Solar PV Building Skins – Structural Requirements and Environmental Benefits

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Abstract

The majority of the photovoltaic (PV) modules used in building skins contains glass, but does not entirely comply with the product standards and design rules for glass in building. As a result, structural applications are subject to individual approval by the building authorities in many cases. This paper presents experimental research on glass based photovoltaic modules, analysing their mechanical properties in comparison with approved construction products. The focus is on glass-glass modules and on the question whether the most common module configurations can be classified as laminated safety glass. Testing included residual resistance testing to study the potential to provide residual load-bearing capacity and shear testing to examine the interaction of photovoltaic cells and interlayer material as well as adhesion characteristics. If approved interlayers are used, glass-glass modules correspond to the safety level of laminated safety glass, because the PV integration does not impair breakage behaviour and improves residual resistance, while the observed reduced adhesive bond does not imply a higher injury risk. Formal classification of photovoltaic products within the product and design standards for glass in building could facilitate the use of building-integrated photovoltaics. Life-cycle assessments of photovoltaic systems so far concentrated on roof-top and ground-mounted installations. Based on these studies, the specific environmental performance of building-integrated systems was analysed. Constructive integration of the PV modules associated with the substitution of conventional materials in the building skin reduce the life-cycle environmental impacts like primary energy demand and greenhouse gas emissions, especially in those areas with suboptimal solar irradiation like façades. The net energy payback times calculated for Central European range from 0.8 and 5.6 years and the net carbon footprint varies between 12 and 192 g CO_2*-eq/kWh.*

Keywords

Photovoltaics, glazing, laminated safety glass, approval, energy payback time, carbon footprint

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1 INTRODUCTION

Solar electricity produced by photovoltaic (PV) systems will play a major role in future energy supply systems. Integrating PV modules into buildings' envelopes can stimulate new architectural applications and improve sustainability of both PV power generation and buildings. The majority of the PV modules used in building skins contains glass as cover and backing material. Their mechanical performance as glazing product has not been adequately characterized (DIBt, 2012). Type approval and0 safety qualification according to the international electrical standards (DIN, 2006; DIN, 2009; DIN, 2007; DIN, 2012a) as well as quality control in module production are adequate for non-structural applications including so-called building attached PV (BAPV) modules in roof-top systems and simple building integrated (BIPV) applications like PV modules used as roof covering (DIBt, 2012). In contrast, these standards are not sufficient for structural applications like façades or overhead glazing (Dimova, Pinto, Feldmann, & Denton, 2014; Schneider, Kleuderlein, & Kuntsche, 2012). Here, the basic requirements for building as well as the safety level, product standards and design rules for glass components apply.

Generally, mechanical resistance and stability as basic requirements for construction works can be verified using regulated construction products with mechanical properties defined in product standards in combination with approved design methods and rules. PV modules do not entirely comply with these standards. As a result, structural BIPV applications are subject to individual approval by the building authorities in many cases. This paper presents experimental research on glass based photovoltaic modules, analysing their mechanical properties in comparison with regulated construction products. The aim is to provide a scientific basis for a formal classification of PV modules as regulated construction products, enabling their use without further approval in the future.

Life-cycle assessment (LCA) is a common method to characterize ecological impacts and benefits of products and processes. It describes the energy and material flows in all live-cycle stages. The environmental impacts of photovoltaic systems heavily depend on the cell technology and the associated energy demand for different production procedures, e. g. polycrystalline or monocrystalline type wafers or different deposition methods for thin-film cells. In this context, the electricity mix at the production site has a significant influence. Benefits arise from the generation of electricity from solar radiation without resource consumption and pollution. The potential PV electricity production essentially depends on the solar irradiation at the installation site and on the electrical efficiency of the PV components.

FIG. 1 Non-structural BIPV with modules as roof covering (left) and structural application as roof glazing or façade glazing. ©Marché International, Kemptthal/CH (left), Bruno Klomfar (middle), Stefanie Flohr, TU Dresden (right)

Various LCA studies already have proved that PV systems produce by far more energy during their life time than was necessary for their production and in most countries reduce greenhouse gas and other emissions. Improvements in production technologies, material utilisation and module efficiency have improved the ecological footprint in the past and will continue in the future. Yet, these studies concentrated on typical roof-top and ground-mounted installations. Therefore, the specific environmental performance of building-integrated modules is analysed considering the lower electricity yields, for example in façades, and the substitution of conventional building elements by the PV modules.

