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Wind-driven Rain Exposure and Assessment of Building Integrated Photovoltaic Systems

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Abstract:

As photovoltaic systems are adopted in more and more building projects, as a climate-friendly and increasingly cheap means of electricity generation, it is becoming desirable to integrate photovoltaic modules in building envelopes. This is done to create a better architectural expression and to save the cost and labour of first installing a conventional façade and then attaching photovoltaics to it. The project *Building integrated photovoltaics for Norway* (BIPV Norway) aims to increase understanding and adoption of building integrated photovoltaics in Nordic climates in general, and Norway in particular.

The worldwide attention towards energy-efficient and zero emission buildings is increasing. In this respect, building integrated photovoltaics (BIPV) represent an interesting solution both for existing and new buildings. This study provides an overview of requirements applicable to BIPV systems from a building technical and physical standpoint, specifically regarding water-tightness. To achieve a practical understanding of the challenges different weather poses to BIPV systems, and the advantages and disadvantages of various solutions, large-scale laboratory tests have been conducted. The water-tightness of three different BIPV systems has been evaluated by subjecting samples of the systems to simulated driving rain in a rain and wind (RAWI) box. In particular, the wind-driven rain-tightness performance of each system has been evaluated, and attempts have been made to explain the performance of each individual system from a building physical viewpoint. Where applicable, various suggestions for improvement have also been made.

Keywords:

1. Building integrated photovoltaics
2. Solar Cells
3. BIPV
4. Wind-driven rain

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Norwegian abstract

Nå som fotovoltaiske solceller blir brukt i stadig flere byggeprosjekter, som en klimavennlig og stadig billigere måte å generere strøm på, blir det ønskelig å integrere solceller i bygningskropper. Dette gjøres for å skape et bedre arkitektonisk uttrykk og for å spare kostnadene ved først å installere en konvensjonell fasade, for så å henge solceller på den. Prosjektet *Bygningsintegrerte solceller i Norge* (BIPV Norge) sikter etter å øke forståelsen for og øke bruken av bygningsintegrerte solceller i et nordisk klima generelt, og i Norge spesielt.

Dette arbeidet er skrevet som en artikkel, som søker å gi et overblikk over tekniske krav som stilles til bygningsintegrerte solceller (BIPV) fra et byggteknisk perspektiv, spesielt med tanke på vanntetthet. Fullskala laboratorieforsøk kjøres for å oppnå en praktisk forståelse av utfordringene vær og klima påfører BIPV-systemer. Vanntettheten til tre forskjellige BIPV-systemer er testet ved å utsette prøvefelt av systemene for simulert slagregn i en regn- og vind (RAWI)-boks. Særlig blir regntettheten til hvert system evaluert, og det blir gjort forsøk på å forklare ytelsen til hvert individuelle system fra et bygningsfysisk perspektiv. Dersom mulig blir også forslag til forbedringer fremmet.

Preface

This thesis is written as the final semester project of the five-year Master of Science program of Civil and Environmental Engineering (Bygg- og Miljøteknikk) at the Norwegian University of Science and Technology (NTNU) during the spring term of 2016.

The work of the thesis is carried out as part of the research project ”Building integrated photovoltaics for Norway” (BIPV Norway), in which NTNU is participant. The thesis is geared towards Work Package 2 of the project, titled ”Technical integration of photovoltaics in buildings”, and its activities 2.1 ”Development of robust components and solutions” and 2.2 ”Accelerated ageing and durability testing in Nordic climate exposure”. The findings will also be presented to the companies that provided us with BIPV systems to test.

The main body of the work consists of large-scale exposure tests of BIPV systems. Its main objective is to use the test results to find advantages and disadvantages of various mounting systems, as well as obtaining knowledge about the technical requirements and challenges of BIPV in roofs and façades in a Nordic climate.

The results are to be presented in a scientific article. The finalized product is written in the style of an article, but appears to be too voluminous to be suitable for publication in its current state. It was proposed to split it into two articles, but for time constraint reasons it was decided to keep it as one long article, which will later be revised by the BIPV Norway team before it can be submitted for publication in an international scientific journal like e.g. *Energy and Buildings*, *Solar Energy* or *Construction and Building Materials*.

I would like to thank my supervisor Bjørn Petter Jelle for guidance, advice and feedback on the planning and coordination of every step in the process: contacting companies to obtain sample materials, contacting SINTEF personnel to assess the various systems, booking time in the laboratory so the tests could be performed, and lastly on writing the article itself. I would also like to thank Ole Aunrønning, Jan Ove Busklein and Øystein Holmberget for crucial help and guidance in the laboratory. Knut Noreng, Christian Schlemminger and Stig Geving have my thanks for valuable input and assessment of the BIPV systems. Per Oskar Asp helped documenting and photographing the work (also providing the front page image). Another big thanks goes to my study group, Troll-ing., for keeping my motivation up throughout the semester.

Erlend Andenæs

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Contents

Process report

Master's Thesis, Erlend Andenæs

Introduction

This process report covers the work on the article ”Wind-driven rain exposure and assessment of building integrated photovoltaic systems”, written during spring 2016.

Expectations prior to the Master's thesis

As I had already written a scientific article for my semester project the previous semester, I felt that I had some good foundations and understanding necessary to write a good Master's thesis. I had already handled article structuring, citations, and finding sources when working on the article ”The influence on snow and ice coverage on the electricity generation from photovoltaic solar cells”. That article, however, was a literature study, whereas the Master's thesis involved laboratory work. The plan was to acquire a few samples of building-integrated photovoltaic (BIPV) systems, perform tests on them in the NTNU and SINTEF Building and Infrastructure laboratory, then write a scientific article about the results. The exact nature of the tests was not specified early on, and it was decided that detail planning should be postponed until we we had the systems delivered and between our hands. This turned out to clump the bulk of the work at the end of the semester, which in hindsight might have been inevitable no matter what we did.

The work

The first phase of the work consisted of finding suppliers of BIPV products to test, select some systems and contact the suppliers, offering to perform the usually-quite-expensive climate simulation tests in exchange for samples of the BIPV systems. This, however, turned out to take *much* longer time than anticipated. Of the six providers initially contacted by e-mail, only three responded (disregarding an automated response with the statement ”we will come back to you soon”, a promise which was not followed up). Early weeks of the semester passed while waiting for responses to e-mails.

Preliminary plans for tests involved climate exposure simulations, accelerated ageing and possibly field investigations. Due to time constraints and certain lab apparatuses being reserved for commercial projects, only the rain and wind (RAWI) tests could be performed for the thesis.

The earliest concrete response came from Sun-Net, an importer of photovoltaic roof tiles. They opted not to participate in the project, because their existing product was to be phased out, replaced by a new photovoltaic tile from august 2016. Testing the old tiles would not give them usable data, and we would not be able to test the new ones in time for the thesis.

Danish PV manufacturer Gaia Solar responded quickly, with mails passing back and forth clarifying what tests were planned, and what products we could be able to test. An agreement was made to ship a sample of the system, but a date could not be specified. From what I understood, Gaia Solar had some troubles with the manufacturing process, and were giving their commercial projects the highest priority while the issues were being sorted out. In the end, it took two months before the panels could be shipped, and they arrived at the laboratory in early May.

My supervisor also put me in contact with Lithuanian PV manufacturer Solitek, with whom he had previously had some correspondence. While Solitek had not been on the initial list of manufacturers to contact, their product was deemed interesting enough, so negotiations were established. Unfortunately, a mismatch between Norwegian and Lithuanian public holidays delayed correspondence, and the shipment was significantly delayed. Solitek's PV modules arrived at the office just days before those from Gaia Solar. It turned out, at a rather late point, that Solitek only provide *modules* for BIPV systems, and not complete systems. The fastening clamps we received were only meant for building *applied* photovoltaic solutions, and not complete integration. As such, the system we were provided was not suitable for our kind of lab investigations.

We had more luck with a local importer, contacted after Sun-Net declined to participate. A small electronics company in Orkanger, Orkla Elektronikk, had just recently begun importing photovoltaic solar tiles from China. The company's owner had contacted my supervisor, the information was passed on to me, and it was decided to have a little meeting at the laboratory to discuss the tests. Karstein from Orkla Solar later helped us mount the tiles in preparations for the test.

Once three sets of BIPV systems were acquired, planning could finally begin in earnest. This, it turned out, also took much longer than I was prepared for. We approached SINTEF and NTNU experts with our plans, asking for professional input and assessment of the BIPV systems as a weather barrier. Materials had to be ordered, schedules written and budgets calculated. We decided to limit testing to the RAWI box, assessing the weather-tightness of the BIPV systems. A substrate frame was built, on which two of the three systems were assembled. It was determined that the Solitek PV modules should be left out of the tests, since it is not designed to form a continuous façade cladding. The centimetre-wide gaps between modules gave away the leakage points without any need for testing.

At last, the tests were conducted at the end of May and early June. Testing ended one week before the deadline for the thesis. At this point, most background material was already written, and thirteen-hour work days were employed to get the thesis finished on time.

Lessons learned/experiences

Things. Take. Time. Good grief. Being reliant on responses from external partners in order to proceed is not very fun, nor efficient. During the first four months of the semester, a total of 10 pages were written on the report.

Contacting industry partners on the phone seems to speed up correspondence significantly, but language barriers may be a problem, and it is harder to document for posterity exactly what was agreed on. In hindsight, it would have been a good idea to start the correspondence already the previous semester, as part of the preparatory semester project.

Summary

The thesis work has been defined by a lot of idle time spent waiting during the first two thirds of the semester, then increasingly more intense work as the end drew closer. Making oneself dependant on external factors turned out to be a very bad idea, as was not having planned concrete tasks to work on while waiting. In hindsight, I realize that detail planning of experiments would have been a time-consuming task with many uncertain factors even if we had started earlier, but it was not particularly fun to effectively postpone the bulk of the work until the very last month before the deadline. In the end, though, we persevered, although the article needs some revision by the BIPV Norway team before being ready for publication.

Wind-driven rain exposure and assessment of building integrated photovoltaic systems

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Abstract

The worldwide attention towards energy-efficient and zero emission buildings is increasing. In this respect, building integrated photovoltaics (BIPV) represent an interesting solution both for existing and new buildings. This study provides an overview of requirements applicable to BIPV systems from a building technical and physical standpoint, specifically regarding water-tightness. To achieve a practical understanding of the challenges different weather poses to BIPV systems, and the advantages and disadvantages of various solutions, large-scale laboratory tests have been conducted. The water-tightness of three different BIPV systems has been evaluated by subjecting samples of the systems to simulated driving rain in a rain and wind (RAWI) box. In particular, the wind-driven rain-tightness performance of each system has been evaluated, and attempts have been made to explain the performance of each individual system from a building physical viewpoint. Where applicable, various suggestions for improvement have also been made.

Keywords

Building integrated photovoltaics, BIPV, Solar cell, Wind-driven rain, Climate

Contents

1. Introduction

Photovoltaic (PV) technology is currently undergoing what may only be described as a revolution. The total global installation of photovoltaic cells has been rising exponentially for several years (IEA PVPS, 2016). In addition to large-scale, ground-mounted installations, photovoltaic systems are being installed on buildings across the globe, for the most part as traditional array systems mounted on rooftops, or on façades. With increased installation of photovoltaics on buildings, it has become desirable to integrate photovoltaic systems in their architectural expression, and give them functionality as building elements. Building integrated photovoltaics (BIPV) are photovoltaic installations that serve as building elements, in addition to producing clean, renewable, on-site electricity. They are mounted in place of traditional building elements, such as roofing or cladding systems, taking on the role as a building envelope as well as a means of generating electricity.

This new utilization of photovoltaics poses additional requirements to the systems, outside of what the PV and electronics industries have traditionally faced. Cladding systems serve a vital function in the building's envelope, which cannot be compromised without risk to the building. When traditional cladding elements are replaced with integrated photovoltaic systems, the same functions need to be maintained. The production efficiency of a photovoltaic module may be sacrificed slightly when it is adapted for building integration purposes, but weather-tightness must be maintained when adapting a building element to photovoltaics. A robust weather skin is required to prevent damage to the building in the long term, and the impact of a compromised building envelope will almost always outweigh the considerations of electricity generation.

For proper integration in buildings, photovoltaic systems need to be investigated in relation to building technical issues. Several authors have looked into this in recent years. Jelle (2013) addressed the issue of snow on photovoltaic roofs, and the conflict between the need to keep snow off the solar cells, and the traditional convention of leaving snow on roofs until it melts.

Since temperature has much influence on photovoltaic electricity production, many researchers have focused on the temperature aspect of BIPV. A poorly planned system may trap heat, and cause overheating of the panels. Fossa et al. (2008) created a model for simulating convective air flow behind a ventilated BIPV façade cladding material. Liao et al. (2007) modelled heat transfer in a BIPV-thermal system. López et al (2014) performed full-scale tests of temperature effects on BIPV systems.

Yet others have chosen to focus on moisture safety and weather-tightness. Fasana and Nelva (2013) looks into water resistance of BIPV systems mounted in traditional roofs. This article will closely follow that of Breivik et al. (2013), who tested a system of roof-mounted BIPV modules, and its performance with respect to water run-off and driving rain.

2. Types of BIPV systems

2.1. Definitions and classification of BIPV

SUPSI-SEAC (2015) points out that ”There is no general consensus within the PV community about the different categories of BIPV”. There is a variety of definitions and categories out there, and each paper on the subject appears to introduce another few.

Peng et al. (2011) define BIPV as such: ”BIPV are photovoltaic materials that are used to replace conventional building materials in parts of the building envelopes”, and furthermore ”BIPV are considered a functional part of the building structure, or they are architecturally integrated into the building's design”. However, this definition does not take into account integrated photovoltaics in building elements outside the building envelope, such as railings or solar shading. A further subdivision into ”envelope BIPV” and ”auxiliary BIPV” appears to encompass every concept currently in use.

The term ”building attached photovoltaics” (BAPV) is often seen in conjunction with BIPV. A building-attached photovoltaic system is a PV system mounted on a building, but with no building technical purpose. The line between BIPV and BAPV can be blurred at times, as some buildings utilize PV elements as part of their architectural expression, but without giving them functional purpose apart from electricity generation.

It is important to remember that proper integration of photovoltaics in buildings does not only involve the solar panels themselves. It is necessary to consider the balance of system (BOS) components as well. This involves various parts of the necessary electrical and mounting systems, as well as the required cables. Whereas the inverters and transformers will usually be located inside the building, cables will necessarily have to run along and/or through the building façades, and as such they should be considered when regarding building technical challenges, especially concerning moisture and fire safety.

Below, a few common subdivisions of BIPV categories are presented.

2.1.1. Foil products

Foil products commonly use amorphous silicone (a-Si) or similar thin-film photovoltaic technologies, and aim to be comparable to ordinary sheets of flexible of roofing products, with integrated solar cells. Their efficiency is rather low, and swapping out defect modules is a very invasive procedure. They are suited for low-profile refurbishment of flat, compact roofs, but see little use in the boreal areas where solar modules need to be mounted at steep angles – in such situations, a traditional roof-mounted PV system is a much better utilization of roof space and money. BIPV foil products retain the advantage of weight; a roll of roof laminate foil weighs much less than tiles or traditional PV systems covering a comparable area. Not many BIPV foil product appear to remain on the European market; the SUPSI-SEAC report (2015) was unable to find any. For this article, it was attempted to obtain a sample of BIPV foil for testing, without success.

2.1.2. Tile products

Photovoltaic tile products aim to imitate traditional roofing tiles as closely as possible, and in many cases they actually *are* roofing tiles with small photovoltaic panels attached. Their power output may be limited, but a well-designed photovoltaic tile system can be visually indistinguishable from a traditional tiled roof. The level of integration varies some; some products mount a single photovoltaic panel across several tiles (so-called large tiles), other systems have a flat photovoltaic panel on each tile (small tiles). Attempts have also been made to make tiles where the photovoltaic panel follows the curve of the tile (Jelle et al. 2012), although this configuration remains to see widespread adoption, at least on the European market.

