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A testing methodology for quantification of wind-driven rain intrusion for building-integrated photovoltaic systems

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ABSTRACT

Wind-driven rain (WDR) exposure is a crucial impact factor to consider for building envelope components and systems. The roof being a climate screen, shields inner structures from various precipitations preventing most of the water from intruding. Although WDR exposure tests are quite common, there is a lack of studies that explore a quantification of water intrusion during such an experiment. Novel technologies such as e.g. building-integrated photovoltaic (BIPV) systems have been steadily more used as the building envelope components, and majority of BIPV systems are designed for roof integration. Such systems are mainly viewed as electricity generators, consequently, the power output and parameters that affect them are usually in focus when these systems are evaluated, whereas little information is available on the weather protection performance of BIPV systems. To address this gap, a series of experiments were conducted to improve the testing methodology of WDR exposure for BIPV systems where quantification of water intrusion was implemented. As a result, a novel framework is presented, which includes a step-by-step test methodology and a detailed description of the construction of a water collection system. Selected BIPV system for roof integration was tested according to the methodology and collected water amounts were provided. The findings in this study demonstrate that quantification of water intrusion is feasible and provides performance-based information that will help improving the design of BIPV systems as climate screens.

1. Introduction

1.1. Wind-driven raintightness test of building envelope components

The primary function of the building envelope is to compile a weather screen protecting the inner building structures and environment from various climate exposures. One of the main climate exposures that affect the building envelope is precipitation. All kinds of precipitation such as horizontal rain, wind-driven rain (WDR), hail, and snow significantly affect the hygrothermal performance of the building envelope.

A relatively young technology that has been introduced to the building industry and that steadily gains more attention is building-integrated photovoltaics (BIPV). BIPV systems are designed for integration into the building envelope along or instead of conventional building envelope components. Additionally to the weather screen function such systems produce electricity on-site [1].

To ensure that components and systems of the building envelope can sufficiently withstand exposure to various precipitations they are subjected to numerous testing, both in laboratories and at outdoor fields. Outdoor testing may require significantly more resources, both economical and timewise, while testing in a laboratory could be done in shorter periods. Testing conducted in laboratories has an unbeatable advantage as climate parameters may easily be controlled under laboratory conditions. Watertightness testing of the building envelope components is usually conducted in laboratories.

One aspect of watertightness testing, including raintightness, in the building industry is that such testing is not a part of Construction products regulation No 305/2011 [2], which specifies harmonized rules for the marketing of construction products in the EU. The watertightness testing for the building envelope systems is therefore voluntary and is not required for them to be sold on the market. Such test may provide valuable information that might be further used either to predict product performance, to compare different products in the same product range or for future product development. The primary layer of a sloped ventilated roof structure, viewed from the outside, is compiled of various roof coverings, for example shingles or tiles, whose main function is to keep as much precipitation out of the inner roof structure as

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possible. Under this layer first lies a ventilated air cavity, and then the underroof. The underroof is a secondary water barrier - a layer of a wind and waterproof membrane, which ensures that the water that went through the primary layer would not enter into the next layers of the roof structure [3].

Rain penetration into the building envelope can create problems that affect the durability of building materials, such as material degradation, mould growth, and wood decay. Rainwater can reach inner roof structures through the areas where the roofing underlayment is fastened by nails and staples. To predict moisture damage quantification of rain penetration through roof tiles may be utilized [4]. Several studies investigated WDR exposure on building facades in different countries [5–9], which shows the importance of risk mitigation associated with moisture-related problems. However, limited information is available on studies focusing on WDR exposure on roofing systems. Investigation of how roofing systems respond to WDR exposure can provide information on design parameters that influence the watertightness of various roof coverings. The design may be improved to minimize water intrusion. Fasana and Nelva [10] found the following aspects of the design of the roof coverings that affect watertightness: the value of the overlap of the roof slates and dimension of the side joint between the roof slates. It was also highlighted that the inclination of the installed roof system plays a critical role and an angle at which the system is the most watertight can be found [10].

Another crucial aspect is that it is often not feasible to access information on the methodology and results used for watertightness testing of the building envelope components and systems. Laboratory investigations are usually carried out by laboratories on assignment by manufacturers, where the results usually are not available for public. Thus, the building envelope components and systems cannot be compared according to their watertightness quality. In international standards watertightness is mostly addressed on material or component level [11]. Therefore, a testing methodology that includes the quantification of water intrusion for roof systems would give the opportunity to compare (a) various conventional roof systems with each other, (b) BIPV systems with traditional (non-BIPV) roof systems, and (c) different BIPV systems with each other. Also, development of new BIPV systems may be challenging without a knowledge base of documented performance of such systems, as well as the same information on conventional roof systems. Therefore, this study focuses on laboratory investigation of BIPV systems and development of a WDR exposure testing methodology that utilizes a quantitative method.

1.2. Principals of watertightness testing

When it comes to WDR exposure testing both the watertightness and raintightness terminology are used to describe the quality of the building envelope components and systems to withstand WDR. The term watertightness is mostly used both in international standards and scientific work, while the term raintightness rarely appears. Even though raintightness may seem as a better description of the quality of the roof systems, the terms watertightness, water leakage and WDR intrusion will be used in this study.

The principal of the watertightness test for roof coverings is to apply a certain quantity of water spray at various ranges of air pressure differences at various slopes at defined conditions with respect to the exterior surface of a roof specimen to observe if water leakages occur [11–13]. The air pressure loads at which water leakages occur and their locations, along with corresponding water leakage intensities, have so far been recorded with the main aim to identify a qualitative description of the water leakages and the limit of watertightness for the tested building envelope systems. However, to be able to classify tested systems, additional test parameters and measurements should be included. More specifically, the watertightness could be characterized by a measured quantity of the water leakages, which will enable a comparison between a large range of different roof (and facade) products in general and BIPV systems in particular. Thus, in the testing methodology of WDR intrusion for BIPV systems presented herein, a water leakage quantification method is proposed and evaluated.

The limit for the amount of water leakage intruding through the system is hardly specified for the building envelope systems. For BIPV systems intended for roof integration, this aspect is mentioned in the standard EN 50583–2 “Photovoltaics in buildings. Part 2: BIPV systems” [14] in annex A “Resistance to wind-driven rain of BIPV roof coverings with discontinuously laid elements – test method”:

- “A water collector shall be provided, capable of recording the amount of leakage water during any pressure step in the test”.
- “Reference leakage rate (10 g/m^2)/5 min, 5 min being the duration of a single test step in the sub-test”.
- “The cases, in which leakages exceeding fine spray and wetting on the underside occur, are considered as being too severe for the application. In any case, the reference leakage rate of (10 g/m^2)/5 min shall not be surpassed”.

Test parameters from watertightness test standards are spray rate, air pressure and the duration of these two parameters [15]. Standards mainly focus on manipulation of air pressure ranges, while water spray rate is usually kept constant. It could be beneficial to manipulate both parameters to simulate WDR exposure more closely to the one that occurs in real conditions. However, this manipulation may be challenging, and more research is needed.

To thoroughly test the building envelope systems as the climate screen it is crucial to test a large-scale model, as the most vital here is to investigate how connection of elements of such systems affect the performance. There are three basic experimental methods that can be used in building science: (a) full-scale models, (b) test cells or (c) experimental modules and large-scale model tests [16]. By the full-scale model it is meant that a whole building in full-scale is taken as a model for test, which usually is performed outdoors [3]. The goal of such test is to collect data on the building performance in real outdoor conditions. By the test cells it is meant that a part of a building, a cell, is tested in outdoor conditions, while the necessary indoor conditions are controlled [17], while outdoor conditions are present as they are. The test cells test may be a connecting point between the full-scale test and the scale model test. By the large-scale model it is meant a model constructed of elements and modules of real size, but the tested fragment of the building envelope fitted to a test specimen. The large-scale model test enables evaluation of various building envelope systems under close-to-identical laboratory conditions as these conditions can be easily replicated in indoor laboratories using similar equipment and methodology.

