TPEDGE: QUALIFICATION OF A GAS-FILLED, ENCAPSULATION-FREE GLASS-GLASS PHOTOVOLTAIC MODULE

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ABSTRACT: With “TPedge” we present an advanced frameless, polymer free encapsulation concept for silicon solar cells which addresses several disadvantages and significant cost factors related to conventional solar modules. “TPedge” represents a gas-filled, edge sealed, glass-glass module without polymeric encapsulation foils that requires less module production time. The cost calculation indicates 15.3% lower module material costs for “TPedge” production compared to the standard module production due to savings for encapsulation foils and frame. The results from successful and extended module testing such as 400x thermal cycling (ΔP_{STC} = 0%), 2000 hours damp-heat (ΔP_{STC} = -1.4%) or 5400 Pa (ΔP_{STC} = -0.9%) mechanical load testing show that critical IEC tests are passed. Additional results show PID stability, hot-spot stability (ΔP_{STC} = -0.6%) and successful hail impact testing (ΔP_{STC} = -0.5%). We consider the TPedge-concept to be ready for IEC certification.

Keywords: PV Module, Module Manufacturing, Durability, Reliability, Cost reduction, Building Integrated PV (BIPV), Encapsulation, Façade, Polymer Film

1 INTRODUCTION

Conventional photovoltaic modules use polymeric foils like ethylene-vinyl acetate (EVA) as solar cell encapsulation. Several effects are known that cause failure or power loss of the solar module and are directly related to the encapsulation material or incomplete protection of the solar cells from environmental influences [1][2][3].

Solar modules are sold with a power guarantee of usually 25 to 30 years. However, degradation effects such as discoloration, degradation and corrosion that is increased by the generation of acetic acid, make much longer lifetimes difficult to reach [4][5].

Especially the stability of polymeric films against the impact of UV light is usually a tradeoff between the desired high transmittance of UV light and the absorption of high energetic photons needed to avoid the degradation of polymer chains.

Additionally a lamination process is needed during module production with polymer foils. This process takes 8-15 minutes [6] and is known to represent a bottle neck in solar module production.

The costs of the foils are a substantial part of the module production costs. Furthermore conventional module concepts rely on aluminum frames to ensure mechanical stability. Those frames add again a significant cost factor to PV module production [7].

Various innovations have been proposed to overcome the disadvantages of polymeric encapsulants including the introduction of ultra-fast cure material, non-curing thermoplastics or other material groups [8], multi stage laminators or glass-glass-laminates with improved aging stability. None of these measures were able to completely eliminate the intrinsic disadvantages of the encapsulation foils at competitive cost levels.

In this work we show that with the “TPedge” approach, a gas-filled glass-glass module with an edge sealing, a significant improvement of long term stability and simultaneously a decrease of module production costs can be realized.

The “TPedge”-module concept applies an edge sealing process, well known from the manufacturing of double glazing insulation windows and therefore on the market for a long time.

The edge sealing consists of a thermoplastic spacer (TPS) filled with drying silicates and a silicone which renders the mechanical stability of the module. The glass spacing is filled with air. A double side coated ARC front glass as used in solar thermal collectors is required to minimize reflection losses.

Small pins consisting of an UV-curing adhesive, glue the solar cells to the rear side glass pane. Glass spacing is provided by a set of transparent distance pins on the front side of the solar cells that cover approximately 0.02% of the cell area and provide additional mechanical stability.

Metal frames or similar additional supporting constructions are not necessary.

Figure 1 shows a schematic drawing of the cross section of a “TPedge”-module with the positions of the adhesive pins on the front and backside of the solar cell. As a comparison the standard module architecture is shown in figure 2.

