Large-Scale Laboratory Investigation of Building Integrated Photovoltaics – A Review of Methods and Opportunities

Anna Fedorova [a*], Bjørn Petter Jelle [ab], Erlend Andenæs [a], Anne Gerd Imenes [cd], Ole Aunrønning [a], Christian Schlemminger [b] and Stig Geving [a]

[a] Norwegian University of Science and Technology (NTNU), Department of Civil and Transport Engineering, 7A Høgskoleringen Str., NO-7491 Trondheim, Norway.
[b] SINTEF Building and Infrastructure, Department of Materials and Structures, NO-7465 Trondheim, Norway.
[c] Teknova AS, Smart Instrumentation Group, NO-4630 Kristiansand, Norway.
[d] University of Agder (UiA), Department of Engineering Sciences, NO-4879 Grimstad, Norway.

Abstract: The world's attention towards energy-efficient and zero emission buildings is increasing, where one key aspect among others is to utilize non-polluting and renewable energy sources. Building integrated photovoltaics (BIPV) represent an interesting solution both for existing and new buildings. For the development of new BIPV products, it is important to address the properties, requirements and possibilities of both the solar cell and building envelope for BIPV. The work presented herein focuses on large-scale laboratory investigations of BIPV with the aim to identify methods and opportunities for future design of improved BIPV systems. This work will summarize concepts, principles, existing standards and apparatuses which can be used in large-scale laboratory investigations of existing and developing BIPV products, with particular emphasis on wind-driven rain exposure and water tightness.

The main and long-term aim of this study is to determine precisely the methods for testing existing BIPV systems, especially with respect to wind-driving rain exposure, and also in general for other outdoor weather strains. Furthermore, robustness and durability issues will also be important to address. Finally, part of the general outcome may also be innovative and totally new BIPV systems, and how to test and characterize these.

Keywords: Building integrated photovoltaics, BIPV, Standards, Solar cell, Accelerated testing, Laboratory tests, Wind-driven rain, Rain tightness, Water leakage.

1. Introduction

According to the data from United Nations Environmental Programme (UNEP) up to 40% of global energy is consumed by buildings and they emit approximately 1/3 of greenhouse gas (GHG) emissions (United Nations Environment Programme, 2009). Due to an expected population increase of 2.5 billion people by 2050 and continuation of its growth in the future the energy system will experience additional pressure (IEC, 2016). With growing energy need, and as energy production nowadays is primarily based on fossil fuels (United Nations Environment Programme, 2009), that release GHG emissions, level of emissions will steadily continue to grow unless severe action is taken. The issue of GHG emission is one of the most significant our society faces and there is a need of finding solutions to cope with it. Among other possible ways, GHG emission mitigation could be achieved by applying energy efficiency approaches and using renewable energy sources (United Nations Environment Programme, 2009). In this regard, the concepts of zero energy (Peterson et al., 2015) and zero emission buildings have been established. According to the European directive on energy performance of buildings, by the end of the year 2020 all new buildings should be "nearly zero energy buildings" (European Parliament, 2010). A promising on-site renewable source of energy is solar energy, and particularly photovoltaics, as it both provides direct production of electricity and can be integrated in the building envelope. This technology is an essential future source of

* Corresponding author.
E-mail: anna.fedorova@ntnu.no

clean and affordable energy (Bonomo et al., 2015) and has its benefits when applying in the building sector.

The concept of building integrated photovoltaics (BIPV) is integration of photovoltaics (PV) into the building envelope skin. The BIPV systems simultaneously serve the dual function of a climate screen and electricity power generator (Jelle, 2015). The cost effectiveness of BIPV is still lower compared to the most conventional roofing materials, as well as to the cost of BAPV systems, but is already cost competitive (Ly et al., 2013). Moreover, taking into account expected reduction in BIPV price and avoidance of the cost of conventional materials, integration of photovoltaics may reduce overall material costs and improve life-cycle cost.

The BIPV is a relatively new and developing market. The existing PV and BIPV standards do not sufficiently take into account long term durability quality and performance of the systems (PVSITES, 2016), especially in severe climate exposures. Hence, European standards need to be adopted for special climate conditions and weather loads. The development of new specific standards and reference codes (Bonomo et al., 2015) are currently being considered by Task 15 in the International Energy Agency Photovoltaic Power Systems Programme (International Energy Agency - PVPS, 2016).

Manufacturers have a various range of interesting and customized BIPV products and solutions for integration into the building sector. Despite this fact, the adaptation and application of BIPV are still slow (Bonomo et al., 2015). One challenge of using BIPV as a source of energy supply is how long it will be able to serve the building energy needs while at the same time sufficiently protecting the inner structure of a building. Another challenge is how to accurately predict and achieve prolonged service life of BIPV products. This may be obtained by performance data from large-scale tests in laboratories and then development of durable and robust product solutions. Large-scale laboratory tests are here defined as investigation of BIPV products by using climate simulation equipment. Tests for PV integrated into building structures samples with application of harsh climate exposures will hopefully lead to development of robust BIPV systems. BIPV must be reliable and serve their functionality with minimization of dismantling and maintenance, ideally not only for the typical guaranteed PV product service life of about 25 years, but for a longer periods of 35-50 years building service life (Yan, 2015).

This study will summarize concepts, principles, existing standards and apparatuses which can be used in large-scale laboratory investigations of existing and developing BIPV products with particular emphasis on wind-driven rain exposure and water tightness. Examples of laboratory and outdoor accelerated testing are given and discussed.

2. Natural and laboratory testing

Being a component of the building envelope, BIPV products must protect the inner building structure and withstand various climate exposures. To ensure quality and durability of materials, miscellaneous tests should be performed. The testing is usually carried out by using either outdoor weathering tests or indoor accelerated laboratory tests (Crewdson, 2008).

2.1 Natural testing

During its operational lifetime a BIPV product will be exposed to a large number of climate strains, which can be divided into the following climate exposure factors (Jelle, 2012):

- Solar radiation, including ultraviolet (UV) radiation.
- Ambient infrared (IR) heat radiation.
- High and low temperatures.
- Temperature changes/cycles.
- Moisture ingress, relative air humidity, rain and wind-driven rain.
- Salt water.
- Physical strains, e.g. snow loads.
- Wind.
- Pollutions.
- Erosion.
- Corrosion.
- Abrasion.

For product tests, the most critical weathering exposures must be considered according to the specific characteristics of the end-use environment (Atlas Material Testing Solutions, n.d.). It is of major importance to ensure that selected BIPV products will endure the climate strains they will be exposed to during the building lifetime.

Climate exposure factors occur and affect building envelope materials in varying combinations. Also note that the total climate strain may be substantially larger than the added sum of the single exposure factors (Delgado, 2016; Jelle, 2012).

