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Smart Glass Coatings for Innovative BIPV Solutions

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Abstract: The glossy appearance of the cover glass of a photovoltaic module is mainly responsible for giving the module a mirroring effect, which is often disturbing in the case of building integrated photovoltaic (BIPV) façade applications. In this work, an innovative approach is presented to reduce the glare of BIPV modules by applying surface coatings to the front glass of the module. Three different glass coating technologies, applied on the outer surface of the photovoltaic module, were investigated: inkjet printing, screen printing, and sol-gel spray coating. The coatings, applied by these technologies in three different colours (grey, anthracite, and terracotta), were characterized with respect to their adhesion, light transmission, and reflection. Their chemical and physical stability after stress impact (condensed water resistance and chemical resistance against acids and salt-fog) was also investigated. The durability of these coatings was further evaluated after performing environmental simulations with artificial sunlight (xenon weathering) on coated glass. Additionally, accelerated aging tests (damp-heat testing, temperature cycling) were performed on the test modules to assess their performance stability. For those coatings, where no stress-induced changes in colour or the optical appearance of the module surface were detected, the potential for the architectural integration of the modules into building facades is high. A minimum glare of less than 0.1% of the specular reflection could be achieved. On the basis of the results of the optical characterization and the durability tests, grey screen-printed BIPV solar modules were installed in a demonstrator test façade. The high electrical performance, resulting in only a 10–11% performance decrease compared to the noncoated reference modules, perfectly showed the suitability of screen-printing in future applications for coloured and glare-reduced BIPV installations.

Keywords: BIPV; facade; coating; glare reduction

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1. Introduction

Not least because of the necessity to reduce greenhouse gas emissions (GHG) to lessen global warming, the efficient use and application of renewable energy sources is more topical than ever before [1]. Among the various industrially exploitable options, photovoltaics (PV) is one of the fastest growing technologies. In this area, building integrated photovoltaics (BIPV) represent a topic that is receiving special focus worldwide [2].

By simultaneously serving as the building envelope material and the power generator, building integrated photovoltaic systems can provide savings in materials and electricity costs, and reduce the use of fossil fuels and the emission of ozone-depleting gases, as requested by the European directive on zero-energy buildings [3,4]. Despite these advantages, the deployment of BIPV remains, nowadays, relatively small. Higher costs, compared to conventional façade elements, and the lack of architecturally appealing products have been identified as the main barriers to the widespread use of photovoltaics in buildings [5–7].

The most common state-of-the-art techniques for modifying the optical appearance of BIPV products use coloured cells, coloured encapsulants, or printed/coated paints on the inner side of the cover glass (well-reviewed in the report of IEA PVPS Task 15, "Coloured BIPV", as well as elsewhere) [8–11].

In this context, for example, commercial products are already available on the market, which have a clear colour effect [12–14]. In most of these applications, either the bulk material of the cover glass itself [13], or the inside of the cover glass, is modified with a colouring or colour-changing layer [12,14]. In most cases, however, the colouring of glass or its coating leads to a loss in the power conversion efficiency (PCE), in the range of about 20% (depending on the colour achieved) [15,16]. In contrast, Fraunhofer ISE could show a very small loss of about 7% by using the Morpho butterfly effect [10,17]. However, here, the colouring layer is applied to the inside of the cover glass, and the disturbing glare on the outside is achieved by a targeted and elaborate application of photonic structures to the outside of the glass.

From a design perspective, most of these solutions have no effect on the reflective properties of the BIPV modules, as they leave the outer cover glass unmodified. However, the real-life aesthetics of such BIPV modules is dominated by mirroring effects that depend on the illumination conditions and the position of the observer [18]. For instance, a typical effect is that the reflections of clouds and/or the ambiance dominate the impression of the building [19,20]. In extreme cases, these effects lead to a disturbing glare, which is not only a marketing issue, but a grave safety issue (traffic) as well [21].

Consequently, the research presented in this work focuses on the development of innovative solutions, allowing for an industrial manufacturing process for BIPV products with an improved visual appearance, at reduced costs and an optimized electrical performance.

The PV modules used in this work were glass–glass modules. This is mainly because the BIPV modules are to be used as a de facto replacement for conventional facade elements. It is, therefore, clear that one of the requirements is a correspondingly long service life. In addition, it has already been shown in the literature that glass–glass modules have a longer service life than glass–foil modules [10,22,23].

Three different technologies for the deposition of coloured coatings on the outside of the front cover glass of PV modules were investigated: inkjet printing, screen-printing, and sol-gel spray coating. The advantage of this approach, in relation to the state-of-the-art approaches, besides colouring, is the reduction of the reflection at the air–glass interface that is the main cause for the mirroring effect of the modules. However, the deposition of the coating on the outside of the front glass makes it more prone to weathering-induced degradation. For this reason, the ability of these coatings to withstand the effects of the long-term penetration of humidity, thermal mismatch, fatigue, or other stresses caused by repeated changes of temperature and humidity, as well as exposure to irradiation and corrosive media (salt, acids), was investigated in accelerated aging tests that were performed in the laboratory. Furthermore, the impact of the investigated coating technologies on the performance of the PV modules was assessed. Finally, prototype BIPV modules, with front glass coated on the outer side by the most promising technology, have been manufactured and were installed in a demonstrator building façade of around 16 m^2 in Mötz (Austria).

