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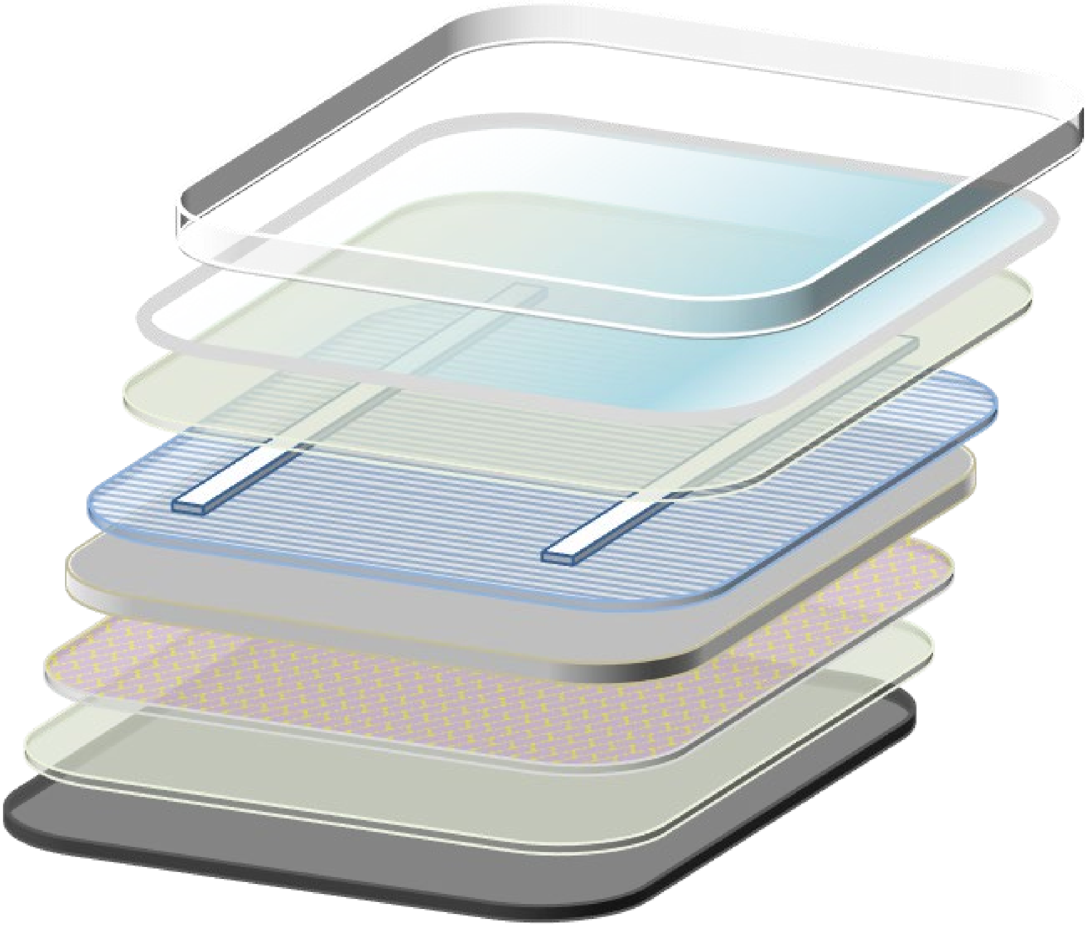

Aesthetically pleasing PV modules for the Built Environment

Parisa Sehati, Ingemar Malmros, Stefan Karlsson and Peter Kovacs

RISE Rapport 2019: 08

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Abstract

Sustainable development of the built environment is in the vicinity with circular economy, green building technology and the integration of renewable energy harvesting devices. Solar energy is an enormous resource, in 90 minutes the sun irradiates energy in an amount that is equal to our entire planet's annual energy need. PV modules is an increasing alternative to generate electricity which has reached grid parity with fossil energy in larger installations. However, fields of PV modules require space and in the built environment the space is scarce, therefore, building applied and building integrated PV has become increasingly interesting. As PV becomes an integrated part in the built environment the aesthetics becomes important, also for it to become accepted among architects. Today, there are many alternatives to make PV modules aesthetically pleasing and many companies develop this further in collaboration with building contractors and architects. In the current report we introduce color, light and PV modules and present a survey of how to make PV modules aesthetically pleasing with a special focus on modification of its color. We present some examples of aesthetically pleasing PV modules and Nordic companies that have been working with developing this. We also list companies that supply roof- as well as façade systems. Finally, we discuss the challenges and the cost implications for aesthetically pleasing PV modules in the built environment.

