Designing the colour, pattern and specularity of building integrated photovoltaics

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Abstract

Photovoltaics shall provide 30% of the national demand for electrical energy in Switzerland by the year 2035. This ambitious goal shall be achieved not by large free-standing power plants, but to a large extent within the built up area. Integration of photovoltaics in the built environment is not only technically challenging, but asks for modules that are accepted as a visible element of architecture. Techniques to tune the visual appearance of photovoltaic modules by modification of their front glass are presented with their impact on the electrical power generation. These include the modulation of colour and light scattering properties, and the application of patterns and imagery. Ongoing research and development, available products, and implementations are presented together with first monitoring results. Preliminary results show that photovoltaics can be integrated into our built environment not only as a functional addition, but a designed element of architecture with only moderate impact on electrical efficiency. It is hoped that this significantly increases the acceptance of the technology and thereby the available area for photovoltaic power generation.

Keywords: Building integrated photovoltaics, building envelopes, architecture, renewable energy.

Introduction

The Energy Performance Building Directive (European Union, 2010) sets a near zero energy target for new buildings after 2021. This is accompanied by the Renewable Energy Sources Directive, that makes the use of renewable energies compulsory in buildings (European Union, 2009). The integration of Photovoltaics (PV), in face of its relatively high power density, in the built area lends itself to mitigate the increasing land use for renewable energies, which poses a particular challenge to densely populated countries (van Zalk & Behrens, 2018).

In Switzerland PV grows at high pace, but almost exclusively by roof-top installation. PV still contributed less than 3 % to the country's net electrical energy demand in 2017 (Bach et al., 2020). In order to fulfil the Swiss energy targets without the use of nuclear power, accelerating the use of solar power within the built up area is one key measure. Besides economic reasoning and peer effects, aesthetical considerations have been identified as key drivers for adoption of PV (Curtius et al., 2018; Hille et al., 2018; Petrovich et al., 2018).

Building-Integrated Photovoltaics (BIPV) aims to transform PV into multifunctional, integral elements of the building envelope (Agathokleous & Kalogirou, 2020; Jelle, 2016; Maturi & Adami, 2018). Besides potential cost reduction and positive effects over the product life-cycle (Bonomo et al., 2017), they promise to address the aesthetically often unsatisfactory results of purely functional attachments, e.g. roof-top installations. Despite this aim, one key barrier for widespread adoption of BIPV has been identified in a conflict with tradition in architecture (Curtius, 2018). A range of products have emerged that aim to overcome the appearance of conventional PV modules (Eder et al., 2019). Namely, the modulation of scattering and colour of reflected, and in the case of semi-transparent PV transmitted, light achieves a variety in appearance that supports the integration of BIPV in the existing building stock as well as in architectural design. Recent developments further provide means to individualise the appearance of modules, and thereby provide a design freedom that has not yet been explored to its full extent.

This article shall give an overview on technologies that aim to enhance the freedom of architects when designing with BIPV by offering a wider range of appearance by modulation of colours and surface finishes. State-of-the-art technologies to minimize the impact of such interventions on power-conversion are contrasted with methods that trade moderate efficiency losses against customisation and availability.

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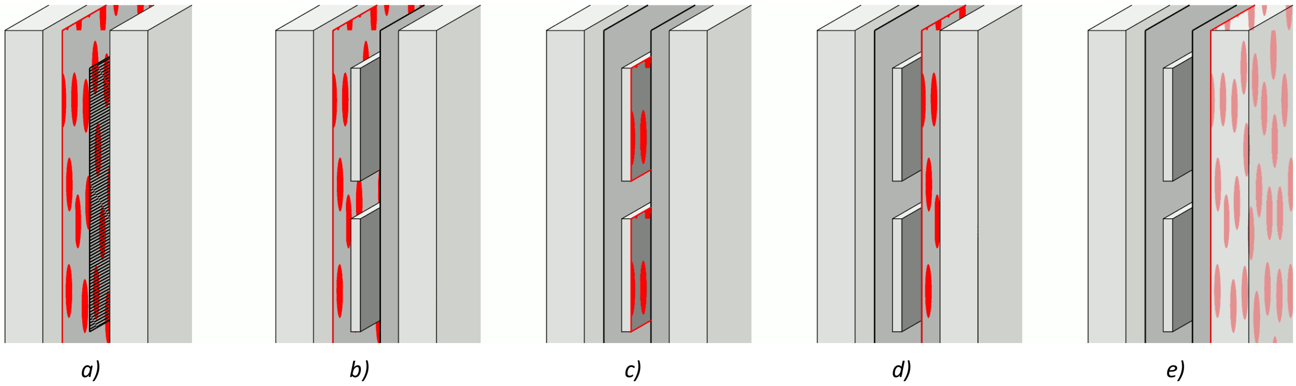


Figure 1: Exemplary positions in a BIPV module where colour can be introduced (red dots). Coloured encapsulant behind active thin film layer (a) and behind solar cells (b); solar cells with coloured coating (c); coloured inter-layer between cells and front glass (d); and coloured back-surface of front glass (e).

