VISUAL DESIGN OF PV-MODULES – A CRUCIAL FACTOR FOR FAÇADE APPLICATION ACCEPTANCE

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ABSTRACT: Increasing the acceptance of façade-integrated PV (photo voltaic) is of great interest. Architects will often be opposed to integrate PV in their design based on visual aspects of available PV products. The project described in this paper addresses this topic by bringing together a known technology - sandblasting of glazing surfaces – and standard, off the shelf PV-modules. The final goal of the project is to provide architects with a catalogue of possible glass-surface visual design elements. Each design element will be given with approximate reduction values for radiation transmission. Thus, ideally a design that is desired can be estimated in regard to PV-performance-values to be expected. A first set of design elements is shown and corresponding radiation transmission reduction values are given. The design elements are differently sandblasted and coloured glass surfaces with various grades of opacity. The reduction in transmission as compared to a standard low iron glass is found to be in the range of 10 to 80 %, mainly depending on the glass colour. Some examples for possible designs are shown. The relative loss in performance compared to an untreated PV-module of the same type is found to be of the same order of magnitude as the accepted spread in module power according to manufacturer data. This is viewed to be an encouraging result.

Keywords: Building Integrated PV (BIPV), Façade, Surface Modification

1 INTRODUCTION

Replacing fossil fuels by renewable energy sources is paramount in regard to a sustainable energy supply. The application of photovoltaic modules (PV) on buildings is to date mostly restricted to roofs. Using building façades would greatly increase the available area for harvesting solar power or can even be necessary for larger buildings to reach NZEB status (see e.g. [1], [2]). Often, though, architects dislike the visual appearance and/or limited visual design options of standard PV modules. There are several solutions to this dilemma available on the market to date (e.g. [3], [4], [5]), which basically focus on introducing the possibility to give colour to the cover glass. Each of these solutions has its merits, however, additional design possibilities should help increase acceptance of façade integrated PV with architects and thus pave the path to a wider application of BIPV in façades. A "sounding board" held with various local key players of the building market gave the following results:

- Overall costs of façade BIPV should not exceed that of similar, non-PV façades. Overall meaning of course that PV yield shall be taken into account.
- A peak yield is not necessarily crucial. If the design appeals, it was felt that many architects and clients would accept efficiency losses of up to 30 %. Some present even allowed for up to 50 % loss.
- Imitations (e.g. wood surface, rough plaster or similar) were not deemed acceptable, in general. Those present agreed that surface treatments must do justice to the material "glass" or have an artistic aspect.
- Older buildings (Wilhelminian style) or heritage buildings should not be considered for façade BIPV, as this would be an unacceptable encroachment on the building character.
- Façade BIPV was generally deemed acceptable for buildings dating from approximately 1950 onwards which more often than not feature simple, unstructured façades.
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The method considered in this paper for the change of visual appearance is the sandblasting with optional addition of colour. The treatment is applied to standard PV modules. This approach has several advantages. Not only can this technique be regarded as proven, it is also applicable to any type of available PV modules. Also, the "glass like" surface remaining with above-mentioned other available solutions is mitigated through sandblasting the glass. In the following, possible visual effects are introduced and a first indication of the expected loss of PV performance due to the surface treatment is given.

2 VISUAL EFFECTS BY SANDBLASTING GLASS SURFACES

Figure 1 shows examples of sandblasted glass surfaces. It is also possible to add colour to the sandblasted surfaces in the process [6]. The visual effect generated depends mainly on grain type, grain size, blast density and duration and blasting power. The grain size used is typically in the range of 50 – 400 μm. Figure 2 shows a detailed view of two sandblasted glass surfaces. Finding the "right" combination of the parameters mentioned in order to achieve a desired result requires extended experimentation and long experience, however. The technique has been used for several decades and there are many examples on buildings world wide available. The sandblasted surface is typically sealed to protect the "chipped" surface structure and has been shown to be durable. Figure 3 shows examples of a sandblasted standard CI(G)S PV modules.

Figure 1: Sandblasted glass. A picture on a glass compartment wall (top) and samples with additional colour (bottom) [6].