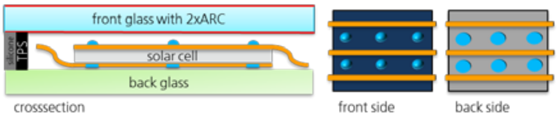

Figure 1: TPedge-module sketch with position of adhesive pins and double layer edge sealing

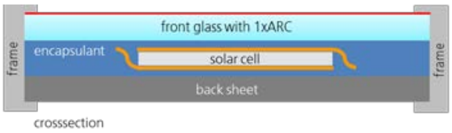

Figure 2: conventional solar module schematics

A wide range of advantages such as simple recycling, reduced fire load and a potential for the use of larger formats results from neither using foils nor lamination. Additionally the module’s hot spot resistance is increased since the “TPedge” concept uses no thermally decomposing cover materials. With only using electrically safe module sealing the “TPedge”-module concept is suitable for higher system voltages. Also module integrated thin bypass diodes have been successfully tested with full size „TPedge“-modules.

2 EXPERIMENTAL

2.1 Module production

The production of "TPedge"-modules is a combination of well-manageable processes that enable reliable and fast manufacturing:

- Glass washing
- Dispensing of fixation pins (back side)
- String layup
- UV-Curing of fixation pins
- Dispensing of distance pins (front side)
- UV-Curing of distance pins
- TPS application (primary seal)
- Sealing press
- Silicone application (secondary seal)

TPS application with an industrial applicator is shown in Figure 3. Figure 4 shows dispensing of the adhesive pins with a semi-automated robot system installed at Fraunhofer ISE.

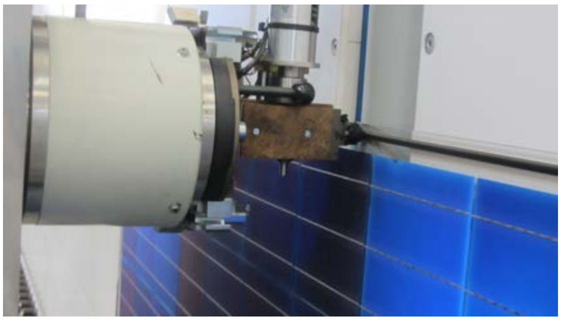

Figure 3: "TPedge"-module production (primary sealing with a Bystronic TPS-applicator)

Cycle times of less than one minute are expected. A production line has been projected using several existing machines that are already used for prototype manufacturing.

Different module setups are produced for detailed module testing and qualification. The modules of setup A contain 60 solar cells. To prove flexibility of the concept several commercially available monocrystalline standard back surface field (BSF) solar cells by different manufacturers are used. The full size modules are built with 3 mm thick, hardened float glass sized 1640x1000 mm. For mechanical testing some modules are built with 2 mm thick glass.

The modules of setup B are customized BIPV modules made of 42 MWT-HIP-back contact solar cells produced at Fraunhofer ISE [9] and connected by structured interconnectors [10]. The modules of setup B are sized 1240 x 1005 mm. A 4 mm thick front glass is partially black enameled on the module edge for architectural purposes. The back glass pane is 5 mm thick.

Automated production equipment at Fraunhofer ISE is used for module manufacturing to ensure reproducible industry-oriented processes. Both module setups are edge sealed using commercially available insulation glass production equipment.

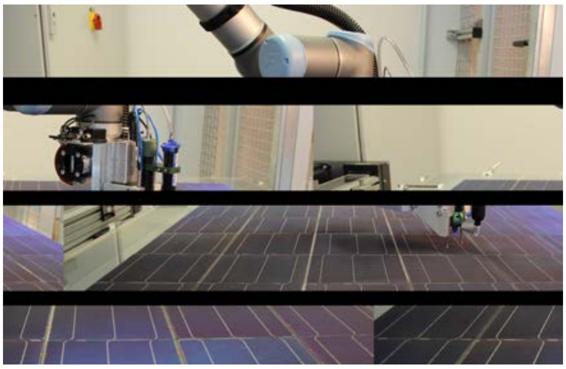

Figure 4: automated dispensing of distance pins on front side of MWT solar cells for BIPV "TPedge"-modules

The pins consist of UV-curing acrylate adhesive. Junction boxes are applied on the back side of setup B covering a drilled hole in the back glass pane. For the PID test additional one-cell modules are produced.

