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Wind-driven rain tightness of building-integrated photovoltaics panels

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Wind-driven rain tightness of building-integrated photovoltaics panels

R Moschetti, L Gullbrekken, SK Asphaug
SINTEF Community, Department of Architecture, Materials and Structures, Trondheim, Norway

Email: lars.gullbrekken@sintef.no

Abstract. The exposure to wind-driven rain (WDR) is a key factor impacting the performance and the durability of the building envelope. Building-integrated photovoltaic (BIPV) panels are increasingly used as roofing and façade materials, but little information is available on their weather protection performance. Although WDR exposure has been qualitatively investigated in laboratories, only few studies have directly quantified the water intrusion through BIPV. This article presents the results from a WDR laboratory test of a BIPV product, where water intrusion was both qualitatively and quantitatively investigated. Furthermore, as roof integration is the primary function of the studied BIPV panels, the results from the same test performed on another traditional roofing material, i.e., concrete tiles, are described and discussed. The test results showed that the BIPV panels performed better as façade cladding than as roofing material, since no quantifiable water leakages were detected at 90° inclination. At 15° and 30° inclinations, the total water leakages through the BIPV system were around 90% lower than those of the concrete tile roofing. This article's findings demonstrate that the quantification of water intrusion through BIPV panels is feasible and can provide significant information for further developing and improving the design of BIPV systems as climate screens.

1. Introduction

The building envelope has the primary function of shielding the indoor environment from weather exposure, such as from rain, wind, hail, and snow. All kinds of precipitation can significantly affect the hygrothermal performance and durability of the building envelope, particularly when occurring simultaneously. For instance, wind-driven rain (WDR), also known as driving rain, originates from the joint occurrence of rain and wind that generates an oblique rain fall [1]. The watertightness of building envelope components can be examined through both laboratory tests and long-term outdoor climate exposure. However, outdoor field testing may lead to a more significant use of resources, especially timewise, compared to laboratory testing. Therefore, the latter is currently more widespread [2]. Although watertightness testing might provide important information to assess and compare the performance of different products, it is currently only voluntary and is not a requirement for product selling on market. Such testing is not included in the construction products regulation No 305/2011 [3], which specifies standardized rules for construction products in the European Union.

Among the available roofing and façade materials, building-integrated photovoltaic (BIPV) panels have lately gained increasing attention. BIPV panels are designed for integration into the building envelope, along or instead of conventional components, and must fulfil the weather screen function in addition to their primary objective of locally generating electricity [4]. However, BIPV systems are not frequently assessed as components integrated in the building envelope and related requirements are still in an early stage in the building industry. For instance, the European standard EN 50583-2 “Photovoltaics in buildings. Part 2: BIPV systems” [5] refers to PV systems intended for roof integration in the annex A: “Resistance to wind-driven rain of BIPV roof coverings with discontinuously laid elements – test method”.

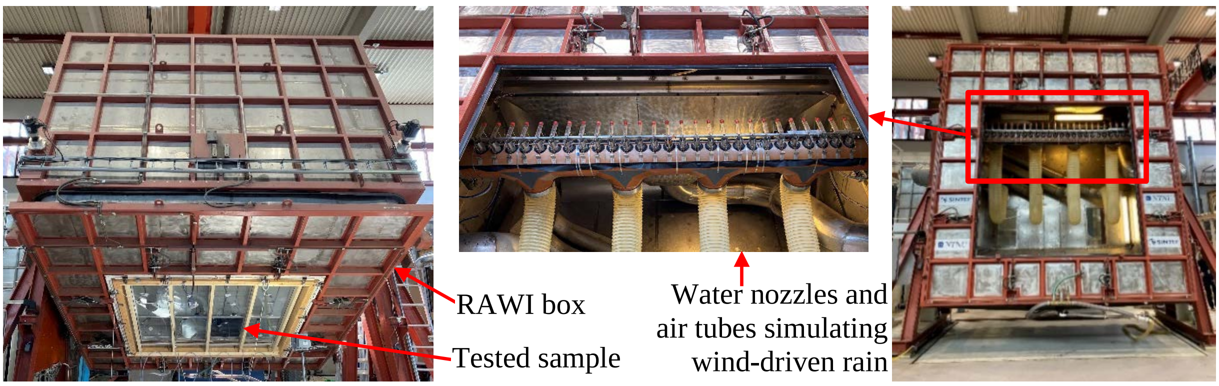
WDR exposure tests in laboratory have recently become common, especially as qualitative investigations of the watertightness level of building envelope. However, little quantitative information is available on the water intrusion through building envelope components, including BIPV systems [6]. Arce-Recatala et al. [7] examined the weathertightness of different types of rear-ventilated façades, by quantifying WDR intrusion into the air cavity and the amount of water reaching the underlying water barrier. Fasana and Nelva [8] carried out a WDR test in a wind tunnel on stone roofs made of gneiss slates, to qualitatively assess the elements' watertightness. Fasana and Nelva [9] carried out WDR experimental tests to study the integration of photovoltaic panels on a roof with clay and concrete tiles, and they qualitatively assessed the water resistance of the critical area of the fitting system. Breivik et al. [10] performed WDR tests on two BIPV modules integrated in the roof, to visually investigate their rain tightness and to examine how they would withstand water intrusion at large-scale conditions. Fedorova et al. [2] [6] focused on the development and evaluation of a testing methodology for quantifying the WDR exposure of PV systems integrated in roof and facade. They also show the results from the application of the developed methodology on specific BIPV systems designed for roof integration.

