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TPEDGE: PROGRESS ON COST-EFFICIENT AND DURABLE EDGE-SEALED PV MODULES

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ABSTRACT: With TPedge we present an advanced frameless, polymer free encapsulation concept for silicon solar cells which addresses disadvantages and cost factors related to conventional solar modules. TPedge is a gas-filled, edge sealed, glass-glass module without polymeric encapsulation foils. The cost calculation indicates 5.7% lower costs of ownership for TPedge compared to the conventional module production due to savings for encapsulation foils and frame. Results from successful and extended module testing (i.e. 4000 hours damp-heat, ΔP_{MPP} = -1.3%) and 4 years of outdoor exposure prove good reliability of the concept. We perform a cell-to-module (CTM) analysis of TPedge and other concepts and calculate gain and loss factors. We find TPedge to have increased reflection losses compared to conventional modules and a lower CTM_{power} ratio (0.906). We combine CTM-analysis and cost calculation and find the specific costs (€/Wp) for TPedge to be 1.2% lower compared to the conventional module concept. Weight analysis shows a lower weight of TPedge modules compared to conventional modules and glass-glass laminates (-0.4 kg). A Carbon footprint analysis performed for different module concepts and important module materials shows a lower CO_2-footprint of the materials used in TPedge modules compared to conventional modules.

Keywords: CTM, Cell-to-Module, Module Manufacturing, Durability, Reliability, Cost reduction, Weight Analysis

1. INTRODUCTION

Conventional photovoltaic modules use polymeric foils like ethylene-vinyl acetate (EVA) as solar cell encapsulation [1]. 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 [2]-[6]. A lamination process is needed for module production to encapsulate the cells in polymer foils. This process takes 8-15 minutes [7] and is known to represent a bottle neck in solar module production. The costs of foils and aluminum frames are a significant cost factor to PV module production [8] for conventional modules. Various innovations have been proposed such as the introduction of ultra-fast cure material, non-curing thermoplastics or other material groups [9] as well as multi-stage laminators for faster processing times or glass-glass-laminates for improved aging stability. None of these measures were able to completely eliminate the intrinsic disadvantages of the encapsulation foils at competitive cost levels.

In previous work we presented the “TPedge” module concept; a gas-filled glass-glass module with an edge sealing [10]-[13] that targets the disadvantages of conventional laminates. This work reveals the progress in the development of this module concept and its maturity by presenting additional results from accelerated aging (4000 hours damp-heat) and outdoor exposure. We compare TPedge with other module concepts such as conventional glass-foil-laminates as well as with glass-glass-laminates.

We perform a weight analysis of module materials and evaluate TPedge modules using 2 mm thin glass on reliability and weight reduction.

We perform a detailed analysis of the cell-to-module (CTM) power ratio of the TPedge concept in comparison to other photovoltaic modules. A cost analysis for the TPedge module concept is performed. We combine results of the CTM-analysis with the cost calculation and calculate specific costs (€/Wp).

2. THE TPEDGE MODULE CONCEPT

The “TPedge”-module concept applies an edge sealing process, well known from the manufacturing of double glazing insulation windows. 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 front glass with anti-reflective coating as used in solar thermal collectors is used to minimize reflection losses.

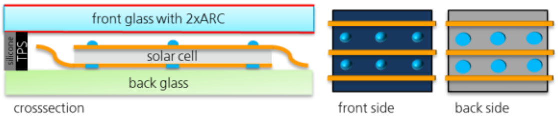

Figure 1: TPedge-module sketch with position of adhesive pins and double layer edge sealing [11]

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.

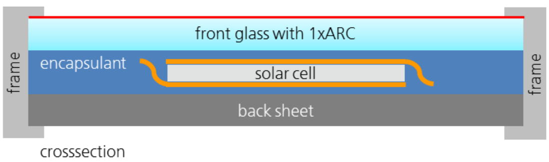

Figure 2: Conventional solar module schematics

3. RELIABILITY TESTING

a. Damp-Heat-Testing

Damp-heat tests according to IEC 61215 and IEC 61730 are performed on seven modules at Fraunhofer ISE TestLab PV Modules, see Table I. Three TPedge modules, three conventional glass-foil-modules and one glass-glass-laminate are tested. One TPedge and one conventional module (B) include a different set of cells and 20 cells per module only. Commercially available module materials are used and modules are manufactured to achieve comparability (same materials, same production parameters etc.). After every 1000 hours power measurements and EL-inspections are performed.