2.1.3. Module products

Module products are in many ways similar to traditional photovoltaic panels used for BAPV applications, or glass cladding panels. Essentially, they are identical to traditional PV modules, but usually with thicker glass and a mounting system allowing the modules to form a weather-tight building skin. Module products may be mounted like traditional roof or façade plates, and present a high power output but a distinct visual profile – there is usually no mistaking a module BIPV product for anything but a solar panel.

The ways module products are integrated in roofs and façades vary between suppliers. They can be mounted in a frame system similar to a window, making a weather-tight façade (Schüco 2016). Alternately, they can be fastened with clamps in a less weather-tight fashion, similar to traditional glass cladding or BAPV (Solitek 2016).

2.1.4. Glazing products

BIPV glazing products seek to use windows or glazing systems as semi-transparent photovoltaic systems. Where an ordinary glazing product has one layer of laminate connecting two panes of glass, a BIPV glazing product has two layers of laminate, with photovoltaic cells sandwiched between. This creates a semi-transparent façade that produces electricity, while making the solar cells visible to the public. PV cells can be spaced far apart to provide high transparency, or packed close to achieve a higher area efficiency. The electricity output is inversely proportional to the transparency of the system, and these two factors have to be considered against another when planning the building – if power output is top priority, the BIPV façade should not be designed as a glazing system. Conversely, if transparency and visibility is of high importance, adding photovoltaic elements to the glazing might not be the best idea to begin with.

2.1.5. Dummy modules

These modules may be found in any BIPV application, and are non-functional elements meant to imitate the visual style of the PV modules, mainly to fill in gaps or complex geometry that cannot practically be filled by PV modules. Dummy modules are usually mounted in the same way as the rest of the BIPV system, but do not generate electricity, and as such they are not subject to the requirements of electrical components. Apart from their visual appearance, dummy modules are functionally indistinguishable from regular façade systems, and for some products they may even *be* regular façade systems. Many BIPV systems are created using an existing cladding product as a basis, such as Gaia Solar's GS Integra Line SP, which in essence are solar modules designed to fit with Steni Protego plates (Gaia Solar 2016). In these cases, the solar modules aim to imitate the visual style of the dummy modules, rather than the other way around, but the term ”dummy modules” is kept to avoid cluttering the nomenclature.

3. Overview of requirements of a BIPV system

3.1. Protection of the underlying structure

Arguably, the most important purpose of a building façade is to keep the weather out of the building. For the structure to remain solid, and insulation materials to function properly, moisture must be prevented from entering the wall/roof construction, both via precipitation and condensation. Outer walls may be considered the ”clothes” of a building, keeping it warm, stylish and covered up. Continuing that allegory, the cladding is like a rain coat, keeping weather exposure from making the clothes underneath wet, cold and quickly worn. A good envelope BIPV system has to protect the underlying construction from weather exposure, be it wind, rain, snow, solar radiation or a combination thereof. The solar industry has always been focused on making photovoltaic modules that can withstand weather exposure on their own – after all, their mode of operation is outdoors all year round. However, BIPV applications require the design of the systems to consider the protection of an underlying structure.

When photovoltaic elements serve as building skin, they have to perform the same functions as traditional claddings do when it comes to weather protection. If the BIPV system is not weather-tight, a robust substructure is needed to protect the inner parts of the structure – wind barrier, insulation, cables/pipes and so on – from weather exposure. This is often the case for plate-based cladding systems, which often do not form a continuous cover. The need to use a more robust substructure varies with the configuration of the cladding system, and should be evaluated on a case-by-case basis.

Note that many cladding and roofing systems are not necessarily made to protect the underlying structure completely on their own. A robust wind barrier or sub-roofing is often required to handle drops of water or UV radiation that passes through the outer cladding. As long as the substructure is is sufficiently robust and other building components well protected, a cladding system does not need to function as a complete weather barrier. Some gaps in the cladding could even help to drain leakage water, and allow moisture to escape. Still, it is advantageous if the cladding stops most of the weather exposure, as this allows for a less expensive sub-structure and lowers the risk of long-term damage to the building.

3.2. Rain, moisture and drainage

Cladding elements and PV modules alike need to withstand moisture. Moisture leaking into a PV panel may corrode the electric contacts and wiring inside, rendering it useless. A good laminate is required to keep water out over time. In addition, the clips, clamps, screws or rails attaching the panels to the underlying structure must be constructed to drain water away, rather than allowing it to pool. Pooled water will take longer to evaporate, act on the materials for a longer time, and increase the risk of corrosion, delamination and biological growth. In addition, water will expand if allowed to freeze, which might cause high stress or even deformations in materials.

Water intrusion through the façade can be handled by a robust sub-structure, but should be avoided if possible. Attaching façade elements to the building's load-bearing system will usually involve elements that penetrate the sub-structure, for instance studs being fastened with screws through the wind barrier. After years of service and climate exposure, such screw holes may widen enough for leakage water to be able to penetrate into the building's insulation or load-bearing system.

3.3. Snow

In many regions of the world, in particular the boreal/polar regions or at high altitude, precipitation may fall as snow rather than rain. Snow will not usually run off the way rain does, but rather accumulate and pile up on any surface exposed to snowfall. Snow may even accumulate on and stick to near-vertical surfaces (Jelle 2013). Snow-melt should be treated with the same considerations as regular run-off water.

There are two main challenges related to snow: Most obviously, snow will reflect and absorb light, drastically reducing the amount of solar radiation reaching the photovoltaic cells, which quickly reduces electricity production to near-zero levels (Andenæs et al., 2015).

The weight of the snow may also pose some challenges, especially in large quantities. A metre-deep layer of snow will weigh hundreds of kilograms per square metre (ISO 4355, Annex A). Brearley (2015) recounts some experiences from the US photovoltaics industry, stating that snow loads may lead to bent frames and fasteners pried out of their rafters, and in some cases, glass breakage. Racking hardware tends to fail before the modules themselves do. Accidents might also happen when attempting to remove snow from photovoltaic arrays, since it is fairly easy to punch a hole in a photovoltaic panel with a broom. Glass/glass modules specifically manufactured for BIPV utilization tend to be tougher than traditional solar panels, but care should still be exercised when trying to remove snow from them mechanically.

Jelle (2013) describes more challenges related to snow removal from photovoltaic roofs. The main issue can be summed up as such: If snow can not be left on the roof, where else can it go? Snow removal from roofs can be intensive with regards to both labour and required space for a snow deposit. Melting the snow requires a large amount of energy. There is also the question of how much electricity production is lost if snow is left on the panels. Snowfall is usually coincident with periods of low solar irradiation, during which not even a fully exposed and clean PV panel will generate much electricity. It may be that leaving the snow on the roof to melt in some cases could be the best solution energy-wise, but more research is required on the subject.

3.4. Wind

All building elements need to be fastened firmly to withstand strong winds. The large, flat surfaces of photovoltaic modules are especially susceptible to stress from gusts of wind, owning to a large surface area and spread-out fastening points.

Wind is also a major component in driving rain, pushing droplets of water through gaps in the structure. As a rule of thumb, it can be said that where wind passes through the system, water will too. Wind-driven rain is the most important moisture source affecting the hygrothermal performance and durability of building façades (Blocken and Carmeliet 2004).

3.5. Solar radiation

Solar radiation, especially ultraviolet (UV) radiation, will degrade many materials, most notably polymers, because of photons breaking molecule bonds in polymer chains (Gijsman et al. 1999). While this radiation is utilized for electricity generation in photovoltaic cells, many building materials need to be shielded from it in order to prevent degradation. Openings between roof tiles or cladding panels may cause parts of the underlying wind barrier to be exposed to UV radiation, which is another reason to reduce such openings to a minimum.

The cladding material itself also need to be resistant to UV radiation-induced degradation. Crystalline silicon-based PV modules tested according to IEC 61215 have to pass a UV preconditioning test, and therefore demonstrate some level of resistance to UV radiation. However, this test is relatively mild compared to real UV exposure during the life time of the module (Ardnt and Puto 2010).

3.6. Module temperature

Photovoltaic electricity generation is quite affected by the temperature of the photovoltaic cells, as the power output decreases when temperature increases. Virtuani et al. (2010) showed that crystalline silicone cells are the most affected by temperature increases, and various thin-film technologies are the least affected. Some degree of temperature control should be issued regardless of module type, especially in warm climates. A ventilated air gap between the modules and the underlying structure will provide some air flow due to the stack effect, serving as passive cooling.

López et al (2014) tested several configurations of BIPV systems under real conditions in Switzerland, and found out that temperature plays a rather small role in the performance ratio of full-scale systems mounted on buildings. According to their findings, a system mounted in direct contact with the building envelope will experience higher temperatures than those mounted as a ventilated façade system. However, annealing effects at high temperatures compensate for the thermal losses to a quite large degree.

3.7. Maintenance

It is important to remember the ”system” part of the term ”photovoltaic system”. While a scratch or a nick in a traditional cladding plate only has local consequences, maybe causing a small perforation that may be fixed with a patch, damage to a photovoltaic module is comparable to a cracked pipe in a plumbing system, or a burnt-out diode in an electric circuit. The whole system is affected by damage to any single part, to the point that a single damaged photovoltaic cell effectively can cancel out the electricity production of the entire module, or in some cases shut down the entire string of serially connected modules (PV Education 2016).

This ”leak effect” (which is not the proper technical term term, but a very illustrative one) means that local damage to a photovoltaic system needs to be addressed to keep electricity production up.

For his reason or others, photovoltaic elements may experience damage or other failure making it necessary to replace one or more modules (IEA-PVPS, 2015). A non-functional module in a string of otherwise working modules may cause mismatch effects in the string, increasing the risk of module damage, as well as causing a loss of electricity generation disproportional to the power output of the damaged area. It is therefore essential to replace affected modules should serious damage occur, ideally in a non-invasive way. It should not be required to dismantle an entire façade just to replace one broken module, nor should module replacement affect the underlying structure to such a degree that a new module cannot effectively be mounted in the same spot (for instance, inserting and removing screws in the same hole in a wooden element, which will cause the wood to lose its grip over time).

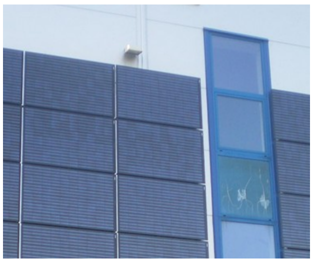
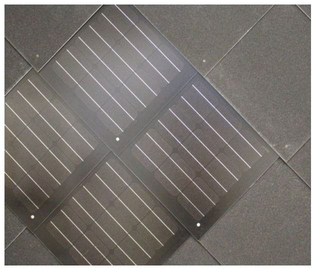
BIPV systems should also be mounted in such a way as to make inspections and cleaning possible. While soiling may mainly be an aesthetic concern for most building elements, rather than a functional one, it will have substantial effect on the functionality of photovoltaic modules, as soiling may drastically reduce photovoltaic electricity generation.

4. Experimental

4.1. Description of BIPV products

For the practical tests discussed in this article, samples of three different BIPV systems were obtained. The sample systems represent three different methods of integration: The Heda Solar 8W Solar tile is a roofing tile with a small integrated photovoltaic panel (Heda Solar 2016). Solitek PV Modules are glass/glass modules suited for BAPV and BIPV application, depending on the selected fastening system (only a BAPV fastening system was provided). Gaia Solar's GS Integra Line SP utilizes overlapping modules, directly mounted using screws penetrating the panel. For an overview of the different systems, see Table 1.

Table 1: Comparison of assessed BIPV systems

	 (Heda Solar 2013)	 (Solitek 2016)	 (Gaia Solar 2014)
Product name	Heda Solar 8W Solar Tile	Solitek PV Module	GS Integra Line SP
Integration	Roof tile	Façade plate	Roof/façade plate
Cell technology	Mono-Si	Poly-Si	Mono-Si
Cell size	2x 156 mm × 156 mm[a]	60x 156 mm × 156 mm	9x 156 mm × 156 mm[a]
Cell efficiency	18 %	17.46 %	16.88 %[b]
Module efficiency	8.19 %[c]	15.44 %	12 %
Dimensions (module) [mm × mm × mm]	325 × 440 × 45	1645 × 986 × 7.6	595 × 595 × 5
Dimensions (effective) [mm × mm]	375 × 285	1660 × 1001 (ass. 15 mm gaps)	555 × 555 mm
Cell coverage (Cell area as a fraction of effective area)	45.5 %	87.8 %	71.1 %
Nominal power (W_{peak})	8 W	250 W	40 W
[a] The cells have rounded corners, making the actual cell area slightly smaller.			
[b] Calculated by author, dividing module efficiency by cell coverage.			
[c] Calculated by author, multiplying cell efficiency by cell coverage.			

4.1.1. Heda Solar 8 W Solar Tile

The Heda Solar 8 W Solar Tile (from here on referred to as the ”Solar Tile” is a plastic-ceramic composite roof tile with an integrated photovoltaic module consisting of two mono-crystalline silicon cells. The tile itself has a large rectangular hole in the middle, in which the photovoltaic module is fastened with silicone glue. The surface of the module is flush with the surface of the tile, forming a continuous, flat, smooth surface. The shape of the tile is reminiscent of traditional Roman ”Imbrex and Tegula” style tiles, with a large flat surface broken by ridges along the longitudinal joints. The size of the solar tiles (width × height) is 32.5 cm × 44 cm. The effective size is stated to be 29.5 cm × 37.5 cm (Heda Solar 2016).

For the sake of comparison to a traditional roofing product, a number of Monier Nova terracotta roof tiles were tested alongside the Heda Solar tiles. The Monier Nova tiles were chosen because they have a profile similar to the Heda Solar tiles. Concrete tiles have material properties closer to the plastic-ceramic composite material of the Heda Solar tiles, but concrete tiles with a similar profile could not be acquired in time for the tests.

4.1.2. Solitek PV Module

Solitek's Glass/Glass modules contain 60 polycrystalline silicon photovoltaic cells encapsulated in laminate foil and tempered glass. In many respects, it resembles a very traditional photovoltaic module, but the robust glass/glass configuration allows it to be mounted like a glass cladding. The modules measure 986 mm × 1645 mm.

The modules are mounted with clamps fixed directly onto the wall studs. The clamps leave a roughly 15 mm horizontal gap between modules, which lets some wind, solar radiation and water through to the underlying wind barrier. A robust substructure is required to prevent damage to building materials. The studs themselves need to be protected too, since the modules and clamps give them little protection from the weather. The size of the vertical gaps between modules depend on the mounting configuration.

The Solitek PV modules may also use other BIPV and BAPV fastening systems, but Solitek has no affiliation with any manufacturer or product line of such. The assessments conducted in this article are based solely on the BAPV clamp system provided to the authors, which may still qualify as a BIPV system in itself.

4.1.3. GS Integra Line SP

Gaia Solar's Integra Line SP consists of large, rhomboid glass/back sheet modules, with EVA laminate and monocrystalline photovoltaic cells. They are designed to be mounted alongside ”Steni Protego” façade/roof plates by the Norwegian façade plate manufacturer Steni, using a configuration used in conventional façades (Steni, 2016). The Steni Protego plates will then serve as the system's dummy modules. The modules are to be mounted in a rhomboid shape, so that all overlap edges are angled towards a single dripping point per plate. The modules are square, measuring 595 mm × 595 mm (814 mm on the diagonal), and are meant to be mounted with a 40 mm overlap over another.

GS Integra Line SP modules are fastened with a clip in the top corner and a screw through the module in the bottom corner. The side corners are kept in place by overlapping modules.

For the tests performed for this article, GS Integra Line SP modules and Steni Protego plates are mounted in the same rig, to investigate not only the performance of the GS Integra Line system, but also how it performs in combination with its companion non-photovoltaic façade system.

4.2. Description of test apparatus with BIPV products

A substrate frame is constructed, emulating a roof or wall construction. The frame is built using 48 mm × 148 mm dimensional lumber, forming a square of 245 cm × 245 cm which fills the template frames used in the RAWI box. More 48 mm × 148 mm lumbers emulating wall studs or rafters are inserted at a centre/centre-distance of 60 cm. Horizontal battens are mounted on top of the frame according to the requirements of the individual systems. The area not covered by the BIPV systems is covered with sheets of 0.15 mm polyethylene foil to fill in the frame. Any remaining gaps are sealed using duct tape. The tests investigate the water-tightness of internal joints between BIPV modules, or between BIPV modules and their respective dummy modules. Joints at the edges of roofs or façades are not considered.