2.2 Module qualification

Module qualification is performed at Fraunhofer ISE TestLab PV modules. Accelerated aging as well as mechanical tests, PID stability and hot spot endurance tests are conducted.

Critical test sequences from IEC 61215 and IEC 61730 are performed and extended on several "TPedge" modules. The test sequence is completed with a two year outdoor exposure in a BIPV façade at Fraunhofer ISE.

We perform standardized and extended test sequences on several "TPedge" modules based on IEC 61215 / 61730 for both module setups.

Each module type is tested for 2x 1000 h of damp-heat (85 °C, 85% r.h.) and 2x 200 thermal cycles (-40 °C/ 85 °C). Modules of setup B are also tested for a combined 1000 h damp-heat and 200 thermal cycles. Tests are accompanied by electrical safety measurements, wet leakage and insulation tests and electroluminescence (EL) inspections.

A hot spot endurance test according to IEC 61215 is performed with a module of setup B as well as a PID-stability test on one-cell samples. The small samples are tested with aluminum foil at 60 °C and -1000 V DC for 16 hours. For this test specially designed PID-sensitive solar cells are used. The PID-stability is also tested on a 60-cell module for -1000 V DC at 25 °C with aluminum foil and for a period of 168 hours.

The mechanical stability of the modules is assessed by performing hail impact and mechanical load tests with uniform loads up to 5400 Pa according to IEC 61215 / 61730 with several different mounting systems at Fraunhofer ISE.

Three different commercial available module clamps and one backrail system are tested. Mechanical load is tested with four and six clamps per module. Modules of setup A (3 mm glasses) are tested for suspended mounting and fixed substructures (mounting construction supports module during load). Several mechanical load tests are performed on one single module (setup A, four tests with 2400 Pa, one test 5400 Pa; five different mounting configurations). Hail and mechanical load tests are additionally performed on modules with 2 millimeter thick glasses. Figure 5 shows the positions of module clamps and backrails during mechanical testing.

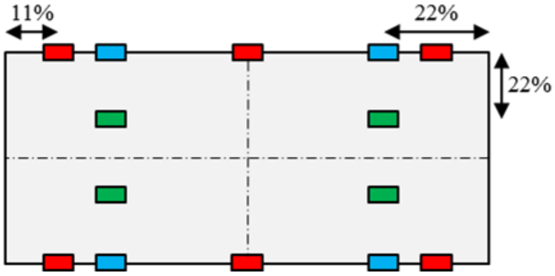

Figure 5: Position of clamps for mounting during mechanical tests with four (blue) and six (red) clamps; position of Backrail-system (green)

Modules are mounted vertically for hail test with six clamps. Three 60-cell modules are tested (2x 3 millimeter glass panes, 1 x 2 millimeter glass). In total 62 hail shots are fired on critical spots (marked with green spots in figure 6) such as pin positions, glass edges and interconnectors.

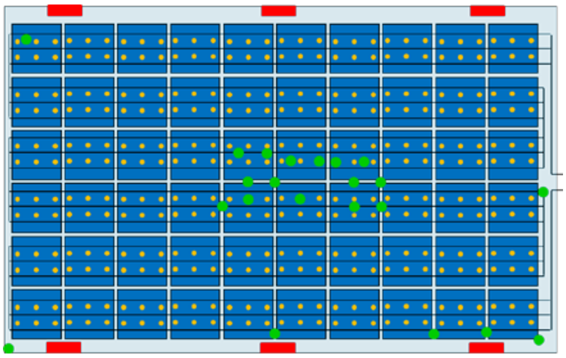

Figure 6: “TPedge”-module with hail impact positions (green), module clamp positions (red) and the positions of the distance pins (orange)

Electroluminescence inspections are performed on all modules before and after testing. Power measurements are performed to assess the aging stability of the modules.

A building façade at Fraunhofer ISE is equipped with ten TPedge-modules of setup B. The modules have been installed in August 2013 and are electrically monitored. The façade is orientated 234.7° south-south-west and the modules are mounted vertically. Figure 7 shows the laboratory building and the TPedge modules.