2 PV PRODUCTS AND METHODOLOGY

2.1 MODULE CONFIGURATIONS IN TERMS OF STRUCTURAL REQUIREMENTS

Photovoltaic modules used as roof coverings or in roof-top systems typically rely on glass-backsheet configurations. The 0.2 to 0.4 mm thick backsheet typically consists of a combination of several polyethylene terephthalate (PET) or PA films with UV and a coating providing UV and hydrolysis resistance. Glass-glass modules are more suitable for integration in roof and façade glazing and can also be processed into insulating glass units. Configurations basically differ according to laminated glass with embedded PV cells and thin-film cells as a coating directly deposited on one of the two glass panes. The embedded cells are separate crystalline silicon wafer cells interconnected with metal soldering ribbons or a continuous polymer substrate coated or printed with thin-film or organic PV cells. The embedded flexible thin-film cells shown in Fig. 2 c) are polymer substrates coated with copper indium gallium diselenide (CIGS) cells, adhesively interconnected and affixed to a carrier mat. Another example would be continuous flexible solar films including organic PV cells. Common interlayer materials are polyvinyl butyral (PVB), ethylene vinyl acetate (EVA), thermoplastic polyolefin (TPO) or silicone-based encapsulants.

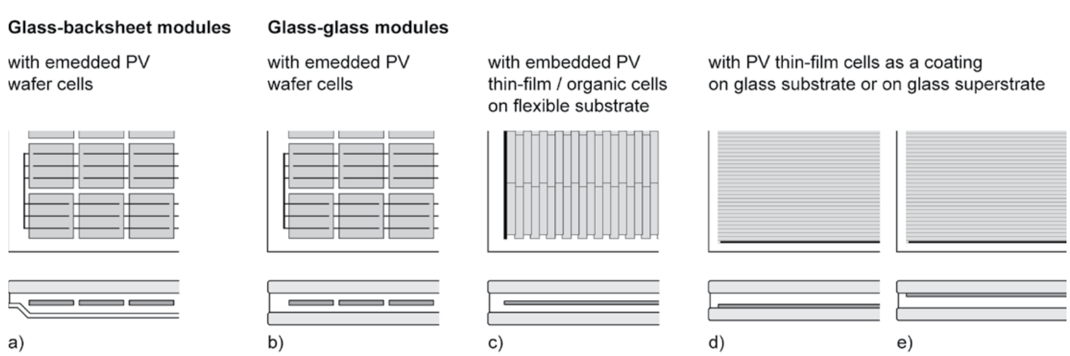

FIG. 2 Views and sections of common types of PV modules

Compared to regulated glass products, there are some uncertainties and deviations from the product and design standards. Glass-backsheet modules at first consist of thermally toughened glass (TTG), but the laminated cell-backsheet bond changes the safety properties: In case of breakage, the laminate sticks together and might fall down as a whole like a wet towel instead of small particles, which are typical for TTG and relatively harmless. Glass-glass modules are analogous in structural configuration to laminated glass. PV modules with embedded cells use regular glass products with well-known mechanical strength properties according to harmonized product standards (DIN, 2012b; DIN, 2015). An exception are innovative thin glass (TG) products, as there is no standard for thin glass yet, but there are products on the market with a national approval (DIBt, 2014). The PV thin-film industry uses float glass (FG) standardized according to DIN (2012c) as substrate or superstrate glass. Although the coating processes influence the mechanical strength properties, the coated panes still can meet the minimum bending strength values of float glass (Hemmerle, 2016).

In various European countries, many glazing applications require the use of laminated safety glass. Thus, classifying glass-glass modules as LSG (DIN, 2011) is desirable, but the specifications and verification methods are not harmonized in detail. Germany's building codes, for instance, used to narrow the general definition of LSG to the exclusive use of PVB as interlayer with no embedded materials and no coating towards the interlayer, as impacts on the adhesion cannot be ruled out. A major issue is residual resistance. A minor question is whether the integrated cells may affect the shear stiffness of the interlayer. The stiffness of the interlayer is influencing the static behaviour of laminated glass, but not all European countries consider this effect. Various PV manufacturers applied for a national technical approval allowing their BIPV modules to be used as LSG. The growing number of granted approvals demonstrates that glass-glass PV modules are generally able to provide structural safety equivalent to laminated safety glass.

2.2 RESIDUAL RESISTANCE TESTING

Residual resistance is a main safety property of laminated safety glass. Post-fracture capacity after breakage of all glasses can only be verified experimentally. However, there are no harmonized test methods to prove residual strength and LSG with PVB is the only acknowledged benchmark. Based on previous schedules by various German building authorities (HMWVL, 2012; LfB BW, 2009; StMI, 2012; Espich, 2011) as well as studies on the correlation between wind load and glazing temperature (Wellershoff, 2006) and temperature increase due to PV integration, a test concept was developed to analyse PV modules in comparison with laminated safety glass of identical dimensions and sections (Hemmerle, 2016). Table 1 shows the standard load scenario and the increased temperature scenario to take account of the temperature dependent mechanical properties of the interlayer materials. The load level of 0.65 kN/m^2 corresponds to half the load-bearing capacity of the unbroken PV modules and LSG references sized 800 mm x 1300 mm and comprising 2 x 3.2 mm float glass.

Table 2 shows the tested PV module types and the related LSG references. For the PV wafer modules, 3.2 mm float glass conform to DIN (2012c) and 2.1 mm thin glass were considered. The modules with flexible CIGS thin-film cells included thermally toughened glass made of patterned glass conform to DIN (2000). The samples were taken from commercial production of three manufacturers: PV wafer modules and LSG 1 by LISEC Austria GmbH, PV superstrate modules and LSG 2 by Masdar PV GmbH; and PV flexible CIGS cells by Solarion AG.