Key words: Aesthetics, Architecture, Colored glass, Coating, Cost, Customer need, PV module, PV installer, Interviews, Paint, Solar cells

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Preface

There is an increasing awareness of the need of sustainable energy sources in today's transforming society. At global level, there are universal goals to be reached until 2030, known as the *Sustainable Development Goals*[1]. Goal number 7 of the document states "*Affordable and clean energy*"[2]. Clean energy is primarily interpreted as solar, wind and geothermal energy.

Decentralization of the production units for solar energy is desirable as there are significant losses from power plants to the final user's location due to resistive heat generation. Maintenance, transmission and transformation costs of generated electricity are also important factors that needs to be considered. Further, the vulnerability of power plants to terrorist attacks as well as natural disasters, makes decentralization a crucial parameter to be considered. In this study, decentralization indicates that rooftop installed solar panels is an interesting route forward [1].

One of the challenges for integrating solar energy into urban areas is the aesthetic applicability of the panels [2]. Concerns are particularly deeper in the historical districts as their explicit features are not necessarily compatible with the appearance of solar panels. On those account, it is crucial to be able to manufacture solar panels with an aesthetically pleasing expression. Color is the very first factor drawing attention to the appearance of panels [3]. There are four distinctive ways of modifying solar panels color: i) adjusting the thickness of anti-reflective (AR) layer on top of the semiconductor ii) applying semiconductors with inherent color iii) modifying the top glass color iv) inserting colored laminate film. These methods will be discussed in more detail in the report.

In this study, we have reviewed the available colors, how the color has been applied to the PV modules and to what extent it will affect the end price of solar modules. Modification of the solar cell color by modification of the AR-layer and changing the semiconducting layer will be briefly touched upon.

This study is intended for architects and solar PV installers who need to have an overview of the possibilities of the solar PV modules with colored glass for Building Integrated PhotoVoltaic (BIPV) applications.

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[1] *http://www.undp.org/content/undp/en/home/sustainable-development-goals.html*

[2] *http://www.undp.org/content/undp/en/home/sustainable-development-goals/goal-7-affordable-and-clean-energy.html*

1 Color and light

A solar cell is a device that convert solar light into direct current (DC) electricity. The spectrum of solar radiation has different wavelengths. Only 3 parts of the solar radiation are useful for generating solar electricity. Theses 3 portions of solar radiation from shortest to longest wavelength are Ultraviolet (UV), Visible and Infrared (IR), see Fig. 1.

