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Final report

Cover Power

Smart Glass Coatings for Innovative Building Integrated Photovoltaic (BiPV) Solutions (Solar ERA.NET CFA ID:30)

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Zusammenfassung

Im Rahmen des Projektes konnte gezeigt werden, inwieweit vier verschiedene Technologien - Inkjet-Druck, Siebdruck, Glasgranulat (Starshine®) und Sol-Gel-Verfahren - hinsichtlich ihrer optischen Eigenschaften, aber auch ihrer Stabilität gegenüber verschiedenen relevanten Witterungseinflüssen als Beschichtungsmaterialien für die BIPV-Anwendung genutzt werden können. Dabei konnte für alle Technologien, außer der Starshine®-Beschichtung demonstriert werden, dass diese für die geplante Applikation infrage kommen. Zusätzlich wurde die Spezifikation der mit diesen Technologien beschichteten BIPV-Module erarbeitet und deren Implementierung in einer Testfassade geplant. Zu diesem Zweck wurde ein eigenes Backrailsystem zur „unsichtbaren" Installation von hinterlüfteten Modulen in einer Fassade konzipiert und entwickelt.

Im letzten Projektjahr wurden die Aktivitäten nunmehr einerseits auf die Realisierung und den Betrieb der Testfassade konzentriert. Andererseits erfolgte eine umfassende Evaluierung und Alterungstests an kleineren Prototypen- sowie an großflächigen BIPV Modulen unter Standardbedingungen, welche final die Eignung der zum Einsatz gebrachten Technologien demonstrieren sollen.

Résumé

Dans le cadre du projet, il a été possible de montrer dans quelle mesure les quatre technologies de revêtement différentes - impression jet d'encre, sérigraphie, granulés de verre (Starshine®) et méthode sol-gel pouvaient être exploitées comme matériau de revêtement extérieur pour les applications BIPV en termes de propriétés optiques mais aussi de stabilité contre diverses influences climatiques pertinentes. Il a été possible de démontrer pour toutes les technologies, à l'exception du revêtement Starshine®, qu'elles sont adaptées à l'application envisagée. De plus, la spécification des modules BIPV revêtus de ces technologies a été élaborée et leur mise en œuvre dans une façade d'essai a été réalisée. À cette fin, un système de rail arrière séparé pour l'installation "invisible" de modules ventilés dans une façade a été conçu et développé.

Au cours de la dernière année du projet, les activités se sont concentrées sur la réalisation et l'exploitation de la façade d'essai. D'autre part, une évaluation complète et des tests de vieillissement ont été effectués sur des prototypes plus petits et des modules BIPV à grande échelle dans des conditions standard, qui visent à démontrer enfin l'adéquation des technologies utilisées. Enfin, en utilisant les trois technologies de revêtement - impression à jet d'encre, sérigraphie et méthode sol-gel, des modules PV bifaciaux ont été produits et leur potentiel pour une utilisation encore plus efficace du photovoltaïque comme source d'énergie renouvelable en ce qui concerne l'utilisation des technologies de revêtement a été examiné.

Summary

In the frame of this project, it was possible to show to what extent four different coating technologies – inkjet printing, screen printing, glass granulate (Starshine®) and sol-gel method - could be exploited as outer coating material for BIPV applications in terms of their optical properties but also their stability against various relevant weathering influences. It was possible to demonstrate for all technologies, except the Starshine®coating, that they are suitable for the planned application. In addition, the specification of the BIPV modules coated with these technologies was developed and their implementation in a test façade was realized. For this purpose, a separate back-rail system for the "invisible" installation of ventilated modules in a façade was designed and developed.

In the last year of the project, the activities were concentrated on the realization and operation of the test façade. On the other hand, a comprehensive evaluation and aging tests was carried out on smaller prototype and large-scale BIPV modules under standard conditions, which are intended to finally demonstrate the suitability of the technologies used. Finally, using the three coating technologies - inkjet printing, screen printing, and sol-gel method, bifacial PV modules were produced and their potential for the even more efficient use of photovoltaics as a renewable energy source with regard to the use of coating technologies was examined.

Main findings

BIPV is a key component of Switzerland’s energy policy that aims to increase energy efficiency and the share of renewable sources as well as to reduce CO_2 emissions. All engineering solutions for the integration of PV modules in building façade and roof with improved aesthetic, low glare and flexible design are mandatory to promote BIPV. The main findings of the project are aligned to this strategy:

- a coating technology (screen printing) proved as glare-reducing and colored industrial solution for the outside of cover glasses for BIPV modules.
- a separate back-rail system for the "invisible" installation of ventilated modules in a façade.

Contents

Abbreviations

BIPV	Building Integrated Photovoltaic
BoM	Bill Of Materials
CO_2	Carbon Dioxide
CSEM	Centre suisse d'électronique et de microtechnique
DH	Damp heat
ESG	Einscheiben-Sicherheitsglas
FDT	Façade Design Technology
FF	Fill Factor
IEC	International Electrotechnical Commission
Isc	Short Circuit Current
ISO	International Organization for Standardization
JR	Joanneum Research
OFI	Osterreichisches Forschungsinstitut für Chemie und Technik
Pmax	Maximum Power
POE	Polyolefin elastomers
PV	Photovoltaic
PVB	Polyvinyl butyral
SFOE	Swiss Federal Office of Energy
STC	Standard Test Conditions
TC	Thermal Cycling
UV	Ultraviolet
Voc	Open Circuit Voltage
WP	Work Package
Xe	Xenon

1 Introduction

1.1 Background information and current situation

By simultaneously serving as the building envelope material and the power generator, building integrated photovoltaic (BIPV) 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 [1,2]. 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 [3–5].

One of the most common state-of-the-art techniques for modifying the optical appearance of BIPV products uses coloured cells, coloured encapsulants, or print-ed/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) [6–9]. In this context, for example, commercial products are already available on the market, which have a clear colour effect [10–12]. In most of these applications, either the bulk material of the cover glass itself, or the inside of the cover glass, is modified with a colouring or colour-changing layer.

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 [13]. For instance, a typical effect is that the reflections of clouds and/or the ambiance dominate the impression of the building [14,15]. 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 [16].

Fraunhofer ISE could show, by using the Morpho butterfly effect, a solution for modifying both colour and the reflective properties of a BIPV module [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.

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, low glaring at reduced costs and an optimized electrical performance.

1.2 Purpose of the project

Four different technologies for the deposition of coloured coatings on glass were investigated: inkjet printing, screen- printing, sol-gel spray coating and glass granulate (Starshine®).