TEST SCENARIO	SAMPLE TEMPERATURE	TEST LOAD	TEST TIME
Standard	+23 °C	0.65 kN/m^2	≥ 72 h
Increased temperature	+50 °C +68 °C	0.325 kN/m^2 0.325 kN/m^2	≥ 24 h ≥ 7 h (sequential after ≥ 24 h at +50 °C)

TABLE 1 Load scenarios

PV CELLS	PV MODULES: SECTION (SEE FIG. 2) AND MATERIALS		LSG REFERENCE
Embedded	b)	FG 3.2 mm | polycrystalline PV wafer cells in 1.0 mm PVB | FG 3.2 mm	LSG 1: FG 3.2 mm | 1.0 mm PVB | FG 3.2 mm
Embedded	b)	TG 2.1 mm | polycrystalline PV wafer cells in 1.0 mm PVB | TG 2.1 mm	(LSG 1)
Embedded	c)	TTG 3.2 mm | CIGS on flexible polyimide in 1.0 mm TPO | TTG 3.2 mm	–
Coating	e)	FG 3.2 mm superstrate coated with a-Si/µ-Si | 0.76 mm PVB | FG 3.2 mm	LSG 2: FG 3.2 mm | 0.76 mm PVB | FG 3.2 mm

TABLE 2 Sections of photovoltaic module samples and laminated safety glass samples used as reference

Testing was carried out on full size components in order to incorporate effects of the cell interconnections. Three samples per sample type and parameter were tested in horizontal position and linear support. Before the test load was applied, the samples were damaged with the aim of breaking both glass layers. The criterions for residual resistance were no failure within the test time and centre deflection that was measured for differentiated comparison.

2.3 SHEAR TESTING

The influence of integrated PV cells on the shear bond of laminated glass was analysed in exploratory axial shear tests on small, cylindrical specimens cut from laminated modules by means of water jet cutting. Their diameter of 34.6 mm resulted in a laminated area A = 27.2 mm^2. Two PV laminates each, incorporating 3, 4 or 6 mm float glass panes, were combined with 6 or 4 mm secondary float glass panes via auxiliary bonds in order to provide sufficient contact surface for the clamping jaws of the testing machine. A structural epoxy adhesive was used for the 0.5 mm auxiliary bonds. A tensile load was applied to the symmetrical specimens to displace the PV glass panes against each other and, thus, to place the interlayers with integrated PV cells under shear stress. The shearing was carried out at room temperature and relative humidity of 30.7 % with a constant load of 400 N for 10 minutes followed by an increasing load at constant crosshead speed of 2 mm/min until failure. Crosshead displacement Δx and load force F were measured to calculate shearing angle or shearing strain γ and shear stress τ according to equation (1) and (2).

$$(1) \quad \gamma \approx \tan\gamma = \frac{\Delta x}{d}$$

$$(2) \quad \tau = \frac{F}{A}$$

The PV module configurations examined were polycrystalline wafer cells integrated in a PVB interlayer with a thickness d = 1.2 mm and CIGS thin-film cells on flexible polyimide substrate affixed to a carrier mat and integrated in a TPO interlayer with a thickness d = 0.8 mm. The interlayer thickness was determined as the difference between the PV laminate thickness and the glass thickness measured after failure. The testing series included three specimen of each type. As a reference, specimens of both types without integrated PV cells were tested.

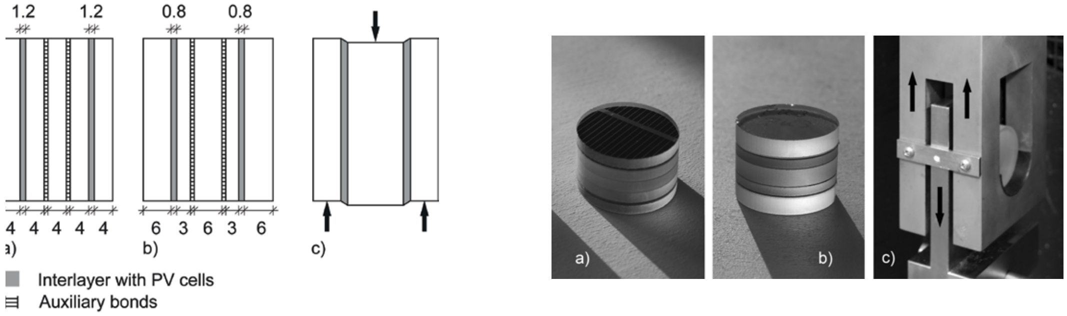

FIG. 3 Shear test specimens incorporating a) PV wafer cells or b) flexible CIGS cells and c) test set-up and apparatus