Compared to the other two basic experimental methods the large-scale model test (c) has both economical and time related advantages, but the exact scale is to be chosen for each specific test case. While full scale and test cells testing of the building envelope systems can provide extensive information and understanding on how various building envelope components work together [3], for the purpose of the present study the large-scale model test was found most appropriate and thus employed in the investigations. Data collected from all mentioned methods may be utilized for future computer simulations.

1.3. Background of WDR tightness experiments for BIPV systems

BIPV, being normally a component of the exterior building skin, must comply with requirements for conventional building envelope components. Primarily coming from the PV industry BIPV systems are subjected to tests and certifications of the electrical power industry, while requirements of the building industry are often neglected [18,19].

Previous laboratory investigations carried out by Breivik et al. [20] and Andenæs et al. [21] utilized a dynamic air pressure test methodology, and showed the feasibility and importance of conducting large-scale experiments with WDR exposure for the BIPV systems. For easier reference they are named Study 1 (experiments done by Breivik et al. [20]) and Study 2 (experiments done by Andenæs et al. [21]). Both studies were based on the test method standard NT BUILD 421 "Roofs: watertightness under pulsating air pressure" [22]. NT BUILD 421 was mainly used in the present study as this is the only standard for evaluating WDR exposure on roofs. This method applies to all components and sections of roofs made of any material to be fitted in roofs at any slope between 0° (horizontal) and 90° (vertical) at their normal operating conditions for which they were designed and installed according to the manufacturers' recommendations in a finished building.

In Study 1 the underlayment, a transparent polycarbonate (Lexan) board, was used under the BIPV system. Areas between the steel roofing and steel fitting were sealed with a self-adhering siliconized paper.

Throughout the duration of the test, the differential air pressure occurred over the underlayment. The test required that the differential air pressure occurred over the BIPV roof sample, so a hole (37 cm × 43 cm) was cut in the underlayment (2.75 m × 2.75 m). During testing, difficulties in maintaining the desired level of air pressure difference were encountered. As a solution to this problem, it was decided to seal the initial hole and to cut a smaller hole (7 cm × 43 cm). However, the same differential air pressure levels were not reached and hence this test phase was terminated.

Compared to Study 1 no underlayment was used in Study 2 [21] that was due to time constraints. The underlayment provides a certain amount of resistance against WDR intrusion due to an air cushion accumulating in the ventilated air gap behind the elements of a real roof or façade structure. Therefore, water leakages were expected to occur quite early in the test and a test procedure with lower load levels was used. In Study 2 the BIPV systems did not cover the whole test frame area thus areas between these BIPV systems, roof tiles and the rest of the frame were sealed using duct tape and a 0.15 mm thick polyethylene foil.

In Study 1 the inclination angle was changed more times during the test than in the present study and Study 2. It was found more time-efficient to adjust the inclination angle once from 30° in phase 1–15° in phase 2. Additionally, the drying time of the test systems between test phases could be shortened. In Study 1 heating fans were used; in Study 2 the test systems were left to air-dry overnight.

2. Methodology

2.1. Equipment

In the present study and previous studies [20,21] WDR was simulated in a specially designed rain and wind (RAWI) box (Fig. 1) at the NTNU and SINTEF Community laboratory in Trondheim in Norway. WDR is simulated by dynamic air pressure and a set of nozzles that spray water on the mounted frame where a test specimen is installed. The RAWI box allows stepless tilting between 0 and 95° from the horizontal plane, controlled pulsating air pressure across the test specimen and run-off water at a constant rate 1.7 L/(m x min) at the top of the test area. A horizontal boom (row) with water nozzles is mounted on rails inside the box and moves up and down at a velocity of 0.2 m/s along the sample 0.6 m above the exterior roof surface spraying WDR at a rate 0.3 L/(m^2 x min). The run-off water and WDR spray rates are the same in NT BUILD 421 [22]. The nozzle boom sprays water and air pressure is supplied in pulses onto a test sample, simulating gusts of wind and rain.

The boom inside the RAWI box, which delivers WDR across the sample area, consists of tubes that supply water down to transparent vertical cylinders where it hits the air stream that blows out of horizontal air tubes and is blown onto the sample area [20].

The duration of the water spray and air pressure exposure are combined in NT BUILD 421 [22] and lasts for 10 min for each increase of air pressure, while the water spray rate stays constant. The parameters given in NT BUILD 421 [22] and the parameters used in the present study and in Study 1 are given in Table 1. The load level 0 (0 Pa air pressure, run-off water) was added along additional levels 6 (600 Pa) and 7 (750 Pa) compared to parameters given in NT BUILD 421 [22]. Pulsating air pressure intervals used in Study 2 were in a lower range and are given in Table 3. As test methodologies used by authors of the present study, and in Studies 1 and 2 differ from each other, a

Table 1
Test parameters of NT BUILD 421 [22] compared to parameters used in BIPV systems testing (present study and Study 1 (Table 2)).

NT BUILD 421 [22]			Present study and Study 1 [20] (Table 3)		
Angle of slope		39°–0°	Angle of slope		30° and 15°
Load level	Duration (min)	Pulsating air pressure intervals (Pa)	Load level	Duration (min)	Pulsating air pressure intervals (Pa)
1	10	0–100	0	10	0 Run-off water
2	10	0–200	1	10	0–100
3	10	0–300	2	10	0–200
4	10	0–400	3	10	0–300
5	10	0–550	4	10	0–400
			5	10	0–500
			6	10	0–600
			7	10	0–750

Fig. 1. Large-scale turnable box for rain and wind tightness testing of sloping building surfaces (RAWI box), while test is running (left) [20] and RAWI box without a test sample (right) [21]. Schematic drawing of RAWI box is shown in Fig. 12.

Table 2
Qualitative observations of water leakages during wind-driven raintightness testing in the RAWI box for the BIPV system Study 3.

Load level	Maximum wind speed (m/s)	Pulsating air pressure (Pa)	Colour mark	**Inclination 30° (Fig. 13a)**	**Inclination 15° (Fig. 13b)**
0	0	0 (run-off water)		No water leakages	No water leakages
1	12.9	0–100		No water leakages	No water leakages
2	18.2	0–200		No water leakages	No water leakages
3	22.3	0–300		No water leakages	Leakages occurred
4	25.8	0–400		Leakages occurred	New leakages occurred
5	28.8	0–500		New leakages occurred	New leakages occurred
6	31.6	0–600		New leakages occurred	New leakages occurred
7	35.3	0–750		No new leakages	New leakages occurred

comparison of these three methodologies is given in Table 3.

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 1–7 (between 100 Pa and 750 Pa, depending on the load level) air pressure inside the box is increased and decreased in cycles (pulses) lasting 5 s, for a period of 10 min.

2.2. Investigated BIPV system

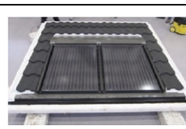
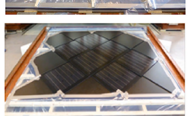
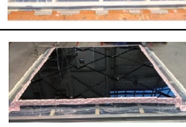
In this study, a BIPV system for roof integration was chosen as the test system. The system was constructed by fish-scale solar shingles. Each solar shingle is a glass-glass module that is compounded by two layers of safety glass with solar cells laminated between them. Fig. 2a shows an outline of the front view of the BIPV system. Fig. 2b presents a range of solar shingles that were used to construct the system: (1) basic solar shingle; (2) solar shingle bottom; (3) solar shingle top; (4) solar shingle left. Fig. 2c shows the placement of rubber elements that were attached to each solar shingle. Reverse anchor-like components are attached to the upper part of the BIPV shingles, with a line of rubber sealing the gap between the shingles. Additionally, rubber gaskets are used under each screw. If needed, the BIPV system can be complimented to fit the roof shape using colour-matching aluminium composite plates, which can be cut to various sizes and forms.