Coloured and patterned BIPV

Colour can be introduced into BIPV by modifying or adding layers of the module assembly (Figure 1). The least problematic modification is the introduction behind the cells, since it does not affect the exposure to solar irradiation. In the case of thin-film modules, where the cells are applied to the back of the front glass, a coloured, transparent encapsulant affects transmission and reflection between the cells (Figure 1 a). In the presence of (opaque) wafers, the coloured layer effects the appearance only of the area between the cells (Figure 1 b). Since this area is typically minimized, the effect is limited, yet easy to achieve. Any other interventions on the outward facing side of the active layer inevitably trade efficiency against appearance, since colour results in the partial reflection of incident light that is lost for power conversion. By modification of the anti-reflection (AR) coating commonly applied to wafers, the colour of the cells themselves can be varied (Figure 1 c). Coloured layers in front of the cells, implemented either as semi-transparent sheets (Figure 1 d) or by printing directly on the front glass (Figure 1 e), overcome this limitation.

Solar cells convert incident irradiance into electrical power. The effective irradiance changes with the direction of the sun relative to the module's orientation, which is typical fixed in BIPV, and the Spectral Power Distribution (SPD) of incident light. Since sun-light's SPD changes with sun altitude and weather conditions, standard spectra are assumed to describe the efficiency of solar cells. Figure 2 a) illustrates the (normalised) spectral power distribution of an air mass 1.5 solar spectrum, with the visible wavelengths highlighted by their corresponding colours.

Overlaid on the solar spectrum are the typical Spectral Response (SR) curves for common solar cell technologies (FHG-ISE, 2010). The SRs of Crystalline Silicon (c-Si), Multicrystalline Silicon (mc-Si) cells, and Copper Indium Gallium Selenide (CIGS) thin film cells indicate that all these technologies harvest similar amount of solar energy in the visible and near infra-red ranges. Only Dye-Sensitized Cells (DSCs) are tuned exclusively at visible wavelengths. The graph shows that all cell technologies but DSC harvest solar energy at approximately equal fraction in the visible and infra-red (above approx.. 780 nm) wavelength regions, with a maximum in the near infra-red at approx. 1000 nm. While near-infrared is invisible for the human eye, the modulation of reflected visual light determines the perceived colour (Figure 2 b).