Figure 7: BIPV-installation of TPedge-modules at Fraunhofer ISE

2.3 Cost Analysis

A cost of ownership calculation is performed for three different module setups. An industrial standard module, a glass-glass-laminate and a TPedge-module are compared. The glass-glass-laminate is included into considerations as the market share of this module type is expected to grow [11]. Cost calculation is performed with the “SCost.module” software developed at Fraunhofer ISE [12]. The Calculation takes material and process costs as well as yield rates, productivity and other significant factors into consideration. The input parameters for TPedge are based on the projected module production line. The cost calculation is performed for an annual production of approximately 200 MWp per year.

For comparability all module concepts are calculated with four busbar, six inch solar cells, a cell efficiency of 18.5% (4.5 Wp) and a cell price of 0.30 €/Wp.

2 RESULTS

2.1 Thermal Cycling and insulation resistance

Thermal cycling is performed with different TPedge-module setups. Figure 8 shows the module A8 before (left) and after 200 thermal cycles. The monocrystalline cells shown in Figure 8 are taken from lowest bin classes and exhibit initial non-critical flaws. Aside from some finger interruptions due to failure of the front side metallization no module related failure mechanism can be observed.

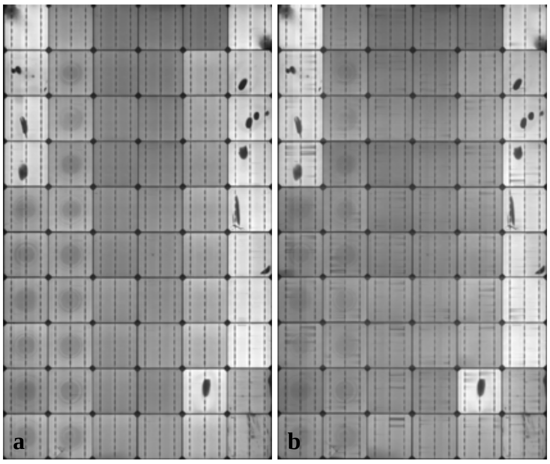

Figure 8: “TPedge”-module A8 before (a) and after (b) thermal cycling test.

For an extended test (400 thermal cycles) module B2 (for BIPV, 42 cells) is used and shows no additional micro cracks after the test. The structured interconnectors used to connect the MWT-solar cells are successfully tested in combination with this TPedge-setup.

Power measurements are performed before and after the test and show a power loss < 5%. Detailed results are listed in table I.

Table I: results of power measurements before and after thermal cycling tests (-40 °C / 85 °C)

Module no.	Thermal cycles	Initial power [W]	Power after test [W]	Change [%]
A4	200	219.6	221.2	+0.7
A7	200	249.7	243.4	-2.6
B2	400	171.1	171.1	±0.0
B3	200	169.1	167.4	-1.0

Certification requires an insulation resistance of 40 MΩm² (at 6000 V) while 2.69 GΩm² is measured for a TPedge-module of setup B.

2.2 Damp Heat

Several modules are tested for extended periods under damp-heat conditions (85 °C, 85% r.h.). Tests are hardened by performing combined tests to modules of setup B. The damp-heat test of module B3 is performed after a thermal cycling test and module B1 is tested on mechanical load 2400 Pa after 1000 hours of damp-heat.

Table II: results of power measurements before and after damp-heat tests (85 °C, 85% r.h.)

Module no.	Test length [h]	Initial power [W]	Power after test [W]	Change [%]
A6	2000	263.0	261.4	-0.6
A8	2000	262.6	258.9	-1.4
B1	2000	163.5	164.6	+0.7
B3	1000	169.1	167.4	-1.0

Figure 9 shows the EL-image of module A6 after 2000 h of damp-heat testing. No changes compared to the initial image can be observed.