2. Materials and Characterisation

2.1. Coating Technologies

The three different glass coating technologies investigated in this work are described below:

- Inkjet (digital) printing: this technology relies on printing inks that are burned into the glass surface during a subsequent tempering/annealing process. Through inkjet (digital) printing, vivid designs (all photographic motifs are possible) can be created. The dot size and the ratio of the printed versus nonprinted area are freely adjustable and influence the degree of transparency. The technology is applied already in the (automotive) glazing industry and in photovoltaics [24].

- Screen-printing: Screen-printing on glass is used to create repeatable patterns, as well as solid areas, on a glass panel. A squeegee spreads the ink across a mesh screen. Afterwards, the glass is tempered and the ink is "fired" to the glass at a high temperature, fusing it to the glass surface. The printing can be precise, and the degree of transparency can be adjusted.
- Sol-gel spray-coating: This coating technology allows for the tuning of the aesthetical appearance (colour and texture) of the glasses [24]. In principle, this technology is based on a SiO_2 sol-gel method, which is also used for the transparent antireflective coatings of the PV modules. However, by mixing the sol-gel solution with inorganic pigments (e.g., iron oxides), and spray-coating the resulting suspension onto glass-substrates, a colouring of the surface can be obtained after a temperature-treatment step. After this tempering, the pigments are firmly attached to the glass surface.

2.2. Sample Characterization

The optical properties, the adhesion, and the chemical stability of the various coatings on a glass surface were characterized on a coated-glass test specimen. For that purpose, cover glass samples were fabricated in the colours, terracotta, grey, and anthracite, by inkjet printing, screen-printing, and sol-gel coating; an exemplary photograph of the inkjet-printed test specimen before exposure to corrosive media or radiation is given in Figure 1.

Figure 1. Photograph of the inkjet-printed test specimen, in the colours, terracotta, grey, and anthracite (**top** to **bottom**), before exposure to corrosive media or radiation.

The hemispherical reflection and transmission data of the coated samples were acquired by a spectrophotometer (Perkin Elmer Lambda 900), equipped with an integrating sphere in the spectral range from 200 nm to 2600 nm.

For the angle-resolved direct reflectance measurements, the coatings were illuminated by collimated light from a Xe light source, and the reflectance values were measured with a CAS140CT array spectrometer by using a GON360 goniometer.

The main characteristics of the prints/coatings and the coating/glass interfaces have been analysed as functions of the impact of various stress conditions: (1) Chemical and physical stability of the coating (degradation, corrosion); (2) Adhesion of the coating to the surface (delamination, spalling); (3) Scratch resistance.

The glass test specimens were characterized by the following procedures:

- Condensed water resistance, EN 1096-2; 4, 14, 21, and 42 days;

- Chemical resistance (acids), AA-0055, BMW Group (May 2018);
- Chemical resistance (salt-fog), EN 1096-2; 10, 21, and 42 days;
- Xe weathering, EN ISO 16474 (only with coated glass).

2.3. BIPV Module Test Samples

The impact of these coatings on the performance and reliability of the BIPV modules was assessed. Test glass/glass photovoltaic modules (40 cm × 40 cm), with coated front glass (coating on the outer surface; see Figure 2), were manufactured, and their electrical performance was compared to the reference modules manufactured with an identical bill of materials, but uncoated front glass.

Figure 2. (**Top**): picture of test glass/glass photovoltaic modules (40 cm × 40 cm): from left to right: reference module, inkjet anthracite, screen-print grey, sol-gel terracotta. (**Bottom**): Scheme of reference and coloured BIPV modules.

Furthermore, the test modules were subjected to various accelerated aging tests and the stress-induced changes of the electrical performance and of the material properties of the coating were determined.

Accelerated aging test BIPV test modules:

- Damp-heat (DH) tests, IEC 61215-2, 1000 h > hail test;
- Temperature cycle (TC) tests, IEC 61215-2, 200 cycles;
- Damp-heat (DH) test, 200 h > UV test (60 kWh/m^2) > pressure water-jetting test

The DH and TC tests were performed in a climatic chamber with controlled temperature and humidity. UV exposure was conducted in a chamber equipped with a metal halide light source, with an irradiance of 112 W/m^2 in the range 280 nm to 400 nm, and a sample temperature of 60 °C. For the hail test, ice balls, with a diameter of 25 mm, were launched with a velocity of 23 m/s in five different positions. The goal of the pressure water-jetting test was to prove the ability of the coating technologies to withstand typical cleaning procedures for PV modules or facades. For this test, a commercial pressure washer, with a maximum water pressure of 180 bar, was used.