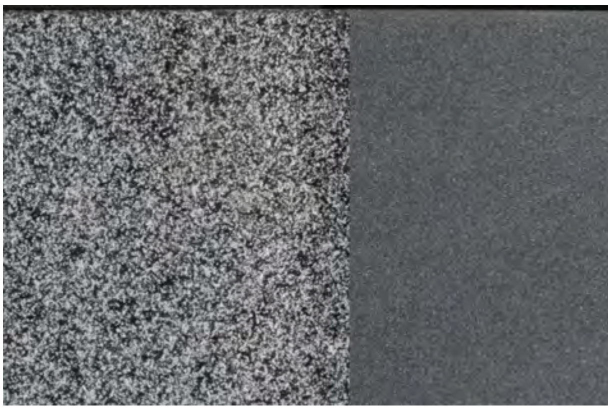


Figure 2: Close-up of two sandblasted glass specimens with different grain-sizes blasted for laboratory measurement.

Figure 3: Standard CI(G)S PV modules after treatment of glass cover with sandblasting techniques (top) and sandblasting & colouring techniques (centre, bottom) [6], [7].

3 EXPECTED PV PERFORMANCE

3.1 Laboratory Measurements

3.1.1 Measurement Setup

The measurement set-up is a combination of a flash-light with a colour spectrum similar to daylight and with a colour temperature of 6'400 K (see Figure 4). The flashlight triggers the spectral measurement device Sekonic C-700R that is able to measure the following parameters:

- Total incoming luminous exposure H [lx s]
- The spectral distribution of the incoming light in the extended visible range from 380nm – 780nm.

The measurements are done in a black painted lab on an optical table to reduce errors due to light scattering and errors from vibration or mechanical instabilities.

After calibrating the setup, the measurements are done by the following procedure:

- The light transmission of the PV-glasses is measured for three incoming light angles (0°, 45° and 65°, where 0° is equivalent to the glass surface normal direction) and each measurement is performed 5 times to average intrinsic errors of the components used (5 % for the spectral measurement device, < 0.3 EV for flash).
- For the 0° measurement setups for direct and diffuse light are used.
- The averaged measured data is set in relation to the reference measurement (untreated low iron glass). The ratio thereof is stored as transmission and loss information for each type of glass treatment.

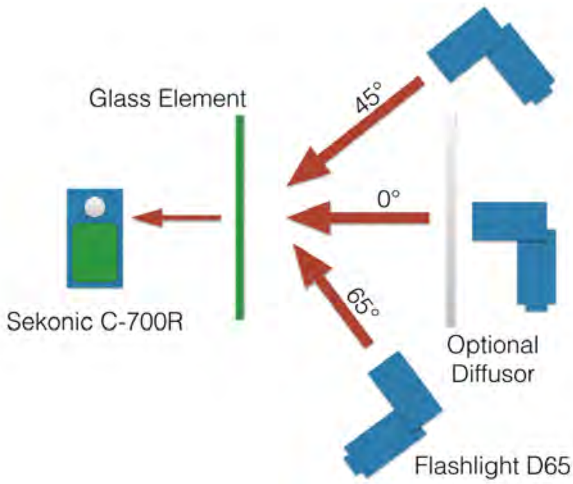


Figure 4: Laboratory Measurement setup consisting of spectral measurement device, flash light and test specimen.

3.1.2 Measurement specimens

The laboratory measurements are to give initial guidelines in regard to the effect of considered surface treatments on glass light transmission and thus likely PV performance degradation. The set of test glasses consists of:

- four blasting grades / particle size ranges (S1 – S4) with two blasting densities ("open", "closed") each,
- magenta-, blue-, yellow- and green-coated glasses with one and two coating layers and
- three different sealing types for protection (A, B, C).

The test glasses are based on standard four-millimetre thick low iron glass. Figure 5 shows some examples of the test specimens. Overall, 56 individual glass specimens were tested to date.