2.3. Test arrangement

In NT BUILD 421 [22] the structural details of a test system are not specified. The test system should be installed according to the manual, using materials that will be used on the actual roof. A structure under roof coverings was built using wooden battens. The BIPV system was installed on a wooden structure according to the manufacturer's manual, and the WDR test was performed in the RAWI box.

The focus of the present methodology was to implement quantification of water intrusion during the WDR test. For this matter it was crucial to find a solution to cover the areas around the tested system in such a way that it would be watertight. Another aspect was to find the optimal solution for utilizing an underlayment for the water collection, which included development and implementation of the water collection system. When the water collection system was ready, trial tests were run to ensure that the system worked correctly. Then the WDR test was performed according to Table 1 right. Acquired data included the limit of watertightness for the tested BIPV system (maximum level of differential air pressure before water leakages occur), amount of water that went through the tested BIPV system, locations where water intrusion occurred and corresponding levels of differential air pressure.

Table 3
Comparison of wind-driven rain exposure test methodologies used for the tested BIPV systems for roof integration.

Study reference	Tested system	Photo of the BIPV system	Pulsating (dynamic) air pressure intervals	Underlayment (Lexan plate)	Water intrusion quantification	Test procedure
Study 1 [20]	DuPont FlexWrap NF		Run-off water (0 Pa), 100 Pa, 200 Pa, 300 Pa, 400 Pa, 500 Pa, 600 Pa, 750 Pa	Yes	No	3 phases of test: 1. run-off water applied at 30°–15° inclinations; 2. Range of pulsating air pressure applied to underlayment at 30° then the system was dried, and range of pulsating air pressure was applied at 15°; 3. An attempt to apply pulsating air pressure to BIPV system (terminated)
Study 2a [21]	Heda Solar 8 W solar tile		Run-off water (0 Pa), 10 Pa, 20 Pa, 30 Pa, 40 Pa, 50 Pa, 60 Pa, 70 Pa, 80 Pa, 90 Pa, 100 Pa, 120 Pa, 150 Pa	No	No	2 phases of test: 1. run-off water and lower range of pulsating air pressure applied to BIPV system at 30° inclination; 2. run-off water and lower range of pulsating air pressure applied to BIPV system at 15° inclination. Phase 2 was carried out on the next day after phase 1.
Study 2b [21]	GS Integra Line SP			No	No	
Study 3 (present study)	Sunstyle roof shingle		Run-off water (0 Pa), 100 Pa, 200 Pa, 300 Pa, 400 Pa, 500 Pa, 600 Pa, 750 Pa	Yes	Yes	2 phases of test: 1. run-off water and a range of pulsating air pressure applied to BIPV system at 30° inclination; 2. run-off water and a range of pulsating air pressure applied to BIPV system at 15° inclination. Phase 2 was carried out on the same day after phase 1.

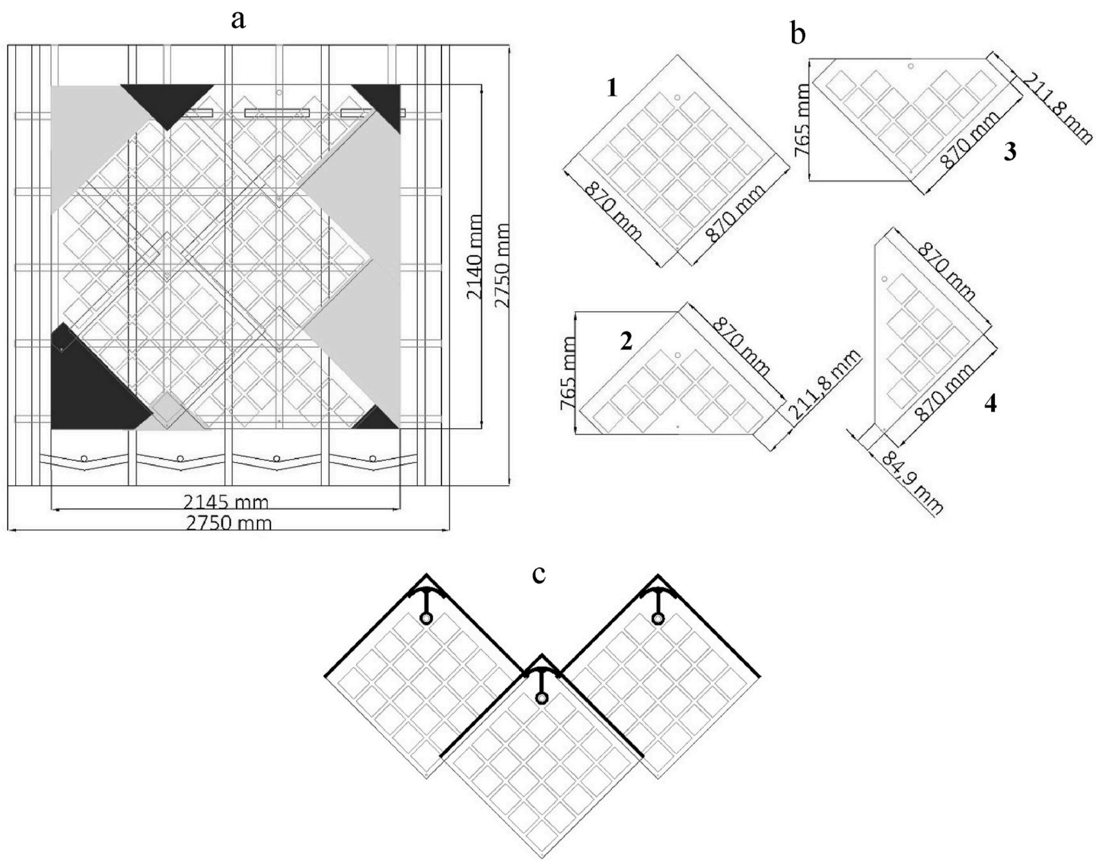


Fig. 2. (a) Front view of the outline of BIPV system in present study (to distinguish components of the system and to make connecting points better visible, BIPV shingles are left transparent, grey parts are metal plates, and black parts are glass-glass parts without PV cells). (b) Range of BIPV shingles: (1) basic solar shingle; (2) solar shingle bottom; (3) solar shingle top; (4) solar shingle left. (c) Rubber element on upper part of the solar shingle schematically shown on the drawing.

2.4. Development of a testing methodology for quantification of wind-driven rain intrusion for BIPV

After analyzing previous studies, planning to use the same RAWI box equipment, several improvement possibilities were identified. Firstly, the underlayment must be used along finding an optimal hole size cut into it, so that the desired air pressure difference can be achieved. The underlayment was also needed for water collection, i.e. a quantification of the water leakages. A water collection system was used for the first time in the RAWI box WDR exposure test. Thus, it took many trials and fails to make this system work properly, at the end the system proved to be feasible to build and use. A transparent polycarbonate (Lexan) board was applied as the underlayment so water leakages could be observed (and collected). The underlayment was fitted into the frame (2.75 m × 2.75 m) and was mounted on the wooden structure secured by screwing wooden battens to it. The wooden battens were spaced 0.6 m from each other and formed four separate sections. As the main frame of the test specimen was wider than the width of these four sections, two small sections were left along section 4 and section1 (Fig. 3). The two smaller sections were not a part of the water collection system, as water was only collected from the four main sections.