Some tests for building materials are conducted by natural outdoor ageing. Real weather conditions could not be simulated in a laboratory entirely covering all possible exposures and their interactions (Crewdson, 2008) and therefore real outdoor ageing should also be considered for the BIPV products testing. However, due to the long time frame of natural ageing tests, it is usually not practically feasible to obtain results from outdoor tests alone. To prove the BIPV products performance quality, a test period of up to 25 years would be required, as this is the manufacturers guaranteed period of the products' service life. To obtain test results in a faster way, products should be studied by accelerated climate ageing tests (Jelle, 2012).

2.2 Laboratory testing

To predict and prove the BIPV product quality under service conditions it is in practice necessary to rely on results from accelerated tests. These tests could have different purposes (Brown et al., 1995):

- Quality assurance.
- Product performance prediction.
- Comparison of different products performance.
- Data for product design development.

For quality assurance it is particularly important that test conditions are standardized and reproducible (Brown et al., 1995). If the purpose of accelerated testing is to prove product quality with regard to a given standard or specification, correlation of test and real life conditions is much reduced. However, if the purpose of the product testing is performance prediction or design development, then correlation between these conditions starts to be essential.

Accelerated tests may be divided in two groups, i.e. climatic tests and weathering tests, according to (Zielnik et al., 2015). The difference between the test methods is in the application of the weather stress conditions to the specimen and the time duration of the tests. During the climate ageing tests, stress conditions are applied simultaneously and during longer periods of time, while weathering tests apply stresses one by one or few at a time in relatively shorter periods. Schematically these test groups are presented in Fig.1 and Fig.2 (based on (Zielnik et al., 2015)).

Furthermore, a simple weathering test is normally not an ageing test. However, often one or a few exposures are used and then test can be called an (accelerated) ageing test.

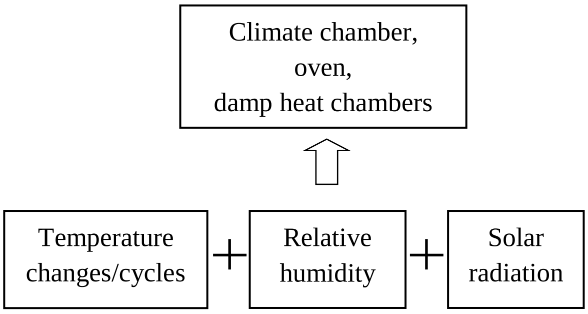

Fig. 1. Climate ageing test.

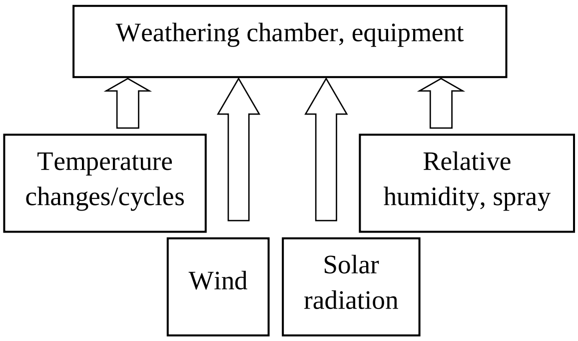

Fig. 2. Weathering ageing test.

No accelerated weathering test program could be defined as complete without correlation to the natural weathering (McGreer, 2001) and therefore the tests should be adapted to the real life conditions. It is of vital importance to simulate only processes that will take place during outdoor ageing. Additional stresses could cause changes or chemical reactions in the materials and components which will not occur in the real life (Jelle, 2012). In this regard, the following principles could be applied to the test design (Zielnik et al., 2015):

- Simultaneous application of weather factors to the specimens – to ensure synergistic and interaction effects.
- Include cyclic changes to test parameters – steady load parameters will neglect mechanical stresses.
- Maximum weathering stress levels should not be exceeded – in regard to not apply stresses which products would not be exposed to during their service life.
- The acceleration of a laboratory test should be limited in regard to avoid distortion of the degradation mechanisms.
- The light source used in laboratory should resemble global solar radiation as closely as possible in the ultraviolet (UV) and (VIS and NIR) wavelength regions.

- Use of simulation of the worst-case service use conditions – because most weather ageing processes are complex and usually not known in details. The focus should be on the real life stresses.

To achieve confidence in the accelerated tests, a comparison between identical specimens exposed to natural and accelerated tests could be used. For instance, surveillance testing (Hardcastle, n.d.) shows how accelerated results directly relate to natural exposures. For example, once a year manufacturers provide BIPV products samples and they will be placed at natural outdoor exposures facilities. Then evaluation of samples behaviour and correlation with laboratory investigation will be done. That will reveal accuracy of tests. This test provides the product life assurance.

For service life prediction and robust performance, a worst-case approach may also be applied. Increased levels of weathering variables such as solar irradiance, temperature and moisture will accelerate failures. Products being exposed to worst-case service use conditions will typically fail faster. By using this approach, the probability of satisfactory performance in environments with milder levels of critical weathering variables usually increases (Hardcastle, n.d.).

Due to the different weathering exposures and testing devices, methods of repeatability and reproducibility can also be adapted to the test design (Hardcastle, n.d.). These study methods are powerful tools to characterize weathering exposure variations., and are defined as (Brown et al., 1995):

- Test repeatability – design test procedure in a way that it will be able to produce the same result of a sample exposed to the climate strains in the same equipment.
- Test reproducibility – designed test procedure should produce the same result of a sample exposed in identical test equipment, each running the same accelerated test.

3. Accelerated ageing apparatuses

BIPV systems represent examples of new product solutions and for such new products it is crucial to prove good quality in terms of satisfactory performance along with demonstration of durability maintenance (Jelle, 2012) that can be compared to the existing building materials used in building envelopes.

To simulate various climate exposures and be able to test the BIPV products in laboratory with exposure to stress factors equal to the comparable building envelope component, different accelerated climate ageing apparatuses could be used. Some of these apparatuses will be discussed here. The BIPV products serve a dual function and therefore must satisfy two types of requirements: electrical and building-related (European Committee for Electrotechnical Standardization, 2016).

Manufacturers of PV modules provide values for the electrical characteristic of the module properties. These values are obtained according to standard test conditions (STC) or nominal operating cell temperature (NOCT) (Jelle and Breivik, 2012). To ensure that the BIPV element will perform satisfactory in terms of electrical behaviour, and not only withstand climate stresses, the tests for solar module properties have to be executed before, during and after the accelerated climate ageing (Jelle, 2013). The solar module tests are further discussed in Section 4.

3.1 Climate ageing test equipment

Testing the BIPV for resistance towards freezing and thawing cycles is especially important in a Nordic climate where frost weathering during winter may be extreme (Jelle, 2012). A unique and specially customized large-scale vertical building envelope climate simulator is depicted in Fig.3. A sample field is placed between the outdoor and indoor climate boxes. The outdoor climate box includes exterior weather exposures like solar radiation (metal halide global (MHG) lamps), water spray and external wind-pressure (e.g. wind-driven rain), and air temperature and humidity control including freezing/thawing cycles (Jelle, 2013). This apparatus is suitable for testing BIPV elements integrated into façades, especially with simulation of Nordic weather conditions.