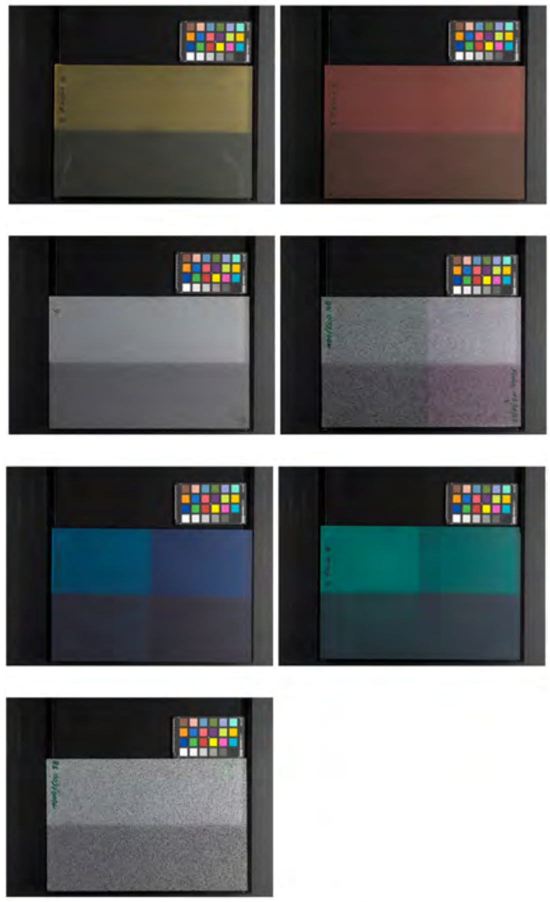


Figure 5: Sandblasted and coloured glass specimens. The pictures show a selection of the test specimens with black and white back-layers.

3.1.3 Laboratory Results

The measurement results show that the surface modification due to sandblasting and the choice of coating can influence the transmission of the PV-glass elements significantly. It is straight forward that colour coatings absorb incoming light relative to the density of the colorants or pigments applied. Figure 6 shows the change in spectral transmittance of two coloured test specimens compared to the reference glass. The values for the red and green glass examples are given as the ratio between the transmittance of coloured and the non-coloured glass. The surface modification due to sandblasting leads to surface scattering, subsurface-scattering, absorption and reflection. In the measurement procedure, the ratio between those effects of surface modification has not been studied in a first step, because the change in overall transmittance is of major interest in regard to PV performance loss. Table I summarizes the results obtained in the form of loss factors compared to an untreated cover glass.

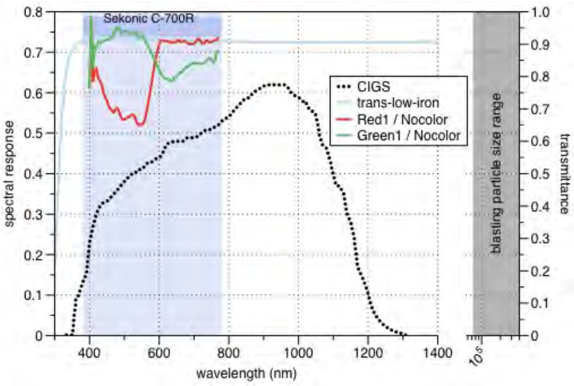


Figure 6: Spectral response of a typical CI(G)S cell, transmittance of a standard low iron glass pane and exemplary relative spectral transmittance values from the laboratory measurements for red and green coatings. The relative transmittance values use the scaling “transmittance” on the right.

Table I: Relative loss of light transmission of sandblasted and sandblasted & coloured glass specimens compared to an untreated but otherwise identical glass pane (4 mm low iron glass). The uncertainty shows the standard deviation of the mean of five measurements with each specimen. S1 to S4 are different blasting grain size intervals, “open” means a less dens blasting structure, “closed” a more dens structure.