2.4. Prototype BIPV Modules and Demonstrator Facade

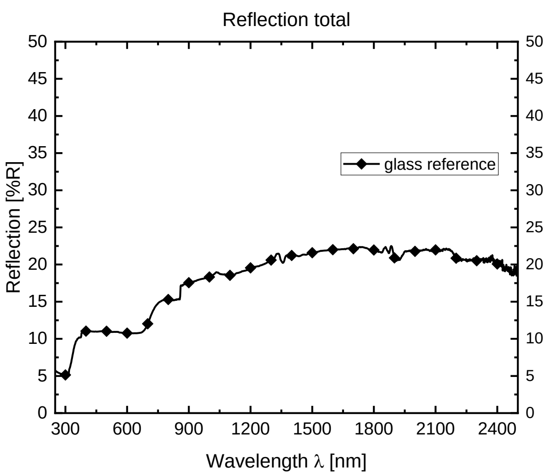
Prototype BIPV modules (1.65 m × 1.0 m), with the front glass coated grey by screen printing, have been manufactured and installed in a demonstrator building façade, with an area of around 16 m^2, in Mötz (Austria). The facade is tilted at 80° and western-oriented (azimuth 95°). A total of ten BIPV modules were installed in the façade, as shown in Figure 3. Six further modules, including the respective noncoated reference modules, were installed on the roof.

Figure 3. Photo of the test façade with grey screen-printed modules.

3. Results and Discussion

3.1. Characterisation of the Coatings

Figure 4 shows the graphs of the total hemispherical reflectance (THR) of the glass samples, without coating, as well as coated with the three different coating technologies (acquired by a spectrophotometer). It can be seen that the THR for all the coated samples is below 25% in the visible range (380–680 nm) for terracotta and grey, and below 20% for anthracite. For the terracotta-coloured coatings, an increase in the reflection fraction, in the range between 550 nm and 600 nm, which is responsible for the red colour perception, is clearly visible. In addition, except for the glass coated by inkjet printing, compared to the noncoated glass, the samples show a stronger reflection in the NIR range. Thus, an efficiency-reducing effect, caused by the elevated temperature of the solar cells in a PV module due to an enhanced absorption in the NIR spectral region, is not expected.



(**a**)

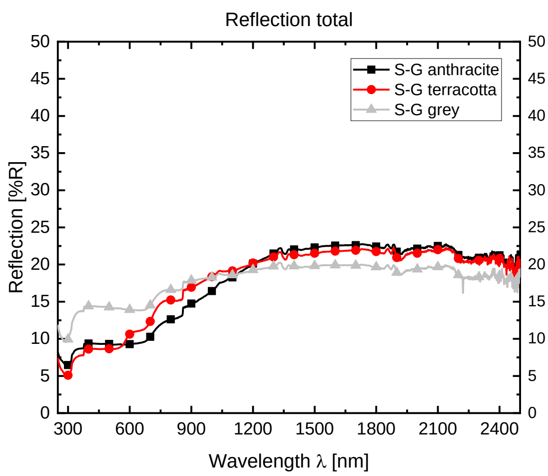


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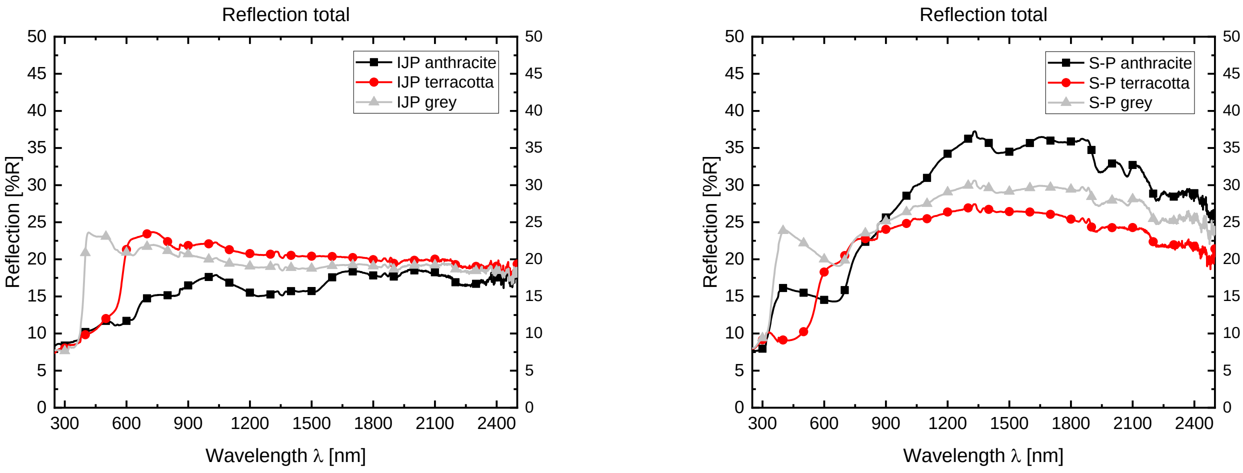
Figure 4. *Cont.*