Fig. 3. Specially customized large-scale vertical building envelope climate simulator consisting of a sample field installed between the exterior and interior climate chambers (Jelle, 2013).

Alongside with BIPV integrated into the façade, products designed for roof integration could be tested in specific apparatuses. A special non-commercial accelerated climate ageing apparatus is shown in Fig.4, which is a combined horizontal UV, temperature and water spray ageing apparatus. This horizontal ageing apparatus is typically applied for testing of roof products (Jelle, 2012).

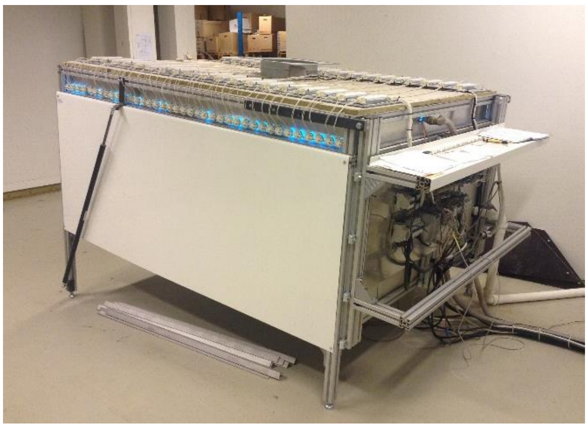

Fig. 4. Accelerated climate ageing of roof samples in a combined horizontal UV, temperature and water spray ageing apparatus.

3.2 Weathering test equipment

Water in various states will often cause degradation of the building materials and components (Jelle, 2012). Therefore, tests for the BIPV water tightness, for example wind-driven rain exposure test, should be performed.

The RAWI (rain and wind tightness) box (Fig.6) simulates wind-driven rain by cyclic air pressure and a set of nozzles that spray water on the mounted frame. The RAWI box allows stepless tilting between 0 and 95 degrees from the horizontal plane, controlled differential air pressure across the test specimen and running run-off water at the top of the test area. A horizontal boom (row) with water nozzles (Fig.5) is mounted on rails inside the box and moves back and forth (up and down) along the sample 0.6 m above the exterior roof surface spraying wind-driven rain at a constant rate (Breivik et al., 2013).

Fig. 5. The boom inside the RAWI box which delivers wind-driven rain across the sample area. The blue tubes on top (blue ellipse) supply water down to the transparent vertical cylinders (blue ellipse) where it hits the air stream that blows out of the air tubes (green arrow) and is blown onto the sample area (Breivik et al., 2013).

The nozzle boom sprays water and air onto the BIPV system, simulating gusts of wind and rain in addition to the pulsating pressure (Breivik et al., 2013).

Fig. 6. Large-scale turnable box for rain and wind tightness testing of sloping building surfaces (RAWI box) (Breivik et al., 2013).

All the shown equipment given in Figs. 3-5 are placed in the NTNU and SINTEF Building and infrastructure laboratory, Trondheim, Norway.

4. BIPV standards and requirements

Laboratory testing of BIPV products should be related to existing standards and codes. However, testing methodology may also be tailor-made for special climate conditions. All solar PV products must be approved by testing centers and laboratories according to current international standards. PV products designed specifically for building integration are still rare and no harmonized standards for actual testing of these products exist (PVSITES, 2016). The information provided by manufacturers is still not enough for BIPV to fully enter the building sector as they can only provide basic electrical performance data and standard module durability certification, while building technical requirements are still missing (Bonomo et al., 2015).

4.1 BIPV related standards

Work towards a specific BIPV standard (EN 50583:2012) is discussed by (Pellegrino et al., 2013). The standard defines a series of requirements for the BIPV element to satisfy building specifications. The actual standard EN 50583:2016 (European Committee for Electrotechnical Standardization, 2016), was released in January 2016. The International Code Council has established criteria for BIPV as a roofing material that dictates its performance in terms of stability, wind resistance, durability, and fire safety. Building product test requirements are set in the acceptance criteria AC 365 (ICC Evaluation Service, 2011).

Existing standards related to BIPV include:

- EN 50583-1 “Photovoltaics in buildings. Part 1: BIPV modules” (European Committee for Electrotechnical Standardization, 2016), EN 50583-2 “Photovoltaics in buildings. Part 2: BIPV systems”.
- AC 365 “Acceptance criteria for building-integrated photovoltaic (BIPV) roof covering systems” (ICC Evaluation Service, 2011).
- ISO 18178 (2015-06-08, TC160) Laminated solar PV glass (ISO, 2016).
- IEC 62980 (2014-09-19) PV modules for building curtain wall applications (International Electrotechnical Commission, 2016a).
- IEC 82-1055-NP PV on roof (International Electrotechnical Commission, 2016b).

For further BIPV product development there is a need for definition of complementary tests for cases when existing tests standards are suitable only for some of the PV modules types (PVSITES, 2016). The results of analysis of the existing standards is described in (PVSITES, 2016), and a review of standards for BIPV façade and roof integration is given in (Rehde et al., 2016).

4.2 PV related standards

As PV production is a global industry, test centers use common international standards. While focus of the existing standards is on PV panel quality and performance, products reliability and safety must be also considered. Likewise, long-term system performance and amount of energy produced over the system’s lifetime should also be addressed (Speer, 2011). The main existing standards for PV modules are the International Electrotechnical Commission (IEC) standards, the European Standards (EN), and the Underwriters Laboratory (UL) standards. National standards should also be taken into account when applying BIPV products in specific countries.

Existing main testing standards for PV include:

- Performance: EN 61215 “Crystalline silicon terrestrial photovoltaic (PV) modules -Design qualification and type approval” (European Committee for Electrotechnical Standardization, 2005) (equal to IEC 61215-1, 1-1, 2), EN 61646 “Thin-film terrestrial photovoltaic (PV) modules -design qualification and type approval” (European Committee for Electrotechnical Standardization, 2008) (equal to IEC 61646).
- Safety: IEC 61730-1 “Photovoltaic (PV) module safety qualification - Part 1: Requirements for construction” (International Electrotechnical Commission, 2016c), IEC 61730-2 “Photovoltaic (PV) module safety qualification - Part 2: Requirements for testing” (International Electrotechnical Commission, 2016d), UL 1703 “UL standard for safety flat-plate photovoltaic modules and panels” (Underwriters Laboratories Inc., 2002).
- Design: IEC 62548 “Photovoltaic (PV) arrays - Design requirements” (International Electrotechnical Commission, 2016e).