At the bottom of the frame a water collection system was built. Following the already built four sections, four water collection sections were formed, where one round hole was cut in each section and a tube was connected to each hole. A triangle profile made of wooden battens was built near each hole and taped to the underlayment with duct tape. From Study 1 [20] it was found that the underlayment must be punctured so that the air pressure will be applied to tested system and the desired levels of air pressure difference could be reached. Hence, four holes (each with a size 5 cm × 40 cm) were cut in the upper part of the underlayment. During the underlayment evaluation prior to testing an idea to cover these holes with a breathable waterproof material was assessed. If water that would go through the connecting points of a tested system would be drained through holes in the upper part of the underlayment, they must have been covered to collect all the water. After first test trials no water was draining through the holes in the underlayment, and they were left uncovered for the duration of the experiments. An outline of the water collection system is shown on Fig. 3. The present study will be further referred as Study 3.

To create a watertight barrier around the BIPV systems, the remaining fragments of the surrounding frame were covered with duct tape and a 0.15 mm thick polyethylene foil. Pretesting had shown a need of a better taping around the systems, as water leakages occurred at the points connecting the duct tape and the BIPV system, as well as between the duct tape and the polyethylene foil, already at 0 load level. The next step included finding a better sealing tape. It was decided to try to apply sealing tapes, which are usually used in underroof structures, as they had proven to be durable enough for prolonged periods [23]. Sealing tapes from Halotex along polyethylene foil were used to create a waterproof cover around the BIPV system. The polyethylene foil was sealed to the test frame using duct tape. Edges of the BIPV system were sealed using three types of sealing tape. The first layer was Halotex Flex Tape 60 mm following the polyethylene foil. Then Halotex Delta Tape 60 mm was placed over the plastic foil, following Halotex Delta Tape 100 mm (Figs. 4 and 5).

Examples of a complete taping are depicted in Fig. 6, from the front point of view before a trial testing and from the back-side point of view during testing.

As mentioned earlier, in the first trial run only duct tape was used, and it was changed to sealing tapes both around the BIPV system and in

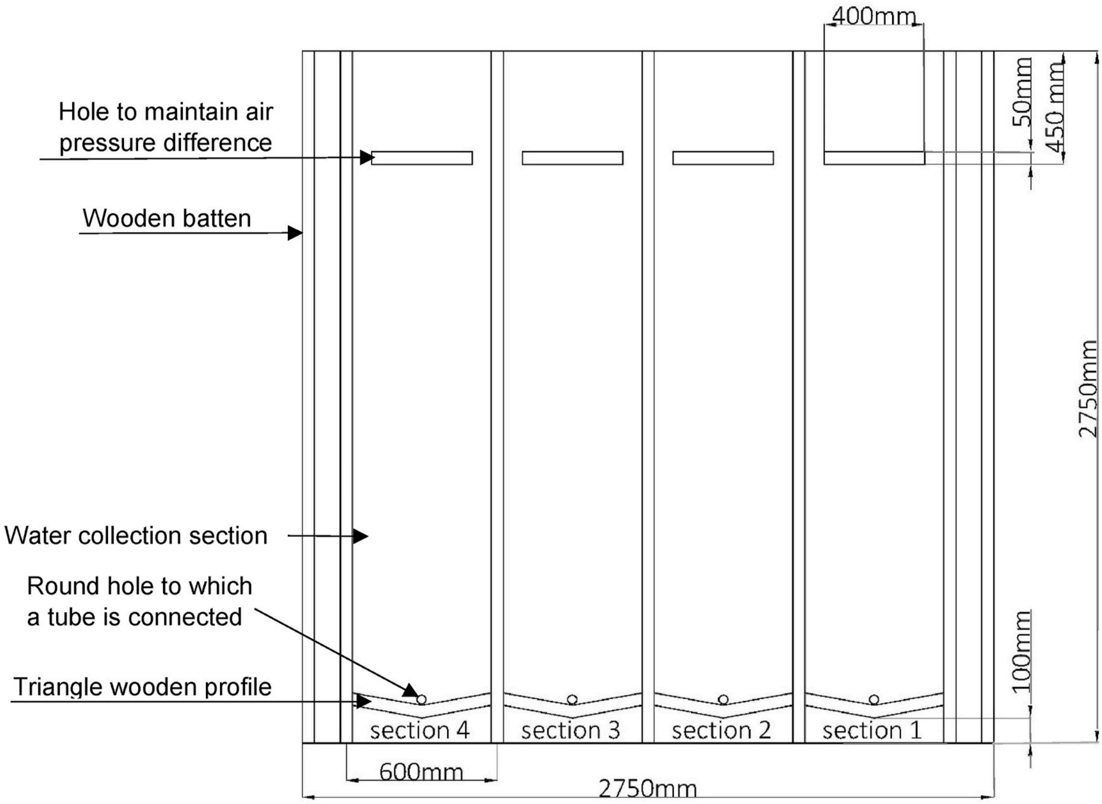


Fig. 3. Outline of the water collection system. Study 3 (Table 3).

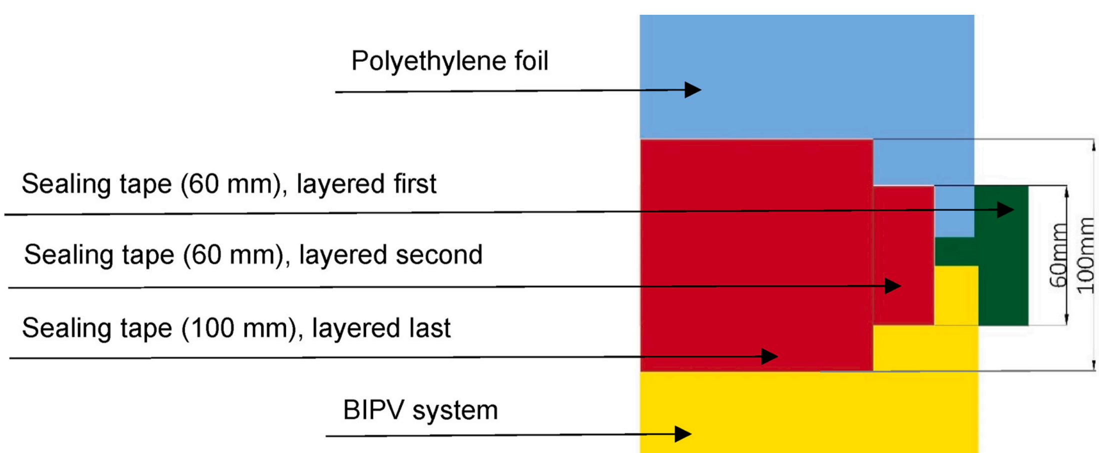


Fig. 4. Schematic drawing of sealing tapes layering.

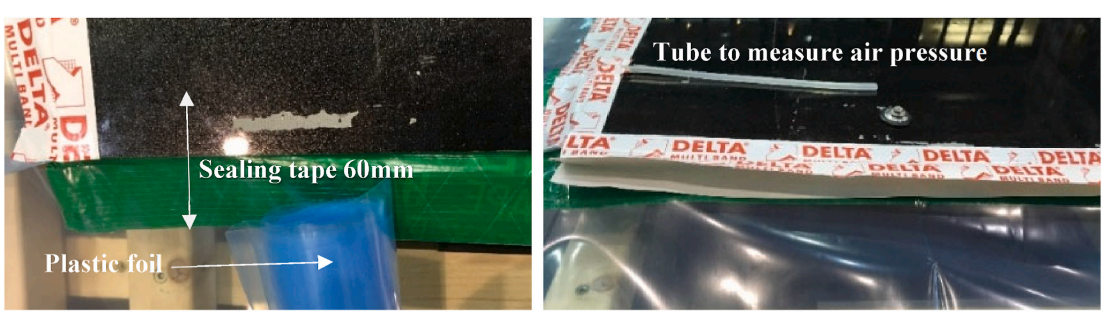


Fig. 5. Sealing the edges of the BIPV system using sealing tapes and polyethylene foil (view from the frontside). On the right photo a tube used to measure the differential air pressure is visible lying on the black module. Study 3 (Table 3).