Glass	**Sandblasted**	**Sandblasted + Blue**	**Sandblasted + Red**	**Sandblasted + Yellow**	**Sandblasted + Green**
0°, no diffusor					
S1 Open	0.15 ± 0.01	0.24 ± 0.01	0.30 ± 0.01	0.12 ± 0.02	0.08 ± 0.02
S1 Closed	0.23 ± 0.01	0.32 ± 0.01	0.43 ± 0.00	0.14 ± 0.01	0.19 ± 0.01
S2 Open	0.27 ± 0.03	0.44 ± 0.02	0.46 ± 0.00	0.18 ± 0.01	0.26 ± 0.00
S2 Closed	0.20 ± 0.01	0.49 ± 0.01	0.58 ± 0.00	0.19 ± 0.01	0.35 ± 0.01
S3 Open	0.12 ± 0.01	0.35 ± 0.01	0.43 ± 0.01	0.13 ± 0.01	0.20 ± 0.01
S3 Closed	0.20 ± 0.01	0.50 ± 0.00	0.56 ± 0.00	0.23 ± 0.01	0.33 ± 0.00
S4 Open	0.09 ± 0.02	0.31 ± 0.02	0.35 ± 0.01	0.14 ± 0.02	0.19 ± 0.01
S4 Closed	0.20 ± 0.01	0.46 ± 0.01	0.57 ± 0.00	0.24 ± 0.01	0.35 ± 0.00
65°, no diffusor					
S1 Open	0.17 ± 0.02	0.31 ± 0.01	0.32 ± 0.01	0.18 ± 0.01	0.13 ± 0.01
S1 Closed	0.36 ± 0.00	0.57 ± 0.01	0.65 ± 0.00	0.34 ± 0.01	0.41 ± 0.01
S2 Open	0.37 ± 0.01	0.62 ± 0.02	0.69 ± 0.00	0.42 ± 0.00	0.49 ± 0.01
S2 Closed	0.43 ± 0.01	0.70 ± 0.01	0.75 ± 0.00	0.48 ± 0.01	0.60 ± 0.00
S3 Open	0.31 ± 0.00	0.45 ± 0.01	0.57 ± 0.01	0.31 ± 0.01	0.42 ± 0.01
S3 Closed	0.42 ± 0.00	0.72 ± 0.00	0.73 ± 0.00	0.49 ± 0.01	0.60 ± 0.00
S4 Open	0.21 ± 0.01	0.39 ± 0.02	0.45 ± 0.00	0.26 ± 0.01	0.30 ± 0.01
S4 Closed	0.41 ± 0.00	0.70 ± 0.01	0.77 ± 0.00	0.46 ± 0.00	0.59 ± 0.00
0°, with diffusor					
S1 Open	0.04 ± 0.01	0.17 ± 0.01	0.26 ± 0.00	0.04 ± 0.03	0.07 ± 0.02
S1 Closed	0.11 ± 0.02	0.26 ± 0.01	0.41 ± 0.01	0.07 ± 0.02	0.18 ± 0.03
S2 Open	0.14 ± 0.01	0.40 ± 0.02	0.44 ± 0.01	0.11 ± 0.01	0.24 ± 0.01
S2 Closed	0.17 ± 0.01	0.42 ± 0.01	0.56 ± 0.01	0.14 ± 0.01	0.30 ± 0.00
S3 Open	0.14 ± 0.01	0.27 ± 0.01	0.41 ± 0.01	0.07 ± 0.01	0.14 ± 0.01
S3 Closed	0.20 ± 0.01	0.47 ± 0.00	0.53 ± 0.01	0.15 ± 0.01	0.30 ± 0.01
S4 Open	0.12 ± 0.01	0.21 ± 0.02	0.29 ± 0.01	0.05 ± 0.02	0.12 ± 0.02
S4 Closed	0.20 ± 0.01	0.41 ± 0.01	0.53 ± 0.01	0.15 ± 0.01	0.30 ± 0.01

3.1.4 Expected overall performance reduction

The PV module cover glass will often not be sandblasted / treated on the full surface. Also, currently it is being looked into the possibility to reduce the actually affected area in sandblasted regions by using printing screens. The overall power loss of a PV module will thus depend on treated area and affected area in the treated area. This can be expressed e.g. by eqn. (1).

$$p_t = p_0\left(1 - \prod r_k\right) \qquad (1)$$

Where
p_t expected module power / yield with treatment,
p_0 module power / yield without treatment,
r_k loss factors / cover ratios.