2.4 AMENDMENT TO LCA STUDIES ON BIPV

Recent LCA studies on rooftop PV systems served as basis to determine the specific environmental footprint of building-integrated PV systems. Common LCA indicators are the energy payback time (EPBT) and the carbon footprint indicating the life-cycle greenhouse gas emissions per kWh solar electricity generated. De Wild-Scholten (2013) has calculated energy payback times between 0.68 and 2.3 years and carbon footprints between 15.8 and 81.4 g CO_2-eq/kWh for a wide range of module technologies using 2011 manufacturers' data with module efficiencies of 14.8 % and 14.1 % (mono-/polycrystalline), 11.9 % (cadmium telluride – CdTe) and 11.7 % (CIGS). Production in China increases the carbon footprint due to the high share of coal in the country's electricity mix. The analysis took mounting structures, cabling, power conditioning and grid connection into account, but excluded installation, operation and maintenance and end-of-life phase. The underlying energy generation refers to Southern European sites and south-facing module surfaces inclined at an optimum angle, which receive a global solar irradiation of 1700 kWh/(m^2a). Life-cycle greenhouse gas emissions of these rooftop PV systems, also without considering end-of-life treatment, are reported (de Wild-Scholten, Cassagne, & Huld, 2014).

In contrast to rooftop systems, different parameters apply to building integrated PV systems. The fact that roof or façade glazing usually requires thicker glass sections, but no backsheets and no aluminium module frames, is neglected due to its minor influence. For crystalline modules, production in China is chosen in order to describe the worst-case scenario. Even though PV modules from European production are widespread in European BIPV applications, China's large market shares in the solar silicon, wafer and solar cell production (de Wild-Scholten, Cassagne, & Huld, 2014) must be considered. Moreover, this paper relates to Central European BIPV installations and a corresponding irradiation of 1294 kWh/(m^2a) on an optimally oriented surface. The reduced potential in electricity generation in roofs and façades of non-ideal east, south and west orientations and under unfavourable temperature conditions were calculated using the dynamic simulation software PV*SOL. On the other hand, PV modules as building skins substitute conventional building elements, e. g. roof tiles or façade cladding. The environmental impact of these were offset against the primary energy content (PEC) and the greenhouse gas emissions of the PV system as a credit. The credits assumed were 47 to 246 MJ/m^2 and -0.1 to 19 kg CO_2-eq/m^2 for roof claddings or 47 to 1080 MJ/m^2 and 16.6 to 67 kg CO_2-eq/m^2 for façade claddings considering a life-cyle of 50 years (El khouli, John, & Zeumer, 2014). Following internationally harmonised approaches, 30 years life expectancy and a power degradation rate of 0.23 % per year were used for the PV modules (Fthenakis et al., 2011).

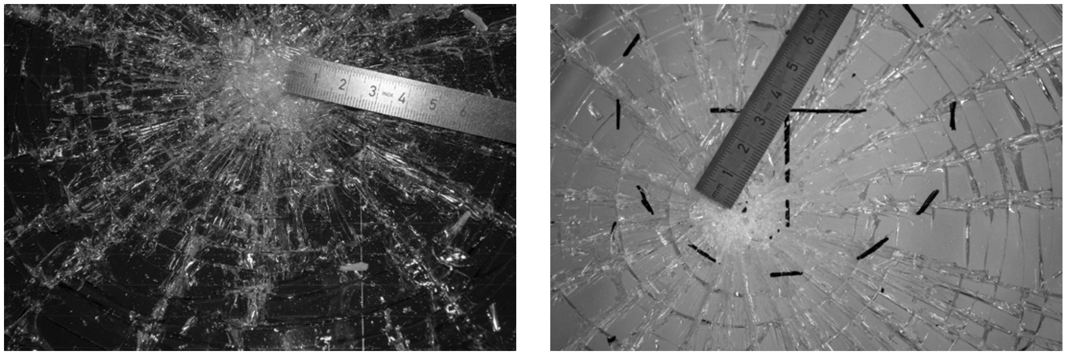

FIG. 4 Larger amount of loose glass splinters on the PV-coated superstrate glass (left) compared to the uncoated LSG cover glass (right) at the point of impact after ball drop

3 RESULTS

3.1 BREAKAGE STRUCTURE AND RESIDUAL RESISTANCE OF GLASS-GLASS PV MODULES

For residual resistance testing, the PV modules and LSG reference samples consisting of float glass and thin glass were damaged through dropping a 4.1 kg steel ball from a height of 2.5 m on the center. Neither the integration of wafer cells nor the thin-film coating significantly influenced the breakage structure. However, mechanical failure within the PV layer of the a-Si/µ-Si superstrate as the impacted side resulted in a larger amount of loose glass splinters. Compared to the float glass modules, the thin glass modules exhibited finer fracture patterns. As the PV modules and the related LSG reference samples in each case were produced by the same manufacturer using the same glass products and interlayers, the results concerning the influence of the PV integration can be generalised. The panes of the PV modules with embedded flexible CIGS cells were damaged using a prick punch and broke into small particles, typical of thermally toughened glass.