- **Ink-jet printing:** this technology relies on printing inks which are fused into the glass during a subsequent tempering or annealing process. By digital (ink-jet) printing vivid designs can be created and the technology is applied already in the (automotive) glazing industry. Ertex-solar has a large area ink-jet printer for ceramic colours available.
- **Screen printing**: the ink is spread by a squeegee across a mesh screen. The glass is tempered, and the ink is “fired” to the glass at a high temperature, fusing it to the glass surface. Printing can be fairly precise, and the degree of transparency can be adjusted.
- **Spray-coating of SiO_2 Sol-Gel solutions** this coating technology has been developed by JOANNEUM RESEARCH [18] which is feasible to tune the aesthetical appearance (colour and texture) of glasses. In principle this technology is based on a SiO_2 Sol-Gel method which is also used for the anti-reflective coatings of PV modules. However, by mixing the Sol-Gel solution with inor-

ganic pigments (e.g. iron-oxides) and spray-coating of the resulting suspension onto glass-substrates a colouring of the surface can be obtained after a temper-step. After tempering, the pigments are firmly attached to the glass surface.

- **Glass granulate**: this technology is based on a coating process of glasses with (e.g. coloured) glass granulate and it has been developed by FDT with the name of Starshine®. The resulting glass surface is highly patterned and the realized façades have a very vivid appearance. FDT is going to transfer this technology from glass facades to PV.

In respect to the state-of-the-art approaches, in this project, the coatings were applied on the outside of the front cover glass of PV modules. The advantage of this approach, 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.

The purpose of the project was to assess the impact of the investigated coating technologies on the performance of the PV modules and to prove their ability 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).

1.3 Objectives

The main project objective remained largely unchanged in the last year of the project: to develop BIPV module prototypes based on glass-glass technology and c-Si solar cells (including bi-facial cells) and applying novel glass coatings for the outer side (environmental side) of the cover glasses. In particular, these module prototypes had to show the following properties:

- flexible and innovative design in terms of colour and surface texture
- minimum glare (less than 0.1% of specular reflection)
- at least 150 W/m² (STC) by exploiting back reflected light in bi-facial cells
- ageing and adhesion of surface coatings investigated and reliable for at 30 years

A further objective was to realize a prototype BIPV installation for demonstrating the feasibility of the prototypes.

2 Description of facility

The project concluded with the realization a demonstrator system on building in Mötz (Tyrol Austria) (Figure 1). For this purpose, prototypes of BIPV modules were produced with grey coated front glass using screen printing. Ten screen printed-coloured BIPV modules were installed on the façade (around 16m²) inclined by 80° and oriented to the west (azimuth 95°) and 6 on the roof (4 screen-printed grey modules, and 2 modules uncoated, as reference modules).

Figure 1: Prepared façade for the installation of the modules (left), completed façade installation and start of the installation of the roof system

Exact specification of the modules: module size 1700 mm x 1016 mm x 12.28 mm (width x height x thickness); glasses used are 5 mm ESG diamond cover glass and 5 mm ESG on the back; cells used were monocrystalline with 5 busbars and a size of 156.75 mm x 156.75 mm; performance of the modules under standard test condition (STC): 277 Wp for the reference modules; 240 Wp (-13.3% power loss) for the colored screen printing.

The modules on the façade, which represent the primary planned application, were mounted rear-ventilated on an aluminum construction. The modules were assembled by a back-rail system invisible from the front, glued to the back, which is connected to the substructure (Figure 2).

Figure 2: Substructure mounting on the façade

After delivery of the modules, the bonding of the back-rails on the modules and the installation of the substructure and the electrical components were carried out.

All modules have a digital single module acquisition in order to collect as many measured values as possible and to monitor the system in real time. The modules are guided in a string to an inverter in a protected outdoor area and, as in the case of commercially available systems, operated as surplus feeders.

3 Procedures and methodology

The activities conducted in the project were structured in individual work packages (WPs). In the following the planned work-flow for the R&D activities is described briefly.

The R&D activities started in **WP2**, dealing mainly with the glass coating technologies. 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. 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 (Mayi 2018);
- Chemical resistance (salt-fog), EN 1096-2; 10, 21, and 42 days;
- Xe weathering, EN ISO 16474 (only with coated glass).

Once the most feasible coating technologies were identified, the design of module prototypes and that of the façade installation was conducted in **WP3**.

Based on the design specification of the previous WPs, module prototypes were developed in **WP4**. In particular the glass coatings evaluated and specified in WP2 were applied on standard scale cover glass plates by realizing designs specified in WP3. The impact of these coatings on the performance (including the case bi-facial ceils) and reliability of the BIPV modules was assessed. 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/m2) > 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/m2 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

In **WP5**, the test installation based on design specifications of WP3 and prototypes produced in WP4 was realized.

Beside these R&D WPs, **WP1** for the management of the project management and **WP6** for the dissemination of the results completed the project structure.

4 Results and discussion

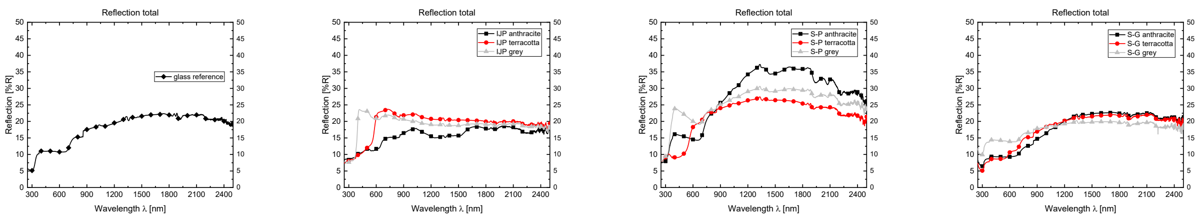
4.1 Glass coating technology (WP2)

During the project, many deposition runs have been done for the different coating technologies – inkjet printing, screen printing, sol-gel method and glass granulate (Starshine®) for grey, anthracite and terracotta colours in order to optimize the process, the durability of the coating and their impact on the visual appearance and on the performance on the PV modules (Figure 3)

ink-jet (digital) printing *screen printing* *sol-gel spray* *glass granulate*

Figure 3: Picture of glass samples coated with the four coating technologies: grey (left) terracotta (canter); anthracite (right).

Figure 4 shows the graphs of the total hemispherical reflectance (THR) of the glass samples, without coating, as well as coated with the 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) (b) (c) (d)

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

A summary of the angle-resolved reflection of the optimized coatings measured by Joanneum Research is showed in Figure 5. For all technologies it can be seen that the direct reflection of the coated side was less than 0.1%. In particular, samples coated by glass granulate technology showed much higher diffuse reflection which is due to lower maximum values in the reflection and by a significant broadening of the reflection characteristics.

