REPEAT – Textile Design for PV Modules!
Design-driven Strategies for Photovoltaic Modules

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Abstract: This paper introduces an interdisciplinary collaboration between textile designers, architects and photovoltaic engineers. Together they have developed an innovative photovoltaic module, that a) features a customized coloured design pattern printed on the front glass, b) has a certain format and can be rotated in all four directions, c) is made of the latest Swiss solar technologies to provide high electrical efficiency. This paper shows general textile design approaches and their adoption for designing photovoltaic modules, the manufacturing of a functional prototype and installations for international exhibitions.

Keywords: textile design strategies, architecture, facade, photovoltaic, pattern

1. Introduction

By 2030 Swiss buildings need to produce 25\% of the national electricity demand through integrated photovoltaics (Bundesamt für Energie BFE, 2016). But currently, building integrated photovoltaics (BIPV) accounts for only 1.5\% of overall demand. Standard photovoltaic modules (PV modules) are visually not appealing and create dark reflective surfaces in rural and urban environments. They appear as alien elements on roofs and walls and are, as such, not accepted by architects. Recent projects in Switzerland feature designed photovoltaics, either with matte finishing to reduce reflection or colours away from the standard black, dark blue and brown. However, customization is expensive. Manufacturing of PV modules is much more cost-effective if the modules are all of the same size and design. Textile design and the philosophy of the repeat can provide a solution that is not only cost-effective but also ensures variety. We present PV modules with special coloured patterns. The PV module is square or rectangular and can be rotated and mounted in all four directions. Many of such PV modules repeated over a larger building facade, can thus create many interesting, dynamic patterns. Supporting approaches for the electrical interconnection between the PV modules of different orientations were recently filed for patents. We present designs and how PV modules look and perform with selected designs.
2. Textile skills and methods meet photovoltaic modules

2.1. Challenges and constraints

The challenge of integrating coloured PV modules in facades is a “wicked” problem (Rittel et al., 1973, p.161). Varied interests are contradictory and compete: on the one hand BIPV should be more often used in order to meet the demands of sustainable energy. On the other hand the market proposes very few varieties of PV modules: black PV modules with a very technological appeal, used for facades, offer high output, but it is still 30% lower than that of roof-mounted PV modules. Using the commercially available one-coloured PV module, the output is further reduced by 20%

Nonetheless architects and urban planners want to be free in choosing monochromatic colours or ornamented designs for the facades of new buildings or for houses in need of renovation. By proposing PV modules, we have to offer a vast choice of colours, designs and modification possibilities. As a benefit these facades generate more energy in comparison to conventional building materials.

The colour requirements for PV modules are high: The colours should appear as full and deep as possible while being as transparent as possible in order to let the light shine through for a high energy performance. The positive aspect of transparency is at the same time a challenge for the colour chart: every colour is mixed with the underground of the black solar wafers. Moreover, using different colours on the same PV module the designer has to guarantee that the colours are equally transparent. Any variation in transparency reduces the performance of the module as a whole (cf. chapter 4).

2.2. Contexts and transfer

Contemporary design must be transdisciplinary. It must acknowledge and integrate technology – and vice versa. For textiles, this means creating new possibilities to unite previously separate practices and interests, such as science, technology, biology, health, well-being as well as the social sciences and a range of creative practices (Jefferies et al., 2016, p.17).

It is important to improve the aesthetics of PV modules for use on facades. Repetitive PV modules of exactly the same size and shape and at even intervals are monotone, sleek and gloomy in appearance. The mostly black (monocrystalline) or blue (polycrystalline) PV modules look predominantly technical.

Here textile design strategies intervene by proposing multi-coloured designs that offer great variation by using or rotating them in different ways. There is not one process or answer, but we believe that textile design methods and analogies will help to lead to a bigger acceptance of designed PV modules on facades.

2.3. Textile skills and methods

“Textiles and technological invention have often gone hand in hand - mechanical devices, the computer and digital processes all affect the ways in which textile designers perceive, process and respond to information. The collaborative process, often involving specialists from different fields is opening up the potential for textile design strategies on various materials and application for use in domestic and global environments” (Jefferies et al., 2016: 8, p.21).

We consider the following textile methods important for designing PV modules:
1. repeats and rotation (to create surfaces)
2. colours (to improve the aesthetic impression)

These textile methods are analogies, which function for textiles as well as for other materials. A good example is tile production, because it offers a vast variety of repeat and design possibilities. This complexity could also be achieved for PV modules designs but on a larger scale.