None of the samples failed in the standard scenario. In comparison with the respective laminated safety glass reference, the PV modules with embedded wafer cells showed 20 to 25 % less centre deflection and the PV thin-film on glass superstrate modules 13 to 14 % less deflection. There was not much of a difference in deflection between the wafer modules with thin glass and with float glass. CIGS PV modules, in spite of comprising only thermally toughened glass, showed considerably lower deflection than any of the float glass samples. Thus, the integration of all three types of PV cells improved the residual resistance.

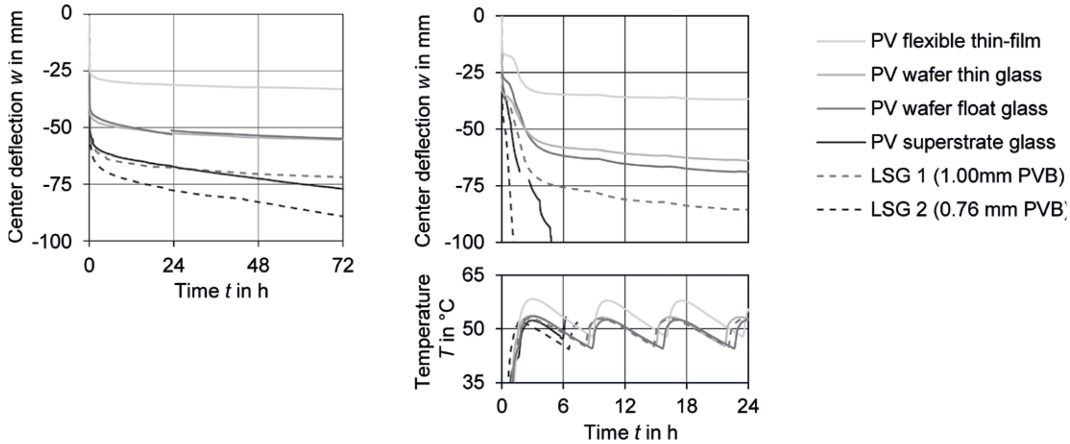

FIG. 5 Mean values of the measured centre deflections in the standard scenario (test load 0.65 kN/m² at room temperature, left) and in the increased temperature scenario (test load 0.325 kN/m² at +50 °C)

In the increased temperature scenario, the test temperature corresponded to the sample temperature measured at the outer glass surface. The interlayer thickness emerged as crucial parameter for the samples using PVB. Both PV and LSG 2 samples with only 0.76 mm PVB layer failed as soon as sample temperatures slightly exceeded +50 °C. PV and LSG 1 samples with 1.00 mm PVB layer passed the test time without failure as well as the CIGS modules with 1.00 mm TPO interlayer. Again, the PV modules with embedded wafer cells showed 20 to 25 % less centre deflection than the LSG reference. Moreover, none of the PV wafer modules failed during the second test period at +68 °C, while two of the three LSG 1 samples failed.

Interconnected wafer cells reinforce the broken laminate, because the soldered interconnectors support tensile forces. This also applies to PV thin-film on glass modules, but to a lesser extent, as these only incorporated one cross-bus ribbon along the transverse axis connecting the outmost cells with the junction box in the centre. Different cross-bus layouts available in other PV thin-film modules may result in different reinforcing effects. Adhesively connected flexible PV cells significantly stiffen the broken laminate, as Fig. 6 shows, because they form an additional layer with good tensile properties. As conventional laminated safety glass made of thermally toughened glass panes becomes flexible once broken and does not provide any residual load bearing capacity, the integrated PV cells do not only improve post breakage behaviour, but are the primary cause of residual resistance. In principle, these findings also apply to other PV technologies using flexible films to be integrated in laminated glass, e. g. organic based photovoltaics.

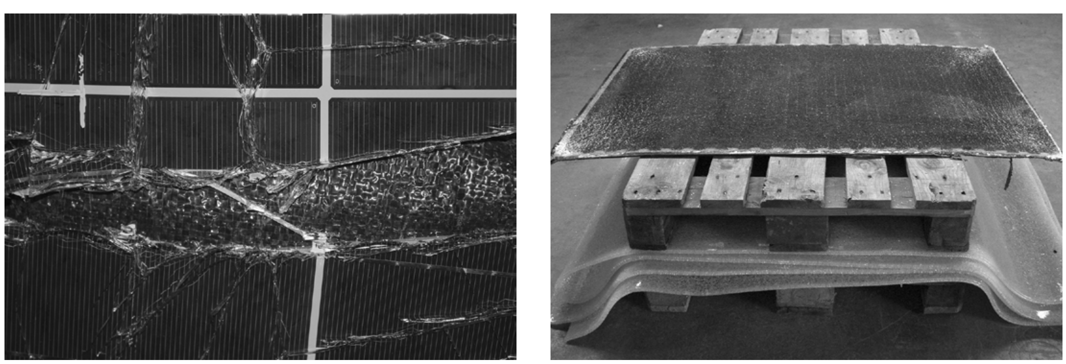

FIG. 6 Improved residual resistance due to PV wafer cells' soldered interconnectors (left, here: at +68 °C) and flexible PV thin-film cells stiffening the broken laminate (right, here: in contrast to LSG made of TTG without integrated PV layer)

The PV cells' solar absorptance results in increased warming of PV modules in the building skin. In order to evaluate whether this might overcompensate the reinforcement effects, the differences in deflection measured at sample temperatures between room temperature and +68 °C have been analysed to calculate a temperature coefficient. As a result, PV modules with embedded wafer cells could heat up to 11 to 18 K above the LSG sample temperature to reach the same deflection. Actually, the expected maximum temperatures of PV modules in the building skin are only 5 to 6 K higher compared to transparent laminated glass (Hemmerle, 2015). Thus, in the worst case, the overall effect of the PV integration on the residual resistance remains positive.

