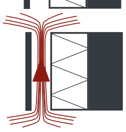
Combustible material in the façades can be exposed to ignition sources



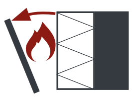
Cable penetration through the façade



Components in the façade (cavity) are hard to inspect or replace



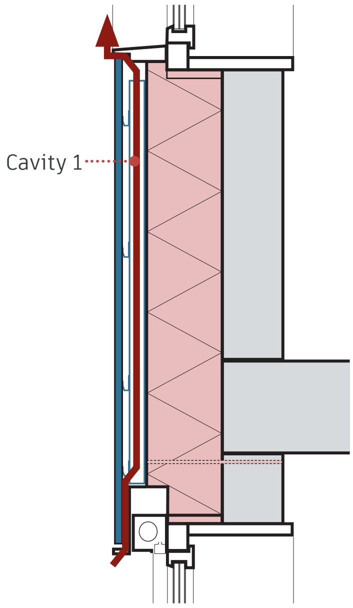
BIPV façades ventilated cavities could enhance fire propagation (chimney effect)

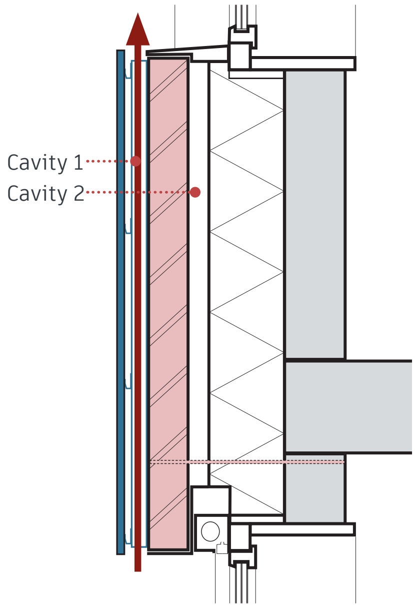


Falling (heavyweight) BIPV modules

4.2.6 BIPV vs BAPV

To highlight why BIPV systems are more critical than BAPV systems, this section will discuss the specific fire-related risks associated with each. PV modules are classified as building-attached when they are attached to a building envelope without serving functional requirements of the envelope. While IEA PVPS Task 15 (2018) clearly distinguishes between BIPV and BAPV systems, Kumar et al. (2019) note that these systems often function identically in electrical performance and configuration. Despite this similarity, BIPV systems can be easily distinguished by their integration into the building envelope (Table 13).





PV type	**BIPV façade (rainscreen)**	**BAPV façade (masonry)**
BIPV module integration	Integrated directly within the building envelope. Once removed, the integrity of the façade is compromised.	Integrated indirectly within the building envelope. Once removed, the integrity of the façade is not compromised.
Architectural Integration	Specifically designed for architectural integration during the building design phase. More aesthetically pleasing.	Has limitations in blending with the existing architecture. Often clunky aesthetics.
Costs	Cost per on average higher than BAPV to produce the equal amount of energy	Cost per on average lower than BIPV to produce the equal amount of energy
Typical cavity configurations	Cavity 1: between BIPV module and cavity materials like insulation, foils, sheet layer	Cavity 1: between BIPV module and bricks
		Cavity 2: between bricks and insulation/foils
Component placement	Cavity 1: junction boxes, cables + plugs, (optimisers, micro-inverters)	Cavity 1: junction boxes, cables + plugs, (optimisers, micro-inverters)
		Cavity 2: cables
	Rest façade: cable (penetrations)	Rest façade: cable (penetrations)
Installation	Generally requires specialized installation expertise due to integration complexity in façade.	Generally easier to install on existing buildings. Executed by less experienced contractors
Maintenance Accessibility	Maintenance is more complex as most electrical components are placed in hard to reach cavity.	Maintenance is less complex as most electrical components are placed in easier to reach cavity.

Table 13: BIPV & BAPV characteristic comparison. Own work

The impact of these characteristics on fire safety is significant. For BAPV (masonry) façade systems, the masonry layer acts as a fire barrier (fire class A1 according to NEN-EN 13501-1) in the event that the module or components catch fire. In contrast, with a BIPV (rainscreen) façade, there is no such fire barrier, and the electrical components and modules are directly adjacent to potentially combustible materials, such as insulation, foils, and sheet layers. This lack of a protective barrier increases the fire risk in BIPV systems. Additionally, cable penetrations in both systems pose a risk, as they can provide pathways for fire and smoke to travel through the façade. Furthermore, the accessibility and maintenance of these systems also affect their safety and performance. Maintenance is more complex for BIPV systems, as most electrical components are placed in hard-to-reach cavities, whereas BAPV systems have components in relatively better accessible locations, simplifying maintenance procedures.

TNO (2019) investigated 23 PV-related fire incidents that occurred in the Netherlands in 2018 and estimated that 80 to 90% of these incidents involved BIPV systems. Although this study focused solely on roof PV systems, the integrated risks of roof BIPV versus BAPV systems are somewhat analogous to those of BIPV versus BAPV façade systems. This high rate underscores the increased fire risk associated with BIPV systems, which is likely due to their integration characteristics and the complexity of maintaining and inspecting these systems.

Figure 62: BAPV façade (masonry). Nieuwegein, the Netherlands. Own photo

Figure 63: BIPV façade (rainscreen). Basel, Switzerland. Source: SolAR (2022)

Figure 64: BAPV façade (masonry). Mijderecht, the Netherlands. Own photo

Figure 65: BIPV façade (rainscreen). Amersfoort, the Netherlands. Source:

4.3 Fire risk parameters

Founded by the fault tree risk analysis, this chapter delves into the development and application of fire risk parameters specifically tailored for BIPV façade systems. These parameters are designed to evaluate and mitigate the most presseing fire risks at various levels of detail: building, façade, and product. The 23 presented risk parameters in this chapter ultimately inform the design support tool, providing a foundational framework for users to analyse fire safety. Notably, the risk parameters at the building and façade levels have been developed in collaboration with Carmen Guchelaar.

4.3.1 Introduction to fire risk parameter approach

> *A specific design criterion or variable which impacts or is impacted by the fire risks of BIPV systems in façades. These risk parameters form the basis for the design support tool, providing a structured framework for evaluating and mitigating fire risks.*
>
> *- risk parameter -*

The development of the risk parameters began with two reference tools: "Risicotool brandveiligheid gevels" (DGMR, 2019) and "Borgingsprotocol" (Nieman & DGMR, 2022). These tools function similarly to the envisioned design support tool but are designed for broader façade assessments and include fewer risk parameters. To better suit BIPV systems, the risk parameters from these documents were used as a starting point and expanded with findings from this study's risk analysis, incorporating a more comprehensive set of factors tailored to BIPV façades.

The methodology for establishing the risk parameters categorizes risks into three levels: the building level, the façade level and the product level.

The risk analysis provided an in-depth examination of potential fire risks, informing the selection and prioritization of risk parameters. Due to the extensive range of risks, not every fire risk can be included in the tool as a risk parameter. Therefore, choices were made based on the risk level and the impact designers have on changing the risk level. Risks were either identified as risk parameters or included in the advice on measures and strategies, ensuring the tool remains focused and practical while still addressing the most significant threats to fire safety.

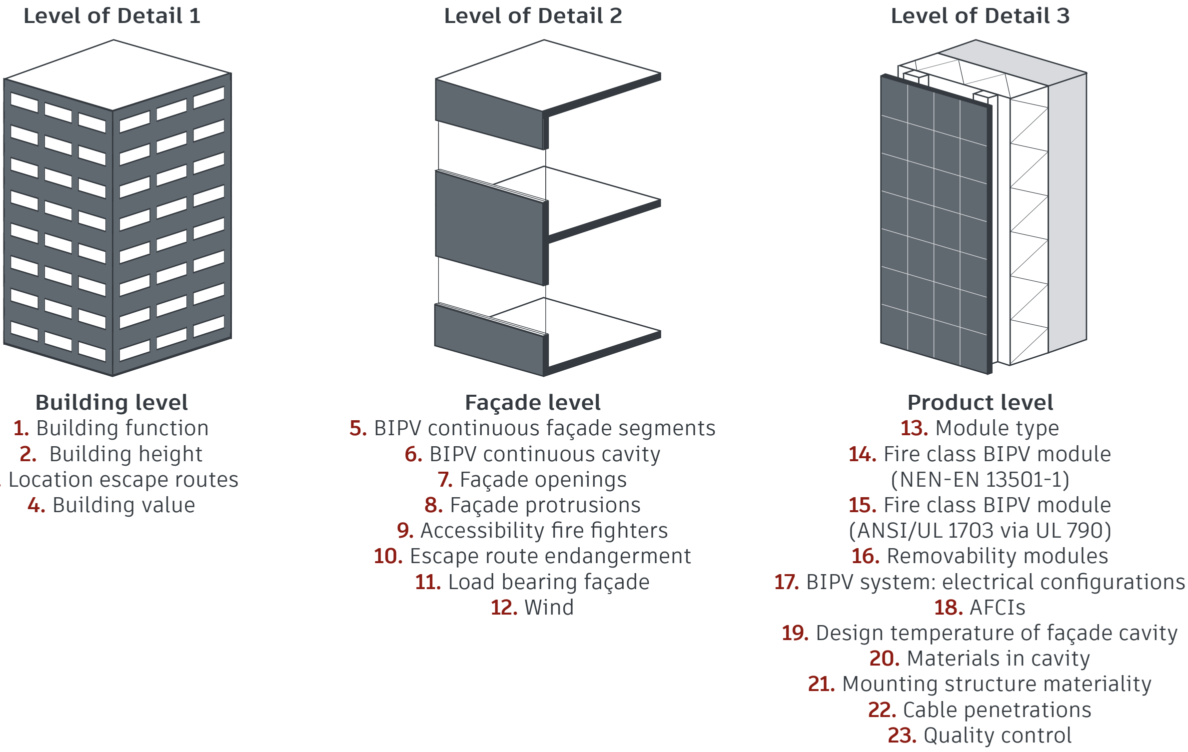


Figure 67: Risk parameters. Own work

4.3.2 Fire risk parameters: building level

1 | **Building function.** Different building functions carry varying levels of fire risk, primarily influenced by the occupants' ability to detect a fire promptly and evacuate independently. Buildings designed for sleeping, such as residential homes and hotels, often present a higher risk because occupants may not detect a fire as quickly while asleep. Similarly, buildings frequented by individuals with limited mobility or self-reliance, like hospitals or care homes, also pose greater risks, as evacuation may be slower. According to the Dutch building decree (Bbl), there are 12 distinct building functions and several sub-functions, each subject to specific fire safety regulations tailored to their risk profiles.

2 | **Building height.** Numerous factors come into play when considering fire safety in relation to building height, but among them, some stand out as particularly critical. The height of a building significantly influences the complexity of evacuation. In taller buildings, the evacuation routes are longer, and more vertical descents are required, which can be particularly challenging for individuals who are not self-reliant or have mobility issues. Additionally, wind speeds increase at higher altitudes, potentially intensifying a fire on upper floors. Access for firefighters is also a critical factor; while standard fire trucks with aerial ladders can typically reach up to 12 meters, taller buildings may require specialized equipment that is not available at all fire stations. Risk parameter 9 elaborates more on accessibility of fire fighters.

3 | **Location escape routes.** The availability and configuration of escape routes are crucial for safe evacuation during a fire. Buildings with only one staircase pose a significant risk if the fire blocks this route, leaving no alternatives for escape. Buildings with multiple staircases offer redundant paths, enhancing safety. However, the effectiveness of multiple staircases also depends on their separation; staircases that are too close to each other may both be compromised by a single fire event, particularly in compact buildings. Ideally, staircases should be spaced sufficiently apart to reduce the likelihood of a fire affecting all available escape routes simultaneously.

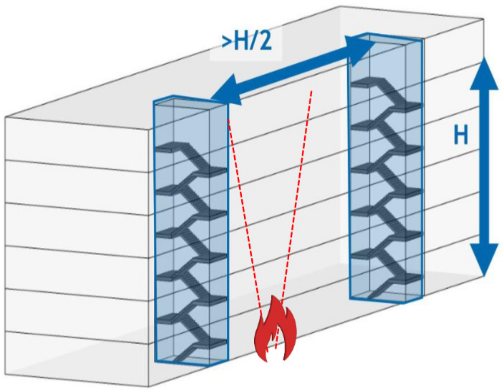


Figure 68: Placement of escape routes. Source: Nieman and DGMR (2022)

4 | **Building value.** The value assigned to a building significantly influences the prioritization and extent of fire safety measures required. High-value buildings, such as museums or historical sites, often necessitate advanced fire protection measures to safeguard irreplaceable contents and preserve cultural heritage. For these buildings, the financial and emotional impact of a fire can be relatively large, prompting the need for strict fire prevention strategies. Conversely, buildings with a lower assessed value might not justify the same level of extensive fire safety investments, although basic protections are still essential to meet safety regulations and prevent loss.

Intrinsic Value: The inherent worth of the property, based on its utility, features, and condition, influencing its market price and replacement cost.

Emotional Value: The sentimental importance of a property to its owners and occupants, often derived from personal experiences, memories, and attachments, making its loss deeply personal and impactful.

Cultural Value: The cultural importance of a building or area, particularly those that contribute to the heritage and identity of a community, preserving historical narratives.

Example: low value

Villa Lichtenberg
Amersfoort, The Netherlands

Residential house

Intrinsic value: low
Emotional value: low
Cultural value: low

Example: medium value

Grosspeter Tower
Basel, Switserland

Office tower

Intrinsic value: high
Emotional value: low
Cultural value: low

Example: high value

Novartis Building, Basel, Switzerland

Exhibition, meeting, and event center

Intrinsic value: high
Emotional value: mid
Cultural value: mid

Figure 69: Risk value examples. Own work

4.3.3 Fire risk parameters: façade level

5 | BIPV continuous façade segments. When a BIPV façade spans multiple fire compartments, it presents a risk for facilitating the spread of fire between compartments. Vertical extensions are particularly vulnerable because fire naturally tends to spread upward more rapidly than horizontally. Thus, BIPV façades that extend vertically across compartments pose a greater risk of promoting vertical fire spread, potentially bypassing compartmentalization designed to contain fires within a single level. Horizontal spans, while still a risk, generally see slower fire progression, but still require fire-stopping measures to prevent lateral fire spread.

6 | BIPV continuous cavity. Ventilated cavities in façades inherently have a high risks regarding fire propagation due to the chimney effect, which significantly accelerates the spread of fire within a façade. Thus, BIPV façades with cavities that span multiple fire compartments vertically present a critical risk, necessitating enhanced fire-stopping measures. Although horizontal spread also poses risks, these are relatively lower compared to vertical spread due to the slower progression of fire laterally

A ventilated cavity has openings to the outside air, allowing flames to enter the cavity from the outside and, subsequently, exit back out. The size and placement of these openings are crucial for further fire spread along the façade. Within the cavity, the rate at which a fire spreads is determined by the material characteristics of the two surfaces, the support structure of the outer layer, and the draft within the cavity

7 | Façade openings. When glass is subjected to fire, or more specifically, heat differences, it breaks. Once the glass of a façade opening is broken, there is a hole in the façade through which fire can spread freely, both from inside to outside and the other way around. Additionally, detailing around façade openings, while not a new concern in fire safety, requires careful attention. These elements must be designed to effectively prevent fire spread by minimizing any gaps or weak points. Proper sealing and fireproofing around these frames are essential to maintain the integrity of the façade as a fire barrier and to protect the cavity from internal fires. This attention to detail ensures that the façade remains robust against fire penetration and spread.

Distributed openings | These facilitate fire spread through multiple points, enabling fire propagation across several fire compartments both horizontally and vertically.

Vertical continuous openings |These openings allow fire to travel upwards quickly, increasing the risk of vertical fire spread while limiting horizontal fire spread.

Horizontal continuous openings | Although these openings enable fire to spread easily across a floor, they also serve as barriers to the more critical vertical fire spread.

Therefore, a façade with transparent parts/windows poses a greater fire spread risk than a closed façade. In the Netherlands, this risk is addressed with WBDBO (NEN 6068 & NEN 6069).

8 | **Façade protrusions.** Interruptions along the BIPV façade, such as horizontal protrusions, can have a significant impact on fire spread, potentially over multiple fire compartments. These interruptions may include features like balconies, galleries, or shading systems. If properly designed and constructed from non-combustible materials, these protrusions can slow down or even prevent the spread of fire by acting as barriers.

When there are horizontal protrusions greater than 0.5 meters, they can effectively act as fire breaks if made from incombustible materials. These larger protrusions can halt the progress of a fire, reducing the risk of vertic fire spread along the façade.

In the case of horizontal protrusions less than 0.5 meters, these smaller interruptions can still provide some benefit in slowing down fire spread, but their effectiveness is less than that of larger protrusions.

If there are no interruptions along the BIPV façade, the fire can spread more easily across the BIPV modules. A smooth, uninterrupted façade provides no barriers to slow down the fire, making it easier for flames to travel vertically.

9 | **Accessibility fire fighters.** Accessibility of the BIPV façade for the fire brigade is vital for effective emergency responses. If the façade is not fully accessible, it impedes firefighting efforts and necessitates more stringent WBDO requirements (NEN 6068 & NEN 6069), which could increase the risk of fire spread and complicate evacuation procedures. It's essential to incorporate accessibility features into the design to improve safety and the efficiency of emergency responses.

Quoting NEN 6069:
"A façade or roof section is presumed to be 'not safely accessible with extinguishing water' for the fire brigade in the following situations:

- if it is located higher than 20 meters above the measurement level; **and**
- if it is both more than 60 meters horizontally distant from a public road and from a fire vehicle's staging area; **or**
- if it cannot be safely approached within less than 30 meters with a fire hose nozzle due to inaccessible terrain or wide water bodies.

10| **Escape route.** The proximity and positioning of BIPV modules relative to escape routes are critical in assessing fire safety risks. If BIPV modules are directly above or have a clear fire trajectory to escape routes, they can significantly increase the risk of obstructing these paths during a fire, potentially endangering occupants attempting to evacuate. While falling debris is a common occurrence in façade fires, the size and weight of BIPV modules pose an enhanced risk, potentially falling on people, blocking escape routes or causing additional structural damage.

The more escape routes are potentially endangered by BIPV systems, the greater the risk. It's important to evaluate these factors carefully to ensure that main escape routes remain unimpeded in case of a fire emergency

11| **Load bearing façade.** Understanding whether a façade is load-bearing helps in assessing the fire risks and necessary safety measures.

Load bearing façades | Critical to the building's structural integrity. In the event of a fire, the failure of a load-bearing façade can lead to partial or complete structural collapse, posing a significant danger to occupants and emergency responders. While the building decree imposes extra strict regulations on the requirements for the main support structure to prevent collapse in case of a fire, mitigating most of the risk, the inherent risks remain higher compared to a non-load-bearing façade.

Non-load bearing façades | Generally, non-load-bearing façades pose a lower structural risk in the event of a fire. These façades do not support the building’s primary structural load, meaning their failure due to fire would not compromise the building's overall stability. However, they still need to be designed to prevent fire spread and maintain fire resistance to protect the building interior and occupants.

12| Wind. The direction and intensity of wind play a significant role in the spread of fire across a BIPV façade. Depending on the wind direction and speed, fire can spread rapidly or in various directions, including sideways or even downwards in extreme cases (figure 1).

Horizontal spread: When the wind blows directly against or parallel the façade, it can drive the flames horizontally, spreading fire quickly across the surface. This can lead to extensive damage over a wide area in a short amount of time.

Vertical Spread: Wind blowing upwards can exacerbate the chimney effect, where flames and hot gases rise rapidly, increasing the risk of vertical fire propagation. This is particularly dangerous in high-rise buildings where fire can spread to upper floors more quickly.

Downward spread: In certain extreme conditions, such as turbulent wind patterns, fire can spread downward, posing a risk to lower levels that are typically considered safer from fire spread.

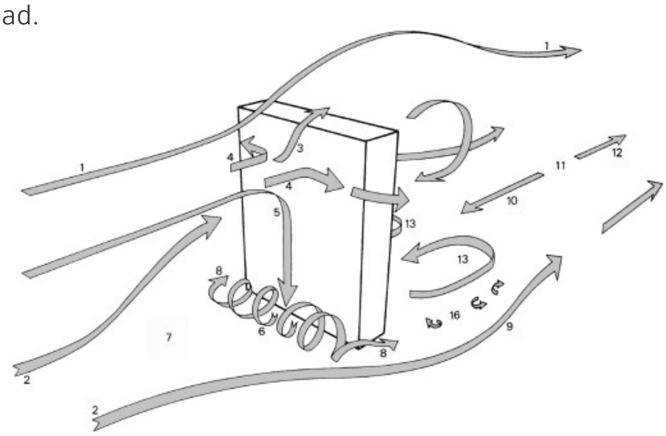


Figure 70: Schematic representation of wind flow pattern. Source: Moonen et al., (2012)

High wind speeds: Strong winds can significantly increase the rate at which a fire spreads. High wind speeds can carry burning debris further, igniting new areas and accelerating the overall spread of the fire.

Variable wind patterns: Changes in wind direction and speed can create unpredictable fire behavior, making it more challenging to control and contain the fire.

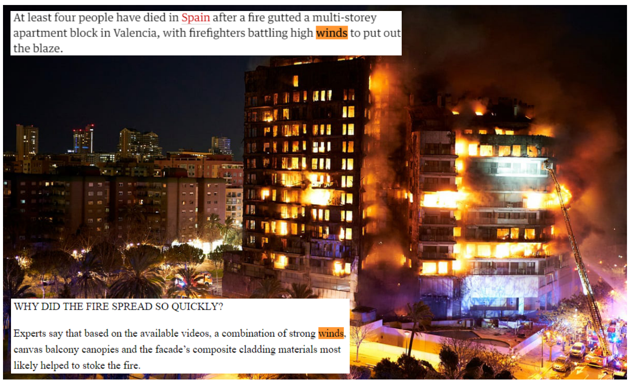


Figure 71: Valencia residential complex fire 22-02-2024. Source: The Guardian (2024)

4.3.4 Fire risk parameters: product level

The risk parameters at the BIPV product level have aready been thoroughly detailed in the FTA analysis. For fire risk information about these risk parameters, please refer to that chapter and identify the relevant sections with the corresponding mark (e.g. [19]).

13| Module type
14| Fire class BIPV module (NEN-EN 13501-1)
15| Fire class BIPV module (ANSI/UL 1703 via UL 790)
16| Removability modules
17| Electrical configurations
18| AFCIs
19| Design temperature of façade cavity
20| Materials in cavity
21| Mounting structure materiality
22| Cable penetrations
23| Quality control

4.4 BIPV measures

The findings from 4.2 Fault tree analysis & 4.3 Fire risk parameterson the fire risks identified a wide range of fire risks related to BIPV façade systems in building contexts. To address these risks, a series of measures and strategies has been developed, serving as input for the design support tool. This chapter provides an overview of the proposed measures.

4.4.1 BIPV measures: risk parameters

This section focuses on measures which are related to the identified risk parameters.

5| **BIPV continuous façade segments.**
Consider segmentizing the BIPV façades that span multiple fire compartments horizontally/vertically to limit a façade fire to singular fire compartment. How? By creating physical gaps or barriers between BIPV modules at the borders of fire compartments.

6| **BIPV continuous cavity.**
Split up the BIPV cavity horizontally/vertically at the fire compartment borders to limit horizontal fire spread to a singular fire compartment. How? Employ a well-performing horizontal fire barrier or split up the cavity through detailing.

7| **Façade openings.**
Strategically place façade openings to prevent critical fire propagation routes, and employ smart detailing around openings and BIPV cavities to prevent fire spread between them (e.g. non-combustible flashings).

9| **Accessibility fire fighters.**
Consult with the local fire brigade to develop alternative strategies for access, fire suppression and evacuation.

10| **Escape route.**
Evaluate the impact of BIPV modules on the escape route to ensure at least one main escape route has enhanced safety measures and assess the need for extra protection on other routes. How? Implement physical barriers, such as cantilevers, around critical areas like exit doors, or use steel mounting structures for BIPV systems above, or not situating BIPV modules above escape routes.

11| **Load bearing façade.**
Critically evaluate the impact of the BIPV system and its potential ignition scenarios on the integrity of the supporting structure to ensure it remains structurally sound and fire-resistant.

12| **Wind.**
Conduct a wind analysis and consider the effects of wind on fire spread.

13| **Module type.**
Always employ glass/glass BIPV modules to minimize cavity fires and prevent enhanced fire propagation.

14| **Fire class BIPV module (NEN-EN 13501-1).**
Ensure the BIPV module meets a minimum fire class of B according to NEN-EN 13501-1. If your BIPV module has a fire class A, verify that the classification is according to NEN-EN 13501-1 rather than another fire classification such as ANSI/UL 1703 (via test method UL 790).

16| **Removability modules.**
Critically consider the ease of removal for BIPV modules to facilitate maintenance and replacement. How? Use mounting systems that allow for this, avoiding glued connections.

17| **Electrical configurations.**
Consider replacing string inverters with micro-inverters to lower the operating voltage of the BIPV system and minimize the risk of electric arcs or consider adding optimizers to improve remote monitoring and control, enhance system performance.

18| **AFCIs.**
Ensure AFCIs are implemented in the system and ensure they are active to limit the possibilities and effects of electric arcs in the system.

19| **Design temperature of façade cavity.**
Ensure the cavity temperature remains below the maximum operating temperature of the electrical components in the façade. How? Increase airflow in the cavity by enlarging cavity openings or increasing cavity depth.

20| Materials in cavity.
Ensure the materials in the BIPV cavity opposite the BIPV module are fire class A2 or A1 to act as a fire barrier (e.g. CEM board 10 mm), minimizing cavity fire and preventing enhanced fire propagation

21| Mounting structure materiality.
Consider using a steel mounting frame to enhance structural integrity during a fire and improve the effectiveness of fire breaks

22| Cable penetrations.
Design cable penetrations to ensure they provide the same level of fire resistance as the façade.

23| Quality control.
Ensure either quality control with InstallQ qualified installers or preferably conducting a SCOPE 12 retrospective inspection by a certified company.

4.4.2 BIPV measures: general

In addition to the measures specifically related to the risk parameters, a set of general measures has been developed that should also be considered.

- The architect / façade designer, BIPV manufacturer and electrical installer should closely collaborate to design the electrical configuration of the BIPV system and adequately implement the effects of the system on the detailing, particularly in the façade (e.g. component placement in façade, cable penetrations, etc.).
- Ensure a maintenance schedule is developed and executed, tailored to the risk of the building to preserve the BIPV system.
- Ensure the BIPV module & system components are designed and installed according the product specifications of the manufacturer.
- Employ measures (e.g. bee beaks) to limit the impact of animals like birds, rodents or other animals nesting in the cavity.
- Minimize the seams between BIPV modules and adjacent exterior façade materials to ensure that joints are tight and well-sealed, thereby restricting pathways for fire to penetrate into the cavity
- Think about design considerations to limit damage to the BIPV modules, potentially caused by a BMU or other external factors
- Employ high quality electrical components with CE marking (be aware of fake certifications).
- Ensure the use of high-quality, heat-resistant and compatible connectors to minimise the possibility of electric arcs.
- Ensure AC and DC cables are extra protected (e.g. double isolated or fire-resistant).
- Prevent moisture penetration of electrical components, especially in the cavity, by avoiding the possibility of still standing water in the cavity and by employing components with a sufficient IP class.
- Employ bypass diodes with lower maximum currents than the junction box specifications to decrease the likelihood of overheating of junction boxes.
- Implement lightning strike provisions (e.g. lightning conductors with overvoltage protection.

4.4.3 One-pager

Due to the extensiveness of the FTA and the numerous measures that could or should be taken, a one-pager has been developed (Figure 72, next page). This document focuses on providing information about the most critical fire risks and the most effective measures to address those risks.

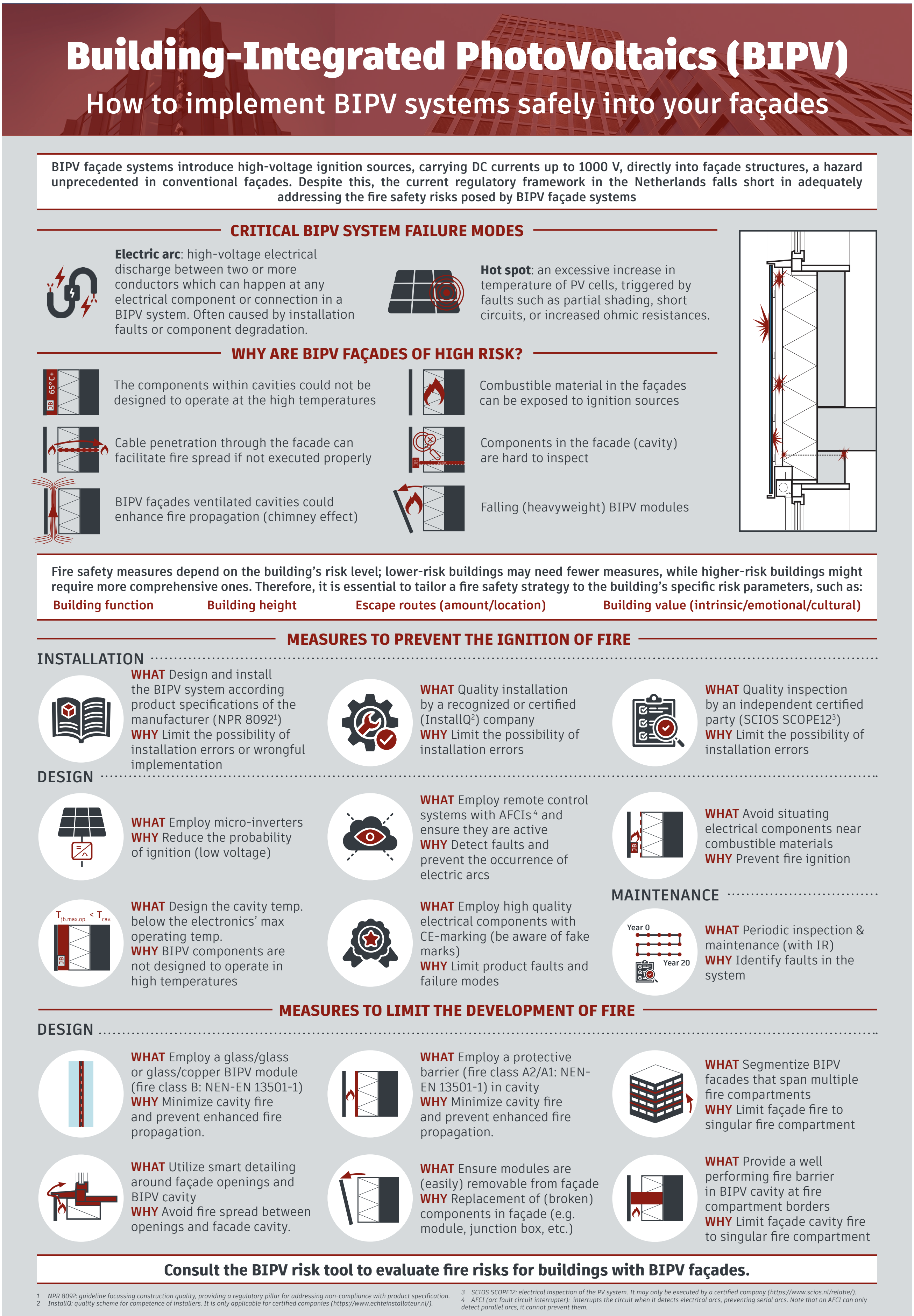


Figure 72: Design support tool sheet: measures. Own work

5

Design Support Tool

5.1 Concept design support tool

This chapter introduces the concept design support tool, providing an overview of its functional aspects rather than detailed technical elaborations. Key points covered include the tool's goal, risk evaluation approach, tiered structure, intended users, optimal usage timing, and best practices for utilization. The initial concept of the tool has been developed in collaboration with Carmen Guchelaar.

5.1.1 Design support tool: goal

The tool is designed address the gap of the pre-normative state of the regulatory framework, by facilitating the spread knowledge, enhancing reach and practical application of research findings, thereby fostering industry-wide implementation. By targeting designers, who greatly influence building design outcomes, the tool ensures practicality and specificity to their needs. This approach is ultimately aimed at promoting an informed decision-making process, equipping designers with the most essential knowledge to achieve fire resilience in buildings with BIPV systems in façades. To realize this goal, the design support tool is structured around several key objectives:

Fire risk identification BIPV | The tool delivers preliminary knowledge on fire risks associated with BIPV systems in façades, based on literature reviews, risk analysis, and expert consultations. This base of knowledge serves to inform and alert users about potential risks in BIPV applications.

Evaluate context beyond product level | The tool goes beyond product-focused assessments to evaluate the wider contexts of building and façade, enhancing understanding of how BIPV systems interact with other design considerations for fire safety.

Provide practical measures and guidelines | The tool offers measures and strategies that are specifically formulated to address the identified context and fire risks. The focus is on delivering solutions that are both effective and minimally restrictive, promoting smarter, adaptable fire safety practices that can be integrated into existing design processes.

Facilitate compliance | Recognizing the complexities and limitations of the regulatory framework for BIPV façades, the tool clarifies applicable regulations and also assesses their adequacy in covering BIPV-specific issues by highlighting limitations.

Foster informed decision-making | The tool enhances decision-making by enabling users to assess the impact of risk parameters and design choices on fire safety. It enables comparison of design considerations, highlighting how each of them influences BIPV systems' fire safety and resilience.

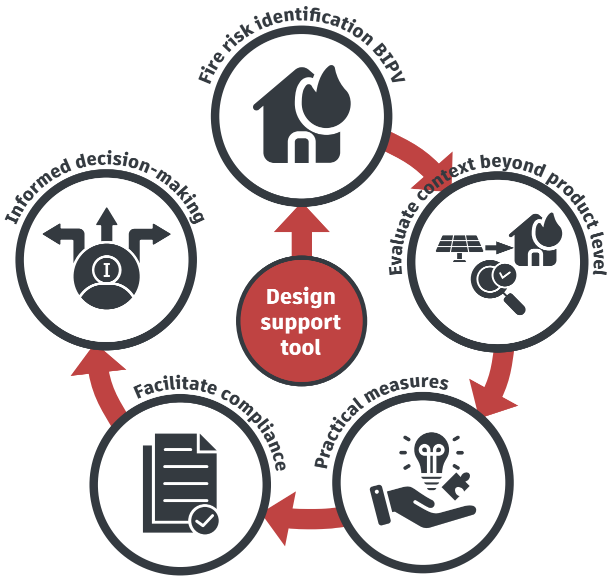


Figure 73: Design support tool objectives. Own work

5.1.2 Design support tool: risk evaluation approach

In the design support tool, risk factors are used to represent the fire safety impact of a design consideration, indicating the relative risk from a "zero-risk" situation. The higher the value, the higher the risk associated with the design consideration. This approach helps to quickly assess and compare the potential impact of different design options, while also facilitating an understanding of how each choice affects overall fire safety within the BIPV context.

Based on the chosen design considerations, the tool evaluates risks on three levels: building, façade, and product. For each level, a weighted evaluation is provided, indicating:

	Low risk	Although less critical, care should still be given to ensure basic safety measures are in place.
	Moderate risk	Care should be taken to implement appropriate safety measures to manage the identified risks.
	High risk	Extra care and higher levels of measures should be implemented to mitigate the risk effectively.

Figure 74: Risk evaluation meaning. Own work

It is important to note that these evaluations indicate the level of risk but do not determine whether it is acceptable or not. For example, a red evaluation does not mean that the situation is unacceptable but rather that it carries a high risk and extra care and higher levels of measures should be implemented to mitigate the risk effectively.

Each risk evaluation is determined by the product of all risk factors from the chosen design considerations (Figure 75). Depending on the total value and the threshold values shown in Figure 76, the risk evaluation indicates either a green, yellow, or red risk.

128
(8) Yes, over more than two fire compartments
(1) No, each BIPV cavity is limited to a single fire
(2) Yes, distributed openings
(1) No
(4) No
(2) Yes, BIPV modules are situated above multiple
(1) No
(1) The facade is subjected to the prevailing wind

Figure 75: Example risk factors evaluation. Own work.

Threshold values risk scores			
Building characteristics	< 16	16 - 63	> 63
Façade characteristics	< 16	16 - 95	> 95
BIPV & facade product characteristics	< 16	16 - 100	> 100

Figure 76: Risk evaluation threshold values. Own work

5.1.4 Design support tool: a tiered approach

Given the complexity and numerous variables affecting the fire safety of BIPV façade systems, this design support tool is not intended to replace the detailed analysis provided by professional fire safety consultants. Instead, it aims to offer practical, general-level knowledge.

Creating a tool that mirrors the depth of advice from fire safety consultants requires including many relevant parameters. However, integrating all these parameters can make the tool extensive and time-consuming, discouraging users who need quick, straightforward information. Balancing depth with usability is a key challenge in tool design. To address this, the insights from this study are divided into two distinct products, each tailored to provide a different level of depth and meet diverse user needs. (Figure 56).

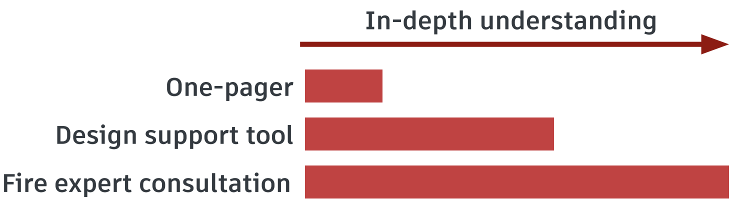


Figure 77: In-depth understanding fire safety BIPV façades per product. Own work

One pager | This document of one page contains the most relevant information about BIPV façade systems and their risks related to fire (Figure 72). It presents the key safety measures and risks in a format that is brief, yet informative. Additionally, by focussing on visual presentation, the aim is to facilitate the rapid absorption and retention of information, making it fit for users who want to grasp the most essential knowledge quickly, making it fit for not just for designers but also for a wider target group (e.g. developers, clients, etc.). This broader accessibility enables that essential safety knowledge can also be quickly and effectively communicated to various other stakeholders.

Design support tool | The design support tool is designed for users requiring a detailed understanding of fire safety in BIPV façade systems. This tool accounts for 23 risk parameters, offering detailed information on each and allowing users to input and adjust their design considerations accordingly. It evaluates the impact of each design choice through risk factors, provides preliminary advice on modifying critical design considerations, and suggests measures and strategies to achieve a fire-safe design based on user inputs.