Wind-driven rain is simulated in a rain and wind (RAWI) box at the NTNU and SINTEF Building and Infrastructure laboratory. The RAWI box simulates wind-driven rain by cyclic air pressure and a set of nozzles that spray water on the mounted frame. A hinge allows for stepless tilting between 0 and 95 degrees from the horizontal plane. A boom with water and air nozzles is mounted on rails inside the box, moving up and down across the mounted frame while blowing air and dripping water. A second set of nozzles is fixed above the mounted frame, spraying water at a constant rate. Heavy fans provide a pulsating static pressure level inside the RAWI box. The nozzle boom sprays water and air onto the BIPV system, simulating gusts of wind and rain in addition to the pulsating pressure. Note that the air stream from the nozzles is too focused to simulate the effects of wind loads over a large area; it is meant to push droplets through gaps rather than press and tug at the structure. For an illustration of the principle behind the set-up, see Annex 2 of NT Build 421.

Figure 1: The RAWI box in the NTNU and SINTEF Building and Infrastructure Laboratory.

4.2.1. Heda Solar 8 W Solar Tile

The system is mounted on 23 mm × 32 mm battens spaced 375 mm apart, to fit the narrow batten groove on the back side of the solar tiles. It should be noted that this is a fairly small dimension for Nordic purposes, where it is recommended to use at least 36 mm thick battens to achieve a sufficient mechanical strength to resist snow loads (SINTEF, 2006). All joints bordering the frame are sealed with polyethylene foil and copious amounts of duct tape, ensuring that the only open joints are those between tiles. The Heda Solar and Monier Nova tiles are mounted in the same frame, but separately, with no common joints.

4.2.2. Solitek PV Module

Partially due to time and cost constraints, practical tests could not be performed with the Solitek PV modules. The RAWI box test is meant to uncover leakage points and evaluate design choices with regards to water run-off and wind-driven rain. Since the design of the supplied Solitek system inherently includes centimetre-wide gaps, leakage points are obvious enough not to warrant a RAWI box test. Instead, the system is mounted on a frame to uncover eventual issues with mounting and maintenance, and given a theoretical evaluation by SINTEF personnel.

4.2.3. GS Integra Line SP

GS Integra Line SP modules and Steni Protego plates are mounted on the substrate frame according to instruction manuals provided by the manufacturer (Steni 2016, Gaia Solar 2016). The system is mounted on 36 mm × 73 mm battens, spaced 379 mm apart (centre-centre distance). The system was delivered with sample plates of Steni Protego Sand and Steni Protego Colour modules, the former of which have a shingle-like surface. The latter set of modules was chosen to be mounted alongside the Gaia Solar modules, their smooth surface making it easier to seal off the edges using PE foil and duct tape. The system is mounted in a diagonal pattern, referred to by the manufacturer as ”Snake skin”. Screws and mounting clips used were supplied by the manufacturer.

Initially, the GS Integra Line modules were mounted and tested in an ”N” shape across the frame, see Figure 4. It was then discovered that the biggest leakages would occur in the corner point between four modules, and deemed desirable to test a set-up where four solar modules would meet in a corner. After initial tests, the set-up was changed slightly and new tests performed, see Figure 5.

4.3. Description of test procedures with BIPV products

The system is very reminiscent of what was tested by Breivik et al. (2013), and the same testing apparatus is utilized, so similar test procedures are followed. It is attempted to test the system's performance against rain and driving rain. The test has two phases, with and without wind pressure.

It should be noted that, due to time constraints, a planned, transparent sub-structure could not be built. The final construction is therefore not as watertight as a real façade/roof would be, where a ”cushion” of air in the ventilated air gap behind the modules provides a certain amount of resistance against wind-driven rain intrusion. The lack of a sub-structure in these tests means that no such air cushion can be formed, making water flow more easily through the façade.

The test is carried out in accordance with the Nordtest method ”NT Build 421 – Watertightness under pulsating wind pressure” (Nordtest 1993). The test method is developed for roofs, but since no equivalent test for façades was found, it was decided to use it to test the façade materials as well. A very low wind pressure coefficient was chosen, to account for the relatively ”open” BIPV modules compared to the roofing foil materials the test method is developed for.

Wind and rain are applied in various load levels, each lasting for 10 minutes. The test is initiated at load level 0, during which the nozzle boom is inactive and only run-off water is applied. At load levels 1-12, the static pressure inside the box is increased and decreased in cycles lasting 15 seconds, for a period of 10 minutes (40 cycles). The overpressure in the box cycles between 0 Pa (ambient pressure) and a specified level (between 10 and 150 Pa, depending on the load level).

Meanwhile, gusts of wind and driving rain are simulated using the nozzle boom. The boom applies constant air pressure and rain load, moving up and down across the test specimen in 15-second cycles, providing increased wind pressure on a small area for a short amount of time as it passes.

Leakage was expected to occur quite early in the tests, as such it was decided to increase pressure in increments of 10 Pa for some load levels, rather than the more common increments of 20 Pa. Changing the pressure levels of the RAWI box is done by changing its fan settings. Complete data for dynamic pressure and wind speed have been calculated in advance only for certain pre-defined load levels, those used most commonly in tests. Some of the unconventional load levels in these tests utilize fan settings outside of those pre-calibrated, meaning that some values are missing from the tables in this section.

The goal of the tests is to identify leakage points, and to tie those to the design of the system.

4.3.1. Heda Solar 8 W Solar Tile

The system is tested for roof angles 15 and 30 degrees from the horizontal plane. A set of terracotta roofing tiles from the manufacturer Monier were tested next to the solar tiles, to provide a comparison with a common roofing solution often found in Norwegian single-dwelling houses. The two systems are mounted with the same batten spacing, 375 mm. While the Heda Solar tiles are designed for this and only this spacing, it was at the upper limit of recommended spacing for the terracotta tiles. As such, they were mounted with the smallest recommended overlap, which might be part of the explanation why almost all the earliest detected leakages happened with the terracotta tiles. A picture of the frame is seen in Figure 2.

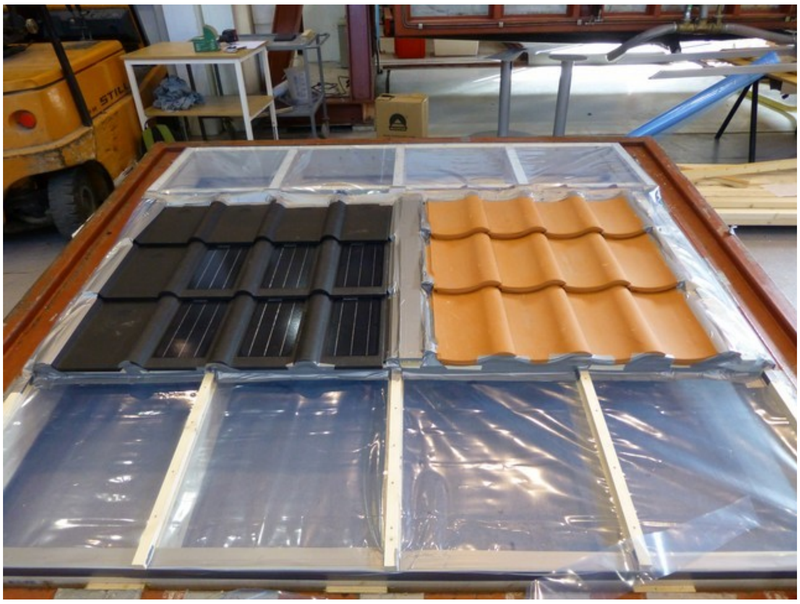


Figure 2: Heda Solar (left) and Monier Nova (right) tiles mounted in the substrate frame. The RAWI box can be seen in the background.

The test was first performed at a roof angle of 30 degrees, as measured along the rafters. A second test was performed at a 15 degree angle on the following day. Pressure was applied in 13 load levels, each level lasting for 10 minutes. This includes load level 0, during which only water spray was applied, with no wind pressure.

For the 15 degree test, which occurred on the following day, the same settings were used as for the 30 degree test. The 15 degree test was terminated after load level 11, when leakages became so severe that there was deemed no point in continuing.

Table 2: Pressure data for the 15 and 30 degree inclination tests of Heda Solar 8W Solar Tiles. Note that the 15 degree test was terminated after load level 11.

Load level	Differential pressure [Pa]	Dynamic pressure [Pa]	Airstream velocity [m/s]	Duration [minutes]
1-0	0	0	0	10
1-1	0-10			10
1-2	0-20	30	18	10
1-3	0-30			10
1-4	0-40	63	27	10
1-5	0-50			10
1-6	0-60	94	33	10
1-7	0-70			10
1-8	0-80	123	37	10
1-9	0-90			10
1-10	0-100			10
1-11	0-120			10
1-12	0-150	225	49	10

4.3.2. Solitek PV Module

No practical tests were conducted with the Solitek PV Modules, because fastening system supplied is intended for BAPV purposes rather than BIPV, and not meant to be watertight. The horizontal gap between two modules is documented in Figure 3, showing clearly where water would penetrate if the system was subjected to driving rain.

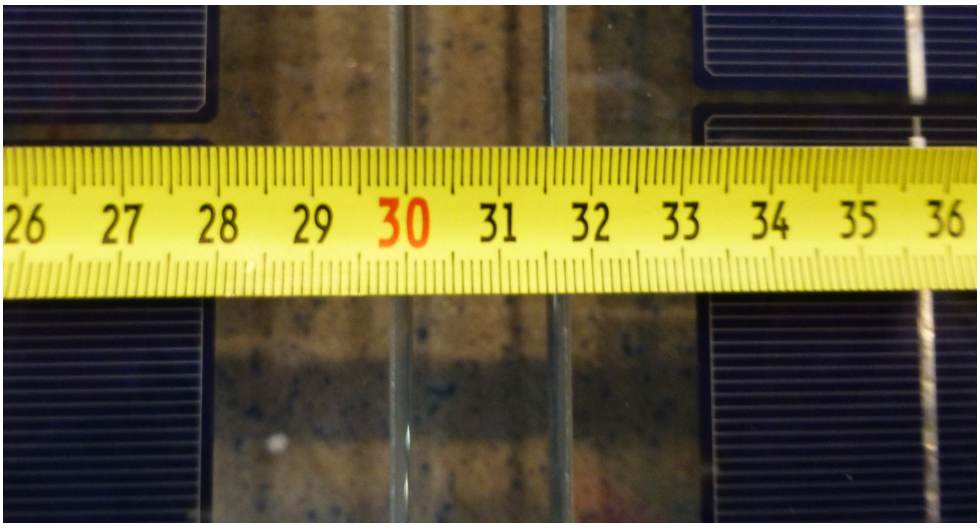


Figure 3: The gap between Solitek PV Modules using the supplied clamp fastening system.

4.3.3. GS Integra Line SP

The system is tested for mounting angles 30 and 90 degrees. Static pressure is increased at increments of 10 or 20 Pa until a maximum level of 150 Pa. The frame was later modified to include more PV panels, and new tests performed. Due to time constraints, the load level of some of the tests of configuration B had to be shortened to 5 minutes instead of 10.

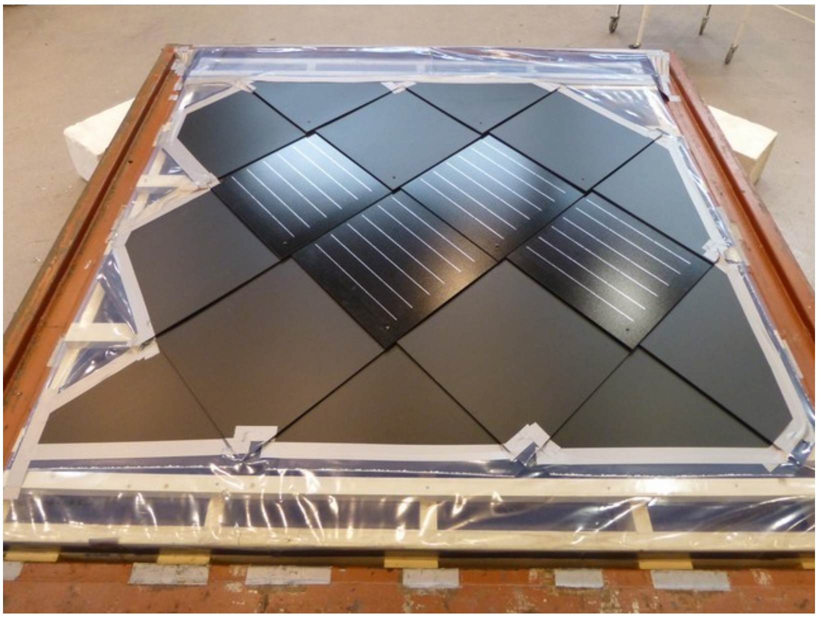


Figure 4: GS Integra Line SP, configuration A, mounted on a substrate frame and ready to be inserted in the RAWI box.

Table 3: Pressure data for the test performed on configuration A of the GS Integra Line SP system, at an inclination of 90 degrees.

Load level	**Differential pressure [Pa]**	**Dynamic pressure [Pa]**	**Airstream velocity [m/s]**	**Duration [minutes]**
A90-0	0	0	0	10
A90-1	0-20	30	18	10
A90-2	0-30			10
A90-3	0-40	63	27	10
A90-4	0-50			10
A90-5	0-60	94	33	10
A90-6	0-70			10
A90-7	0-80	123	37	10
A90-8	0-100			10
A90-9	0-120			10
A90-10	0-150	225	49	10

Table 4: Pressure data for the test performed on configuration A of the GS Integra Line SP system, at an inclination of 30 degrees.

Load level	Differential pressure [Pa]	Dynamic pressure [Pa]	Airstream velocity [m/s]	Duration [minutes]
A30-0	0	0	0	10
A30-1	0-10			10
A30-2	0-20	30	18	10
A30-3	0-30			10
A30-4	0-40	63	27	10
A30-5	0-60	94	33	10
A30-6	0-80	123	37	10
A30-7	0-90			10
A30-8	0-100			10
A30-9	0-120			10
A30-10	0-150	225	49	10

Figure 5: GS Integra Line SP, configuration B, with a greater number of PV modules. The corners where four PV modules meet are particularly important.

The following static and dynamic pressures were applied during the tests of Configuration B. Note that, due to time constraints, the duration of each step was shortened to 5 minutes rather than 10. The parameters for the tests performed on configuration B are summarized in Tables 5 and 6.

Table 5: Pressure data for the test performed on configuration B of the GS Integra Line SP system, at an inclination of 90 degrees.

Load level	**Differential pressure [Pa]**	**Dynamic pressure [Pa]**	**Airstream velocity [m/s]**	**Duration [minutes]**
B90-0	0	0	0	10
B90-1	0-10			10
B90-2	0-20	30	18	5
B90-3	0-30			5
B90-4	0-40	63	27	5
B90-5	0-50			5
B90-6	0-60	94	33	5
B90-7	0-80	123	37	5
B90-8	0-90			5
B90-9	0-100			5
B90-10	0-110	168	43	5
B90-11	0-120			5
B90-12	0-150	225	49	5

Table 6: Pressure data for the test performed on configuration B of the GS Integra Line SP system, at an inclination of 30 degrees.

Load level	Differential pressure [Pa]	Dynamic pressure [Pa]	Airstream velocity [m/s]	Duration [minutes]
B30-0	0	0	0	10
B30-1	0-10			10
B30-2	0-20	30	18	5
B30-3	0-30			5
B30-4	0-40	63	27	5
B30-5	0-60	94	33	5
B30-6	0-70			5
B30-7	0-80	123	37	5
B30-8	0-90			5
B30-9	0-100			5
B30-10	0-110	168	43	5
B30-11	0-120			5
B30-12	0-150	225	49	5

4.4. Comparison to traditional building materials

4.4.1. Heda Solar 8 W Solar Tile

It is important to note that the design considerations for a Chinese-made roof tile is different than those demanded in a Nordic climate. As such, the Heda Solar 8 W roofing tile lacks a few design elements commonly found in Norwegian roof tiles. This does not necessarily make it a bad design, but it may impact its suitability for use in a Nordic climate. Figure 6 shows a Heda Solar 8 W Solar Tile next to a conventional terracotta roof tile. Note that the conventional tile features double-grooved interlocks and specified drainage paths for water to drain from the interlocks. The Heda Solar tiles are fixed to battens via a rather narrow groove, meaning that it is only compatible with fairly small battens. Conventional tiles commonly use protruding nibs instead, resting on the batten only on one side, so that battens of any dimension can be used.