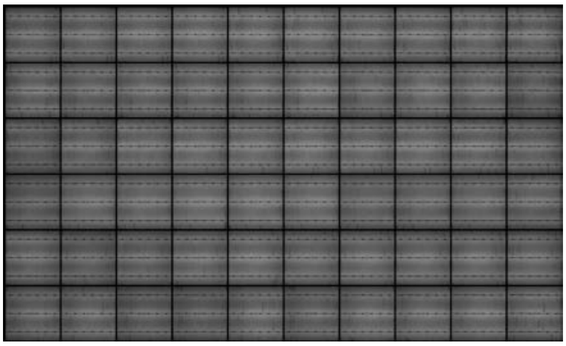

Figure 9: “TPedge”-module A6 after 2000 h of damp-heat testing

The results show an excellent damp-heat resistance of TPedge-modules. The tests will be continued at Fraunhofer ISE until failure occurs.

2.3 Potential Induced Degradation

We perform two tests on the PID-stability of TPedge-modules. The first test (25 °C, -1000 V DC, 168 hours) uses the 60-cell TPedge-module A4 that is also used for thermal cycling tests. The second test (60 °C, -1000 V DC, 16 hours) uses six one-cell samples. Three of them are “TPedge”-modules and three are references with standard EVA encapsulation. Both tests show no PID of the TPedge-modules while for the EVA references a significant degradation is measurable. Figure 10 shows the results of power measurements before and after the PID-test. The red line marks a 5% power loss used as fail criteria in IEC 61215. Since the solar cells used in the small samples are specially designed to be PID-sensitive, the result underlines the PID-stability of the TPedge-concept.

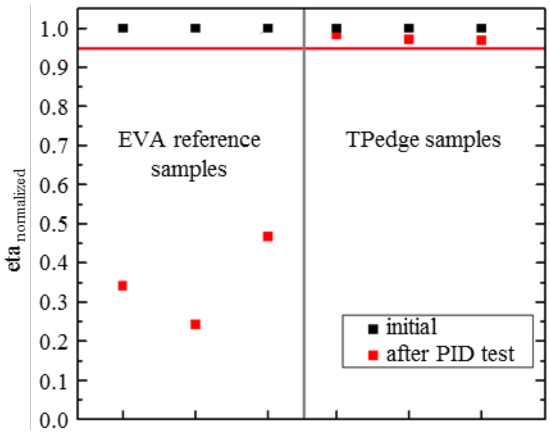

Figure 10: Reference- and “TPedge”-modules before and after PID-resistance tests (60 °C, -1000 V DC, 16 hours)

2.4 Hot Spot Endurance Test

We test TPedge-module B4 for hot-spot endurance according to IEC 61215 / IEC 61730. Power measurement and electroluminescence inspection are performed before and after the test.

The results show no significant power loss. No changes were found in the electroluminescence inspection. Table III shows the results of power measurements performed on module B4

Table III: results of power measurements before and after hot-spot resistance test of module B4

Module no.	Initial power [W]	Power after test [W]	Change [%]
B4	171.9	170.9	-0.6

2.5 Mechanical Load test

The results of the mechanical load test show strong deflection of all tested modules during the test. Figure 11 shows the deflection of a “TPedge”-module built with 2 mm glass panes under a load of 2400 Pa mounted with backrails.

Figure 11: “TPedge”-module with 2 mm glass panes, backrails and supported mounting during mechanical load test (2400 Pa)

For modules with clamps this leads to the risk of modules slipping out of the clamps which would result in test failure. Nonetheless feasible solutions could be identified that allow a safe module mounting for loads up to 5400 Pa with commercially available clamp systems. Also backrail systems are successfully tested.

With backrail mounting the module is glued to the mounting structure and therefore the deflection is reduced and no slipping is possible. A module with 3 mm glasses has been successfully tested for extended loads up to 5400 Pa. Figure 12 shows the deflection of the modules during mechanical load test.