3.2 INFLUENCE OF PV CELLS ON SHEAR BOND AND ADHESION

Shear testing showed that integrating PV wafer cells in the PVB interlayer did not significantly influence the shear modulus. Yet, the specimen with integrated cells failed earlier than those without PV and exhibited adhesive failure at the interface between PVB and the rear side of the silicon wafer cells.

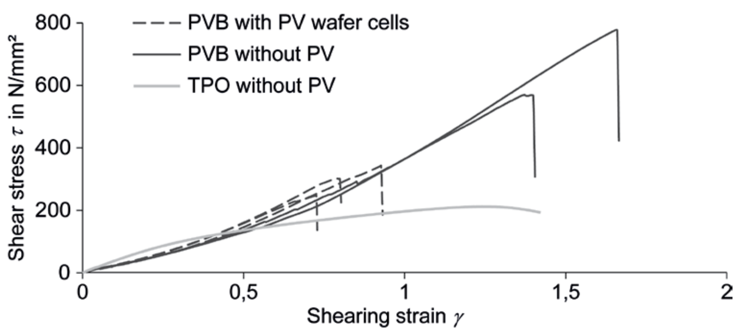

FIG. 7 Shear stress to shear strain diagram at +22 °C and 30.7 % relative humidity

Consequently, the PV cells reduced adhesive bond within the laminate. All specimens with flexible CIGS cells integrated in the TPO interlayer already failed adhesively during the constant load phase at the interface between the self-adhesive rear side of the CIGS cells and the carrier mat. Thus, the embedded CIGS cells also reduced adhesive bond within the laminate. Shear bond could only be determined for the specimens without CIGS cells with the results confirming the lower stiffness of the TPO interlayer in comparison with PVB at room temperature.

3.3 ENERGY PAYBACK TIME AND CARBON FOOTPRINT OF PHOTOVOLTAIC BUILDING SKINS

For Central Europe, an average solar irradiation of 1294 kWh/(m^2a) on an optimally oriented surface was calculated using country-specific annual irradiation data and country areas presented by de Wild-Scholten, Cassagne, & Huld (2014). Assuming a performance ratio of 0.77, the electricity generation averages 996 kWh/(kW_pa). According to the simulation results, the yield decreases to 85 to 75 % on roofs facing west or east, to up to 67 % on south façades and to up to 53 % on west or east façades. Based on this lower electricity generation (see Electricity generation and energy payback times (EPBT) for Central European BIPV installations), the energy payback times calculated by de Wild-Scholten (2013, see section 2.4) for Southern Europe and optimum orientation were proportionally converted. Without considering credits, the energy payback times of PV roof systems installed in Central Europe with optimally oriented module surfaces increase to values between 1.9 or 3.0 years for systems with crystalline silicon modules and 0.9 or 1.3 years with thin-film modules. Less favourable east or west orientations result in longer periods of 2.4 to 4.0 and 1.2 to 1.9 years. In south façades, the primary energy balance turns positive after 1.3 to 4.5 years, depending on the module technology, in east or west façades after 1.6 to 5.7 years.

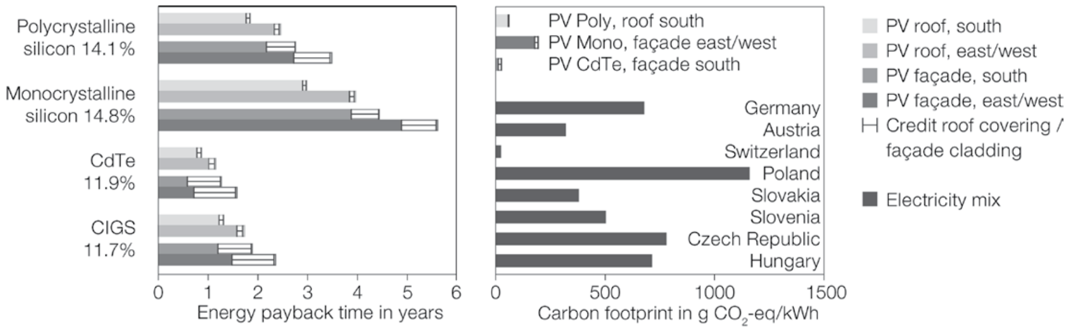

FIG. 8 Energy payback time depending on PV technology and BIPV application in Central Europe and carbon footprint in comparison with country electricity mixes