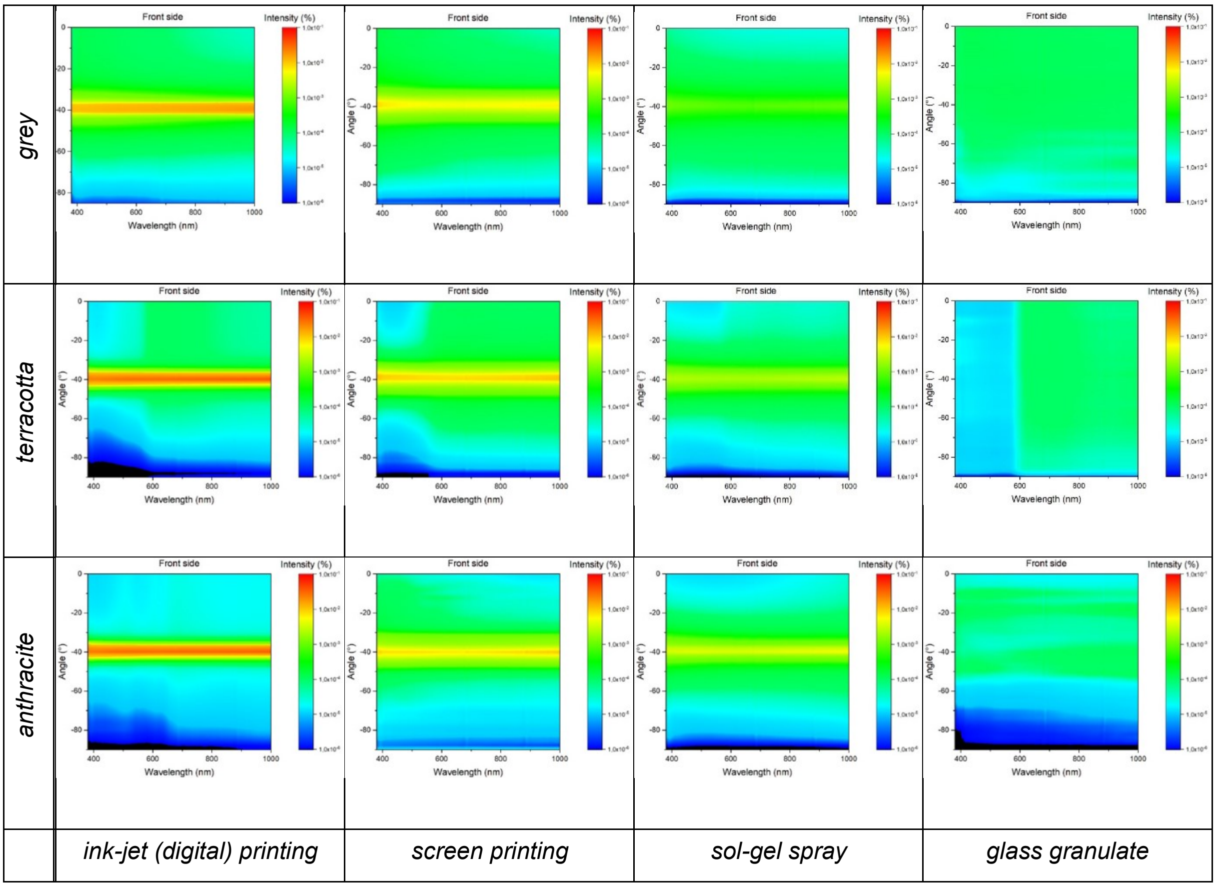


Figure 5: Graphical representation of the angle-dependent reflection at the coated side of test glasses

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. Figure 6 shows the respective spectral transmittance.

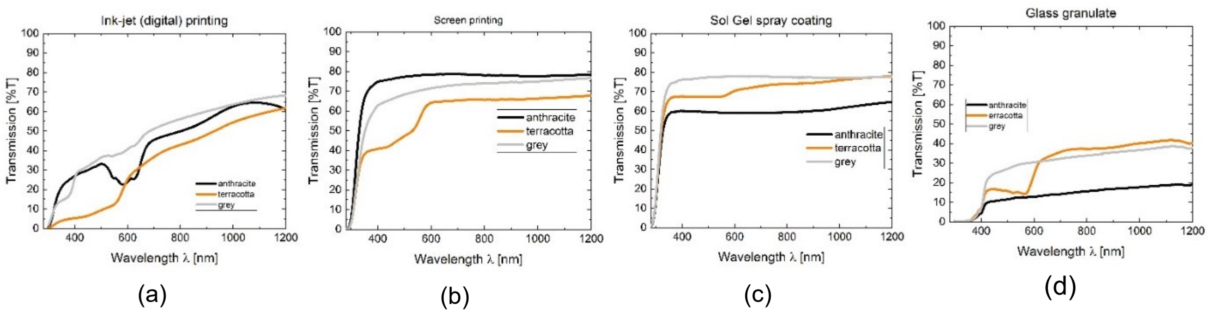


Figure 6 Transmission characteristics of terracotta-, grey-, and anthracite-coloured glasses, coated by inkjet printing (a), screen-printing (b), sol-gel (c) and glass granulate (d) technology.

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.

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

For a photovoltaic glass, τ_e represents the proportion of the solar spectral photon irradiance Ep(λ), 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 [18]

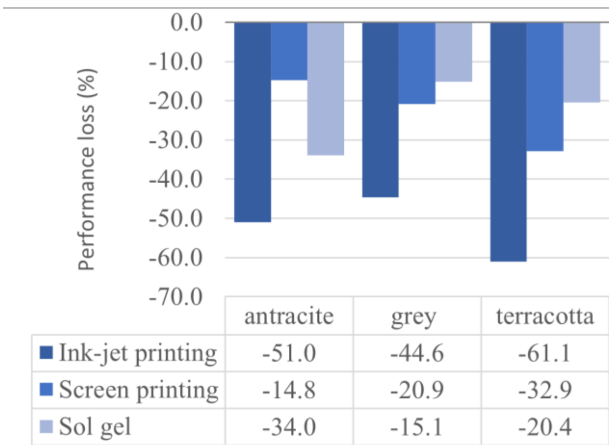


Figure 7 Estimated performance losses induced by each covered glass for a standard photovoltaic cell with respect to an uncoated glass, calculated as the ratio of the effective hemispherical transmittance of photon irradiance, τe.

The results of the study of the durability of the prints/coatings performed by OFI, with respect to their chemical and physical stability and the adhesion of the coating to the surface, are summarized in Table 1.

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, "✓"; minor degradation "O" (changes observed without influence on the performance or aesthetics; unacceptable degradation, "X" (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	✓	o	o
So-gel spray						
grey	x	✓	x	x	x	x
anthracite	x	✓	x	x	x	x
terracotta	o	✓	x	o	o	✓
Glass granulate						
grey	x	x	x	x	x	x
anthracite	x	x	x	x	x	x
terracotta	x	x	x	x	x	x

The inkjet and screen-printed coatings showed good durability results against condensed water, salt impact, UV irradiation, and thermal cycling and humidity freeze test. Only the contact of sulphuric acid with the screen prints showed un-acceptable degradation effects. The sol-gel coating showed good stability for terracotta against condensed water, sulphuric acid, UV irradiation, and the thermal cycling and humidity freeze test. An inacceptable degradation was observed after the salt-fog test. Samples coated with the glass granulate technology did not pass any of the required tests.