5.1.5 Design support tool: who is the intended user?

The design support tool aims to spread knowledge on achieving fire-resilient buildings with BIPV systems in façades, addressing the gap in the regulatory framework. It targets a specific user group to ensure practicality and relevance to their needs. Focusing on designers, including architects and façade engineers, is strategic as they significantly influence building design. By equipping them with knowledge about fire safety in BIPV façade systems, the tool can enhance informed decision-making during the design process. As designers adopt these principles, they can potentially set benchmarks for industry-wide fire safety standards.

While the tool is designed for designers, it may also benefit other stakeholders like BIPV manufacturers, fire safety consultants, developers, and clients. However, since its content is tailored for designers, it might not fully meet the needs of other users. For example, the technical considerations may be too complex for clients. To address this, a one-pager has been developed to enhance the tool's overall impact in promoting fire safety in BIPV-equipped buildings.

5.1.6 Design support tool: when to use?

The tool is most effective at the earliest stages of the design process to provide comprehensive guidance on design considerations, measures, and strategies at varying levels of detail. It offers advice on different levels of detail, for example, on façade layout for BIPV module placement and lower-level advice regarding materiality and detailing. Implementing these considerations early is crucial, as changes made later can disrupt completed work and require time-consuming revisions. However, the design support tool is not limited to early-stage use. If introduced later in the process, it can serve as a validation tool to ensure earlier decisions align with best practices (Figure 78). As design choices evolve, users can immediately see the impact of these changes by re-evaluating the situation with the tool, allowing for real-time adjustments and refinements to maintain optimal safety and performance.

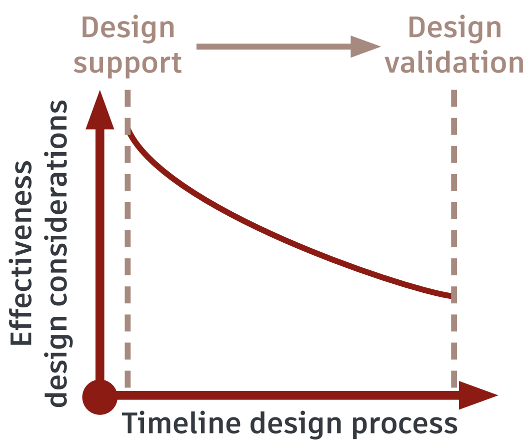


Figure 78: Design support tool usage. Own work

5.1.7 Design support tool: how to utilize the tool optimally?

To maximize the effectiveness of the design support tool, it is recommended to use and fill it in individually. By doing so, the designer can develop a foundational body of knowledge, which can then be applied during key stages of the design process, such as at the drawing table, in discussions with stakeholders, and during design presentations.

Using the tool at the drawing table | When used at the drawing table, the tool not only provides specific guidance on integrating fire safety considerations into architectural designs but also facilitates a variant or parameter study, supporting the search for the best-fit solution. This process helps identify which design parameters have the most significant influence on enhancing the building's fire resilience, allowing designers to make informed decisions about material choices and façade configuration

Using the tool in discussions with stakeholders | In discussions with stakeholders, the tool can serve as a reference that substantiates design choices. This supports productive conversations, ensuring that all parties understand the importance of fire safety measures and agree on the best practices to implement.

Using the tool in design presentations | During design presentations, the tool can help designers showcase the rationale behind their design decisions, particularly regarding fire safety. This enhances the credibility of their proposals and demonstrates a commitment to building safety.

It is not recommended to fill in the tool collaboratively in larger groups. The reason for this is twofold: first, the tool contains a substantial amount of detailed information which can take considerable time to process and discuss. Group settings might lead to prolonged sessions that could reduce the focus or lead to consensus challenges. If the goal of such a session is to leverage diverse perspectives to enhance understanding, then this approach can be beneficial, but the user should be aware of the potential for this dynamic to arise. Second, the detailed and specific nature of the information might need individual reflection to fully understand and apply the insights to one's specific situation. This is harder to achieve in a group setting, where different opinions and interpretations can make it difficult to grasp and implement the information clearly.

However, if it is opted for to collaboratively fill in the tool in larger groups, it is crucial to strategize the session carefully beforehand. Consider which aspects of the tool are essential for group input and limit the focus to those to prevent overwhelming participants with too much information. For example, it might be beneficial to concentrate on filling in only the risk overview sheet and retrieve preliminary advices from the façade overview sheets during group sessions. This approach helps streamline the discussion and ensures that all participants engage with the most relevant data effectively, enhancing productivity and clarity.

5.2 Design support tool

This chapter introduces the design support tool developed from the knowledge gained in previous chapters. It details the tool's setup, highlighting the functionalities and possibilities of each sheet. Step-by-step instructions and explanations on how to navigate the tool, input data, and interpret results to make informed design decisions.

5.2.1 Design support tool: setup

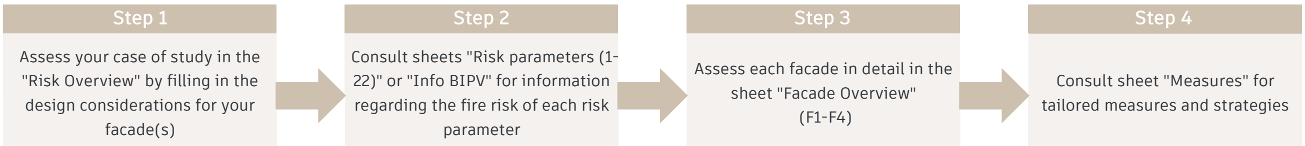


Figure 79: Four-stepped guide design support tool. Own work

Figure 79 outlines a four-stepped approach on how to effectively use the tool, providing a structured method for engaging with its features. Below is an overview of the various sheets included in the tool:

Home | Serving as the home page of the tool, this sheet offers essential information about the tool, helping users understand its structure and purpose.

Info BIPV | This sheet provides basic information about the fire safety of BIPV façade systems. It covers the fundamental fire risks and the key considerations for incorporating BIPV safely into façade designs.

Risk overview | This is the main sheet of the tool and is the only sheet where users can input data. Users can enter all relevant design considerations for various risk parameters and assess the impact of each through specified risk factors, enabling a holistic view of potential vulnerabilities

Façade overview (F1-F4) | These sheets offer a more detailed analyses for each façade, derived from data entered in the "Risk Overview" sheet, and provides a brief comment/advice on each design consideration.

Measures | This sheet provide a series of measures and strategies that the user can or should employ, based on the input in the "Risk overview" sheet.

Risk parameters(1-22) | These sheets provide more detailed information on each of the 22 risk parameters. They offer insights and data, helping users understand the nuances and implications of each risk parameter.

The upcoming sub-chapters titled "Design support tool sheet elaboration: ..." will not showcase all the sheets developed for the tool but will instead highlight the most relevant ones. For an overview of all the Excel sheets, please refer to Appendix II.

5.2.2 Design support tool sheet elaboration: Home

As the home sheet of the tool, this sheet serves as an introduction to the tool explaining about:

1 | Sheet setup
2 | How to use the tool?
3 | Information on risk factors and evaluation categories
4 | What does the tool do?
5 | Who is the intended user?
6 | When to use the tool?
7 | How to utilize the tool optimally?

Moreover, it includes a guide detailing the tool's setup and functionalities, which can be found in Appendix II. This guide provides users with a more detailed explanation about the sheet setup and functionalities, ensuring a thorough understanding of how to navigate and utilize the tool.

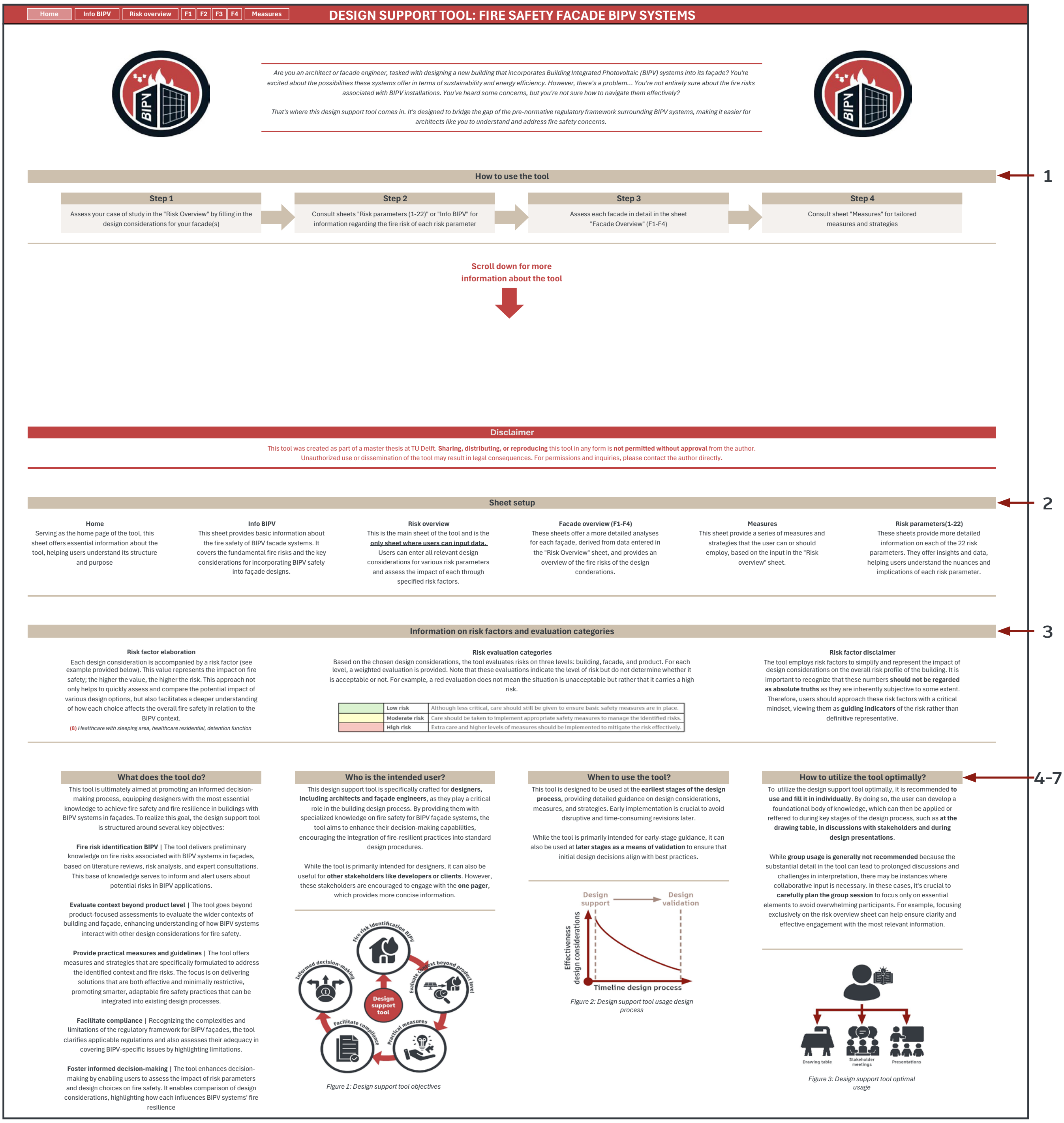


Figure 80: Design support tool sheet: Home. Own work

5.2.3 Design support tool sheet elaboration: info BIPV

This sheet currently showcases the one-pager, which is shown 4.4.3 One-pager, and provides basic information about the fire safety of BIPV façade systems. It covers the fundamental fire risks and the key considerations for incorporating BIPV safely into façade designs. This page could also be transformed such that it focusses more on elaborating the basics of BIPV systems, providing a summary of the information highlighted in Chapter 2.

5.2.4 Design support tool sheet elaboration: Risk Overview

As the main sheet of the tool, this is the only sheet where users can input data. Designed to evaluate one building with up to four façades, this sheet has the following functionalities:

1 | **Façade selection.** Users can select the number of façades to be assessed. This choice dynamically updates the user interface across all sheets, displaying only the relevant sheets, columns, and rows associated with the selected façades.

2 | **Building characteristics.** This part is where the user inputs design considerations for risk parameters relevant to building characteristics. Each design consideration is tied to a specific risk factor value, affecting the overall risk assessment of the building. Based on the input, the overall risk level will be highlighted in green, yellow, or red, indicating low, moderate, or high risk, respectively.

3 | **Façade characteristics.** Same as building characteristics, focussing on façade characteristics.

4 | **Product characteristics.** Same as building characteristics, focussing on product characteristics.

5 | **Overview risk score.** This part creates an overview of the risk scores for all three levels of details for each façade, allowing the user to easily compare results.

To facilitate ease of use and clarify where data should be entered, cells designated for user input are highlighted with red text font. More detailed elaboration of the sheet can be viewed in Appendix II.

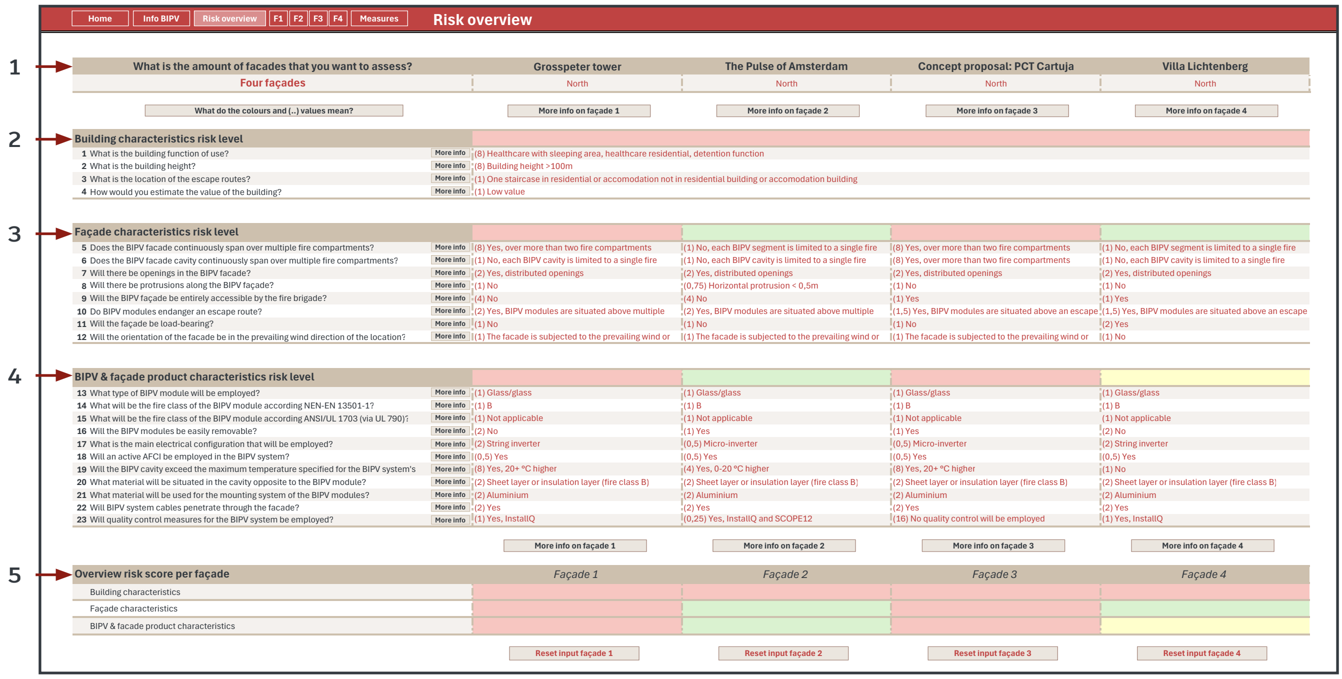


Figure 81: Design support tool sheet: Risk Overview. Own work

5.2.5 Design support tool sheet elaboration: Façade Overview (F1-F4)

For each façade assessed in the "Risk Overview" sheet, a corresponding façade overview sheet provides a detailed analysis, expanding on the data from the "Risk Overview" sheet. This detailed assessment allows users to thoroughly evaluate each façade, enhancing their awareness of potential impacts and encouraging reconsideration of design choices, especially in high-risk scenarios.

1 | **Risk overview input.** This section highlights the data input for the selected façade from the "Risk Overview" sheet, ensuring that users have a clear reference to the information used in the assessment.

2 | **Influence on fire safety.** For each risk parameter, a brief note is provided on the chosen design consideration explaining about it's impact on fire safety. This helps users understand the implications of their design decisions on overall safety. This note is extracted from the risk parameter sheets (Figure 85.5).

3 | **Risk impact.** The impact of each design consideration is emphasized through visual representation to enhance the user's comprehension of potential risks. This visual approach allows the users to quickly grasp the severity and implications of their design choices.

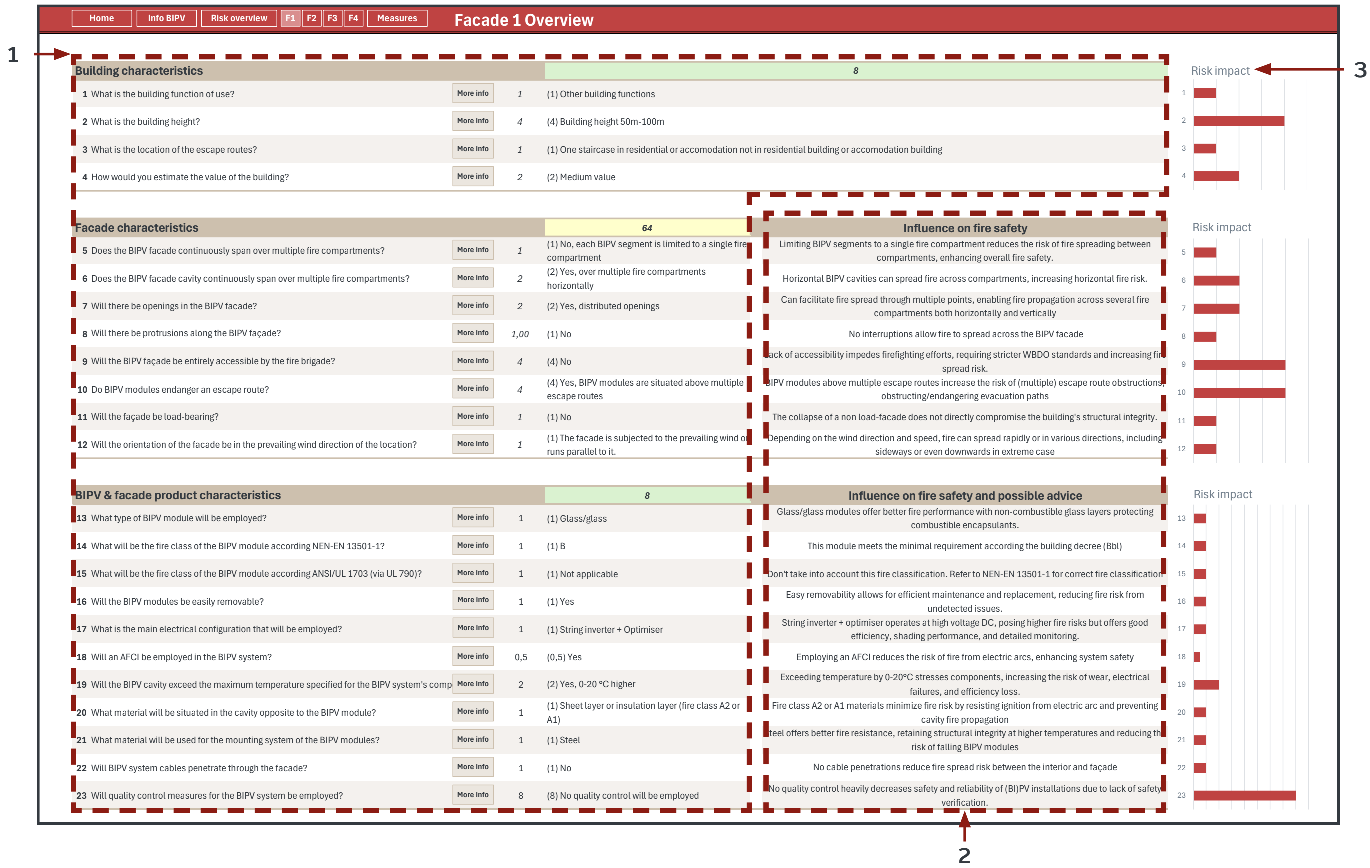


Figure 82: Design support tool sheet: Façade Overview. Own work

5.2.6 Design support tool sheet elaboration: Risk Parameters (1-23)

These sheets provide more detailed information on each of the 23 risk parameters, helping users understand the nuances and implications of each risk parameter. Each risk parameter sheet contains a similar layout, providing information on the following:

1 | Risk parameter. This section outlines the specific question and design considerations related to the parameter, along with an optional elaboration for additional context.
2 | What to fill in? This section provides a brief elaboration on the risk parameter question and, if needed, additional guidance on the design considerations.
3 | Fire risk. This section details the fire risk of the risk parameter and each design consideration, enabling users to make informed decisions regarding safety.
4 | Supporting images. To improve understanding, images are included that visually represent the fire risk information.
5 | Fire risk note. Each sheet includes a hidden column with a note on the fire safety of the design consideration (Figure 85), which is extracted for the "Façade Overview" sheet (Figure 82.2).

Figure 83: Design support tool sheet: Risk Parameter (4). Own work

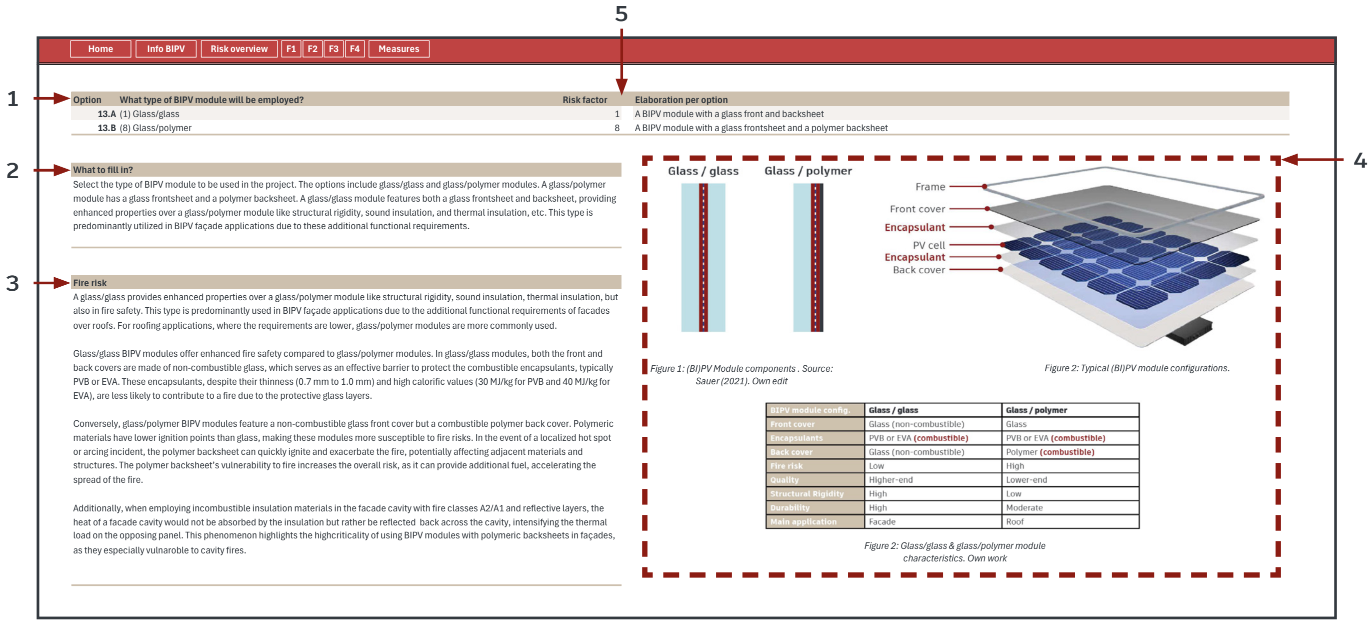


Figure 84: Design support tool sheet: Risk Parameter (13). Own work

Option	What type of BIPV module will be employed?	Risk factor	Note
13.A	(1) Glass/glass	1	Glass/glass modules offer better fire performance with non-combustible glass layers protecting combustible encapsulants.
13.B	(8) Glass/polymer	8	Glass/polymer modules pose higher fire risks due to combustible polymer backsheets, increasing susceptibility to ignition and fire spread

Figure 85: Design support tool sheet: Risk Parameter (13) hidden fire risk note. Own work

5.2.7 Design support tool sheet elaboration: Measures

This sheet provide a series of measures and strategies that the user can or should employ, based on the input in the "Risk overview" sheet. Depending on the importance and nature of each measure or strategy, the advice is presented as either a suggestion or a requirement. Suggestions are phrased as recommendations (e.g., "Consider ...", "Think about..."), while requirements are presented as mandatory actions (e.g., "Ensure ...").

1 | **Compliance.** This section highlights the relevant compliance requirements for BIPV façades in the Netherlands.
2 | **General measures.** This section provides essential measures that should always be considered, regardless of the building's design context.
3 | **Façade measures.** Based on the input data from the "Risk Overview" sheet, this section offers tailored measures and strategies specific to each façade. This overview is generated via the sheet "Measures_Source" (Figure 87). The number of measures vary with the risk level of the façade: higher-risk façades have more measures, while lower-risk façades have fewer. Additionally, the measures are presented in a risk-oriented hierarchy, with the most effective or essential measures shown first.

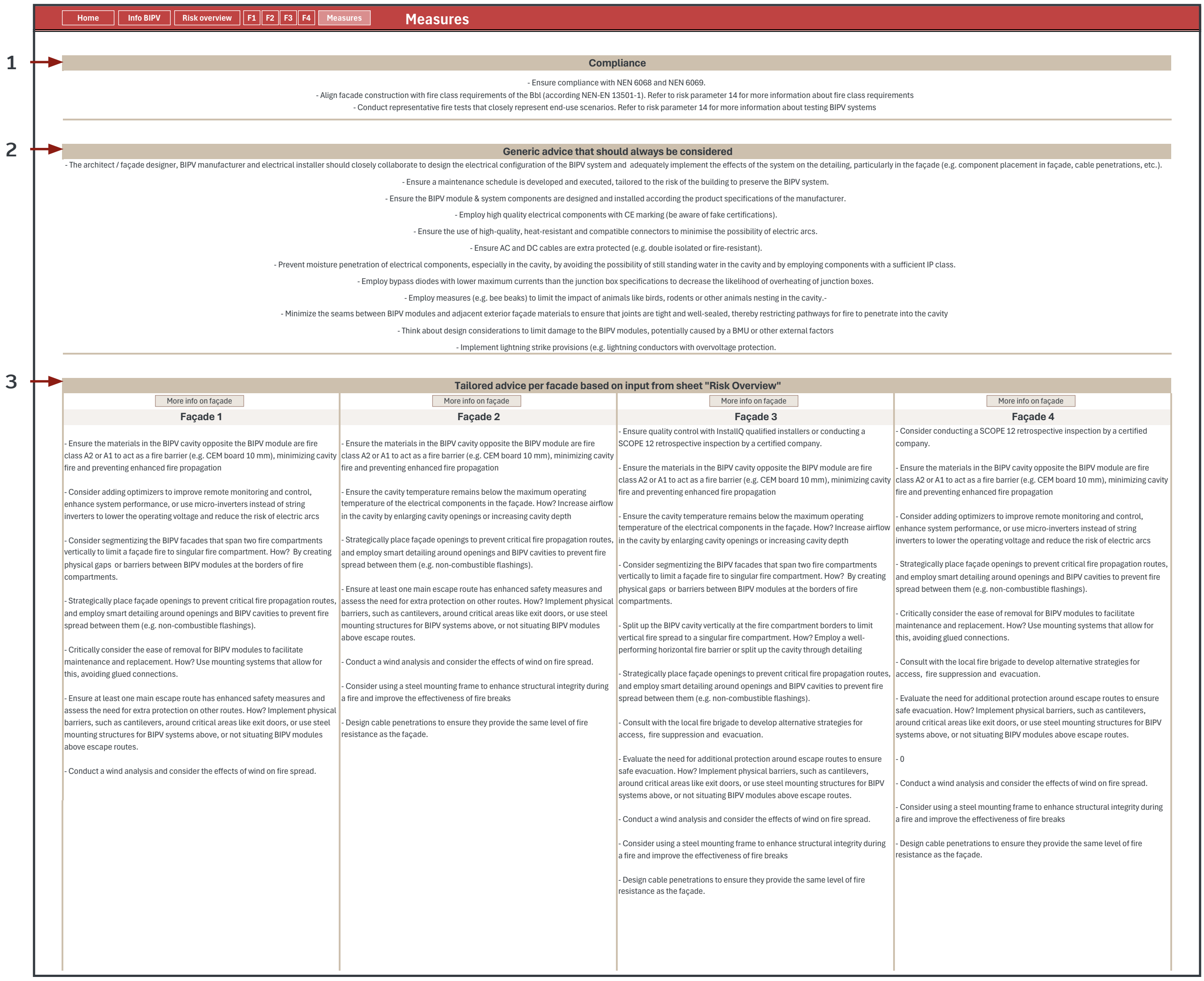
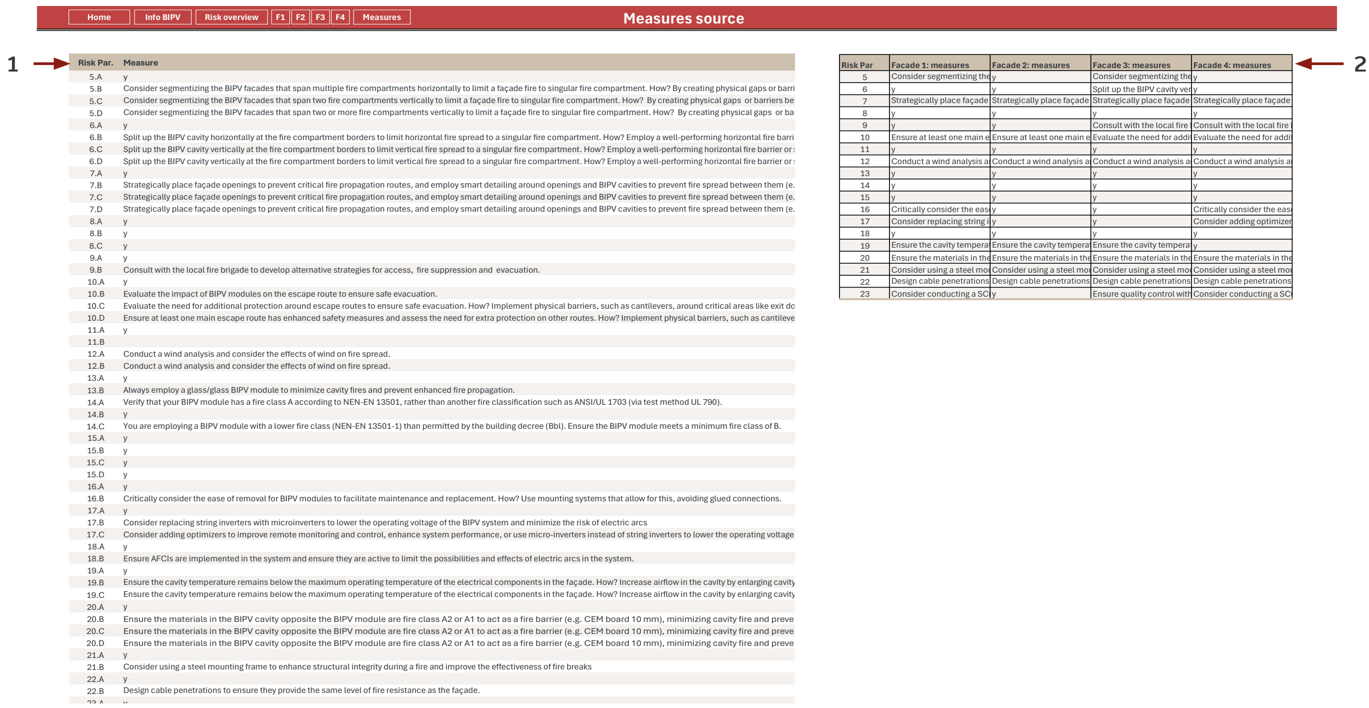


Figure 86: Design support tool sheet: Measures. Own work

5.2.8 Design support tool sheet elaboration: Measures_Source (hidden)

The "Measures_Source" sheet is hidden for the user, but enhances the interactivity and effectiveness of the "Measures" sheet by generating a tailored overview.

1 | Measures. This table lists the relevant measures or strategies linked to specific design considerations.
2 | Measures link to input data. This table connects user input from the "Risk Overview" sheet to the applicable measures (1 | Measures overview).



Risk Par.	Measure
5.A	y
5.B	Consider segmentizing the BIPV facades that span multiple fire compartments horizontally to limit a façade fire to singular fire compartment. How? By creating physical gaps or barri
5.C	Consider segmentizing the BIPV facades that span two fire compartments vertically to limit a façade fire to singular fire compartment. How? By creating physical gaps or barriers be
5.D	Consider segmentizing the BIPV facades that span two or more fire compartments vertically to limit a façade fire to singular fire compartment. How? By creating physical gaps or ba
6.A	y
6.B	Split up the BIPV cavity horizontally at the fire compartment borders to limit horizontal fire spread to a singular fire compartment. How? Employ a well-performing horizontal fire barri
6.C	Split up the BIPV cavity vertically at the fire compartment borders to limit vertical fire spread to a singular fire compartment. How? Employ a well-performing horizontal fire barrier or
6.D	Split up the BIPV cavity vertically at the fire compartment borders to limit vertical fire spread to a singular fire compartment. How? Employ a well-performing horizontal fire barrier or
7.A	y
7.B	Strategically place façade openings to prevent critical fire propagation routes, and employ smart detailing around openings and BIPV cavities to prevent fire spread between them (e.
7.C	Strategically place façade openings to prevent critical fire propagation routes, and employ smart detailing around openings and BIPV cavities to prevent fire spread between them (e.
7.D	Strategically place façade openings to prevent critical fire propagation routes, and employ smart detailing around openings and BIPV cavities to prevent fire spread between them (e.
8.A	y
8.B	y
8.C	y
9.A	y
9.B	Consult with the local fire brigade to develop alternative strategies for access, fire suppression and evacuation.
10.A	y
10.B	Evaluate the impact of BIPV modules on the escape route to ensure safe evacuation.
10.C	Evaluate the need for additional protection around escape routes to ensure safe evacuation. How? Implement physical barriers, such as cantilevers, around critical areas like exit do
10.D	Ensure at least one main escape route has enhanced safety measures and assess the need for extra protection on other routes. How? Implement physical barriers, such as cantileve
11.A	y
11.B	
12.A	Conduct a wind analysis and consider the effects of wind on fire spread.
12.B	Conduct a wind analysis and consider the effects of wind on fire spread.
13.A	y
13.B	Always employ a glass/glass BIPV module to minimize cavity fires and prevent enhanced fire propagation.
14.A	Verify that your BIPV module has a fire class A according to NEN-EN 13501, rather than another fire classification such as ANSI/UL 1703 (via test method UL 790).
14.B	y
14.C	You are employing a BIPV module with a lower fire class (NEN-EN 13501-1) than permitted by the building decree (Bbl). Ensure the BIPV module meets a minimum fire class of B.
15.A	y
15.B	y
15.C	y
15.D	y
16.A	y
16.B	Critically consider the ease of removal for BIPV modules to facilitate maintenance and replacement. How? Use mounting systems that allow for this, avoiding glued connections.
17.A	y
17.B	Consider replacing string inverters with microinverters to lower the operating voltage of the BIPV system and minimize the risk of electric arcs
17.C	Consider adding optimizers to improve remote monitoring and control, enhance system performance, or use micro-inverters instead of string inverters to lower the operating voltage
18.A	y
18.B	Ensure AFCIs are implemented in the system and ensure they are active to limit the possibilities and effects of electric arcs in the system.
19.A	y
19.B	Ensure the cavity temperature remains below the maximum operating temperature of the electrical components in the façade. How? Increase airflow in the cavity by enlarging cavity
19.C	Ensure the cavity temperature remains below the maximum operating temperature of the electrical components in the façade. How? Increase airflow in the cavity by enlarging cavity
20.A	y
20.B	Ensure the materials in the BIPV cavity opposite the BIPV module are fire class A2 or A1 to act as a fire barrier (e.g. CEM board 10 mm), minimizing cavity fire and preve
20.C	Ensure the materials in the BIPV cavity opposite the BIPV module are fire class A2 or A1 to act as a fire barrier (e.g. CEM board 10 mm), minimizing cavity fire and preve
20.D	Ensure the materials in the BIPV cavity opposite the BIPV module are fire class A2 or A1 to act as a fire barrier (e.g. CEM board 10 mm), minimizing cavity fire and preve
21.A	y
21.B	Consider using a steel mounting frame to enhance structural integrity during a fire and improve the effectiveness of fire breaks
22.A	y
22.B	Design cable penetrations to ensure they provide the same level of fire resistance as the façade.

Risk Par	Facade 1: measures	Facade 2: measures	Facade 3: measures	Facade 4: measures
5	Consider segmentizing the	y	Consider segmentizing the	y
6	y	y	Split up the BIPV cavity ver	y
7	Strategically place façade	Strategically place façade	Strategically place façade	Strategically place façade
8	y	y	y	y
9	y	y	Consult with the local fire	Consult with the local fire
10	Ensure at least one main e	Ensure at least one main e	Evaluate the need for addi	Evaluate the need for addi
11	y	y	y	y
12	Conduct a wind analysis a	Conduct a wind analysis a	Conduct a wind analysis a	Conduct a wind analysis a
13	y	y	y	y
14	y	y	y	y
15	y	y	y	y
16	Critically consider the eas	y	y	Critically consider the eas
17	Consider replacing string i	y	y	Consider adding optimizer
18	y	y	y	y
19	Ensure the cavity tempera	Ensure the cavity tempera	Ensure the cavity tempera	y
20	Ensure the materials in the	Ensure the materials in the	Ensure the materials in the	Ensure the materials in the
21	Consider using a steel mo	Consider using a steel mo	Consider using a steel mo	Consider using a steel mo
22	Design cable penetrations	Design cable penetrations	Design cable penetrations	Design cable penetrations
23	Consider conducting a SC	y	Ensure quality control with	Consider conducting a SC

Figure 87: Design support tool sheet: Measures_Source. Own work

Refer to Appendix III for the Excel functions utilized to generate the tailored measures

5.2.9 Design support tool elaboration: user interface

The tool has several features to improve the user experience, utilizing Excel functions and VBA code. An overview of the features not yet highlighted in the previous "sheet elaboration" sub-chapters:

Navigation bar | To facilitate easy navigation throughout the tool, each sheet is equipped with a navigation bar that guides users through the main sheets (Figure 88).