Additional standards for climate and weathering testing of PV modules include:

- IEC 61345 “UV test for photovoltaic (PV) modules” (International Electrotechnical Commission, 1998).
- IEC 61701 “Salt mist corrosion testing of photovoltaic (PV) modules” (International Electrotechnical Commission, 2011).
- IEC 62716 “Photovoltaic (PV) modules - Ammonia corrosion testing” (International Electrotechnical Commission, 2013a).
- IEC TS 62782 “Photovoltaic (PV) modules - Cyclic (dynamic) mechanical load testing” (International Electrotechnical Commission, 2016f).
- IEC TS 62804-1 “Photovoltaic (PV) modules - Test methods for the detection of potential-induced degradation - Part 1: Crystalline silicon” (International Electrotechnical Commission, 2015).
- IEC 60721-2-1 “Classification of environmental conditions - Part 2-1: Environmental conditions appearing in nature - Temperature and humidity” (International Electrotechnical Commission, 2013b).

For further detailed information, it is referred to the standards themselves.

IEC, EN and UL standard test requirements initially address qualification characteristics of PV modules (PVSITES, 2016). These tests are designed primarily to test failures during the “infant mortality” period (Zielnik, n.d.). Fig. 7 shows failure rates during the service life of PV.

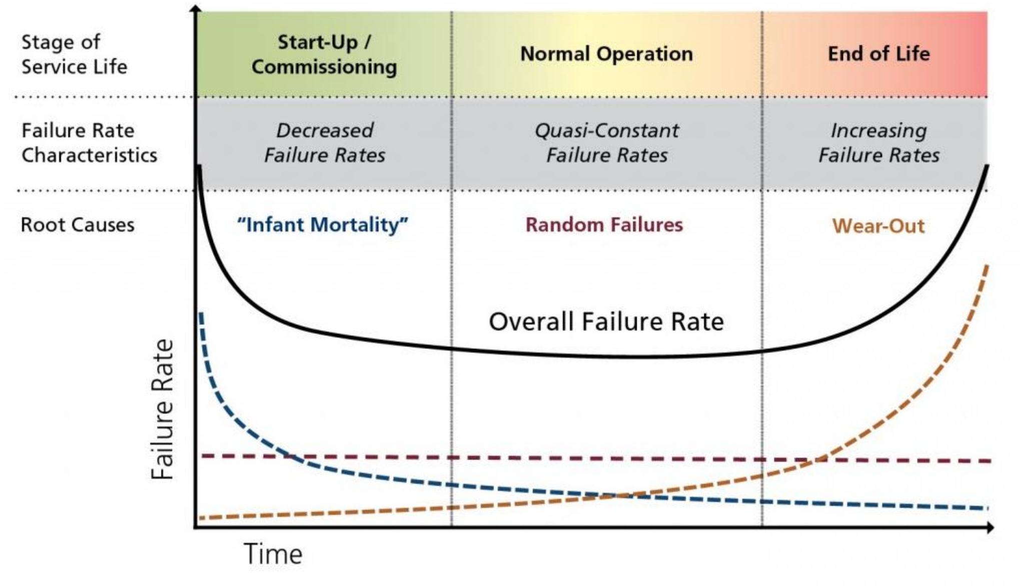

Fig. 7. The "Bathtub curve" of failures occurring in solar PV modules (Sirkin, n.d.).

Stress levels defined in the standard tests are limited, and passing the qualification test means that the product has met a specific set of requirements. These tests are important but cannot specify long-term performance of the products and provide a prediction of product lifetime (Wohlgemuth, 2008) in real climate conditions. Prediction of long-term performance is not intended by the test requirements but must be considered as additional necessary requirements (PVSITES, 2016). Tests for prolonged performance of the BIPV products will lead to improvements in terms of overall economic viability, safety concerns, product development and warranty period, with lower risk to financial expenses (Zielnik, n.d.). Due to variability of weather exposures all over the globe it is not possible to test BIPV products for every climate, i.e. specific tests are being conducted.

4.3 <u>An overview of BIPV requirements</u>

The BIPV element as a building envelope component will have to fulfill the following requirements (European Committee for Electrotechnical Standardization, 2016):

- Weather impact protection: rain, wind, snow, hail.
- Mechanical rigidity or structural integrity.
- Fire protection.
- Energy economy (shading, daylighting, thermal insulation).
- Noise protection.
- Separation between indoor and outdoor environments.
- Security, safety.

The BIPV element as an electrical component should fulfil requirements according to the IEC 61215 and IEC 61646 test conditions for design qualification of crystalline and thin film PV modules:

- Insulation sufficiency and wet leakage current.
- Current and voltage characteristics.
- Maximum power (electrical performance) at standard test conditions, nominal operating temperature and at low irradiance conditions.

- Temperature coefficients of current, voltage and power.
- Nominal operating cell or module temperatures.
- Thermal performance (bypass diodes, hot spots endurance).
- Outdoor exposure, UV, light soaking, temperature cycles, humidity freeze and damp heat.
- Mechanical exposure (load, hail impact, robustness of terminations).

The electrical characteristics of a PV module are defined at standard test conditions STC (corresponding to irradiation 1000 W/m^2, cell temperature 25 °C, and standard ASTM G173-03 spectrum):

- Solar cell efficiency (η).
- Fill factor (FF).
- Maximum power (P_{max}).
- Voltage at maximum power (V_{Pmax}).
- Current at maximum power (I_{Pmax}).
- Voltage at open circuit (V_{oc}).
- Current at short circuit (I_{sc}).
- Temperature coefficients for V_{oc} , I_{sc}, and P_{max}.

The conditions at STC are not generally representative for typical operation conditions, for instance in a Nordic climate with predominantly lower sun angles and intensities. The international PV community is currently discussing whether standards could be adapted to better represent typical conditions in different regions, for instance in Task 13 of the IEA PVPS program entitled "Performance and Reliability of Photovoltaic Systems" (International Energy Agency - PVPS, 2015).

Additional electro-technical requirements are also applicable to BIPV elements. As an electrical component it must have protection against (European Committee for Electrotechnical Standardization, 2016):

- Hazards arising from the electrical equipment.
- Hazards which may be caused by external influences on the electrical equipment.

5. Experimental investigations of BIPV

When traditional building envelope elements are replaced with PV products, the BIPV elements need to maintain the same building functions and therefore need to be investigated to fulfill additional requirements (Breivik et al., 2013). In other words, for the BIPV products weather resistance must be maintained. The hardest climate factor to materials is water (Delgado, 2016) and besides structural degradations it may cause mold growth. One of the main moisture sources affecting the hydrothermal performance and durability of the building envelope is wind-driven rain (Blocken and Carmeliet, 2004). It is thus of major importance to test the BIPV products for rain tightness and durability requirements. Improper water drainage can affect and reduce roof longevity and before the installation an assessment of BIPV systems performance should be conducted (Ly et al., 2013). Furthermore, for testing and evaluation of the BIPV products it is also necessary to consider the balance of system (BOS) (Andenæs, 2016), involving mounting and fastening systems, connections, and electrical cables (Gullbrekken et al., 2015). Cables are especially important to consider as they are placed along and through the building roof and façades.