4.2 Design (WP3)

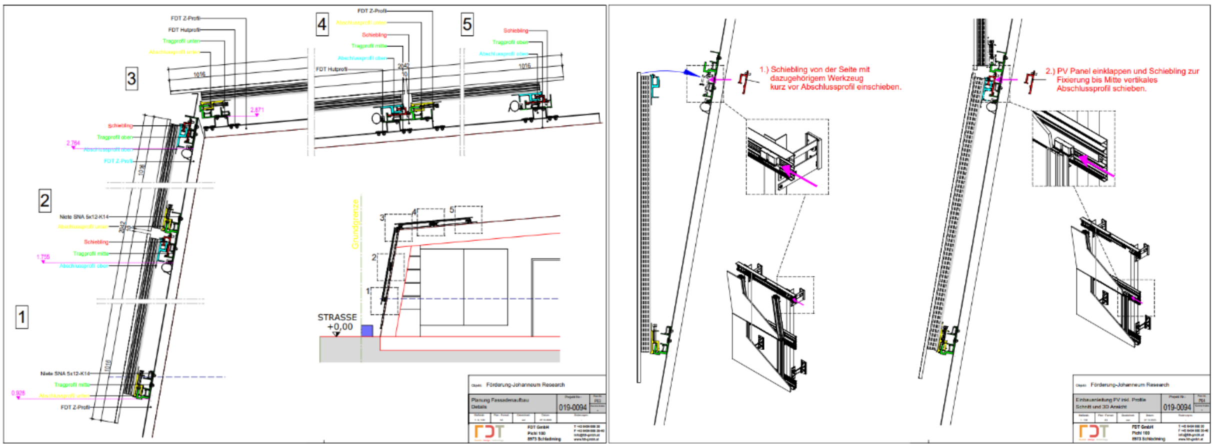
On the basis of the results of the durability test of the prints/coatings, and on the prospective of a successful architectural integration in a building façade and roof, inkjet anthracite, screen-print grey, and sol-gel terracotta were selected as the most promising solutions for prototype modules. The exact specification of the modules is listed below (Figure 8). The PV modules are glass–glass modules. This is mainly due to the fact that the BIPV modules are to be used as a de facto replacement for conventional facade elements. 5 mm ESG diamond was selected as cover glass with the coated side on the external surface and 5 mm ESG on the back. The module size was fixed to 1700 mm x 1016 mm x 12.28 mm (width x height x thickness). The specified size of the modules was proposed due to the easy handling during transport as well as during installation. The cells were 5BB monocrystalline cells with a size of 156.75 mm x 156.75 mm. A standard layer of transparent PVB was selected at the front of the cells and a combination of transparent/black PVB layers at the back to turn opaque the space between the cells and create a uniform black background (precondition to have a module with a homogeneous appearance at the front side).

Figure 8: Scheme of coloured BIPV modules designed in the frame of the project.

The following goals were set in advance for the substructure system:

- Static suitability
- Solution in the sense of an overall system
- High design standards
- High degree of prefabrication in production - reduction of assembly times on the construction site
- Easy installation
- Easy handling during maintenance, cleaning or testing behind the façade
- Serial suitability
- High safety (especially in relation to module crash)
- Flexible use independent of wall structure or substrate

The catalogue of these objectives was incorporated into the development work of the technicians entrusted with the tasks, which in the end worked out a system suitable for series production. The results horizontal support profiles developed in the project by FDT can be fixed on an existing, leveled surface, which later take over the supporting function of the modules (Figure 9a). This system thus makes it possible to have enough space behind the facade for efficient back ventilation. A sophisticated suspension system has also been developed for securing the PV modules on the façade. The system was also designed in such a way that the modules can later be removed individually in the facade surface and changed, if necessary, without having to dismantle the elements above them.



(a) (b)

Figure 9: (a) Detailed drawing of the design of the substructure for the installation of the PV modules on the facade and roof. (b) Detailed drawing of the suspension system for the PV modules on the façade

A pre-assembled construction was selected as system profiles, which are mounted on the back glasses. This allows a certain degree of local independence during pre-assembly. In particular, the profiles can be delivered to the PV manufacturer in advance and applied to the PV modules by means of adhesive technology at the factory. In addition, this process flow increases the quality and assembly efficiency for the future PV façade.

4.3 Prototype modules (WP4)

Based on the results of the tests of the coatings from WP2, the evaluated glass coatings, inkjet anthracite, screen-print grey were produced by ertex-solar, and sol-gel terracotta by Joanneum Research on standard scale cover glass panels (1.0m x 1.7m) and on smaller scale (0.4m x 0.4m). Module prototypes were manufactured by ertex-solar based on the specification of WP3. Modules with transparent front glass were manufactured as well in order to act as a performance reference to the printed modules (Figure 10 and Figure 11).

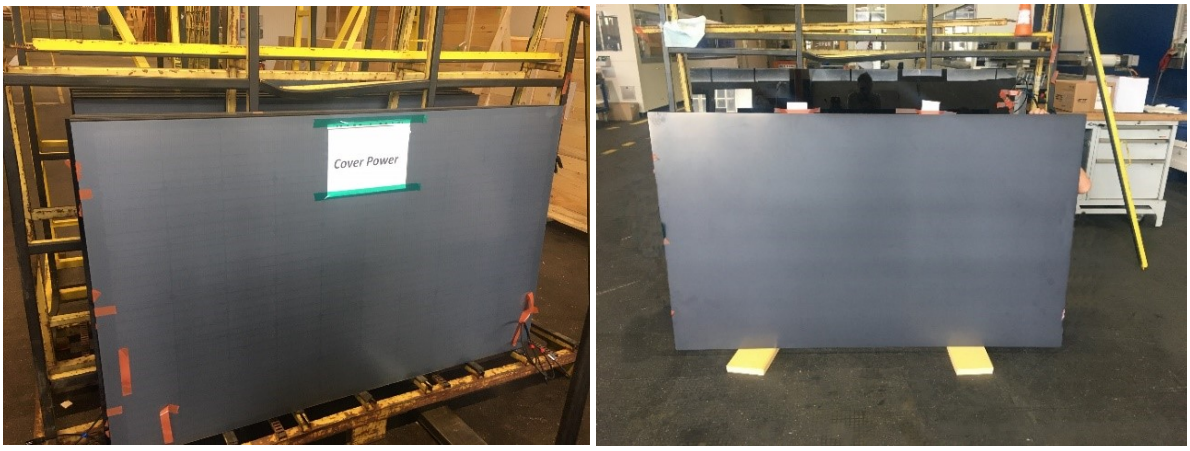


Figure 10: Large-area PV modules with screen printing coating in grey (left) and digital printing technology (right).

Figure 11: Image of the prototype modules produced by ertex-solar (40 x 40cm) with (from left to right): clear, inkjet printed (grey), screen-printed (grey) and sol-gel sprayed (terracotta) front glass.