2.4. Textile analogy “REPEAT”

“We are constantly surrounded by repeat patterns in nature and in urban areas. They are part of our everyday life” (Washburn et al, 1988, p.52). Facades moulded with PV modules do not have the variety of repeats that we are accustomed to seeing on brick walls, paving stones, fences and so on. The key idea is to have a PV module of one or more colours as one unit with a single pattern, so that it can be multiplied and arranged in different repetition orders and orientations to cover an entire facade. This approach is a common textile design principle. Single patterns and their repetition orders cover a larger surface, eventually creating playful patterns.

Moussavi and Kubo (2006) propose that by using repeated units in architecture we enable serial, branded, weighted and modular effects. In addition to using these effects to achieve our targets, we have adopted another: the symmetrical effect. Figures 1 – 5 below demonstrate these effects.

Figure 1. The serial effect: a single unit or image becomes part of a system. Through repetition, for example in a half drop repeat, the regular rhythm can be circumvented (e.g. Eberswalde Library, Herzog & de Meuron architects and Thomas Ruff, cf. Caspary, 2013, p.147).

Figure 2. The branded effect: through customized printed PV Modules with large scale lettering this effect refers to an urban context (e.g. Santa Monica Place Garage, F. Gehry architect, cf. Moussavi et al, 2006, pp.182-183; and Printshop Veenman, Neutelings Riedijk Architects, cf. Caspary, 2013, p.156).
Figure 3. The weighted effect: The height decreases from top to bottom or vice versa, which subtly distorts the scale of the building, making it seem far taller than it really is (e.g. Ricola Laufen Warehouse, Herzog & de Meuron architects, cf. Moussavi et al, 2006, pp.148-149).

Figure 4. The modular effect: composite module types in varying widths and heights are combined, producing a highly varied surface when arrayed on facades (e.g. Berlin Free University, Candilis, Josic, Wood, Prouvé, cf. Moussavi et al, 2006, pp.86-87).

Figure 5. The symmetrical effect: the original unit is mirrored horizontally or vertically. The facade would then be built of two types of modules and play with symmetrical patterns (e.g. Pachinko Tiger Kagitori/PTK, Hitoshi Abe, cf. Pell, 2010, pp.60-61; and Mies van der Rohe Barcelona Pavillon, cf. Washburn et al, 1988, p.46).

The concept of rotating single units within the repeat process is of particular interest to our ongoing research project. "A rotation has exactly one fixed point, the center of the rotation. A rotation is completely specified when we know its center, the angle of rotation, and if it is clockwise or counterclockwise" (Washburn et al, 1988, p.48). Massouvi and Kubo (2006) refer to a complex effect that is visualized in figure 6. As we work a lot with this principle (cf. chapter 3.4.), we want to highlight and explain how variations are created by rotating units.

Figure 6. The complex effect: by using one module we generate a complex composition of elements through rotation. The complex effect is the result of using one or mirrored units (e.g. Federation Square, Lab Architecture Studio, cf. Moussavi et al, 2006, p.114-115).
2.5. Textile analogy “COLOUR”

A main topic in the integration of BIPV is the application of colour and pattern. Colours transport emotions and provide a range of designs on PV modules. The challenge of achieving a bandwidth of designs out of a restricted colour palette is an important and well known task in Textile Design.

Due to the fact that a restricted colour palette will be used (cf. chapter 3.3.), a selection of basic and blended colours will be developed. In addition to colour illusion, the colour mixing plays a crucial part in this research project. “Two colours (or more), perceived simultaneously, are seen combined and thus merged into one new colour. In this process, the two original colours are first annulled and made invisible, and then replaced by a substitute called ‘optical mixtures’” (Albers, 1963, p 33).

Moussavi and Kubo (2006) propose four colour concepts that we consider important since they allow for differentiated, tonal, gradated and alternating effects, as explained in figures 8 – 11.

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Figure 7. Variation is achieved by using two-dimensional patterns preserving the same colours in different colourways. On the left side one unit with different colourways is used, while on the right side three mirrored units are used (cf. figure 17).

Figure 8. The differentiated effect: the focus here is on printed multi-tone modules. A maximum of three colours shall generate the greatest possible differentiated effect on a surface, thus a very typical principle of the Textile Design process (e.g. Boehringer Ingelheim Offices and Laboratories, Sauerbruch Hutton architects, cf. Moussavi et al., 2006, p.156-157).

Figure 9. The tonal effect: this effect is achieved by colour coding (e.g. Laban Dance Center, Herzog & de Meuron architects, cf. Moussavi et al, 2006, pp.172-173).
Figure 10. The gradated effect: this effect is made through a composition of multi-tone or monochrome modules arrayed in a repeating pattern, for example to affect the scale of the building or to blend in with the landscape or the sky (e.g. Ricola Mulhouse Factory, Herzog & de Meuron architects, cf. Moussavi et al, 2006, pp.176-177).

