Building integrated photovoltaic at NEST – Preliminary test bedding results

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Abstract. This paper presents preliminary results on the visual and energy assessment of colored photovoltaics modules installed at the Meet2Create unit of the NEST pilot- and demonstration site at Empa in Dübendorf. The installation contains mono-crystalline PV modules with three different types of front glass (float, silk and satinated) and three different patterns printed on them (shutter, curve and ornament). Each printed PV module and three unprinted reference modules are monitored separately over a period of one year. With float glass, the visual appearance is dominated by reflections of the environment, an disturbing effect that does not appear with the matte and brighter satinated glass, where the colored print pattern remains visible across all viewing angles. Interestingly, the energy output is relatively similar. Compared to the unprinted reference PV modules, the losses with float, silk and satinated glass are 68, 75, and 72% respectively. While the different print patterns do not yield a significant difference. Satinated glass is thus an interesting alternative to the common float and structured front glass when visual appearance and energy efficiency matters.

1. Introduction
By 2035, photovoltaic shall make 30% of Swiss’ electricity supply, replacing nuclear power, as set by the government. Not through large power plants, but through integration into roofs and facades of existing and new buildings. However, a large number of proposals for building integrated photovoltaics are dismissed by the public or authorities, because of poor visual integration even though the proposals may be ecologically and economically feasible. Hence, several leading PV researcher from Switzerland aim their research and development towards improving visual aspects and not just electrical and economic efficiency [1-3]. Hence, a large variety of colored PV modules have been developed, featured in some projects in pilot- and demonstration (P&D) projects in Switzerland [4].

2. PV installation at NEST
The NEST building at Empa Dübendorf is a national pilot- and demonstration site for innovative building technologies, including building integrated photovoltaics. The Lucerne University of Applied Sciences and Arts (HSLU) supplied the Meet2Create unit on the first floor with full height glazing along the street façade. On March 2018, PV modules were installed as railings on the existing façades as can
be seen in figure 1. The PV modules are squarish glass-glass laminates with 49 mono-crystalline cells with active wire connection. Each printed PV module is different. Figure 2 shows three different design patterns (shutter, curve and ornament) applied with digital ceramic print on the backside of the front glass. Each design comes with three different glass types, the standard float and structured PV glass (silk) and satinated glass, which is not common for PV modules. In addition, reference modules were installed with float glass and without printing. Eight PV modules were installed on the longer facade, six colored PV modules framed by two reference modules. Four modules were installed on the shorter side, including one reference module. Back rails were laminated to the rear glass, fitting into standard facade mounting systems. Each PV module is electrically connected to a power-optimizer (micro-inverter) feeding into one central inverter connected to the building grid. HSLU developed the PV module design and specification based on their meta-c-print method in collaboration with technology transfer from Userhuus AG. The front glass was printed and supplied by Glas Trösch and the PV modules were laminated by GES in Germany. The mechanical installation was made by Diethelm, the electrical by BE Netz.

2.1. Meta-c-print
This method extends the typical opaque ceramic printing on architectural glass into controlled translucent printing photovoltaic glass. The different opacities of the base color inks for a given printer (usually red, green, yellow, black and white) are normalized so that the transmission is homogeneous across all colors, avoiding dangerous hot-spot effects in PV modules, that could reduce electrical performance or result in thermal stress. In addition the normalization can be set to achieve a certain PV efficiency. Here the method was used to optimize three different designs to yield 75% of the electrical performance of a PV module without print. The method is developed by HSLU and patents filed accordingly.

2.2. Key to numbering PV module positions and layout
Figure 2 shows the three different design patterns (shutter, ornament, curve), their combination with the three different glass types (float, silk, satinated) and the position of the resulting PV module including that of the reference modules.
3. Research question
The research question is of interdisciplinary nature. What is the impact of architectural interventions on the energy and visual performance of PV modules. Architectural interventions such as the use of satinated front glass to achieve a matte finish and the use of print patterns to visually structure flat surfaces. What is the effect of the glass types and of the print patterns, what matters more? Do architectural interventions always come with energy losses and vice versa, or can there be a good combination?

4. Methodology
Our approach was test bedding in a real environment, such as the NEST building. Lab based assessments were also performed in this case, and will be presented and correlated with field measurements in a following paper. Two assessments are made. First, the electrical power output of each printed PV modules in comparison to a reference PV module over a full year with data supplied from the commercial inverter system. And second, a more qualitative visual assessment by taking pictures of modules from various viewer positions, showing reflections of the sun disk that can override the appearance of the printed pattern.

5. Results
5.1. Energy assessment
Figure 3a shows a screenshot of the monitoring system web interface. The menu on the left lists all 12 PV modules as separate strings, while the graph on the right charts the individual string power output over one year from 1.5.2018 to 30.4.2019. Figure 3b shows the orientation of the PV modules. 8 PV modules on the longer façade face northwest, with index starting with 1 for the northernmost PV module, which is the leftmost PV module in figure 1. Those on the shorter side face southwest with indices 9-12. Figure 4 shows the exported raw data after post-processing with Excel, corrected by the sky-view factor for PV modules 9-12 (see chapter 6.1). The power outputs were normalized to the reference modules of each façade to show the losses through the architectural interventions.
Figure 3a. Power output in web interface, the four lower lines represent the four modules facing south west.

Figure 3b. PV module layout with different orientations

Figure 4. Relative performance comparison of all 12 PV modules.