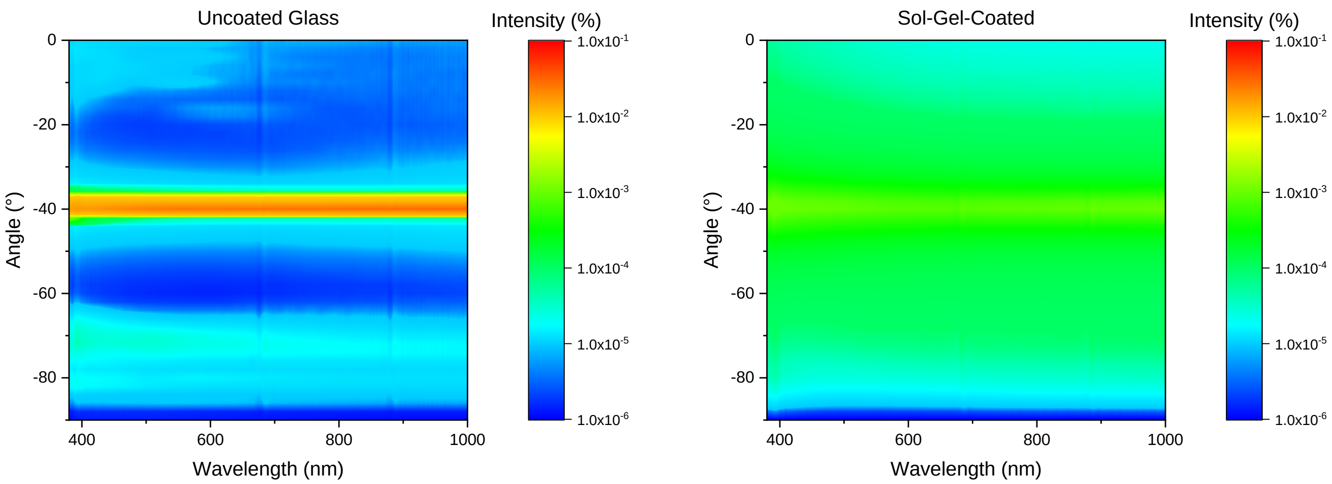


(**c**) (**d**)

Figure 4. Total hemispherical reflection of uncoated glass (**a**), terracotta-, grey-, and anthracite-coloured glasses, coated by sol-gel technology (**b**), inkjet printing (**c**), and screen-printing (**d**).

To prove the suitability of the coatings to reduce the glare stemming from the mirroring (specular) reflection, the corresponding false colour representations of the angle-resolved reflection are shown in Figure 5. All coated samples provide a significantly higher diffuse component of reflection, compared to the uncoated sample. This is clearly visible in the lower maximum values in the reflection, as well as by the clear broadening of the overall reflection characteristics. In particular, a direct reflection on the coated side of less than 0.1% could be achieved for all coatings.

In addition to the necessary reflection properties (for colour perception and glare reduction), a glass coating suitable for BIPV applications has to obtain the highest possible transmission in the relevant spectral range for the conversion of light into electrical energy by the solar cell. For this reason, the transmission properties of the coated cover glasses were measured in the range between 250 nm and 1200 nm. Figure 6 shows the respective spectral transmittance, τ(λ), exemplarily for the sol-gel and screen-printed samples. Transmission values above 55% were obtained for all samples and were in the range of 70–80% for the grey and terracotta sol-gel samples, as well as for the grey- and anthracite-coated screen-printed samples.



(**a**) (**b**)

Figure 5. *Cont.*

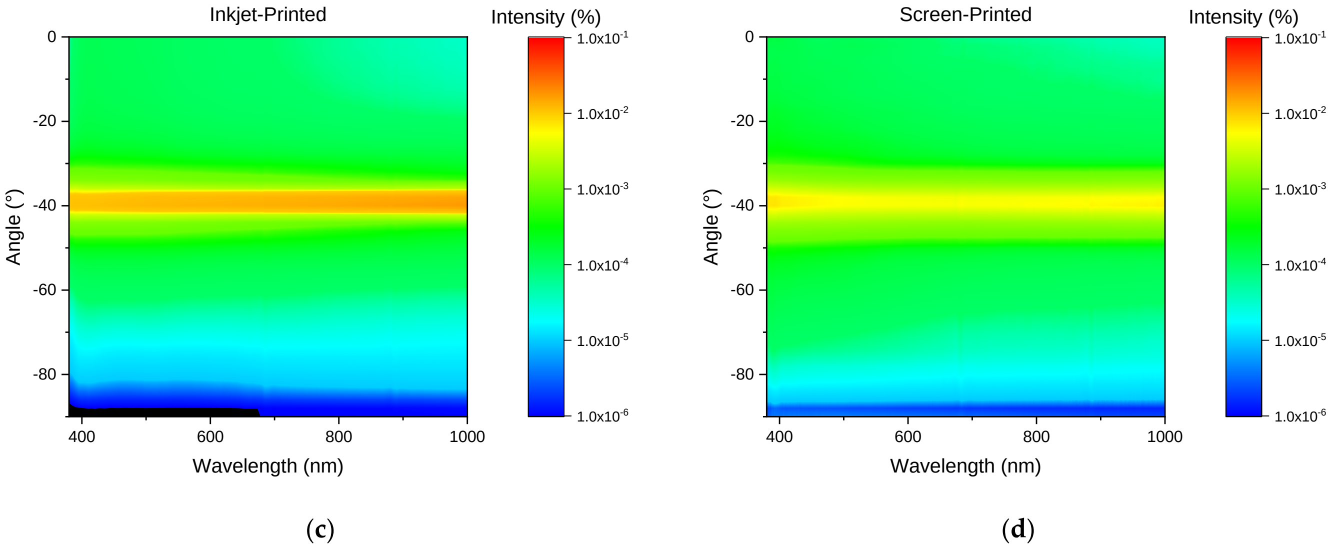


Figure 5. Angle-resolved reflection spectra for an uncoated glass sample (**a**) and for grey-coloured front glass samples, coated by the three different technologies: sol-gel-coating (**b**), inkjet-printing (**c**) and screen-printing (**d**). The lowering of the reflection maximum and the broadening of the overall reflection is clearly visible for all coatings, compared to the bare glass. (angle of incidence: 40°).