Figure 11. The alternating effect: this is generated by using one-dimensional patterns and preserving the same colours in different colourways. If a design admits translations in only one direction, the design is called a band, strip, frieze, or one-dimensional pattern (Washburn et al, 1988, p.52). (e.g. IBM Training and Manufacturing Center, Saarinen, cf. Moussavi et al, 2006, pp.164-165).

3. Design approach and first results

As textile designers we were not familiar with the technical details of PV technology at the beginning of the project. We were able to think freely about how the different parts of a PV module could be modulated to generate novel aesthetics.

We started thinking about the single layers (cf. figure 12) of a module and how to manipulate them in order to generate a new appearance. PV modules basically consist of two glass layers with wafers in-between. A visit to a PV module manufacturing company gave us first-hand insight into the production processes. The following chapter shows design approaches to every layer and which pragmatic design interventions in the production and assembling process could lead to a new PV module aesthetic.

Figure 12. The structure of a PV module: glass, Ethylenvinylacetat (EVA), solar cells, EVA, glass (cf. Wesselak et al., 2013/2016, p.68, adapted).
3.1. First Layer – back glass and foil (EVA)

The back glass layer has been identified as the first layer that has a potential of changing the look of PV modules. Usually this layer is laminated with a black foil. The black foil ensures that the surface is perceived as homogenously black as possible. On rethinking the lamination process, partially coloured modules could easily be created by simply switching the foil colour. As seen in figure 13 a coloured back glass produces a non-homogenous surfaces and highlights the single wafers.

![Figure 13. Visualisation of different PV module sizes with an orange back glass foil](image)

3.2. Second Layer - wafers

The wafers themselves are the in-between layers of the PV modules. Their form, size and colour are defined by standardized silicon (Si) production. These features are difficult to change as their standardization ensures the cost effectiveness of the product. Nevertheless one simple way of intervening at this level is to change the strict placement of the single wafers. The placement can be modified by skipping single wafers or changing the distances between them. Both approaches allow differentiating the surface without major modifications in the purchase of silicon materials or the reorganization of the placement process itself.

Focusing on the placement of the single wafers might require working with coloured foil or without any colour on the rear layer of the glass.

![Figure 14. Left side: a standard PV module size 1300mm x 875mm with a maximum of 8 x 5 wafers assembled with only 6 x 5 wafers, which are 148mm, 74mm, 37mm, 19mm, 10mm apart, respectively. Right side: several PV modules repeated using mirrored units.](image)
3.3. Third layer – front glass

The cover glass of the PV modules was identified as the third layer. The third layer can be manipulated by printing, coloured foil or using different glass materials such as structured glass. As the last two options have already been investigated by many research projects and companies we focused on a rather novel printing technology that was tested in a first feasibility study. The usability of colour-printed glass for PV modules was analysed and it could be shown that the printing only marginally restricts energy effectiveness. In further research projects, a method to correlate colour, print parameters and electrical efficiencies was developed and registered. It is called the meta-C-print method and will be explained further in chapter 4.

One main challenge in printing on PV modules is the rigorous regulations in using new elements or materials in the product. The regulations require certificates for every colour applied. Therefore a minimal amount of colour is highly interesting in order to keep the production costs low. To not limit colour choices the phenomenology of optical mixture is adopted. Anderson Feisner and Reed (2014) describe that optical mixing is the result of two or more colours mixing visually to ‘become’ another colour. By working with this phenomenon we created varying colourways simply by changing the weight of each colour. Figure 15 shows three-colour printing with different amounts of orange, white and black.

So far we experimented in particular with the possibilities of optical mixture. As discussed in chapter 2.3, other colour concepts will also be important in our further research. As mentioned above, Moussavi and Kubo (2006) introduce us to four different effects: the differentiated, tonal, gradated and alternating effect.

![Figure 15. All three colourways use the same three colours (black, white and orange). By weighting the colour application differently, different optical mixed colours appear.](image)

3.4. Fourth layer - arrangement

The arrangement of the PV modules on a facade was identified as the fourth and last layer. Although the arrangement or construction is not specifically part of the object itself, it is a major variable in working on the design of BIPV. Therefore we want to consider it as stand-alone layer.

As mentioned in 2.3. the installation of PV modules currently consists primarily of the serial repetition of same-size modules. We consider the combination of different module sizes in more complex arrangements as great potential in designing building facades. For example, in comparison to the monotonous repetition of the PV modules, a wall with the same but slightly uneven arranged bricks corresponds with our visual habit and therefore appears familiar.
By applying different repeating methods, one print design can offer many new overall appearances. This system could help PV module producers to hold costs down while offering considerable variety.
The goals targeted for the fourth layer required new fixing systems to provide maximum flexibility for the application of the designed PV modules. This will be part of future research activity. The aim will be to generate a fixing system for the use of PV modules in different sizes and based on the principle of rotation. This is the challenge involved in ensuring versatile design possibilities.