The main aim of this article is to present the results from a WDR laboratory test of a BIPV product, where water intrusion was investigated. Moreover, as roof integration is the primary function of the studied BIPV panels, the results from the same test on another traditional roofing material, i.e., concrete tiles, are also described and discussed. The scientific novelty of this work lies in the description of the WDR test findings, from both a qualitative and a quantitative point of view. This is significant in the current literature, where the water intrusion through building envelope materials has mainly been qualitatively assessed. Therefore, the article presents a methodology for performing such a test, together with quantitative results that can be used to benchmark BIPV's rain tightness. Furthermore, by also presenting the test results on concrete tiles, this study allows the comparison of the rain tightness of different building envelope solutions, which was seldom performed in the past.

2. Methods

2.1 Test method

The WDR laboratory test described in this article was performed in accordance with NT Build 421 Roofs: Watertightness under pulsating air pressure [11], but with some adjustments/modifications, based on [2].



(a) (b) (c)

Figure 1 Large scale box for rain and wind tightness testing of building surfaces with various inclinations (RAWI box). (a) Inclined apparatus during a test running. (b) Detail of the raw of nozzles spraying water and air tubes blowing air stream on the test sample. (c) View of the apparatus interior.

The apparatus used for the tests is a large-scale rotatable rain and wind (RAWI) box, as shown in figure 1. The RAWI box is a chamber with an opening where the sample can be applied and tilted to the desired slope, between 0° and 95° from the horizontal plane. In the RAWI box, run-off water and water spray are applied simultaneously to the test sample under pulsating air pressure on different load levels, as shown in table 1. Run-off water is applied by a horizontal row of nozzles spraying water evenly above the top of the test sample at a constant rate of 1.7 L/(m x min). Water spray is applied over the whole exterior surface of the sample by a bar with nozzles moving up and down along the test sample at a velocity of 0.2 m/s and spraying water at a rate 0.3 L/(m^2 x min), while an air stream is blown by air tubes, at controlled air pressure levels. The total amount of water applied on the samples at each load level for 10 minutes is ca. 41 L at level 0 and ca. 58 L at all the other levels.
Two main tests were run in the RAWI box for the tested systems:
1. Only run-off water without applying any air pressure (load level 0 in table 1).
2. Run-off water and water spray under pulsating air pressure applied to the façade/roofing system (load levels 1-8 in table 1).

Table 1 Load levels and corresponding pulsating air pressure intervals used during the WDR test.

Load Level	Pulsating air pressure intervals	Maximum wind speed	Weather condition	Duration (min)
0	0	0	-	10
1	0 – 100	12.9	Strong breeze	10
2	0 – 200	18.2	Fresh gale	10
3	0 – 300	22.3	Strong gale	10
4	0 – 400	25.8	Storm	10
5	0 – 500	28.8	Violent storm	10
6	0 – 550[a)]	30.2	Violent storm	10
7	0 – 600	31.6	Violent storm	10
8	0 – 750[a)]	35.3	Hurricane	10

[a)] Additional air pressure intervals to those suggested in NT Build 421.