Table I: Power measurement results before and after damp-heat tests (85 °C, 85% r.h.)

	Initial Power [Wp]	After 4000 h damp-heat [Wp]	number of cells
TPedge A1	262.97	259.55	60
TPedge A2	262.62	260.67	60
TPedge B2	81.81	81.54	20
Conventional A1	274.87	217.59	60
Conventional A2	274.49	159.94	60
Conventional B2	86.06	84.06	20
Glass-Glass A1	272.34	263.59	60

Test results show only minor damp-heat-related effects on TPedge modules (ΔP_{MPP} < 1.3%). The conventional glass-backsheet modules using cells of manufacturer A fail after 4000 hours with a power loss of 27% and 41%. The smaller module using cells of manufacturer B is measured with a power loss below the 5% fail criteria (ΔP_{MPP} = -2.3%).

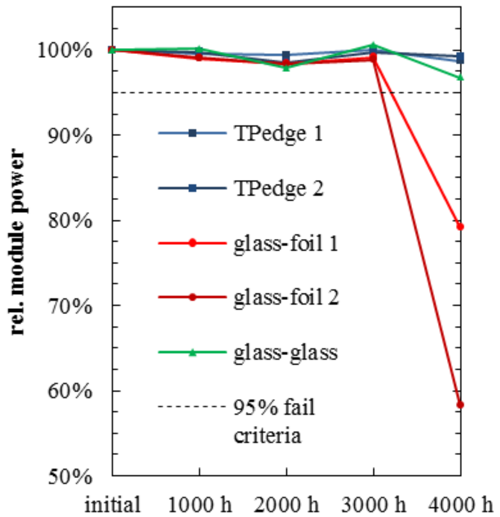

Figure 3: Power measurement results of full sized modules of different setups after several damp-heat-measurement cycles

Aging of the full size modules is clearly visible in the electroluminescence-images (Figure 4). The glass-glass-laminate withstands the extended test (ΔP_{MPP} = -3.2%) but EL shows damp-heat induced degradation in cells close to the module edge (Figure 4).

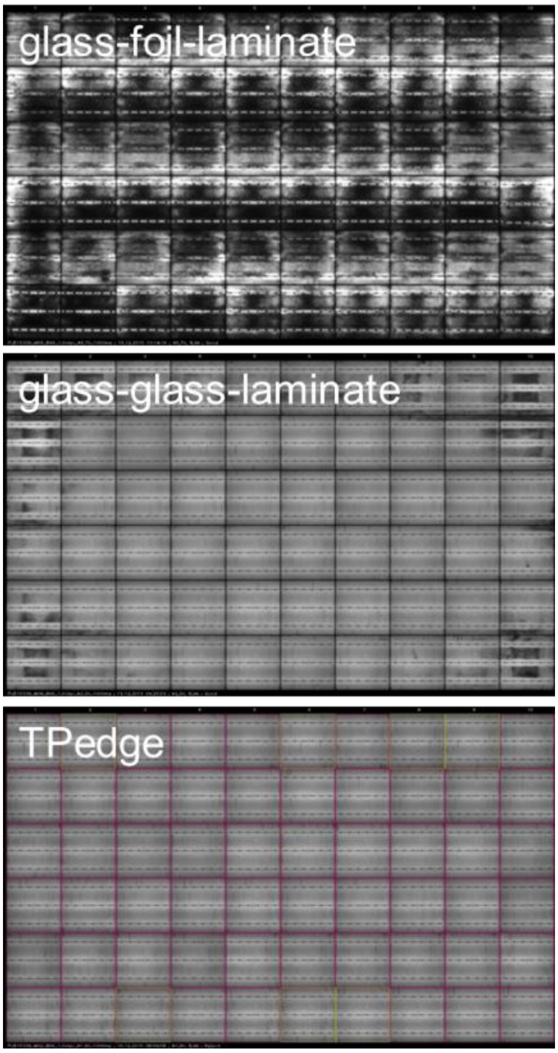

Figure 4: EL-images of different modules after 4000 hours damp-heat-testing

b. Outdoor Testing

Since August 2013 ten TPedge BiPV modules are operating in a vertical façade at Fraunhofer ISE, Freiburg (Figure 5) [14]. The modules contain MWT back-contact cells processed at Fraunhofer ISE PV-TEC [14] that are soldered to strings at Fraunhofer ISE ModuleTEC using the technology of shaped interconnectors [15].