Figure 88: Navigation bar. Own work

Reference buttons | Throughout the tool, several buttons are added to navigate to other sheets (Figure 89), allowing the user to move easily between different parts of the tool.

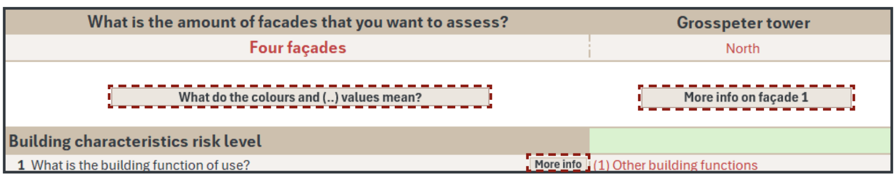


Figure 89: Reference buttons. Own work

Amount of façades | On the "Risk Overview" sheet, users can select the number of façades they want to assess, with a maximum of four. Based on this selection, the interface dynamically adjusts in the following aspects: façade column visibility "Risk Overview" sheet, façade column visibility "Measures" sheet, "Façade" sheet visibility, navigation bar button "F1-F4" visibility on all sheets. This filter is implemented using VBA module: RiskOverview_Filter_Façade_Amount.

Reset input | At the "Risk Overview Sheet", the user can easily reset the input of a façade for all design considerations (Figure 90). This reset button is implemented using VBA module: Protect_Unprotect.

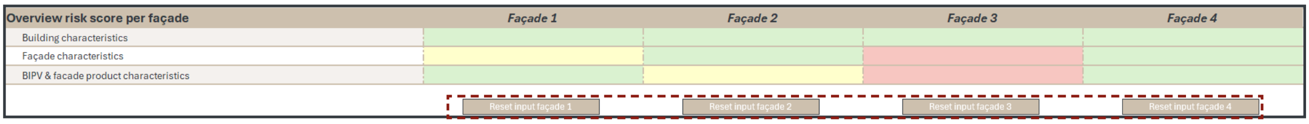


Figure 90: Reset input. Own work

Protection sheets | To prevent users from editing cells they are not supposed to modify, all sheets and cells are protected, with the exception of cells in the "Risk Overview" sheet where the text is colored red. This protection is implemented using VBA module: RiskOverview_Reset_Input.

Disclaimers | To make users aware of the tool's limitations and responsibilities, two disclaimers are displayed every time the Excel tool is opened. This disclaimers are implemented using VBA module: Disclaimer

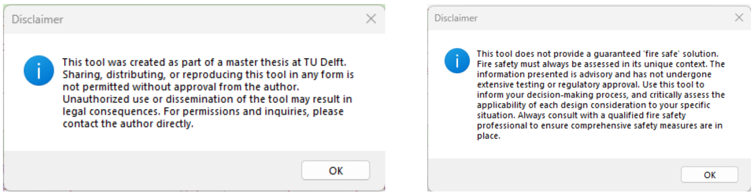


Figure 91: Disclaimers. Own work

Refer to Appendix III for the code of the VBA modules

5.3 Design support tool development

This chapter details the development process of the design support tool, explaining the rationale behind the visibility of risk factor evaluations and the definition and refinement of risk factors. It describes how case studies were employed to enhance the tool's accuracy and reliability. Additionally, it highlights the incorporation of user feedback from various stakeholders, ensuring the tool's practicality and effectiveness.

5.3.1 Risk factor evaluation visibility user

A deliberate choice has been made not to show the risk factor evaluation values and threshold values to the user. Displaying these was found to potentially lead to misuse, misinterpretation, or selective focus on certain factors, undermining the tool's goal and effectiveness. Additionally, users might prioritize risk factor values over holistic safety considerations. Therefore, users only see a green, yellow, or red evaluation without a total risk factor, fostering the focus remains on overall fire safety rather than individual risk scores.

16	
(2) Yes, over multiple fire compartments	(2) Yes, over multiple fire compartments
(2) Yes, over multiple fire compartments	(2) Yes, over multiple fire compartments
(1) No	(1) Yes, horizontal continuous openings
(1) No	(1) No
(1) Yes	(1) Yes
(4) Yes, BIPV modules are situated above	(4) Yes, BIPV modules are situated above
(1) No	(1) No
(1) The facade is subjected to the prevailing wind	(1) The facade is subjected to the prevailing wind

Figure 92: Example risk factors evaluation (left: actual values, right: user interface). Own work.

Threshold values risk scores			
Building characteristics	< 16	16 - 63	> 63
Façade characteristics	< 16	16 - 95	> 95
BIPV & facade product characteristics	< 16	16 - 100	> 100

Figure 93: Risk evaluation threshold values (hidden). Own work

5.3.2 Defining risk factors

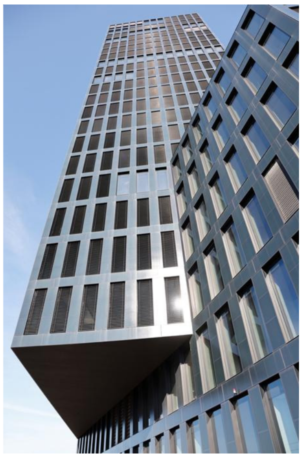
The risk factors employed for the tool represent the relative risk from a "zero-risk" situation. The initial determination of these values was based on the documents "Risicotool brandveiligheid gevels" (DGMR, 2019) and "Borgingsprotocol" (Nieman & DGMR, 2022). However, since these documents focused on fewer and different risk parameters, additional adjustments and considerations were made to tailor the risk factors specifically to the context of BIPV façade systems.

Subsequently, risk factors were adjusted through education reasoning, utilizing the knowledge gained through this study. The last refinement step involved fine-tuning the risk factors by employing 8 case studies in the tool. The case studies are highlighted in the next two pages. By utilizing these case studies, the goal was to align the tool's risk evaluations (green/yellow/red) with how a fire safety expert would assess such situations. This iterative process ensured that the tool's evaluations were more representative, enhancing its reliability.

Due to a lack of data, especially for product-level design considerations, some assumptions were made. This allowed the completion of the risk evaluation framework, ensuring the tool provides valuable guidance despite data limitations. Assumptions were always made for the following risk parameters:

16 Removability modules
17 BIPV system: electrical configurations
18 AFCIs
19 Design temperature of façade cavity
23 Quality control

Notable characteristics which are assumptions are marked with * on the following two pages.

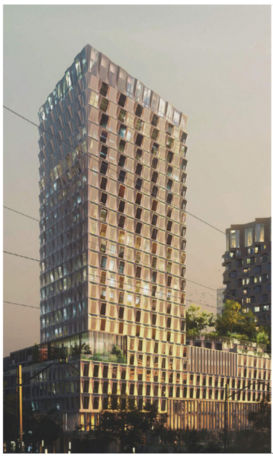
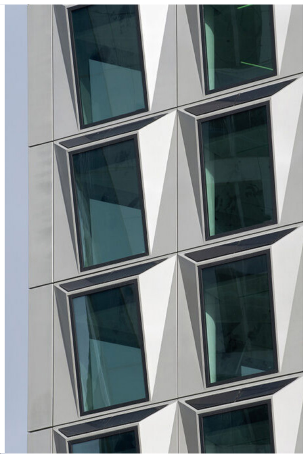



Case 1:
Grosspeter Tower (Basel, Switserland)
Source: Hueck (2023)

Notable characteristics
- High-rise office building (two escape routes)
- BIPV modules span entire façade (highly critical without effective fire barriers).
- No ventilation openings spotted, potentially high cavity temperatures.
++ AFCI*
+ InstallQ*

Prediction risk evaluation

Building	Façade	Product

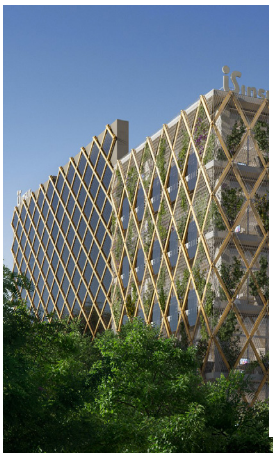
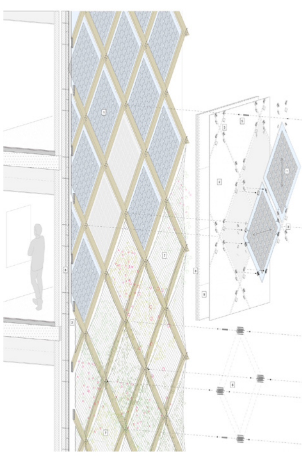



Case 2:
The Pulse of Amsterdam (Amsterdam, The Netherlands)
Source: (VORM & EDGE, 2023)

Notable characteristics
-- High-rise office building (one escape route*)
+ Segmentation BIPV modules/cavities
+ Micro-inverter
+ AFCI
++ InstallQ + SCOPE12*

Prediction risk evaluation

Building	Façade	Product

Case 3:
Concept proposal: PCT Cartuja (Sevilla, Spain)
Source: Biren & AGi architects (2023)

Notable characteristics
- Mid-rise residential building
- BIPV modules span entire façade
-- Combustible materials façade cavity
++ AFCI*
--- No quality control*

Prediction risk evaluation

Building	Façade	Product

Case 4:
Villa Lichtenberg (Amersfoort, The Netherlands)
Source: Solarix (2023)

Notable characteristics
++ Low-rise residential house
- Combustible materials façade cavity
+- String inverter*
++ AFCI*
+ InstallQ*

Prediction risk evaluation

Building	Façade	Product

Case 5:
Breeze Hotel (Amsterdam, The Netherlands)
Source: De Ingenieur (2019)

Notable characteristics
-     Mid-rise hotel
+   Segmentation BIPV modules/cavities
++   AFCI*
---   No quality control*

Prediction risk evaluation

Building	Façade	Product

Case 6:
Soltech factory (Thorpark Gent, Belgium)
Source: Kameleon Solar & Soltech (2024)

Notable characteristics
++   Low-rise factory
+   Small BIPV segment with no direct trajectory to façade opening
++   AFCI*
+   InstallQ*

Prediction risk evaluation

Building	Façade	Product

Case 7:
Bornholms Hospital (Bornholm, Denmark)
Source: Sehati et al. (2019)

Notable characteristics
--   Low-rise hospital
-     BIPV façade spans multiple fire compartments
++   AFCI*
+   InstallQ*

Prediction risk evaluation

Building	Façade	Product

Case 8:
ROTT UP (Rotterdam, The Netherlands)
Source: own student project (MEGA, 2023)

Notable characteristics
--   High-rise residential building
-     Wooden façade modules
+   Segmentation BIPV modules/cavities
--   No AFCI*
++   SCOPE12*

Prediction risk evaluation

Building	Façade	Product

What is the amount of facades that you want to assess?		Grosspeter tower	The pulse of amsterdam	Concept proposal: PCT Cartuja	Villa Lichtenberg
One façade		North	North	North	North
What do the colours and (..) values mean?		More info on façade 1	More info on façade 1	More info on façade 1	More info on façade 1
Building characteristics risk level					
1 What is the building function of use?	More info	(1) Other building functions	(4) Residential in a residential building, accomodation i	(4) Residential in a residential building, accomodation i	(1) Other building functions
2 What is the building height?	More info	(4) Building height 50m-100m	(8) Building height >100m	(2) Building height 15m-50m	(1) Building height <15m
3 What is the location of the escape routes?	More info	(2) Two staircases on distance <H/2 in two cores	(2) Two staircases on distance <H/2 in two cores	(2) Two staircases on distance <H/2 in two cores	(1) One staircase in residential or accomodation not in
4 How would you estimate the value of the building?	More info	(2) Medium value	(4) High value	(2) Medium value	(1) Low value
Façade characteristics risk level					
5 Does the BIPV facade continuously span over multiple fire compartments?	More info	(8) Yes, over more than two fire compartments	(1) No, each BIPV segment is limited to a single fire	(8) Yes, over more than two fire compartments	(1) No, each BIPV segment is limited to a single fire
6 Does the BIPV facade cavity continuously span over multiple fire compartments?	More info	(1) No, each BIPV cavity is limited to a single fire	(1) No, each BIPV cavity is limited to a single fire	(8) Yes, over more than two fire compartments	(1) No, each BIPV cavity is limited to a single fire
7 Will there be openings in the BIPV facade?	More info	(2) Yes, distributed openings	(2) Yes, distributed openings	(2) Yes, distributed openings	(2) Yes, distributed openings
8 Will there be protrusions along the BIPV façade?	More info	(1) No	(0,75) Horizontal protrusion < 0,5m	(1) No	(1) No
9 Will the BIPV façade be entirely accessible by the fire brigade?	More info	(4) No	(4) No	(1) Yes	(1) Yes
10 Do BIPV modules endanger an escape route?	More info	(2) Yes, BIPV modules are situated above multiple	(2) Yes, BIPV modules are situated above multiple	(1,5) Yes, BIPV modules are situated above an escape	(1,5) Yes, BIPV modules are situated above an escape
11 Will the façade be load-bearing?	More info	(1) No	(1) No	(1) No	(2) Yes
12 Will the orientation of the facade be in the prevailing wind direction of the location?	More info	(1) The facade is subjected to the prevailing wind or	(1) The facade is subjected to the prevailing wind or	(1) The facade is subjected to the prevailing wind or	(1) No
BIPV & façade product characteristics risk level					
13 What type of BIPV module will be employed?	More info	(1) Glass/glass	(1) Glass/glass	(1) Glass/glass	(1) Glass/glass
14 What will be the fire class of the BIPV module according NEN-EN 13501-1?	More info	(1) B	(1) B	(1) B	(1) B
15 What will be the fire class of the BIPV module according ANSI/UL 1703 (via UL 790)?	More info	(1) Not applicable	(1) Not applicable	(1) Not applicable	(1) Not applicable
16 Will the BIPV modules be easily removable?	More info	(2) No	(1) Yes	(1) Yes	(2) No
17 What is the main electrical configuration that will be employed?	More info	(2) String inverter	(0,5) Micro-inverter	(0,5) Micro-inverter	(2) String inverter
18 Will an AFCI be employed in the BIPV system?	More info	(0,5) Yes	(0,5) Yes	(0,5) Yes	(0,5) Yes
19 Will the BIPV cavity exceed the maximum temperature specified for the BIPV system's	More info	(8) Yes, 20+ °C higher	(4) Yes, 0-20 °C higher	(4) Yes, 0-20 °C higher	(1) No
20 What material will be situated in the cavity opposite to the BIPV module?	More info	(2) Sheet layer or insulation layer (fire class B)	(2) Sheet layer or insulation layer (fire class B)	(2) Sheet layer or insulation layer (fire class B)	(2) Sheet layer or insulation layer (fire class B)
21 What material will be used for the mounting system of the BIPV modules?	More info	(2) Aluminium	(2) Aluminium	(2) Aluminium	(2) Aluminium
22 Will BIPV system cables penetrate through the facade?	More info	(2) Yes	(2) Yes	(2) Yes	(2) Yes
23 Will quality control measures for the BIPV system be employed?	More info	(1) Yes, InstallQ	(0,25) Yes, InstallQ and SCOPE12	(16) No quality control will be employed	(1) Yes, InstallQ

Figure 94: Case study results (1-4). Own work.

What is the amount of facades that you want to assess?		Hotel Breeze	Soltech Factory	Bornholms Hospital	Rott Up
One façade		North	North	North	North
What do the colours and (..) values mean?		More info on façade 1	More info on façade 1	More info on façade 1	More info on façade 1
Building characteristics risk level					
1 What is the building function of use?	More info	(4) Residential in a residential building, accomodation i	(1) Other building functions	(8) Healthcare with sleeping area, healthcare residentia	(4) Residential in a residential building, accomodation i
2 What is the building height?	More info	(2) Building height 15m-50m	(2) Building height 15m-50m	(2) Building height 15m-50m	(8) Building height >100m
3 What is the location of the escape routes?	More info	(2) Two staircases on distance <H/2 in two cores	(2) Two staircases on distance <H/2 in two cores	(2) Two staircases on distance <H/2 in two cores	(4) Two staircases on distance <H/2 in one core
4 How would you estimate the value of the building?	More info	(2) Medium value	(2) Medium value	(2) Medium value	(4) High value
Façade characteristics risk level					
5 Does the BIPV facade continuously span over multiple fire compartments?	More info	(1) No, each BIPV segment is limited to a single fire	(1) No, each BIPV segment is limited to a single fire	(8) Yes, over more than two fire compartments	(1) No, each BIPV segment is limited to a single fire
6 Does the BIPV facade cavity continuously span over multiple fire compartments?	More info	(1) No, each BIPV cavity is limited to a single fire	(1) No, each BIPV cavity is limited to a single fire	(1) No, each BIPV cavity is limited to a single fire	(1) No, each BIPV cavity is limited to a single fire
7 Will there be openings in the BIPV facade?	More info	(2) Yes, distributed openings	(1) No	(2) Yes, distributed openings	(2) Yes, distributed openings
8 Will there be protrusions along the BIPV façade?	More info	(1) No	(1) No	(1) No	(1) No
9 Will the BIPV façade be entirely accessible by the fire brigade?	More info	(1) Yes	(1) Yes	(1) Yes	(1) Yes
10 Do BIPV modules endanger an escape route?	More info	(1) No	(1) No	(1,5) Yes, BIPV modules are situated above an escape	(1) No
11 Will the façade be load-bearing?	More info	(1) No	(1) No	(1) No	(1) No
12 Will the orientation of the facade be in the prevailing wind direction of the location?	More info	(1) The facade is subjected to the prevailing wind or	(1) No	(1) The facade is subjected to the prevailing wind or	(1) No
BIPV & façade product characteristics risk level					
13 What type of BIPV module will be employed?	More info	(1) Glass/glass	(1) Glass/glass	(1) Glass/glass	(1) Glass/glass
14 What will be the fire class of the BIPV module according NEN-EN 13501-1?	More info	(1) B	(1) B	(1) B	(1) B
15 What will be the fire class of the BIPV module according ANSI/UL 1703 (via UL 790)?	More info	(1) Not applicable	(1) Not applicable	(1) Not applicable	(1) Not applicable
16 Will the BIPV modules be easily removable?	More info	(2) No	(1) Yes	(2) No	(2) No
17 What is the main electrical configuration that will be employed?	More info	(1) String inverter + Optimiser	(1) String inverter + Optimiser	(2) String inverter	(1) String inverter + Optimiser
18 Will an AFCI be employed in the BIPV system?	More info	(0,5) Yes	(0,5) Yes	(0,5) Yes	(8) No
19 Will the BIPV cavity exceed the maximum temperature specified for the BIPV system's	More info	(1) No	(4) Yes, 0-20 °C higher	(4) Yes, 0-20 °C higher	(4) Yes, 0-20 °C higher
20 What material will be situated in the cavity opposite to the BIPV module?	More info	(2) Sheet layer or insulation layer (fire class B)	(1) Sheet layer or insulation layer (fire class A2 or A1)	(1) Sheet layer or insulation layer (fire class A2 or A1)	(2) Sheet layer or insulation layer (fire class B)
21 What material will be used for the mounting system of the BIPV modules?	More info	(2) Aluminium	(2) Aluminium	(2) Aluminium	(2) Aluminium
22 Will BIPV system cables penetrate through the facade?	More info	(2) Yes	(2) Yes	(2) Yes	(2) Yes
23 Will quality control measures for the BIPV system be employed?	More info	(16) No quality control will be employed	(1) Yes, InstallQ	(1) Yes, InstallQ	(0,5) Yes, SCOPE12

Figure 95: Case study results (5-8). Own work.

The results from filling in the case studies in the tool are shown in Figure 94 and Figure 95. Focusing on addressing design considerations with the highest risk factor is considered the most effective way to reduce risk. An overview of the critical design considerations is provided below:

Building level	**Façade level**	**Product level**
1 (8) Healthcare with sleeping area, healthcare residential, detention function 2 (8) Building height >100m 3 (8) One staircase 1 (6) Sleeping function with reduced self reliance 1 (4) Residential in a residential building, accommodation in an accommodation building 1 (4) Childcare with sleeping area 2 (4) Building height 50m-100m 3 (4) Two staircases on distance <H/2 in one core 4 (4) High value building	6 (8) BIPV cavity over more than two fire compartments vertically 5 (8) BIPV façade over more than two fire compartments vertically 6 (6) BIPV cavity over two fire compartments vertically 5 (4) BIPV façade over two fire compartments vertically 9 (4) BIPV façade not accessible by fire brigade 7 (3) Vertical continuous openings in façade 7 (2) Distributed openings in façade 10 (2) BIPV modules are situated above multiple escape routes	23 (16) No quality control 13 (8) Glass/polymer BIPV module 14 (8) BIPV module fire class C or lower (NEN-EN 13501-1) 18 (8) No AFCI 19 (8) Yes, 20+ °C higher temperature in cavity than specified for a BIPV system's component 20 (8) Materiality cavity: sheet layer or insulation layer (fire class D or lower) 20 (4) Materiality cavity: sheet layer or insulation layer (fire class C)

5.3.3 User feedback implementation

To improve the tool, it has been tested with a small group of people to gather feedback on its functionality, usability, and effectiveness in achieving its goals. Table 14 provides an overview of the feedback gathered from users other than the mentors, highlighting improvements or comments and indicating whether they have been implemented or are proposed as future developments.

To summarize, the principle of the tool was positively received. Feedback mostly focused on the need for more detailed guidance for façade engineers, the tool's educational value for those unfamiliar with BIPV systems, and its utility in communicating fire safety considerations to clients. Additional suggestions included enhancing the user interface, providing clearer explanations for risk evaluations, and ensuring the tool remains accessible and user-friendly. This feedback underscores the importance of professional tool development with experienced software developers to enhance usability and intuitive user experience. Collaboration with fire safety experts is crucial to ensure the tool's accuracy, comprehensiveness, and alignment with current and future regulations.

Feedback / experience	**Improvement / comment**	
BIPV façade manufacturer: Stefan Dewaffel (Soltech)		
The tool has too much information on first sight. Can be experienced by users as a hurdle once they look at the tool, scaring them off in utilizing it.	Improve the briefing when sending out the tool, highlighting the extend of information, but that the tool can be used in 4 simple steps. Note: this feedback validates value of one-pager.	Implemented
Architects might use the tool more as a validation tool rather than a design support tool. Due to their broad responsibilities and lesser focus on fire safety, using the tool will most likely not be a priority. It can be expected that the tool will only be utilized by them when specific concerns or unknowns arise in a project.	Gather feedback from architects to validate this prediction and potentially identify improvements.	Future development
Overall, there is a risk of users misusing this document to selectively support their arguments. Users might use a green rating as justification to avoid implementing any fire safety measures, which is particularly relevant for developers.	Gather feedback from developers to validate this prediction and identify improvements. Consider sharing only the one-pager with developers, not the tool.	Future development
While validating the value of this tool, manufacturers see it as a short-term threat as it could slow down adoption or even deter clients. Especially if the tool will be implemented in a norm. However, in the long term, it will ultimately aid in safe implementation and build client trust by ensuring fire safety measures are in place.	To address manufacturers' concerns about short-term impacts on adoption, it is recommended to emphasize the tool's role in enhancing long-term safety. Additionally, integrating feedback from manufacturers during the tool's development will ensure it meets industry needs and fosters broader acceptance.	Future development
The risk factors were positively received as a means to identify which design consideration impact fire safety and to what extend.	Validation of risk factor approach	
There is strong belief that the tool can be useful, seeing potential for its proper development to support consultants in providing tailored advice more efficiently. Additionally, façade engineers can benefit from streamlined design processes and enhanced fire safety assessments.	Validation of concept	
The tool could also be valuable in convincing authorities that specific fire risks have been thoroughly considered and addressed. This demonstration of proactive risk management may facilitate improved regulatory approval and enhance credibility.	New perspective, validation of concept	
The tool could also be valuable for façade manufacturers, which seek to validate new façade system concepts on fire safety performance.	New perspective, validation of concept	
Façade engineers: Maaike Berckmoes & Pieter Verhoeven (vk-architects-engineers)		
As façade engineers, they seek detailed advice on this topic. The tool offers some guidance but not at the level they most commonly require for their design processes. Normally, this level of detail is provided by norms, but is currently absent. Thus, the tool serves as a starting point and helps bridge the gap until such norms are established, providing insights and advice on a higher level of detail.	Develop the tool's content in collaboration with experts from norm institutions. This collaboration could shape the tool to align with upcoming norms or help develop new norms based on the tool's framework.	Future development
The tool is currently more valuable as a design support tool for engineers who are not familiar with the fire safety of BIPV systems, helping them understand the most critical aspects. However, it is less useful for designers who are already familiar with these systems, as they seek more detailed and specific guidance	Gather feedback from façade engineers which are not familiar with BIPV systems and their fire safety to validate this prediction and potentially identify improvements for the tool.	Future development
Façade engineers often focus on detailed aspects, sometimes overlooking the integration of considerations at higher levels. Therefore, this tool is valuable as it allows them to take a broader view and ensure that higher-level fire safety considerations are integrated into their designs	New perspective, validation of concept	
The tool is seen valuable for translating façade engineers' fire safety considerations to clients and/or architects. It helps clearly communicate the importance of fire safety measures, aiding client understanding of risks and the necessity of specific design decisions.	Validation of concept	
A client can also use this tool to challenge the architect or designer on their design choices.	New perspective, validation of concept	
Being able to compare different façades/designs is interesting as this allows for better-informed decision-making and comparing fire safety strategies.	Validation of concept	

Master Student Building Technology: Ece Sel		
Experienced a misinterpretation of the meaning of the risk evaluations (green/yellow/red). What do they mean? Is red not acceptable? Should it always be green?	Add an elaboration about risk factors and their evaluation categories. Also added a button on the "Risk Overview" sheet, referring to it.	Implemented
Emphasized the value of the visualization of the risk factors. It really helped in quickly understanding the impact of design considerations. Questioned whether it was possible to implement in the "Risk Overview" sheet, as in the façade overview sheet it is more "hidden".	Consider dedicating a page to a single façade where users can input their information and directly see the impact of fire risks through visualizations.	Future development
The visibility of façade button was not that obvious. Leading to a potential oversight to the valuable information on the "Façade Overview" sheets.	Add extra buttons which lead to the "Façade Overview" sheets.	Implemented
Dummy user: Mandy ten Damme		
Be aware that not everyone has your knowledge about the tool and its intended functionality. The tool contains a lot of information, so it is crucial to ensure users are not overloaded with data all at once, as this can cause confusion and hinder effective use	Simplify the interface and provide clearer, step-by-step guidance to help users navigate the tool and understand its features gradually.	Future development

Table 14: Feedback overview. Own work

6

Discussion & Conclusions

6.1 Discussion

6.1.1 Fire safety BIPV systems in façades

In the discourse of fire safety concerning BIPV systems integrated into façades, the concern revolves around whether the associated fire risks are inherently high and acceptable or not. While it's true that BIPV façades present unique challenges due to their integration into the building envelope, there is base level of knowledge on how to manage these risks effectively.

The design and construction requirements of BIPV modules for façades ensure that they meet higher standards than traditional roof-mounted PV systems; façade modules are engineered to meet fire class B requirements, as outlined by the Dutch Building Decree (Bbl), as well as enhanced mechanical rigidity standards necessary for façade applications. As such, BIPV façade panels are typically constructed as glass/glass modules, which offer superior fire performance compared to the more common glass/polymer modules used in roof installations. This inherent improvement in material performance suggests that BIPV façade panels are designed with a higher safety margin in mind.

However, as façades are integral to a building's aesthetic and structural design, they present unique challenges for fire safety that must be addressed in each situation. Façades inherently increase the possibilities of fire propagation compared to roofs due to the vertical spread of fire, the "chimney effect" in cavity ventilated systems, and the proximity of combustible building materials. This enhances the rapid spread of flames and smoke vertically. Moreover, façades are in closer proximity to occupied spaces, raising significant concerns about the impact on building occupants during a fire. The architectural integration of façade systems also adds complexity to fire spread and mitigation efforts, as these systems are often more complex than roof systems.

In addition to the inherent risks of façades, BIPV façade systems introduce further risks. They expose combustible materials to new ignition sources, contain components within cavities that may not be designed to operate at high temperatures, present inspection challenges due to the complexity of the façade structure, improperly executed cable penetrations can facilitate fire spread, and the heavyweight BIPV modules pose a risk of injury or blocking pathways if they fall.

Despite these concerns, if the risks associated with BIPV façade systems were excessively high, insurers, who represent societal risk, would likely raise more alarms. This could suggests that BIPV façade systems have not experienced major failures, or that current risk mitigation measures are deemed sufficient. However, it's important to recognize that insurance companies may have vested interests that could influence their assessments, potentially balancing commercial implications against actual safety risks.

Currently, our society does not demand a zero-failure rate for these systems, which would be ideal but impractical from both technological and economic perspectives. Instead, there is an agreement to accept a higher level of risk, influenced heavily by the push towards sustainable and green building practices. This balance between risk and sustainability represents a challenge in the development and implementation of BIPV systems in façades, indicating that while significant steps have been made, the journey towards achieving an optimal level of fire safety in these innovative systems is ongoing.

Nevertheless, through the findings of this study, a wide variety of measures have been found to enhance fire safety in BIPV façade systems. To narrow it down, it is most effective to first focus on preventing the ignition of fire. This can primarily be achieved by proper design and installation of electrical systems, validating them through quality schemes, and performing periodic maintenance with infrared (IR) inspections. While quality installation by accredited installers (InstallQ) minimizes errors, it doesn't eliminate them entirely. Therefore, independent quality inspections (SCOPE12) are crucial for added safety and reliability. Subsequently, to limit the development of fire, it is essential to always employ a glass/glass or glass/copper BIPV module (fire class B: NEN-EN 13501-1), and use a protective fire barrier (fire class A2/A1: NEN-EN 13501-1) in the cavity. Additionally, segmenting BIPV façades and cavities that span multiple fire compartments through physical barriers or well-performing cavity barriers is necessary. Utilizing smart detailing around façade openings and BIPV cavities, ensuring modules are easily removable from the façade, and implementing well-performing cable penetrations through the façade are also critical steps.

As these measures require an integrated approach, it is emphasized that the architect, façade designer, BIPV manufacturer and electrical installer should closely collaborate to design the electrical configuration of the BIPV system and adequately implement the effects of the system on the detailing, particularly in the façade (e.g. component placement in façade, cable penetrations, etc.).

Overall, the findings of this study, combined with existing fire safety practices, form a robust foundation for employing BIPV systems in façades with a certain level of fire safety and resilience. There is a clear pathway for future advancements to further mitigate these risks to even more acceptable levels. However, for this potential to be fully realized, the regulatory framework must be updated to specifically address the unique risks associated with BIPV façade systems, taking into account the building context. Until such regulatory changes are implemented, the sector must rely heavily on experts for ensuring safety. This reliability on experts is critical, and in their absence or misjudgment, it may only be a matter of time before BIPV façade fires occur, potentially with disastrous consequences (Figure 109), as all the ingredients for a recipe of disaster are present.

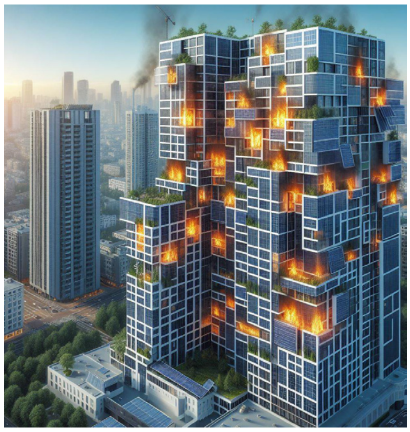


Figure 109: Building on fire with BIPV (AI generated with DALL-E 2). Own work

6.1.2 Risk analysis

The effectiveness of the risk analysis in systematically assessing the risks associated with BIPV systems in façades was demonstrated through the use of the fault tree analysis (FTA). By categorizing various ignition scenarios related to each component and their specific locations within the building, as well as distinguishing potential fire trajectories, the FTA ensured a thorough examination of all relevant aspects of fire safety. This systematic approach ensured a thorough examination of fire safety aspects, helping to identify potential risks and minimize overlooked scenarios, thereby creating a robust framework for understanding and mitigating fire risks in façades.

However, while the analysis was effective for this thesis, it is not exhaustive or definitive. Much of the analysis extrapolated from BAPV systems or BIPV on roofs, supplemented by educated reasoning where direct data was lacking. Therefore, the findings should be viewed as preliminary. Specific research tailored to BIPV in façades is critical to validate the risks and refine the mitigation strategies developed here, as highlighted in 7.1.2 Future recommendations: research fire safety BIPV façades. This research is essential to ensure strategies are based on solid, context-specific evidence.

Design deviations | The risk analysis identified the most relevant risks associated with a standard parapet BIPV façade, the most common scenario, and these findings are also applicable to other configurations. This provides a solid foundation for understanding fire risks in various BIPV façade designs. However, the FTA did not cover the full range of possible façade design deviations. Variations in façade geometry, material composition, and cavity configurations were addressed through design parameters but were not explored in equal depth. Future research, as recommended in 7.1.2 Future recommendations: research fire safety BIPV façades, could explore these deviations more comprehensively to ensure a more robust and versatile understanding of fire risks associated with diverse BIPV façade designs.

6.1.3 Design support tool

The interplay between raising awareness and conducting research is crucial for advancing BIPV façade fire safety. Awareness initiatives, like this design support tool, foster a safety-oriented mindset among designers and stakeholders, ensuring safety considerations are integrated into the design process. Concurrently, research provides the evidence needed to refine these safety considerations and adapt them to evolving technological and architectural developments. By combining awareness with research, the industry can ensure safety measures are scientifically grounded and practically applicable, achieving higher fire safety and fire resilience in buildings with BIPV systems.

However, it can be questioned whether this tool-based method effectively addresses the core issue of achieving fire-safe and fire-resilient buildings with BIPV systems. While the tool can potentially succeed in raising awareness and providing initial guidance for designers, it currently serves as a stepping stone toward broader fire safety concerns. This is due to the lack of supporting research needed to validate the tool's input and output. As detailed in 7.1 Future recommendations, further research is essential to thoroughly assess, evaluate, and validate the risks associated with BIPV systems in façades. Ongoing studies are necessary to enhance the tool, transforming it from a basic guide into a comprehensive and reliable resource for implementing fire-safe BIPV systems.

To provide a comprehensive review, the effectiveness of the design support tool is evaluated against the original objectives outlined 5.1.1 Design support tool: goal:

Fire risk identification BIPV | The goal of providing preliminary knowledge on fire risks associated with BIPV systems in façades is achieved via the FTA. This approach has laid a solid foundation for understanding these risks. However, these risks have not all been empirically validated, as elaborated in 6.1.2 Risk analysis While the tool highlights theoretical risks, further research is needed to explore the practical impacts on actual BIPV installations, as outlined in 7.1.2 Future recommendations: research fire safety BIPV façades.

Evaluate context beyond product level | The tool implements BIPV considerations at product, façade, and building levels through risk parameters, highlighting how BIPV design choices impact overall fire safety. It provides valuable insights into present risks, allowing users to understand critical connections between design decisions and safety implications. However, the tool does not determine whether a risk is acceptable; it is up to the user to critically assess and verify. This flexibility allows for nuanced evaluation based on specific project requirements and regulatory standards, a task best performed by professionals. While the tool does not capture every cascading effect of design considerations, it emphasizes the interconnected nature of these decisions, encouraging users to consider the broader impact of their choices.

Recognizing the tool's limitations and its inability to cover every aspect of fire safety was crucial for its development. The complexity of fire safety necessitates the consideration of many factors, leading to deliberate choices about which parameters to include. These decisions were informed by literature reviews and expert consultations to prioritize the most significant parameters while maintaining practicality and usability. Highlighting the difficulty in this, in essence, every design consideration can be seen as a risk parameter. Measures or strategies proposed by the tool are essentially also risk parameters, but are not explicitly highlighted as such. The decision on defining which design considerations became a risk parameter was based on two key reasonings: first, focusing on the most critical design considerations regarding fire risks; and second, including considerations where a designer has the most impact. For instance, maintenance was included as a measure, not a risk parameter, as interviews indicated that designers have minimal influence over it.

As a result, some parameters remain unaccounted for, highlighting the tool's limitations compared to the in-depth expertise of fire safety professionals. However, the tool's goal was not to match expert advice but to provide a preliminary framework guiding users through essential fire safety considerations for façades with BIPV. By doing so, the tool helps users navigate the complexities of fire safety, promoting a more comprehensive and proactive approach to risk management in BIPV system design and implementation.

Provide practical measures and guidelines | The tool succeeds to offer a wide variety of measures and strategies tailored to the input of the user. However, validating these measures through testing and research is essential to confirm their efficacy and safety in real-world applications. 7.1.2 Future recommendations: research fire safety BIPV façades outlines the most pressing measures requiring testing.

The tool proposes numerous measures, both directive and suggestive. However, it does not validate that the implementation of specific measures will achieve a sufficient level of safety. Instead, it provides an overview of potential strategies and leaves room for users to be critical in evaluating and applying these measures to their specific situations. While it could be an ultimate goal for a tool like this to be able validate the sufficiency of fire safety measures, this is highly complex, if not impossible, due to the interconnected nature of design and fire safety and the nuanced perspective required.

The tailored measures are currently presented in a risk-oriented hierarchy. However, improvements could be made by implementing a cost-oriented hierarchy, as discussed in section 7.1.3. This would help balance safety considerations with budget constraints, making the tool even more practical and applicable in real-world scenarios.

Facilitate compliance | The tool succeeds to facilitate compliance by providing an overview of relevant regulations, codes, and guidelines. However, its depth in addressing detailed compliance requirements is limited due to the lack of regulations specifically tailored for BIPV systems. 7.1.3 Future recommendations: regulatory framework fire safety BIPV façades outlines proposals for improving the regulatory framework to create a more robust compliance environment for BIPV technologies. Additionally, the compliance analysis in this thesis aimed at being exploratory rather than exhaustive, which may have led to potential oversights or misinterpretations. 7.1.1 Future recommendations: design support tool recommends a more thorough compliance analysis to ensure a comprehensive and accurate understanding of the regulatory landscape.