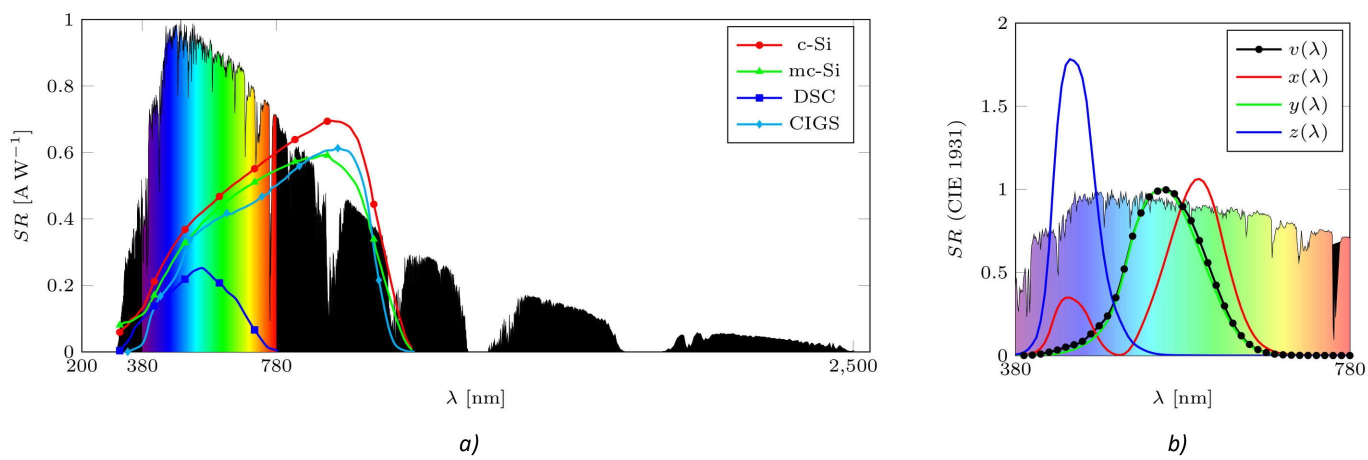
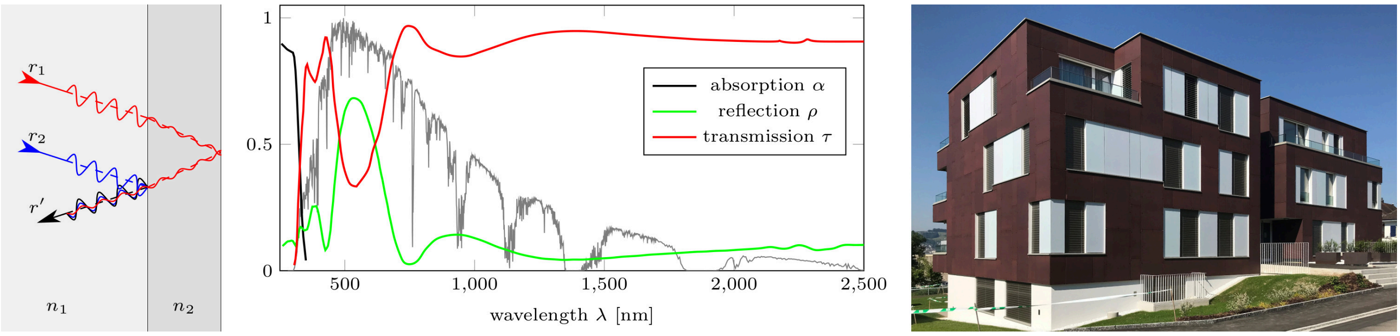


Figure 2: Spectral response of different solar cell technologies with standard AM 1.5 solar spectrum in the background (a). Spectral response of the human eye in photopic vision v, and tristimulus curves x,y,z describing colour perception (b).



a) *b)* *c)*

Figure 3: Constructive interference by a thin film (refractive index n2) on glass (n1), enhancing reflection for a given wavelength. The optical mechanism allowed the development of coating achieving color by reflection at selected wavelength (b, data from Schüler et al., 2006). Extending the reflected wavelength range over the entire visible spectrum allowed the development of filters on foils that can achieve even a bright white appearance when integrated into BIPV, as demonstrated on a residential building in Männedorf, Switzerland (c, Architect: René Schmid, modules with Solaxess technology manufactured by Issol.).

Interference – modulating reflection in the wavelength domain

Interference by stacks of thin dielectric films allows the engineering of spectral filters. For a given wavelength range, reflection is enhanced by constructive interference, when phases of light reflected from the front and back surfaces coincide (Figure 3 a), or suppressed by destructive interference if the phases are shifted. This allows to tune the ratio of transmission and reflection at given wavelengths. Thin films not only lend themselves to applications in AR coatings to increase transmission. If a particular, narrow wavelength range is reflected, they form dichroic filters that achieve saturated colours. Figure 3 b) illustrates this mechanism to achieve green reflection at minimal losses (Andreas Schüler et al., 2006). Additive colour mixing is achieved by reflection at multiple wavelength ranges.

AR coating is a standard process in the manufacturing of solar cells increase absorption and thereby the potential for power conversion. Coloured cells can be produced by only minimal modification of the AR coating (Figure 1 c). Since the industrialised manufacturing of solar cells is optimized for high throughput, constant properties, and low cost, such interventions are limited to the mass-production of a set of colours, and offer little potential for customisation.

If interference filters are applied to the front glass rather than the cell (Figure 1 e), the colour configuration becomes part of the module manufacturing process. Dichroic filters have been applied directly to the front glass of solar collectors to achieve colour at minimal optical losses (A. Schüler et al., 2005). Applied to BIPV, this approach allows produce coloured front glasses that can be combined with arbitrary solar cells into modules.