Figure 5: Façade application of 70 TPedge BiPV modules at Fraunhofer ISE, Freiburg

In 2015 60 additional modules of two different sizes (42 and 14 cells) have been added to the façade. During installation of the additional modules an inspection of a previously installed module has been performed. No damage has been discovered using electroluminescence (Figure 6). A power measurement shows a ΔP_{MPP} of -1.9% of the inspected module (measurement uncertainty of initial and final measurement is 1.6%).

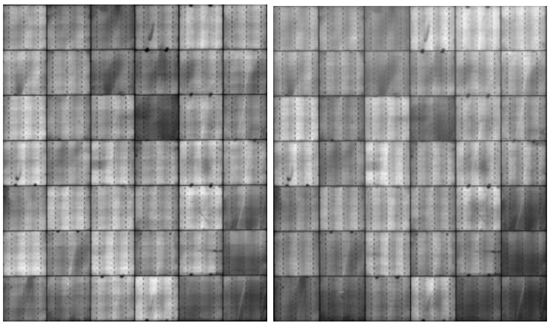

Figure 6: EL-image of BiPV module before (left) and after (right) two years of outdoor exposure. prototype MWT back-contact solar cells

Monitoring results show no decrease in the performance ratio of the installed modules (Figure 7).

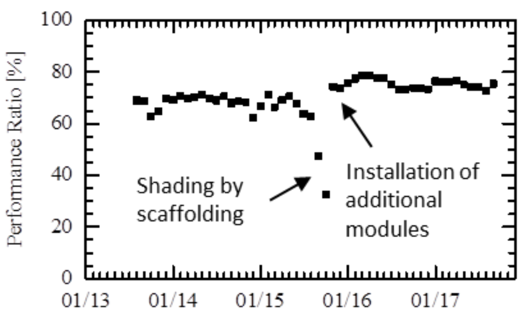

Figure 7: Performance ratio of TPedge BiPV application (modules facing 30° south, vertically installed)

Additional outdoor testing has been performed on nine full sizes modules of different setups. Four TPedge modules, three conventional modules and two glass-glass modules are tested for 14 months in Freiburg. Modules are similar to the modules tested for damp-heat-resistance. Cells of two different manufacturers and a TPedge module using 2 mm thin glass are tested.

The modules show no signs of degradation or power loss (ΔP_{MPP} < 0.9%) after 14 months of outdoor exposure. Electroluminescence shows no change between initial images and images after testing.

Additional test results regarding TPedge can be found in previous publications. Results of extended thermal cycling, mechanical load testing, PID-stability, hail stability have been published earlier [10][11][13].

4. WEIGHT REDUCTION

TPedge is a double glass module so that a higher weight is expected for a TPedge setup using two 3 mm glass panes compared to a conventional module. We measure the weight of module components and analyze weight reduction potentials.

Table II: Specific weight of module components

Component	Weight	
Glass (3 mm)	7.5	kg/m²
Glass (2 mm)	5.0	kg/m²
Encapsulant	0.4	kg/m²
Backsheet	0.45	kg/m²
Solar cells	11.0	g/pcs
String ribbon	17.0	g/m
Cell ribbon	2.6	g/m
Edge sealing	0.1	kg/module
Aluminum frame	2.5	kg/module
Junction box + cables	1.9	kg/pcs

Analysis shows that weight reduction of 30% is possible by using 2 mm thin glass for TPedge instead of 3 mm glass. Also TPedge using thin glass features the lowest weight compared to a conventional module (3 mm glass) and a glass-glass-laminate (2x 2 mm glass) (Figure 8).