Foster an informed decision-making process | The tool enhances decision-making by applying weights to the risk parameters and design parameters via risk factors. This approach helps quickly assess and compare the potential impact of various design options and facilitates a deeper understanding of how each choice affects overall fire safety in the BIPV context. However, it's important to acknowledge that while risk factors provide a structured approach to evaluating risks, they inherently come with limitations.

The risk factors were determined relative from a standard "zero risk" baseline, meaning they have no absolute value but are used for comparative purposes. The subjective nature of assigning weights can introduce biases, and the simplification required to make complex scenarios manageable may overlook some nuances of fire safety risks. Additionally, the bandwidths for risk evaluation (green/yellow/red) are arbitrary, with the beginning of a bandwidth not necessarily equating to the same level of risk as the end, which could result in varying perceptions of risk severity within the same category.

Despite these constraints, employing risk factors is found as a practical means of prioritizing and addressing risks in a systematic manner, which has also been confirmed by user feedback. In 7.1.1 Future recommendations: design support tool it is highlighted how these risk factors can be improved.

Additionally, the following aspects of the design support tool are discussed:

Excel as a tool | The choice of Excel for developing the design support tool was driven by practical considerations. Excel's quick development capabilities, flexibility in handling data, and ease of data visualization made it suitable for a tool requiring iterative adjustments based on user feedback. Additionally, its widespread availability and familiarity among professionals reduce the learning curve and eliminate the need for additional software, ensuring smooth integration into existing workflows.

However, Excel's suitability as the ultimate platform for the tool should be questioned. While effective for initial development, Excel has limitations in UI/UX design, scalability and collaborative features. These issues affect the tool's ease of use and efficiency, as confirmed by user feedback. Transitioning to a web-based platform could enhance accessibility and usability while retaining Excel's core capabilities. 7.1.1 Future recommendations: design support tool outlines how this transition can be achieved.

Limitation in-depth advices | The measures and strategies proposed by the tool are limited to a certain level of depth to maintain general applicability across various BIPV systems. This prevents the tool from being able to address the intricacies specific to each unique architectural context. While the tool provides broad, foundational insights, it avoids excessive complexity to ensure user-friendliness and accessibility.

Therefore, while the tool provides a foundation for understanding and implementing basic fire safety measures, it recommends development in close collaboration with fire safety experts for more comprehensive, tailored guidance that considers the specific nuances of individual projects, especially in medium and high risk context.

6.2 Conclusions

6.2.1 Answering main research question

RQ 1 | Can a risk-based design support tool aid designers of façades in the design process to achieve fire safe and fire resilient designs when integrating building-integrated photovoltaic systems?

Yes, a risk-based design tool can support designers in achieving fire resilient designs when integrating BIPV systems into façades. The tool developed for this study has demonstrated its foundational capability by providing a framework that highlights critical fire safety considerations through 23 risk parameters. It allows users to conduct a risk assessment for their façades and offers specific measures and strategies based on user input for various design considerations. User feedback has confirmed the tool's potential, indicating its effectiveness in raising awareness among designers about the unique challenges posed by BIPV systems in façades. This facilitates informed decision-making and promotes the integration of fire safety into the design process from the outset.

However, this tool does not provide a guaranteed 'fire safe' solution. Fire safety should always be assessed in its unique context, especially due to electro-technical characteristics of BIPV systems. The information presented is advisory and has not undergone extensive testing or regulatory approval. The tool should be used to inform a decision-making process, where the user still needs to critically assess the applicability of each design consideration or measure. Therefore, when there is any doubt, it is advised to consult with a qualified fire safety professional.

Additionally, it's important to recognize that the tool is a preliminary setup. While it lays down a solid framework for addressing fire risks, it is still in its early stages. The effectiveness of the tool is dependent on the accuracy and comprehensiveness of the data it utilizes. As of now, the tool integrates a base level of knowledge and incorporates standard risk assessment practices, but it requires further refinement through empirical research and end-use testing.

The tool is particularly relevant in the current pre-normative state where specific regulations for BIPV façades are not fully established. It guides designers through the complexities of fire safety in BIPV systems, compensating for the lack of comprehensive regulatory guidance. Once the regulatory framework is updated to address BIPV fire risks, the tool's role could evolve to serve as a starting point fore regulatory developments or to support the regulatory framework by translating complex regulations into easy-to-use guidelines.

6.2.2 Answering sub research questions

SQ 1 | What are photovoltaics and their main characteristics?
Photovoltaics (PV) convert sunlight into electricity using materials that exhibit the photovoltaic effect. PV cells harness this effect to generate direct current (DC), which can be converted into alternating current (AC) for practical use. These cells are assembled into modules, forming PV systems to meet various energy demands, with grid-connected systems being the most common in the Netherlands. First-generation silicon-based cells dominate the market with a 90% share. Emerging third and fourth generations suggest future innovation and advancement in the field.

SQ 2 | What are building integrated photovoltaics and their main characteristics?
Building-integrated photovoltaics (BIPV) are specialized PV modules designed to replace conventional building materials while providing building functionalities. Due to the wide variety of BIPV systems and modules, the IEA PVPS Task 15 (2021) has developed a functional categorization that includes application category, system, module, component, and material, potentially serving as a foundation for future regulatory developments. BIPV façade systems can be classified into three types: rainscreen façades, double skin façades, and curtain walls/windows. Typical BIPV module types are: glass/ glass and glass/polymer and glass/copper. Depending on the required electrical configuration, these systems employ various components, and can broadly categorized into three main system configurations: string inverter, string inverter with optimizer, and micro-inverter. First-generation glass/glass BIPV modules are most common due to their compliance with fire class B (NEN-EN 13501-1) and the mechanical rigidity required for façades.

SQ 3 | What are the fundamental principles behind fire safety engineering in the built environment?
Fire safety engineering intersects private and public law, focusing on protecting lives, property, and the environment within the built environment. It aims to understand, prevent, and mitigate the effects of fires, enhancing the fire safety and resilience of buildings. This discipline adopts a structured, multifaceted approach centred on risk subsystems, applied in an effective sequence to maximize fire protection:

1. Prevent the ignition of a fire
2. Limit the development of a fire
3. Limit the spread of fire within the building
4. Limit spread of smoke within the building
5. Maintain the structural integrity of the building
6. Maintain the escape and access routes
7. Limit the spread of fire and consequences for the surroundings

In the Netherlands, the Dutch Building Decree (Bbl) sets specific performance requirements for fire safety. Fire safety engineering extends these with a risk-oriented approach, adding layers of protection where the regulatory framework may be inadequate. This comprehensive strategy ensures a broader, more thorough approach to fire safety, critical for safeguarding modern buildings against evolving fire risks.

SQ 4 | What are the relevant fire safety standards and codes for façades with BIPV systems in the Netherlands?
In the Netherlands, the fire safety of façades is governed by a regulatory framework rooted in the building decree (Bbl), which references to codes. For façades incorporating BIPV, the decree mandates two key performance requirements: the façades and BIPV modules must achieve a minimum fire class according NEN-EN 13501-1, typically fire class B, and comply with the "branddoorslag" and "brandoverslag" requirements as outlined in NEN 6068 and NEN 6069. Additionally, the upcoming NPR 6999 will require stricter fire classes of A2 for high-risk buildings, tested through ISO 13785-1, DIN 4102-20, or BS 8414. This will potentially create a barrier for BIPV façade employment, as these modules have not yet achieved fire class A2.

While the regulatory framework establishes some performance benchmarks for BIPV systems in façades, it is not specifically tailored to address the unique challenges posed by BIPV façades, a concern that was already applicable to BAPV systems, and even more so for BIPV. Identified gaps include the adequacy of testing methods, the absence of BIPV-specific regulations and shortcomings in fire detection and suppression strategies.

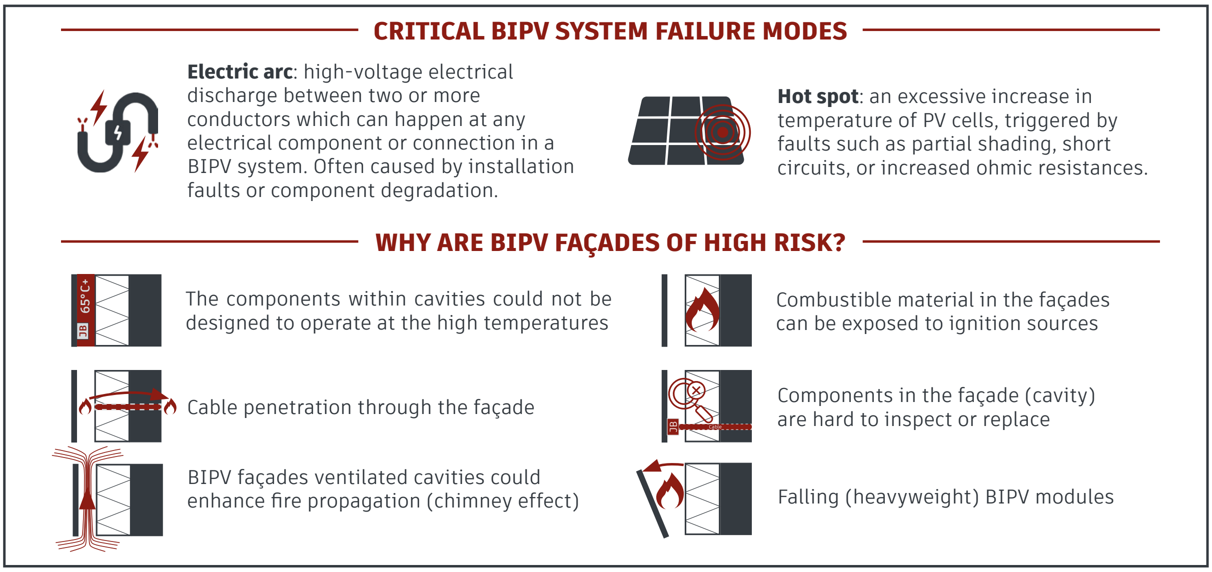
Regarding testing methods, several BIPV system-related characteristics are not adequately addressed: unique ignition sources, electrically active testing, fire suppression, and toxic smoke emissions. Additionally, the SBI-test (NEN-EN 13823), used to determine the fire class according to NEN-EN 13501-1, does not sufficiently account for factors such as façade cavity ventilation, fire source, set-up scale, and connections.

Furthermore, while NEN 1010, also directed by the Bbl, addresses the quality of materials and components used in PV systems, it falls short in enforcing quality control. To bridge this regulatory gap, non-statutory quality schemes like InstallQ or SCIOS SCOPE12 could be employed to increase safety for the installation and operation of BIPV systems.

SQ 5 | How can classical risk theories contribute to the identification and documentation of the fire risks of BIPV systems in façades?
Throughout this master thesis, classical risk theories have proved to enhance the identification and documentation of fire risks associated with BIPV systems in façades. Using a qualitative fault tree analysis (FTA), founded by knowledge gained through the literature review and expert consultation, allowed for a systematic exploration of events leading to a top event, effectively identifying and prioritizing risks based on event interdependencies. Additionally, the chosen qualitative FTA method aligned well with the research goals, handling the complexities of BIPV systems without needing extensive quantitative data. This approach deepened the understanding of potential fire risks and aided in developing specific safety measures and strategies, ensuring that safety considerations are integral to the design and implementation of BIPV systems.

SQ 6 | What are the fire risks associated with employing BIPV systems in façades?

Through the FTA analysis, an overview has been created of the fire risks associated with employing BIPV in façades. Fundamentally, BIPV systems in façades are of high risk as they introduce high-voltage ignition sources, carrying AC currents up to 1000 V, directly into the façade, representing a hazard that was unprecedented in conventional façade designs. Ideally, the regulatory framework should be equipped to address such emerging risks; however, current standards fall short in this regard, inherently increasing the risks associated with these systems.



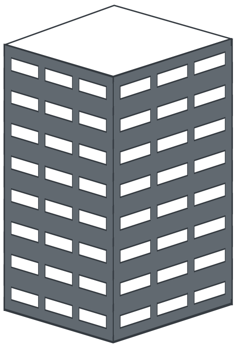
BIPV modules contain encapsulants, typically EVA or PVB, which are both combustible and have high calorific values. Glass/polymer modules pose a higher fire risk due to the combustible of the polymer backsheet, which can exacerbate fire spread both from and to the module. In contrast, glass/glass modules offer superior fire resistance and structural integrity, making them a safer choice for façade applications, emphasizing the importance of avoiding glass/polymer modules in façades.

BIPV systems can be designed and installed incorrectly, potentially leading to component failures and electric faults. Key components such as inverters, junction boxes, plug connectors, BIPV modules, and optimizers are critical in BIPV façade systems. These components already showed high failure rates in BAPV roof systems (TUV Rheinland & Fraunhofer-Institut, 2018) and are likely more vulnerable due to increased environmental stresses in façade cavities and limited inspection or maintenance. While quality control schemes like InstallQ and retrospective inspections address these issues, their non-statutory nature means BIPV systems may still be deployed without adequate quality control, thereby increasing risk. Additionally, potential component failures due to degradation underscore the importance of regular maintenance and inspection. Birds, rodents, and insects may nest in or around the BIPV cavity, bringing in combustible materials, chewing on cables, or blocking ventilation gaps, leading to overheating, reduced efficiency and potentially fire. Wind and deformations in façades can cause movements and vibrations, loosening connections and cable transitions, potentially causing electrical faults or system failures, and causing wear and tear on the modules and mounting structures, reducing their lifespan.

SQ 7 | How can a designer effectively prevent or mitigate the fire risks associated with BIPV systems in façades?

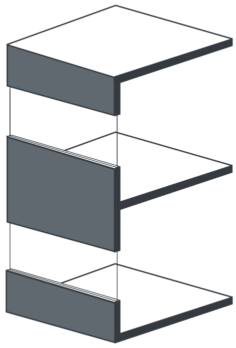
Given the variety of design considerations at the building, façade, and BIPV product levels related to fire risks, there is no one-size-fits-all answer. Designers must always critically evaluate design considerations in light of fire risks presented by BIPV systems. In total, 23 risk parameters have been identified as main factors that impact or are influenced by BIPV systems in façades. While more risk parameters exist, these 23 provide a comprehensive framework for assessing and addressing fire safety

Level of Detail 1



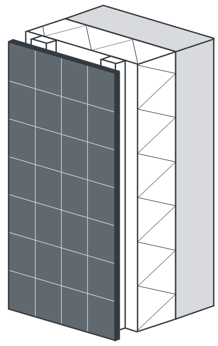
Building level
1. Building function
2. Building height
3. Location escape routes
4. Building value

Level of Detail 2



Façade level
5. BIPV continuous façade segments
6. BIPV continuous cavity
7. Façade openings
8. Façade protrusions
9. Accessibility fire fighters
10. Escape route endangerment
11. Load bearing façade
12. Wind

Level of Detail 3



Product level
13. Module type
14. Fire class BIPV module (NEN-EN 13501-1)
15. Fire class BIPV module (ANSI/UL 1703 via UL 790)
16. Removability modules
17. BIPV system: electrical configurations
18. AFCIs
19. Design temperature of façade cavity
20. Materials in cavity
21. Mounting structure materiality
22. Cable penetrations
23. Quality control

To emphasize the most effective measures and strategies that can be implemented, addressing the first two risk subsystems (1: Prevent the ignition of a fire, 2: Limit the development of a fire), the following key actions are outlined. Adhering to these measures will provide a substantial basis for achieve a fire safe and fire resilient design.

The architect / façade designer, BIPV manufacturer and electrical installer should closely collaborate to design the electrical configuration of the BIPV system and adequately implement the effects of the system on the detailing, particularly in the façade (e.g. component placement in façade, cable penetrations, etc.).

MEASURES TO PREVENT THE IGNITION OF FIRE

INSTALLATION

WHAT Design and install the BIPV system according product specifications of the manufacturer (NPR 8092)
WHY Limit the possibility of installation errors or wrongful implementation

WHAT Quality installation by a recognized or certified (InstallQ) company
WHY Limit the possibility of installation errors

WHAT Quality inspection by an independent certified party (SCIOS SCOPE12)
WHY Limit the possibility of installation errors

DESIGN

WHAT Employ micro-inverters
WHY Reduce the probability of ignition (low voltage)

WHAT Employ remote control systems with AFCIs and ensure they are active
WHY Detect faults and prevent the occurrence of electric arcs

WHAT Avoid situating electrical components near combustible materials
WHY Prevent fire ignition

$T_{jb.max.op.} < T_{cav.}$

WHAT Design the cavity temp. below the electronics' max operating temp.
WHY BIPV components are not designed to operate in high temperatures

WHAT Employ high quality electrical components with CE-marking (be aware of fake marks)
WHY Limit product faults and failure modes

MAINTENANCE

Year 0
Year 20

WHAT Periodic inspection & maintenance (with IR)
WHY Identify faults in the system

MEASURES TO LIMIT THE DEVELOPMENT OF FIRE

DESIGN

WHAT Employ a glass/glass or glass/copper BIPV module (fire class B: NEN-EN 13501-1)
WHY Minimize cavity fire and prevent enhanced fire propagation.

WHAT Employ a protective barrier (fire class A2/A1: NEN-EN 13501-1) in cavity
WHY Minimize cavity fire and prevent enhanced fire propagation.

WHAT Segmentize BIPV façades that span multiple fire compartments
WHY Limit façade fire to singular fire compartment

WHAT Utilize smart detailing around façade openings and BIPV cavity
WHY Avoid fire spread between openings and façade cavity.

WHAT Ensure modules are (easily) removable from façade
WHY Replacement of (broken) components in façade (e.g. module, junction box, etc.)

WHAT Provide a well performing fire barrier in BIPV cavity at fire compartment borders
WHY Limit façade cavity fire to singular fire compartment

SQ 8 | Do PV employed in façades pose a higher risk than PV systems employed on roofs?

Risk related to fire safety can generally be defined by the risk neutral formula: risk = probability of occurrence * probability of fire development * severity of damage. To address this sub-research question, each evaluation criterion can be assessed semi-quantitatively. While quantitative data is available for PV roof systems, there is a lack of such data for PV façade systems, necessitating a semi-qualitative approach.

Probability of occurrence

Currently, the international rate of fires for PV systems on roofs (both BIPV and BAPV) is 1 fire per year per 0.0289 MW installed (Mohd Nizam Ong et al., 2022). For PV façade systems, no data indicating occurrences of fires has been identified. This could be due to underreporting, lower installation rates of PV façade systems or potentially a lower probability of fire occurrence in PV façades compared to PV roof systems.

The quality of installation plays a critical role in fire incidents. Given the more complex and high-performance requirements of façade installations, BIPV façade systems are likely installed by more skilled technicians. In contrast, PV roof systems may be installed by less skilled workers, making them more prone to installation errors that could lead to fires. Therefore, the risk of fire occurrence may be higher for roof systems than for PV façade systems.

Probability of fire development

PV façade installations generally have an increased risk of being adjacent to materials that could contribute to the spread of a fire. Additionally, fires in façades are likely to spread rapidly due to the "chimney effect" in the cavity, causing fires to propagate more extensively compared to roof fires, which are less likely to spread due to their horizontal layout. This is supported by data showing that most roof PV system fires are small in scale (Mohd Nizam Ong et al., 2022). Thus, PV façade systems may present a higher risk of fire development compared to roof systems.

Severity of damage

Fires in PV façade systems can spread vertically much faster due to the chimney effect, potentially affecting multiple building levels and compartments, which complicates firefighting efforts. The proximity of façade fires to interior spaces increases the risk of rapid fire and smoke ingress into occupied areas, enhancing the danger to building occupants. Additionally, façade fires can cause significant structural damage within a building. These factors collectively contribute to a potentially higher severity of damage in PV façade systems compared to roof systems, leading to higher repair costs and potential disruption of business continuity.

In conclusion, while direct comparative data is lacking, the semi-quantitative assessment suggests that PV systems in façades could potentially pose a higher risk than PV systems on roofs. This increased risk is primarily due to the expected heightened probability of fire development and the greater potential severity of damage, despite the lower likelihood of occurrence. Addressing these risks is crucial for improving fire resilience and overall fire safety in buildings with PV installations in the façade. However, as no validating data is currently available, only educated reasoning can be employed until quantitative data becomes accessible.

7

Future Recommendations & Reflection

7.1 Future recommendations

7.1.1 Future recommendations: design support tool

Extend focus | This thesis and the design support tool has laid a solid foundational layer of knowledge for BIPV rainscreen façades. However, there is potential to integrate other systems like curtain walls, windows, and double skin façades. By translating the knowledge gained from rainscreen façades to these systems, considering their roughly similar electrical configurations and contexts, a comprehensive foundation for BIPV in façades can be established. Once this basis is solidified, the methodology can be extended to include BIPV in roofs and subsequently BAPV façades and roofs. Additionally, integrating externally applied devices for both BIPV and BAPV can be explored, ensuring a thorough understanding and risk assessment across all building-integrated and building-applied photovoltaic systems.

Expert input | Currently, the tool has been developed with the aid of experts. However, for further development, it is highly recommended to closely involve fire safety experts throughout the process. Their expertise can help refine risk parameters and measures, ensuring that the tool better reflects the latest fire safety standards and best practices. Additionally, their input can help identify and address potential gaps in the tool's functionality, improve the accuracy of risk assessments, and ensure the recommendations provided are both practical and effective. This collaboration can ultimately enhance the tool's reliability and credibility, making it a more valuable resource for users.

Tool development | To enhance the design support tool, involving software developers to create a web-based platform is of high value. A web-based tool offers easy access, collaboration possibilities, and many more advantages over Excel. The primary focus should be on improving the user interface (UI) and user experience (UX) to make the tool intuitive and efficient. The UI design should feature a clean, user-friendly interface that simplifies navigation and ensures all functions are easily accessible. UX enhancements should streamline the workflow, reducing and simplifying the steps required to input data and obtain results. Additionally, the tool should account for the interdependency of risk parameters. For example, if BIPV façade cavities are limited to one fire compartment, the risk factor for vertical/horizontal continuation of BIPV façade modules over multiple fire compartments should be adjusted accordingly.

Gathering feedback | Currently, the tool has been developed in collaboration with fire safety experts and the mentors, and it has received feedback from façade engineers, a BIPV façade manufacturer, a student, and a dummy user. This feedback has set the stage for several valuable improvements and future development proposals. It is recommended to test the tool with a broader range of stakeholders to gain even more valuable insights. A particular focus should go towards architects, façade engineers with no prior knowledge of fire safety for BIPV façades, norm institutions, and developers. Engaging these additional stakeholders will help to refine the tool further, ensuring it meets the diverse needs of all potential users and aligns with industry standards and expectations.

Case studies | Employing more case studies will enhance the accuracy and reliability of the tool. For example, additional case studies can help refine risk parameters by determining which design considerations are relevant enough to become risk parameters, improve tailored and adequate measures, and refine risk factors and threshold values. The more case studies included, the more accurate and reliable the tool becomes. AI and machine learning can potentially aid in this process by efficiently analysing large datasets from multiple case studies to identify patterns and correlations.

Compliance analysis | The compliance analysis facilitates compliance by providing an overview of relevant regulations, codes, and guidelines. However, it is recommended to improve the integration of compliance for future development of the tool. For example, the tool could reference specific sections of the Bbl, integrate existing tools for NEN6068 and NEN6069 calculations, or highlight more detailed test specifics of NEN-EN 13501-1 and ANSI/UL 1703 (via UL 790). Additionally, implementing a detailed compliance checklist for BIPV systems could enhance the tool's utility.

Measures: costs vs. risk reduction | The current hierarchy of measures in the design support tool is risk-based, prioritizing the highest risks. However, costs are also crucial in implementing safety measures. Therefore, evaluating the relationship between costs and risk reduction is necessary. Figure 109 illustrates this relationship, showing different measures in terms of their cost and the corresponding reduction in risk. To improve the hierarchy, balancing both cost and effectiveness is essential. Measures that offer significant risk reduction at lower costs should be prioritized. A plot like Figure 110 can guide this by identifying which measures provide the best trade-off between cost and risk reduction.

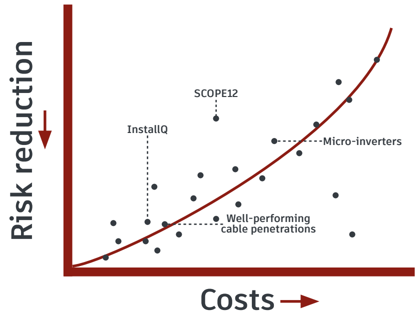


Figure 110: Costs vs risk reduction. Own work

Focusing on measures that lie along or above the curve in Figure 110 would ensure that the selected interventions are both cost-effective and impactful. Measures below the curve offer less risk reduction at higher costs and should be considered secondary.

7.1.2 Future recommendations: research fire safety BIPV façades

In-depth risk analysis BIPV façade systems | The risk analysis conducted in this thesis, while effective for its intended scope, was relatively exploratory compared to comprehensive risk analyses like multi-organizational project TUV of Rheinland & Fraunhofer-Institut (2018). For further development of the tool, a more extensive risk analysis is recommended.

Given the current size of the BIPV façade market, a full-scale risk analysis may not yet be feasible. As the market grows and more data becomes available, a large-scale analysis will become more realistic. In the meantime, a small or medium-scale risk analysis could be conducted to bridge the gap, building upon the knowledge from Rheinland & Fraunhofer-Institut (2018). This would allow for a more detailed assessment than currently available while remaining adequate for the overall problem. An FMEA study like this, which focuses on ignition scenarios, could be complemented with a FTA to address fire propagation possibilities. The FTA should then incorporate common design deviations of façades, enabling a comprehensive examination of how different design elements can influence fire spread.

As the market grows and more data becomes available, transitioning to a (semi-)quantitative risk analysis would be beneficial. Initially, qualitative methods like FMEA and FTA could provide a solid foundation, but integrating quantitative data in future analyses would enhance the robustness and accuracy of the risk assessments.

By progressively building on current methodologies and integrating both qualitative and quantitative approaches, future research can enhance the understanding and management of fire risks in BIPV façade systems. This dual approach will not only improve the design and implementation of safety measures but also support the development of more safe, resilient and sustainable building practices involving BIPV technologies.

Non-combustible encapsulants | Common encapsulants like EVA and PVB have high calorific values, increasing the risk of ignition and fire propagation. Further research should focus on developing non-combustible encapsulants to decrease these risks, enhance overall fire safety, and improve the safety and resilience of BIPV modules.

Test proposal: BIPV design considerations | Fire tests should be executed to understand the fire performance of BIPV façades better, focusing on the impact of different design considerations. Mid-scale tests, particularly with the upcoming ISO 13785-1 test method, provide a balance between insight and cost-effectiveness. While large-scale tests offer comprehensive insights, they are expensive, though costs can be mitigated with multiple tests. Small-scale tests fail to represent end-use fire behaviour accurately.

Fire testing should focus on typical design considerations that impact fire propagation and performance of mounting structures. All tests should be consistent, varying only one parameter at a time. BIPV glass/glass modules should be the standard. Key parameters to test include:

- Mounting structure (aluminum vs. steel vs. wood)
- Water-repellent foils
- Insulation types (reflective vs. non-reflective)
- Impact of seams and openings (size and placement)

Test proposal: fire barrier performance | Stølen et al. (2024) found that fire barriers failed when the aluminum mounting structure failed, allowing fire to bypass the barriers. Future fire testing should focus on enhancing fire barrier performance in conjunction with the mounting structure. Since aluminum fails quickly in a fire, research should assess the performance of better performing materials, such as steel. This research should determine if steel frames maintain their structural integrity long enough to ensure adequate fire containment. As a result of this research, there should be a market shift towards the better-performing mounting structures.

Test proposal: cavity temperature | Conduct tests to determine the impact of elevated temperatures in a BIPV cavity on the ignition possibilities resulting from an electric arc. Specifically, assess whether typical façade components are more likely to ignite when exposed to an electric arc in higher cavity temperatures. While it can be hypothesized that elevated temperatures could increase ignition likelihood, actual testing will provide concrete data and potentially reveal additional nuances, thereby offering valuable insights into the fire risks associated with BIPV systems.

Test proposal: Fire suppression electrically active BIPV modules | Although it has been suggested that electrically active BIPV modules pose no danger of electric shocks to firefighters due to the dilution of current by the water flow, no validating data has been found. Therefore, it is recommended to perform testing to confirm this assumption and dispel the prevailing sentiment in academic papers that there is a risk (Yang et al., 2022; Olsøet al., 2023). Testing should consider parameters such as system voltage, water flow rate, and suppression distance.

7.1.3 Future recommendations: regulatory framework fire safety BIPV façades

Potential impact of tool on regulatory framework | This tool has the potential to act as an initial domino stone, setting a series of actions into motion that could influence the regulatory framework for fire safety in BIPV façades. Currently, there is a lack of momentum regarding the establishment of comprehensive regulations for BIPV systems in façades in the Netherlands. By providing a preliminary approach to identifying and mitigating fire risks, this tool can initiate broader discussions and actions among stakeholders. Subsequently, it can become an initiative that would initiate and inform the development of an NPR, which could then influence the creation of specific codes. Eventually, these codes could be integrated and directed by the building decree (Bbl), ensuring a robust regulatory framework that enhances fire safety in BIPV façades.

Reporting & documenting fire causes | Accurate data is essential for understanding fire risks, identifying trends, and implementing effective prevention strategies. Without comprehensive statistics, stakeholders face gaps in knowledge, hindering the development of adequate safety measures. In the Netherlands, while firefighters do document all fire causes, this data is currently not effectively utilized by CBS or other agencies. The quality of this data can therefore potentially be questionable because it lacks emphasis on thoroughness, resulting in insufficient depth and specificity to draw meaningful conclusions about fire causes, especially for newer technologies like BIPV systems.

To address these issues, it could be beneficial to establish a statutory system for documenting and reporting fire causes. One approach is to follow the example set in the United States, where the Occupational Safety and Health Administration (OSHA) mandates independent fire source investigations. This method ensures that fire causes are accurately identified and reported, providing valuable data for improving fire safety standards and practices. Implementing a similar system in the Netherlands could enhance risk management, informed decision-making, and overall safety for BIPV systems and other emerging technologies.

SCOPE12 enforcement | Currently, SCOPE12 is not statutory, with no foreseeable prospect of it becoming mandatory. Despite this, SCOPE12 provides significant value by ensuring high standards for PV system installations. In Belgium, the Algemeen Reglement op de Elektrische Installaties (AREI) is mandatory, and research should explore how SCOPE12 could potentially become statutory like AREI. Alternatively, enforcement could be achieved through other means, such as via insurance companies. Therefore, it is advised to improve lobbying with insurance companies to always require SCOPE12 as a prerequisite for obtaining building insurance.

BIPV façade fire test method | Testing via the SBI method does not properly represent the unique fire risks for BIPV systems, as these systems introduce additional internal fire sources. Therefore, developing a new test method specifically for BIPV in façades is necessary.

Creating such a fire test from scratch would require significant resources, which might not match the urgency of the issue. Therefore, it is advisable to explore the potential of utilizing existing testing setups with minor adjustments to fit the BIPV façade context. The test should focus on representing unique fire ignition scenarios within the façade cavity, considering the placement of ignition sources in relation to critical sections of the cavity, such as near combustible façade materials and electrical components. Ideally, a mid-scale test would be the most suitable, balancing the need for detailed insights with practical resource considerations.

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7.2 Reflection

7.2.1 Reflection on research method and results

The ultimate goal of this study was to achieve fire-safe and fire-resilient buildings with BIPV systems integrated into façades. This objective was inherently complex and depended on various factors, including regulatory frameworks, technological advancements, and practical implementation strategies. The study partially addressed this goal by focusing on identifying fire risks, developing a design support tool, and raising awareness about BIPV façade fire safety. Fully solving the problem of fire safety for BIPV façade systems and creating entirely fire-resilient buildings was beyond the study's scope. Therefore, it was crucial to clearly define the research's scope and limitations. By setting realistic goals, the study systematically addressed its specific objectives, contributing to the overarching goal of enhancing fire safety and fire resilience in buildings with BIPV systems, even if it did not fully solve the problem.

One of the primary objectives of the research was to raise awareness about the fire risks associated with BIPV façades. By highlighting these risks, the study emphasized critical safety concerns, potentially driving future safety enhancements and regulatory developments. However, creating awareness requires more than just executing and publishing the study. Active engagement with industry stakeholders, ongoing education, and widespread distribution of findings and the tool are essential for achieving actual awareness. This study provided preliminary information necessary to initiate awareness and can potentially serve as a foundation for broader knowledge dissemination.

The research approach faced significant challenges, particularly the lack of supportive empirical data on BIPV fire safety, which is common when exploring novel fields. This limitation restricted the ability to fully validate the findings, rendering some findings more speculative. Additionally, the tool does not fully account for all interdependencies of fire risks, limiting its accuracy and effectiveness. To address the weaknesses of this study, multiple future developments were outlined, which are arguably among the most critical components of this research.

Several potential threats could impact the research’s effectiveness. One significant threat is the risk of the findings and the tool being misinterpreted as absolute truths, leading to overreliance without considering their limitations and the evolving nature of fire safety knowledge. The rapid growth of the sector means the information can quickly become outdated as new data and technologies emerge, necessitating regular updates to maintain relevance and accuracy. Additionally, incorrect assumptions due to the lack of empirical data could spread misinformation.

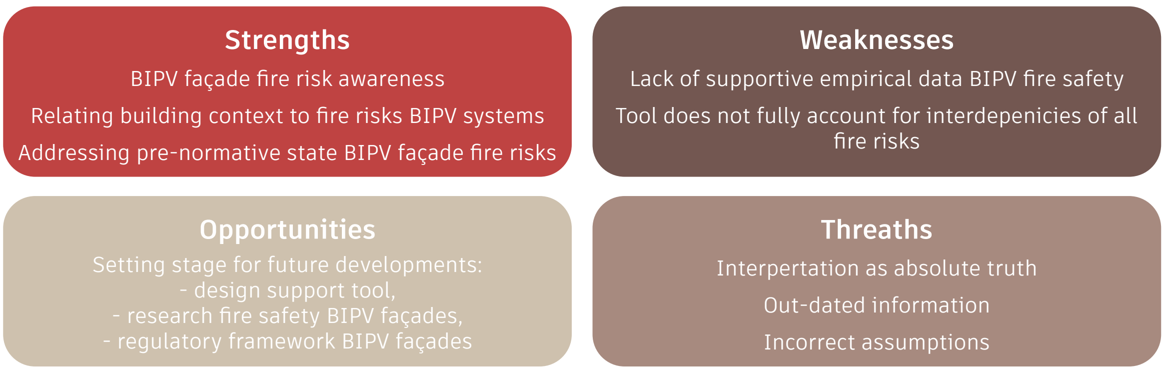

Figure 111: SWOT analysis reseach method. Own work

7.2.2 Reflection on relation research and design

The development of the design support tool enhanced the understanding of fire risks associated with BIPV systems in façades, emphasizing the value of research by design. The foundational knowledge for this study, established through the literature review, experts consultation and the fault tree risk analysis, was refined and contextualized during the tool's development. For example, as the tool’s framework required linking information within its specific context, it necessitated an evaluation of each design consideration and its associated risk factors. This process forced to think about the impact of every design element in relation to others, providing deeper insights into fire risks beyond the initial risk analysis.

This iterative process of tool development and knowledge acquisition was mutually reinforcing. As insights gained from developing the tool expanded the knowledge base, they also identified critical areas for further study and refinement. This synergy between the tool and the growing body of knowledge helped in ensuring that both elements evolved together, enhancing the understanding and application of fire safety measures in BIPV façade systems.

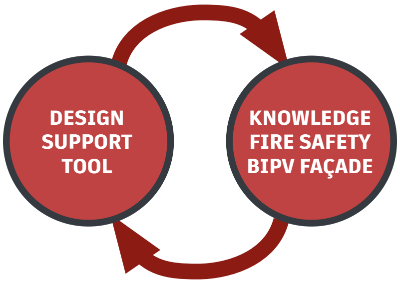

Figure 112: Research by design. Own work

7.2.3 Reflection on method adjustments

Adjustments to methodology were necessary to align the research process with the study's objectives and constraints. Here, I reflect on these adjustments and their rationale.

Risk analysis | Finding the appropriate format for the risk analysis was a significant challenge throughout the thesis, with numerous changes made to address encountered obstacles. The main objective was to systematically assess various scenarios leading to fire-related risks, allowing for the formulation of preventive and mitigative measures. Initially, a what-if analysis was planned, but this method's limitations, including its linear format and inability to capture scenario interdependencies, necessitated a switch to a fault tree analysis (FTA). The FTA provided a flexible framework to visualize scenario interdependencies and accurately assess risks.

The assessment criteria also underwent adjustments. Initially, probability and severity were considered, but it became crucial to distinguish between the probability of fire occurrence and fire development due to their different influencing factors. The evaluation criteria were thus refined to include the probability of fire occurrence, fire development, and the severity of potential damage. However, applying these criteria consistently proved challenging due to context-dependent values. Ultimately, a qualitative approach was adopted to better understand and address fire risks.

Additionally, the analysis initially planned to involve stakeholders from various fields, but this was revised to focus solely on collaboration with fire safety experts. This shift was due to the potential for stakeholder bias and their lack of necessary expertise to accurately assess evaluation criteria.

In conclusion, the final format of a qualitative fault tree analysis conducted with fire safety experts effectively addressed the complexities of fire scenarios, providing a robust framework for systematically identifying and assessing risks associated with BIPV systems.

Rainscreen façade focus | Initially, the scope was intended to encompass all BIPV façade types: rainscreen façades, curtain walls, double façades, and windows. However, the complexities and unique challenges of rainscreen façades required concentrated effort, leading to the underrepresentation and exclusion of the other types in the risk analysis and design support tool. While the findings for rainscreen façades can be extrapolated to other façade types, these areas did not receive the detailed exploration and specific attention they require

Visual representation | This thesis covers a wide range of concepts related to the fire safety of BIPV façade systems, providing a foundational layer of knowledge. However, reflecting on the representation, some parts are underrepresented visually, particularly the elaboration on risk parameters and measures. Visual representation is crucial as it allows readers to more easily understand complex concepts and measures, enhancing the value and usability of the tool. Improving visual aids would help in conveying information more effectively, making the content more accessible and actionable for users.