5.1 <u>Wind-driven rain test for BIPV</u>

Wind-driven rain laboratory investigations have been studied by (Breivik et al., 2013) and (Andenæs, 2016).

(Breivik et al., 2013) investigated mono-crystalline PV modules for roof integration. A large-scale turnable box for rain and wind tightness (RAWI box) testing of sloping building surfaces was used for the test. Large-scale testing with run-off water and wind-driven rain with incremental pulsating differential overpressure over the sample at two different inclinations (15 and 30 degrees) were performed.

A roof sample with two integrated DuPont Gevity BIPV modules is shown in Fig. 8. The photo was taken during testing in the RAWI box.

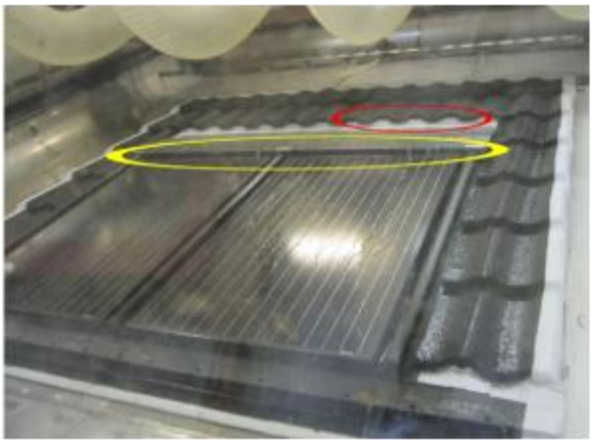

Fig. 8. Sample roof with integrated DuPont Gevity modules inside the RAWI box during testing, the colored ellipses denote leakage points (Breivik et al., 2013).

Test results showed that the BIPV module system withstood wind-driven rain stress sufficiently, without leakages in connection with the joints. However, a small quantity of penetration water was detected that is not crucial for the roof construction problems caused by moisture but this water penetration is nevertheless unwanted. Tests were made with two BIPV modules mounted on the roof sample. For further investigations, tests of larger mounted areas should be performed, with the objective of testing both the vertical and the horizontal joints (Breivik et al., 2013).

(Andenæs, 2016) investigated two types of BIPV: a roof tile and an overlapping module which could be used in a roof or a façade integration. The tested type of photovoltaic technology was mono-crystalline silicon cell.

The BIPV roof tiles chosen for investigation were the Heda Solar 8 W Solar Tiles. These tiles consist of a plastic-ceramic composite roof tile with an integrated photovoltaic module. The tile has a large rectangular hole in the middle where the photovoltaic module is fastened with silicone glue. To compare BIPV roof tiles with traditional roof tiles Monier Nova terracotta roof tiles were chosen by reason of similarity to the Heda Solar tiles profile. The tested samples are depicted in Fig. 9.

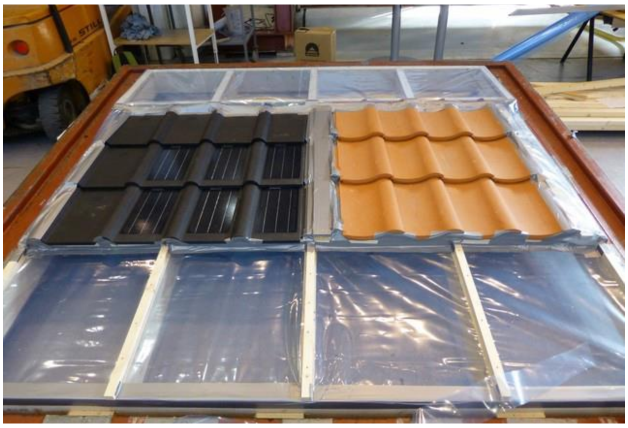

Fig. 9. Heda Solar (left) and Monier Nova (right) tiles mounted in the substrate frame (Andenæs, 2016).

The second tested module type was Gaia Solar's Integra Line SP. This module consists of large, rhomboid glass/back sheet modules, with EVA laminate and monocrystalline silicon PV cells. They are designed to be mounted alongside “Steni Protego” façade/roof plates which serve as the system’s dummy modules. Two types of system configurations were tested, i.e. with 4 and 7 integrated modules (Fig. 10 and Fig. 11, respectively).

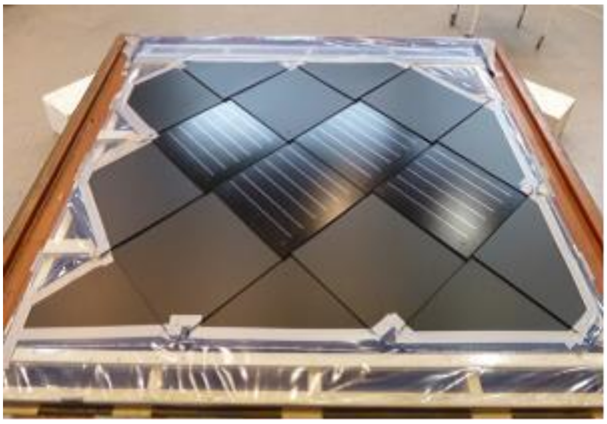

Fig. 10. GS Integra Line SP (configuration A) mounted on a substrate frame (Andenæs, 2016).

Fig. 11. GS Integra Line SP (configuration B) with a greater number of PV modules (Andenæs, 2016).

The test procedure and the equipment used in the test were reminiscent of work by (Breivik et al., 2013). The tests investigated the water-tightness of internal joints between BIPV modules and between BIPV modules and their respective dummy modules. The test has been done in two phases, with and without wind pressure.

The tests for the solar roof tile were performed at two inclinations, 30 and 15 degrees. During the test with 30 degrees inclination, leakage between the traditional terracotta tiles started to occur at pressure level 6 (60 Pa), and at pressure level 7 (70 Pa) between the BIPV roof tiles. With increasing pressure levels, leakages between the terracotta tiles started to occur more frequently. Although leakage is undesired, the leaked water tended to cling to the underside of the terracotta tiles and drain away rather than drip. Between the BIPV roof tiles, fewer leakages occurred and only at high pressure levels. Observed leakage points are shown in Fig. 12, where the roof sample with the terracotta tiles installation (light-orange colored squares) is shown on the left side and installation of the BIPV roof tiles with the system's dummy modules (yellow and light-blue colored squares, respectively).

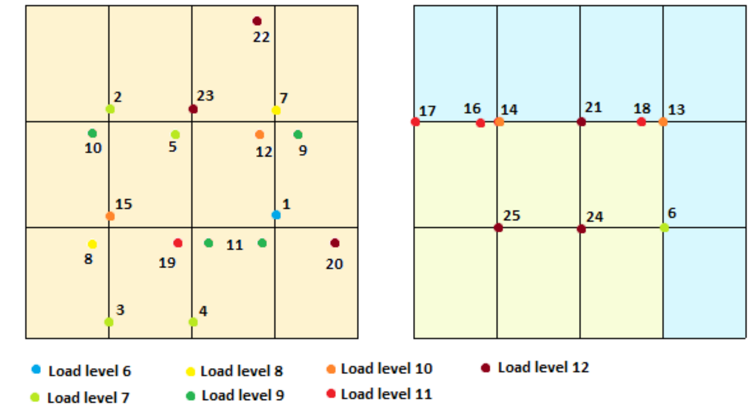

Fig. 12. Leakage points observed during the rain tightness test of the BIPV roof tile at a 30 degree inclination (Andenæs, 2016).