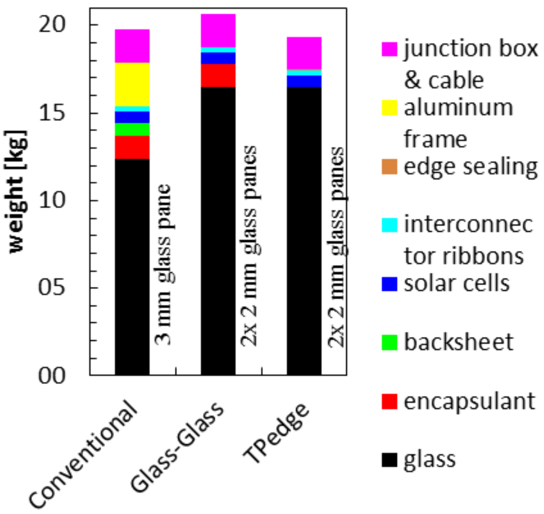

Figure 8: Weight analysis of different module concepts; edge sealing not visible due to small contribution to module weight

We have reported in previous publications [11][13] that the reduction of weight for the TPedge concept is possible by using 2 mm thin glass. Previously reported laboratory reliability tests cover mechanical load, damp-heat as well as hail tests. Outdoor test results with thin glass TPedge modules have also been presented. We demonstrated that the weight of TPedge modules can be successfully reduced without compromising on reliability.

5. CTM-ANALYSIS

We perform a cell-to-module analysis of different module concepts to analyze estimated losses from the additional air-glass interface in TPedge modules. Analysis is performed using Fraunhofer ISE SmartCalc.CTM [17]-[20]. The bill of materials of the analyzed setups is shown in Table III.

Table III: Bill of materials of analyzed module concepts

Component	Specification
Front glass	2.0 mm for glass-glass-laminate (1x ARC) and TPedge (2x ARC); 3.0 mm for conventional modules (1x ARC)
Rear glass	2.0 mm for TPedge and glass-glass laminates (no ARC)
Backsheet	White Tedlar-PET backsheet, 0.35 mm for conventional module
Encapsulant	EVA, 460 µm for laminates; air for TPedge
Solar cells	4.77 Wp, mono-crystalline, pseudo-square, 3 busbars (tapered)
String ribbon	6.0x0.3 mm copper core with SnPbAg coating
Cell ribbon	1.5x0.2 mm copper core with SnPbAg coating

Analysis confirms the additional reflection losses on position 2 (inner interface) of the TPedge front glass (Figure 9). Also coupling gains from module encapsulation reduce the module power of TPedge modules compared to conventional laminates. Reduction of interconnector losses is caused by lower currents of TPedge modules due to decreased irradiance on cell level. While TPedge features only small coupling gains, losses from encapsulant absorption become negligible due to the thin (< 1 mm) air filling of the glass spacing. The CTM_{power}-ratio of the analyzed conventional module is calculated to be 0.954. The CTM_{power} for TPedge is 0.906. Another analysis is performed for a glass-glass-laminate. CTM_{power} of 0.947 for the analyzed glass-glass setup is lower compared to the conventional module due to reduced cover coupling gains of the transparent rear glass [21].

Simulation results are compared with power measurement. Differences between measurement and simulation are below 0.3% for all three concepts.