PV modules 1, 8 and 9 yield 100% being the reference modules. All printed PV modules along the west facades show results between 66 and 75% compared to the reference modules, or losses between 25 and 34%. Within a print pattern, the silk glass provides the best and the float glass the worst results. Interestingly, the satinated glass performs well and close to that of the silk glass. PV modules 2-4 and 5-7 have different print patterns, but the variation between the print pattern is with 4-5% (absolute) only half of the variation between the glass types. On the southwest façade, all PV modules perform better, with silk glass almost 80%, followed by the satinated and float glass.

5.2. Visual assessment

Figure 5 shows a series of photos taken of the four PV modules 9-12 during a sunny day. The topmost picture is taken from a viewing angle so that the sun disk is to be mirrored in the leftmost PV module. The picture below has a slightly different viewing angle, so that the sun is to be mirrored from the second left PV module, and so on. The PV modules with float glass (9 and 11) reflect the sun disk visibly. The unprinted float glass scatters the sun disk image more as the reflecting surface is more inhomogeneous (cells, cell gap). The print pattern on PV module 11 makes the reflecting surface more homogeneous.
and hence the reflecting sun disk is more pronounced. The silk glass (10) scatters the sun disk into a large bright surface, where no print pattern can be seen at all. Quite the opposite is true for the satinated glass (12). There is no reflection of the sun disk visible and the print pattern remains always visible across the different viewing angles.

Figure 5. Top left, sun disk to be mirrored in leftmost PV module (9). Bottom left, sun disk to be mirrored in PV module 10. Top right, sun disk to be mirrored in PV module 11. Bottom right, sun disk to be mirrored in PV module 12.

6. Discussion
Measurements results need to always be examined for uncertainties, before results can be generalized. One general uncertainty is the performance of the PV cells. Their efficiency range and hence that of the PV module can be ± 5% of the rated efficiency. Measurements variations that fall within this range, such as the difference caused by the print patterns, can be considered insignificant. Further, the selected methodology of test bedding under real operating conditions has its limitations that need to be taken into consideration when interpreting the results.

6.1. Sky-view factor
One major aspect are the shading conditions of the PV modules. Figure 1 shows that the southwest façade is shaded by a cantilevering floor slab above, where the reference PV module at the corner would experience fewer shading as the last PV module 12. This near shading through the building itself does not exist on the northwest façade, but all facades experience far shading and reflections from surrounding buildings. Such shading effects were assessed on-site as much as possible through a sun path obstruction camera (Suneye) which quantifies the percentage of the sky that is obstructed by surrounding buildings and trees, as shown in figure 6. Such sky-view factors were established for all PV modules and applied to normalize the power output results in figure 4. However, their performance results are still higher (70-79%) than on the northwest façade (66-75%), indicating that the normalization factor is rather uncertain. The trend, silk, followed by satinated than float is still the same.

Figure 6. Fisheye view of the sky dome above PV module 9, augmented with the corresponding sun path area (yellow) and visualization of obstruction (green)
6.2. Light trapping

It is quite surprising that the satinated glass always results in better electrical performance of the PV modules compared to float glass. Standalone satinated glass appears less transmissive and brighter compared to float glass on first sight and as such one would expect lower electrical performance. Figure 7 shows the hemispherical transmission for incoming light across different incident angles, where float (clear) glass always shows a higher light transmission compared to satinated glass [5]. Structured (similar to satinated) glass used as front glass in PV modules generally show lower losses at shallow light incidence angle compared to float glass [6-7], an effect that is more predominant in the field compared to lab tests under standard test conditions, where the light incident angle is always perpendicular. Hypothetically, the additional printing reduces the angular losses or sensitivity even more. Figure 5 shows an always matte appearance of satinated glass with little reflection, suggesting that more light is trapped and being used for electricity conversion. But this hypothesis needs further research based on the compositional reflectance and transmission models for multilayer specimens [8-9].

![Figure 7. Comparison of hemispherical light transmission through clear (float) and matte (satinated) glass across different angles of incident light.](image)

7. Conclusion

The power output comparison ranks silk glass first, followed by satinated and float glass, while certain effects can still not be explained. The visual assessment indicates that satinated glass provides the best results, as reflections are lowest and hence printed patterns remain best visible across all viewing angles. Silk glass on the other side reflects over a rather large and bright area, potentially causing glare. Hence a holistic ranking would suggest satinated first, followed by float and silk last. Satinated glass would be a well-balanced choice if both assessments are considered. With reference to the research questions, one could preliminarily conclude that glass type matters more than print pattern and that satinated glass shows a superior visual hence architectural performance while still being energy efficient.

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9. References

[1] Nazeeruddin Md K, Baranoff E, Grätzel M 2011, Solar Energy 85 6 1172ff
[2] Heinstein P, Perret-Aebi L E, Palou J E, Cattaneo G, Li H Y, Mussolino V, Sansonnens L, Ballif C. Cisbat 2015
[3] Jolissaint N, Hanbali R, Hadorn J C, Schüler A. 2017 Energy Procedia 122 175ff
[4] Wittkopf S 2018, Tec 21, 2018
[5] Grobe L, Wittkopf S, Apian-Bennewitz P, Proceedings SPIE 7725, Photonics for Solar Energy Systems III, 772510, 2010
[6] Ebert M, Stascheit H, Hädrich I, Eitner, U, 29th European PV Solar Energy Conference, 2014
[7] Khoo YS, Singh JP, Walsh TM, Aberle AG. IEEE Journal of Photovoltaics 4(1) 2014
[8] Hébert M, Hersch RD, Becker J-M, Journal of the Optical Society of America (24) 2007
[9] Walter B, Marschner SR, Li H, Torrance KE, Proceedings 18th Eurographics Conference on Rendering Techniques 2007