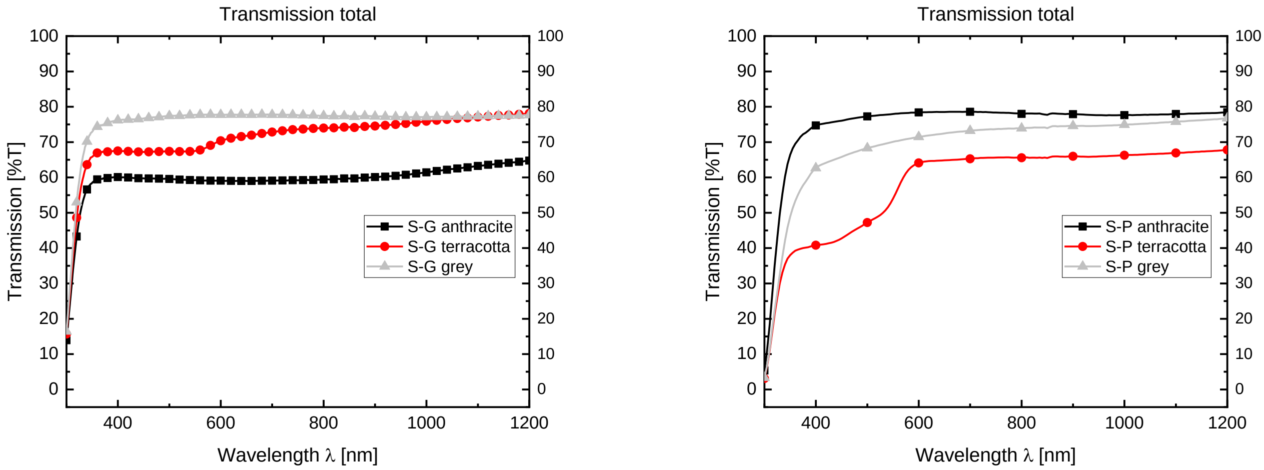


Figure 6. Transmission characteristics for coloured cover glasses coated by sol-gel (**left**) and screen-print (**right**) technologies.

To estimate the performance loss induced by each covered glass, its effective hemispherical transmittance of the photon irradiance, τ_e, was then calculated using the following formula, as defined in IEC 62805-2, and the values were compared to the case of an uncoated glass:

$$\tau_e = \frac{\int \tau(\lambda) E_p(\lambda) d\lambda}{\int E_p(\lambda) d\lambda} \quad (1)$$

For a photovoltaic glass, τ_e represents the proportion of the solar spectral photon irradiance $Ep(\lambda)$, optically transmitted through the glass in the range of the spectrum where the photovoltaic cell absorbs the light. The results of the estimated performance losses are shown in Figure 7.

Performance losses up to 60% were calculated for the inkjet printing technology, while more promising results were obtained for the screen-printing and sol-gel technologies. Yet, in this context, it has to be noted that performance losses of only 11–18% could be shown for the applied inkjet technology [24].

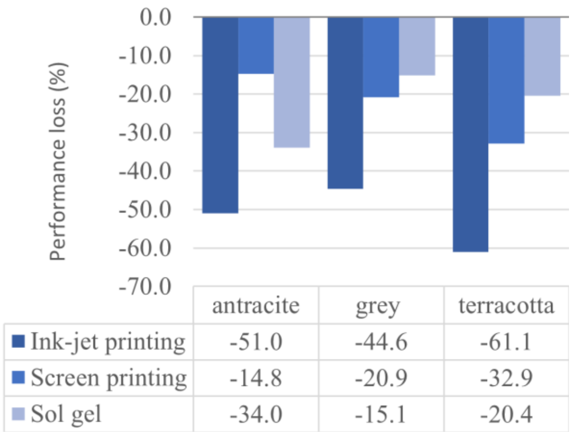


Figure 7. Estimated performance losses induced by each covered glass for a standard photovoltaic cell with respect to an uncoated glass, calculated as the ratio of the effective hemispherical transmittance of photon irradiance, τ_e.

The durability of the prints/coatings, with respect to their chemical and physical stability and the adhesion of the coating to the surface, was tested. The results are summarized in Table 1. The inkjet and screen-printed coatings showed good durability results against condensed water, salt impact, UV irradiation, and the cycling climate chamber tests' thermal cycling and humidity freeze. Only the contact of sulphuric acid with the screen prints showed unacceptable degradation effects. The sol-gel coating showed good stability for terracotta against condensed water, sulphuric acid, UV irradiation, and the cycling climate chamber tests' thermal cycling and humidity freeze. An inacceptable degradation was observed after the salt-fog test.

Table 1. Summary of the effect of accelerated aging tests on the three applied coating technologies: ((1) EN 1096 Glass in building—Coated glass—Part 2: Requirements and test methods for Class A, B, and S coatings; (2) IEC 61215 Terrestrial photovoltaic (PV) modules—Design qualification and type approval—Part 2: Test procedures; (3) ISO 16474 paints and varnishes—Methods of exposure to laboratory light sources—Part 3: Fluorescent UV lamps). The degradation levels defined were "no degradation" and "minor degradation", and the changes observed without influence on the performance or aesthetics were defined as "unacceptable degradation": degradation has a measurable impact on aesthetics or performance.