For the 15 degree test, leakages in the longitudinal joints between terracotta tiles were remarkably few. Leakages were first observed at slightly higher pressures than during the previous test. The leakages observed during the tests with 15 degree inclination are shown in Fig. 13. 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 the terracotta tiles in this test, for unknown reasons.

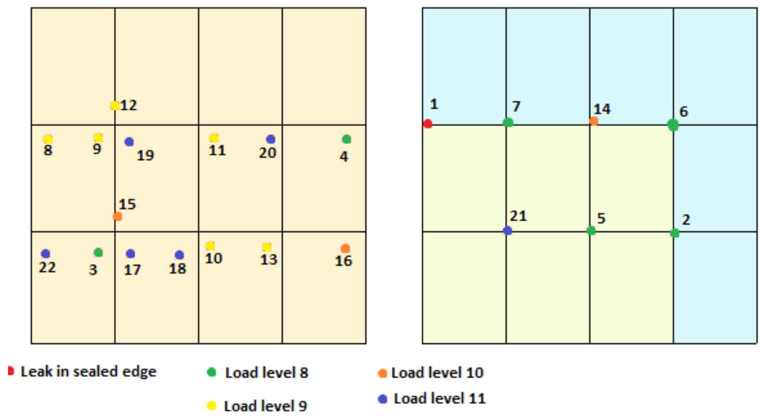

Fig. 13. Leakage points observed during rain tightness test of BIPV roof tile at 15 degree inclination (Andenæs, 2016).

During the test different leakages were observed. The tested BIPV roof tiles have a simple design but proved to be relatively watertight compared to the traditional terracotta tiles. The tests proved that the BIPV roof tiles had experienced less leakages compare to the traditional terracotta tiles. However, improvement of the BIPV roof tiles' weather-tightness could be achieved by providing the solar tiles with the same ribs as the dummy tiles. The dummy tiles have the ribs on the back side of the "wing" that 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. Conducted tests revealed that simultaneous investigation of the BIPV tiles and the equivalent roof tiles provide comprehensive evaluation of material behaviour under wind-driven rain exposure. Further investigation could be done on a joint sample of the roof sample where BIPV integrated and connected to the traditional roof tiles.

For the second type of BIPV, which can be integrated into both the roof and façade, test inclinations of 30 and 90 degrees were chosen. The test results showed that the system experienced more leakages when mounted at a 30 degree angle than when mounted vertically. Also, due to an issue with the fastening system, more leakages occurred than expected. Tested modules came with pre-bored screw holes (while usually modules are delivered with sealed screw holes) and the pre-bored hole was barely smaller than the head of the fastening screws. Consequently, leakage occurred immediately when the tests started. Water leaking through the screw holes drained itself away when the system was mounted vertically, but at a 30 degree angle it led to some dripping. An attempt to improve the water tightness of the tested BIPV by trying to fasten screws more tightly led to the destruction of a few modules. Making screw holes larger and lining the edges of the holes with a ring of rubber or other elastic material could be a way of improvement. This solution would reduce the risk of module breakage by eliminating direct contact between the glass of the modules and the screw heads.

Examination of water resistance of PV modules integrated into the roof and a method for its experimental investigation has also been presented by (Fasana and Nelva, 2013). The integrated systems must have proper water resistance. Usually, water tightness of roof coverings in discontinuous elements is guaranteed by the coupling of slope and overlap of the elements. Discontinuity occurred when devices, such as PV modules, were integrated into the roof.

Test equipment consisted of a tiltable frame with a wind tunnel and with the ability to simulate rain, runoff water flow and grazing wind. The main issue of the integrated roof systems found by this study was the local infiltration at the interior corners of the panels, which happened due to the concentration of the water flowing down from the side channel and the corresponding overflow at the eave. A roof sample with two different types of covering with integrated photovoltaic system was subjected to simulation of wind and rain with progressive increase of the pressure difference between the top and bottom cover, at time intervals of 5 min. The first type of integrated panel was concrete roofing tile and the second were over and under clay tiles. The test was repeated for different slopes of the roof sample.

Three main ways to prevent water infiltration in integrated PV panels into the roof were found by (Fasana and Nelva, 2013):

- Build a complete underlay, with superior level of the panel compare to the roofing level.
- Having a local underlay with connection to the panels.
- Replace locally the original covering by the panel with connections to the elements around.

The first two described experimental works, conducting wind-driven rain test, evaluated the behaviour of BIPV systems themselves. The main purpose of the studies was to find the most suitable BIPV product specifically for Nordic climate conditions. The outcome is knowledge of BIPV system behaviour and comparison of it to equivalent traditional roof material. While the last one studied how integration of the same PV module, but in different ways, on traditional roofs affect water tightness of complete roof structures and how the integrated structure could be improved.

5.2 Additional example of BIPV tests

The main focus of this study is on the wind-driven rain testing of BIPV and application of this test to mono-crystalline silicon PV integrated into the roof structure. For large-scale investigations it is important to conduct more and various tests, for example humidity and temperature exposure tests.

5.2.1 Humidity and temperature test for BIPV

High humidity and low humidity environments with different temperature levels could significantly affect the BIPV product’s performance and durability. For instance, the reliability and performance of thin-film copper indium gallium selenide (CIGS) BIPV have been evaluated by (Feist et al., 2012) and (Ly et al., 2013). In the first study accelerated weathering tests were performed by six different variations of temperature and relative humidity controlled environments. Characteristic current-voltage (I-V) curves were periodically monitored during the exposure. No statistically significant change in performance was observed until nearly 2000 hours of exposure. The BIPV tested at the high humidity exposure conditions demonstrated progressive degradation compared to the modules tested in the lowest humidity conditions. Exposure to the low humidity conditions demonstrated highly stable performance without significant degradation. The authors concluded that for the low humidity conditions the tested CIGS BIPV modules are capable of providing long lifetime performance. The second study showed the behaviour of thin-film BIPV when integrating onto the roof surface at the real outdoor conditions. The tested products are no longer on the market. However, the study revealed significant problems of using thin-film PV as the roof material: the damages due to snow build-up, the exposure of the encapsulation to freezing temperatures and mold growth which caused delamination of PV.