7.2.4 Reflection on personal process

Fire safety in the built environment is a complex discipline, only briefly covered in both the undergraduate Bouwkunde and the master track of Building Technology. Consequently, understanding this field required extensive research before addressing the primary objectives: performing the risk analysis and developing the design support tool. The research journey to grasp fire safety and BIPV was more time-consuming than anticipated due to the abundance of relevant principles and concepts. I would like to reflect on the following points regarding the process and developments during this thesis:

Collaboration Carmen | My collaboration with Carmen played a significant role in this study. Together, we navigated the new and complex field of fire safety, discussing relevant findings and deepening our understanding. We provided each other with input and suggestions for our thesis setup and process. Additionally, our joint efforts in developing the framework of the design support tool and defining relevant risk parameters were particularly valuable in the early stages, ensuring a solid foundation of the tool.

Becoming a BIPV fire safety expert | Zooming out from this thesis, being a BIPV fire safety expert is a highly specialized and unique field, as this knowledge is often absent among many designers. What is actually really interesting is that through the execution of this thesis, starting with no prior knowledge in both BIPV and fire safety, I can say I have developed into a junior BIPV façade fire safety expert. This is something I consider as invaluable, providing me with a new a critical perspective on the integration of fire safety in building designs. Regardless of where I end up after this master's program, the skills and knowledge gained from this thesis will enable me to critically assess fire safety considerations, a valuable asset in any role within the building and construction industry.

Nuance risk perspective | While working on this thesis focused on fire risks associated with BIPV systems in façades, it was essential to maintain a realistic perspective on risk. Constant exposure to potential risk can distort the perception of their frequency or severity. Given the limited statistical data for BIPV systems in façades and the lack of recorded fires directly attributed to them, it's clear that such incidents are rare. This doesn't mean there is no risk, but it provides context for the current risk levels.

These facts informed the design support tool output, ensuring that while precautions and mitigation strategies are necessary, they must also be proportionate to the actual level of risk observed. This balance is vital to avoid overestimating potential dangers and ensures that safety measures are both effective and rational, promoting an informed approach to risk management in BIPV applications.

Consulting fire safety experts | Engaging with fire safety experts from DGMR was crucial for this thesis. Their expertise provided quick access to relevant principles and data, streamlining the research process. Their guidance helped interpret complex concepts and refine methodologies, proving more practical than literature studies alone. Their involvement enriched the thesis with valuable insights and aligned it with the latest advancements in fire safety. Reflecting on the process, I realize that when the initial consultant could no longer assist, I should have been quicker and less hesitant in reaching out for new consultants, as this would have improved my decision-making process earlier on.

Consulting a broader spectrum of experts | While consulting with fire safety experts from DGMR significantly enriched my thesis, there was potential to enhance the research by engaging a broader range of professionals. Despite discussions with various academic professors, fire safety experts, manufacturers, a fire test lab representative, façade engineers, and an insurer, I could have expanded this network further. Engaging additional experts such as fire brigade members, standards authorities like NEN, fire consultants from other firms, façade BIPV installers and SCOPE12 inspection companies could have provided a more comprehensive understanding from more perspectives. However, due to practical constraints like time and accessibility, I had to prioritize interactions that offered the most value, balancing resource management with capturing broad expert knowledge.

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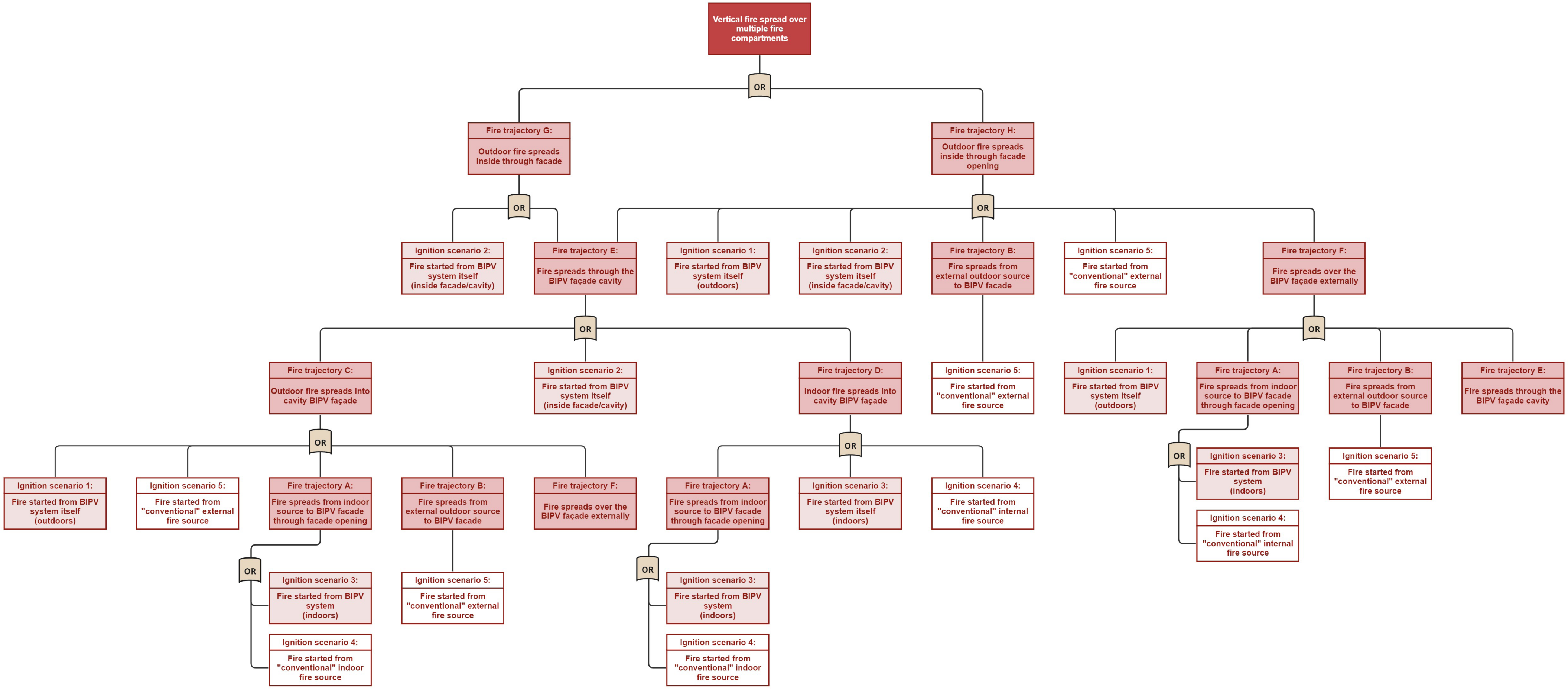
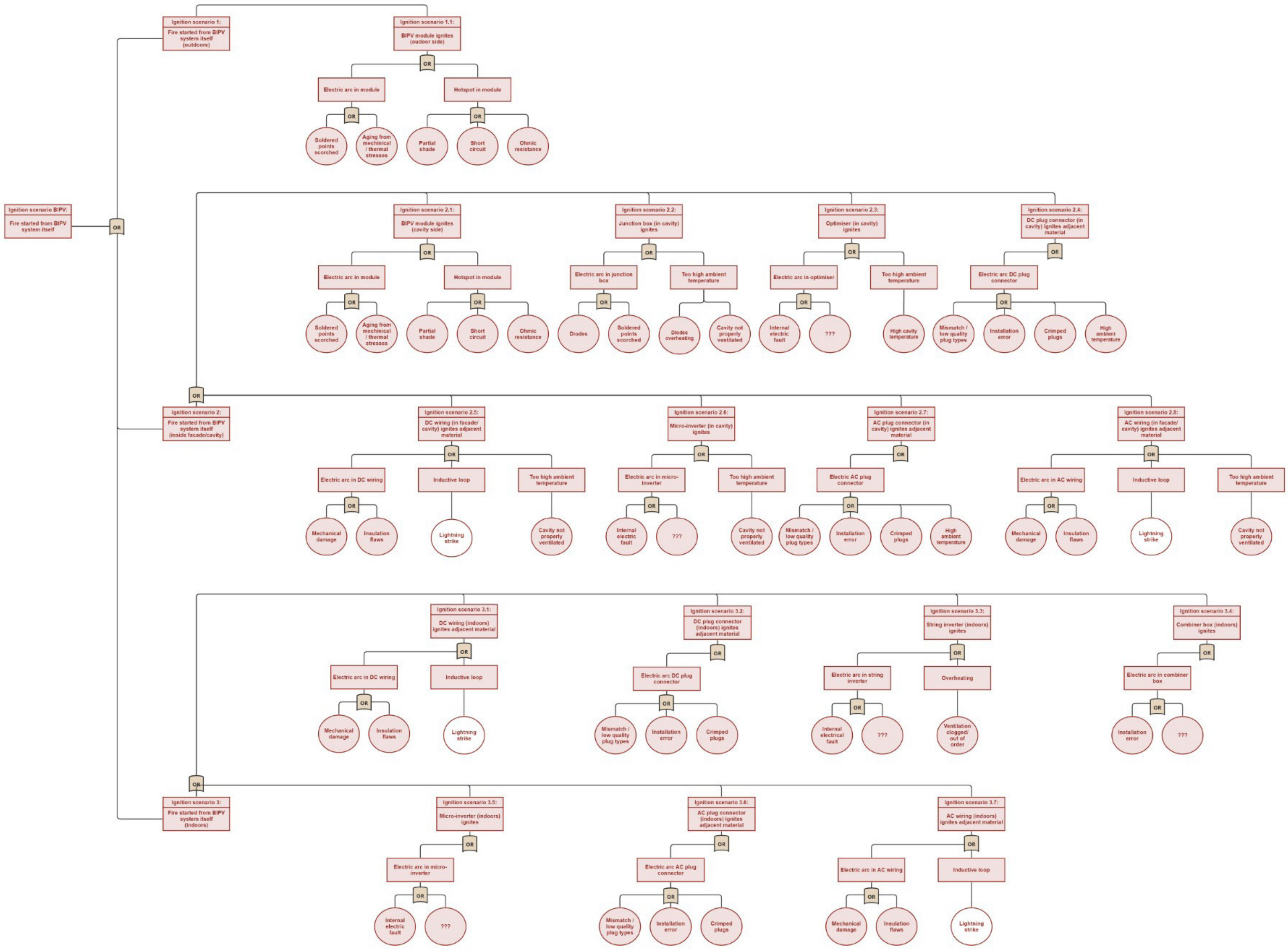
Appendix

Appendix I

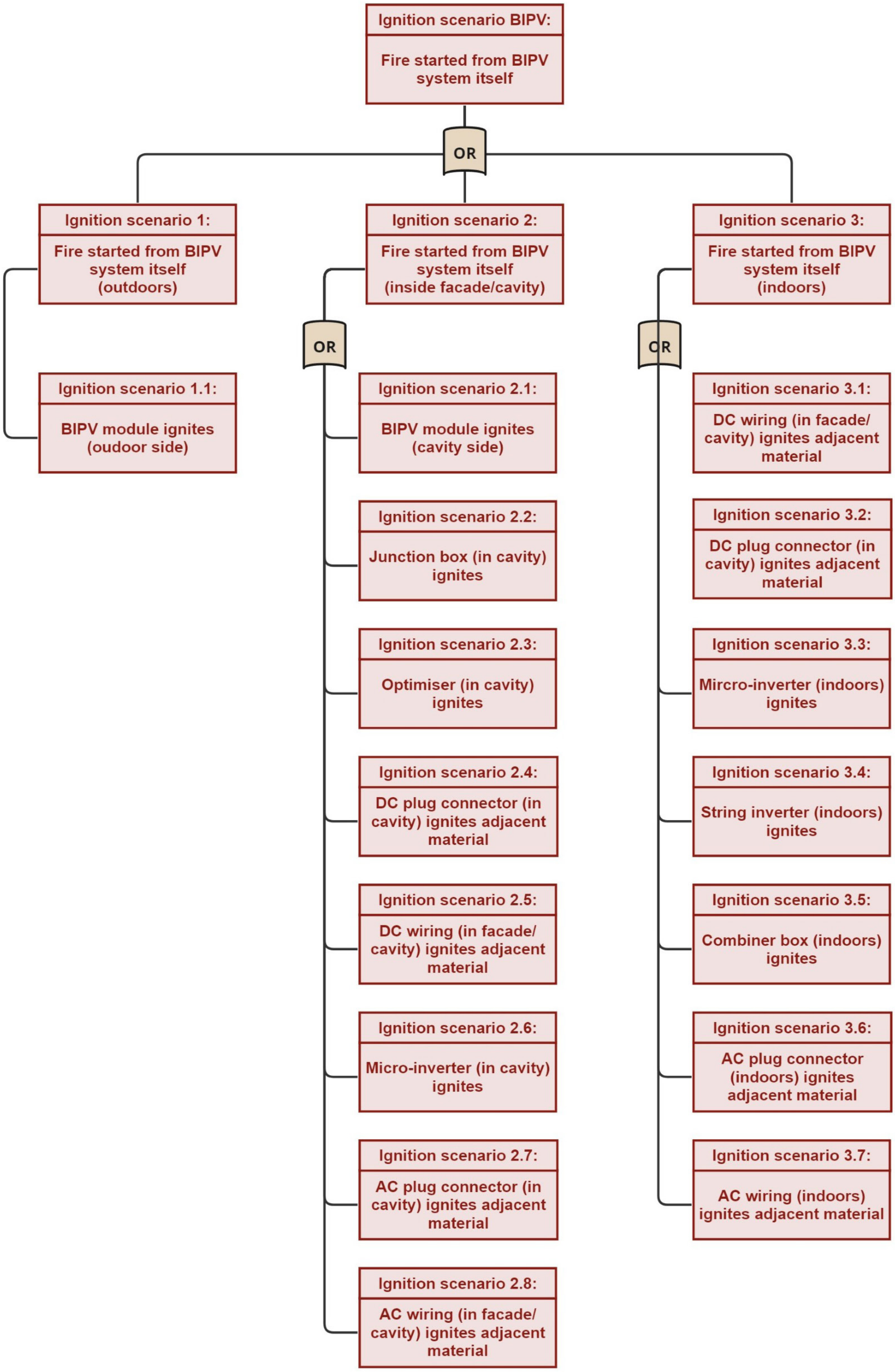
FTA1: Vertical fire spread over multiple fire compartments



Appendix I

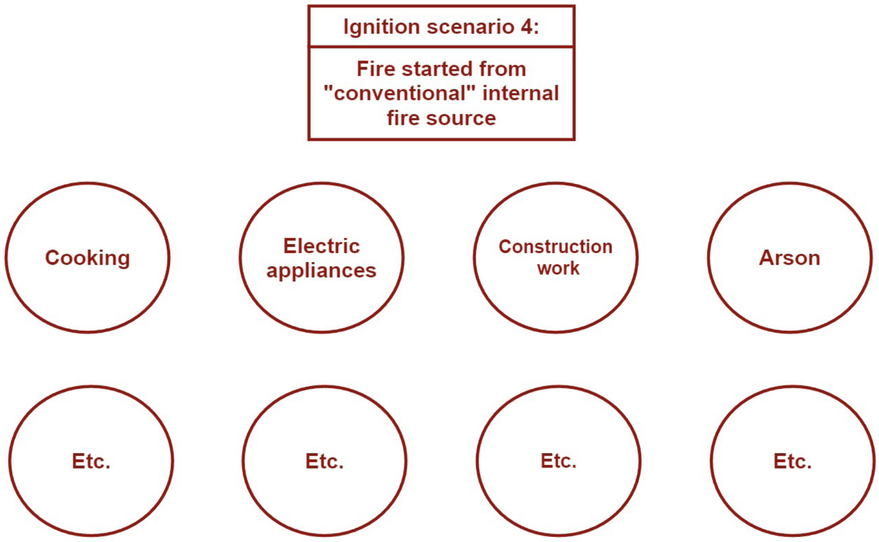

Ignition scenario BIPV: Fire started from BIPV system itself
OR
Ignition scenario 1: Fire started from BIPV system itself (outdoors)
Ignition scenario 1.1: BIPV module ignites (outdoor side)
Electric arc in module
Hotspot in module
Soldered points scorched
Aging from mechinical / thermal stresses
Partial shade
Short circuit
Ohmic resistance
Ignition scenario 2: Fire started from BIPV system itself (inside facade/cavity)
Ignition scenario 2.1: BIPV module ignites (cavity side)
Ignition scenario 2.2: Junction box (in cavity) ignites
Electric arc in junction box
Too high ambient temperature
Diodes
Soldered points scorched
Diodes overheating
Cavity not properly ventilated
Ignition scenario 2.3: Optimiser (in cavity) ignites
Electric arc in optimiser
Internal electric fault
???
High cavity temperature
Ignition scenario 2.4: DC plug connector (in cavity) ignites adjacent material
Electric arc DC plug connector
Mismatch / low quality plug types
Installation error
Crimped plugs
High ambient temperature
Ignition scenario 2.5: DC wiring (in facade/ cavity) ignites adjacent material
Electric arc in DC wiring
Inductive loop
Mechanical damage
Insulation flaws
Lightning strike
Ignition scenario 2.6: Micro-inverter (in cavity) ignites
Electric arc in micro-inverter
Ignition scenario 2.7: AC plug connector (in cavity) ignites adjacent material
Electric AC plug connector
Ignition scenario 2.8: AC wiring (in facade/ cavity) ignites adjacent material
Electric arc in AC wiring
Ignition scenario 3: Fire started from BIPV system itself (indoors)
Ignition scenario 3.1: DC wiring (indoors) ignites adjacent material
Ignition scenario 3.2: DC plug connector (indoors) ignites adjacent material
Ignition scenario 3.3: String inverter (indoors) ignites
Electric arc in string inverter
Overheating
Internal electrical fault
Ventilation clogged/ out of order
Ignition scenario 3.4: Combiner box (indoors) ignites
Electric arc in combiner box
Ignition scenario 3.5: Micro-inverter (indoors) ignites
Ignition scenario 3.6: AC plug connector (indoors) ignites adjacent material
Electric arc AC plug connector
Ignition scenario 3.7: AC wiring (indoors) ignites adjacent material

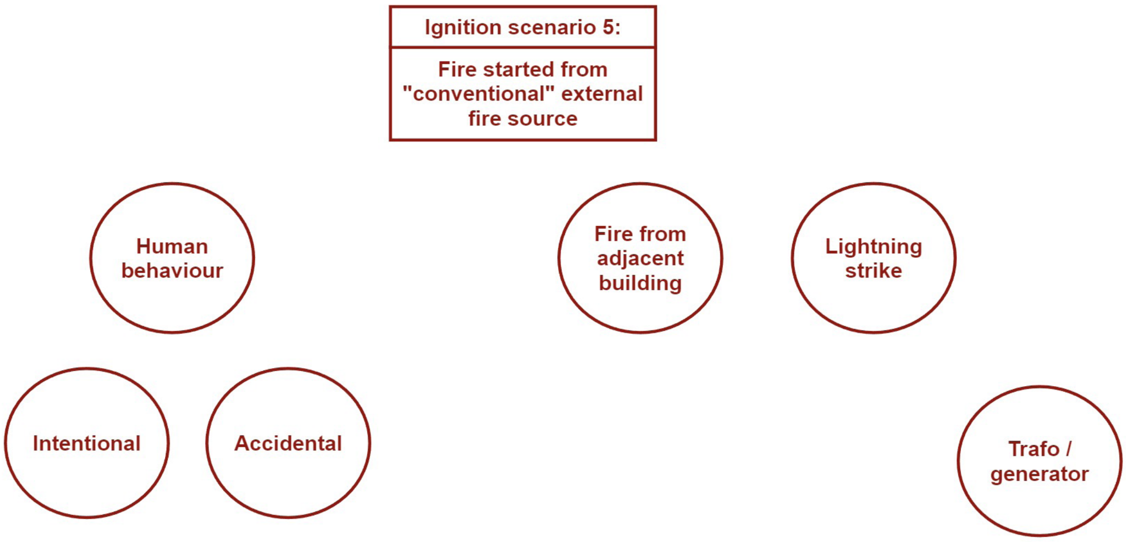
Appendix I



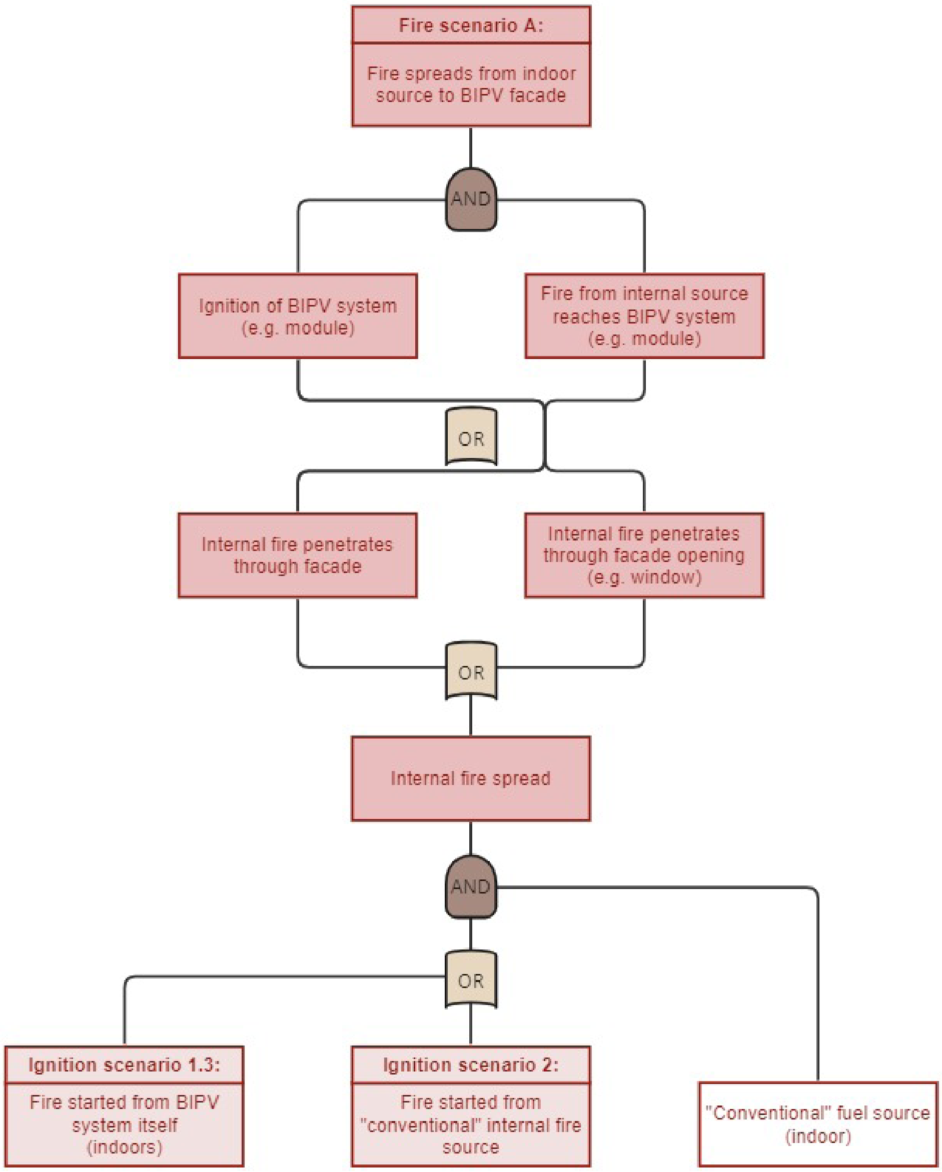
Ignition scenario BIPV:
Fire started from BIPV system itself
OR
Ignition scenario 1:
Fire started from BIPV system itself (outdoors)
Ignition scenario 2:
Fire started from BIPV system itself (inside facade/cavity)
Ignition scenario 3:
Fire started from BIPV system itself (indoors)
Ignition scenario 1.1:
BIPV module ignites (oudoor side)
OR
Ignition scenario 2.1:
BIPV module ignites (cavity side)
Ignition scenario 2.2:
Junction box (in cavity) ignites
Ignition scenario 2.3:
Optimiser (in cavity) ignites
Ignition scenario 2.4:
DC plug connector (in cavity) ignites adjacent material
Ignition scenario 2.5:
DC wiring (in facade/ cavity) ignites adjacent material
Ignition scenario 2.6:
Micro-inverter (in cavity) ignites
Ignition scenario 2.7:
AC plug connector (in cavity) ignites adjacent material
Ignition scenario 2.8:
AC wiring (in facade/ cavity) ignites adjacent material
OR
Ignition scenario 3.1:
DC wiring (in facade/ cavity) ignites adjacent material
Ignition scenario 3.2:
DC plug connector (in cavity) ignites adjacent material
Ignition scenario 3.3:
Mircro-inverter (indoors) ignites
Ignition scenario 3.4:
String inverter (indoors) ignites
Ignition scenario 3.5:
Combiner box (indoors) ignites
Ignition scenario 3.6:
AC plug connector (indoors) ignites adjacent material
Ignition scenario 3.7:
AC wiring (indoors) ignites adjacent material

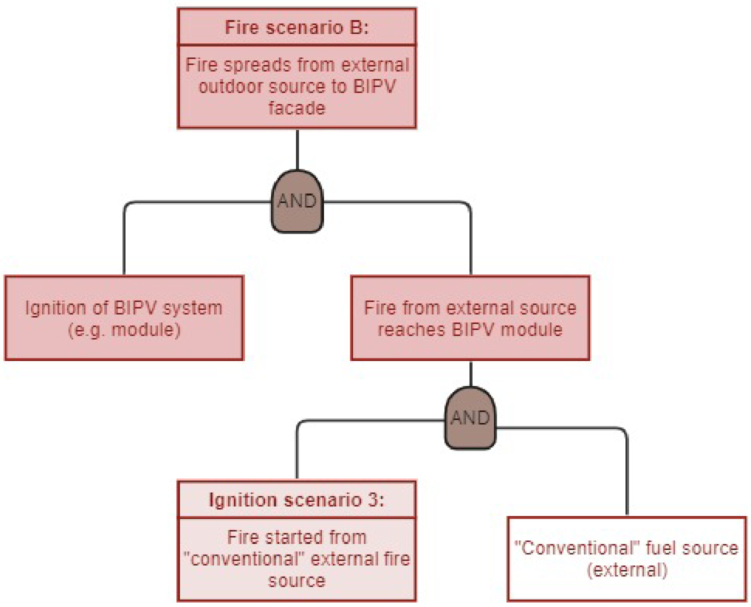
Appendix I


Ignition scenario 4:
Fire started from "conventional" internal fire source
Cooking
Electric appliances
Construction work
Arson
Etc.
Etc.
Etc.
Etc.

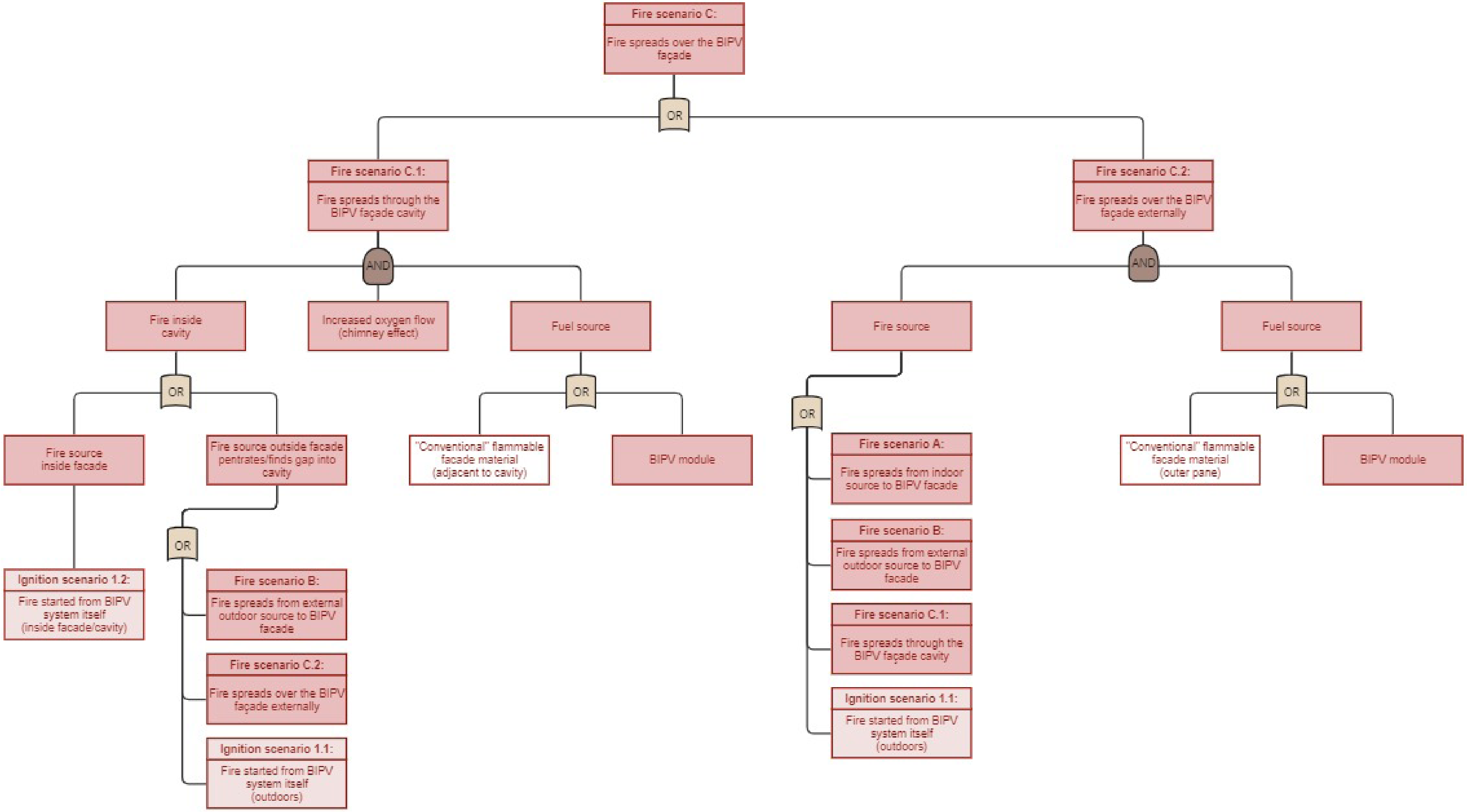

Ignition scenario 5:
Fire started from "conventional" external fire source
Human behaviour
Fire from adjacent building
Lightning strike
Intentional
Accidental
Trafo / generator

Appendix I


Fire scenario A:
Fire spreads from indoor source to BIPV facade
AND
Ignition of BIPV system (e.g. module)
Fire from internal source reaches BIPV system (e.g. module)
OR
Internal fire penetrates through facade
Internal fire penetrates through facade opening (e.g. window)
OR
Internal fire spread
AND
OR
Ignition scenario 1.3:
Fire started from BIPV system itself (indoors)
Ignition scenario 2:
Fire started from "conventional" internal fire source
"Conventional" fuel source (indoor)

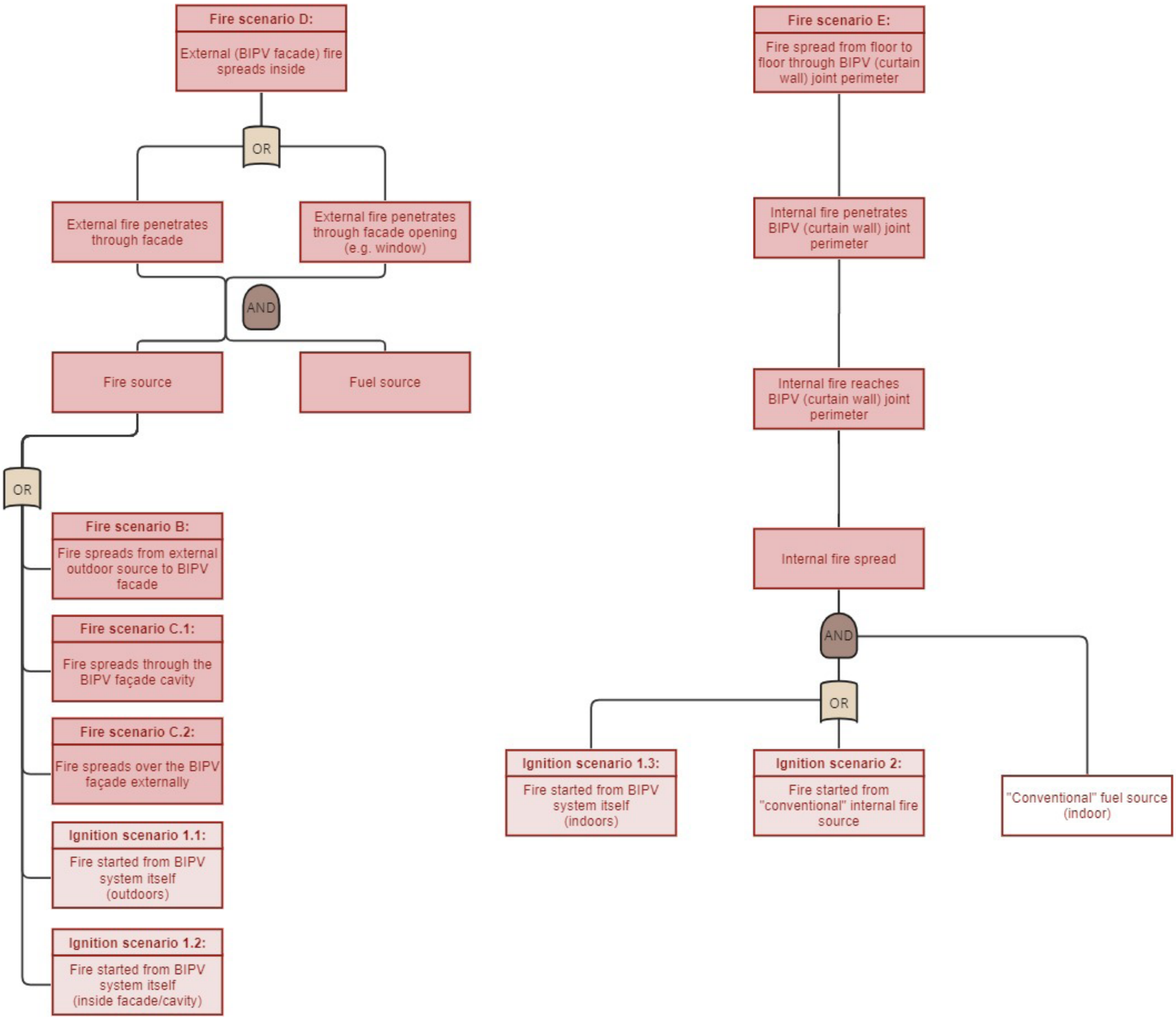

Fire scenario B:
Fire spreads from external outdoor source to BIPV facade
AND
Ignition of BIPV system (e.g. module)
Fire from external source reaches BIPV module
AND
Ignition scenario 3:
Fire started from "conventional" external fire source
"Conventional" fuel source (external)

Appendix I



Fire scenario C:
Fire spreads over the BIPV façade
OR
Fire scenario C.1:
Fire spreads through the BIPV façade cavity
AND
Fire inside cavity
Increased oxygen flow (chimney effect)
Fuel source
OR
Fire source inside facade
Fire source outside facade pentrates/finds gap into cavity
Ignition scenario 1.2:
Fire started from BIPV system itself (inside facade/cavity)
OR
Fire scenario B:
Fire spreads from external outdoor source to BIPV facade
Fire scenario C.2:
Fire spreads over the BIPV façade externally
Ignition scenario 1.1:
Fire started from BIPV system itself (outdoors)
OR
"Conventional" flammable facade material (adjacent to cavity)
BIPV module
Fire scenario C.2:
Fire spreads over the BIPV façade externally
AND
Fire source
Fuel source
OR
Fire scenario A:
Fire spreads from indoor source to BIPV facade
Fire scenario B:
Fire spreads from external outdoor source to BIPV facade
Fire scenario C.1:
Fire spreads through the BIPV façade cavity
Ignition scenario 1.1:
Fire started from BIPV system itself (outdoors)
OR
"Conventional" flammable facade material (outer pane)
BIPV module

Appendix I


Fire scenario D:
External (BIPV facade) fire spreads inside
OR
External fire penetrates through facade
External fire penetrates through facade opening (e.g. window)
AND
Fire source
Fuel source
OR
Fire scenario B:
Fire spreads from external outdoor source to BIPV facade
Fire scenario C.1:
Fire spreads through the BIPV façade cavity
Fire scenario C.2:
Fire spreads over the BIPV façade externally
Ignition scenario 1.1:
Fire started from BIPV system itself (outdoors)
Ignition scenario 1.2:
Fire started from BIPV system itself (inside facade/cavity)
Fire scenario E:
Fire spread from floor to floor through BIPV (curtain wall) joint perimeter
Internal fire penetrates BIPV (curtain wall) joint perimeter
Internal fire reaches BIPV (curtain wall) joint perimeter
Internal fire spread
AND
OR
Ignition scenario 1.3:
Fire started from BIPV system itself (indoors)
Ignition scenario 2:
Fire started from "conventional" internal fire source
"Conventional" fuel source (indoor)

Appendix II

Sheet: Home

Home | Info BIPV | Risk overview | F1 | F2 | F3 | F4 | Measures

DESIGN SUPPORT TOOL: FIRE SAFETY FACADE BIPV SYSTEMS

Are you an architect or facade engineer, tasked with designing a new building that incorporates Building Integrated Photovoltaic (BIPV) systems into its façade? You're excited about the possibilities these systems offer in terms of sustainability and energy efficiency. However, there's a problem... You're not entirely sure about the fire risks associated with BIPV installations. You've heard some concerns, but you're not sure how to navigate them effectively?

That's where this design support tool comes in. It's designed to bridge the gap of the pre-normative regulatory framework surrounding BIPV systems, making it easier for architects like you to understand and address fire safety concerns.

How to use the tool

Step 1	Step 2	Step 3	Step 4
Assess your case of study in the "Risk Overview" by filling in the design considerations for your facade(s)	Consult sheets "Risk parameters (1-22)" or "Info BIPV" for information regarding the fire risk of each risk parameter	Assess each facade in detail in the sheet "Facade Overview" (F1-F4)	Consult sheet "Measures" for tailored measures and strategies

Scroll down for more information about the tool

Appendix II

Disclaimer

Sheet setup

Home
Serving as the home page of the tool, this sheet offers essential information about the tool, helping users understand its structure and purpose

Info BIPV
This sheet provides basic information about the fire safety of BIPV facade systems. It covers the fundamental fire risks and the key considerations for incorporating BIPV safely into façade designs.