In

Table 2, the deviations of the electrical parameters of the colored prototype modules compared to the reference module measured at CSEM are shown. The decrease in maximum power (Pmax) is mainly due to the reduction in short circuit current (Isc) caused by lower transmission of the coated front glass. The fluctuations of open circuit voltage (Voc) and fill factor (FF) compensate for each other. The measured values are aligned with the previously estimated ones (

Figure 7), with the higher power and current losses for the inkjet technology, and lower losses for the sol-gel and screen-print technologies.

Table 2 Change in the electrical parameters of colored prototype modules compared to the reference module with clear glass, measured by the CSEM

	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 Figure 12, the variation of the electrical performance of the small modules after the accelerated aging tests performed in laboratory at CSEM are shown.

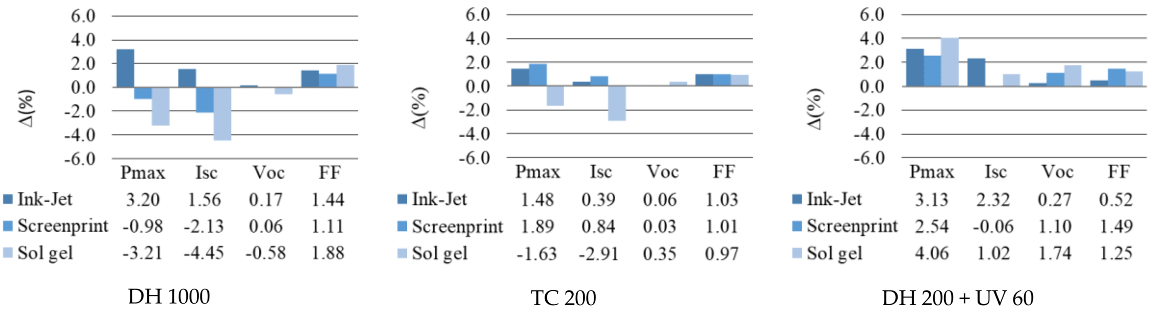
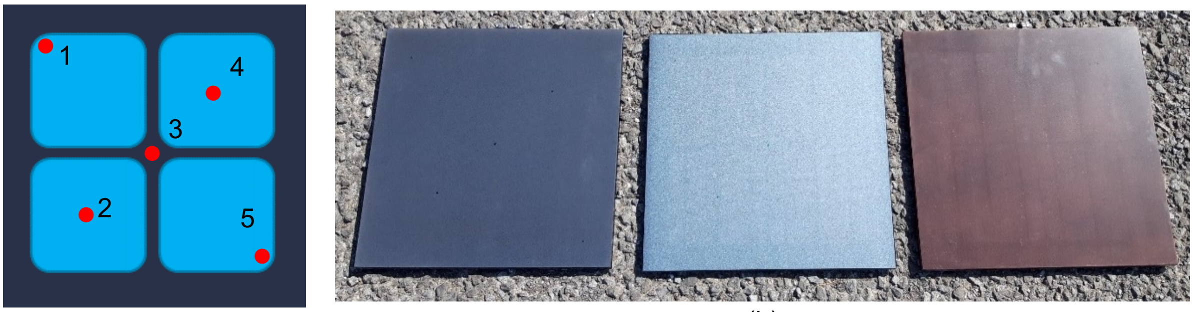


Figure 12: Changes in the electrical parameters of the prototype modules after aging

Degradation of the outer coating applied to the front glass only affects the short-circuit current (Isc) of the test modules, but not the Voc of the test modules. The fluctuation in maximum performance (Pmax) was below the target limit of 3% for all technologies after the aging tests.

Neither after the hail test nor after the pressurized water jet test were any signs of damage to the coating as shown in Figure 13 and Figure 14.



(a) (b)

Figure 13: Hail test: (a) impact site; (b) Image of the test modules after the hail test: inkjet anthracite, screen printing grey, sol-gel terracotta (from left to right).

(a) (b)

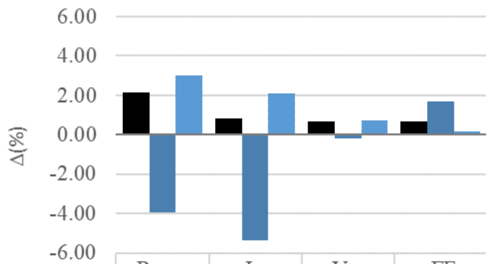
Figure 14: Pressurized water jet test: (a) Image of the water jet; (b) Image of the test modules after the waterjet test: inkjet, anthracite, screen printing grey, sol-gel terracotta (from left to right).

In parallel to the laboratory test of small prototype modules, two full-size modules with inkjet printed and screen printed front cover were installed by the CSEM on a flat roof of a building in Neuchatel with an azimuth of 175° and an inclination of 10° together with a reference module with clear front glass (Figure 15Figure 15). The two colored modules were installed from January 20, 2021 to October 14, 2021, the reference module from January 27, 2021. July 2021 to October 14, 2021.

Figure 15 Image of the two-colour prototype produced by ertex and installed by CSEM on a flat roof of a building in Neuchatel (left: inkjet printing; right: screen printing)

The deviations of the electrical parameters of the colored full size modules in respect to the reference full size modules were consistent with the values measured on the small prototypes and confirm a loss of 37%% for the module with the inkjet printed front glass, while a loss of 13.1% was calculated for the module with the screen-printed front glass. In both cases, the power loss is caused by the reduction in Isc, as the fluctuations of Voc and FF balance each other.

Figure 16 shows the variation of the electrical parameters measured at the end of the exposure time compared to the values measured at the beginning. For the inkjet printed front glass module, a 4% decrease in Pmax was measured due to a decrease in Isc.



	Pmax	Isc	Voc	FF
REF2	2.15	0.81	0.66	0.67
Ink-jet	-3.97	-5.37	-0.20	1.68
Screenprint	2.98	2.09	0.71	0.16

Figure 16 Change in the electrical parameters of the modules after they have been operated on the roof in Neuchatel.

The decrease in electricity could be due to the degradation of the printed coating, as shown in Figure 17 The change in the structural composition of the coating, which is visible as a change in color uniformity, led to a reduction in optical transmission and, consequently, in the current generated by the module.

Figure 17 Images of the module with inkjet printed (grey) front glass after it was weathered in Neuchatel from 20 January 2021 to 14 October 2021.

For the reference module and for the module with screen-printed (grey) front cover, on the other hand, even a slight increase in the electrical parameters and thus the overall performance was observed.

The advantage of using highly efficient bi-facial solar cells to compensate the power losses due to the cover glass coating, was assessed at CSEM by manufacturing small scale prototype modules (0.4 m x 0.4 m). For these modules, different Bill of Materials (BoM) was used in respect to the results of WP3. high efficiency (η=22.75%) heterojunction M4 solar were used interconnected by multiwire technology. The back-cover glass was painted by opaque black paint only around the cells. Clear POE encapsulant was used both at the front and at the back of the cells (Figure 18).