(a) (b)

Figure 6: Front and back comparison between a Heda Solar 8W Solar tile and a Monier Nova terracotta roof tile.

To avoid water intrusion by driving rain, a ”rain trap”, or pressure drop element, is often employed in the interlocks of roof tiles in the form of a deep groove. The principle behind this feature is that the airstream through the joints between tiles is diverted through a narrow opening into a larger ”chamber”, causing air velocity to drop rapidly due to volume expansion. The Heda Solar 8 W roofing tile employs such a groove along the bottom edge, divided vertically to form two smaller chambers. The more conventional Monier Nova tile uses deep grooves on both the front and back side of the tile, creating a more efficient rain barrier as well as a stable, double-grooved interlock.

Roof tiles often employ double-grooved interlocks for increased stability. The Heda Solar tile uses a single groove instead, making the tile a little less stable and less resistant to water intrusion through the longitudinal interlocks. The Monier Nova tile's interlocks have a small gap to drain away any water from the ”rain traps”.

Another design consideration is the number of fastening points for each tile. The Heda Solar 8 W tiles have two screw holes along the top edge of each tile (see fig. 6), but no fastening along the bottom edge. Roof tiles are often fastened with screws and clips along both the top and bottom edge to prevent them from ”flapping” in strong winds, as if mounted on a hinge. Strong fastening screws at the top edge will keep the tiles from falling off entirely, but there is still a risk that the rattling could lead to breakage. For conventional roof tiles, so-called ”storm clips” are available. These are not available for the Heda Solar tiles, although it is possible to drill a hole for an extra screw to create a three-point fastening. This, however, is not part of the tile's original design.

4.4.2. Solitek PV Module

The large glass/glass modules themselves appear to serve as effective weather barriers for the areas directly beneath their cover, glass being both rain tight and weather-resistant. However, there are gaps roughly 15 millimetres wide between the panels, through which wind and rain may pass freely.

Disregarding the area of the clamps, the gaps will constitute approximately 2.4 % of the total area covered with the BIPV system.

The gaps have the advantage of allowing pressure equalization between the outside air and the ventilated air gap very quickly. As such, any pressure difference between the front and back side of the modules will be reduced, which again reduces stresses on the panels under strong gusts of wind.

The clamps fixing the panels to wall studs are well-padded with rubber, preventing direct contact between glass and metal, and hence local build-up of stresses. The corner of the clamps is a steep 90 degrees, which concentrates the stresses around the corners to a slightly larger degree than a rounded design. The Norwegian standard NS 3510 recommends the corners of glass clamps to be rounded with a radius of at least 5 mm.

While the supplied fastening method for the Solitek modules technically is a form of BAPV, conventional building façades employing similar solutions have been found. Figure 7 compares the Solitek modules to the façade of the SINTEF Technology and Society building in Trondheim, which uses even smaller clamps to keep glass plates in place.

(a)

(b)

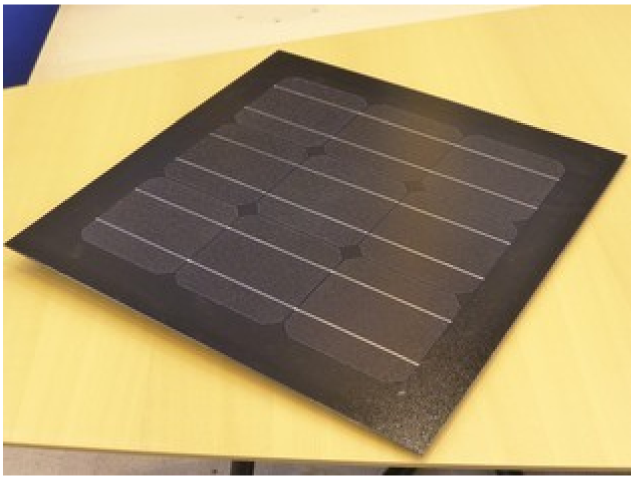
Figure 7: Comparison between Solitek PV Modules (a) and a conventional glass cladding at the SINTEF Technology and Society building in Klæbuveien 153, Trondheim (b).

The Solitek PV Module also has a very non-invasive installation method, with each panel secured with 4-6 clamps. Loosening the clamps and replacing a module is a fairly easy task, which does not affect other nearby panels to a great degree.

As noted in Table 1, the Solitek PV module has the largest PV area compared to its total area among the considered systems, and will generate the most electricity per square meter.

As of yet, Solitek does not offer companion dummy modules to be mounted alongside their system.

4.4.3. GS Integra Line SP



(a)

(b)

Figure 8: Comparison between a Gaia Solar GS Integra Line SP module, and recently dismantled, traditional slate roofing tiles. Note the markings of age on the slate tiles, which show how they were mounted.

The system has many apparent properties in common with traditional rhomboid slate roofs, but is assumed to be more watertight due to its use of fastening screws rather than clips.

GS Integra Line SP is based on Steni façade plates, polymer composite plates which have been in use in building envelopes since 1965, and achieved SINTEF certification (SINTEF 2000). The ”Steni Protego” product which GS Integra Line SP is designed to be used alongside, is a relatively new configuration of the Steni façade plates. The plates themselves remain identical to those certified by SINTEF, but are mounted in a slightly different fashion. On a material level, the dummy modules of the GS Integra Line SP system are already well documented to work as a conventional cladding material.

When mounting traditional cladding panels, fastening screws are usually screwed tight to secure the panels as firmly as possible. With GS Integra Line SP, this may cause some issues. The Steni Protego plates overlap one another when mounted, and will bend slightly if screws are tightened too hard or unevenly across one panel. This bending may cause corners and edges to protrude ever so slightly, decreasing the contact area between the plate and the one overlapping it. A combination of protruding corners and too tight fastening of screws caused one GS Integra Line SP module to crack during mounting on the substructure frame. Since the modules are made from tempered glass, which has an inherent property of internal stresses, the crack propagated and destroyed the module. This should be regarded as a human error rather than a design mistake, albeit one which may happen quickly and unexpectedly if one is not careful.

(a) (b)

Figure 9: A GS Integra Line SP panel broke during mounting (a). It was discovered that uneven tightening of the screws on the panels underneath had caused a protrusion close to the solar panel's screw hole (b), which led to high stresses as the solar panel was fixed in place. The cracks quickly propagated and destroyed the panel.

5. Results and discussion

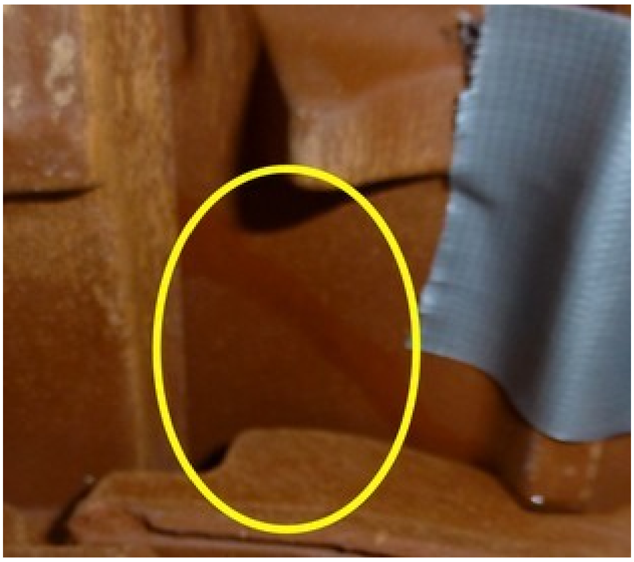
5.1. Results

5.1.1. Heda Solar 8 W Solar Tile

The observed leakages could be grouped in a few general categories, described below.

A common location for leakages, which also occurred very early, was a leak in the lower corner between solar tiles. Wind would blow through the corner between tiles, and form an air stream along the underside of the overlapping tile. For the terracotta tiles, this stream would usually run diagonally from the point of entry, to the top of the tile underneath. See Figure 10 (a). This mode of leakage was the first to occur, and occurred in 7 of the 9 terracotta tiles, discounting the 3 which had the relevant corner sealed.

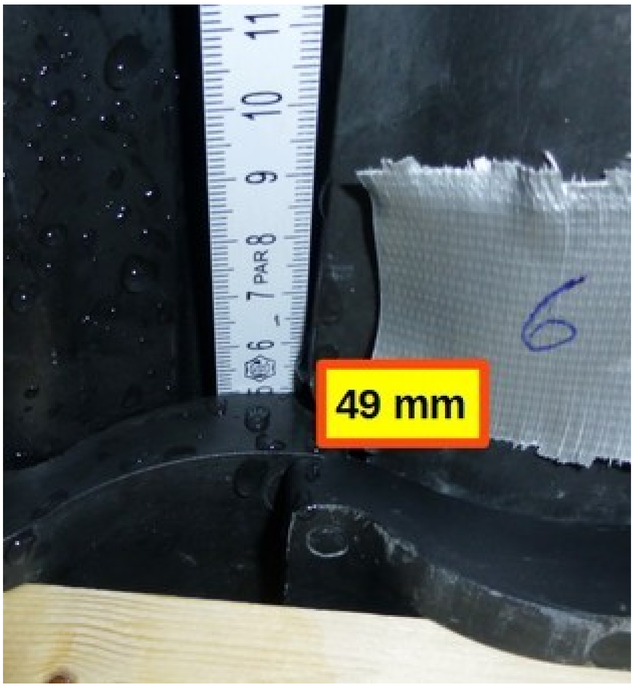
A similar leakage mode occurred in the Heda Solar tiles. It was noted that the ”wing” of the dummy tiles have ribs on the back side, creating an extra barrier for rain water. The ”wing” of the solar tiles did not have these ribs, creating a larger cavity along the corner joint, see Figure 11. Drops did not trickle along the back side of these tiles, instead a phenomenon was observed where drops were built up over multiple passes of the nozzle boom, and flung out of the cavity once they had grown to a sufficient size.



(a)

(b)

Figure 10: Corner leakages occurring between two Monier Nova tiles (a, within yellow ellipse) and two Heda Solar tiles (b, within green circle).



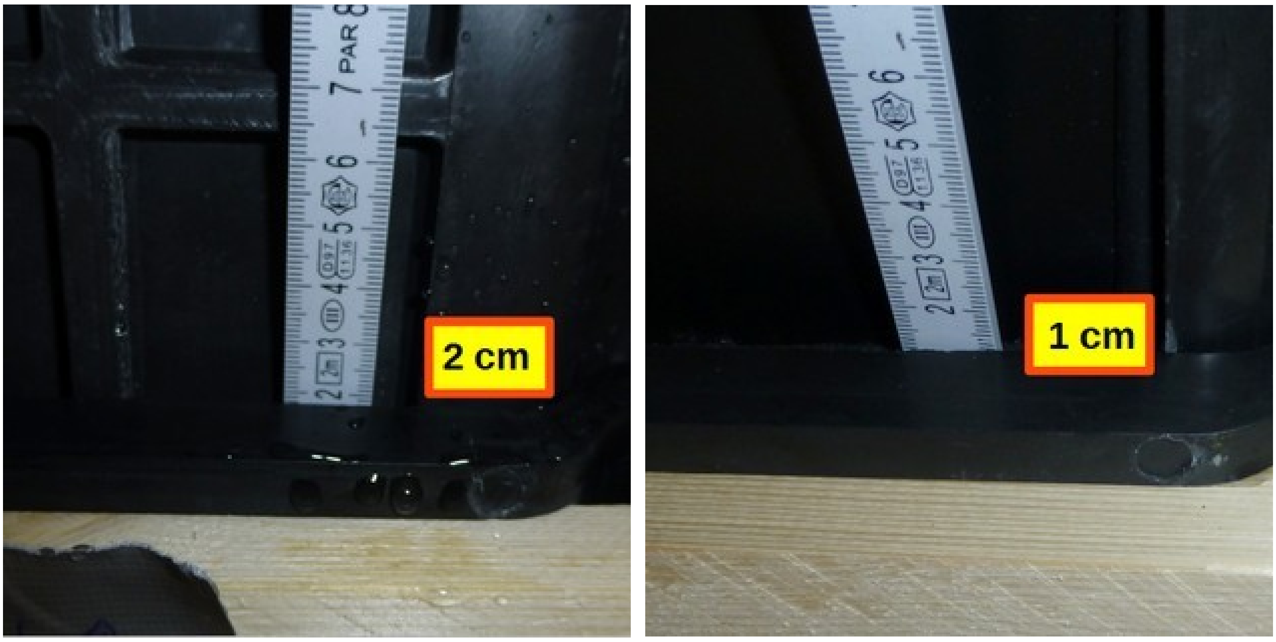
(a)

(b)

Figure 11: Cavities at the lower corner joint on the back side of a solar tile (a) and a dummy tile (b). The ribs on the dummy tile close the cavity, creating a more rain tight joint at lower pressures.

The screw holes of the terracotta tiles also experienced a lot of leakage. Of the 16 unsealed screw holes in the frame, 9 sprung a leak during the 30 degree test and 13 during the 15 degree test. A point to note is that it is not common practise to fix every tile in a roof in place with screws. Screw holes are sealed upon manufacture – they do not penetrate the tile – and unused holes stay watertight unless the seal is broken. Here, every tile was fixed with two screws, unsealing every screw hole (although those on the top row were sealed again prior to the test). No leakages were observed at the screw holes of the Heda Solar tiles.

The dummy Heda Solar tiles experienced some leakages along the bottom edge at very high wind pressures. This could be caused by the grid-pattern of ribs along the tiles' back side, creating a comparatively small contact surface along the latitudinal joints (see Figure 12). The Solar tile has a single, thick, horizontal rib along the entire contact surface, increasing the contact area and making the joint more water tight. At high pressures, these joints were ”belching” water whenever the nozzle boom passed. It is also possible that these leaks are an extension of the corner leaks, where water follows a different path at sufficiently high pressures. The open cavity of the solar tiles allow wind to pass straight through without ”catching” the tile. A closed cavity lets strong winds force the tiles apart, blowing run-off water through the joints.



(a) (b)

Figure 12: Comparison of cavities in the latitudinal joint below a dummy tile (a) and a solar tile (b). Note that the cavity is almost one full centimetre deeper in a dummy tile.

Figures 13 and 14 show the leakage points observed during the 30 degree and 15 degree tests, respectively. Overall, the Heda Solar tile proved to be unexpectedly watertight, considering their simple design compared to the terracotta tiles. Prior to the tests, it was feared that significant leakage would occur at pressures as low as 30 Pa (load level 3), and that the solar roofing tiles would experience leakages long before the more traditional terracotta tiles. In the end, leakage occurred first during load level 6, when moisture was detected on the underside of one of the terracotta tiles. During level 7, the first leakage occurred between the solar tiles. During the 30 degree test, 11 of the first 12 leakages occurred among the terracotta tiles, although the leaked water tended to cling to the underside of the terracotta tiles, and drain away rather than drip.