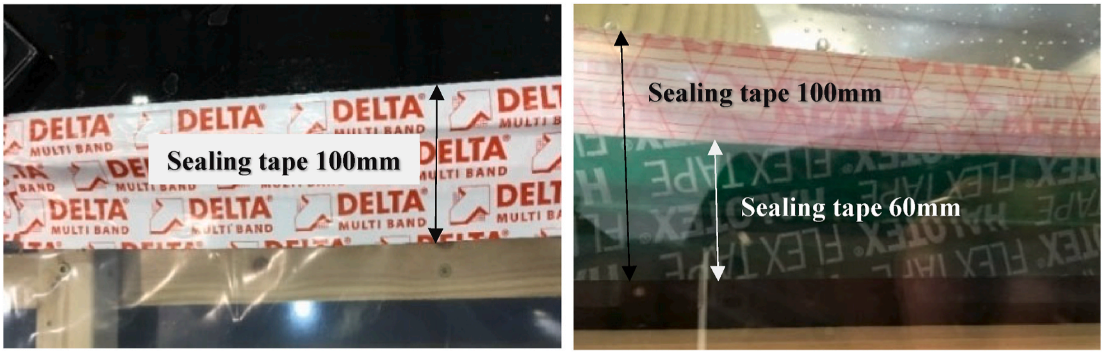


Fig. 6. View of a complete taping from the frontside (left) and from the backside (right). Study 3 (Table 3).

the water collection system. Wooden triangle profiles were then covered on the top and on the bottom side with duct tape (marked with number 1 on Fig. 7), while on the side part of each triangle profile where they were connected to the underlayment, Haloproof multi xtreme flex tape was attached (marked with number 2 on Fig. 7) to seal the gap and ensure that all the water would be collected. Then double-sided sealing tape was attached to the upper part of each triangle profile. Later, plastic foil was attached to this double-sided tape (marked with number 3 on Fig. 7). Step by step procedure of the present methodology is summarized in Fig. 8.

2.5. Evaluation of the developed methodology

After taping of the BIPV system was completed (Fig. 9) several trial runs were conducted (Fig. 10), starting from 0 load level (no air pressure, run-off water only), and increasing load levels according to Table 1 (right). The focus at this point was to monitor areas with taping to ensure that water leakages did not occur there. Hence, only water going through joints in the BIPV system, including joints between BIPV tiles and non-PV tiles (dummies), was collected. Taping had to be fixed in various places across the edges with small fragments of Halotex Delta Tape 60 mm. Taping at the bottom side of the BIPV system also had to be fixed. Here water should drain away, but the sealing tape was stopping this drainage at a few points and subsequently this water erroneously went to the water collector system, which was observed during trial run. Before water leakages were collected for recording, some parts of the sealing tape in the drainage areas were cut and plasticine was added underneath some locations between the tiles. After such adjustments were done, water leakages occurred only between tiles and the rest of the water was draining as it would on an actual roof.

The four water collection sections were numbered and respective containers for water collection were placed at the end of each tube connected to their section. The tubes were partially filled with water so that the air pressure measurements would not be interfered. The four sections with the water collection system at the bottom of the sections are shown in Fig. 10 (except the water collection containers), with some details depicted in Fig. 11. See also Figs. 12 and 13 which show the water collection containers. In Fig. 10 left, one of the four holes that are cut in the upper part of the underlayment is marked with a white rectangle.

At this point the taping was fixed and the test was run up to load level 4 (400 Pa), and as there were no leakages it was decided to run the first main test for this BIPV system. The test continued further with load levels 5, 6 and 7. One of the important aspects in WDR testing when using scale models is to make sure that the air pressure is evenly distributed across the whole area of the test system. In the RAWI box the air pressure is measured automatically, but usually there is no underlayment underneath the test system and the air pressure difference is set with respect to the ambient air pressure in the laboratory.

As in case of this test method, the air pressure difference must be set with respect to the air pressure underneath the tested BIPV system, hence a tube (Figs. 12 and 13) was placed under the BIPV system in the upper left corner and the other end of the tube then connected to the RAWI box. Along with this measurement, it was decided to measure the air pressure difference externally. For this matter one tube of the same diameter was installed during the taping stage on top of the BIPV system in the upper right corner (Fig. 5 right). Later this tube was connected to the external micromanometer (Figs. 12 and 13). Another tube of the same diameter was placed underneath the BIPV system. This tube was consistently moved across five points: each of the corners of the BIPV system and the middle part. Measurements were taken at each load level at the beginning of each of them and compared to the level of air

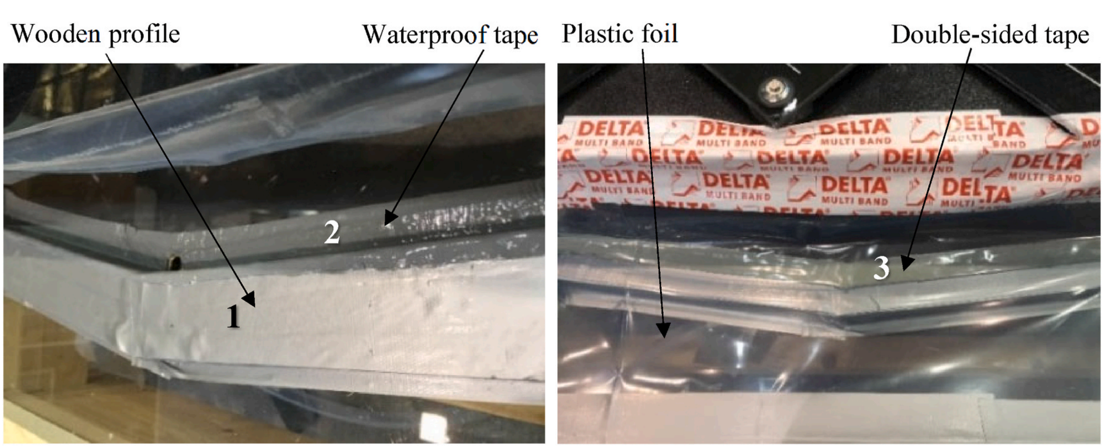


Fig. 7. Triangle wooden profile covered by duct tape (1) built on the underlayment. Waterproof tape sealing the gap between the underlayment and the triangle wooden profile (2), and double-sided tape sealing area between the triangle wooden profile and plastic foil (3). Study 3 (Table 3).