The shift of phases causing interference effects depends on the length that light travels within the layer as a function of direction, and on the wavelength. This results in an angular dependence of the reflected spectrum. To overcome the angular dependence of the resulting, apparent colour, structured interference filters have been developed. The bionic approach mimic effects on the wings of Morpho butterflies by Bragg stacks, and has been demonstrated to achieve highly saturated, uniform colour on PV modules (Figure 4 a) with losses of approx. 7% compared to uncoated glass (Bläsi et al., 2017).

The functional separation of colour appearance from the front glass further increases the flexibility in applications. Multilayer coatings can be applied to transparent or translucent sheets rather than glass. These sheets can be laminated to the back of the front glass Foils (Figure 1 d). Optionally their functionality can be enhanced by tuned light scattering properties to enhance the saturation and to obfuscate the cell structure. Such sheets can be combined with any solar cell and front glass into modules.

a) *b)*

Figure 4: Interference by Bragg stacks applied to the back of the front glass, producing saturated colours with minimal directional dependency (a). Colour by absorption in transparent BIPV comprising thin-film modules with coloured, transparent encapsulant (b).

Coated sheets featuring an extended range of reflected wavelengths, covering the entire visible spectrum, make it possible to even produce bright white BIPV (Heinstein et al., 2015). Since losses due to reflection of visible light are significant, the sheets are combined with solar cells that are particularly sensitive to irradiance in the near infrared, which is only minimally affected by additional layer. The technology has been developed by the research and technology organization CSEM, and was commercialised by Solaxess SA, Switzerland. The technology was integrated e.g. into modules manufactured by ISSOL, Belgium, that were installed recently on a residential building by architect René Schmid in Männedorf, Switzerland (Figure 3 c).

Dyes and pigments – colour by absorption modulated in the spatial domain

The application of dyes and pigments to opaque building surfaces, such as walls and shutters, has a long tradition and gives colour to our built environment. Wavelengths of incident light are absorbed to different degrees and converted to heat, while the remaining fraction is scattered, e.g. transmitted or reflected. The resulting different spectral compositions of incident and scattered light cause the perception of colour. The combination of different pigments, with their corresponding absorption spectra, results in subtractive colour mixing.

Other than interference filters, that theoretically use all incident light either to generate electrical power (if transmitted) or to evoke colour (if reflected), absorption constitutes an unavoidable optical loss. When applied to layers behind the solar cell, e.g. by use of a coloured, transparent encapsulant behind thin-film cells which are directly sputtered to the front glass, this loss does not affect the irradiance on the cell, but only dims the transmitted light. The lamination of pre-fabricated, coloured sheets offers a means to apply uniform colours or pre-defined patterns to BIPV at large scale. Exemplary for this approach is the façade design of a car park in Lindköping, Sweden by AG Arkitekter AB (Figure 4 b). Coloured, semi-transparent CdTe thin-film modules by Soltech Energy were combined with expanded metal meshes to form an effectful skin for the car park.

Digital ceramic printing allows to reproduce colours, as well as imagery, on glass. Techniques similar to inkjet printing are employed and achieve comparable resolution (Wilson & Elstner, 2018). Pigments and frits are deposited on the glass and form an enamel on the surface that, together with the background (typically the front-surface of the solar cells or the back-sheet) determines the effective colour of the module. During the tempering of the glass this enamel is fused (Wilson & Elstner, 2018).

Depending on the ink, the enamel can be translucent or opaque. Alternating printed, opaque and clear areas tune the effective transmissivity, and thereby the effect on colour as well as on power conversion. The pattern formed by the solar cells is effectively obfuscated by the print and can appear uniform when viewed from a distance. Besides the density of coated and clear areas, the thickness of the enamel affects the saturation and transmission (Schregle & Wittkopf, 2018), i.e. a dense coating with a translucent enamel can result in the same effective transmission and saturation as a pattern of opaque areas. A pattern of squares was printed to the front glass of BIPV modules supplied by Issol (Figure 6 a). The modules effectively hide the solar cells, and achieve a homogeneous appearance in a residential building in Zurich, Switzerland (Figure 6 b), designed by the architectural firm kämpfen für architektur AG.