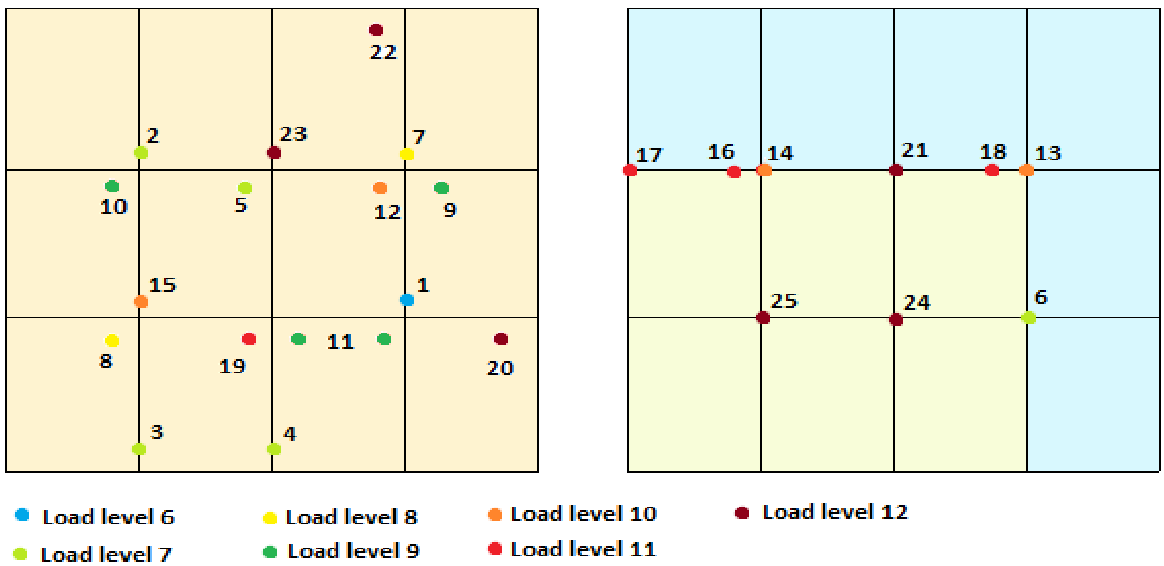


Figure 13: Leakage points observed during the test at a 30 degree angle. Monier Nova terracotta roofing tiles coloured in red. Solar tiles coloured light yellow. Dummy tiles coloured blue. Note that ”paired” leakages in the dummy tiles (14 and 16, 13 and 18) may be the same leak, where water followed a different path at high pressures. For the 15 degree test, these were grouped together rather than counted separately. Note that the set-up is illustrated as seen from behind.

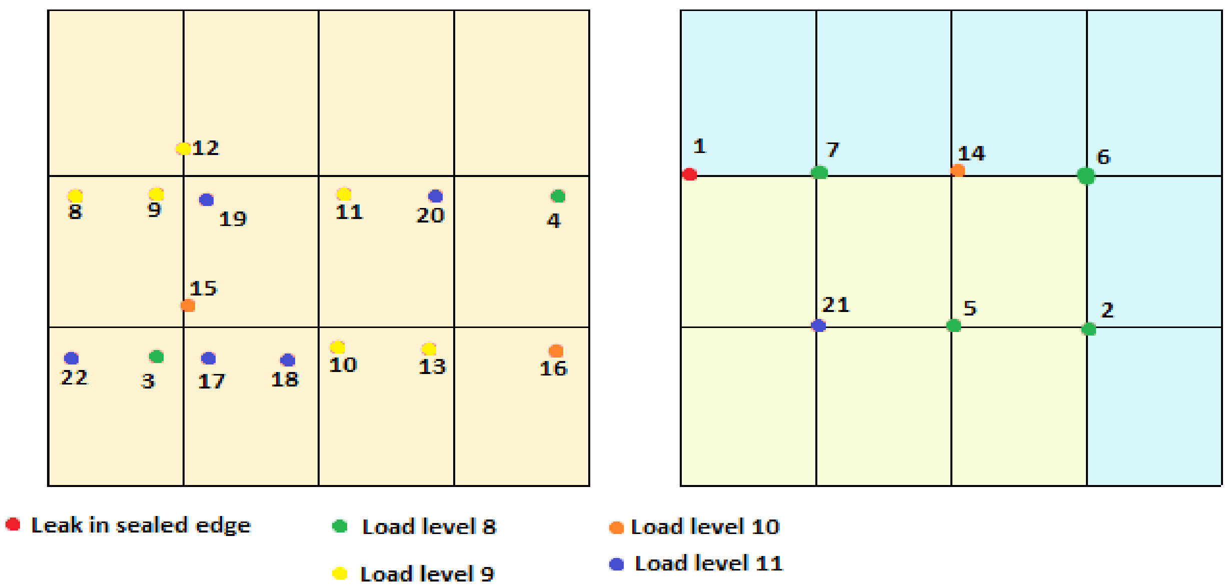


Figure 14: Leakage points observed during the rain tightness test at 15 degree inclination. Points of the same colour indicate leakages which happened during the same load level. Note that the set-up is illustrated as seen from behind.

For the 15 degree test, leakages in the longitudinal joints between terracotta tiles were remarkably uncommon. Leakages were first observed at slightly higher pressures than during the previous test. A possible explanation is that the smaller inclination meant gravity was pulling the tiles together with greater force, giving wind less opportunity to force open a gap. More leakages occurred in the screw holes of terracotta tiles in this test, for unknown reasons.

5.1.2. Solitek PV Module

Practical tests were not conducted with the Solitek PV Modules, for reasons stated in section 4.2.2.

5.1.3. GS Integra Line SP

Leakages observed in the tests are illustrated in Figures 16 - 19. Note that the set-ups are illustrated as seen from behind, and therefore mirrored compared to Figures 4 and 5. The leakages between modules manifested along the entire length of the joint between two plates, and rarely as a ”spot leak” in the corner between four plates, though in most cases the latter could be regarded as an extension of the former. Joints where PV modules overlapped other PV modules were determined to be the most weather-tight, followed by joints where Steni plates overlapped PV modules. Joints where PV modules overlapped Steni plates were the least water-tight by far. The system experienced more leakages when mounted at a 30 degree angle than when mounted vertically.

It seems evident that the system is most prone to leakages where the Gaia Solar panels overlap the Steni plates, due to a difference in thickness between the two types of plates. The Steni plates are 6 mm thick, the GS Integra Line SP modules 5 mm but tapered at the edges. Screw heads protruding from Steni plates are also a major factor, as shown in Figure 15. After a GS Integra Line SP module was broken during mounting, the research team was hesitant to tighten the fastening screws too much, in fear of destroying more panels. This might have left some screws looser than what is intended by the manufacturer, and possibly affected the outcome of the tests slightly.

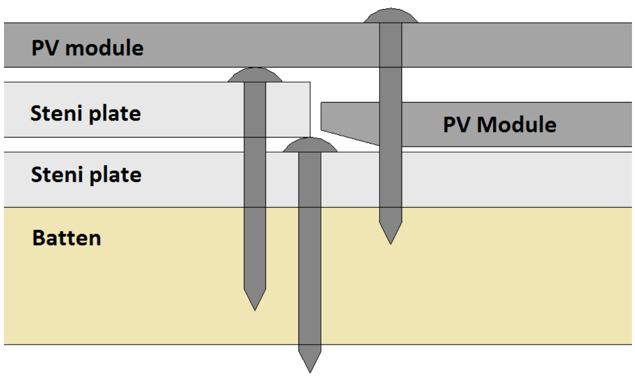


Figure 15: A particularly problematic joint where two PV modules overlap two Steni plates. The Steni plates build up much higher than the PV modules do, particularly because of the screws, resulting in a very open joint. Drawing not to scale.

The GS Integra Line SP modules are usually delivered with a sealed screw hole, but one of those used in the first test came with the screw hole pre-bored. This led to immediate leakage, as the pre-bored hole was barely smaller than the head of the fastening screws. Water leaking through the screw hole drained itself away when the system was mounted vertically, but at a 30 degree angle it led to some dripping.

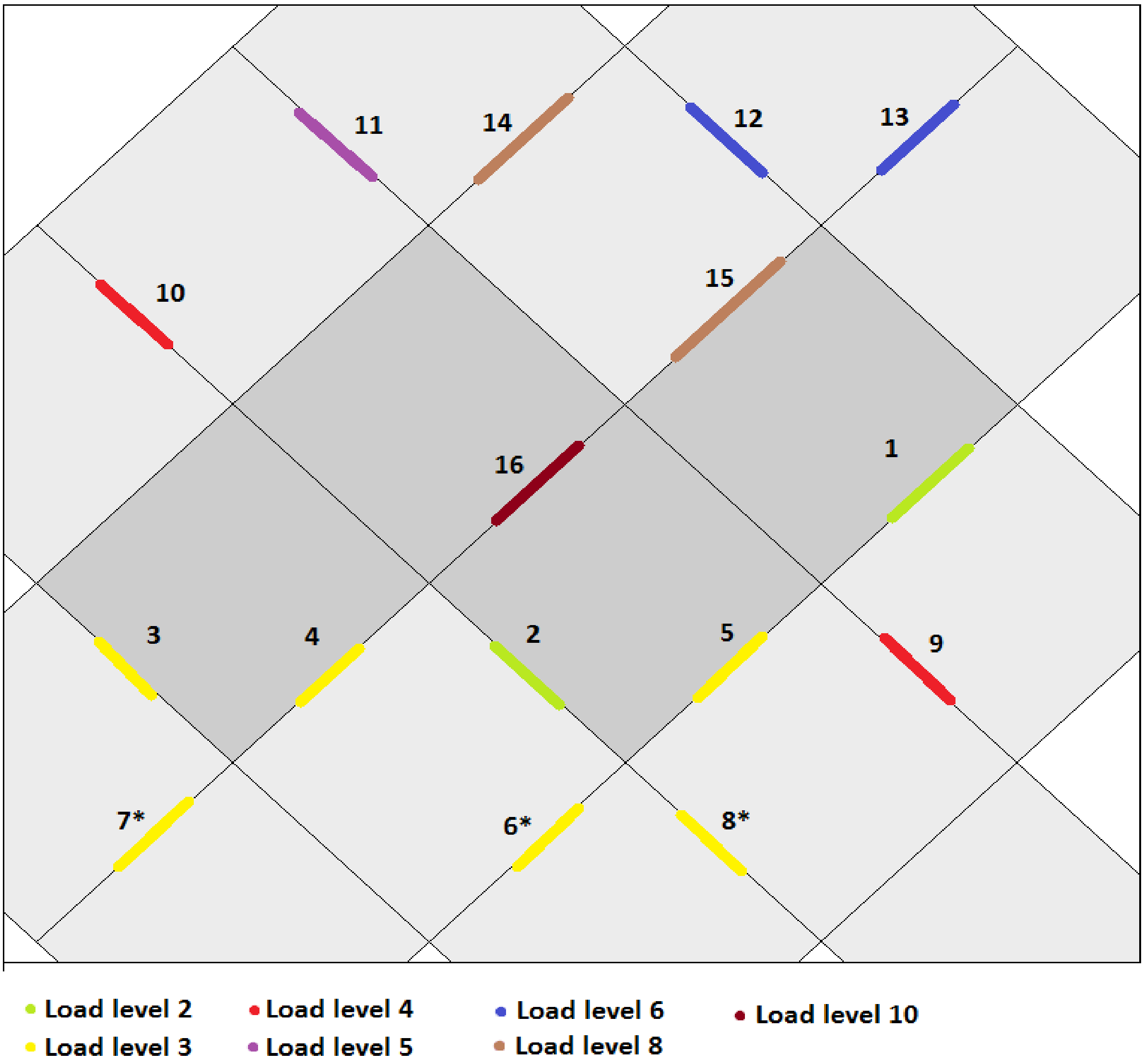


Figure 16: Leakages observed during the 30 degree inclination test of GS Integra Line SP modules in combination with Steni Protego Colour plates. Leaks marked with the same colour occurred at the same load levels. Observations marked with an asterisk (*) indicates that water was observed in the joint, but was later determined to be run-off water from a leak above rather than a new leakage point. The length of the lines is irrelevant.

There was a slight problem with water run-off on the back side of the modules, making it difficult to identify leakage points. Several joints were mistakenly identified as leakage points, because of great water run-off from above making it appear as if the joint was leaking. At higher pressures, actual leakage might have occurred, but it was difficult to say for certain when, due to the relatively high volume of water running along the joints. Attempts were made to isolate the joints by absorbing run-off water from above using paper towels, but abandoned as water leaked through.

When re-configuring the set-up, replacing three Steni Protego plates with additional GS Integra Line SP modules, it became apparent that replacing damaged modules on a large roof would be a daunting task. The system had to be dismantled from the top down, right-to left. It was necessary to strip down the entire frame to replace two modules at the bottom. During re-assembly, another module was destroyed after a screw was fastened too tightly.

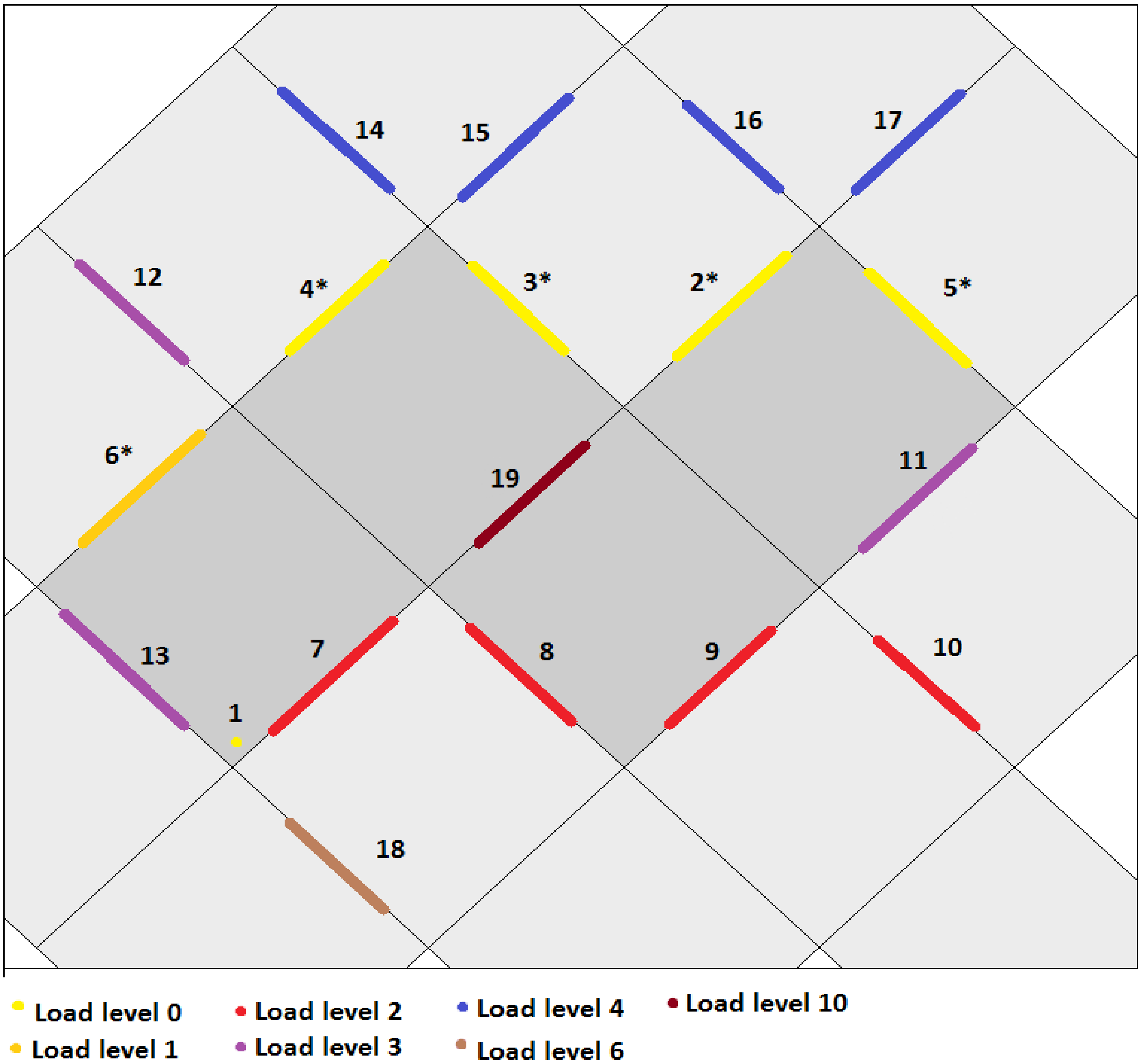


Figure 17: Leakages observed during the 30 degree inclination test of GS Integra Line SP modules in combination with Steni Protego Colour plates. Leaks marked with the same colour occurred at the same load levels. Observations marked with an asterisk (*) indicates that water was observed in the joint, but a leak did not happen (no penetration). The length of the lines is irrelevant.