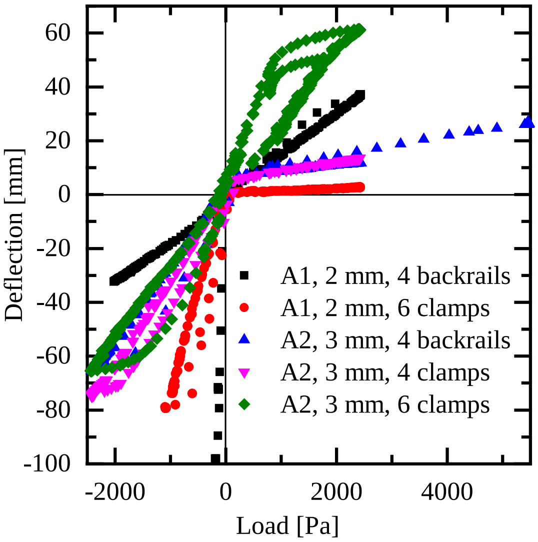

Figure 12: Deflection of module center under mechanical load for different mounting setups, modules and loads

Initial measurements of module A2 have been performed in November 2011 and final measurements are executed after completion of five mechanical load tests using module A2 in May 2015. Table IV shows the results of power measurements performed before and after the mechanical load tests. No significant change in the module power output can be observed after mechanical load test.

Table IV: results of power measurements before and after mechanical load tests

Module no.	Initial power [W]	Power after test [W]	Change [%]
A2	221.0	219.4	-0.9
A3	220.4	221.6	+0.6
B1	163.5	164.6	+0.7

On module B1 the mechanical load test is performed after 1000 h of damp-heat. Because module B1 is of different format than the modules A2 and A3 and because it has been manufactured for a BIPV-application, a different mounting solution is used.

Power measurements indicate no power loss within measurement uncertainties before and after the mechanical load test procedures.

2.6 Hail Impact Test

Hail tests are performed with modules both with 2 and 3 mm thick glasses. Out of 62 hail shots fired at the modules only three cause insignificant micro cracks. Figure 13 shows the EL-images before and after the test of module A1 which is built with 2 mm glass panes.

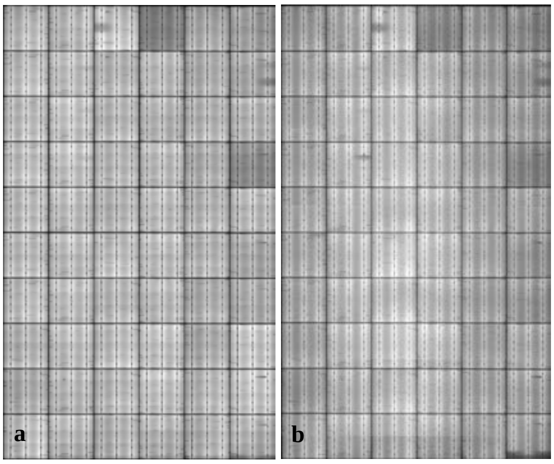

Figure 13: TPedge-module A1 with 2 mm glass panes before (a) and after (b) hail impact test

A change in module power cannot be detected within measurement uncertainties. Table V shows the results of power measurements before and after the hail impact tests.

Table V: results of power measurements before and after hail impact tests

Module no.	Initial power [W]	Power after test [W]	Change [%]
A1	260.7	259.3	-0.5
A4	219.6	221.2	+0.7
A5	220.0	221.9	+0.9

2.7 Cost Analysis

A cost calculation is performed for three module setups. Results show a significant advantage of the TPedge-concept compared to the industrial standard as well as to a glass-glass-laminate.

Saving the metal frame is the main factor for the glass-glass-module's price advantage compared to the standard module. Table VI shows the module material costs for three different module setups. The TPedge-module's material costs are 15.3% lower than the standard module's. Figure 13 shows the material cost structure of different module setups.