Digital ceramic printing, due to its capability to reproduce arbitrary imagery on glass, lends it to the manufacturing of individualised patterned modules. The high spatial resolution allows even detailed geometries, and even figurative ornaments. However, the application of a non-uniform coating potentially exposes interconnected solar cells to different levels of irradiance. Such effects reduce the efficiency of the module, and can even lead to so-called hot spots. This is addressed by a dedicated pre-processing step in meta-c printing, that optimizes the enamel's translucency (Figure 5 a) based on a given image or pattern (Figure 5 b). The aim is to achieve a given target efficiency of the module, e.g. 80% compared to an uncoated front glass, and the even distribution of irradiance on the cells.

a) b) c)

Figure 5: Enamel layer printed on glass by meta-c process (a). The dots fuse into a quasi-continuous, translucent layer on the prototype of a front glass (b). The process was applied to a set of BIPV modules showcasing the technology at Umweltarena, Switzerland (c).

a) *b)* *c)* *d)*

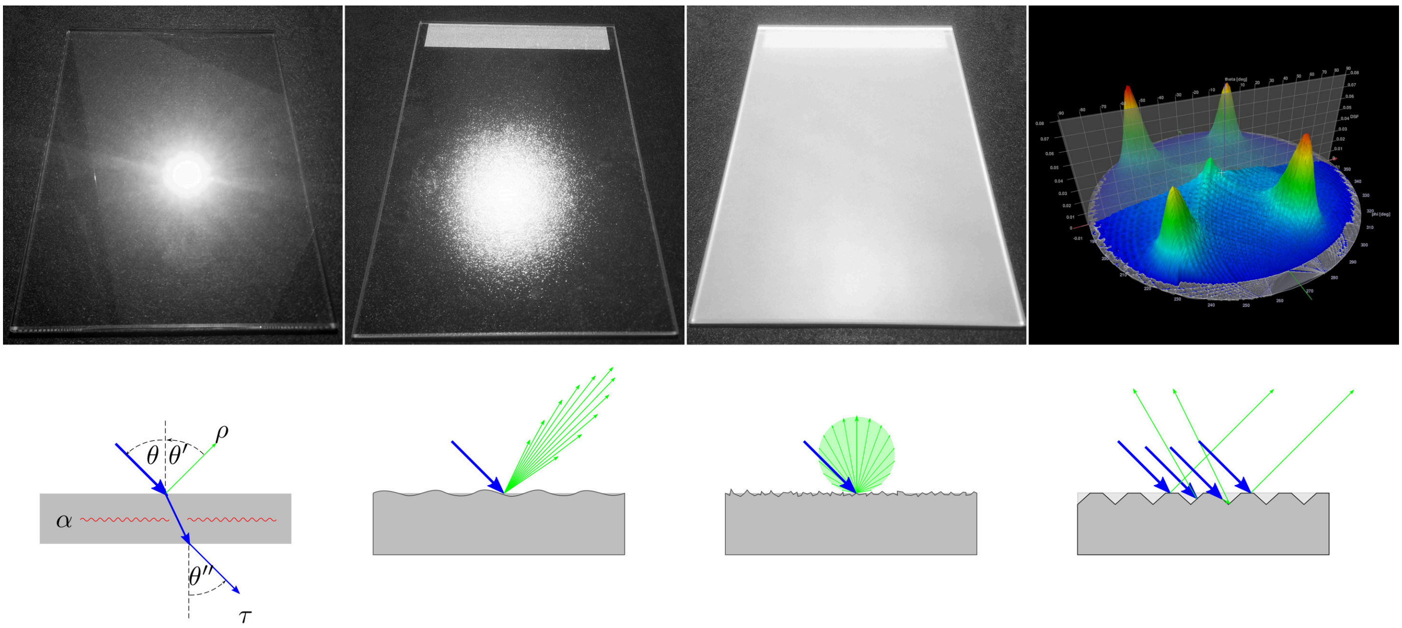
Figure 6: Pattern of alternating opaque and transparent squares on Issol module (a) producing the homogenous appearance of the BIPV façade on a residential building in Zurich (b). Demonstration of imagery printed on PV modules at Umweltarena (c) and as steles along the shore of Lake Lucerne (d).

The meta-c printing technique's applicability to imagery and patterns has been demonstrated e.g. in the installation of the Swissness Façade at Umweltarena, Switzerland's national public exhibition centre for applied energy efficiency and renewables (Figure 5 c). A recent installation of steles along the shore of the Lake Lucerne showcases the possibilities in the reproduction of detailed imagery on BIPV modules (Figure 6 d).

Tuning appearance by light scattering

In particular under sunny sky conditions, the appearance of conventional PV modules is affected by contrast due to the high intensity of the specular reflection of the sun on the outward surface of the front glass, and the cells' low diffuse reflection forming a dark background. This contrasts regular, mostly diffuse reflection by established opaque building materials.