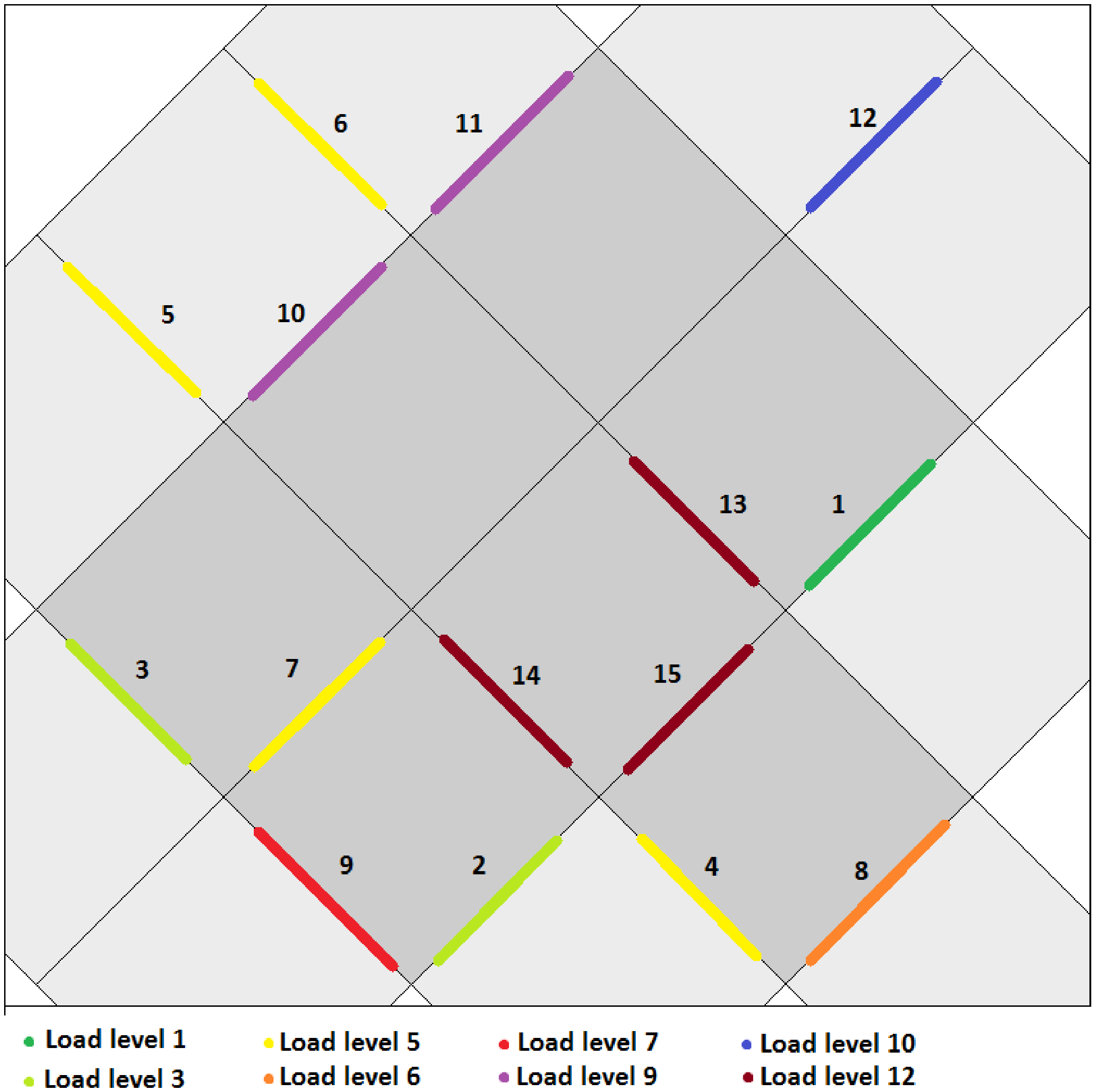


Figure 18: Leakage points observed during the test of Gaia Solar modules, configuration B, at an inclination of 90 degrees.

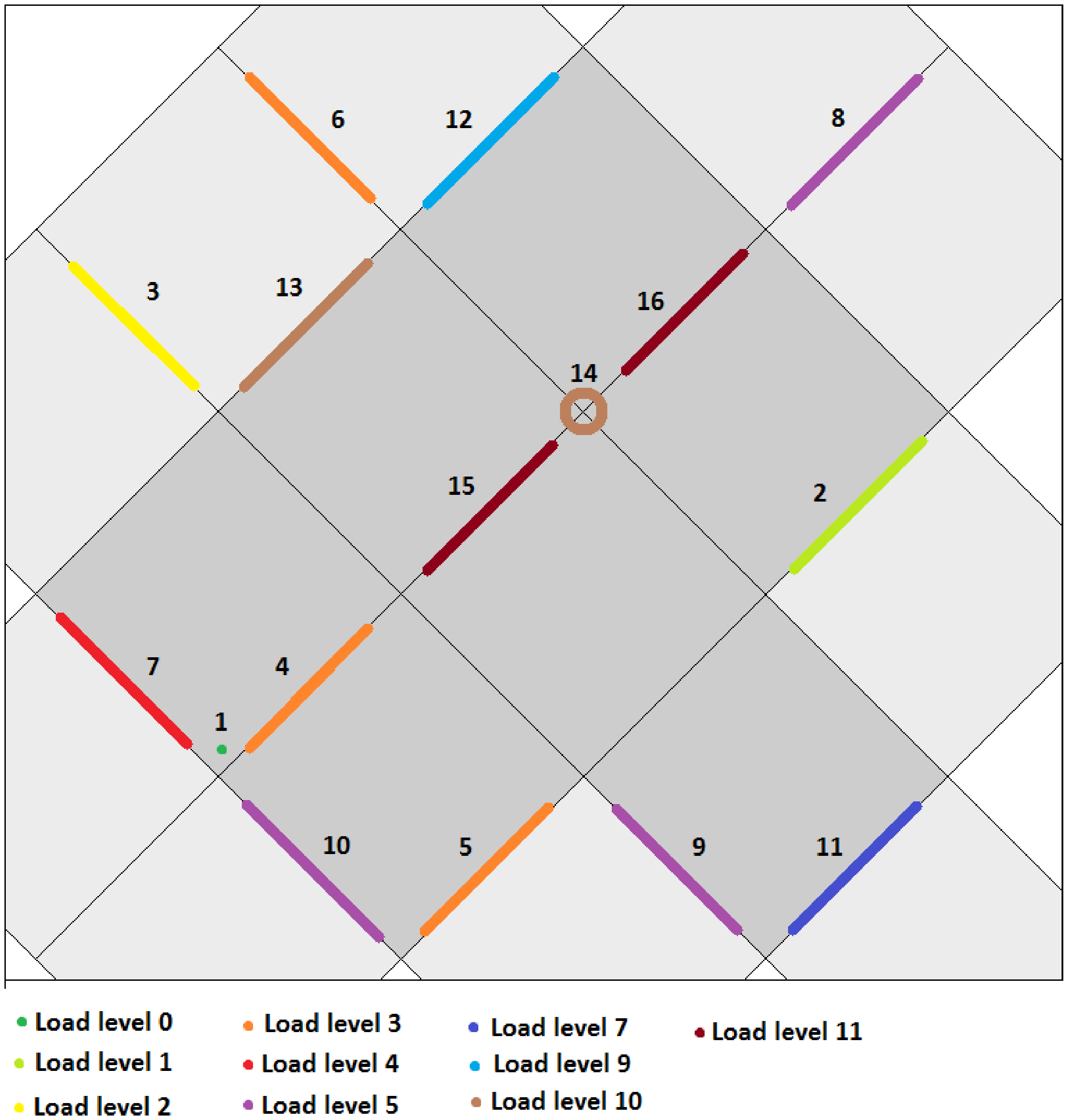


Figure 19: Leakage points observed during the test of Gaia Solar and Steni Protego modules, configuration B, at an inclination of 30 degrees. Note that leak 1 occurred in a pre-bored screw hole with all sealant removed upon delivery. Leakage 14 might have been caused by a horizontal gap between modules, which also allowed leakages 15 and 16 at high pressure.

5.2. Possible improvements

5.2.1 Heda Solar 8 W Solar Tile

As shown in Figure 20, the solar tiles and the dummy tiles look rather different on the back side. The ribs on the back side of the ”wing” of the dummy tiles create a closed chamber in the joint, and prevent leakage at low to moderate wind pressures. At high wind pressures, wind presumably catches the chamber and lifts the tile slightly, allowing a greater amount of water to leak through the horizontal joint. However, over long periods of time, the leakages prevented in moderate winds are much bigger than those caused in extreme winds. Giving the solar tiles the same ribs as the dummy tiles would, overall, make the system more weather-tight in the long run. The advantage of the ”ribs” is illustrated in Figure 21.

The interlocks of the tiles could also be improved, with a proper drainage groove as seen in conventional roofing tiles, see Figure 6. While the Heda Solar proved quite watertight in tests, the horizontal grooves have no proper interlocks, which reduces their stability to some degree. Storm clips could also be developed for the tiles, these do not necessarily have to impact the design of the tile itself.

The snow load resistance of the Heda 8W Solar tiles could be improved significantly by giving them a back-side profile that allows for larger battens to be used. Currently, the battens have to be smaller than 30 millimetres wide to fit properly against the tile, which is rather puny as far as tile battens go. The problem could be worked around by spacing rafters closer together, giving the battens a shorter span, but this is not a very cost-effective measure.

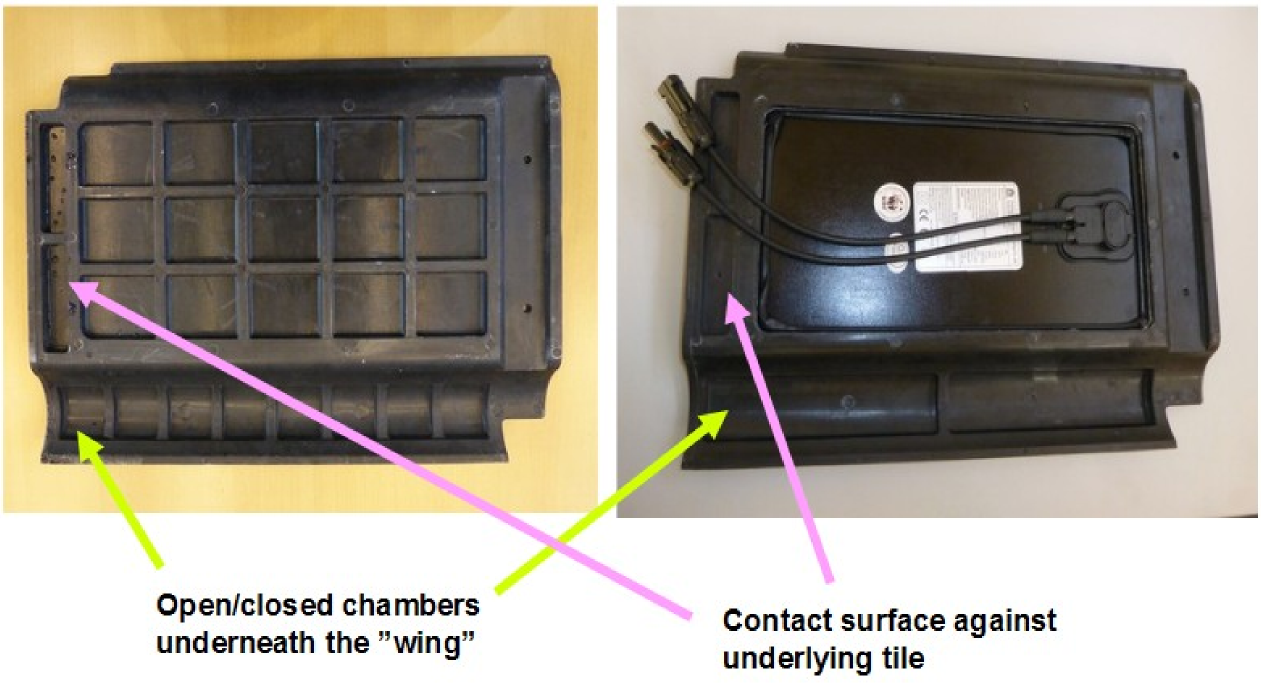


Figure 20: The different back sides of the Heda Solar tiles and their accompanying dummy tiles.

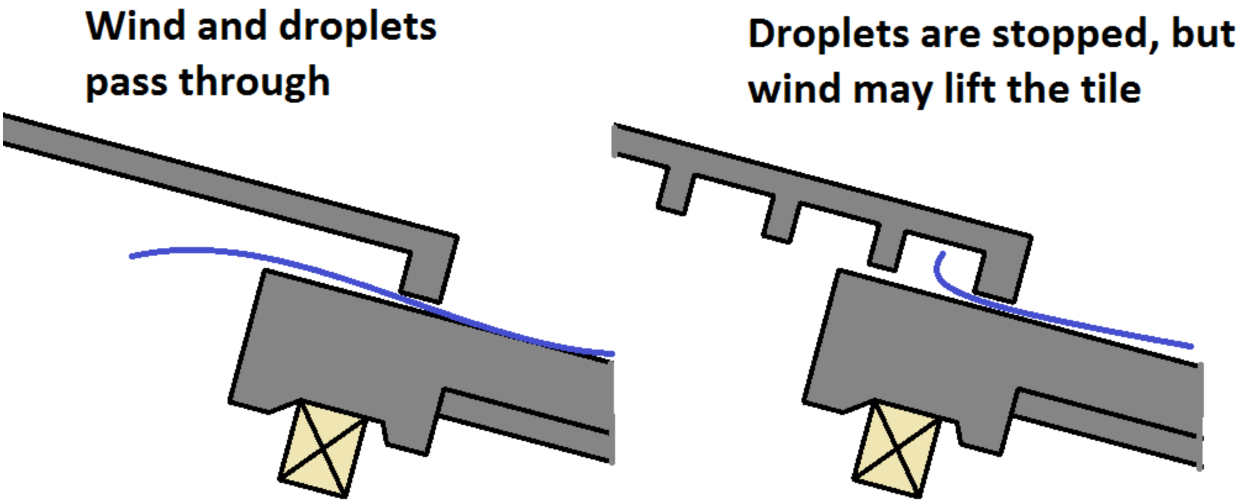


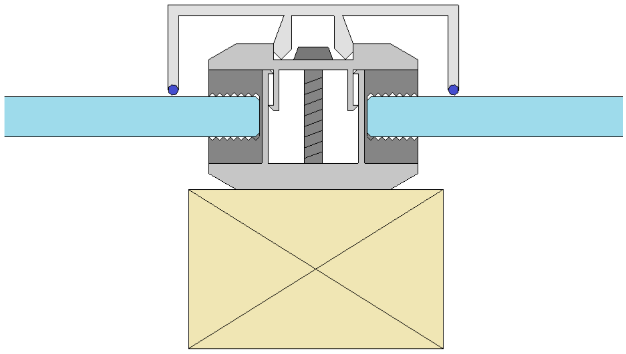
Figure 21: Principle illustration of wind blowing through the corner joints of Heda Solar tiles, with and without the ribs underneath the "wings" (drawing not to scale).

5.2.2 Solitek PV Module

The system, as supplied for these tests, uses clamps that were intended for BAPV purposes. Solitek manufactures PV modules for BIPV usage, but currently offers no complete system of integration. Other PV manufacturers have entered partnerships with façade product manufacturers to offer a complete package, where one company provides the PV modules and another the fastening system. Such a partnership ensures a working solution with respect to both PV and cladding requirements, and makes it easier for customers to buy a complete system without having to organize suppliers themselves.