Risk overview
This is the main sheet of the tool and is the **only sheet where users can input data.** Users can enter all relevant design considerations for various risk parameters and assess the impact of each through specified risk factors.

Facade overview (F1-F4)
These sheets offer a more detailed analyses for each façade, derived from data entered in the "Risk Overview" sheet, and provides an overview of the fire risks of the design conderations.

Measures
This sheet provide a series of measures and strategies that the user can or should employ, based on the input in the "Risk overview" sheet.

Risk parameters(1-22)
These sheets provide more detailed information on each of the 22 risk parameters. They offer insights and data, helping users understand the nuances and implications of each risk parameter.

Information on risk factors and evaluation categories

example provided below). This value represents the impact on fire safety; the higher the value, the higher the risk. This approach not only helps to quickly assess and compare the potential impact of various design options, but also facilitates a deeper understanding of how each choice affects the overall fire safety in relation to the BIPV context.

(8) *Healthcare with sleeping area, healthcare residential, detention function*

level, a weighted evaluation is provided. Note that these evaluations indicate the level of risk but do not determine whether it is acceptable or not. For example, a red evaluation does not mean the situation is unacceptable but rather that it carries a high risk.

	Low risk	Although less critical, care should still be given to ensure basic safety measures are in place.
	Moderate risk	Care should be taken to implement appropriate safety measures to manage the identified risks.
	High risk	Extra care and higher levels of measures should be implemented to mitigate the risk effectively.

design considerations on the overall risk profile of the building. It is important to recognize that these numbers **should not be regarded as absolute truths** as they are inherently subjective to some extent. Therefore, users should approach these risk factors with a critical mindset, viewing them as **guiding indicators** of the risk rather than definitive representative.

What does the tool do?

This tool is ultimately aimed at promoting an informed decision-making process, equipping designers with the most essential knowledge to achieve fire safety and fire resilience in buildings with BIPV systems in façades. To realize this goal, the design support tool is structured around several key objectives:

Fire risk identification BIPV | The tool delivers preliminary knowledge on fire risks associated with BIPV systems in façades, based on literature reviews, risk analysis, and expert consultations. This base of knowledge serves to inform and alert users about potential risks in BIPV applications.

Evaluate context beyond product level | The tool goes beyond product-focused assessments to evaluate the wider contexts of building and façade, enhancing understanding of how BIPV systems interact with other design considerations for fire safety.

Provide practical measures and guidelines | The tool offers measures and strategies that are specifically formulated to address the identified context and fire risks. The focus is on delivering solutions that are both effective and minimally restrictive, promoting smarter, adaptable fire safety practices that can be integrated into existing design processes.

Facilitate compliance | Recognizing the complexities and limitations of the regulatory framework for BIPV façades, the tool clarifies applicable regulations and also assesses their adequacy in covering BIPV-specific issues by highlighting limitations.

Foster informed decision-making | The tool enhances decision-making by enabling users to assess the impact of risk parameters and design choices on fire safety. It enables comparison of design considerations, highlighting how each influences BIPV systems' fire resilience

Who is the intended user?

This design support tool is specifically crafted for **designers, including architects and façade engineers**, as they play a critical role in the building design process. By providing them with specialized knowledge on fire safety for BIPV façade systems, the tool aims to enhance their decision-making capabilities, encouraging the integration of fire-resilient practices into standard design procedures.

While the tool is primarily intended for designers, it can also be useful for **other stakeholders like developers or clients**. However, these stakeholders are encouraged to engage with the **one pager**, which provides more concise information.

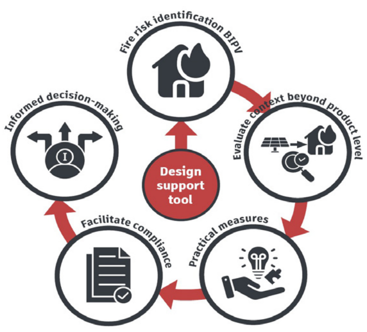


Figure 1: Design support tool objectives

When to use the tool?

This tool is designed to be used at the **earliest stages of the design process**, providing detailed guidance on design considerations, measures, and strategies. Early implementation is crucial to avoid disruptive and time-consuming revisions later.

While the tool is primarily intended for early-stage guidance, it can also be used at **later stages as a means of validation** to ensure that initial design decisions align with best practices.

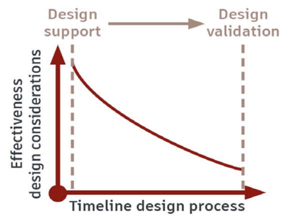


Figure 2: Design support tool usage design process

How to utilize the tool optimally?

To utilize the design support tool optimally, it is recommended **to use and fill it in individually**. By doing so, the user can develop a foundational body of knowledge, which can then be applied or reffered to during key stages of the design process, such as **at the drawing table, in discussions with stakeholders and during design presentations**.

While **group usage is generally not recommended** because the substantial detail in the tool can lead to prolonged discussions and challenges in interpretation, there may be instances where collaborative input is necessary. In these cases, it's crucial to **carefully plan the group session** to focus only on essential elements to avoid overwhelming participants. For example, focusing exclusively on the risk overview sheet can help ensure clarity and effective engagement with the most relevant information.

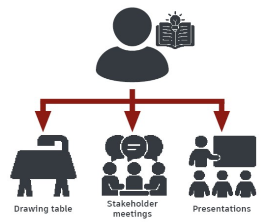


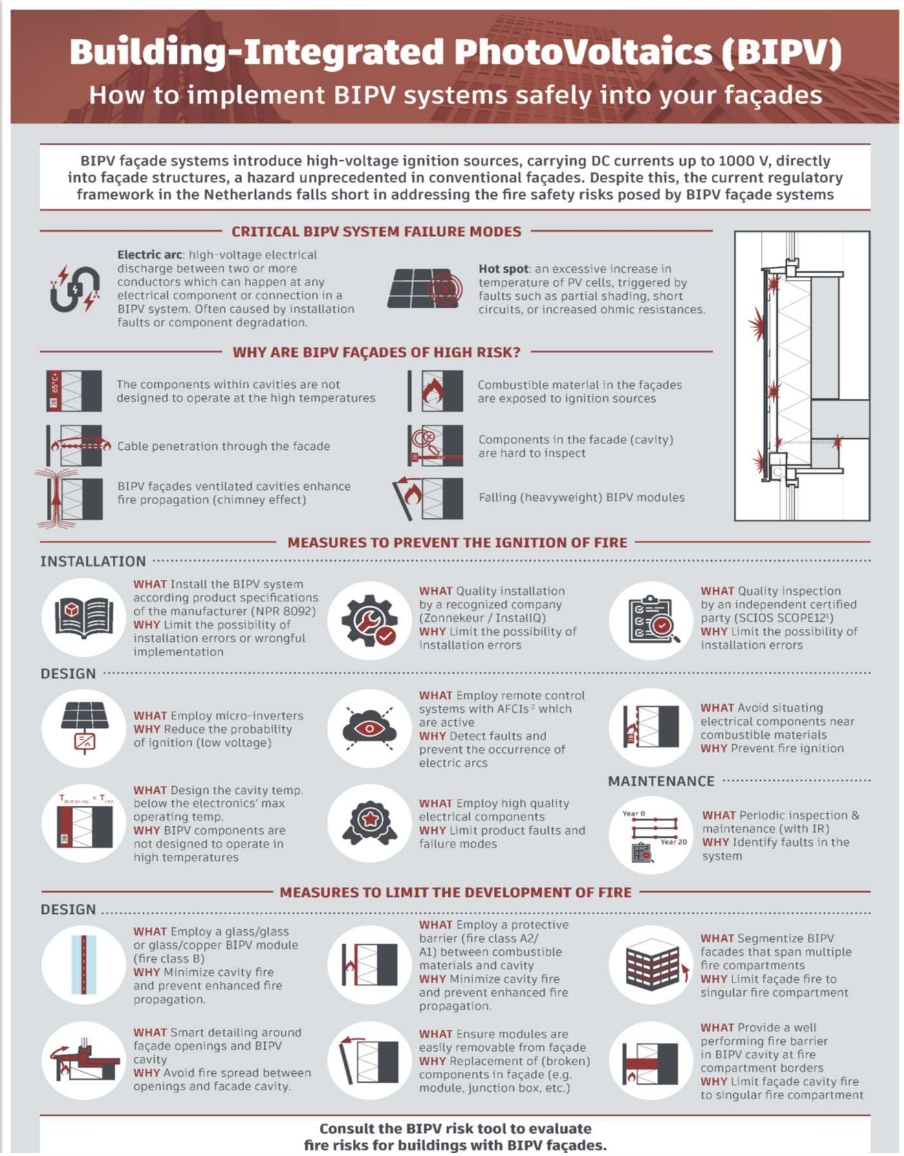
Figure 3: Design support tool optimal usage

Appendix II

Info BIPV

Info BIPV

This one-pager highlights some of the most relevant risks associated with BIPV systems in facades and offers some essential and effective measures to address these risks



Appendix II

Sheet: Risk overview

Home | Info BIPV | Risk overview | F1 | F2 | F3 | F4 | Measures

Risk overview

What is the amount of facades that you want to assess?	Grosspeter tower	The Pulse of Amsterdam	Concept proposal: PCT Cartuja	Villa Lichtenberg
Four façades	North	North	North	North
What do the colours and (..) values mean?	More info on façade 1	More info on façade 2	More info on façade 3	More info on façade 4

Building characteristics risk level		
1 What is the building function of use?	More info	(8) Healthcare with sleeping area, healthcare residential, detention function
2 What is the building height?	More info	(8) Building height >100m
3 What is the location of the escape routes?	More info	(1) One staircase in residential or accomodation not in residential building or accomodation building
4 How would you estimate the value of the building?	More info	(1) Low value

Façade characteristics risk level		Façade 1	Façade 2	Façade 3	Façade 4
5 Does the BIPV facade continuously span over multiple fire compartments?	More info	(8) Yes, over more than two fire compartments	(1) No, each BIPV segment is limited to a single fire	(8) Yes, over more than two fire compartments	(1) No, each BIPV segment is limited to a single fire
6 Does the BIPV facade cavity continuously span over multiple fire compartments?	More info	(1) No, each BIPV cavity is limited to a single fire	(1) No, each BIPV cavity is limited to a single fire	(8) Yes, over more than two fire compartments	(1) No, each BIPV cavity is limited to a single fire
7 Will there be openings in the BIPV facade?	More info	(2) Yes, distributed openings	(2) Yes, distributed openings	(2) Yes, distributed openings	(2) Yes, distributed openings
8 Will there be protrusions along the BIPV façade?	More info	(1) No	(0,75) Horizontal protrusion < 0,5m	(1) No	(1) No
9 Will the BIPV façade be entirely accessible by the fire brigade?	More info	(4) No	(4) No	(1) Yes	(1) Yes
10 Do BIPV modules endanger an escape route?	More info	(2) Yes, BIPV modules are situated above multiple	(2) Yes, BIPV modules are situated above multiple	(1,5) Yes, BIPV modules are situated above an escape	(1,5) Yes, BIPV modules are situated above an escape
11 Will the façade be load-bearing?	More info	(1) No	(1) No	(1) No	(2) Yes
12 Will the orientation of the facade be in the prevailing wind direction of the location?	More info	(1) The facade is subjected to the prevailing wind or	(1) The facade is subjected to the prevailing wind or	(1) The facade is subjected to the prevailing wind or	(1) No

BIPV & façade product characteristics risk level		Façade 1	Façade 2	Façade 3	Façade 4
13 What type of BIPV module will be employed?	More info	(1) Glass/glass	(1) Glass/glass	(1) Glass/glass	(1) Glass/glass
14 What will be the fire class of the BIPV module according NEN-EN 13501-1?	More info	(1) B	(1) B	(1) B	(1) B
15 What will be the fire class of the BIPV module according ANSI/UL 1703 (via UL 790)?	More info	(1) Not applicable	(1) Not applicable	(1) Not applicable	(1) Not applicable
16 Will the BIPV modules be easily removable?	More info	(2) No	(1) Yes	(1) Yes	(2) No
17 What is the main electrical configuration that will be employed?	More info	(2) String inverter	(0,5) Micro-inverter	(0,5) Micro-inverter	(2) String inverter
18 Will an active AFCI be employed in the BIPV system?	More info	(0,5) Yes	(0,5) Yes	(0,5) Yes	(0,5) Yes
19 Will the BIPV cavity exceed the maximum temperature specified for the BIPV system's	More info	(8) Yes, 20+ °C higher	(4) Yes, 0-20 °C higher	(8) Yes, 20+ °C higher	(1) No
20 What material will be situated in the cavity opposite to the BIPV module?	More info	(2) Sheet layer or insulation layer (fire class B)	(2) Sheet layer or insulation layer (fire class B)	(2) Sheet layer or insulation layer (fire class B)	(2) Sheet layer or insulation layer (fire class B)
21 What material will be used for the mounting system of the BIPV modules?	More info	(2) Aluminium	(2) Aluminium	(2) Aluminium	(2) Aluminium
22 Will BIPV system cables penetrate through the facade?	More info	(2) Yes	(2) Yes	(2) Yes	(2) Yes
23 Will quality control measures for the BIPV system be employed?	More info	(1) Yes, InstallQ	(0,25) Yes, InstallQ and SCOPE12	(16) No quality control will be employed	(1) Yes, InstallQ

	More info on façade 1	More info on façade 2	More info on façade 3	More info on façade 4

Overview risk score per façade	*Façade 1*	*Façade 2*	*Façade 3*	*Façade 4*
Building characteristics				
Façade characteristics				
BIPV & facade product characteristics				

	Reset input façade 1	Reset input façade 2	Reset input façade 3	Reset input façade 4

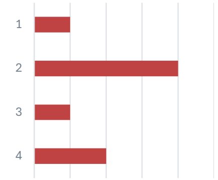
Appendix II

Sheet: Façade overview

Facade 1 Overview

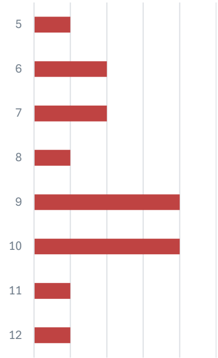
Building characteristics			8
1	What is the building function of use? More info	1	(1) Other building functions
2	What is the building height? More info	4	(4) Building height 50m-100m
3	What is the location of the escape routes? More info	1	(1) One staircase in residential or accomodation not in residential building or accomodation building
4	How would you estimate the value of the building? More info	2	(2) Medium value

Risk impact



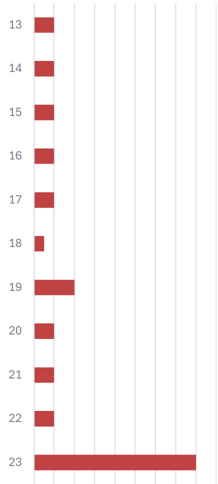
Facade characteristics			64	Influence on fire safety
5	Does the BIPV facade continuously span over multiple fire compartments? More info	1	(1) No, each BIPV segment is limited to a single fire compartment	Limiting BIPV segments to a single fire compartment reduces the risk of fire spreading between compartments, enhancing overall fire safety.
6	Does the BIPV facade cavity continuously span over multiple fire compartments? More info	2	(2) Yes, over multiple fire compartments horizontally	Horizontal BIPV cavities can spread fire across compartments, increasing horizontal fire risk.
7	Will there be openings in the BIPV facade? More info	2	(2) Yes, distributed openings	Can facilitate fire spread through multiple points, enabling fire propagation across several fire compartments both horizontally and vertically
8	Will there be protrusions along the BIPV façade? More info	1,00	(1) No	No interruptions allow fire to spread across the BIPV facade
9	Will the BIPV façade be entirely accessible by the fire brigade? More info	4	(4) No	Lack of accessibility impedes firefighting efforts, requiring stricter WBDO standards and increasing fire spread risk.
10	Do BIPV modules endanger an escape route? More info	4	(4) Yes, BIPV modules are situated above multiple escape routes	BIPV modules above multiple escape routes increase the risk of (multiple) escape route obstructions, obstructing/endangering evacuation paths
11	Will the façade be load-bearing? More info	1	(1) No	The collapse of a non load-facade does not directly compromise the building's structural integrity.
12	Will the orientation of the facade be in the prevailing wind direction of the location? More info	1	(1) The facade is subjected to the prevailing wind or runs parallel to it.	Depending on the wind direction and speed, fire can spread rapidly or in various directions, including sideways or even downwards in extreme case

Risk impact



BIPV & facade product characteristics			8	Influence on fire safety and possible advice
13	What type of BIPV module will be employed? More info	1	(1) Glass/glass	Glass/glass modules offer better fire performance with non-combustible glass layers protecting combustible encapsulants.
14	What will be the fire class of the BIPV module according NEN-EN 13501-1? More info	1	(1) B	This module meets the minimal requirement according the building decree (Bbl)
15	What will be the fire class of the BIPV module according ANSI/UL 1703 (via UL 790)? More info	1	(1) Not applicable	Don't take into account this fire classification. Refer to NEN-EN 13501-1 for correct fire classification
16	Will the BIPV modules be easily removable? More info	1	(1) Yes	Easy removability allows for efficient maintenance and replacement, reducing fire risk from undetected issues.
17	What is the main electrical configuration that will be employed? More info	1	(1) String inverter + Optimiser	String inverter + optimiser operates at high voltage DC, posing higher fire risks but offers good efficiency, shading performance, and detailed monitoring.
18	Will an AFCI be employed in the BIPV system? More info	0,5	(0,5) Yes	Employing an AFCI reduces the risk of fire from electric arcs, enhancing system safety
19	Will the BIPV cavity exceed the maximum temperature specified for the BIPV system's comp More info	2	(2) Yes, 0-20 °C higher	Exceeding temperature by 0-20°C stresses components, increasing the risk of wear, electrical failures, and efficiency loss.
20	What material will be situated in the cavity opposite to the BIPV module? More info	1	(1) Sheet layer or insulation layer (fire class A2 or A1)	Fire class A2 or A1 materials minimize fire risk by resisting ignition from electric arc and preventing cavity fire propagation
21	What material will be used for the mounting system of the BIPV modules? More info	1	(1) Steel	Steel offers better fire resistance, retaining structural integrity at higher temperatures and reducing the risk of falling BIPV modules
22	Will BIPV system cables penetrate through the facade? More info	1	(1) No	No cable penetrations reduce fire spread risk between the interior and façade
23	Will quality control measures for the BIPV system be employed? More info	8	(8) No quality control will be employed	No quality control heavily decreases safety and reliability of (BI)PV installations due to lack of safety verification.

Risk impact



Appendix II

Home | Info BIPV | Risk overview | F1 | F2 | F3 | F4 | Measures

Measures

Compliance

- Ensure compliance with NEN 6068 and NEN 6069.
- Align facade construction with fire class requirements of the Bbl (according NEN-EN 13501-1). Refer to risk parameter 14 for more information about fire class requirements
- Conduct representative fire tests that closely represent end-use scenarios. Refer to risk parameter 14 for more information about testing BIPV systems

Generic advice that should always be considered

- The architect / façade designer, BIPV manufacturer and electrical installer should closely collaborate to design the electrical configuration of the BIPV system and adequately implement the effects of the system on the detailing, particularly in the façade (e.g. component placement in façade, cable penetrations, etc.).
- Ensure a maintenance schedule is developed and executed, tailored to the risk of the building to preserve the BIPV system.
- Ensure the BIPV module & system components are designed and installed according the product specifications of the manufacturer.
- Employ high quality electrical components with CE marking (be aware of fake certifications).
- Ensure the use of high-quality, heat-resistant and compatible connectors to minimise the possibility of electric arcs.
- Ensure AC and DC cables are extra protected (e.g. double isolated or fire-resistant).
- Prevent moisture penetration of electrical components, especially in the cavity, by avoiding the possibility of still standing water in the cavity and by employing components with a sufficient IP class.
- Employ bypass diodes with lower maximum currents than the junction box specifications to decrease the likelihood of overheating of junction boxes.
- Employ measures (e.g. bee beaks) to limit the impact of animals like birds, rodents or other animals nesting in the cavity.-
- Minimize the seams between BIPV modules and adjacent exterior façade materials to ensure that joints are tight and well-sealed, thereby restricting pathways for fire to penetrate into the cavity
- Think about design considerations to limit damage to the BIPV modules, potentially caused by a BMU or other external factors
- Implement lightning strike provisions (e.g. lightning conductors with overvoltage protection.

Tailored advice per facade based on input from sheet "Risk Overview"

Façade 1

More info on façade

- Ensure the materials in the BIPV cavity opposite the BIPV module are fire class A2 or A1 to act as a fire barrier (e.g. CEM board 10 mm), minimizing cavity fire and preventing enhanced fire propagation

- Consider adding optimizers to improve remote monitoring and control, enhance system performance, or use micro-inverters instead of string inverters to lower the operating voltage and reduce the risk of electric arcs

- Consider segmentizing the BIPV facades that span two fire compartments vertically to limit a façade fire to singular fire compartment. How? By creating physical gaps or barriers between BIPV modules at the borders of fire compartments.

- Strategically place façade openings to prevent critical fire propagation routes, and employ smart detailing around openings and BIPV cavities to prevent fire spread between them (e.g. non-combustible flashings).

- Critically consider the ease of removal for BIPV modules to facilitate maintenance and replacement. How? Use mounting systems that allow for this, avoiding glued connections.

- Ensure at least one main escape route has enhanced safety measures and assess the need for extra protection on other routes. How? Implement physical barriers, such as cantilevers, around critical areas like exit doors, or use steel mounting structures for BIPV systems above, or not situating BIPV modules above escape routes.

Façade 2

More info on façade

- Ensure the materials in the BIPV cavity opposite the BIPV module are fire class A2 or A1 to act as a fire barrier (e.g. CEM board 10 mm), minimizing cavity fire and preventing enhanced fire propagation

- Ensure the cavity temperature remains below the maximum operating temperature of the electrical components in the façade. How? Increase airflow in the cavity by enlarging cavity openings or increasing cavity depth

- Strategically place façade openings to prevent critical fire propagation routes, and employ smart detailing around openings and BIPV cavities to prevent fire spread between them (e.g. non-combustible flashings).

- Ensure at least one main escape route has enhanced safety measures and assess the need for extra protection on other routes. How? Implement physical barriers, such as cantilevers, around critical areas like exit doors, or use steel mounting structures for BIPV systems above, or not situating BIPV modules above escape routes.

- Conduct a wind analysis and consider the effects of wind on fire spread.

- Consider using a steel mounting frame to enhance structural integrity during a fire and improve the effectiveness of fire breaks

- Design cable penetrations to ensure they provide the same level of fire resistance as the façade.

Façade 3

More info on façade

- Ensure quality control with InstallQ qualified installers or conducting a SCOPE 12 retrospective inspection by a certified company.

- Ensure the materials in the BIPV cavity opposite the BIPV module are fire class A2 or A1 to act as a fire barrier (e.g. CEM board 10 mm), minimizing cavity fire and preventing enhanced fire propagation

- Ensure the cavity temperature remains below the maximum operating temperature of the electrical components in the façade. How? Increase airflow in the cavity by enlarging cavity openings or increasing cavity depth

- Consider segmentizing the BIPV facades that span two fire compartments vertically to limit a façade fire to singular fire compartment. How? By creating physical gaps or barriers between BIPV modules at the borders of fire compartments.

- Split up the BIPV cavity vertically at the fire compartment borders to limit vertical fire spread to a singular fire compartment. How? Employ a well-performing horizontal fire barrier or split up the cavity through detailing

- Strategically place façade openings to prevent critical fire propagation routes, and employ smart detailing around openings and BIPV cavities to prevent fire spread between them (e.g. non-combustible flashings).

- Consult with the local fire brigade to develop alternative strategies for access, fire suppression and evacuation.

- Evaluate the need for additional protection around escape routes to ensure

Façade 4

More info on façade

- Consider conducting a SCOPE 12 retrospective inspection by a certified company.

- Ensure the materials in the BIPV cavity opposite the BIPV module are fire class A2 or A1 to act as a fire barrier (e.g. CEM board 10 mm), minimizing cavity fire and preventing enhanced fire propagation

- Consider adding optimizers to improve remote monitoring and control, enhance system performance, or use micro-inverters instead of string inverters to lower the operating voltage and reduce the risk of electric arcs

- Strategically place façade openings to prevent critical fire propagation routes, and employ smart detailing around openings and BIPV cavities to prevent fire spread between them (e.g. non-combustible flashings).

- Critically consider the ease of removal for BIPV modules to facilitate maintenance and replacement. How? Use mounting systems that allow for this, avoiding glued connections.

- Consult with the local fire brigade to develop alternative strategies for access, fire suppression and evacuation.

- Evaluate the need for additional protection around escape routes to ensure safe evacuation. How? Implement physical barriers, such as cantilevers, around critical areas like exit doors, or use steel mounting structures for BIPV systems above, or not situating BIPV modules above escape routes.

- 0

Measures source

Risk Par.	Measure
5.A	y
5.B	Consider segmentizing the BIPV facades that span multiple fire compartments horizontally to limit a façade fire to singular fire compartment. How? By creating physical gaps or barri
5.C	Consider segmentizing the BIPV facades that span multiple fire compartments vertically to limit a façade fire to singular fire compartment. How? By creating physical gaps or barrie
6.A	y
6.B	Split up the BIPV cavity horizontally at the fire compartment borders to limit horizontal fire spread to a singular fire compartment. How? Employ a well-performing horizontal fire barri
6.C	Split up the BIPV cavity vertically at the fire compartment borders to limit vertical fire spread to a singular fire compartment. How? Employ a well-performing horizontal fire barrier or s
7.A	y
7.B	Strategically place façade openings to prevent critical fire propagation routes, and employ smart detailing around openings and BIPV cavities to prevent fire spread between them.
7.C	Strategically place façade openings to prevent critical fire propagation routes, and employ smart detailing around openings and BIPV cavities to prevent fire spread between them.
7.D	Strategically place façade openings to prevent critical fire propagation routes, and employ smart detailing around openings and BIPV cavities to prevent fire spread between them.
8.A	y
8.B	y
8.C	y
9.A	y
9.B	Consult with the local fire brigade to develop alternative strategies for access, fire suppression and evacuation.
10.A	y
10.B	Evaluate the impact of BIPV modules on the escape route to ensure safe evacuation.
10.C	Evaluate the need for additional protection around escape routes to ensure safe evacuation. How? Implement physical barriers, such as cantilevers, around critical areas like exit do
10.D	Ensure at least one main escape route has enhanced safety measures and assess the need for extra protection on other routes. How? Implement physical barriers, such as cantileve
11.A	y
11.B	Critically evaluate the impact of the BIPV system and its potential ignition scenarios on the integrity of the supporting structure to ensure it remains structurally sound and fire-resista
12.A	y
12.B	y
13.A	y
13.B	Always employ a glass/glass BIPV module to minimize cavity fires and prevent enhanced fire propagation.
14.A	Verify that your BIPV module has a fire class A according to NEN-EN 13501, rather than another fire classification such as ANSI/UL 1703 (via test method UL 790).
14.B	y
14.C	You are employing a BIPV module with a lower fire class (NEN-EN 13501-1) than permitted by the building decree (Bbl). Ensure the BIPV module meets a minimum fire class of B.
15.A	y
15.B	y
15.C	y
15.D	y
16.A	y
16.B	Critically consider the ease of removal for BIPV modules to facilitate maintenance and replacement. How? Use mounting systems that allow for this, avoiding glued connections.
17.A	y
17.B	Consider replacing string inverters with microinverters to lower the operating voltage of the BIPV system and minimize the risk of electric arcs
17.C	Consider adding optimizers to improve remote monitoring and control, enhance system performance, or use microinverters instead of string inverters to lower the operating voltage a
18.A	y
18.B	Ensure AFCIs are implemented in the system and ensure they are active to to limit the possibilities and effects of electric arcs in the system.
19.A	y
19.B	Ensure the cavity temperature remains below the maximum operating temperature of the electrical components in the façade. How? Increase airflow in the cavity by enlarging cavity
19.C	Ensure the cavity temperature remains below the maximum operating temperature of the electrical components in the façade. How? Increase airflow in the cavity by enlarging cavity
20.A	y
20.B	Ensure the materials in the BIPV cavity opposite the BIPV module are fire class A2 or A1 to act as a fire barrier (e.g. CEM board 10 mm), minimizing cavity fire and preve
21.A	y
21.B	Consider using a steel mounting frame to enhance structural integrity during a fire and improve the effectiveness of fire breaks
22.A	y
22.B	Design cable penetrations to ensure they provide the same level of fire resistance as the façade.
23.A	y
23.B	y
23.C	Consider conducting a SCOPE 12 retrospective inspection by a certified company.
23.D	Ensure quality control with InstallQ qualified installers or conducting a SCOPE 12 retrospective inspection by a certified company.

Risk Par	Facade 1: measures	Facade 2: measures	Facade 3: measures	Facade 4: measures
5	y	y	Consider segmentizing the	Please fill in RP5
6	Split up the BIPV cavity hor	y	Split up the BIPV cavity ver	Please fill in RP6
7	Strategically place façade	Strategically place façade	Strategically place façade	Please fill in RP7
8	y	y	y	Please fill in RP8
9	y	y	y	Please fill in RP9
10	Ensure at least one main e	Ensure at least one main e	Ensure at least one main e	Please fill in RP10
11	y	y	Critically evaluate the imp	Please fill in RP11
12	y	y	y	Please fill in RP12
13	y	Always employ a glass/gla	Always employ a glass/gla	Please fill in RP13
14	y	y	You are employing a BIPV r	Please fill in RP14
15	y	y	y	Please fill in RP15
16	y	y	Critically consider the eas	Please fill in RP16
17	Consider replacing string i	y	Consider adding optimizer	Please fill in RP17
18	y	y	Ensure AFCIs are impleme	Please fill in RP18
19	Ensure the cavity temperat	y	Ensure the cavity temperat	Please fill in RP19
20	y	y	Ensure the materials in the	Please fill in RP20
21	y	Consider using a steel mou	Consider using a steel mou	Please fill in RP21
22	y	Design cable penetrations	Design cable penetrations	Please fill in RP22
23	Ensure quality control with	Ensure quality control with	Ensure quality control with	Please fill in RP23

Appendix II

Sheet: Risk parameter 1 & 2

Option	What is the building function of use?	Risk factor	Elaboration per option
1.A	(1) Other building functions	1	All functions other than those mentioned from B to E
1.B	(4) Residential in a residential building, accomodation in an accomodation building	4	A residential and an accommodation building are buildings where there are more than one residential or accommodation function respectively which share a circulation space ('verkeersruimte'). This does not include ground-based single family homes which are linked. These fall under option A.
1.C	(4) Childcare with sleeping area	4	
1.D	(6) Sleeping function with reduced self reliance	6	Reduced self-reliance means there are relatively many people present who are slower in evacuating than average. For example, this is the case in senior housing
1.E	(8) Healthcare with sleeping area, healthcare residential, detention function	8	

What to fill in?

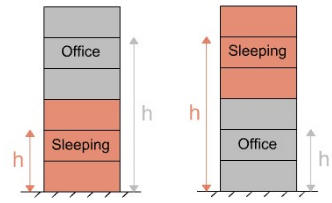
Fill in the primary function of the building. If the building has multiple functions, refer to the tool on the right to determine the most critical function. Enter all the functions along with their corresponding heights within the building. The tool will calculate the criticality based on both function and height, and the most critical function will be highlighted in red. If more than one function is highlighted, select the one with the highest risk factor for the building's function.

Fire risk

Different building functions carry varying levels of fire risk, primarily influenced by the occupants' ability to detect a fire promptly and evacuate independently. Buildings designed for sleeping, such as residential homes and hotels, often present a higher risk because occupants may not detect a fire as quickly while asleep. Similarly, buildings frequented by individuals with limited mobility or self-reliance, like hospitals or care homes, also pose greater risks, as evacuation may be slower. According to the Dutch building decree (Bbl), there are 12 distinct building functions and several subfunctions, each subject to specific fire safety regulations tailored to their risk profiles.

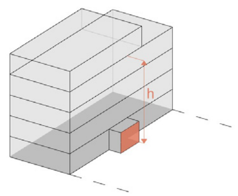
Tool to test most critical function

Building function	Height	Criticality value
(1) Other building functions	(1) Building height <15m	1
(4) Residential in a residential building, accomodation in an accomodation building	(1) Building height <15m	4
"Please select"	"Please select"	"Please fill in"
"Please select"	"Please select"	"Please fill in"
"Please select"	"Please select"	"Please fill in"
"Please select"	"Please select"	"Please fill in"



Home | Info BIPV | Risk overview | F1 | F2 | F3 | F4 | Measures

Option	What is the building height?	Risk factor
2.A	(1) Building height <15m	1
2.B	(2) Building height 15m-50m	2
2.C	(4) Building height 50m-100m	4
2.D	(8) Building height >100m	8

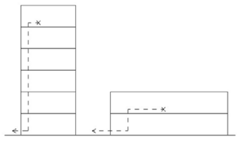


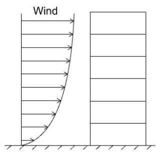
What to fill in?

Fill in the height of the highest occupied floor, measured from the height of the terrain at the ground level of the building's main entrance.

Fire risk

Numerous factors come into play when considering fire safety in relation to building height, but among them, some stand out as particularly critical. The height of a building significantly influences the complexity of evacuation. In taller buildings, the evacuation routes are longer, and more vertical descents are required, which can be particularly challenging for individuals who are not self-reliant or have mobility issues. Additionally, wind speeds increase at higher altitudes, potentially intensifying a fire on upper floors. Access for firefighters is also a critical factor; while standard fire trucks with aerial ladders can typically reach up to 12 meters, taller buildings may require specialized equipment that is not available at all fire stations. Risk parameter 9 elaborates more on accessability of fire fighters.





Appendix II

Option	What is the location of the escape routes?	Risk factor	Elaboration per option
3.A	(1) The building has only one floor	1	This option applies to buildings consisting of a single ground level, without any additional floors or elevated areas.
3.B	(1) One staircase in residential or accomodation not in residential building or accomodation building	1	This option refers to buildings where a single staircase serves multiple distinct residential or accommodation functions that share a common circulation space. This configuration typically includes ground-based single-family homes, both detached and semi-detached.
3.C	(1) Two staircases on distance >H/2	1	This indicates that the two staircases are separated by a distance greater than half the building's height.
3.D	(2) Two staircases on distance <H/2 in two cores	2	This configuration means that the distance between the staircases is less than half the building's height. The term 'in two cores' specifies that these staircases are located in separate structural cores.
3.E	(4) Two staircases on distance <H/2 in one core	4	This configuration means that the distance between the staircases is less than half the building's height. The term 'in one core' indicates that these staircases are, spiral or winding, in the same core.
3.F	(8) One staircase	8	This option is applicable when there is only a single staircase available for vertical circulation

What to fill in?

Select the escape route configuration applicable to your building. This is dependand on the distance between the two farthest apart accessible staircases in relation to the building height (H). Do not consider the distance between staircases if they are not both accessible to individuals evacuating. If there are more than two staircases, assess the distance between all of them and chose the most critical one.

Fire risk

The availability and configuration of escape routes are crucial for safe evacuation during a fire. Buildings with only one staircase pose a significant risk if the fire blocks this route, leaving no alternatives for escape. Buildings with multiple staircases offer redundant paths, enhancing safety. However, the effectiveness of multiple staircases also depends on their separation; staircases that are too close to each other may both be compromised by a single fire event, particularly in compact buildings. Ideally, staircases should be spaced sufficiently apart to reduce the likelihood of a fire affecting all available escape routes simultaneously.

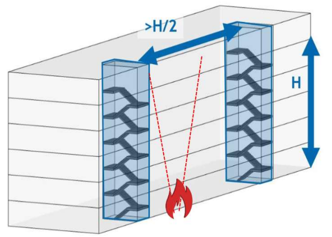


Figure 1: Placement of escape routes. Source: Nieman and DGMR (2022)

Appendix II

Home | Info BIPV | Risk overview | F1 | F2 | F3 | F4 | Measures

Option	How would you estimate the value of the building?	Risk factor
4.A	(1) Low value	1
4.B	(2) Medium value	2
4.C	(4) High value	4

What to fill in?

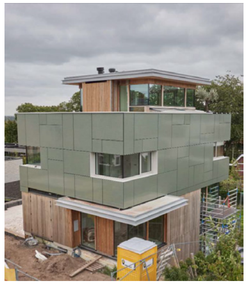
Fill in the building's value, considering factors such as its intrinsic, emotional or cultural importance. This value assessment should reflect both the building's physical structure and its contents. For instance, a museum may be considered of high value due to its irreplaceable artifacts and cultural significance. A factory, depending on its operational importance and the value of its machinery, might be assigned a medium or high value.

Fire risk

The value assigned to a building significantly influences the prioritization and extent of fire safety measures required. High-value buildings, such as museums or historical sites, often necessitate advanced fire protection measures to safeguard irreplaceable contents and preserve cultural heritage. For these buildings, the financial and emotional impact of a fire can be relatively large, prompting the need for strict fire prevention strategies. Conversely, buildings with a lower assessed value might not justify the same level of extensive fire safety investments, although basic protections are still essential to meet safety regulations and prevent loss.

Intrinsic Value: The inherent worth of the property, based on its utility, features, and condition, influencing its market price and replacement cost.
Emotional Value: The sentimental importance of a property to its owners and occupants, often derived from personal experiences, memories, and attachments, making its loss deeply personal and impactful.
Cultural Value: The cultural importance of a building or area, particularly those that contribute to the heritage and identity of a community, preserving historical narratives.

Example: low value



Villa Lichtenberg
Amersfoort, The Netherlands

Residential house

Intrinsic value: low
Emotional value: low
Cultural value: low

Example: medium value

Grosspeter Tower
Basel, Switzerland

Office tower

Intrinsic value: high
Emotional value: low
Cultural value: low

Example: high value

Novartis Building, Basel, Switzerland

Exhibition, meeting, and event center

Intrinsic value: high
Emotional value: mid
Cultural value: mid

Appendix II

Sheet: Risk parameter 5 & 6

Home | Info BIPV | Risk overview | F1 | F2 | F3 | F4 | Measures

Option	Does the BIPV facade continuously span over multiple fire compartments?	Risk factor
5.A	(1) No, each BIPV segment is limited to a single fire compartment	1
5.B	(2) Yes, over multiple fire compartments horizontally	2
5.C	(4) Yes, over two fire compartments vertically	4
5.D	(8) Yes, over more than two fire compartments vertically	8

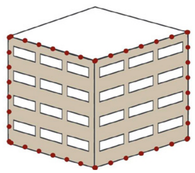
What to fill in?