For example, if 50 % of the module surface has a design-treatment and the loss (the reduction of transmission as compared to an untreated cover glass) due to the treatment is 20 % (e.g. 0° w/o diffusor, S2, closed, no colour), overall a 10 % power / yield reduction is expected. If the actually treated area can be reduced to e.g. 85 % without changing the visual effect, then an overall power / yield reduction of 8.5 % would be expected (see section 3.3). Of course, actual solar radiation situations will be a mix of direct and diffuse radiation where the direct radiation will have varying angles of incidence.

3.2 Full scale comparison measurements

At the time of writing of this paper, two full-scale measurement campaigns have been initiated. The PV modules are mounted in a vertical position facing south in both cases. The measurement site is not shaded. The data is acquired via the optimizer for each separate module and consists of hourly or daily yield.

A) A selected set of surface designs applied to PV-modules is submitted to a full scale measurement campaign in order to "ballpark" the actual performance which can be expected (see Figure 3 for the designs considered, here).
B) A series of basic design elements are applied to PV-modules of different types and also measured in full scale in comparison to untreated, otherwise identical PV-modules. Figure 7 shows the surface treatments used, here.

Results for A) are shown in Table II. Results for B) are not available at this stage. The initial results from A) are quite encouraging. Performance loss due to the surface treatments according to Figure 3 is in the order of magnitude of the variation between the PV-modules themselves.

Prior to surface treatment for B), the PV-modules used are measured without treatment for several days in order to ascertain the spread of their yield under identical boundary conditions (see Table III for results). It can be seen that especially the selection of CI(G)S modules have a quite large spread in yield. The largest spread observed here is found for the "CIS" modules considered and lies just inside the manufacturer data given. Of course, this spread must be taken into account in the evaluation of the treated modules.

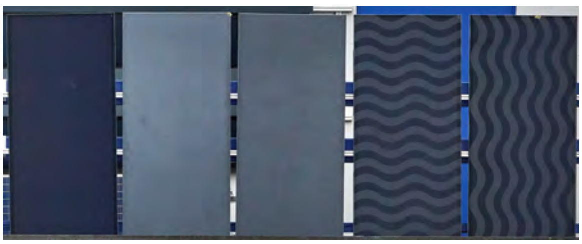


Figure 7: Untreated and treated CI(G)S PV modules. From left to right: Untreated reference module, "closed", "open", 50 % coverage with "arbitrary" designs (horizontal and vertical waves). These measurements are on-going at the time of writing of this paper.

Table II: Measurements w/ designs according to Figure 3. PV-module vertical, orientation south, location Basel (Switzerland), the measurement period is April 16th through May 3rd 2016 (18 days). The leftmost column (typeset bold) refers to an untreated module of the same type as the treated modules.

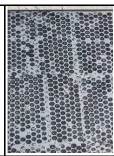
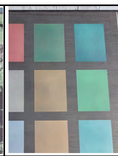
	Un-treated module				
yield	**6000**	5290	5870	5560	Wh
rel. yield	**100.0**	88.2	97.8	92.7	%
yield diff.	-	-11.8	-2.2	-7.3	%

Table III: Reference measurements, PV modules vertical, orientation south, location Basel (Switzerland), measurement period March 22nd through April 6th, 2016 (16 days).

	Ref. module	Module 1	Module 2	Module 3	Module 4
	m-Si				
yield (Wh):	**8436**	8512	8502	8758	8528
rel. yield (%)	**100.0**	100.9	100.8	103.8	101.1
yield diff. (%)	-	0.9	0.8	3.8	1.1
	c-Si				
yield (Wh):	**7648**	7850	7687	7480	7637
rel. yield (%)	**100.0**	102.6	100.5	97.8	99.9
yield diff. (%)	-	2.6	0.5	-2.2	-0.1
	CIS				
yield (Wh):	**4937**	5190	5449	4839	5211
rel. yield (%)	**100.0**	105.1	110.4	98.0	105.6
yield diff. (%)	-	5.1	10.4	-2.0	5.6
	CIGS				
yield (Wh):	**4029**	4131	3973	4026	4211
rel. yield (%)	**100.0**	102.6	98.6	99.9	104.5
yield diff. (%)	-	2.6	-1.4	-0.1	4.5