It is possible to work off the clamp solution to make an improved BIPV system too. The open gaps between the panels compromise the system's weather-tightness to a very large degree. Certain cladding and BIPV systems utilize weatherproofing strips to cover panel gaps, which keeps most wind-driven rain and run-off water out. It could be advantageous for Solitek to adapt such a system to their modules, making it more weather-tight. The supplied clamps have grooves in them where a waterproofing strip could potentially be fastened. A picture of the clamps, and a principle illustration of a waterproofing strip, is shown in Figure 22.

(a)



(b)

Figure 22: Fastening clamps for Solitek PV Modules (a) and principle illustration of waterproofing strip system (b).

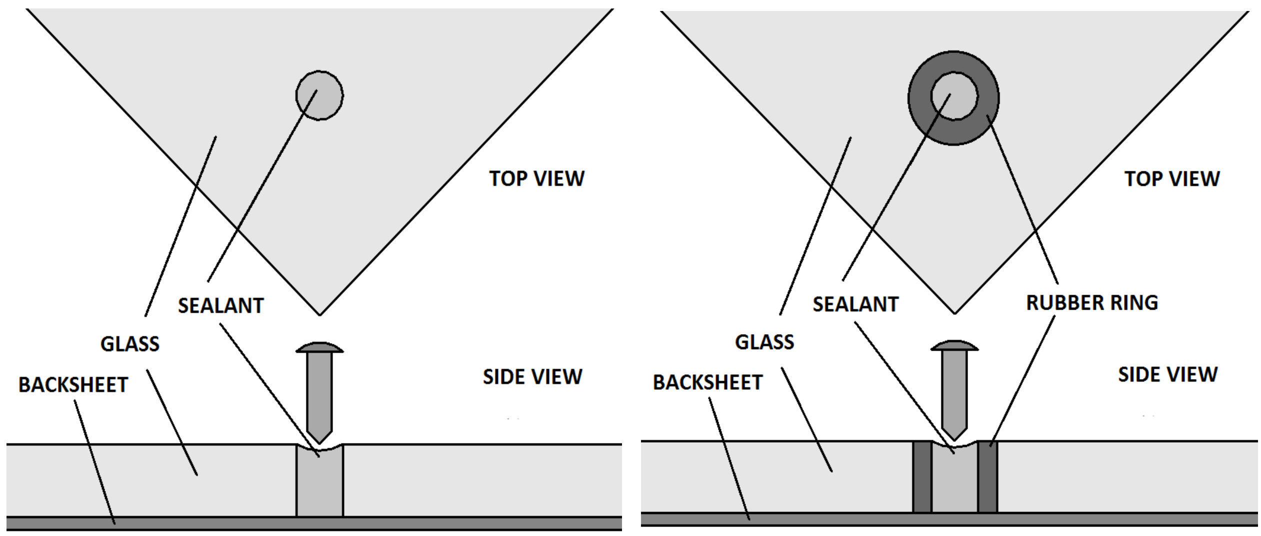
5.2.3 GS Integra Line SP

The screws appear to be crucial elements to this system's design. Screws protruding from underlying panels prevent a tight overlap. Fastening screws through the PV modules themselves carry an inherent risk of breakage, which again could lead to loss of the module. This is presumably the reason why every PV module only comes with one screw hole, the minimum necessary to keep the panel in place.

Recessed holes for screws heads would create a smoother and more tight overlap between panels. This could be difficult to pull off with the Steni Protego plates, which consist of a glass-fibre polymer composite. Alternately, the recesses for screw heads could be placed on the back side of the GS Integra Line SP modules. The system is designed for a specific and fixed distance between plates, so the locations of the screws relative to other plates remain fixed. It would be possible to place the recesses directly above the screw heads of underlying panels.

The singular screw hole in the bottom corner of the PV modules could also be improved. We propose to make the pre-bored and sealed hole larger, but lining the edges of the hole with a ring of rubber or other elastic material. This would eliminate direct contact between the glass and screw heads, reducing the risk of module breakage when the screws are tightened.

Employing rubber pads between the screw head and the glass would decrease the risk of breakage and make the screw hole more water-tight, but also build out the screw head even more, causing an overall more open joint. Ideally, screw heads should protrude as little as possible from the surface of the module, to keep joints as narrow as possible (See figure 15 for illustration).



(a) (b)

Figure 23: The current (a) and proposed (b) concept of fastening screws for GS Integra Line SP modules (drawing not to scale).

5.3. Future research paths

A possible future research path involves testing the modules again with a proper sub-structure, to more accurately assess their water-tightness when mounted on an actual structure, and possibly see what kind of exposure the sub-structure will be exposed to.

Slight modifications to the modules could also be carried out in the laboratory, followed by tests to see whether the design is improved or not. Using an extra screw to fasten the Heda Solar tiles might make them less vulnerable to wind loads, but does it have any effect on their hygrothermal performance?

The Solitek PV modules, while not practical to subject to weather-tightness tests, could be tested according to other standards, for instance impact tests or exposure to UV radiation. Large plate-based modules may be used to integrate photovoltaics in balcony railings or sun shading, as well as plate glass cladding. Once a proper waterproofing/drainage strip is installed, it would also be interesting to test the weather-tightness of the module.

The long-term effects of UV radiation exposure are also very important to investigate in order to assess the longevity of a BIPV system. Since PV modules generally involve a glass front cover, rubber or silicone is often used in clamps or grouts to fix the modules in place, or fix solar panels to the rest of the BIPV module. The robustness of these polymers is critical to the water-tightness and endurance of the BIPV system in the long run.

BIPV can also be mounted in other ways than those seen in this article, for instance frame systems

(Schüco 2016), rails, and integration in glazing. Samples of BIPV systems utilizing those fastening concepts should also be tested, to get a broader understanding of the available solutions and how they perform with regards to weather-tightness.

6. Conclusions

Three different building integrated photovoltaic (BIPV) systems have been evaluated by the means of conducting large-scale laboratory investigations of wind-driven rain tightness. IThere there are advantages and disadvantages to all the studied systems, also concerning the principles they utilize to integrate photovoltaics in the building façades and roofs.

Photovoltaic roofing tiles have a high level of visual integration, and may have a weather-tightness comparable to conventional roofing tiles. However, the ones investigated in this study have a rather low photovoltaic area efficiency, and produce a small amount of electricity per square meter compared to conventional photovoltaic arrays. A large number of electrical connectors is also required.

A BIPV module system based on clamps has the disadvantage of leaving gaps between modules, thus necessitating sealing remedies or a robust sub-structure with a water- and ultraviolet resistant wind barrier. On the plus side, they are quick and easy to mount and replace, and have a module efficiency comparable to conventional photovoltaic systems. Such systems sometimes blur the line between BIPV and building applied (attached, added) photovoltaics (BAPV), providing a low level of integration but a large electricity generation.

The weather-resistance of a BIPV system based on overlapping plates and penetrating fastening screws is largely governed by the fastening system. Protruding screw heads will prevent overlaps from being properly closed, leading to gaps in the façade or roof which will let wind and water through. Screws penetrating the module itself also carries a risk of breakage when mounting or replacing the modules. Design measures should be taken to prevent damage during mounting. Overlapping plates may also be difficult to replace should any of them break.

Acknowledgements

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Appendix A: Observed leakages

Heda Solar 8 W Solar Tile + Monier Nova terracotta tile

30 degree inclination

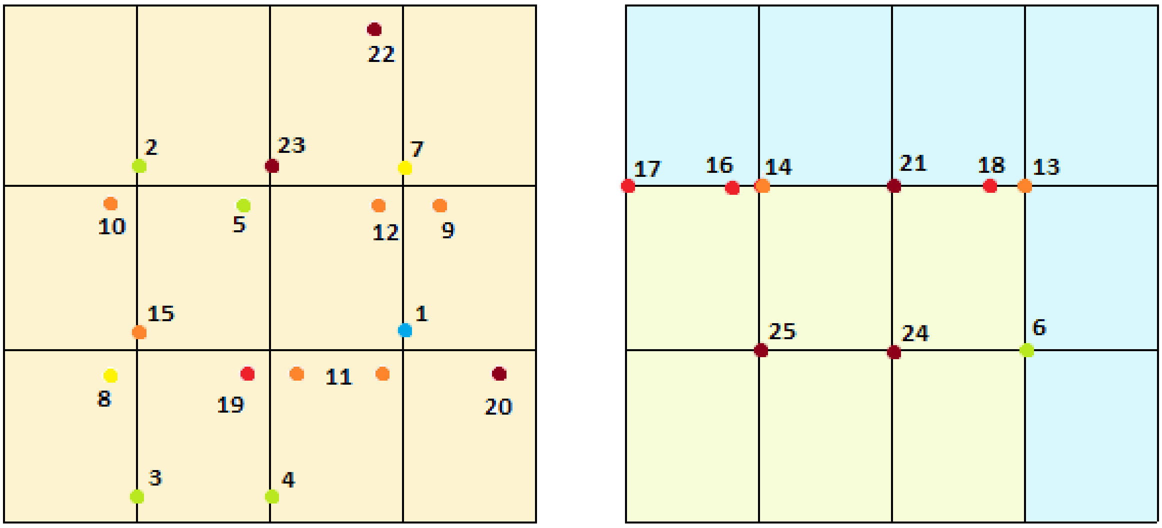


Figure 1: Observed leakage points during the test at a 30 degree angle. Monier Nova terracotta roofing tiles marked in red. Solar tiles marked in light yellow. ”Dummy” solar tiles marked in blue. Note that ”paired” leakages in the dummy tiles (14 and 16, 13 and 18) may be the same leak, where water followed a different path at high pressures. For the 15 degree test, these were grouped together rather than counted separately.

Heda Solar/Monier Nova roof tiles tested at 30 degrees inclination				
Leakage point no.	**Occurred at load level**	**Occurred at pressure [Pa]**	**Location/type**	**Comment**
1	6	60	Corner	Seemed to disappear and dry out shortly after first appearance, even though cycle was still ongoing.

2	7	70	Tile corner	
3	7	70	Tile corner	
4	7	70	Tile corner	
5	7	70	Screw hole	
6	7	70	Dummy-solar corner	
7	8	80	Tile corner	
8	8	80	Screw hole	
9	9	90	Screw hole	
10	9	90	Screw hole	
11	9	90	Screw holes	Leak occurred in both screw holes simultaneously. Mistakenly labelled as one leak.
12	10	100	Screw hole	Did eventually cause much dripping, from 2-3 drops per second at first appearance, forming a solid stream at 150 Pa.
13	10	100	Dummy-dummy corner	
14	10	100	Dummy-dummy corner	
15	10	100	Tile corner	
16	11	120	Bottom edge of dummy tile	May be an extension of leak 14.
17	11	120	Dummy-edge corner	Likely irrelevant, caused by a leakage in the side waterproofing rather than a leakage between tiles
18	11	120	Bottom edge of dummy tile	May be an extension of leak 13.
19	11	120	Screw hole	
20	12	150	Screw hole	
21	12	150	Dummy-dummy corner	
22	12	150	Screw hole	Probably connected to a leak in the waterproofing seal, as the topmost row of screw holes were taped over and meant to be

				outside the boundaries of the test area.
23	12	150	Tile corner	
24	12	150	Solar-solar corner	
25	12	150	Solar-solar corner	

15 degree inclination

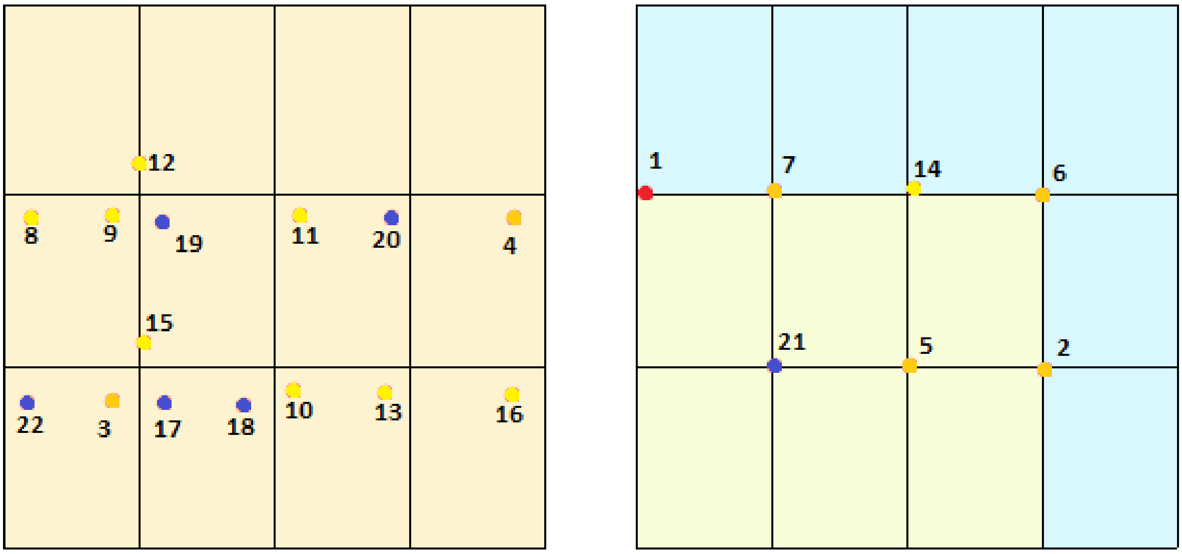


Figure 2: Leakage points observed during the rain tightness test at 15 degree inclination.

Heda Solar/Monier Nova roof tiles tested at 15 degrees inclination				
Leakage point no.	**Occurred at load level**	**Occurred at pressure [Pa]**	**Location/type**	**Comment**
1	7	70	Dummy-edge corner	Likely irrelevant, caused by a leakage in the side waterproofing rather than a leakage between tiles. See leak 17 in previous test.

2	8	80	Dummy-solar corner	
3	8	80	Screw hole	
4	8	80	Screw hole	
5	8	80	Solar-solar corner	
6	8	80	Dummy-dummy corner	
7	8	80	Dummy-dummy corner	
8	9	90	Screw hole	
9	9	90	Screw hole	
10	9	90	Screw hole	
11	9	90	Screw hole	
12	9	90	Tile longitudinal joint	
13	9	90	Screw hole	
14	10	100	Dummy-dummy corner	
15	10	100	Tile longitudinal joint	
16	10	100	Screw hole	
17	11	120	Screw hole	
18	11	120	Screw hole	
19	11	120	Screw hole	
20	11	120	Screw hole	
21	11	120	Solar-solar corner	Very slight leak, despite occurring at high pressure.
22	11	120	Screw hole	