Furthermore, high temperatures and temperature cycles could be considered as important stress factors affecting the BIPV product’s performance. Due to limited cooling compared to a free-standing PV system, the temperature could rise to higher levels with a negative effect on the operation of the BIPV product. Operation at elevated temperatures can have a significant effect on both solar conversion efficiency, depending on PV technology, and the lifetime performance due to temperature-induced degradation. Accelerated ageing performance tests could be used for detailed study the temperature dependence of the BIPV products degradation mechanisms in the laboratory (Konttinen et al., 2006).

6. Discussions

During the product lifetime a BIPV element, as a part of the building envelope, is exposed to various climate strains ranging from solar radiation to snow loads. Usually, manufacturers guarantee a BIPV service life of 25 years while the products serve even longer periods of time. The PV modules guarantee usually means that maximum performance reduction in a module operation would be 1% per year or less but it varies from one type of PV to another (Dirk and Kurtz, 2012). However, certified products are tested at standard test conditions and sufficient information on product behaviour at real climate conditions is not provided. The existing standards and codes are applicable for PV mostly and are designed for the qualification characteristics of PV modules but are not meant to evaluate long-term performance of the products or provide a prediction of the product lifetime. Moreover, there is still a need for proper testing standards and methodologies for BIPV products as the market is expected to grow in the future and integration of PV will increase. To predict and assure longer service life of the products and to develop durable and robust solutions for BIPV, accelerated laboratory investigations should be performed.

Laboratory accelerated tests could be divided into two groups, i.e. weather tests and climate ageing tests. The main difference between them is the time frame of exposures that are applied to the products. Thus the climate test is associated with a relatively long periods of time, whereas the weather test with shorter time periods. Weather tests could have a limitation in the number of simultaneous stresses applied (such as temperature cycling, relative air humidity or solar radiation). Due to this, for the estimation of long-term product weather resistance and durability, climate ageing tests have to be conducted as well. It is of major importance to combine multiple stresses into a single test cycles, such as combining temperature and humidity cycling, and freezing/thawing cycles and solar radiation, to better simulate the natural environment and to have results for the BIPV behaviour prediction at real climate conditions.

In general, two types of PV integration exist: roof and façade integration. The type of BIPV product will significantly affect the possible issues of performance and durability in integrated systems, as well as the method of integration. Thus a methodology for laboratory investigations of various BIPV solutions should be developed and carried out.

Alongside with accelerated tests, the identification of degradation mechanisms through experiments, modelling and simulation can lead directly to lifetime improvements. Outdoor testing and correlation with accelerated laboratory investigations is important to ensure correct evaluation of the BIPV durability and robustness under real life climate exposures.

Future development of BIPV products will require specific standards and codes for more sufficient integration in building design. Large scale investigations of BIPV have to be performed to prove reliability of the different products. Wind-driven rain test studies examples revealed that BIPV usually show satisfactory water tightness. However, fastening system must be taken into account and there is a need to pay particular attention in relation to both way of PV integration and appropriate mounting system. Conducting the wind-driven rain test, by testing BIPV and the traditional roof tiles simultaneously, provide comprehensive information on material performance. Further laboratory investigations should include:

- Testing of various types of BIPV.
- Testing of different types of integration.
- Conducting tests when BIPV elements are integrated and connected to the traditional building envelope materials.
- Development of the methodology for testing at specific climate exposure conditions.
- Testing BIPV in climate ageing equipment.
- Evaluation of durability properties and robustness of BIPV.

7. Conclusions

Building integrated photovoltaics (BIPV) will continue their development in the future. The interest in application of BIPV is steadily growing and especially in association with zero energy and zero emission buildings concepts, which could be considered as one of the main future strategies for achieving lower level of greenhouse gas (GHG) emissions and its mitigation in the building sector. Being a part of the building envelope skin, BIPV elements must be resistant to withstand the natural ageing stress factors and simultaneously maintain satisfactory energy output at a steady level for at least 20–30 years, and desirable to have prolonged service life as BIPV. High reliability and durability are significant factors in increasing the amount of electricity a module is expected to produce over its lifetime, which is equivalent to decreasing BIPV electricity price and lower the carbon footprint of the material. A key challenge for BIPV technologies is the estimation of BIPV lifetime. Accelerated laboratory tests will give valuable knowledge about the critical parameters for increased durability and lifetime of BIPV products, which may lead to an improvement of existing products and the development of new ones.

The discussed principles of testing BIPV products and the laboratory tests experience will be applied to the development of the BIPV testing methodology. Comparison and evaluation of the existing standards reveals the gap where special complementary requirements should be applied. The apparatuses for laboratory investigations, showed in this study, will be used in large-scale testing of existing, and also developing, BIPV products. As the main exposure affecting the building envelope materials is the moisture source particular emphasis of future testing of BIPV will be on the wind-driven rain exposure and water tightness testing.

Acknowledgements

This work has been supported by the Research Council of Norway and several partners through the research project “Building Integrated Photovoltaics for Norway” (BIPV Norway).

References

Andenæs, E., 2016. Wind-driven rain exposure and assessment of building integrated photovoltaic systems, Master thesis, Norwegian University of Science and Technology (NTNU). Available from: NTNU Open.

Atlas Material Testing Solutions, n.d. Weathering Test Methods. Available from: http://atlas-mts.com/technical-information/library/service-life-prediction-and-numerical-weathering-test-methods/weathering-test-methods/ (accessed 11.2.16).

Blocken, B., Carmeliet, J., 2004, A review of wind-driven rain research in building science, Journal of Wind Engineering and Industrial Aerodynamics, vol. 92, pp. 1079–1130.

Bonomo, P., Chatzipanagi, A., Frontini, F., 2015, Overview and analysis of current BIPV products: new criteria for supporting the technological transfer in the building sector, International Journal of Architecture Technology and Sustainability, vol. 0, no.1, pp. 67–85.

Breivik, C., Jelle, B.P., Time, B., Holmberget, Ø., Nygård, J., Bergheim, E., Dalehaug, A., 2013, Large-scale experimental wind-driven rain exposure investigations of building integrated photovoltaics, Solar Energy, vol. 90, pp. 179–187.

Brown, R.P., Kockott, D., Trubiroha, P., Ketola, W., Shorthouse, J., 1995, A review of accelerated durability tests, VAMAS Technical Report No 18, Teddington, National physical laboratory.

Crewdson, M., 2011, Outdoor weathering must verify accelerated testing, Homestead, Q-Lab Weathering Research Service.

Delgado, J.M.P.Q., 2016, New approaches to building pathology and durability, Singapore, Springer.

Dirk, C.J., Kurtz, S.R., 2012, Photovoltaic degradation rates — an analytical review, Progress in Photovoltaics: Research and Applications. Available from: http://www.osti.gov/bridge

European Committee for Electrotechnical Standardization, 2016, Photovoltaics in buildings - Part 1: BIPV modules, EN 50583-1-2016.

European Committee for Electrotechnical Standardization, 2008, Thin-Film Terrestrial Photovoltaic (PV)Modules—Design Qualification and Type Approval, EN 61646-2008.