	Condensed Water (1)	Sulfuric Acid (1)	Salt-Fog (1)	Thermal Cycling (2)	Humidity and Freeze (2)	UV Radiation (3)
Ink-jet (digital) printing						
grey	o	✓	o	o	o	o
anthracite	o	✓	o	✓	✓	✓
terracotta	o	o	o	✓	✓	✓
Screen-printing						
grey	✓	x	o	✓	✓	o
anthracite	✓	x	o	✓	✓	o
terracotta	o	x	o	x	o	o
So-gel spray						
grey	x	✓	x	x	x	x
anthracite	x	✓	x	x	x	x
terracotta	o	✓	x	o	o	✓

Note: ✓: no degradation; o: minor degradation; x: unacceptable degradation.

3.2. Characterisation of the PV Test Modules

On the basis of the results of the durability test of the prints/coatings, and on the prospective of a successful architectural integration in a building façade and roof, inkjet anthracite, screen-print grey, and sol-gel terracotta were selected as the most promising solutions for actual performance testing with 4-cell test modules.

The electrical performance of these 4-cell test modules, with clear and coated front glass (Figure 2), were measured by an LED solar simulator, according to IEC60904.

The decrease in the electrical parameters-maximum power (Pmax), short circuit current (Isc), open circuit voltage (Voc) and fill-factor (FF)-of the test modules, with inkjet anthracite, screen-print grey, and sol-gel terracotta coatings for the front glass, with respect to the reference modules with clear front glass, are shown in Table 2. The decrease in Pmax is mainly due to the reduction of Isc, caused by a reduced transmission of the coated front glass (Figure 6). The variations in Voc and FF compensate each other. The measured values are aligned with the previously estimated ones (Figure 7), with higher power and current losses for the inkjet technology, and lower losses for the sol-gel and screen- print technologies.

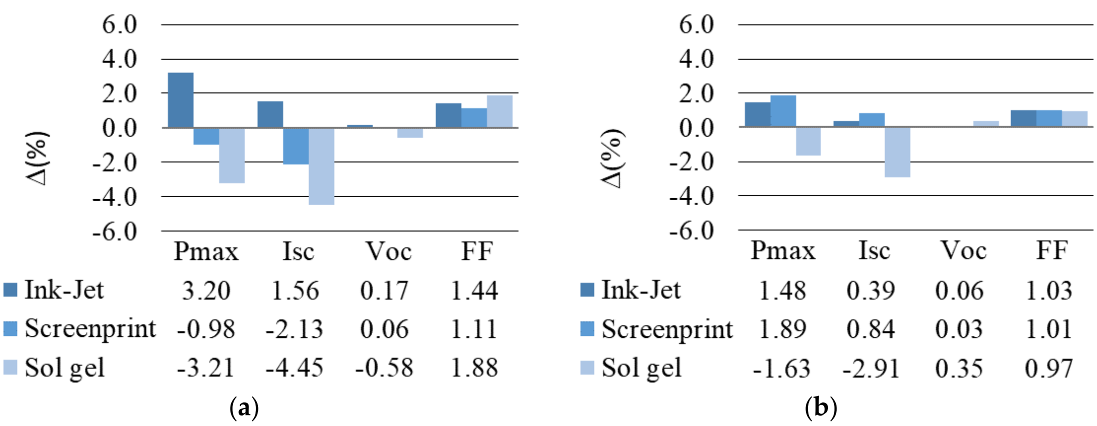
Table 2. Decrease in the electrical parameters of test modules with coated front glass, with respect to the reference test module with clear front glass, measured before starting accelerated aging test.

	ΔPmax	**ΔIsc**	**ΔVoc**	**ΔFF**
Inkjet—anthracite	−36.8%	−37.1%	−1.7%	2.3%
Screen printing—grey	−13.4%	−13.3%	−0.7%	0.6%
Sol-gel—terracotta	−25.9%	−25.6%	−1.7%	1.3%

In order to determine the impact of the different induced stress conditions on the performance of the modules, accelerated aging tests (DH 1000 h, TC 200 cycles, and DH 200 h plus UV 60 kWh/m^2) were conducted, and the performance of the modules after these tests was compared to the previously measured data. In addition, a visual inspection analysis was performed to detect any coating failures.

The variation in the electrical parameters Pmax, Isc, Voc and FF, after the weathering tests is summarized in Figure 8. A degradation of the outside coating applied on the front glass only had an impact on Isc of the test modules, but no effect on the Voc. The variation in Pmax was below the 5% limit, requested by the IEC61215 norm, for all the technologies after the weathering tests.

No evidence of any coating degradation was observed after the hail test, nor after the pressure water-jetting test, as shown in Figures 9 and 10.