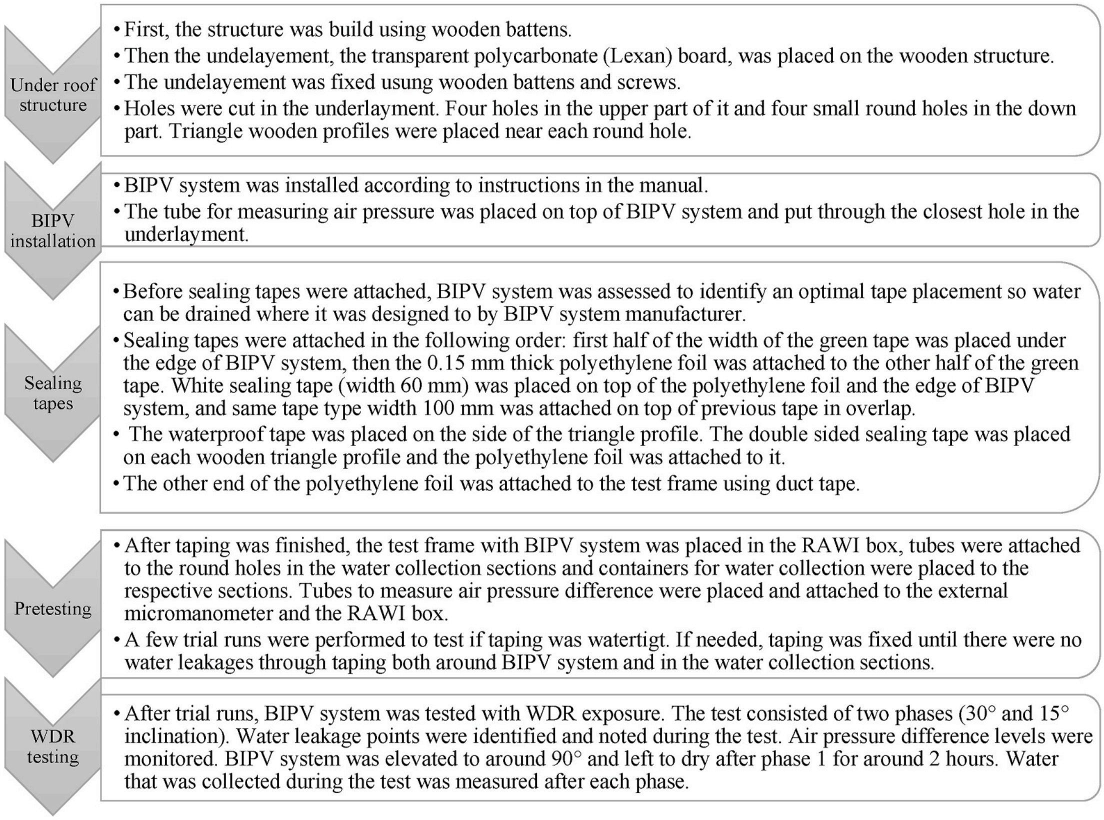


Fig. 8. Summary of the present test methodology.

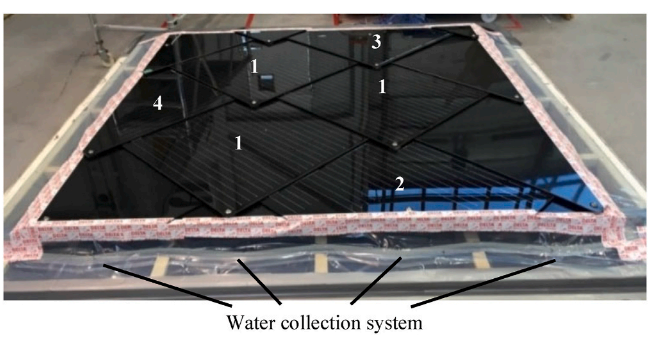


Fig. 9. The BIPV system with completed taping before testing. Study 3 (Table 3). Range of BIPV shingles: (1) basic solar shingle; (2) solar shingle bottom; (3) solar shingle top; (4) solar shingle left.

pressure measured by the RAWI box. All load levels during all test runs reached the desired values with minor error margins.

3. Results and discussion

3.1. The watertightness performance of tested BIPV system

The test was conducted in 2 phases, similar to the phases in Study 2. Phase 1 for the system inclined at 30° and phase 2 for the system inclined at 15°. Each phase started at load level 0 and then steadily continued up to load level 7 (Table 1, right and Table 3). The amount of water collected during each load level was low, and it was therefore decided to measure the water leakage once all load levels were applied. Even though it was proposed to measure the amount of water collected during each load level, it was not performed for this test. After the test for 30° inclination was over, the BIPV system was elevated and left to dry in air so that the water collection measurements during the next test would be more accurate.

It was decided to conduct phase 2 on the same day as phase 1. Partially because the sealing tape was already tested and no water leakages through it were expected to appear, but also to shorten the time when the tested system was installed in the RAWI box. A few water droplets that remained on the underlayment prior phase 2 of the test were not distracting observations of water leakages occurring during phase 2, as all points of water leakages were clearly visible and marked consequently with an erasable marker. The remaining droplets were also considered not significant to influence the water measurements. At the end of 2 phases of the test it was concluded that it was not obligatory to use heat fans to dry the underlayment or the inner side of the tested system, neither to leave it to dry during a long time. It was enough to lift the system to a steeper angle and leave it in this position for few hours.

Observations are summarized in Table 2 and water leakage points are market in Fig. 14. The results of collected water from testing of the Sunstyle BIPV system is presented in Fig. 15. The BIPV system showed a high watertightness level. During the test at 30° inclination leakages started to occur at 400 Pa (load level 4). Then new leakages continued to occur at 500 Pa (load level 5) and 600 Pa (load level 6). No new leakages occurred at 750 Pa (load level 7). Compared with the results of the test at 30° inclination, at 15° inclination leakages occurred one load level earlier, at 300 Pa (load level 3). New leakages continued to occur at each next load level applied (load levels 4, 5, 6, and 7). It may indicate that the tested system experienced higher WDR impact at the lower angle of inclination. The limit of watertightness for the tested BIPV system is at 300 Pa at 30° inclination and at 200 Pa at 15° inclination.

The main points where leakages occurred are in areas of metal plates overlapping BIPV shingles. The width of the metal plates is 2–3 times less than the width of the BIPV shingles. Already at low load levels, the metal plates were slightly bending that later lead to creating points of water leakage. Along with BIPV modules, metal plates were used to

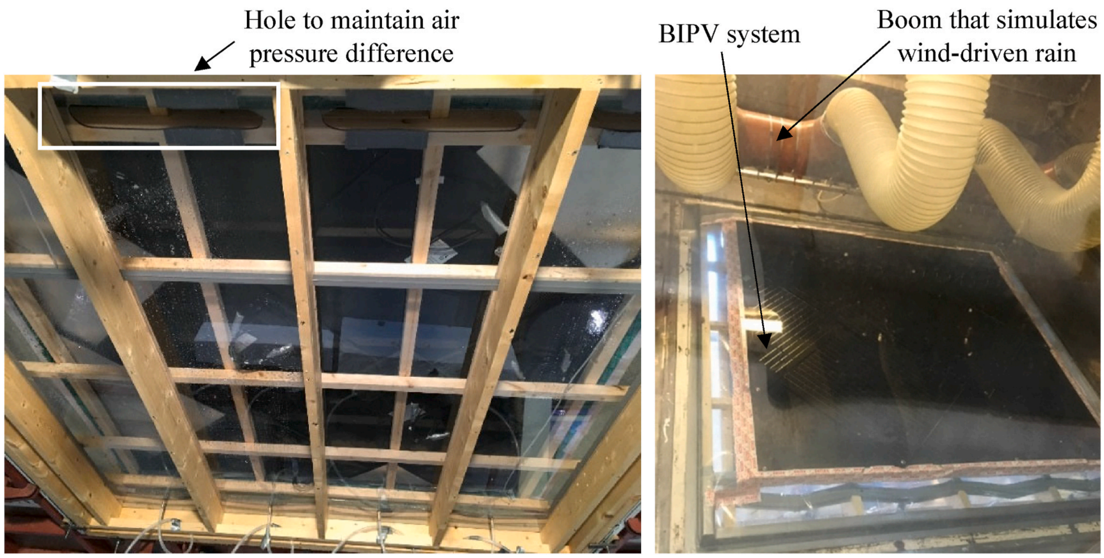


Fig. 10. The BIPV system during trial runs viewed from the outside (left) and inside (right) of the RAWI box. Study 3 (Table 3).