Fill in whether the BIPV façade stretches over more than one fire compartments and how the fire compartments are situated relative to one another. In case both horizontal and vertical is relevant, fill in vertically.

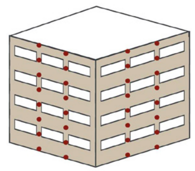
Fire risk

When a BIPV façade spans multiple fire compartments, it presents a risk for facilitating the spread of fire between compartments. Vertical extensions are particularly vulnerable because fire naturally tends to spread upward more rapidly than horizontally. Thus, BIPV façades that extend vertically across compartments pose a greater risk of promoting vertical fire spread, potentially bypassing compartmentalization designed to contain fires within a single level. Horizontal spans, while still a risk, generally see slower fire progression, but still require fire-stopping measures to prevent lateral fire spread.

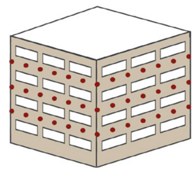
BIPV segment is limited to a single fire compartment



BIPV segment over multiple fire compartments horizontally



BIPV segment over multiple fire compartments vertically



Home | Info BIPV | Risk overview | F1 | F2 | F3 | F4 | Measures

Option	Does the BIPV facade cavity continuously span over multiple fire compartments?	Risk factor
6.A	(1) No, each BIPV cavity is limited to a single fire compartment	1
6.B	(4) Yes, over multiple fire compartments horizontally	4
6.C	(6) Yes, over two fire compartments vertically	6
6.D	(8) Yes, over more than two fire compartments vertically	8

What to fill in?

Fill in whether the BIPV cavity stretches over more than one fire compartments and how the fire compartments are situated relative to one another. In case both horizontal and vertical is relevant, fill in vertically.

Fire risk

Ventilated cavities in façades inherently have a high risks regarding fire propagation due to the chimney effect, which significantly accelerates the spread of fire within a façade. Thus, BIPV facades with cavities that span multiple fire compartments vertically present a critical risk, necessitating enhanced fire-stopping measures. Although horizontal spread also poses risks, these are relatively lower compared to vertical spread due to the slower progression of fire laterally

A ventilated cavity has openings to the outside air, allowing flames to enter the cavity from the outside and, subsequently, exit back out. The size and placement of these openings are crucial for further fire spread along the façade. Within the cavity, the rate at which a fire spreads is determined by the material characteristics of the two surfaces, the support structure of the outer layer, and the draft within the cavity.

Appendix II

Option	Will there be openings in the BIPV facade?	Risk factor
7.A	(1) No	1
7.B	(2) Yes, distributed openings	2
7.C	(3) Yes, vertical continuous openings	3
7.D	(1) Yes, horizontal continuous openings	1

What to fill in?

Indicate whether the BIPV facade will have any openings and, if so, specify the type of openings.

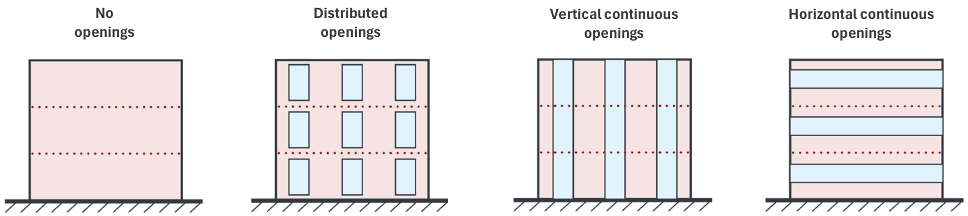
Fire risk

When glass is subjected to fire, or more specifically, heat differences, it breaks. Once the glass of a facade opening is broken, there is a hole in the façade through which fire can spread freely, both from inside to outside and the other way around. Therefore, a wall with transparent parts/windows poses a greater fire spread risk than a closed façade. In the Netherlands, this risk is addressed with WBDBO (NEN 6068 & NEN 6069)

Distributed openings | These facilitate fire spread through multiple points, enabling fire propagation across several fire compartments both horizontally and vertically

Vertical continuous openings |These openings allow fire to travel upwards quickly, increasing the risk of vertical fire spread while limiting horizontal fire spread.

Horizontal continuous openings | Although these openings enable fire to spread easily across a floor, they also serve as barriers to the more critical vertical fire spread.



Home | Info BIPV | Risk overview | F1 | F2 | F3 | F4 | Measures

Option	Will there be protrusions along the BIPV façade?	Risk factor
8.A	(1) No	1
8.B	(0,75) Horizontal protrusion < 0,5m	0,75
8.C	(0,5) Horizontal protrusion > 0,5m	0,5

Horizontal protrusion > 0.5m

Horizontal protrusion < 0.5m

No horizontal protrusion

What to fill in?

Fill in wheter there will be interruptions along the BIPV facade as these can interrupt fire spread across the facade.

Fire risk

Interruptions along the BIPV facade, such as horizontal protrusions, can have a significant impact on fire spread, potentially over multiple fire compartments. These interruptions may include features like balconies, galleries, or shading systems. If properly designed and constructed from non-combustible materials, these protrusions can slow down or even prevent the spread of fire by acting as barriers.

When there are **horizontal protrusions greater than 0.5 meters**, they can effectively act as fire breaks if made from incombustible materials. These larger protrusions can halt the progress of a fire, reducing the risk of vertic fire spread along the facade.

In the case of **horizontal protrusions less than 0.5 meters**, these smaller interruptions can still provide some benefit in slowing down fire spread, but their effectiveness is less than that of larger protrusions.

If there are no interruptions along the BIPV facade, the fire can spread more easily across the BIPV modules. A smooth, uninterrupted facade provides no barriers to slow down the fire, making it easier for flames to travel vertically.

Option	Will the BIPV façade be entirely accessible by the fire brigade?	Risk factor
9.A	(1) Yes	1
9.B	(4) No	4

What to fill in?

To determine if the facade is accessible for the fire brigade, apply the accessibility criteria as defined by NEN 6069 provided below to determine this.

Fire risk

Accessibility of the BIPV façade for the fire brigade is vital for effective emergency responses. If the façade is not fully accessible, it impedes firefighting efforts and necessitates more stringent WBDO requirements (NEN 6068 & NEN 6069), which could increase the risk of fire spread and complicate evacuation procedures. It's essential to incorporate accessibility features into the design to improve safety and the efficiency of emergency responses.

Quoting NEN 6069:

"A facade or roof section is presumed to be 'not safely accessible with extinguishing water' for the fire brigade in the following situations:
— if it is located higher than 20 meters above the measurement level; ***and***
— if it is both more than 60 meters horizontally distant from a public road and from a fire vehicle's staging area; ***or***
— if it cannot be safely approached within less than 30 meters with a fire hose nozzle due to inaccessible terrain or wide water bodies.

If a situation is practically deemed 'safely accessible with extinguishing water' for the fire brigade, this must be justified by the assessor to the satisfaction of the competent authority.

This justification may consist of an explanation of how the fire brigade can still safely reach the facades with extinguishing water. For instance, in consultation with the fire brigade's operational service, it might be decided to install a dry riser with a take-off point in the middle of a large inner garden that is not accessible for fire vehicles, so the facades can still be safely reached with extinguishing water, despite the distance to the staging area or public road being greater than 60 meters.

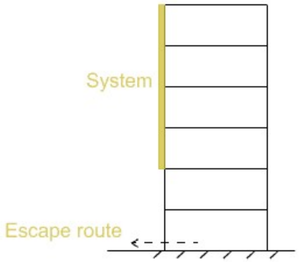
Additionally, in some municipalities, construction along wide public waterways is permitted, even though facade and roof sections may not be 'safely accessible with extinguishing water' according to the criteria mentioned above, because the fire brigade has other means available (such as fire boats).

If it is not evident that the facades can be safely reached with extinguishing water and there is no intention to make the dense facade parts fire-resistant for 60 minutes if necessary, it is always required to consult with the competent authority before submitting a building permit application for the construction activity. "

Appendix II

Home | Info BIPV | Risk overview | F1 | F2 | F3 | F4 | Measures

Option	Do BIPV modules endanger an escape route?	Risk factor
10.A	(1) No	1
10.B	(2) Yes, there is a clear fire trajectory from an BIPV module to an escape route	2
10.C	(2) Yes, BIPV modules are situated above an escape route	2
10.D	(4) Yes, BIPV modules are situated above multiple escape routes	4



What to fill in?

Indicate whether the BIPV modules endanger an escape route based on their positioning and the fire trajectory.

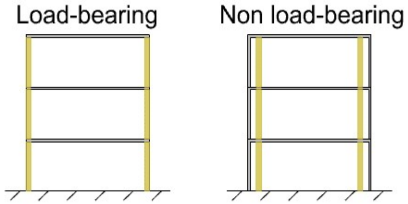
Fire risk

The proximity and positioning of BIPV modules relative to escape routes are critical in assessing fire safety risks. If BIPV modules are directly above or have a clear fire trajectory to escape routes, they can significantly increase the risk of obstructing these paths during a fire, potentially endangering occupants attempting to evacuate. While falling debris is a common occurrence in façade fires, the size and weight of BIPV modules pose an enhanced risk, potentially falling on people, blocking escape routes or causing additional structural damage.

The more escape routes are potentially endangered by BIPV systems, the greater the risk. It's important to evaluate these factors carefully to ensure that main escape routes remain unimpeded in case of a fire emergency

Home | Info BIPV | Risk overview | F1 | F2 | F3 | F4 | Measures

Option	Will the façade be load-bearing?	Risk factor
11.A	(1) No	1
11.B	(2) Yes	2



What to fill in?

Fill in if the façade is load-bearing or if the façade only supports its own weight.

Fire risk

Understanding whether a facade is load-bearing helps in assessing the fire risks and necessary safety measures.

Load-bearing facades | Critical to the building's structural integrity. In the event of a fire, the failure of a load-bearing facade can lead to partial or complete structural collapse, posing a significant danger to occupants and emergency responders. While the building decree imposes extra strict regulations on the requirements for the main support structure to prevent collapse in case of a fire, mitigating most of the risk, the inherent risks remain higher compared to a non-load-bearing facade.

Non-load-bearing | Generally, non-load-bearing facades pose a lower structural risk in the event of a fire. These facades do not support the building's primary structural load, meaning their failure due to fire would not compromise the building's overall stability. However, they still need to be designed to prevent fire spread and maintain fire resistance to protect the building interior and occupants.

Option	Will the orientation of the facade be in the prevailing wind direction of the location?	Risk factor
12.A	(1) No	1
12.B	(1) The facade is subjected to the prevailing wind or runs parallel to it.	1

What to fill in?

Determine whether or not the façade is subjected to the prevailing wind of the location or runs parallel to it. While no difference in risk factor is directly attributed due to the complex nature of wind, this parameter is included to raise awareness about the impact of wind. Thoughtful consideration should be given to wind effects, which may require analysis beyond the capability of this tool.

Fire risk

The direction and intensity of wind play a significant role in the spread of fire across a BIPV facade. Depending on the wind direction and speed, fire can spread rapidly or in various directions, including sideways or even downwards in extreme cases (figure 1).

1. Wind-driven fire spread:

Horizontal spread: When the wind blows directly against or parallel the facade, it can drive the flames horizontally, spreading fire quickly across the surface. This can lead to extensive damage over a wide area in a short amount of time.

Vertical Spread: Wind blowing upwards can exacerbate the chimney effect, where flames and hot gases rise rapidly, increasing the risk of vertical fire propagation. This is particularly dangerous in high-rise buildings where fire can spread to upper floors more quickly.

Downward spread: In certain extreme conditions, such as turbulent wind patterns, fire can spread downward, posing a risk to lower levels that are typically considered safer from fire spread.

Wind Speed and Intensity:

2. Wind speed and intensity:

High wind speeds: Strong winds can significantly increase the rate at which a fire spreads. High wind speeds can carry burning debris further, igniting new areas and accelerating the overall spread of the fire.

Variable wind patterns: Changes in wind direction and speed can create unpredictable fire behavior, making it more challenging to control and contain the fire.

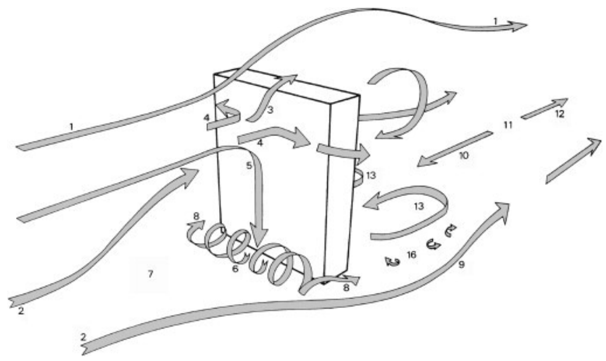


Figure 1: Schematic representation of wind flow pattern. Source: Moonen et al., (2012)

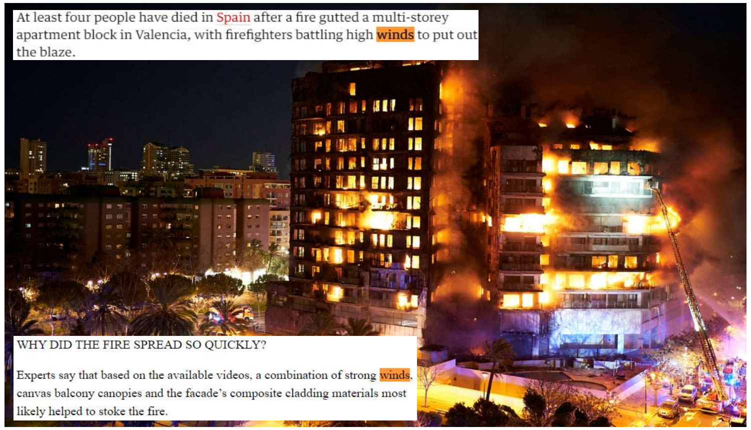


Figure 2: 22-02-2024 Valencia residential complex fire. Source: The Guardian (2024)

Option	What type of BIPV module will be employed?	Risk factor	Elaboration per option
13.A	(1) Glass/glass	1	A BIPV module with a glass front and backsheet
13.B	(8) Glass/polymer	8	A BIPV module with a glass frontsheet and a polymer backsheet

What to fill in?

Select the type of BIPV module to be used in the project. The options include glass/glass and glass/polymer modules. A glass/polymer module has a glass frontsheet and a polymer backsheet. A glass/glass module features both a glass frontsheet and backsheet, providing enhanced properties over a glass/polymer module like structural rigidity, sound insulation, and thermal insulation, etc. This type is predominantly utilized in BIPV façade applications due to these additional functional requirements.

Fire risk

A glass/glass provides enhanced properties over a glass/polymer module like structural rigidity, sound insulation, thermal insulation, but also in fire safety. This type is predominantly used in BIPV façade applications due to the additional functional requirements of facades over roofs. For roofing applications, where the requirements are lower, glass/polymer modules are more commonly used.

Glass/glass BIPV modules offer enhanced fire safety compared to glass/polymer modules. In glass/glass modules, both the front and back covers are made of non-combustible glass, which serves as an effective barrier to protect the combustible encapsulants, typically PVB or EVA. These encapsulants, despite their thinness (0.7 mm to 1.0 mm) and high calorific values (30 MJ/kg for PVB and 40 MJ/kg for EVA), are less likely to contribute to a fire due to the protective glass layers.

Conversely, glass/polymer BIPV modules feature a non-combustible glass front cover but a combustible polymer back cover. Polymeric materials have lower ignition points than glass, making these modules more susceptible to fire risks. In the event of a localized hot spot or arcing incident, the polymer backsheet can quickly ignite and exacerbate the fire, potentially affecting adjacent materials and structures. The polymer backsheet's vulnerability to fire increases the overall risk, as it can provide additional fuel, accelerating the spread of the fire.

Additionally, when employing incombustible insulation materials in the facade cavity with fire classes A2/A1 and reflective layers, the heat of a facade cavity would not be absorbed by the insulation but rather be reflected back across the cavity, intensifying the thermal load on the opposing panel. This phenomenon highlights the highcriticality of using BIPV modules with polymeric backsheets in façades, as they especially vulnaroble to cavity fires.

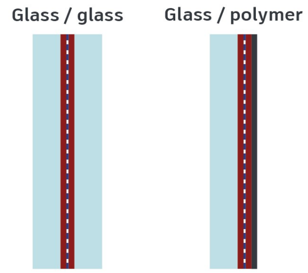


Figure 1: (BI)PV Module components . Source: Sauer (2021). Own edit

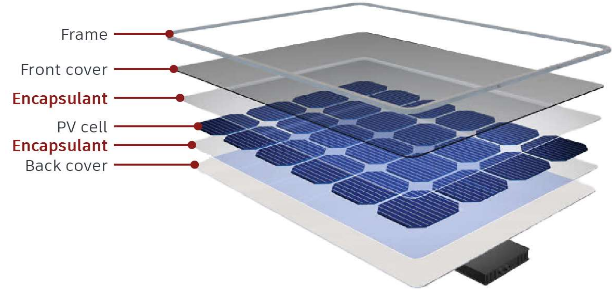


Figure 2: Typical (BI)PV module configurations.

BIPV module config.	Glass / glass	Glass / polymer
Front cover	Glass (non-combustible)	Glass
Encapsulants	PVB or EVA **(combustible)**	PVB or EVA **(combustible)**
Back cover	Glass (non-combustible)	Polymer **(combustible)**
Fire risk	Low	High
Quality	Higher-end	Lower-end
Structural Rigidity	High	Low
Durability	High	Moderate
Main application	Facade	Roof

Figure 2: Glass/glass & glass/polymer module characteristics. Own work

Appendix II

Option	What will be the fire class of the BIPV module according NEN-EN 13501-1?	Risk factor
14.A	(?) A2/A1	?
14.B	(1) B	1
14.C	(8) C or lower	8

What to fill in?

Enter the fire class of the BIPV module as classified under NEN-EN 13501-1. Note that this classification corresponds to the fire class requirements as referenced in the Bbl (Building decree). Ensure that the fire class selected matches the requirements set in thes regulations (figure 1).

Fire risk

In the Netherlands, fire safety standards and codes for BIPV systems in façades align with the regulations for façades, as these modules are treated as conventional building materials. As such, BIPV modules must meet the fire classification requirements outlined in NEN-EN 13501-1, adhering to the minimum classes specified in Figure 2 . These modules are evaluated using the same testing methods detailed in Figure 4, with the SBI test being most commonly used (Figure 1).

The current market standard for BIPV facade modules is fire class B. No modules have been identified as fire class A2 or A1 during the course of this studie. This is a result of the modules containing combustible encapsulants, EVA or PVB, which limit the potential to achieve fire class A2 or A1.

By current market standards for fire tests for facade products and configurations, BIPV facade systems are tested using the SBI-test (NEN-EN 13823). However, this test has several limitations in the context of BIPV facades:
Ventilation | The SBI-test does not account for the impact of a naturally ventilated cavity on fire development, as it only positions the fire source against the exterior pane and overlooks the unique fire behavior within these cavities.
Fire load | The SBI-test does not reflect real-world fire conditions adequately because it uses a 30 kW burner, which fails to simulate the critical temperatures for material ignition, thus not capturing the full potential of fire propagation.
Set-up scale | The SBI test fails to fully account for the importance of setup scale because it does not replicate end-use conditions accurately, particularly regarding factors such as ventilation, surface airflow, and thermal deformation of the construction elements.
Connections | The limited dimensions of the SBI test prevent the examination of critical façade connections such as window/door frames and transitions, which are essential pathways for fire spread in building façades

To address the above-mentioned limitations, the introduction of NPR 6999 in the Netherlands will enhance the testing possibilities (Figure 5). For instance, ISO 13785-1 offers a practical intermediary solution as it bridges the gap between the limited SBI test and the more extensive, costly alternatives such as DIN 4102-20 or BS 8414, thus allowing for a balanced and effective evaluation of fire safety. However, it should be noted that these methods do not represent the unique ignition source of BIPV systems.

Additionally, upcoming regulations from the Bbl, influenced by the new NPR 6999, will impose stricter requirements and will require to adhere to one of these options:
1. | Ensure that the façade meets fire class A2.
2. | A portion of the façade construction must comply with option 1 and shield more combustible materials with fire-resistant cladding that meets EI15 standards.
3. | Test the façade construction on a larger scale than is currently customary and ensure compliance with a specific class according to NPR 6999.

As the BIPV market currently does not provide modules that meet fire class A2 or A1, these upcoming requirements could pose challenges.

Rules of thumb fire class facade structure

Derrived from "Handreiking: beoordeling brandveiligheid gevels" from DGMR, some rules of thumb for determining the fire class of a facade:

1 | A facade never has a better fire classification locally than the external side of the facade's outer layer. For a Class B facade, the exterior must therefore meet Class B. This is certain.
2 | A facade meets Class B if it is constructed from components that comply with Classes A1 and A2 of NEN-EN 13501-1. This is certain.
3 | A facade with a ventilated cavity meets Class B if the exterior of the outer layer or one of the cavity surfaces meets Class B, and the remaining parts comply with Class A2 or A1 of NEN-EN 13501-1. This is highly plausible.
4 | A facade with a limited ventilated cavity meets Class B if the cavity surfaces and any cavity foil comply with Class B, the remaining components comply with Class A2 or A1 of NEN-EN 13501-1, and the cavity closure has only limited openings. This is sufficiently plausible.
Note | A facade with a commonly ventilated cavity and multiple components that individually meet Class B or worse often does NOT achieve Class B.

Figure 1: SBI-test with PIZ BIPV cladding system. Source: IEA PVPS Task 15 (2023)

New building	
Artikel 2.68	
Façade height < 2.5 m	B (if highest floor > 5m)
Façade height > 13 m	B
*1 Façade height > 30 m	A2 (sleeping function with reduced self-reliance), B (other functions)
*1 Façade height > 50 m	A2 (sleeping function), B (other functions)
Façade adjacent to extra protected escape route	B (cell function), C (other functions)
Façade adjacent to protected escape route	B (cell function), C (sleeping function), D (other functions)
Façade part (other)	D
Exception: doors, windows, window frames	D
Artikel 2.84 and 2.94	
Façade between two fire compartments	B (condition WBDBO / NEN 6068)
Façade between protected sub fire compartments and fire compartments	B (condition WBDBO / NEN 6068)
*1 Expected to be implemented in Bbl · Classes A2/B/C/D according NEN-EN 13501-1	

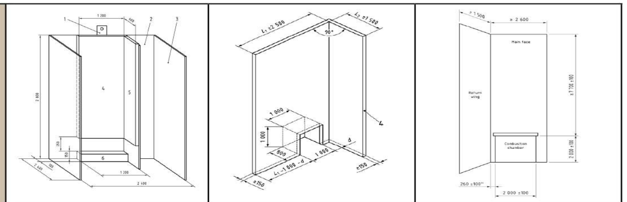
Figure 2: Summary of minimal fire classes from "Besluit bouwwerken leefomgeving (Bbl)

Test name	Applicable fire classes
Non-Combustibility test (NEN-EN ISO 1182)	A1, A2
Heat of Combustion test (NEN-EN ISO 1716)	A1, A2
Single Burning Item (SBI) test (NEN-EN 13823)	A2, B, C, D
Small Flame test (NEN-EN ISO 11925-2)	B, C, D, E, F

Figure 3: Current fire test used in the Netherlands for determining fire classes of building products

Euro classification	Fire behaviour of the material		Smoke production		Droplet forming	
A1	No contribution	Non-combustible	S1	Barely	D0	None
A2	Almost no contribution	Almost non-combustible	S2	Average	D1	Some
B	Limited contribution	Limited combustibility	S3	Big	D2	Quite a lot
C	Big contribution	Combustible				
D	High contribution	Easily combustible				
E	Very high contribution	Highly combustible				
F	Dangerous contribution	Very highly combustible				

Figure 4: Fire class definitions from "Besluit bouwwerken leefomgeving (Bbl)



Test method	ISO 13785-1	DIN 4102-20	BS 8414
Height:	2.5 meter	5.5 meter	9.5 meter
Flame source:	~100 KW	~ 320 kW	~ 3 MW
Cost estimation:	+ -	+	+ +
Execution time:	+ -	+	+ +

Figure 5: Overview of mid-large scale fire tests NPR 6999. Sources: van Mierlo, personal communication (march 2024)

Option	What will be the fire class of the BIPV module according ANSI/UL 1703 (via UL 790)?	Risk factor
15.A	(1) Not applicable	1
15.B	(1) A	1
15.C	(4) B	4
15.D	(8) C	8

What to fill in?

Enter the fire class of the BIPV module as classified by ANSI/UL 1703 (via UL 790 test method). Note that this classification **does not** correspond to the fire class requirements as referenced in the Bbl (Building decree).

Fire risk

(BI)PV modules can also have a certified fire class rating according to the ANSI/UL 1703 standard (via UL 790 test method). This standard assesses the module's fire performance and categorizes it into one of three classes: A, B, or C, which aligns with the classification categories of NEN-EN 13501-1. However, it's crucial to note a common misconception: equating a fire class from ANSI/UL 1703 (via UL 790) directly with a fire class from NEN-EN 13501-1 is inaccurate, as the UL 790 test method is designed for roof applications. The two standards evaluate different parameters and utilize varying thresholds for their classifications, which can lead to significant differences in fire safety ratings.

As a designer, you must be aware of these differences and ensure that the BIPV facade modules comply with the standards outlined by the Building Decree (Bbl): fire class standards according NEN-EN 13501-1. The fire class rating according ANSI/UL 1703 (via UL 790) provide limited insight into the fire performance of BIPV facade modules and should not be used as a refference.

Figure 1: UL 790 test with PV. Source: Cobouw (2020)

Home | Info BIPV | Risk overview | F1 | F2 | F3 | F4 | Measures

Option	Will the BIPV modules be easily removable?	Risk factor
16.A	(1) Yes	1
16.B	(4) No	4

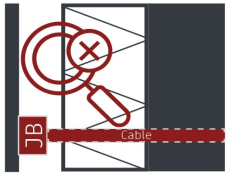
What to fill in?

Fill in whether the BIPV modules can be easily removed from the mounting structure to allow for replacement of components or inspection.

Fire risk

Components in BIPV systems can fail before the end of their expected lifetime due to various issues such as damage or wear. While manufacturers may claim a 50-year lifespan for BIPV modules, this is not always realistic. In practice, the actual lifespan can be shorter, necessitating replacement before the end of the building façade's lifespan. Smaller electrical components, like junction boxes, typically have a much shorter lifespan, estimated at around 20 years, far less than that of the façade.

Regular inspections or remote control are crucial for identifying potential issues like wear, defects, or improper installations in BIPV systems, which help prevent system failures or hazardous conditions. However, the integration of these systems into façades often makes components difficult to access for routine checks, complicating maintenance and increasing the risk of undetected issues that could ultimately lead to electric arcs. Easy removability is crucial for effective maintenance and replacement of components. This is highly dependent on the mounting system used. If the mounting structure and BIPV module are connected with a glued bond, it can make removal extremely challenging, if not impossible, without damaging the module or the façade.



Option	What is the main electrical configuration that will be employed?	Risk factor
17.A	(0,5) Micro-inverter	0,5
17.B	(1) String inverter + Optimiser	1
17.C	(2) String inverter	2

What to fill in?

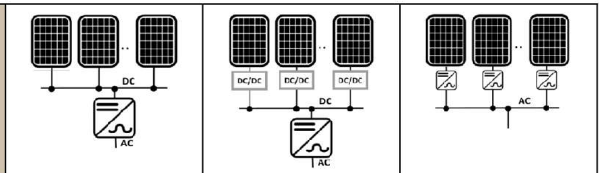
Fill in what the main electrical configuration is that will be employed, which relates back to the type of inverter.

Fire risk

Micro-inverter | The micro-inverter configuration involves placing an inverter for every one to two modules, typically within the facade cavity. This setup operates at low voltage AC (<80 V) on the facade, significantly reducing the fire risk compared to high voltage systems. At lower voltages around 80 volts, electric arcs are much less likely or even impossible and not capable of causing damage.This low voltage characteristic makes micro-inverters the safest option in terms of fire risk. However, the complexity of maintenance and higher costs are notable downsides, balanced by improved efficiency and shading performance. The advanced module-level monitoring allows for precise performance tracking and early detection of potential issues, enhancing overall safety and reliability.

String Inverter + Optimiser | In the string inverter + optimiser configuration, one inverter manages 10-20 modules, while each module has its own optimiser, typically placed in the facade. The system operates at high voltage DC (<1000 V) in the facade, presenting a high fire risk due to the potential for arcing and overheating in the high voltage DC environment. The use of optimisers enhances safety by allowing individual module control, reducing the likelihood of overheating and potential fires compared to traditional string inverters. This setup strikes a balance between cost, efficiency, and safety, offering high efficiency and good shading performance. Maintenance is more complex due to optimiser placed in the cavity being hard to reach, and monitoring capabilities are advanced, providing detailed insights at the module level.

String Inverter | A traditional string inverter configuration uses a single inverter for every 10-20 modules, with the inverter usually placed indoors. The system operates at high voltage DC (<1000 V) in the facade, presenting a high fire risk due to the potential for arcing and overheating in the high voltage DC environment. This setup is simpler and less expensive but sacrifices safety and performance. The entire string is affected if one module is shaded, leading to poor shading performance and medium efficiency. Maintenance is more straightforward, but monitoring is basic, limited to the string level, offering minimal insights into individual module performance or potential issues.



Electrical config.	**String inverter**	**String inverter + optimiser**	**Micro-inverter**
Typical components	1 inverter per 10-20 modules	1 inverter per 10-20 modules 1 optimiser per 1 module	1 inverter per 1-2 modules
Typical placement components	String inverter: indoors	String inverter: indoors Optimiser: in facade	Micro-inverter: facade cavity
Voltage in facade	High voltage DC (<1000 V)	High voltage DC (<1000 V)	Low voltage AC (<80 V)
Fire risk	High	Medium	Low
Costs	Low	Medium	High
Efficiency	Medium	High (due to individual module optimization)	High (due to individual module optimization)
Shading Performance	Poor (whole string affected)	Good (only shaded module affected)	Excellent (each module independent)
Flexibility	Low (dependent on string design)	High (independent module control)	Very high (independent module control)
Maintenance	Simple	Moderate	Complex
Monitoring	Basic (string level)	Advanced (module level)	Advanced (module level)

Figure 1: Characteristics of main electrical configurations BIPV systems

Appendix II

Option	Will an active AFCI be employed in the BIPV system?	Risk factor
18.A	(0,5) Yes	0,5
18.B	(8) No	8

What to fill in?

Fill in whether an AFCI will be integrated in the BIPV system.

Fire risk

The primary risk in BIPV systems is the occurrence of electric arcs. An arc forms when a strong electric current jumps across an air gap between two conductors, a common phenomenon possible in all electrical connections and components throughout the system. Such discharges can generate intense heat, reaching several 1000°C in standard (BI)PV systems. DC arcs are more stable and more dangerous than AC arcs, with arcs in lower voltage systems having a smaller impact on ignition.

Several factors can contribute to the occurrence of electric arcs, including improper installation, product faults, or the deterioration of components over time due to environmental conditions.

An **arc fault circuit interrupter (AFCI)** is a specialized circuit breaker designed to interrupt the circuit when it detects electrical arcs. While AFCIs are effective at detecting the arcs and interrupting these the circuit, they are not infallible and only able to prevent serial arcs. Parallel arcs can only be detected, not prevented. These devices are often integrated into modern inverters by default, though not all inverters come equipped with them, **and even when installed they may not always be activated.**

Despite their proven efficacy in enhancing electrical safety by reducing the risk of fire from arc faults, AFCIs frequently trigger false

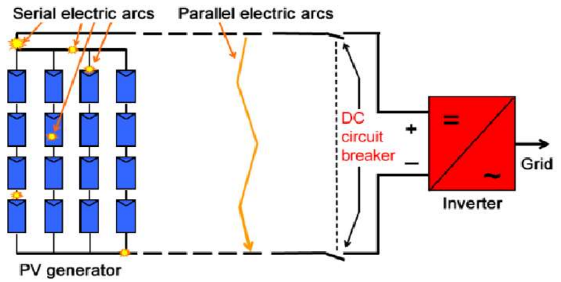


Figure 1: Serial and parallel electric arcs in PV systems. Source: TUV Rheinland et. al. (2018)

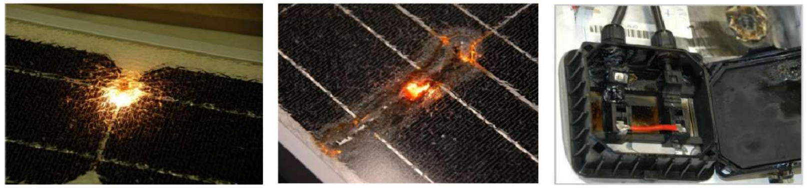


Figure 2: Electric arcs in PV modules and junction box. Source: TUV Rheinland et. al. (2018)

Home | Info BIPV | Risk overview | F1 | F2 | F3 | F4 | Measures

Option	Will the BIPV cavity exceed the maximum temperature specified for the BIPV system's components?	Risk factor
19.A	(1) No	1
19.B	(4) Yes, 0-20 °C higher	4
19.C	(8) Yes, 20+ °C higher	8

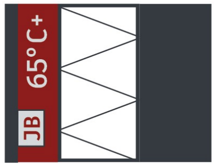
What to fill in?

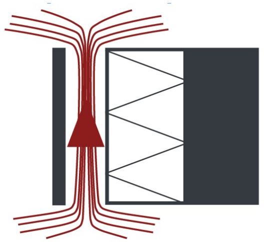
Fill in if the BIPV cavity will exceed the maximum operating temperature specified for the BIPV system's components situated in the facade? If the design temperature of you facade cavity is unkown, you should assume a maximum temperature of 65+ °C.

Fire risk

The already high risk of ventilated cavities is amplified in façades equipped with BIPV systems, primarily due to the elevated cavity temperatures. BIPV systems, generate heat during energy conversion, contributing to increased cavity temperatures. Typical product specifications of BIPV modules allow BIPV modules to achieve a surface temperature up to 85°C, and an cavity temperature of 65°C. However, real-world applications frequently surpass these temperatures limits.

Normally, an increased temperature in the façade cavity is not really a big risk, but within the context of BIPV it has two downsides. Firstly, the elevated ambient temperatures within the cavity push the limits of the electrical components, many of which may not be designed for such conditions. This can accelerate component wear or lead to internal electrical failures, ultimately resulting in electric arcs. Additionally, elevated temperatures impact BIPV module efficiency, with estimations suggesting a reduction of approximately 2-3% in efficiency for every 10°C increase.





Option	What material will be situated in the cavity opposite to the BIPV module?	Risk factor
20.A	(1) Sheet layer or insulation layer (fire class A2 or A1)	1
20.B	(2) Sheet layer or insulation layer (fire class B)	2
20.B	(4) Sheet layer or insulation layer (fire class C)	4
20.B	(8) Sheet layer or insulation layer (fire class D or lower)	8

What to fill in?

Fill in what the opposite material in cavity will be opposite to the BIPV module.

Fire risk

The primary risk in BIPV systems is the occurrence of electric arcs. However, it's important to note that an electric arc alone does not automatically lead to a fire; the critical factor is whether there are combustible materials nearby that could ignite. This risk is particularly significant when electrical components are installed near combustible facade materials like foils or insulation.

Additionally, ventilated cavities in façades already inherently have a high risks regarding fire propagation due to the chimney effect, which significantly accelerates the spread of fire within a façade. Within the cavity, the rate at which a fire spreads is determined by the material characteristics of the two surfaces, the support structure of the outer layer, and the draft within the cavity.

The outer layer in this context is the BIPV module. If it is a glass/glass module with a fire class of B, then to achieve an overall facade fire class of B (as required by the building decree (Bbl)), the material on the opposite side of the cavity must be of at least fire class A2 or A1, as outlined in rule of thumb 4 from the 'Rules of thumb for facade fire class structure'.

Rules of thumb fire class facade structure

Derrived from "Handreiking: beoordeling brandveiligheid gevels" from DGMR, some rules of thumb for determining the fire class of a facade:

1 | A facade never has a better fire classification locally than the external side of the facade's outer layer. For a Class B facade, the exterior must therefore meet Class B. This is certain.

2 | A facade meets Class B if it is constructed from components that comply with Classes A1 and A2 of NEN-EN 13501-1. This is certain.

3 | A facade with a ventilated cavity meets Class B if the exterior of the outer layer or one of the cavity surfaces meets Class B, and the remaining parts comply with Class A2 or A1 of NEN-EN 13501-1. This is highly plausible.

4 | A facade with a limited ventilated cavity meets Class B if the cavity surfaces and any cavity foil comply with Class B, the remaining components comply with Class A2 or A1 of NEN-EN 13501-1, and the cavity closure has only limited openings. This is sufficiently plausible.

Note | A facade with a commonly ventilated cavity and multiple components that individually meet Class B or worse often does NOT achieve Class B.

Option	What material will be used for the mounting system of the BIPV modules?	Risk factor
21.A	(1) Steel	1
21.B	(2) Aluminium	2

What to fill in?

Fill in what material will be used for the mounting system of the BIPV modules.

Fire risk

In the event of a fire, it is probable that the structural integrity of the mounting frame will be compromised, leading to the BIPV modules falling. While falling debris is a common occurrence in façade fires, the size and weight of BIPV modules pose an enhanced risk, potentially falling on people, blocking escape routes or causing additional structural damage. Aluminum mounting frames are the market standard for mounting BIPV facade modules, but steel mounting frames also exist.

Aluminium | Aluminum loses 50% of its structural strength at temperatures around 200°C and melts at approximately 600°C. Thus, in the event of a fire, it is highly probable that the structural integrity of the aluminum will be compromised, resulting in BIPV modules falling down.

Steel | Although heavier, steel offers significantly better fire resistance than aluminum. Steel retains its structural integrity at higher temperatures as the melting point is around 1400 °C . Consequently, steel mounting frames provide additional time during a fire, potentially preventing or delaying the collapse of BIPV modules

Special attention should also be given to the impact of falling BIPV modules on the effectiveness of fire breaks. When these modules fall, they can expose potential pathways for fire to bypass the fire breaks, undermining their function.