In the case of ideally flat float glass (Figure 7 a), Fresnel equations describe reflection as a function of the incident angle as almost constant with approx. 4% up to approx. 60 °, but quickly increasing with theta toward grazing. For such oblique angles, mirror-like reflections of the surroundings on the outward surface become more apparent. In addition to that, the pattern of the solar cells is visible through the clear glass unless scattering layers are embedded in the module. Consequently, the appearance of colour and patterns applied to the inward facing surface of the front glass or embedded sheets is affected. Since reflection on the glass surface is mirror-like, even for normal incidence (theta approx. 0°) the sun with its high luminance of approx. 1.5e9 cd m-2 forms an extremely bright image of angular diameter approx. 0.5°. While the same effect occurs at any glass surface, e.g. windows, due to the potentially extended areas of covered by BIPV negative effects, e.g. glare, are discussed and often hinder the application in urban settings.



a) *b)* *c)* *d)*

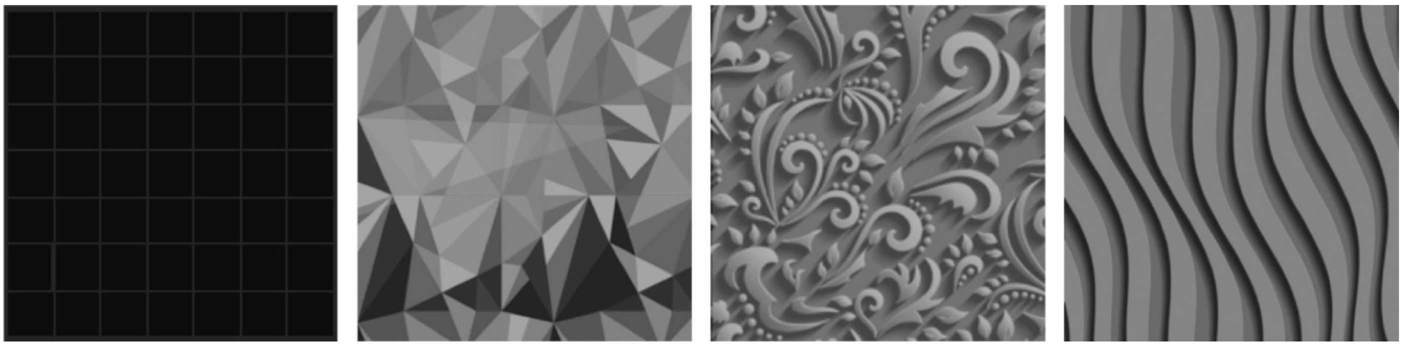
Figure 7: Light scattering by glass surfaces. Mirror-like reflection by float glass (a). Forward scattering around main direction (b). Diffuse, Lambertian reflection (c). Irregular deflection by structured glass for glare control (d).

Figure 8: "Solaris" in Zurich Wollishofen. The cladding of roof and vertical facade with red, structured BIPV overcomes the synthetic, uniform appearance of standard modules and supported the integration in an urban context.

The geometry of the glass surface affects its light scattering, and is applied to tune the efficiency of power conversion as well as the appearance of modules. The moderate modulation of the outward facing surface (Figure 7 b) produces forward scattering around the mirror-direction and a larger apparent image of the reflected sun. The peak luminance of the highlight on the panel decreases with the increasing solid angle. With regards to glare, the potential glare source increases in size but decreases in intensity. Colour, e.g. printed to the back of the glass or by embedded layers, remains visible, only the extended mirror-image of the sun obfuscates the dimmer, coloured reflection. Depending on the degree of perturbation, the contours of patterns seen through the front glass are softened.
The maximum perturbation of the glass surface is reached when all possible orientations relative occur equally. Under this condition, reflected light is distributed to all directions (Figure 7 c). Such diffuse, or Lambertian, reflection causes a uniform brightness on the glass – it lights up as a bright surface in the colour of the light source. Under direct sunlight, the local highlight by reflection of the sun is extended over the entire surface, accordingly its luminance decreases. In BIPV, such diffuse reflection introduces losses due to the high overall reflectance. The diffuse reflection on the front surface inherits the colour of the light source, which is perceived as white. It is additively mixed with the light reflected from the colour reflected from embedded layers or the back surface. Consequently, increasing diffuse reflection desaturates the colour and decreases the contrast of patterns.
The application of regular structures such as inverted pyramids to the front-glass of PV is applied to decrease losses by reflection, and thereby increase the power conversion efficiency of modules. A similar approach has been proposed to reduce glare. The application of a geometric pattern, introducing few surface orientations, splits the primary direction of specular reflection. Figure 7 d) illustrates the distribution of light reflected by a BIPV module with an anti-glare micro-structure. The hemisphere of outgoing directions is projected so that the radius corresponds to the off-normal angle theta. Rather than reflecting to one direction, the micro-structure splits reflections into four main directions, reducing the maximum luminance to approx. ¼. Since the micro-surfaces are not perfectly planar and parallel, forward scattering similar to (Figure 7 b) occurs around each main direction, further reducing the effective luminance. Applied to a vertical façade, the micro-structure multiplies the number of potential glare sources and increases their sizes, but significantly decreases the maximum luminance.
A residential building in Zurich, the “Solaris” building by huggenbergerfries Architekten AG, employs a regularly structured front-glass not for functional reasons but to overcome the uniform appearance of typical BIPV (Figure 8). Prism glass, vertically oriented, produces an anisotropic, widened reflection of sun-light. The red colour is achieved by meta-c printing on the back. The entire building envelope, comprising vertical façade as well as the inclined roof, is cladded with the customised modules. Compared to standard PV, the customization by leads to a loss of little less than 39% but achieves an aesthetical quality that allowed the large-scale application of BIPV in an urban context and increased acceptance for the technology.