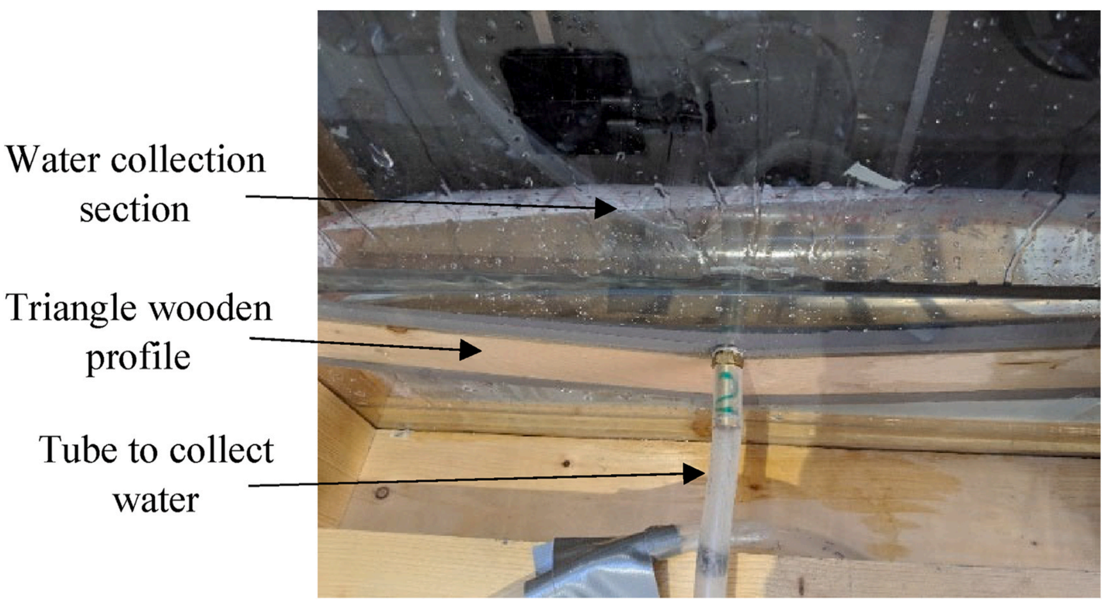


Fig. 11. The water collection sections viewed from the back side of the BIPV system. Study 3 (Table 3).

complete the system. Water leakages occurred mostly at points where the metal plates overlapped the BIPV modules. Even though the metal plates were only partially placed on water collection section 3 and mostly on section 4, most water leakages were collected in section 3. The amount of water collected from sections 4, 2, and 1 at the 30° inclination did not exceed 500 g, which is very low, considering that air pressure levels up to hurricane weather conditions were applied. During the mounting of this BIPV system, it was observed that the system would be very watertight as modules of the system were screwed to each other tightly, and various rubber sealant elements were used.

WDR test is quite a usual way to assess design quality of roof coverings. However, only after quantification of the water leakages, an actual watertightness of the system can be identified, thus enabling quantified comparisons with other systems. Conventional roof elements do not usually use sealant elements but are designed with openings for water drainage. Therefore, the watertightness level of traditional roof systems is expected to be significantly lower than roof systems with sealant elements. It might be beneficial to test more roof systems using quantification of water leakages to collect data on how the design of roof system is correlated with the system watertightness.

3.2. Comparison of the present methodology and previous methodologies

The present test methodology and methodologies from Study 1 and 2 are summarized in Table 3. The main distinctions of Study 3 can be highlighted as follow:

- Water intrusion quantification using the underlayment was implemented.
- Holes of optimal size that were cut in the underlayment were found.
- Layering of sealing tapes was used to cover areas around the BIPV systems.
- Time between test phases was shortened.

The main aim of Study 3 was to implement quantification of water intrusion during WDR testing in the RAWI box. This aim was

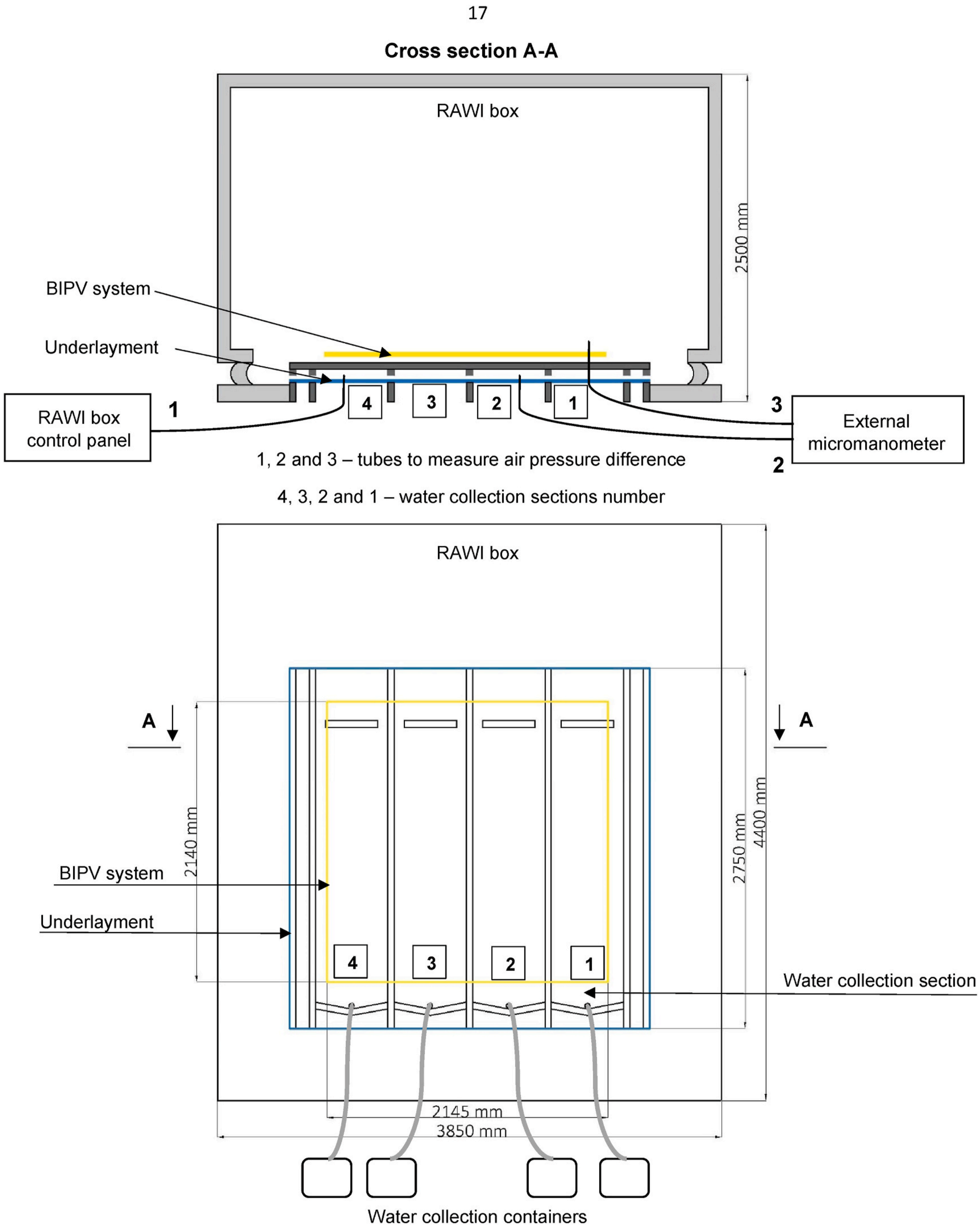


Fig. 12. Schematic drawing of raintightness test setup with four water collecting sections connected by tubes to four containers where the leakage water was collected. Additionally, a set of 3 tubes was used to measure air pressure difference. Tube 1 for measuring the differential air pressure by the RAWI box, and tubes 2 and 3 for measuring the differential air pressure connected to the external micromanometer. Study 3 (Table 3). Dimensions of the water collection system are given in Fig. 3. Upper sketch depicts a cross section top view of the RAWI box, whereas the lower sketch shows the front face of the RAWI box (see e.g. right photo in Fig. 1 and left photo in Fig. 13 for front face of the RAWI box with additional details).