2.2 Frame and water collection system
A metal surround fitted to the opening of the RAWI box was used as a basis for the test samples. A timber frame made of beams/studs (with cross section of 148 mm x 48 mm), with a centre-to-centre (c/c) distance of 600 mm, was built into the metal surround. A transparent polycarbonate board was mounted on the beams/studs, to represent the roofing underlayment in a roof construction or the exterior air and water barrier in a wall construction. Vertical wooden battens, with a cross section of 30 mm x 48 mm and a c/c distance of 600 mm, were mounted on the underlayment, together with horizontal wooden battens. Then, the BIPV panels were installed with a c/c distance of 371 mm, while the concrete tiles were mounted with a c/c distance of 310 mm. The final system consisted of four equally sized vertical sections between the wooden beams/studs. For the quantification of water leakages through the test samples, a water collection system was built at the bottom of the underlayment. A hole was cut at the bottom of each section and a hose nipple with a tube was connected to each hole. An aluminum water channel was installed in connection to each hole to lead any possible leakage water to the holes through the tubes, into containers placed outside the RAWI box. The water collection system is shown in figure 2, with the aluminum channels on the underlayment and the containers and tubes outside the apparatus. For the BIPV system, an additional water collection system was installed backside the four panels constituting the lower row on the frame This allowed to collect leakage water that may flow on the rear side of the BIPV panels when testing at 90° inclination. This system consisted of a V-shaped aluminum water channel leading any possible

water leakage dripping on the back of all eight panels to tubes and then into containers placed outside the RAWI box.

(a) (b) (c)

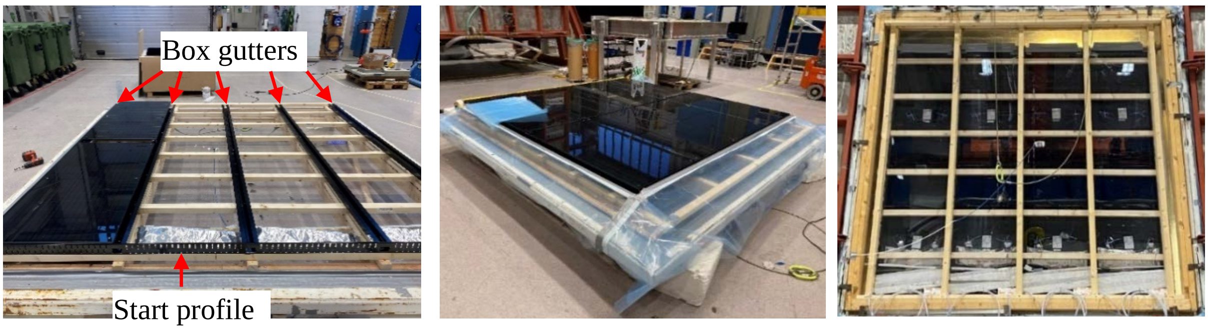
Figure 2 (a) Metal surround with timber frame and transparent underlayment board, horizontal and vertical battens and aluminium channels for water collection. (b) Water containers and tubes outside the apparatus. (c) Additional water collection system on the backside of the BIPV panels.

In order to apply the desired pressure across the test samples, four 50×400 mm rectangular holes (one in each of the four vertical sections) were cut in the upper part of the underlayment. To measure the pressure difference across the systems, a pressure nipple with a tube was installed in the middle of the test area (on the underlayment). Note that the current study was performed with full pressure drop over the tested systems, both as façade cladding and as roofing component. This is conservative and should also be taken into account when assessing the amount of water penetrating the systems.

2.3 Test samples

2.3.1 BIPV system

The analysed BIPV system consisted of eight PV panels, 1 aluminium start profile, 5 box gutter profiles, and a sealant. The start profile had five main openings, ensuring water drainage from the box gutters, together with numerous small openings between them. First, the start profile was fastened on the first horizontal batten at the bottom of the frame, where the water collection system was located. Then, the 5 box gutter profiles were placed and screwed on the horizontal wooden battens in correspondence with each vertical batten. Afterwards, the PV panels were fit into the box gutters one by one and screwed through their side aluminium profiles on the wooden battens. The four lower panels placed at the water collection system on the underlayment had an integrated aluminium profile where the upper four panels were fastened and then sealed with the provided sealant. After the installation of the BIPV panels, the perimeter around the test area was covered with a 0.15 mm thick polyethylene (PE) foil, fastened to the panels through double-sided tape and duct tape. See figure 3.