Monitored impact of ceramic printing and surface finishes on power conversion

The impact of different light scattering properties and print patterns on the appearance and power conversion efficiency was assessed under realistic conditions at the “Nest” building in Dübendorf, Switzerland (Wittkopf, 2019). The building is a platform hosting pilot-installations and demonstrating innovative building technologies contributed by universities, research institutions and the private sector in Switzerland.
Three patterns (Figure 9 b-d) were printed on the back of three different types of front glass: Float glass without further processing, silk glass with an etched front surface, and satinated glass with a frit applied to the outer surface. In addition to the nine testing specimens, three reference modules were assembled with clear float glass (Figure 9 a). Meta-c preprocessing optimized the prints for uniform transmissivity, and an electrical power output target of 75% compared to the reference modules.



a) b) c) d)

Figure 9: Arrangement of solar cells behind clear float glass (a). Patterns 1 (a), 2 (b), and 3 (c) applied by meta-c print on the backside of the front glass of the modules at Nest.

Figure 10: Installation of modules at Nest.

	Clear	Pattern 1	Pattern 2	Pattern 3	Average
Silk glass	NA	#2 75 %	#5 71 %	#10 79 %	75 %
Float glass	#1, #8, #9 100 %	#3 71 %	#6 66 %	#11 70 %	69 %
Satinated glass	NA	#4 73 %	#7 67 %	#12 74 %	71 %
Average	100 %	73 %	68 %	74 %	72 %

Table 1: Power output of the modules relative to the reference (clear float glass).

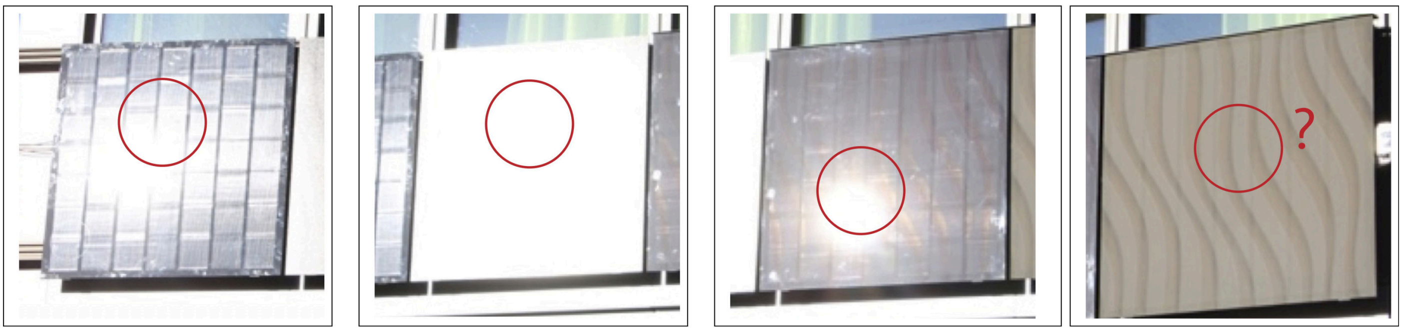
The front glasses were assembled into glass-glass modules, featuring 49 crystalline solar cells each, and mounted on the South- and East facades. The modules were connected through individual micro-converters and one common, central inverter to the building grid. This setup allowed to continuously monitor the electrical power generated by each module. The influence of the front glass set aside, an equal power conversion efficiency of all modules was assumed. Due to tolerances in the rating of BIPV modules, an error margin of +-5% has to be expected.