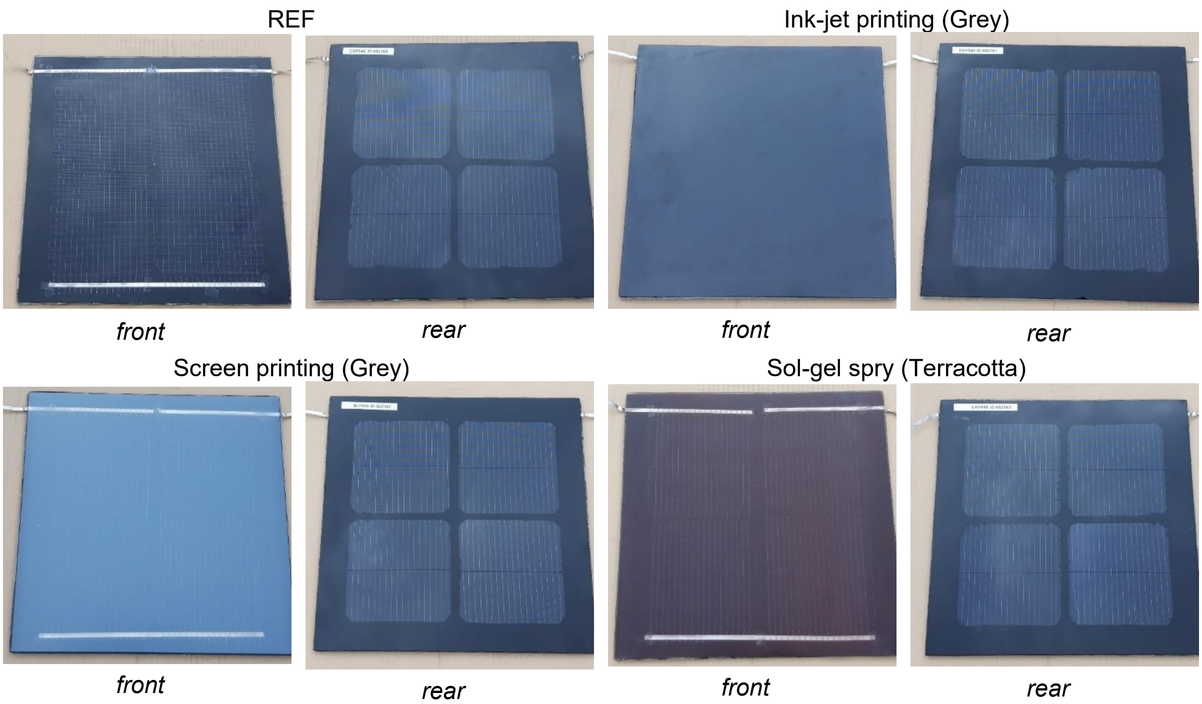


Figure 18 Pictures of prototype demo modules with bifacial solar cells

Pmax, Isc and Voc measured according to IEC technical specification TS 60904-1-2, both at the front and rear side of each module at CSEM are showed in Figure 19 together with the bifaciality coefficients calculated according to the equations here below.

$$\varphi_{Isc} = \frac{Isc_r}{Isc_f} \qquad \varphi_{Voc} = \frac{Voc_r}{Voc_f} \qquad \varphi_{Pmax} = \frac{Pmax_r}{Pmax_f}$$

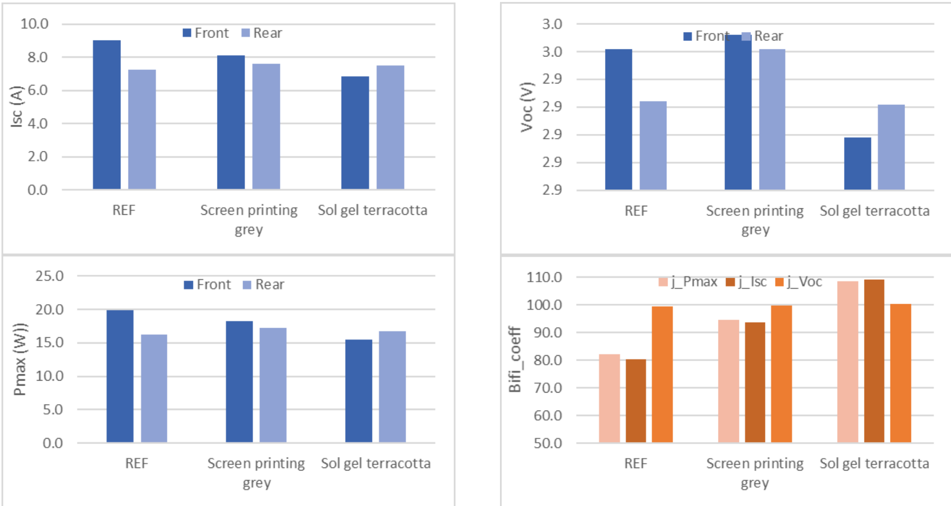


Figure 19 Maximum power (Pmax), short circuit current (isc) and the open circuit voltage (Voc) of the prototype bifacial modules measured both at the front and rear side; bifaciality coefficients

For Voc, the bifaciality is close to 100% for all the samples, while for Isc and Pmax, we obtained values close to 80% for the REF modules, 90% for the screen-print (grey) and almost 110% for the sol gel (terracotta). The high bifaciality coefficients of colored modules in respect to the reference one is a consequence of the fact that these modules have lower current/power at the front side but the same current/power at the back side.

The gain of full-size modules as a function of the irradiance on the rear side (Gr), calculated based on the measured gain in power generation yielded by the bifaciality of the cells is showed in Figure 20 together with target value of 150W/m^2 (STC) defined by the project. By using high efficient photovoltaic cells (η=22.75%), the target values can already be reached even without exploiting harvested power at the back of the module in the case of screen print (grey) color. In case of sol-gel (terracotta) color, instead, a rear side irradiance of at least 150W/m^2 is needed.

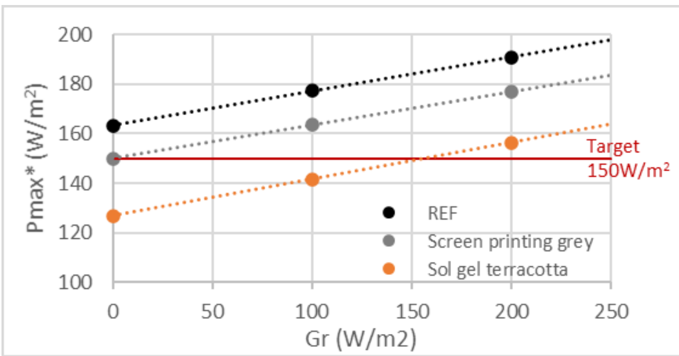


Figure 20 Pmax of a bifacial full size module as a function of the irradiance on the back Gr.