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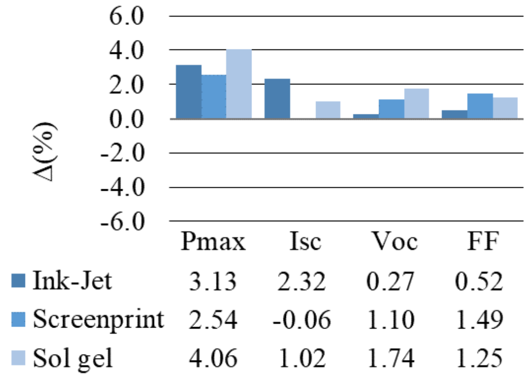
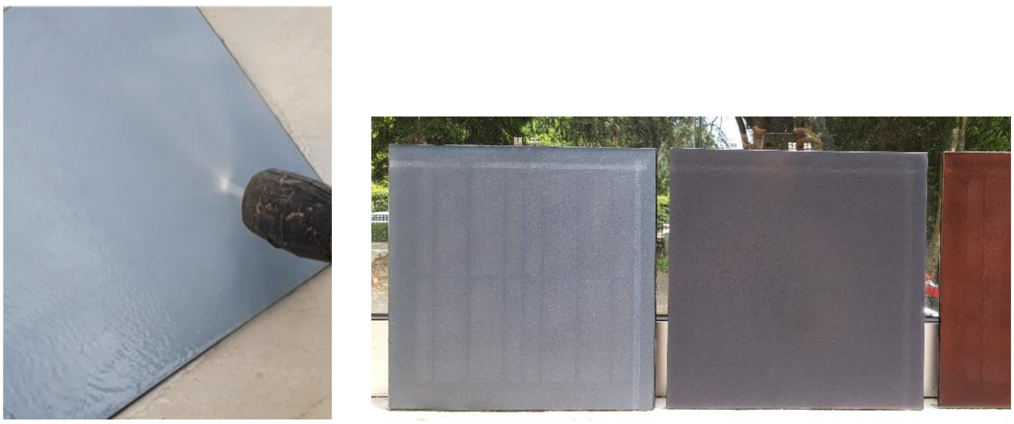


(**c**)

Figure 8. Variations in the electrical parameters of the test modules after weathering tests: DH 1000 h (**a**), TC 200 cycles (**b**) and DH 200 h plus UV 60 kWh/m^2 (**c**).

(**a**) (**b**)

Figure 9. Hail test: (**a**) impact location; (**b**) picture of the test modules after the hail test: inkjet anthracite, screen-print grey, sol-gel terracotta (from left to right).



(**a**) (**b**)

Figure 10. Pressure water-jetting test: (**a**) picture of the water jet; (**b**) picture of the test modules after the water jetting test: inkjet, anthracite, screen-print grey, sol-gel terracotta (from left to right).

3.3. FACADE

On the basis of the results of the optical characterisation, the durability tests and the impact of the coatings on the electrical performance, BIPV modules with the grey screen-printing were chosen for the realization of the demonstrator building in Mötz (Austria). This demonstrator features 16 active PV modules: 10 BIPV modules in the façade

(Figure 11), and 6 on the roof (4 screen-printed grey modules, and 2 modules uncoated, as reference modules).

Exact specifications of the modules: module size was 1700 mm × 1016 mm × 12.28 mm (width × height × thickness); glasses used were 5 mm ESG diamond as cover glass, and 5 mm ESG on the back side; cells used were 5BB mono cells, with a size of 156.75 mm × 156.75 mm; module power under STC conditions was 240 Wp for the coloured modules, and 277 Wp for the reference modules.

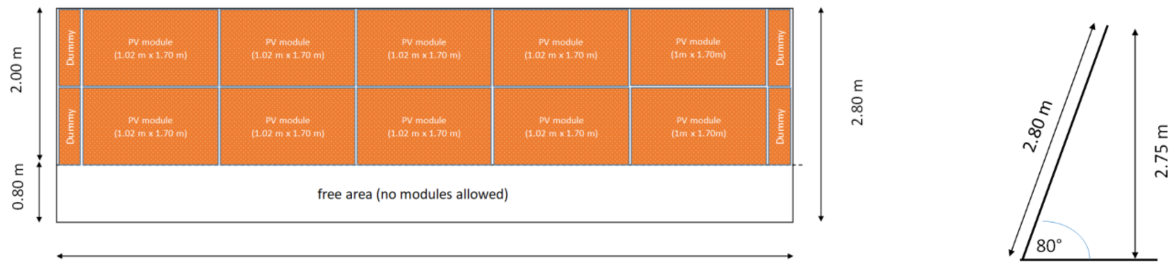


Figure 11. Design layout of the demonstrator facade in Mötz (Austria).

Because of the orientation and inclination of the facade, only 66% of the horizontal global radiation can be harvested, with the total global radiation incident on the plane of the BIPV modules amounting to 830 kWh per year. The BIPV modules with the grey screen-printed front glass are potentially able to generate 1.7 MWh per year, according to the simulation performed by the PVsyst software package. The same façade would generate 1.92 MWh/year at the equator (Bata, Equatorial Guinea), and 1.24 MWh/year close to the North Pole (Svalbard Islands, Norway).

3.4. Results of Façade Modules

Figure 12 summarizes the façade and the roof PV module layout for the test site, as described above.