4. Prototype of PV module

The objective here was to identify one square design and produce 20 identical PV modules. Out of the many designs that were developed (see figs. 17 and 18) was eventually selected (fig. 17). It is comprised of thin stripes (red, white and black) arranged in two zones of perpendicular orientation. Figure 17 shows interesting patterns when the PV module is rotated and repeated over a larger area.

The first step in production was to determine the print opacity for the best visual and electrical results. The more opaque the print is, the better the visual appearance and perception, however the less light is transmitted to the PV cell behind. Standard PV modules usually have clear solar glass on top of the PV cells, with visible light transmissions of up to 95%. An additional print would obviously reduce the transmission, depending on the type of print. Traditional silk screen printing features a thick print, new digital ceramic printing provides generally thinner printing as well as better control of the print parameters. Hence digital ceramic printing was selected and the degree of translucency for every colour was optimized through the meta-C-print © method, so that all colours have the same solar transmission. Using that method, the reduction in electrical efficiency can be minimized, e.g. 20% compared to a standard PV module without any print, and then the translucency for every colour is adjusted and set in a print file. Without such optimization, different colours would result in different solar transmissions creating the so called “hot-spot” problem in PV modules, which would significantly reduce the efficiency of the PV module and also create thermal stress that may damage it. Using the meta-C-print © method we processed the original design into four different print files with resulting efficiency losses of 10, 20, 30 and 40%. We printed those optimized design on 1:1 glass sheets and performed visual inspections, before selecting the setting for actual assembly into a PV module. For the visual inspection, all four printed glasses were put in front of a PV module with standard black cells (cf. figure 19). We assessed the resulting colour from the blend of the printed translucent colour and the black background colour of the PV cells and concluded that the print with 20% provides a good compromise of being close to the original design and not having too much reduction in electrical performance.
After the selection of the print file, 20 sets were printed and assembled manually into PV modules. The latest Swiss technologies were used, e.g. heterojunction PV cells combining monocrystalline PV cells with additional thin film PV for high efficient cells and smart wire connection instead of the usual 3 or 5 bus bars. This way, the active area of the cells is visually very homogenous, without any electrical components shining through and disturbing the design. 16 cells were arranged in a matrix of 4 x 4, resulting in an overall dimension of approx. 70 x 70 cm and a weight of 13 kg. However the individual cells still required cross connectors, which are visually very prominent. Figure 20 shows the electrical components of the PV module.
The PV modules were then assembled as a ventilated PV facade for demonstration purposes. Figure 21 shows the installation as planned and how it was actually presented at the international conference Advanced Building Skins in Bern in October 2016. In addition to the 1:1 scale PV facade, we also provided a small-scale version of the PV modules as magnetic pads clipped to a metal pillar. Visitors could play with the pads, rearrange them to design different facades, and experience how little modification (rotation) is required to generate dynamic patterns over larger areas.

In addition, a postcard was designed illustrating the design idea and approach together with the industrial partners.
5. Conclusion and Outlook

PV modules analysed from a designer’s point of view reveal a potential for future application in architecture because of their extended use on facades through textile design methods. The project hopefully shows that merging colour, repeat and rotation on an industrial scale is an appealing innovation within the architectural landscape that will be well received by the market.

We have experienced that textile designers working with PV modules evoke scepticism from professionals with a different background. This was the impetus for demonstrating that textile design methods, based on visual images, samples of printed glass and flow charts, are feasible and merit interdisciplinary collaboration from an early stage onwards.

In other words, our design-driven project requires an interdisciplinary team of engineers, architects, designers and other experts to implement textile design methods on PV modules. Hazel Clark describes in her text “New Approaches to Textile Design” and in her conclusion about collaborations between designers and scientists that, as life becomes more complex in the twenty-first-century, all types of design practices must respond and that trans-disciplinary and collective approaches can lead to the re-evaluation of tradition, while integrating the use of technology. These strategies clearly show that PV modules can make a much more substantial contribution (Jefferies et al., 2016, p.24).

The dynamic exchange that is taking place between architecture, engineering and textile design strategies is creating a new range of possibilities that takes all three disciplines in exciting new directions. Not only do textile strategies provide new inspiration for architects, they also present fresh possibilities for eco-friendly planners. The potential of coloured PV modules on facades will change the experience of architecture forever.
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