4.4 Demonstrator system (WP5)

Figure 21 shows the arrangement of the PV modules on the façade and on the roof of the demonstrator building as described above.

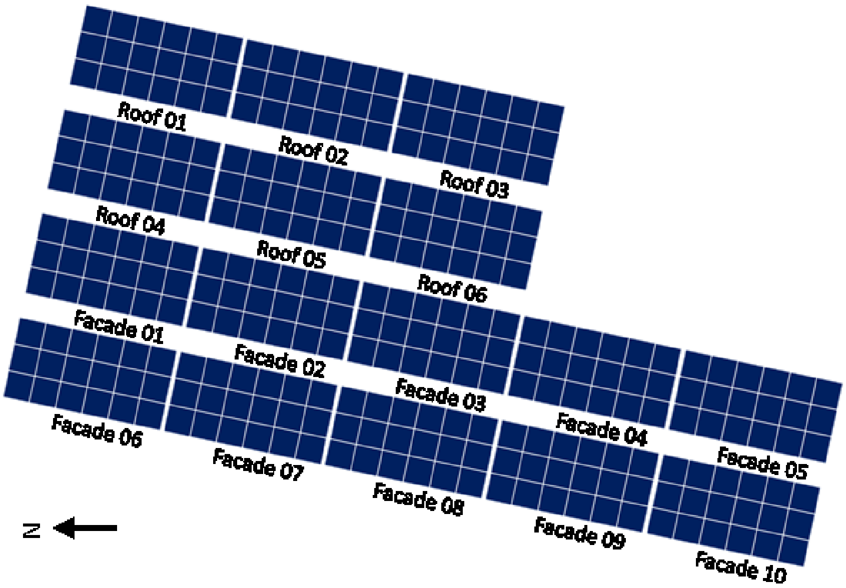


Figure 21 Layout of the occupancy of the façade or roof with the respective modules

The energy yields of the test system (reference and screen printing; façade and roof) for the months of March 2021 to July 2021 are shown in Figure 22.

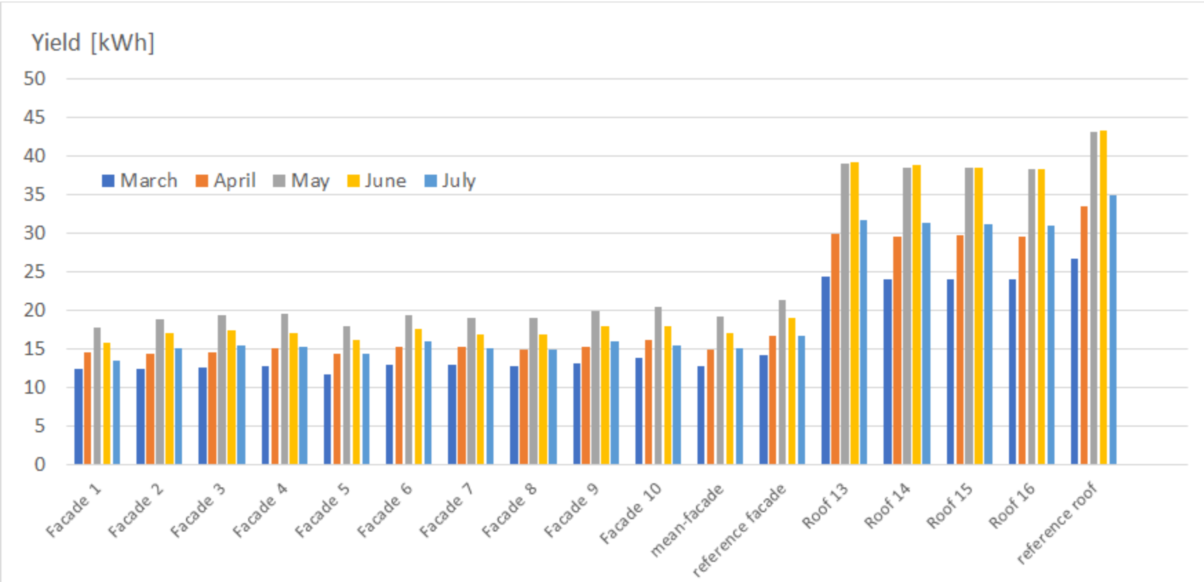
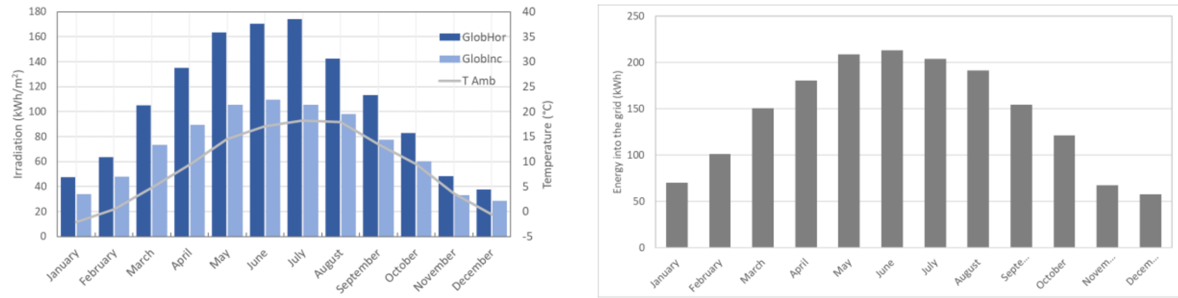


Figure 22: Performance data of the façade and roof modules of the test facility in Mötz for the months of March 2021 to July 2021. The respective yield in kWh is shown both for the reference modules and for the grey-coloured modules coated in the screen printing process.

The grey screen-printed modules installed on the roof show only a 10-11% lower performance compared to the uncoated reference modules (in accordance with the measurements at STC). As expected, due to the West orientation and the 80° inclination of the façade, the yield of the modules in the façade is lower (~50%) than that of the modules mounted on the roof, with the ratio changing with the season (high in winter, lower in summer). These results are consistent with the expected yield in the literature depending on orientation and slope [2]. However, the low performance reduction of the grey screen printing PV modules compared to the uncoated reference modules of about 10% shows very well the suitability of screen printing technology for coloured, efficient BIPV applications. The measured values of the monthly energy yield of the colored modules in the façade agree well with the simulation results performed by the PVsyst software package: 15.1 kWh in March, 18.1 kWh in April, 20.9 in May and 21.3 kWh in June (Figure 24).



(a) (b)

Figure 23 (a) Monthly global radiation and air temperature demonstrator facade in Mötz (Austria); (b) Monthly energy production through BIPV modules with grey, screen-printed front glass (PVsyst)

Figure 24 shows the performance curve of the modules installed on the façade. The orientation of the façade system (100° deviation to the west) requires the late achievement of the maximum outputs for the modules. The shading effect caused by the neighboring building is clearly recognizable, which drastically reduces the PV power gained from about 17:15.