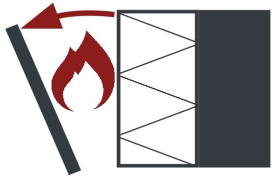
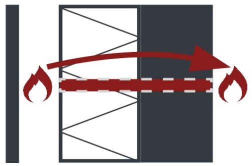


Figure 2: Large scale test BIPV facade. Impact falling BIPV modules. Source: Stølen et al. (2024)

Option	Will BIPV system cables penetrate through the facade?	Risk factor
22.A	(1) No	1
22.B	(2) Yes	2



What to fill in?

Fill in whether or not BIPV system cables penetrate through the facade. Cable penetration is always the case when the inverters are located inside the building. However, if inverters are installed externally, penetration through the facade is not be necessary.

Fire risk

Cable penetrations through the façade represent critical vulnerabilities, as they can facilitate the transfer of fire between the building's interior and the façade (cavity), if not designed properly.

A risk could be that the fire performance characteristics of cable penetrations don't match those of the façade system itself. For example, if the façade materials lose structural integrity under fire conditions and deform, but the materials used for cable penetrations do not, this differential behavior can lead to the formation of gaps. Such gaps can provide a path for fire and smoke to spread from the interior into the BIPV cavity, propagating the spread of fire. Thus, simply applying fire proof cable penetrations is not sufficient.

Option	Will quality control measures for the BIPV system be employed?	Risk factor
23.A	(0,25) Yes, InstallQ and SCOPE12	0,25
23.B	(0,5) Yes, SCOPE12	0,5
23.C	(1) Yes, InstallQ	1
23.D	(16) No quality control will be employed	16

What to fill in?

Indicate whether quality control measures for the BIPV system will be employed.

Fire risk

The Netherlands has quality schemes like SCIOS Scope 12 and InstallQ to ensure the safety and reliability of (BI)PV installations. The main difference between quality of installation scheme InstallQ and quality inspection scheme SCIOS Scope 12 lies in their focus (Figure1). InstallQ adresses the competence and processes of installers from the (e-)design phase through to installation, ensuring high-quality workmanship and adherence to safety standards. SCIOS Scope 12 focuses on the post-installation phase, providing retrospective inspections to verify the safety and performance of the completed systems

InstallQ | Ensures that certified installation companies and advisors are well-known in relevant regulations and guidelines, applying them safely and effectively in practice. These professionals can provide legally valid documents such as energy labels and tailored advice and can guarantee the quality of installation, replacement, or maintenance of systems. InstallQ regularly evaluates and monitors these companies through inspections by InstallQ inspectors or certifying institutions.

Scope12 | A detailed inspection of PV installations to verify safety and compliance with manufacturer guidelines and applicable standards. This includes for example ensuring proper insulation, adequate fuses and protective equipment to prevent overloads, and regular maintenance to uphold safety throughout the installation's lifespan. Additionally, Scope 12 inspections address points such as reviewing drawings and documents, verifying electrical equipment compliance, conducting visual inspections, measuring current and voltage, and performing thermographic analysis (including drone inspections and data analysis).

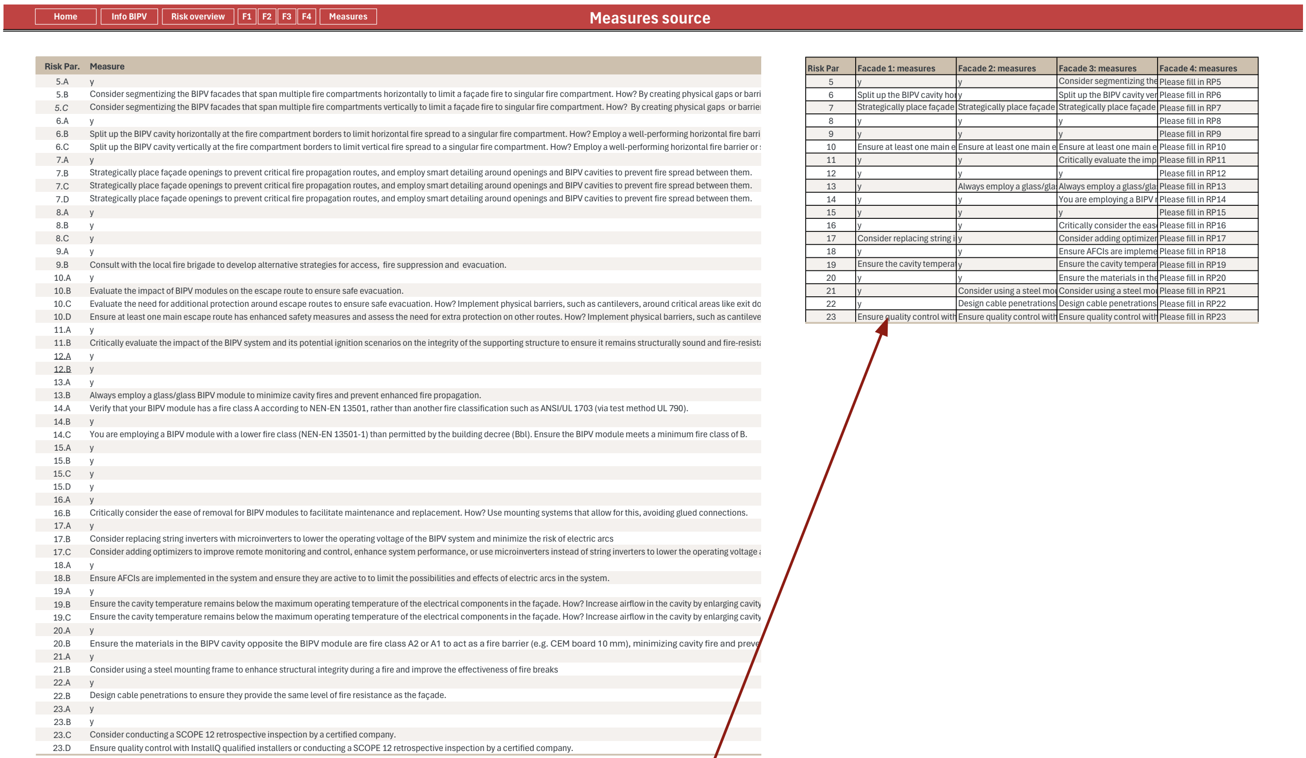
While quality installation by accredited installers minimizes installation errors, it does not fully eliminate them, as mistakes can always occur. Therefore, independent quality inspection is of high value, ensuring an additional layer of safety and reliability.

	installQ aantoonbaar beter	SCIOS GECERTIFICEERD SCIOS INSPECTIES SCOPE 8,10 & 12
Scope	Professional competence of installers	Retrospective inspection of existing installations
Systems	BIPV & BAPV	BIPV & BAPV
When relevant	During and before installation	After installation
Initiated By	Techniek Nederland, Holland Solar and Verbond van Verzekeraars	Verbond van Verzekeraars, Holland Solar and various inspection companies, represented by trade organizations such as iKeur and Techniek Nederland.
Regulatory status	Non-statuary	Non-statuary
Accredited companies	*https://www.echteinstallateur.nl/*	*https://www.scios.nl/relatie/*

Figure 1: InstallQ and SCOPE12 comparison

Appendix III

Excel functions: measures



Home | Info BIPV | Risk overview | F1 | F2 | F3 | F4 | Measures

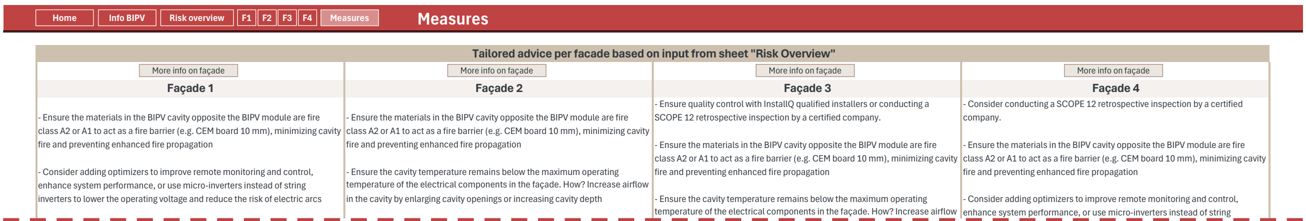
Measures source

Risk Par.	Measure
5.A	y
5.B	Consider segmentizing the BIPV facades that span multiple fire compartments horizontally to limit a façade fire to singular fire compartment. How? By creating physical gaps or barri
5.C	Consider segmentizing the BIPV facades that span multiple fire compartments vertically to limit a façade fire to singular fire compartment. How? By creating physical gaps or barrie
6.A	y
6.B	Split up the BIPV cavity horizontally at the fire compartment borders to limit horizontal fire spread to a singular fire compartment. How? Employ a well-performing horizontal fire barri
6.C	Split up the BIPV cavity vertically at the fire compartment borders to limit vertical fire spread to a singular fire compartment. How? Employ a well-performing horizontal fire barrier or
7.A	y
7.B	Strategically place façade openings to prevent critical fire propagation routes, and employ smart detailing around openings and BIPV cavities to prevent fire spread between them.
7.C	Strategically place façade openings to prevent critical fire propagation routes, and employ smart detailing around openings and BIPV cavities to prevent fire spread between them.
7.D	Strategically place façade openings to prevent critical fire propagation routes, and employ smart detailing around openings and BIPV cavities to prevent fire spread between them.
8.A	y
8.B	y
8.C	y
9.A	y
9.B	Consult with the local fire brigade to develop alternative strategies for access, fire suppression and evacuation.
10.A	y
10.B	Evaluate the impact of BIPV modules on the escape route to ensure safe evacuation.
10.C	Evaluate the need for additional protection around escape routes to ensure safe evacuation. How? Implement physical barriers, such as cantilevers, around critical areas like exit do
10.D	Ensure at least one main escape route has enhanced safety measures and assess the need for extra protection on other routes. How? Implement physical barriers, such as cantileve
11.A	y
11.B	Critically evaluate the impact of the BIPV system and its potential ignition scenarios on the integrity of the supporting structure to ensure it remains structurally sound and fire-resista
12.A	y
12.B	y
13.A	y
13.B	Always employ a glass/glass BIPV module to minimize cavity fires and prevent enhanced fire propagation.
14.A	Verify that your BIPV module has a fire class A according to NEN-EN 13501, rather than another fire classification such as ANSI/UL 1703 (via test method UL 790).
14.B	y
14.C	You are employing a BIPV module with a lower fire class (NEN-EN 13501-1) than permitted by the building decree (Bbl). Ensure the BIPV module meets a minimum fire class of B.
15.A	y
15.B	y
15.C	y
15.D	y
16.A	y
16.B	Critically consider the ease of removal for BIPV modules to facilitate maintenance and replacement. How? Use mounting systems that allow for this, avoiding glued connections.
17.A	y
17.B	Consider replacing string inverters with microinverters to lower the operating voltage of the BIPV system and minimize the risk of electric arcs
17.C	Consider adding optimizers to improve remote monitoring and control, enhance system performance, or use microinverters instead of string inverters to lower the operating voltage a
18.A	y
18.B	Ensure AFCIs are implemented in the system and ensure they are active to to limit the possibilities and effects of electric arcs in the system.
19.A	y
19.B	Ensure the cavity temperature remains below the maximum operating temperature of the electrical components in the façade. How? Increase airflow in the cavity by enlarging cavity
19.C	Ensure the cavity temperature remains below the maximum operating temperature of the electrical components in the façade. How? Increase airflow in the cavity by enlarging cavity
20.A	y
20.B	Ensure the materials in the BIPV cavity opposite the BIPV module are fire class A2 or A1 to act as a fire barrier (e.g. CEM board 10 mm), minimizing cavity fire and preve
21.A	y
21.B	Consider using a steel mounting frame to enhance structural integrity during a fire and improve the effectiveness of fire breaks
22.A	y
22.B	Design cable penetrations to ensure they provide the same level of fire resistance as the façade.
23.A	y
23.B	y
23.C	Consider conducting a SCOPE 12 retrospective inspection by a certified company.
23.D	Ensure quality control with InstallQ qualified installers or conducting a SCOPE 12 retrospective inspection by a certified company.

Risk Par	Facade 1: measures	Facade 2: measures	Facade 3: measures	Facade 4: measures
5	y	y	Consider segmentizing the	Please fill in RP5
6	Split up the BIPV cavity hor	y	Split up the BIPV cavity ver	Please fill in RP6
7	Strategically place façade	Strategically place façade	Strategically place façade	Please fill in RP7
8	y	y	y	Please fill in RP8
9	y	y	y	Please fill in RP9
10	Ensure at least one main e	Ensure at least one main e	Ensure at least one main e	Please fill in RP10
11	y	y	Critically evaluate the imp	Please fill in RP11
12	y	y	y	Please fill in RP12
13	y	Always employ a glass/gla	Always employ a glass/gla	Please fill in RP13
14	y	y	You are employing a BIPV r	Please fill in RP14
15	y	y	y	Please fill in RP15
16	y	y	Critically consider the eas	Please fill in RP16
17	Consider replacing string i	y	Consider adding optimizer	Please fill in RP17
18	y	y	Ensure AFCIs are impleme	Please fill in RP18
19	Ensure the cavity tempera	y	Ensure the cavity tempera	Please fill in RP19
20	y	y	Ensure the materials in the	Please fill in RP20
21	y	Consider using a steel mo	Consider using a steel mo	Please fill in RP21
22	y	Design cable penetrations	Design cable penetrations	Please fill in RP22
23	Ensure quality control with	Ensure quality control with	Ensure quality control with	Please fill in RP23

Function: link measures to design consideration input

```
=
ALS(RiskOverview!F37='23'!$C$6;$C$53;
ALS(RiskOverview!F37='23'!$C$7;$C$54;
ALS(RiskOverview!F37='23'!$C$8;$C$55;
ALS(RiskOverview!F37='23'!$C$9;$C$56;"Please fill in RP23"
))))
```



Home | Info BIPV | Risk overview | F1 | F2 | F3 | F4 | Measures

Measures

Tailored advice per facade based on input from sheet "Risk Overview"			
More info on façade	More info on façade	More info on façade	More info on façade
Façade 1	**Façade 2**	**Façade 3**	**Façade 4**
- Ensure the materials in the BIPV cavity opposite the BIPV module are fire class A2 or A1 to act as a fire barrier (e.g. CEM board 10 mm), minimizing cavity fire and preventing enhanced fire propagation - Consider adding optimizers to improve remote monitoring and control, enhance system performance, or use micro-inverters instead of string inverters to lower the operating voltage and reduce the risk of electric arcs	- Ensure the materials in the BIPV cavity opposite the BIPV module are fire class A2 or A1 to act as a fire barrier (e.g. CEM board 10 mm), minimizing cavity fire and preventing enhanced fire propagation - Ensure the cavity temperature remains below the maximum operating temperature of the electrical components in the façade. How? Increase airflow in the cavity by enlarging cavity openings or increasing cavity depth	- Ensure quality control with InstallQ qualified installers or conducting a SCOPE 12 retrospective inspection by a certified company. - Ensure the materials in the BIPV cavity opposite the BIPV module are fire class A2 or A1 to act as a fire barrier (e.g. CEM board 10 mm), minimizing cavity fire and preventing enhanced fire propagation - Ensure the cavity temperature remains below the maximum operating temperature of the electrical components in the façade. How? Increase airflow	- Consider conducting a SCOPE 12 retrospective inspection by a certified company. - Ensure the materials in the BIPV cavity opposite the BIPV module are fire class A2 or A1 to act as a fire barrier (e.g. CEM board 10 mm), minimizing cavity fire and preventing enhanced fire propagation - Consider adding optimizers to improve remote monitoring and control, enhance system performance, or use micro-inverters instead of string

Function: extract measures

```
=
ALS(Measures_Source!I23="y";"";"- "&Measures_Source!I23&TEKEN(10))&TEKEN(10)&
ALS(Measures_Source!I20="y";"";"- "&Measures_Source!I20&TEKEN(10)&TEKEN(10))&
ALS(Measures_Source!I17="y";"";"- "&Measures_Source!I17&TEKEN(10)&TEKEN(10))&
ALS(Measures_Source!I18="y";"";"- "&Measures_Source!I18&TEKEN(10)&TEKEN(10))&
ALS(Measures_Source!I19="y";"";"- "&Measures_Source!I19&TEKEN(10)&TEKEN(10))&
ALS(Measures_Source!I13="y";"";"- "&Measures_Source!I13&TEKEN(10)&TEKEN(10))&
ALS(Measures_Source!I5="y";"";"- "&Measures_Source!I5&TEKEN(10)&TEKEN(10))&
ALS(Measures_Source!I6="y";"";"- "&Measures_Source!I6&TEKEN(10)&TEKEN(10))&
ALS(Measures_Source!I7="y";"";"- "&Measures_Source!I7&TEKEN(10)&TEKEN(10))&
ALS(Measures_Source!I16="y";"";"- "&Measures_Source!I16&TEKEN(10)&TEKEN(10))&
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ALS(Measures_Source!I9="y";"";"- "&Measures_Source!I9&TEKEN(10)&TEKEN(10))&
ALS(Measures_Source!I10="y";"";"- "&Measures_Source!I10&TEKEN(10)&TEKEN(10))&
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ALS(Measures_Source!I12="y";"";"- "&Measures_Source!I12&TEKEN(10)&TEKEN(10))&
ALS(Measures_Source!I14="y";"";"- "&Measures_Source!I14&TEKEN(10)&TEKEN(10))&
ALS(Measures_Source!I15="y";"";"- "&Measures_Source!I15&TEKEN(10)&TEKEN(10))&
ALS(Measures_Source!I21="y";"";"- "&Measures_Source!I21&TEKEN(10)&TEKEN(10))&
ALS(Measures_Source!I22="y";"";"- "&Measures_Source!I22&TEKEN(10)
)
```

Appendix III

Module: RiskOverview_Filter_Façade_Amount

```
Sub VerbergEnToonKolommenEnBladen()
    Dim selectedValue As String
    Dim ws As Worksheet
    Dim sheetsToChange As Variant
    Dim sheet As Variant

    selectedValue = ThisWorkbook.Sheets("RiskOverview").Range("B5").Value
    sheetsToChange = Array("RiskOverview", "Home", "BIPVinfo", "Measures", "F1", "F2", "F3", "F4", "1", "2", "3", "4", "5", "6", "7", "8", "9",
"10", "11", "12", "13", "14", "15", "16", "17", "18", "19", "20", "21", "22", "23") ' List of sheets for updating shapes

    ' Handle column visibility only on "RiskOverview"
    With ThisWorkbook.Sheets("RiskOverview")
        Select Case selectedValue
            Case "One façade"
                .Columns("F:F").Hidden = False
                .Columns("H:H").Hidden = True
                .Columns("J:J").Hidden = True
                .Columns("L:L").Hidden = True
            Case "Two façades"
                .Columns("F:F").Hidden = False
                .Columns("H:H").Hidden = False
                .Columns("J:J").Hidden = True
                .Columns("L:L").Hidden = True
            Case "Three façades"
                .Columns("F:F").Hidden = False
                .Columns("H:H").Hidden = False
                .Columns("J:J").Hidden = False
                .Columns("L:L").Hidden = True
            Case "Four façades"
                .Columns("F:F").Hidden = False
                .Columns("H:H").Hidden = False
                .Columns("J:J").Hidden = False
                .Columns("L:L").Hidden = False
        End Select
    End With

    ' Handle column and row visibility on "Measures"
    With ThisWorkbook.Sheets("Measures")
        Select Case selectedValue
            Case "One façade"
                .Columns("C:E").Hidden = True
            Case "Two façades"
                .Columns("C:C").Hidden = False
                .Columns("D:E").Hidden = True
            Case "Three façades"
                .Columns("C:D").Hidden = False
                .Columns("E:E").Hidden = True
            Case "Four façades"
                .Columns("C:E").Hidden = False
        End Select
    End With

    ' Update f1,f2,f3,f4 shape visibility on all specified sheets
    For Each sheet In sheetsToChange
        Set ws = ThisWorkbook.Sheets(sheet)
        Select Case selectedValue
            Case "One façade"
                ws.Shapes("F2_Knop").Visible = msoFalse
                ws.Shapes("F3_Knop").Visible = msoFalse
                ws.Shapes("F4_Knop").Visible = msoFalse
                ws.Shapes("F1_Knop").Visible = msoTrue
            Case "Two façades"
                ws.Shapes("F3_Knop").Visible = msoFalse
                ws.Shapes("F4_Knop").Visible = msoFalse
                ws.Shapes("F1_Knop").Visible = msoTrue
                ws.Shapes("F2_Knop").Visible = msoTrue
            Case "Three façades"
                ws.Shapes("F4_Knop").Visible = msoFalse
                ws.Shapes("F1_Knop").Visible = msoTrue
                ws.Shapes("F2_Knop").Visible = msoTrue
                ws.Shapes("F3_Knop").Visible = msoTrue
```

... Code continues on next page ...

```
        Case "Four façades"
            ws.Shapes("F1_Knop").Visible = msoTrue
            ws.Shapes("F2_Knop").Visible = msoTrue
            ws.Shapes("F3_Knop").Visible = msoTrue
            ws.Shapes("F4_Knop").Visible = msoTrue

    End Select
  Next sheet

  ' Verberg en toon specifieke bladen
  For Each ws In ThisWorkbook.Sheets
    Select Case ws.Name
        Case "F1"
            ws.Visible = IIf(selectedValue = "One façade" Or selectedValue = "Two façades" Or selectedValue = "Three façades" Or selectedValue = "Four façades", xlSheetVisible, xlSheetHidden)
        Case "F2"
            ws.Visible = IIf(selectedValue = "Two façades" Or selectedValue = "Three façades" Or selectedValue = "Four façades", xlSheetVisible, xlSheetHidden)
        Case "F3"
            ws.Visible = IIf(selectedValue = "Three façades" Or selectedValue = "Four façades", xlSheetVisible, xlSheetHidden)
        Case "F4"
            ws.Visible = IIf(selectedValue = "Four façades", xlSheetVisible, xlSheetHidden)
    End Select
  Next ws
End Sub
```

Module: RiskOverview_Reset_Input

```
Function ConfirmReset() As Boolean
  Dim response As Integer
  ' Display a message box with Yes, No, and Cancel options
  response = MsgBox("Are you sure you want to reset all input?", vbYesNoCancel + vbQuestion, "Confirm Reset")

  ' Return True if Yes was selected, False otherwise
  ConfirmReset = (response = vbYes)
End Function
Sub SetDefaultValuesF1()
  ' Check for user confirmation before running code
  If ConfirmReset() Then
    Range("F16:F23").Value = """Please select"""
    Range("F27:F38").Value = """Please select"""
  End If
End Sub

Sub SetDefaultValuesF2()
  ' Check for user confirmation before running code
  If ConfirmReset() Then
    Range("H16:H23").Value = """Please select"""
    Range("H27:H38").Value = """Please select"""
  End If
End Sub

Sub SetDefaultValuesF3()
  ' Check for user confirmation before running code
  If ConfirmReset() Then
    Range("J16:J23").Value = """Please select"""
    Range("J27:J38").Value = """Please select"""
  End If
End Sub

Sub SetDefaultValuesF4()
  ' Check for user confirmation before running code
  If ConfirmReset() Then
    Range("L16:L23").Value = """Please select"""
    Range("L27:L37").Value = """Please select"""
  End If
End Sub
```

Appendix III

Module: Protect_Unprotect

```
Sub a_protect_all_sheets()
top:
    pass = InputBox("Wachtwoord?")
    repass = InputBox("Bevestig wachtwoord")
    If Not (pass = repass) Then
        MsgBox "Wachtwoord is onjuist"
        GoTo top
    End If
    For i = 1 To Worksheets.Count
        If Worksheets(i).ProtectContents = True Then GoTo oops
    Next
    For Each s In ActiveWorkbook.Worksheets
        If s.Name = "RiskOverview" Then
            s.Protect password:=pass, DrawingObjects:=True, Contents:=True, Scenarios:=True, AllowFormattingColumns:=True
            s.EnableSelection = xlUnlockedCells
        ElseIf s.Name = "Measures" Then
            s.Protect password:=pass, DrawingObjects:=True, Contents:=True, Scenarios:=True, AllowFormattingColumns:=True, Allow-
FormattingRows:=True
            s.EnableSelection = xlUnlockedCells
        Else
            s.Protect password:=pass, DrawingObjects:=True, Contents:=True, Scenarios:=True
            s.EnableSelection = xlUnlockedCells
        End If
    Next
    Exit Sub
oops:
    MsgBox "Waarschijnlijk zijn sommige bladen nog beveiligd. Verwijder de beveiliging van deze bladen en start deze Macro
opnieuw."
End Sub

Sub a_unprotect_all_sheets()
    On Error GoTo booboo
    unpass = InputBox("Voer het wachtwoord in:")
    For Each Worksheet In ActiveWorkbook.Worksheets
        Worksheet.Unprotect password:=unpass
    Next
    Exit Sub
booboo:
    MsgBox "Wachtwoord onjuist! (CapsLock aan? Controleer Wachtwoord, etc.)"
End Sub
```

Module: Disclaimer

```
Private Sub Workbook_Open()
    Dim message1 As String
    Dim message2 As String

    message1 = "This tool was created as part of a master thesis at TU Delft. Sharing, distributing, or reproducing this tool in any
form is not permitted without approval from the author. Unauthorized use or dissemination of the tool may result in legal conse-
quences. For permissions and inquiries, please contact the author directly."
    MsgBox message1, vbInformation, "Disclaimer"

    message2 = "This tool does not provide a guaranteed 'fire safe' solution. Fire safety must always be assessed in its unique
context. The information presented is advisory and has not undergone extensive testing or regulatory approval. Use this tool to
inform your decision-making process, and critically assess the applicability of each design consideration to your specific situa-
tion. Always consult with a qualified fire safety professional to ensure comprehensive safety measures are in place."
    MsgBox message2, vbInformation, "Disclaimer"
End Sub
```

3.X Fire safety principles

This chapter explores fire safety engineering and principles governing the built environment. Fires, with their inherent complexity, require a multifaceted understanding rooted in fundamental principles and evolving methodologies. From the basic principles of fire dynamics to the application of risk-based approaches, this chapter serves as a guide through the key concepts that shape fire safety strategies. Ultimately, by understanding the fundamental principles that support fire safety decisions, insights for the development of an effective tool are gained. With this knowledge, the tool can propose strategies and measures that are grounded in these principles, enhancing the effectiveness and credibility.

3.X.1 Principle of fire

The basics of fires are relatively simple. A fire requires three components to ignite: fuel, oxygen, and heat, forming what is known as the fire triangle (Breunese & Maljaars, 2015). If any of these components is absent, a fire cannot occur. However, fires become complex when exposed to non-standard conditions, such as those found in the built environment. In these settings, there are many factors impacting the three main components of the fire triangle, making fire dynamics unpredictable and challenging to manage.

3.X.2 Fire safety principles in the built environment

Fire safety in the built environment is a multifaceted domain aimed at protecting against fire hazards. Given the many factors involved, an integrated approach across disciplines is essential to ensure the safety of lives and property. Derived from public law, the primary objectives are (Ruud van Herpen, 2023):

1 | Limiting loss of life in the event of a fire situation.
2 | Limiting fire spread to neighbouring properties in the event of a fire situation.

To achieve these objectives, fire safety principles are structured to sub-objectives, or so-called risk subsystems. These risk subsystems should be focussed on in the sequence presented below, as this is considered to be the most effective order for fire protection (Ruud van Herpen, 2023):

1 | Prevent the ignition of a fire
2 | Limit the development of a fire
3 | Limit the spread of fire within the building
4 | Limit spread of smoke within the building
5 | Maintain the structural integrity of the building
6 | Maintain the escape and access routes
7 | Limit the spread of fire and consequences for the surroundings

In addition to the public law objectives, it is crucial to consider private law wishes that encompass the intrinsic, emotional, and cultural values of the built environment:

Intrinsic Value | The inherent worth of the property, based on its utility, features, and condition, influencing its market price and replacement cost.

Emotional Value | The sentimental importance of a property to its owners and occupants, often derived from personal experiences, memories, and attachments, making its loss deeply personal and impactful.

Cultural Value | The cultural importance of a building or area, particularly those that contribute to the heritage and identity of a community, preserving historical narratives.

Integrating these private law considerations ensures a holistic approach to fire safety, aligning with both the practical requirements of public safety and the broader needs of preserving the emotional and cultural fabric of the built environment.

The risk subsystems for each project contain project-specific characteristics and are dealt with by utilizing the knowledge of five different disciplines. Collaboratively, the disciplines of fire safety physics (fire characteristics), structural fire safety engineering (building characteristics), fire safety psychonomics (human characteristics), fire intervention science (intervention characteristics), and environmental fire safety (environmental characteristics), ensure that the risk subsystems are translated into design measures & strategies. The focus of the project-specific characteristics are (Hagen & Witloks, 2018):

Fire characteristics | the ignition, propagation and consequences of fire.

Building characteristics | the building's architectural and structural configuration, the systems which are related to the occurrence, propagation and effects of fire and egress possibilities.

Human characteristics | human behaviour within environment and its impact on fire dynamics.

Intervention characteristics | emergency response procedures involving both external fire services and internal responders.

Environmental characteristics | the building's location in relation to the fire safety.

Through the combined efforts of the disciplines, they contribute to the development and implementation of strategies aimed at minimizing fire risks and enhancing the safety of building occupants. Figure 113 showcases how the characteristics are interrelated. While the focus of this thesis will primarily revolve around building characteristics, it is crucial to acknowledge the existence of other disciplines and integrate them effectively to ensure comprehensive fire safety measures.

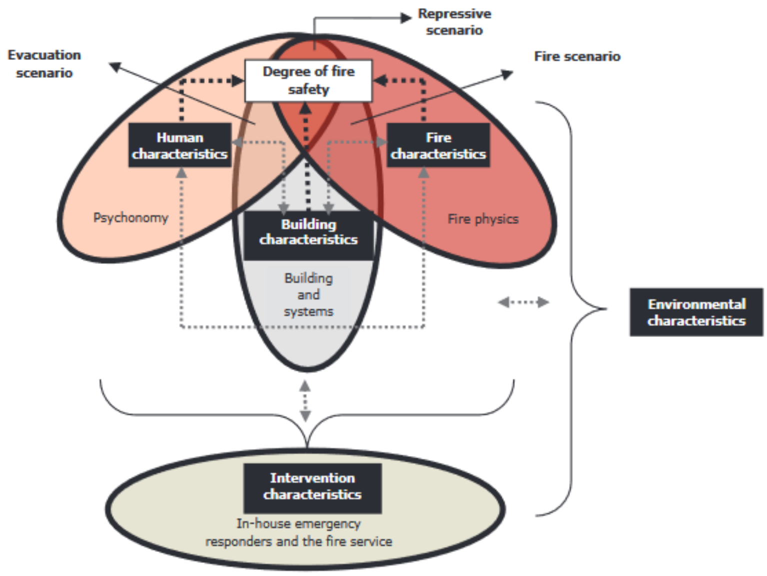

Figure 113: Interrelations of critical characteristics fire safety. Source: Hagen & Witloks (2018)

3.X.3 Level of fire safety

Achieving absolute fire safety in a building is unattainable, as doing so would compromise the building's functionality and make it impractical for use. Therefore, the fire risks which are present, should be as low as reasonably possible (ALARP) (Hagen & Witloks, 2018). This means implementing effective fire safety strategies and measures that prioritize the protection of lives and property, while making sure they don't compromise the building's functionality or practicality for its intended use. In the Netherlands, the "Besluit bouwwerken leefomgeving (Bbl), which was previously the "Bouwbesluit", and its assigned codes strive to ensure a minimal level of fire safety, without compromising the building's functionality or practicality. This is considered to be the minimal level of fire safety by public law. However, it is a frequent misconception to assume that meeting these regulations ensures proper fire safety for every situation. Therefore, a higher level of fire safety should often be strived for, where the level of fire safety depends on the main objectives, taking into account the intrinsic, emotional, and cultural values, and the characteristics of the building (Figure 113).

3.X.4 Fire safety engineering: from prescriptive-based to risk-based

In the Netherlands, the Bbl is the main set of regulations for fire safety and is mainly designed to be prescriptive-based, prescribing a normative set of regulations which contain threshold values for performance requirements (Hagen & Witloks, 2018). From a legal point of view, this prescriptive-based approach makes sense, as it ensures consistency and uniformity in the implementation of fire safety measures across different building projects, thereby enhancing clarity and enforceability of the regulations. This set of regulations is considered to appropriate for traditional and low-risk buildings. However, when buildings are not built using traditional construction methods or of higher risk, the Bbl fails to provide sufficient flexibility or detailed guidance to address all potential fire safety challenges and scenarios. Compliance with the prescriptions does not necessarily guarantee sufficient fire safety or fire resilience, as the true measure of fire safety lies in achieving an appropriate level of protection for each specific building.

In this context, the field of fire safety engineering has risen as a risk-oriented discipline, complementing the prescriptive-based approach of the Bbl. To summarize the differences between the prescriptive-based Bbl and risk-based fire safety approaches, Table 15 shows an overview. Fire safety engineering emphasizes a performance-based approach, considering the previously mentioned characteristics as fire behaviour, building design, human behaviour, environmental factors, and intervention strategies to minimize risks effectively. It’s vision quotes:

> *“The design of a building must be considered more coherently, taking fire safety into consideration: which risks are there, which measures can be taken in view of them, what are the residual risks and how can they be minimised. Contrary to the current approach, where there are generic rules related to the use of a building, the new risk approach should lead to a restriction of the specific risks inherent in a certain building.”*
>
> *- Hagen & Witloks (2018) -*

In fire safety engineering, a critical aspect is its reliance on expert opinions as this is an uncertain and variable factor. Depending on the expertise of different assessment parties, the outcomes may vary and potentially result in insufficient or excessive solutions. Despite these inconsistencies, fire safety engineering solutions have demonstrated superior effectiveness compared to prescriptive-based approaches (Hagen & Witloks, 2018).

One could then argue to implement a risk-based decree for fire safety in the Netherlands, due to its proven effectiveness in other sectors, just like the “Besluit risico’s zware ongevallen - BRZO“. However, the Netherlands currently lacks such a decree, and its adoption in the near future seems unlikely (Hagen & Witloks, 2018). This is primarily due to the insufficient data available in this field, which is essential for developing statutory decrees for safety based on risks. This master thesis will attempt to address this gap by providing a qualitatively risk-based approach for safely implementing BIPV systems in façades, taking into account the characteristics of the building.

Prescriptive-based	**Risk-based**
Prescriptive system	Performance-based system
Based on agreements	Based on risks
Normative fire development	Natural fire development
Coarse-meshed	Fine-meshed
Conservative	Progressive
Frustrates innovation	Promotes innovation
Hardly suitable for bespoke solutions	Suitable for bespoke solutions
Relatively simple	More complex
Unambiguous	Not unambiguous
Equal before the law	Less equal before the law or less probability of being equal before the law

Table 15: Rule-based vs risk-based. Source: Hagen & Witloks (2018). Own edit

3.X.5 Fire safety engineering: equivalence principle

As already mentioned, the Bbl is aimed at achieving the primary and sub-objectives. However, recognizing that there can be multiple ways to achieve these objectives, the equivalence principle was established. The requirements from the Bbl are one interpretation on how to achieve the fire safety objectives, but many other options provide to achieve the same goals. Therefore, the principle allows for the possibility to deviate from the standard requirements from the Bbl, as long as it can be proven that the alternative solutions provide an equal level of safety and adhere in the same way to the fire safety objectives.

3.X.6 Fire safety engineering: fire growth & consequences

Due to the complexity and dynamic nature of a fire, it is hard to predict how a fire will actually develop. Therefore, within the realm of fire safety engineering, it is not common practice to try and predict this exactly. Subsequently, the focus is rather on comprehending fire growth through two main aspects: fire curves and fire scenarios (Hagen & Witloks, 2018).

Fire curves illustrate the growth of a fire over a period of time for a specific building component. It showcases the development of the fire in terms of temperature, radiation, calorific value, or other relevant factors. These curves, commonly known as 'standard' fire curves, are used to evaluate a building or its components' fire resistance and are established under controlled laboratory conditions with test setups according to codes. However, these conditions often do not reflect real-world scenarios, as the laboratory setups and fire tests can significantly differ from actual end-use applications. Therefore, within fire safety engineering, fire curves are not regarded as definitive truths but more as valuable reference points that provide a foundation for further analysis, taking into account the unique characteristics and context-specific factors of each project (Hagen & Witloks, 2018).

Fire scenarios are the fundamental principle within fire safety engineering for determining the growth of a fire. A fire scenario creates insights in the development, scale, and consequence of a fire. The definition is:

> *"A fire scenario is a theoretical description of a realistically imaginable fire based on some pre-selected factors that determine the growth and the development of a fire (and smoke), the output of which is the impact of such fire for the people in the building, the fixtures and fittings of the building and the actual building"*
>
> *- Hagen & Witloks (2018) -*

As there are many theoretically possible fire scenarios for fire development, attention should be focused only on those deemed to have significant consequences. The determination of this threshold, as well as the identification of fire scenarios, relies on expert opinion (Hagen & Witloks, 2018). Subsequently, a list of all potential protection options can be compiled. These protection options should then be matched with fire scenarios until the consequence of each fire scenario is deemed to have an acceptable level of consequence. Figure 114 visually represents the above-mentioned steps, highlighting the relations between the steps. This principle also form the basis for this research.

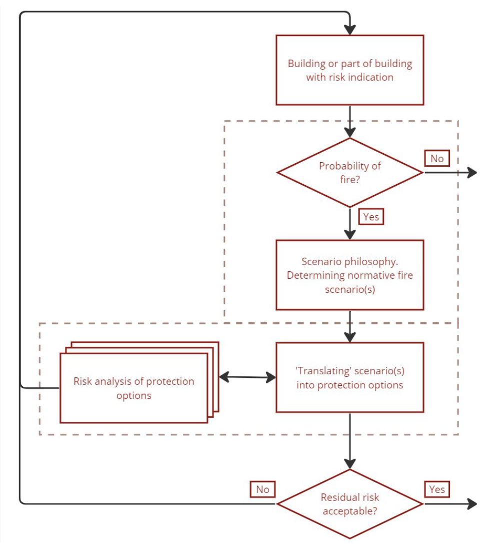

Figure 114: Fire safety engineering risk-based assessment model. Source: Hagen & Witloks (2018). Own edit