European Committee for Electrotechnical Standardization, 2005, Crystalline Silicon Terrestrial Photovoltaic (PV) Modules—Design Qualification and Type Approval, EN 61215-2005.

European Parliament, 2010, Directive 2010/31/EU of the European parliament and of the council of 19 May 2010 on the energy performance of buildings, Strasbourg.

Fasana, S., Nelva, R., 2013, Improvementt of the water resistancy in the integration of photovoltaic panels on traditional roofs, Construction and Building Materials, vol. 48, pp. 1081–1091.

Feist, R., Mills, M., Ramesh, N., 2012, Methodology for delivering reliable CIGS based building integrated photovoltaic (BIPV) products, Reliability physics symposium (IRPS), 2012 IEEE International.

Gullbrekken, L., Kvande, T., Time, B., 2015, Roof-integrated PV in Nordic climate - building physical challenges, Energy Procedia, 6th International Building Physics Conference, vol. 78, pp. 1962–1967.

H. K. Hardcastle, n.d. Weathering Experimenter's Toolbox. Available from: http://atlas-mts.com/technical-information/library/design-of-experiment/weathering-experimenters-toolbox/ (accessed 11.2.16).

ICC Evaluation Service, 2011, Acceptance criteria for building-integrated photovoltaic (BIPV) roof covering systems, AC365.

IEC, 2016, IECRE System - Rules of procedure for the certification of photovoltaic systems according to the IECRE-PV schemes.

International Electrotechnical Commission, 2016a, Photovoltaic modules for building curtain wall applications, IEC 62980 ED1-2016.

International Electrotechnical Commission, 2016b, Photovoltaics (PV) on roof, IEC 82-1055-NP-2016.

International Electrotechnical Commission, 2016c, Photovoltaic (PV) module safety qualification - part 1: requirements for construction, IEC 61730-1.

International Electrotechnical Commission, 2016d, Photovoltaic (PV) module safety qualification - part 2: requirements for testing, IEC 61730-2.

International Electrotechnical Commission, 2016e, Photovoltaic (PV) arrays - Design requirements, IEC 62548.

International Electrotechnical Commission, 2016f, Photovoltaic (PV) modules - cyclic (dynamic) mechanical load testing, IEC TS 62782.

International Electrotechnical Commission, 2015, Photovoltaic (PV) modules - test methods for the detection of potential-induced degradation - part 1: crystalline silicon, IEC TS 62804-1.

International Electrotechnical Commission, 2013a, Photovoltaic (PV) modules – ammonia corrosion testing, IEC 62716.

International Electrotechnical Commission, 2013b, Classification of environmental conditions - part 2-1: environmental conditions appearing in nature - temperature and humidity, IEC 60721-2-1.

International Electrotechnical Commission, 2011, Salt mist corrosion testing of photovoltaic (PV) modules, IEC 61701.

International Electrotechnical Commission, 1998, UV test for photovoltaic (PV) modules, IEC 61345.

International Energy Agency - PVPS, 2016, Task 15: Building Integrated PV. Enabling framework for the acceleration of BIPV. Available from: http://iea-pvps.org/index.php?id=task15 (accessed 11.30.16).

International Energy Agency - PVPS, 2015, Task 13: Performance and Reliability of Photovoltaic Systems. Available from: http://www.iea-pvps.org/index.php?id=57 (accessed 9.21.16).

International Organization for Standardization, 2016, Glass in building - laminated solar photovoltaic glass for use in buildings, ISO/FDIS 18178.

Jelle, B.P., 2015, Building integrated photovoltaics: a concise description of the current state of the art and possible research pathways, Energies vol. 9, issue 1, pp. 21.

Jelle, B.P., 2013, The role of accelerated climate ageing of building materials, components and structures in the laboratory, the 7th Nordic Conference on Construction Economics and Organisation, Construction Researchers on Economics and Organisation in the Nordic region (CREON) & Akademika Publishing, Trondheim.

Jelle, B.P., 2012, Accelerated climate ageing of building materials, components and structures in the laboratory, Journal of Material Science, vol. 47, pp. 6475–6496.

Jelle, B.P., Breivik, C., 2012, State-of-the-art Building Integrated Photovoltaics, Energy Procedia, vol. 20, pp. 68–77.

Konttinen, P., Carlsson, T., Lund, P., Lehtinen, T., 2006, Estimating thermal stress in BIPV modules, International Journal of Energy Research, vol. 30, pp. 1264–1277.

Ly, P., Ban-Weiss, G., Finch, N., Wray, C., Ogburn, M. de, Delp, W., Akbari, H., Smaby, S., Levinson, R., Gean, B., 2013, Building integrated photovoltaic (BIPV) roofs for sustainability and energy efficiency, Washington, Naval Facilities Engineering Command.

McGreer, M., 2001, Weathering testing guidebook, U.S.A, ATLAS material testing solutions.

Pellegrino, M., Flaminio, G., Graditi, G., 2013, Testing and standards for new BIPV products, IECON 2013 - 39th Annual Conference of the IEEE Industrial Electronics Society, pp. 8127–8132.

Peterson, K., Torcellini, P., Grant, R., 2015, A common definition for zero energy buildings, Washington, The National Institute of Building Sciences.

PVSITES, 2016, Standardization needs for BIPV, CEA, Tecnalia, CTCV, Available from: https://pvsites.eu.

Rehde, F., Szacsvay, T., Peppas, A., al, et, 2016, Review of standards for integrating BIPV-modules in building facade and roof, Freiburg, Fraunhofer ISE.

Sirkin, J., n.d. Fraunhofer's photovoltaic durability initiative reduces solar investment risks. Available from: http://www.cleantechnotes.org/2013/02/22/fraunhofers-photovoltaic-durability-initiative-reducing-investment-risks (accessed 11.2.2016)

Speer, B.K., 2011, Solar PV Quality Assurance from the Developer's Perspective. Available from: https://financere.nrel.gov/finance/content/solar-pv-quality-assurance (accessed 11.1.16).

Underwriters Laboratories Inc., 2002, UL standard for safety flat-plate photovoltaic modules and panels, UL 1703.

United Nations Environment Programme, 2009, Buildings and climate change. Summary for decision-makers, Paris, UNEP SBCI.

Wohlgemuth, J.H., 2008, Reliability of PV systems, reliability of photovoltaic cells, modules, components and systems.

Yan, J., 2015, Handbook of clean energy systems. John Wiley & Sons, Chennai, Markono Media Pte Ltd.

Zielnik, A., n.d. PV durability and reliability issues. Available from: http://www.renewableenergyworld.com/articles/print/pvw/volume-1/issue-5/solar-energy/pv-durability-and-reliability-issues.html (accessed 9.21.16).

Zielnik, A., Riedl, A., Senf, S., 2015, Applying the fundamental principles of weathering and how they apply to environmental durability testing of PV backsheets, 3rd ATLAS/NIST workshop on photovoltaic materials durability, Gaithersburg.