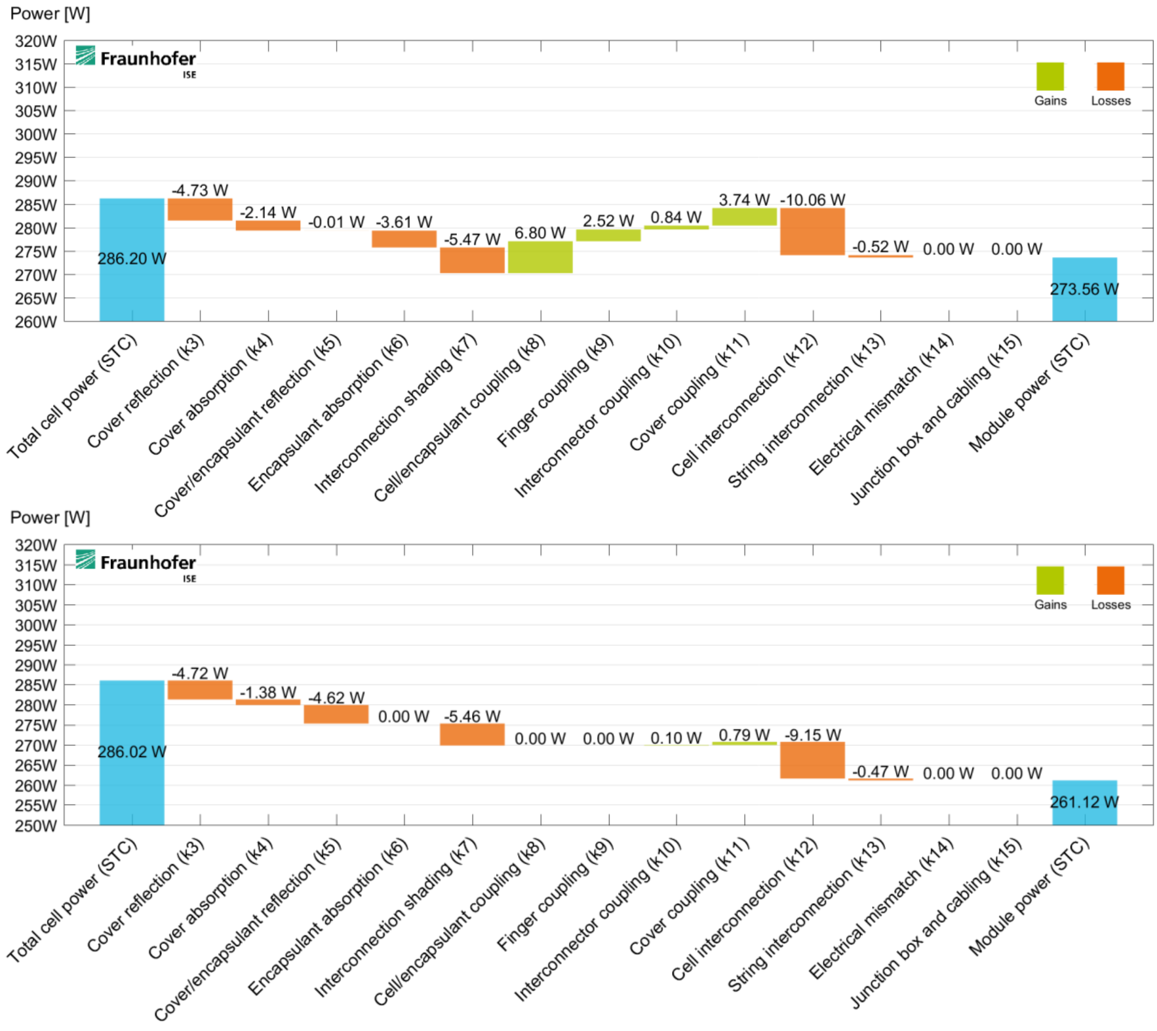

Figure 9: Cell-to-module analysis of a conventional module (top) and a TPedge solar module (bottom)

6. COST ANALYSIS

We perform a cost of ownership calculation for three module concepts using material and process costs. Calculation is performed with a cost analysis tool developed by Fraunhofer ISE considering material and process costs [16]. Important material costs are shown in Table IV.

Table IV: material prices as input for cost analysis

Component	Price	
Safety glass, 0x ARC	4.50	€/m²
Safety glass, 1x ARC	5.40	€/m²
Safety glass, 2x ARC	5.90	€/m²
Encapsulant	1.30	€/m²
Backsheet	2.00	€/pcs
Solar cells	0.225	€/Wp
String ribbon	0.04	€/m
Cell ribbon	0.24	€/m
Pin adhesive	200	€/l
Aluminum frame	6.00	€/pcs
Junction box + cable	4.00	€/pcs

We find TPedge to have lower Cost of Ownership than the other module concepts (Figure 10). While costs for solar cells, junction boxes, labeling etc. are the same for all concepts costs for glass, encapsulants, edge sealing and the aluminum frame are different. Saving the frame is the main factor for the glass-glass-modules price advantage compared to the conventional module. TPedge is cheaper due to the missing polymer foils.

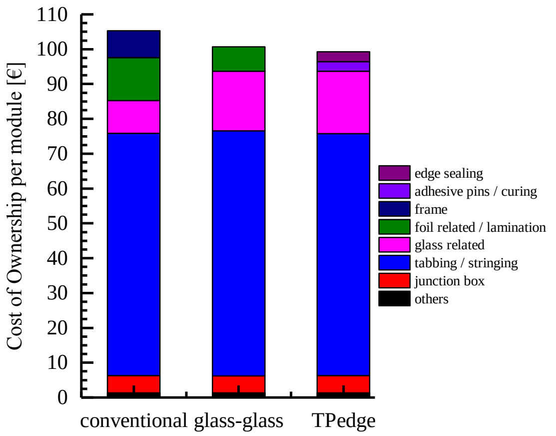

Figure 10: Cost of Ownership of different modules concepts. The cell costs are included in the tabbing/stringing part.