3.3 Optimization procedure

As described in section 1.1.1, the sandblasting technique most appropriate for the visual design of PV modules is still in development. Figure 8 (centre and right) shows initial approaches to the above-mentioned reduction of covered area by using screening techniques. The potential of such optimisations is not yet fully tapped. However, it is expected that it should be possible to avoid more than 10 % actual coverage without significant impact on the visual effect.

The other area of improvement identified was which colour type to use. Currently, colours with embedded reflecting particles are being evaluated for suitability.

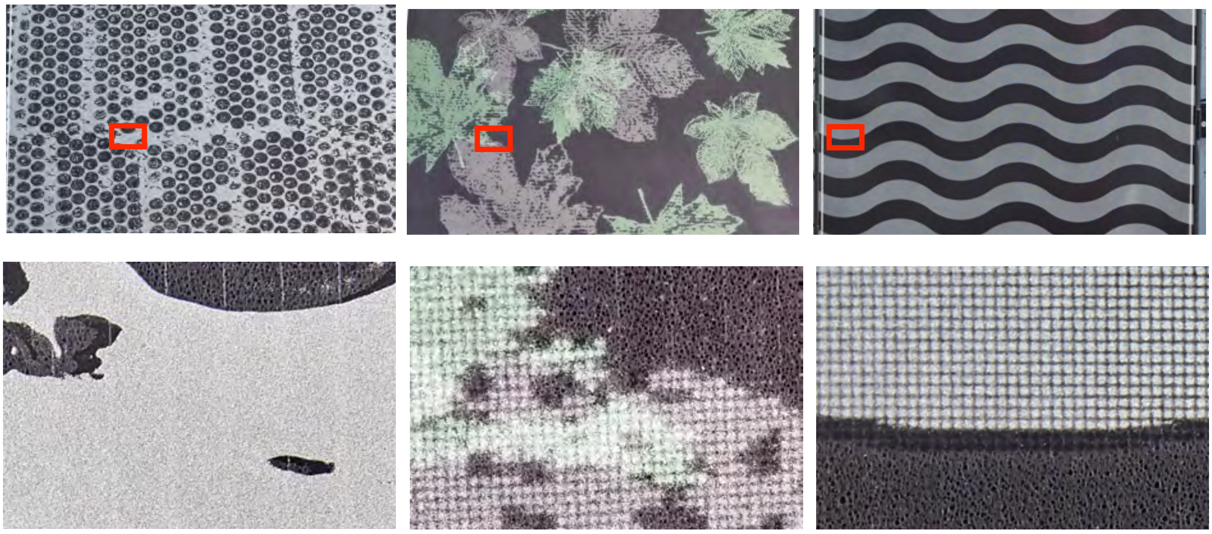


Figure 8: Detail examples (bottom row) of the sandblasted surface structures based on the PV modules shown in Figure 3. “Closed” structure with very fine grain on the left, more open structures in the middle and on the right with larger and again fine grain, respectively.

4 CONCLUSIONS & OUTLOOK

New design possibilities are an important component for mass application of Façade-BIPV. The sandblasting technique is a very promising option in this regard. A wide variety of surface designs can be applied to standard PV modules by a proven technique. The loss in efficiency depends on structure density and colour choice. The optimization of the blasting grain sizes, structure density and type of colour used is on-going. Initial results obtained are quite promising.

Architects will be provided with a wide range of possible design elements. Apart from the continued optimizations mentioned, further areas of interest are e.g. questions of product warranty and loss thereof due to “tampering” with the product “PV module”. These and other practical aspects of the solution proposed will be considered in the further scope of the project of which the results described herein are a part. Implementation of a PV façade cladding featuring modules treated by sandblasting and colouring is scheduled for a building in Basel near the end of the current year.

Acknowledgements

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