Gaia Solar GS Integra Line SP

Configuration A

90 degree inclination

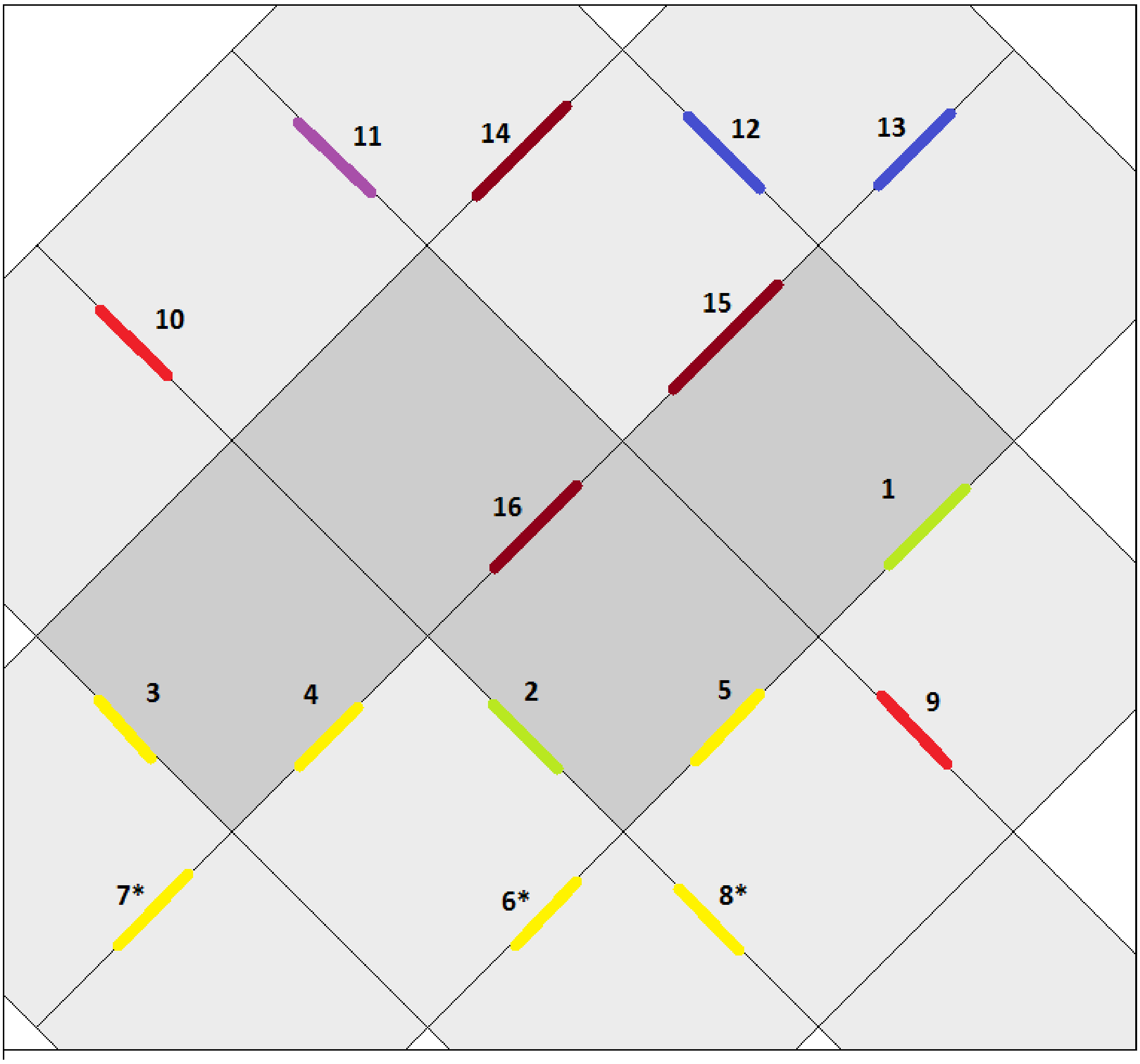


Figure 3: Leakages observed during the 30 degree inclination test of GS Integra Line SP modules in combination with Steni Protego Colour plates. Leaks marked with the same colour occurred at the same load levels. Observations marked with an asterisk (*) indicates that water was observed in the joint, but was later determined to be run-off water from a leak above rather than a new leakage point.

Leakage point no.	Occurred at load level	Occurred at pressure [Pa]	Notes
1	2	20	

2	2	20	
3	3	40	
4	3	40	
5	3	40	
6*	3	40	Water observed, but later found out to be drips from above
7*	3	40	Same as 6
8*	3	40	Same as 6
9	4	50	
10	5	60	
11	5	60	
12	6	70	
13	6	70	
14	8	100	
15	8	100	
16	10	150	Only leak to occur between two solar modules

30 degree inclination

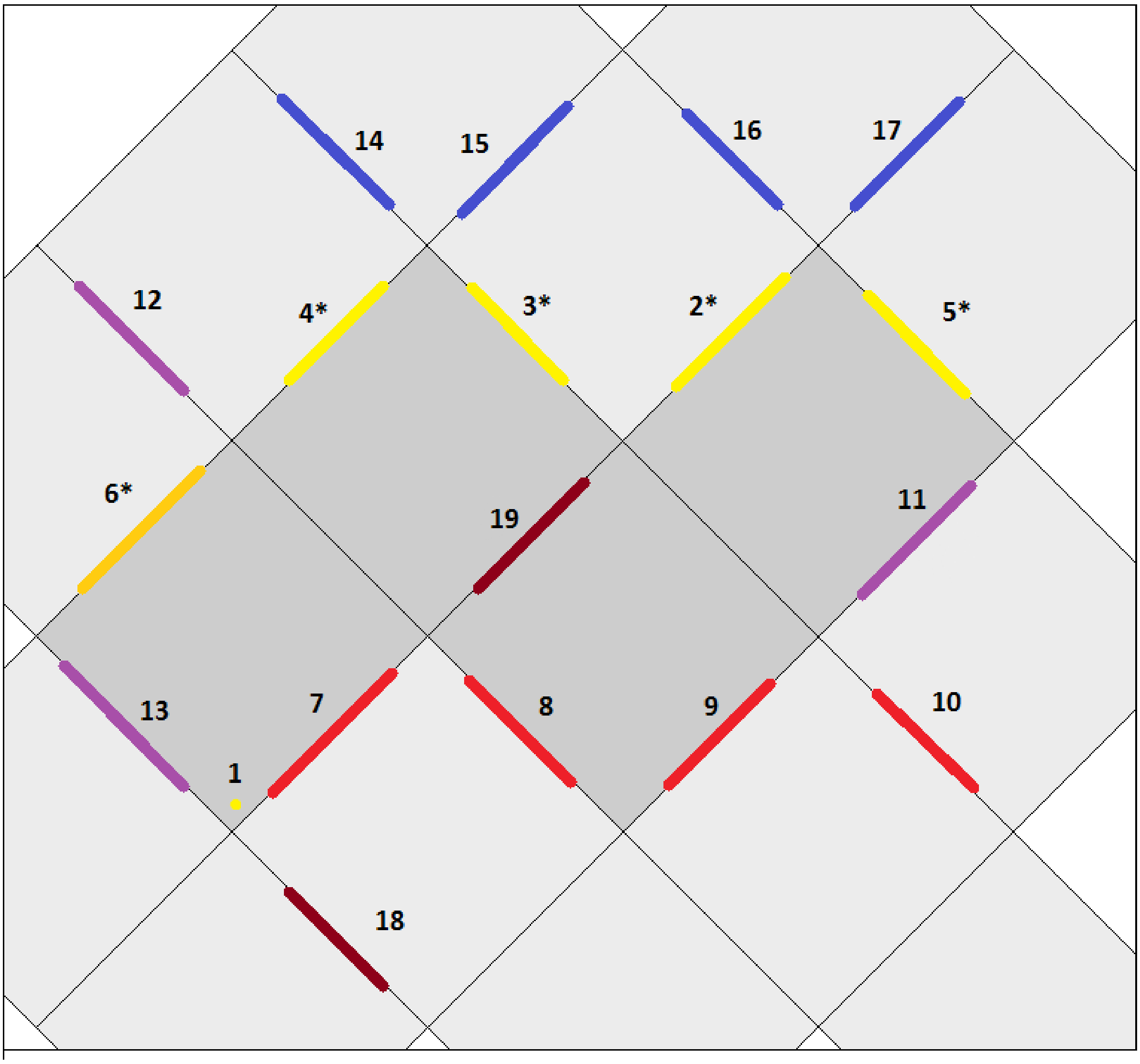


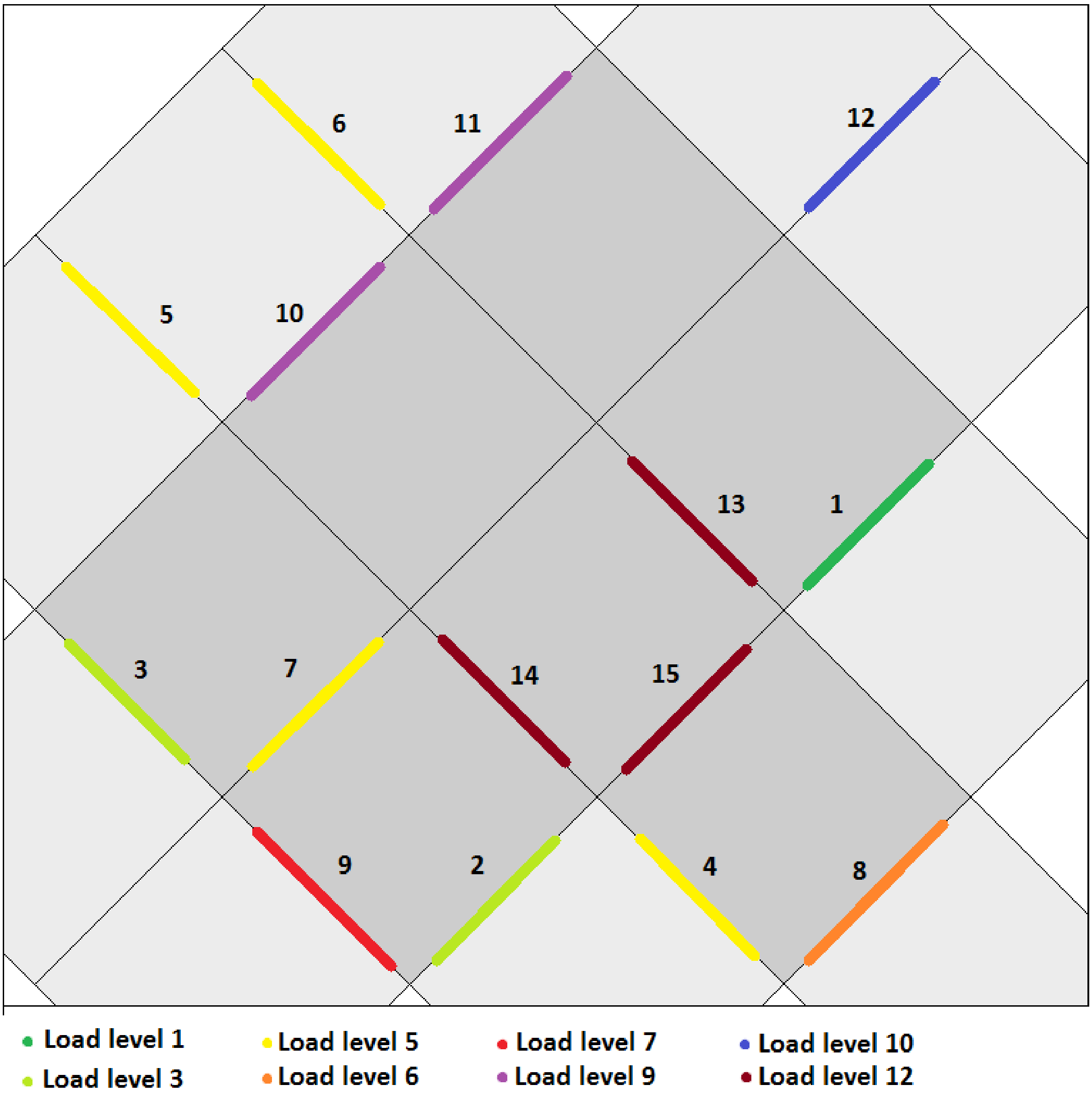
Figure 4: Leakages observed during the 30 degree inclination test of GS Integra Line SP modules in combination with Steni Protego Colour plates. Leaks marked with the same colour occurred at the same load levels. Observations marked with an asterisk (*) indicates that water was observed in the joint, but a leak did not happen (no penetration).

Leakage point no.	**Occurred at load level**	**Occurred at pressure [Pa]**	**Notes**
1	0	0	Screw hole
2*	0	0	Water was observed in the joint, but no actual penetration occurred.
3*	0	0	Same as 2
4*	0	0	Same as 2

5*	0	0	Same as 2
6*	1	10	Same as 2
7	2	20	
8	2	20	
9	2	20	
10	2	20	
11	3	30	
12	3	30	
13	3	30	
14	4	40	
15	4	40	
16	4	40	
17	4	40	
18	6	80	
19	10	150	Pressure jacked up specifically to provoke a leak between two solar panels.

Configuration B

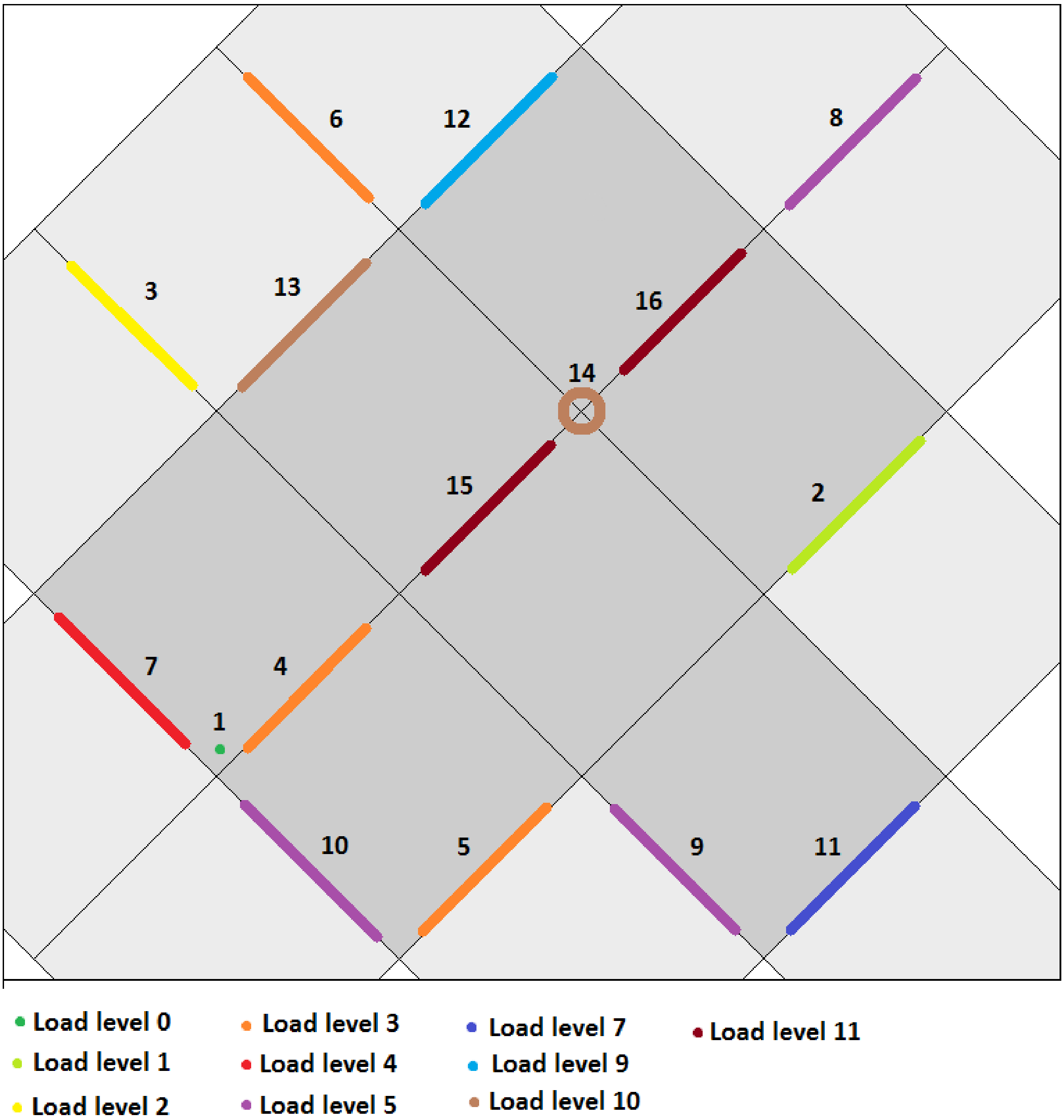
90 degree inclination



Leakage point no.	Occurred at load level	Occurred at pressure [Pa]	Notes
1	1	20	
2	3	40	
3	3	40	
4	5	60	

5	5	60	
6	5	60	
7	5	60	
8	6	70	
9	7	80	
10	9	100	
11	9	100	
12	10	110	
13	12	150	
14	12	150	
15	12	150	

30 degree inclination



Leakage point no.	Occurred at load level	Occurred at pressure [Pa]	Notes
1	0	0	Pre-bored screw hole with all sealant removed.
2	1	20	

3	2	30	
4	3	40	
5	3	40	
6	3	40	
7	4	50	
8	5	60	
9	5	60	
10	5	60	
11	7	80	
12	9	100	
13	10	120	
14	10	120	Water blew in through corner, no leak in edges. Possible mounting error, as some modules did not line up well during mounting.
15	11	150	May be extension of leak 14.
16	11	150	May be extension of leak 14.