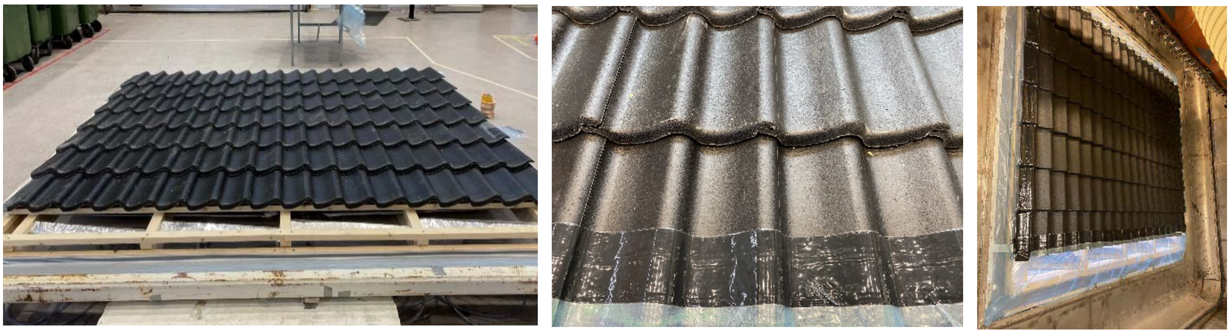


(a) (b) (c)

Figure 3 (a) Base frame with horizontal and vertical wooden battens, start profile, box gutters, and two mounted PV panels. (b) BIPV test sample with the PE foil around the frame. (c) BIPV test sample fitted into the RAWI box.

2.3.2 Concrete tile roofing

The second test sample was prepared with concrete tiles, as shown in figure 4. The test area consisted of seven rows of tiles, which were mounted following the installation manual and were fastened using recommended screws. After the installation of the roofing, the perimeter around the test area was covered with a 0.15 mm thick polyethylene foil (PE foil), fastened to the roofing through double-sided tape, joint filler, duct tape, and bitumen sealing tape.



(a) (b) (c)

Figure 4 (a) Concrete tile test sample. (b) Bitumen sealing tape used to further secure the joint between the plastic foil and the tiles. (c) Concrete tiles test sample, with the PE foil around the frame, viewed from inside the RAWI box.

2.4 Test setups and procedure

The surround of the test sample was fitted in the opening of the RAWI box and the apparatus was tilted to the desired slope. Run-off water and water spray under pulsating air pressure were applied simultaneously to the sample under the load levels presented in table 1. During the test, the sample was inspected for water leakages to identify the specific points where leakages occurred at the different pressure levels.

3. Results and discussion

The results of the laboratory tests are given both in form of quantitative amount of water collected and in form of qualitative observations of the water leakages.

3.1 BIPV panels

Figure 5 illustrates the amount of water collected at each load level applied to the BIPV panels. Note that the amounts given in figure 5 for each level are approximate. For instance, the water collected at 400 Pa for the test at 15° and at 500 Pa for the test at 30° also include minor water amounts collected at lower load levels. The test results show that the BIPV panels performed better as façade cladding than as roofing material, since no quantifiable water leakages were detected at 90° inclination. Water leakages were instead quantifiable at 15° and 30° inclinations, where the collected water at 30° was about 10% lower than that at 15°. Note that the amount of water collected in 10 minutes at the tested load levels corresponded to up to 1.7% at 15° inclination and 2% at 30° inclination, with respect to the total amount of run-off water and water spray employed on the test samples. This confirmed the relatively low water leakage rate through the tested BIPV panels.

Table 2 summarizes a qualitative assessment of the observed leakages during the tests. Most of the leakage positions registered during all tests were observed in the vertical joints between box gutters and PV panels. Note that the water may flow in these joints for a certain distance before becoming visible as droplets and dripping down to the underlayment. Furthermore, no quantifiable water was collected during the tests at 90° inclination also because some small amounts of water flowed down in the joints between the panels and the box gutters or on the side of the gutters without dripping onto the underlayment, where it could be quantified. This was also the case for some of the leakage water during the tests at 15° and 30° inclination.