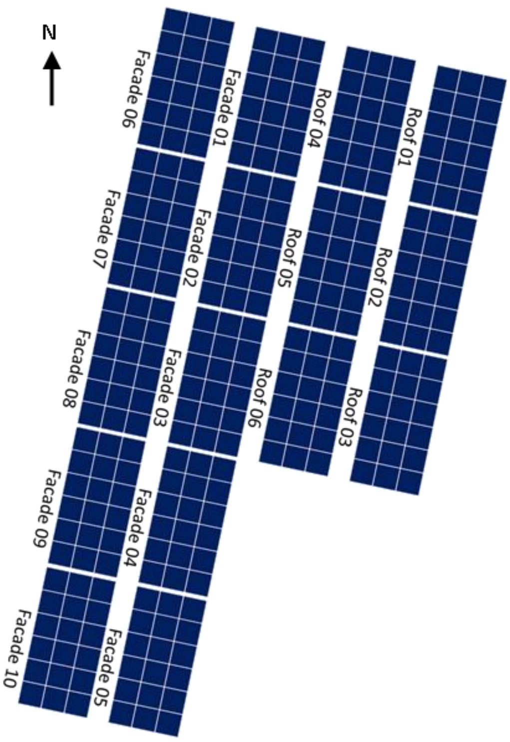


Figure 12. BIPV test site, module layout for test site (roof and façade).

The energy yield data of the test system (façade and roof) for the months from March 2021 to July 2021 are presented in Figure 13. The grey screen-printed modules show only a 10–11% lower performance, compared to the uncoated reference modules. As expected, because of the W-orientation and the 80° inclination of the façade, the yield of the modules in the façade is lower (~50%), compared to those mounted on the roof, with the ratio changing with the season (high in winter, lower in summer). These results are well in line with the yield expected depending on the orientation and tilt, as presented in the literature [25]. The low performance reduction of the grey screen-printed PV modules, compared to the noncoated reference modules, of around 10%, shows the suitability of the screen-printing technology for coloured and efficient BIPV applications. The deviation from the yield simulated above can be explained by the, in relation, lower yield of the façade during summer. The measured values of the monthly energy yield of the coloured modules in the façade are well-aligned with the simulation results of 15.1 kWh in March, 18.1 kWh in April, 20.9 kWh in May, and 21.3 kWh in June.

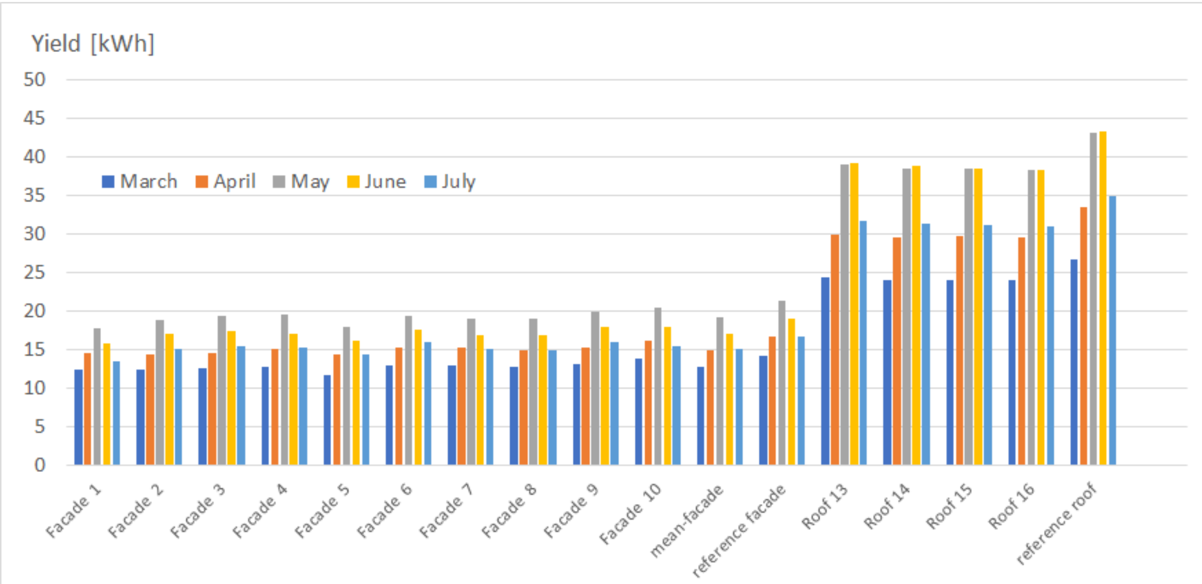


Figure 13. Performance data of the façade and roof modules of the test system in Mötz for the months from March 2021 to July 2021. The respective yield in kWh is shown for the reference modules, as well as for the grey-coloured modules coated by screen printing.

4. Conclusions

Three different coating technologies—inkjet printing, screen printing, and sol-gel spray coating—have been tested for their suitability to act as glare-reducing colour coatings for the outer side of cover glasses used for BIPV applications. It could be shown that all these technologies provide the optical properties necessary to fulfil the requirements for BIPV applications. In particular, a considerable glare reduction, resulting in a direct (specular) reflection below 0.1%, was achieved. Durability testing proved the high stability of the coatings against various weathering conditions. Based on the optical characterization and the durability testing, the grey screen-printed BIPV solar modules were installed in a demonstrator test façade. The high electrical performance, resulting in only a 10–11% performance decrease compared to the noncoated reference modules, perfectly showed the suitability of screen-printing as a future application for coloured and glare-reduced BIPV installations.

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