The primary energy content of building elements that are potentially substituted by the PV modules were taken from El khouli, John, & Zeumer (2014) and refer to a life-cyle of 50 years. Adjusting these values to the PV modules' life-cyle of 30 years reduced the deductible credits to 28 to 648 MJ/m². The energy payback times by de Wild-Scholten (2013) can be converted into primary energy contents of the PV systems in MJ/m² via multiplication by the annual electricity generation, the primary energy efficiency of the substituted electricity mix and the PV module efficiency. Depending on the module technology and the material of the substituted roof or façade claddings, the respective credit amounts to 1 to 55 % of the primary energy content of the BIPV system and thus reduces the energy payback time by 0.02 to 0.9 years. The net EPBT ranges between 0.8 and 5.6 years.

PV INTEGRATION	YIELD IN KWH/ KW_PA	EPBT IN YEARS MIN (CDTE)	EPBT IN YEARS MAX (MONO CN)	CREDIT IN MJ PEC/M² MIN	CREDIT IN MJ PEC/M² MAX	CREDIT IN YEARS MIN (CDTE)	CREDIT IN YEARS MAX (CIGS)	NET EPBT IN YEARS MIN (CDTE)	NET EPBT IN YEARS MAX (MONO CN)
Roof, optimum orientation	996	0.9	3.0	28	148	0.02	0.1	0.8	3.0
Roof east or west oriented	747	1.2	4.0	28	148	0.02	0.1	1.0	4.0
Façade, south oriented	667	1.3	4.5	28	648	0.03	0.7	0.6	4.4
Façade, east or west oriented	528	1.6	5.7	28	648	0.03	0.9	0.7	5.6

FIG. 9 Electricity generation and energy payback times (EPBT) for Central European BIPV installations

Available carbon footprint values of PV systems (see section) were also converted to relate to electricity yields or BIPV systems in Central Europe. The greenhouse gas emissions of roof or façade elements were allocated to the PV modules' life-cyle of 30 years. The resulting potential credits range from -0.06 to 40.2 g CO_2-eq/m². This corresponds to 0 to 59 % of the life-cycle greenhouse gas emissions of PV systems per m² module area, depending on the module technology and efficiency. Thus, credits for substituted roof or façade cladding can reduce the carbon footprint of Central European BIPV systems from 20 to 197 g CO_2-eq per kWh to 12 to 192 g CO_2-eq/kWh.

PV INTEGRATION	LIFE-CYCLE EMISSIONS IN G CO_2-EQ/KWH		CREDIT IN G CO_2-EQ/M^2		CREDIT IN G CO_2-EQ/KWH		NET EMISSIONS IN G CO_2-EQ/KWH	
	MIN (CDTE)	MAX (MONO CN)	MIN	MAX	MIN (MONO)	MAX (CIGS)	MIN (CDTE)	MAX (MONO)
Roof, optimum orientation	20.2	104	-0.06	10.0	-0.02	3.6	16.8	104
Roof east or west oriented	26.9	139	-0.06	10.0	-0.02	4.7	22.4	139
Façade, south oriented	29.3	156	11.4	40.2	3.8	18.2	12.0	152
Façade, east or west oriented	36.7	197	11.4	40.2	4.9	22.8	15.1	192

FIG. 10 Life-cycle greenhouse gas emissions of BIPV and credits to consider substituted roof covering or façade cladding

Since own consumption or grid feed-in of the PV electricity substitutes conventional electricity generation, the carbon footprint of the electricity mix of the respective country approximates the greenhouse gas emissions avoided by the PV system. Balancing life-cycle emissions against emission reductions, PV and BIPV systems significantly contribute to decreasing greenhouse gas emissions in most European countries. In the future, the increase in the share of renewable energy will reduce the potential savings.

4 DISCUSSION

4.1 GLASS-GLASS PV MODULES AS LAMINATED SAFETY GLASS

Evaluating the residual resistance test results from section , integration of all three PV cell types proved to enhance resistance compared to laminated safety glass. Thus, the design standards should classify standard PV module configurations to provide the same residual load-bearing capacities as laminated safety glass of the same sections without integrated PV cells. Only special designs should require experimental verification. In terms of residual strength of PV modules with wafer cells, 2.1 mm thin glass is comparable to 3.2 mm float glass, as the measured deflections showed.

Addressing other important properties of LSG, adhesion of interlayer to glass provides sticking of broken glass pieces and minimizes the injury risk. The lower adhesion of PVB to the rear side of the silicon wafer cells than to glass as well as between the self-adhesive rear side of the CIGS cells and the carrier mat showed no negative influence on residual resistance or on the sticking of broken glass pieces, as these interfaces with reduced adhesion were enclosed in the interlayer. Residual resistance testing of the PV thin-film on glass modules showed very good adhesion of PVB to the PV coating, namely the back contact layer. The critical issue is mechanical failure within the PV layer, which is sensitive to aging; and the resulting larger number of glass splinters associated with increased injury risk when the PV coated glass pane is the impacted side and broken glass pieces may fall down on accessible areas, depending on the structure and position of the glazing. However, splinter size and quantity observed were non-dangerous. In the absence of current reference values, the limits defined in a withdrawn standard (DIN, 1990) justify this evaluation. Further investigations on PV thin-film on glass substrate and superstrate glass modules would be of interest to affirm the low risk potential of broken glass pieces and should consider aging effects.