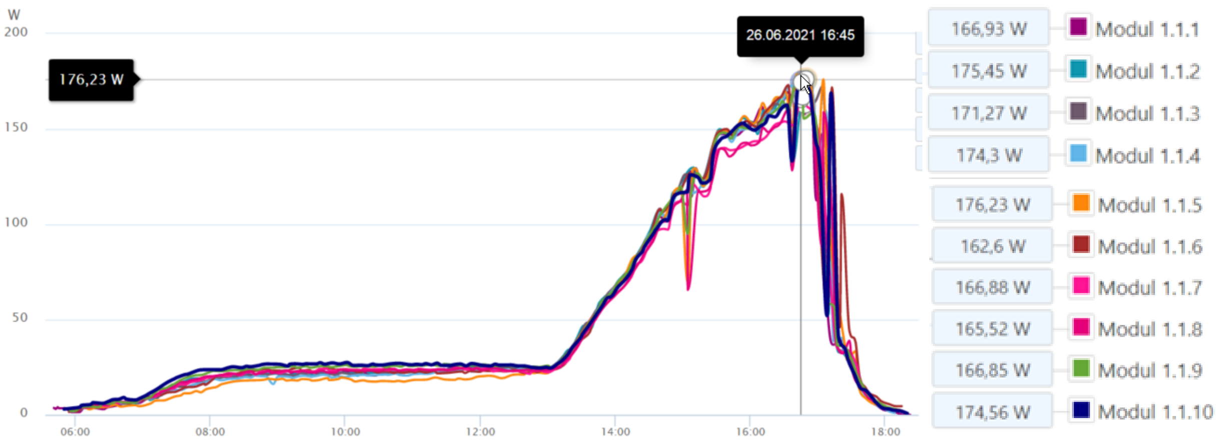


Figure 24: Overview Performance curve [kW] of the façade system on a fair weather day (26.06.2021).

A similar performance range of the demonstrators' modules could also be observed for bad weather days (Figure 25). In the case of the façade modules, a higher dispersion of the achieved power can also be observed, which can be justified by the inefficient operation in low light and thus far away from the optimal operating conditions of the solar cells.

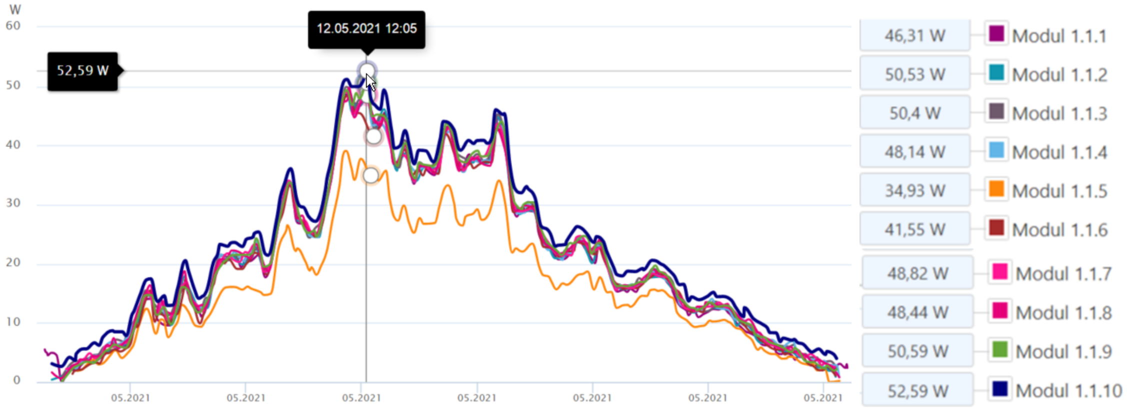


Figure 25 : Overview of the performance curve [kW] of the façade system on a bad weather day

5 Conclusions

In the Cover Power project, four different coating technologies - inkjet printing, screen printing, sol-gel spray coating and glass granules(Starshine®) - were tested for their suitability as glare-reducing color coating for the outside of cover glasses for BIPV applications. It has been shown that apart from the Starshine®coating, all these technologies provide the necessary optical properties to meet the requirements for BIPV applications. In particular, a considerable glare reduction has been achieved, resulting in a direct (reflective) reflection below 0.1%. Accelerated tests proved a high stability of the optically relevant coatings against various weather conditions. On the basis of the optical characterization and the durability tests, screen printing BIPV solar modules were installed in a demonstration building in Mötz (Tyrol Austria). The high electrical power of the screen-printed modules, which resulted in a power drop of only 10-11% compared to uncoated reference modules, showed the suitability of this technology as a future application for colored and glare-reduced BIPV systems. By using high efficient photovoltaic cells (η=22.75%), the target values of 150W/m^2 was reached in the case of screen print grey coating even without exploiting harvested power at the back of the module of bifacial cells.

6 Outlook and next steps

An economic exploitation of the results is considered possible by the partners. In particular, screen printing technology has proven itself in use under real conditions. This is where ertex-solar is planning to focus its effort in the coming months.

Joanneum Research plans further cooperative research activities in the field of sol-gel coating. The main focus will be on increasing the stability of the coating with regard to weather influences. An industrial partner who is able to support in this area must also be identified

All the coating technologies evaluated in the project require a high temperature annealing process to “fix” the coating on the glass surface. CSEM will investigate a different solution that can be applied by skipping this process step. This approach would be very convenient for the module manufacturers as it would not require any special front glass supply and it would concern modules already manufactured and /or installed.

7 National and international cooperation

In the last year of the project, there were several changes in terms of key employees at the partners. On the one hand, Thomas Buchsteiner, managing director of FDT GmbH, left the consortium on 01.02.2021. His tasks were taken over by Andrea Gruber and Tobias Behrens. Furthermore, FDT GmbH was renamed GFT Fassaden GmbH in the course of the year.

At ertex-solar, Managing Director Dieter Moor also left the company on 28.02.2021. His tasks were continued by Mrs. Michaela Fink until 31.08.2021 and Mr. Christian Ullrich.

Changes in the project process were primarily necessary due to a pandemic-related delay in the delivery and assembly of the (full-surface) prototype modules. Through efficient coordination between the partners, the achievement of the essential project goals could nevertheless be ensured. The cooperation between the partners was excellent, with a lively exchange of technology know-how and efficient coordination with regard to the realization of the full-surface modules and the test façade.

8 Publications

G.Cattaneo, “BIPV products with innovative glass coatings for low glare photovoltaic façades” Proceeding of 14th Advanced Building Skins Conference, Bern 2020

R.Trattnig, G. Cattaneo, Y. Voronko, G. C. Eder, D. Moor, F. Jamschek, T. Buchsteiner, “Smart Glass Coatings for Innovative BIPV Solutions”, 2021 / Sustainability 2021, 13(22), 12775; https://doi.org/10.3390/su132212775

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