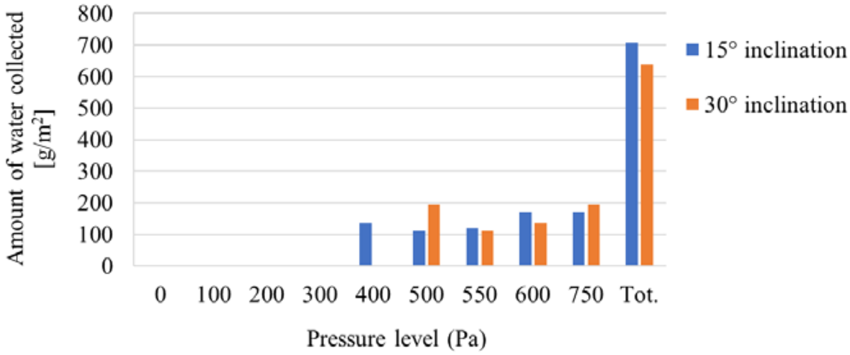


Figure 5 Quantitative measurement of water collected in all sections at the analysed pressure levels applied to the BIPV panels.

Table 2 Qualitative observations of water leakages in the BIPV test.

Pressure difference (Pa)	15° inclination	30° inclination	90° inclination
0	No leakages.	No leakages.	No leakages.
0 – 100	Droplets in vertical joints between box gutters and panels and in cross sections between horizontal and vertical joints.	Droplets in vertical joints between two box gutters adjacent to one of the panels.	Droplets in one of the vertical joints between a box gutter and a panel.
0 – 200	New leakage positions in vertical joints and cross sections.	New leakage positions in several vertical joints. Droplets observed in cross sections between horizontal and vertical joints.	New leakage positions in vertical joints between two box gutters and a panel.
0 – 300	Additional leakage positions in vertical joints.	New leakage positions in vertical joints.	New leakage position in a vertical joint between one box gutter and one of the panels.
0 – 400	Same as above.	New leakage positions in vertical joints and cross sections.	Additional leakage positions in several vertical joints.
0 – 500	Same as above.	New leakage positions in vertical joints.	Same as above.
0 – 550	New leakage positions in vertical joints and increased leakage intensity in existing positions.	New leakage positions in vertical joints and increased leakage intensity in existing positions.	New leakage positions in vertical joints and increased leakage intensity in existing positions.
0 – 600	Same as above.	Same as above.	Same as above.
0 – 750	Same as above.	Same as above.	Same as above.

3.2 Concrete tiles

Figure 6 shows the total amount of water collected during the tests on the concrete tiles, while table 3 summarizes qualitative observations of leakages.

Water leakages were quantifiable both at 15° and 30° inclinations, and the collected water at 30° was about 40% lower than that at 15°. The quantified water leakages were up to 20% at 15° inclination and 15% at 30° inclination of the total amount of run-off water and water spray employed on the test samples.

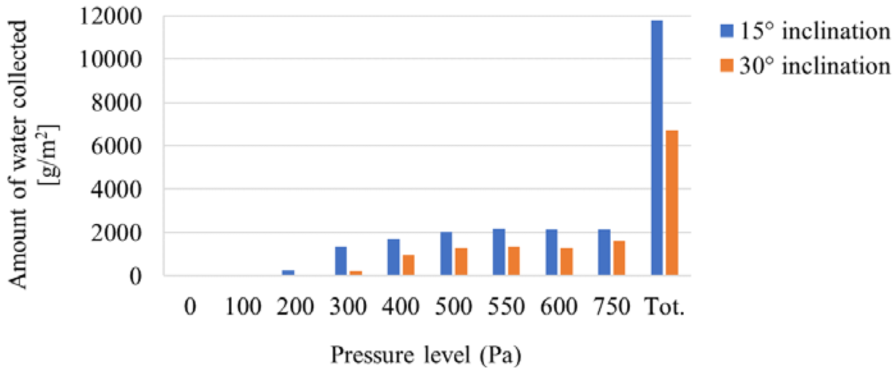


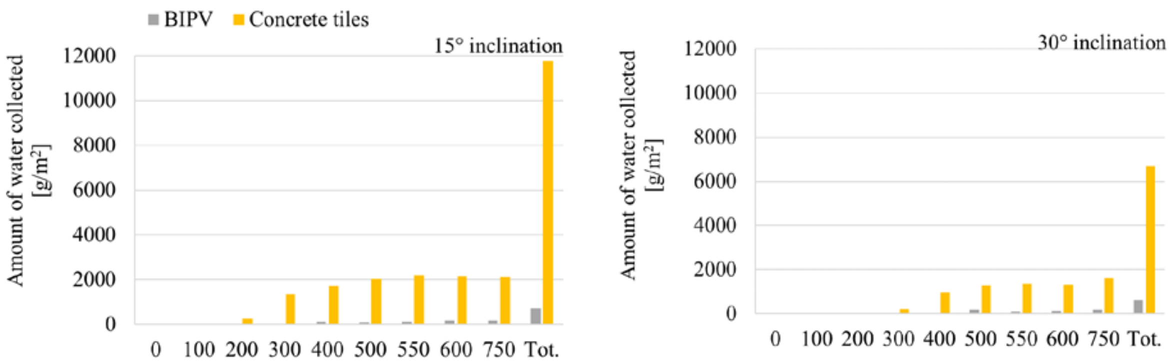
Figure 6 Quantitative measurement of water collected in all sections at the analysed pressure levels applied to the concrete tiles.