successfully achieved. The underlayment was used as a part of the water collection system, the optimal size of holes was found, and water was collected during WDR experiments. While Study 1 also used underlayment, it was found difficult to find the right size of holes to cut in it so the differential air pressure could be applied to the tested BIPV system and maintain the desired level of air pressure. Even though air pressure intervals of the same magnitude as in Study 3 were applied in Study 1, differential air pressure was applied to the underlayment and not to the tested BIPV system. Qualitative data on placement of water intrusion obtained in Study 1 may differ from data that can be obtained if the same system is tested according to the test methodology from Study 3. Therefore, data from Study 1 cannot be compared to data from Study 3. Data obtained in Study 2 also cannot be compared to data from Study 3. No underlayment was used in Study 2 and air pressure intervals of a lower range were used. Therefore, qualitative data on placement of water intrusion obtained in Study 2 (a and b) may differ from data that can be obtained if the same systems are tested according to the test methodology from Study 3. In conclusion, qualitative data from Study 1 and Study 2 cannot be compared to qualitative data from Study 3. However, testing methodologies can be compared (Table 3) and this

Fig. 13. Raintightness test setup in the laboratory. The set of 3 tubes to measure air pressure difference are marked. Tube 1 for measuring the differential air pressure by the RAWI box, and tubes 2 and 3 for measuring the differential air pressure connected to the external micromanometer. Study 3 (Table 3).

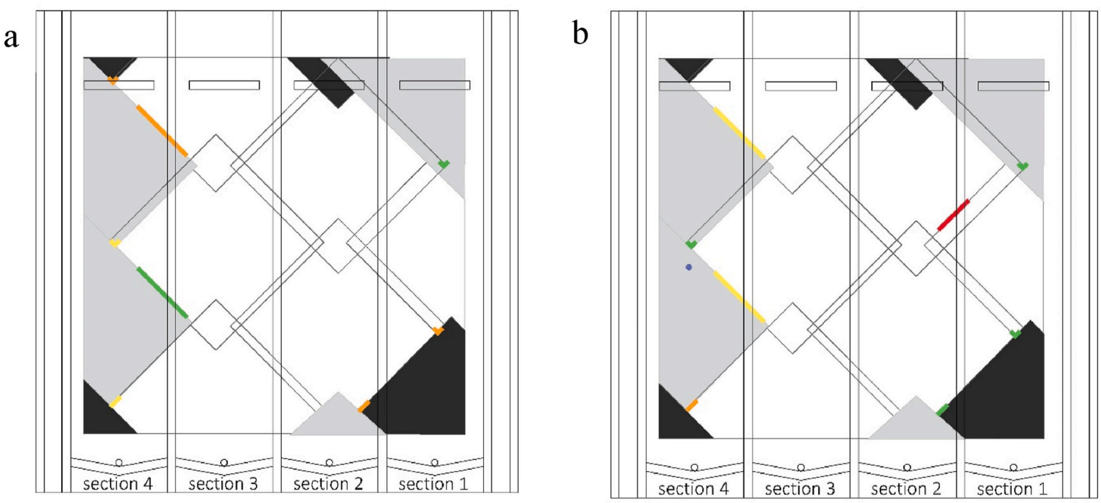


Fig. 14. Location of water leakage points for the BIPV system Study 3 with corresponding colours as given in Table 2. (a) First test phase (inclination 30°); (b) second test phase (inclination 15°). View from the backside of the BIPV system. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

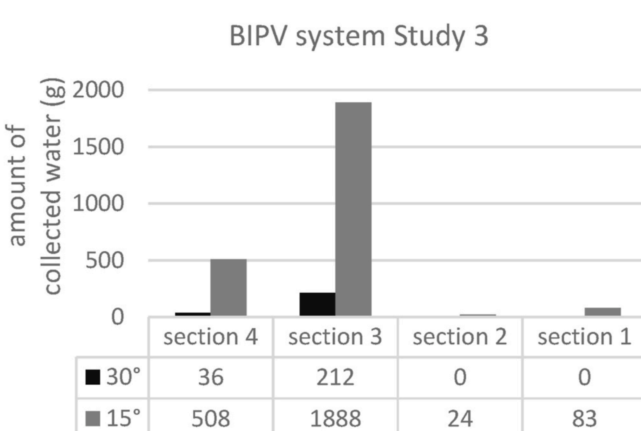


Fig. 15. The results of water collection from testing of BIPV system Study 3.

comparison helped to improve the present methodology. It must be noted that in the present study the preparation time before the test and trial testing took a considerable amount of time. Taping a large area with sealing tapes was challenging, and the tape had to be fixed multiple times during trial tests. Then once the tape was fixed, the test procedure was straightforward.

4. Conclusions

The wind-driven rain (WDR) research field is complex and broad. It spreads from a micro-scale, covering the investigation of WDR exposure itself, its intensity, field measurements, etc. to a macro scale, when the subject of study explores how WDR affects the building envelope systems or the whole building. The present study focused on development and evaluation of a test methodology for assessing building-integrated photovoltaic (BIPV) systems ability to withstand WDR. The main novelty of the methodology is quantification of water intrusion collected during testing.

Critical aspects of the present methodology can be summarized as follow.

1) An underlayment must be used to enable water collection and replicate conditions of a real roof installation when an air cushion accumulates in the ventilated air gap behind the elements and makes the roof system more watertight. Four holes each with a size 5 cm × 40 cm for a test area of 2.75 m × 2.75 m were enough to reach the desired air pressure load levels. These holes are also needed so that the air pressure difference will be applied to the test system. If no

wholes are cut in the underlayment, the air pressure difference is applied to the underlayment. The underlayment is also a vital part of the water collection system.
2) To collect water from underneath the tested systems, edges around each system must be sealed. For that matter, a range of waterproof sealant tapes can be used.
3) The water collection system can be constructed using sections formed by wooden battens of the under-roof structure. At the bottom of each section, simple triangle profiles can be built for a more accessible water collection.
4) During the test, it is advised to measure the air pressure difference under the test system. Measurements applying an external micromanometer can be used to ensure that the air pressure distribution is even across the system. Two tubes connected to the micromanometer may be used when one is placed on top of the system, and the other one thoroughly moved under the system.
5) The test system areas should preferably be of the same size, and/or with a representative joint length amount, so that the water collection results could easily be compared.

The present test methodology may be further improved by implementation of automatic measurement of the amount of water leakages that can be applied at each level of air pressure. Then the duration of application of each air pressure load level (the duration of a single test step in the sub-test) may be shortened down from 10 min to 5min, i.e. so that water leakage measurements can be compared to a reference leakage rate of (10 g/m^2)/5 min. More systems should be tested according to the presented methodology, BIPV systems, and conventional roof systems. When choosing an outline of systems to test it should be of the same size so the WDR exposure will be applied to the same area.

Test parameters used in this study are standard for the WDR test. Ideally, parameters should be calculated from information on driving rain intensities, wind pressure rates, water droplet sizes that are likely to occur for climate conditions at a specific location where the tested systems will be installed and used. Suppose several systems of the same specimen size will be tested according to this methodology. In that case, it will be possible to collect and create a database of the tested systems' watertightness level and forthcoming ones. This information can be useful for both the BIPV market and the scientific community, and roof and facade products in general. Firstly, as the methodology can be used by certificating institutions giving quality assurance for products available on the market. Secondly, such data may provide some directions for manufacturers and designers developing the products. Then these systems could become more accessible for customers and resellers to choose better-suited systems for a particular location. Simultaneously, data from performance-based tests may be used for computer simulations and future system upgrades and developments.

Declaration of competing interest

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

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