Table VI: material costs for different module setups (without solar cells), compared to standard module

Module	material costs [€]	%
standard	39.56	100
glass-glass	36.22	91.5
TPedge	33.50	84.7

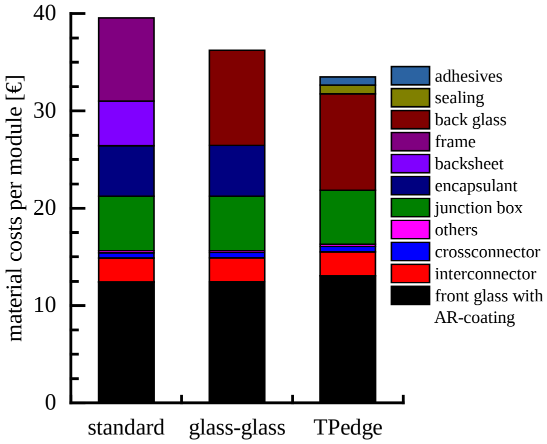

Figure 14: material cost structure for different module setups (without solar cells)

Considering production steps and equipment, TPedge is able to compete with the other module concepts. While "TPedge" module production has more production steps (adhesive dispensing, UV-curing, TPS application, pressing, secondary sealing) than standard module production they are faster (cycle time < 1 minute). Figure 15 shows the cost of ownership structure for different module setups.

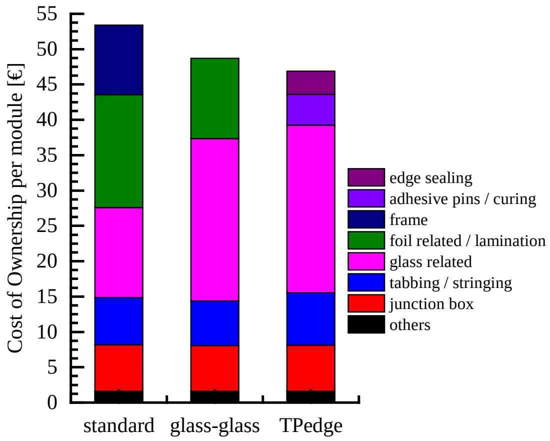

Figure 15: material cost structure for different module setups (without solar cells)

The use of the TPedge module concept leads to a total cost of ownership reduction of 12.3%. Table VII shows the reduction of different module setups compared to the standard module.

Table VII: Costs of Ownership for different module setups (without solar cells), compared to standard module

Module	cost of ownership [€]	%
standard	53.42	100
glass-glass	48.70	91.2
TPedge	46.87	87.7

Calculations of the specific module costs (€/Wp) based on cell to module losses [13] show that TPedge is competitive to the standard module concept. While the conventional module is produced at 0.519 €/Wp, the glass-glass and the TPedge module offer 0.507 €/Wp (2.4% reduction compared to standard module).

3 SUMMARY & OUTLOOK

The "TPedge"-module concept has been intensively tested on critical stress factors. Tests have been successfully passed with several full size modules. We expect that module certification according to IEC 61730 and 61215 can be successfully passed. Table IIX summarizes the test results. All critical certification tests are successfully passed and requirements are exceeded in most tests.

Table IIX: overview of important and critical certification tests on full size and BIPV modules

Test	Status	Remarks
Damp-Heat	passed	2000 h
Thermal Cycling	passed	400 cycles
Mechanical load	passed	5400 Pa
Hail stability	passed	several modules
PID stability	passed	
Hot spot endurance	passed	
UV stability	passed	
Outdoor Exposure	passed	> 1500 kWh/m²

Accompanying electrical safety tests have been passed as well as the tests listed in Table IIX.

The maturity of the "TPedge" module concept has been demonstrated. Customized BIPV modules as well as full size modules with different commercially available solar cells have been manufactured and innovative features such as back-contact cells and structured interconnectors have been used.

Possibilities of an automated production have been successfully demonstrated and a module production line was projected.

A cost analysis shows that "TPedge" offers advantages in material costs, costs of ownership and energy production costs compared to industrial standard modules as well as glass-glass-laminates.

Aging tests will be continued and different module setups will be compared in long-term outdoor exposure tests. Additional work will focus on yield prediction and efficiency evaluation of the "TPedge"-module and competitive concepts.

Sixty additional "TPedge"-BIPV-modules will be installed and monitored at Fraunhofer ISE in 2015.

4 ACKNOWLEDGEMENTS

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