Costs of the analyzed setups are shown in Table V. We find the TPedge module to save 5.7% compared to the conventional module setup and to have the lowest costs of all compared module concepts.

Table V: Cost of Ownership of different module concepts

Module	Price	
Conventional module	105.32 €	100%
Glass-glass laminate	100.69 €	95.6%
TPedge	99.28 €	94.3%

Combining the results of CTM-analysis with the cost analysis we are able to calculate the specific costs (€/Wp). Modules in the cost calculation use 4.77 Wp solar cells as those were used for prototyping and CTM-analysis. Results are displayed in Table VI.

Table VI: Specific costs of different module concepts

	Conventional Module	Glass-glass Laminate	TPedge
COO	105.32 €	100.69 €	99.28 €
CTM	0.954	0.947	0.906
Specific Costs	0.385 €/Wp	0.382 €/Wp	0.390 €/Wp
	100%	96.8%	98.7%

We find the conventional module setup to have the highest specific costs and TPedge to save 1.4%. In the analyzed setups the frameless glass-glass laminate has the lowest specific costs (-3.5% compared to the conventional setup).

Additional costs resulting from logistics (e.g. packaging) or system integration (e.g. mounting) have not been considered.

7. CARBON FOOTPRINT

We perform an analysis of the carbon footprint of the materials that are used for module production. We consider important materials that are characteristic for the module concepts. Materials that are the same in all analyzed concepts (solar cells, junction boxes etc.) are ignored (ceteris paribus). Data is obtained from literature [22]-[33].

Table VII: CO_2 footprint of important module materials

Component	CO_2-footprint	
Glass (3 mm)	14.0	kg $_{CO2}$/m²
Glass (2 mm)	9.3	kg $_{CO2}$/m²
Encapsulant	0.8	kg $_{CO2}$/m²
Backsheet	0.7	kg $_{CO2}$/m²
Aluminum frame	19.4	kg $_{CO2}$/module

The glass-glass-laminate and TPedge use two 2 mm thin glasses. Modules have a size of 1.65 x 1.00 m² and – if applicable – use two layers of encapsulant and one backsheet. Analysis shows that materials used in TPedge feature a lower CO_2-footprint compared the other concepts (Figure 11). Additional effects from energy consumption during production (e.g. lamination) have not been considered.

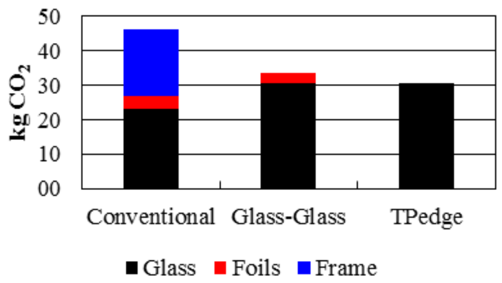

Figure 11: Combined CO_2-footprint of materials used for module production

8. SUMMARY

TPedge is successfully tested in an extended damp-heat test (4000 hours, 85 °C, 85%r.h.) with a change in P_{MPP} < 1.3%. Electroluminescence imaging reveals no defects in TPedge modules due to testing. We find damp-heat induced aging effects in the manufactured reference modules (conventional glass-backsheet and glass-glass configuration).

Cell-to-module analysis of TPedge, glass-backsheet and glass-glass modules shows increased reflection losses of TPedge. CTM_{power} ratio for TPedge (0.906) is lower than for conventional (0.954) and glass-glass-laminates (0.957).

Cost calculation shows lower cost of ownership (COO) of the TPedge module compared to the conventional module (94.3%) and the glass-glass-laminate (95.6%).

We calculate the specific costs (€/Wp) using results of COO- and CTM-analysis and find TPedge to have lower specific costs than the conventional module (98.8%).

We measure the weight of important module components and analyze weight reduction potentials for TPedge. We find a weight reduction of 30% possible by switching from 3 mm to 2 mm glass panes. Frameless thin-glass TPedge modules are lighter that framed glass-backsheet modules. Modules using 2 mm glass panes successfully perform in laboratory and outdoor testing so that weight reduction does not compromise the excellent reliability properties of TPedge concept.

We calculate the carbon footprint of module materials for different module concepts and find TPedge to have a 34% lower CO_2-footprint considering important module materials.

9. ACKNOWLEDGEMENTS

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