Table 3 Qualitative observations of water leakages in the concrete tile roofing test.

Pressure difference (Pa)	15° inclination	30° inclination
0	No leakages.	No leakages.
0 – 100	Several leakages in X-joints between 4 stones.	Some droplets in vertical joints.
0 – 200	Increased leakages in some positions. New leakages observed in horizontal joints between 2 stones.	Several leakages in X-joints between 4 stones, especially in the top and bottom of the sections.
0 – 300	New leakages in horizontal joints.	New leakages in horizontal joints, especially in the middle of the sections.
0 – 400	Same as above.	New leakages in horizontal joints. Increased leakages, especially in positions in the top and bottom of the sections.
0 – 500	Same as above.	New leakages in horizontal joints.
0 – 550	Same as above.	Same as above.
0 – 600	Same as above.	Same as above.
0 – 750	No new leakages observed.	No new leakages observed.

3.3 Comparison between the BIPV system and the concrete tiles

Figure 7 shows a comparison of the total water amount collected, at 15° and 30 inclinations, for BIPV panels and concrete tiles. The total measured water through the BIPV system was evidently lower than that through the concrete tiles. Specifically, the collected water for the BIPV panels at the two analysed inclinations was about 90% lower than that for the concrete tile roofing.



(a) (b)

Figure 7 Quantitative measurement of water collected during tests at 15° (a) and 30° (b) for BIPV panels and concrete tiles.

3.4 Comparison between the BIPV systems in this article and in previous studies

A comparison with the results from previous similar studies was not straightforward due to different assumptions and test sample structure. Therefore, we compared our results with those for the BIPV systems from [6], where the same apparatus and test conditions were employed. See table 4.

Table 4 Total water amount through the BIPV system of this study and three BIPV systems in [6].

	15° inclination				30° inclination			
	BIPV in this study	BIPV 1 in [6]	BIPV 2 in [6]	BIPV 3 in [6]	BIPV in this study	BIPV 1 in [6]	BIPV 2 in [6]	BIPV 3 in [6]
Amount of water (g/m^2)	706	1722	54718	13424	638	54	58541	10542

The results' comparison showed that the BIPV panels analysed in this study performed significantly better than BIPV 2 and BIPV 3 examined in [6] at 15° and 30° inclinations, with water leakages up to 98% lower. However, BIPV 1 from [6] showed better results than those of the BIPV from our study, especially at 30° inclination, where the water leakages were ca. 10 times lower.

4. Conclusions

This article described the findings from a wind-driven rain (WDR) laboratory test of a building integrated photovoltaic (BIPV) product, where water intrusion was both qualitatively and quantitatively investigated. Furthermore, the findings from the same test performed on another roofing material, i.e., concrete tiles, were described and discussed to allow results' comparability. This article's scientific novelty is based on the presentation of quantitative WDR test results, as mainly qualitative findings are available in the current literature. The latter also lacks comparative studies on the rain tightness of different building envelope solutions, which was provided in this article.

The test results showed that the BIPV panels performed better as façade cladding than as roofing material, since no quantifiable water leakages were detected at 90° inclination. At 15° and 30° inclinations, water intrusion was instead quantifiable, but the total water leakages through the BIPV system were around 90% lower than those of the concrete tile roofing. The BIPV panels showed a relatively low water leakage rate, with an amount of water collected in 10 minutes at the tested load levels up to 2% of the total amount of run-off water and water spray employed on the test samples.

The findings from this paper demonstrate that the quantification of water intrusion through BIPV panels is feasible and can provide significant information for further developing and improving the design of BIPV systems as climate screens. Future work could include the testing of more BIPV panels with the same methodology and test conditions. This would allow defining a database of the watertightness level of several BIPV systems, which could be useful for both the actors involved in the BIPV market and the scientific community.

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