Over a period of one year, the electrical power output of all panels was monitored. To compensate for nonequal irradiance on the modules due to their different orientations and overhangs (Figure 10), each modules output was normalized with that of the nearest reference module. The latter, by definition, achieve a relative efficiency of 100%. Table 1 shows the relative efficiencies of the modules as averages over the entire monitoring period.

The study revealed that, due to the common transmissivity target in the meta-c optimization, the printed patterns had no significant effect on power conversion. The maximum absolute deviations by the different patterns from the average for each glass type (rows in Table 1) were 4%, 3%, and 4% for silk, float, and satinated glass respectively, and within the measurement uncertainty of 5%. Similarly, the effect of the front glass was low. The maximum deviations by the different glass types for each pattern (columns in Table 1) were 2%, 3%, and 5% for patterns 1 to 3 respectively.

To assess the impact of light scattering by the different front surfaces of the different glasses on the perception of the pattern printed on their backsides, photographs were taken on a sunny day so the the mirror-image of the sun occurred in four modules (Figure 11). The inhomogeneous reflection from the pattern of solar cells obfuscate the mirror-image of the sun in the case of clear float glass (Figure 11 a). The etched surface of the silk glass (Figure 11 b) appears bright due to diffuse reflection to an extent that renders the pattern on its back invisible. The pattern printed to the back of the float glass (Figure 11 c) is visible, but affected due to the high luminance of the mirror-like reflection of the sun, and the regular cell structure shining through the print. The satinated glass suppresses this high luminance, but does not appear bright by itself so that the diffuse reflection from the print is visible without distraction reflections by the frontside (Figure 11 d).

The dual assessment of power conversion efficiency and appearance revealed that the designer is free in choosing front-glass and printing pattern according to the desired appearance. While the light scattering properties had little impact on the electrical power output, the impact of the different print patterns was compensated by the meta-c pre-processing, that tuned the printing parameters of all patterns for one common efficiency target. The measurement accuracy was limited by the rating tolerances, and may not have revealed subtle differences e.g. between the different glass types. However, the accuracy of 5% reflects typical conditions in the application of BIPV under realistic conditions due to the uncertainties in module specifications.



a) b) c) d)

Figure 11: Reflection of the sun on the front glasses of modules 9 (clear float, or reference, a), and pattern 3 printed on modules 10 (silk, b), 11 (float, c), and 12 (satinated, d). The expected position of the sun's mirror-image on each module is indicated by the red circles.

Conclusions

BIPV offers design opportunities in architecture that go well beyond the iconic image of PV for technological advances. The presented techniques allow to introduce colour into opaque and transparent BIPV with different motivations and effects. Arbitrary colour applied to the cells can stress the regular structure of crystalline and multicrystalline modules. Interference coating on sheets and front-glass offer means to achieve highly saturated colour at minimal optical losses, or to tune the appearance of modules over a wide range of scattering, colour and reflectance with white BIPV as an extreme case when higher losses are acceptable. Ceramic printing finally allows customisation even at low quantities, and thereby the individualisation of the appearance of BIPV. The meta-c pre-processing helps to avoid problematic effects of printing on the front glass, and to reach a given electrical power output with arbitrary patterns, colours and motives.

The pilot installation of modules at NEST revealed the importance of the light scattering properties of the front glass. In particular under sunny sky conditions, the mirror image of the sun in the case of specular reflection, and the apparent uniform brightness of the module in the case of diffuse reflection, overlay any colour or pattern that is applied to the embedded surfaces and potentially renders them invisible. A moderate front-scattering was found to be most effective in the case of ceramic print on the inside of the front glass. Beyond its utilisation for light trapping, potential applications of structured glass in BIPV to overcome the uniform, synthetic appearance, and to mitigate negative effects such as glare, ask for further research.

It remains a challenge for architects and other professionals involved in planning with BIPV to advise for the proper balance between aesthetic aspects, and the efficient power conversion. BIPV, if understood not only as a multi-functional building component, but an integral element of architecture, has to account for both. As demonstrated in this study, appearance and efficiency are not fixed properties, but can be configured. Moderating such potentially conflicting targets according for a particular building in its context poses a challenging, yet rewarding design task for architects.

Acknowledgments

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