Shear bond depends on the interlayer material used. Neither the shear testing presented in this paper nor previous studies, e. g. by Weller & Härth (2005) or Friedman & Kirchner (2009), found negative influences of integrated PV cells on the shear modulus of glass laminates. It is not possible to evaluate whether the observed breakage at lower shear stress due to adhesive failure at the rear surface of the PV cells is critical or not. Test methods to characterize the time and temperature dependent viscoelastic material properties of interlayer materials have neither been harmonized yet, nor are there any minimum requirements. Albrecht & Maniatis (2003) made shear tests on glass laminates with and without various PV cells and various interlayers. They also found a negative effect of integrated PV cells on breakage shear stress at room temperature, but a positive effect at +60 °C. In the building skin, PV modules reach higher temperatures than transparent glazing. Thus, PVB, which exhibits a drastical loss in stiffness at temperatures larger than room temperature, generally is not the best choice for BIPV modules. Tear resistance of the interlayer turned out to be essential related to residual strength of PV thin-film on glass modules.

LSG moreover requires pendulum testing (DIN, 2003) to classify the pendulum body impact resistance. The tests also provide information on breakage behaviour. Comparative pendulum tests on pre-damaged glass laminates with and without PV wafer cells and EVA interlayer by Friedmann & Kirchner (2013) showed no significant influence of the embedded solar cells on crack propagation and impact resistance. The test results from section also indicated no influence of integrated PV cells on the breakage structure of laminated glass.

As a conclusion, the tested glass-glass module configurations are basically evaluated to provide a safety level which is at least equivalent to laminated safety glass, if the interlayer material is approved for use in laminated safety glass. The PV integration does not impair breakage behaviour and improves residual resistance, while the observed reduced adhesive bond does not imply a higher injury risk. Thus, a classification in future editions of the European LSG product standard (DIN, 2011) is recommended. The harmonised standard defines conformity assessment by the manufacturer including initial type testing and factory production control (DIN, 2011; DIN, 2005). These procedures are not common in the PV industry's mass production, but have been established by those manufacturers holding a national technical approval for PV modules for use as laminated safety glass.

Glas-backsheet modules require differentiation depending on the intended glazing structure. As vertical glazing, the modules can fulfil similar mechanical safety properties as laminated glass. In case of breakage, the backsheet binds the small TTG particles and, supported by own weight, prevents the broken laminate from slipping out of the support structure. Glass-backsheet modules might as well be used on par with monolithic TTG, as TTG does not always crumble into small particles at once, but large fragments may fall down in practice. For horizontal glazing, glass-backsheet modules are not recommended without additional structural elements as support for the broken laminate.

4.2 ENVIRONMENTAL LIFE-CYCLE BENEFITS OF PHOTOVOLTAIC BUILDING SKINS

The analysis of energy payback time and carbon footprint of PV modules buildings showed significant differences between the available technologies and the potential applications with similar tendencies of both indicators. Compared to rooftop systems, the lower electricity generation of building integrated systems results in reduced environmental benefits, but are partially outweighed by the material savings when the modules substitute conventional roof coverings or façade claddings. Thin-film modules with generally low environmental impacts and larger specific areas even enable overcompensation. Heading for climate neutral buildings, all appropriate areas in the building envelope must be used for energy production instead of focussing on those with highest solar exposure. Building integration improves the environmental footprint of unfavourably oriented PV installations in particular. Active building skins incorporating PV electricity generation aim at compensating environmental impacts of the whole building and life-cycle assessment must be performed at building level. This requires differentiated and up-to-date life-cycle inventories describing the relevant module types and manufacturing used in buildings instead of mass products for large commercial PV power systems. End of life scenarios need to be included, as future module recycling will provide further environmental benefits.

5 CONCLUSIONS

With rising energy standards, the use of photovoltaic systems in buildings becomes mainstream. Constructive integration of the PV modules associated with the substitution of conventional materials in the building skin reduce the life-cycle environmental impacts like primary energy demand and greenhouse gas emissions, especially in those areas with suboptimal solar irradiation like façades. Up to now, the use of PV modules as construction product often requires individual verification or approval procedures due to the lack for harmonized product qualification and design rules. Based on experimental testing, the mechanical performance of the most relevant module configurations was examined in comparison with approved glass products. The research provides systematic and material-based knowledge enabling classification of glass based PV modules as regulated construction products according to the existing standards. According to the presented results, glass-glass modules correspond to the safety level of laminated safety glass. Formal classification could significantly reduce the need for additional testing and approval, and thus facilitate the use of building-integrated photovoltaics.

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