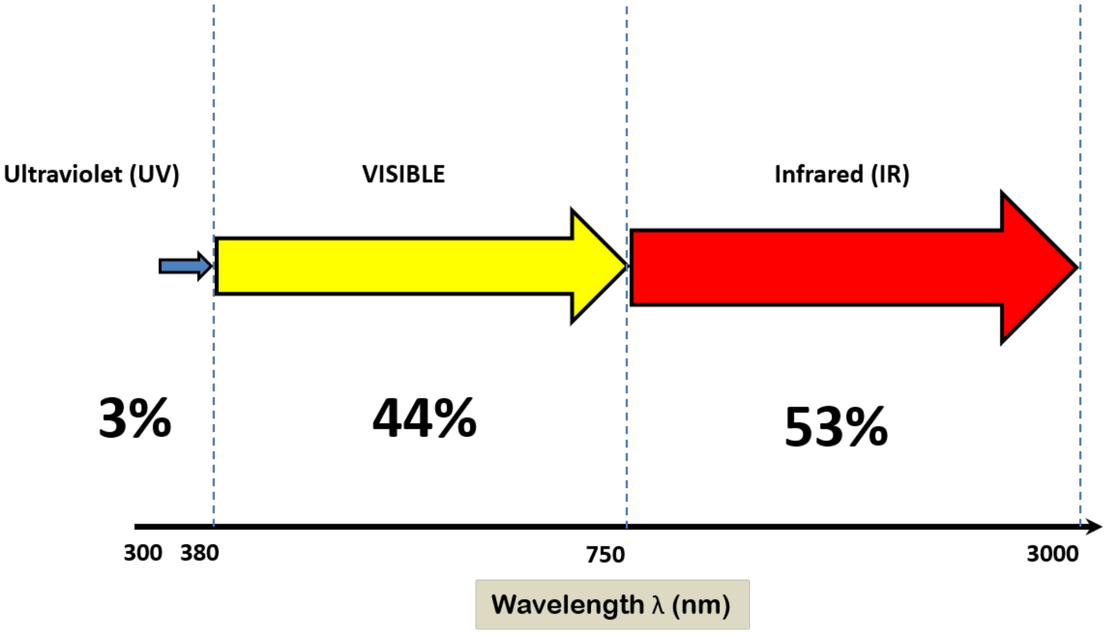

Figure 1 Different regions of the solar spectrum which can be used to generate solar electricity and their corresponding wavelengths

The visible region of the solar radiation covers an area from ~ 380 nm- 780 nm. Sir Isaac Newton (1672) was the first to discover that visible light is composed of different colors with different wavelengths. He observed that white light shining through a prism resolved it to its component colors: violet, blue, green, yellow, orange and red. He realized that each of the colors have specific wavelengths and it is not possible to refract (i.e., resolve, separate) them further to any other colors. A naturally occurring phenomenon exhibiting different colors of visible light is rainbows that are a result of rain droplets behaving as prisms refracting the white light into rainbow colors. Table 1 shows the color-wavelength relation. In this study, light refers to white light, i.e., composed of different colors/wavelengths.

Table 1: Colors of rainbow with their associated wavelengths.

Color	Wavelength (nm)
Violet	380-450
Blue	450-495
Green	495-570
Yellow	570-590
Orange	590-620
Red	620-750

If incident light is colored, its color will be expressed explicitly. Incident light to an object interacts with it in three different ways: i) part of the light will be reflected (R) ii) another part will be transmitted (T) iii) and the rest will be absorbed (A). Parts of the light may also be scattered (S) meaning any deviation from the straight trajectory of light because of interaction with inhomogeneities in the material. The absorbed light will be completely or partly transformed into heat causing the object to experience an increase of temperature. It is noteworthy to realize that the total sum of reflection, transmission, absorption and scattering is equal to 1:

$$R+T+A+S=1$$

Let us now focus on what it means that an apple is green, or a keyboard is black. We experience different wavelengths of the visible region as color. For us to observe a color, the opaque object being observed needs to reflect light otherwise it is perceived as black. Opaque objects reflecting parts of the light that shines on them and absorb the rest will have a color other than black and white. Opaque objects reflecting all wavelengths will appear white while an object reflecting blue light will appear blue. Absorbed light causes the object to heat up. The reflected light reaching our eye will stimulate the cone cells in the eye and a signal will be sent to our brain. Our brain analyses the information and as a result we *perceive* a color, for example green (see Figure 2).

Figure 2 An opaque object reflects part of the ***incoming light****. Based on the* ***reflected light*** *reaching the eye, our brain perceives the color. Some portion of the* ***incident light*** *will be* ***absorbed*** *which heats up the object.*

How does a translucent or transparent object interact with the incoming light? A translucent or transparent object will reflect and absorb portion of the light, like an opaque object but it also transmits part of the light. Our eye receives the transmitted rays and based on the wavelength/color of the transmitted light, we *perceive* its color (see Figure 3).

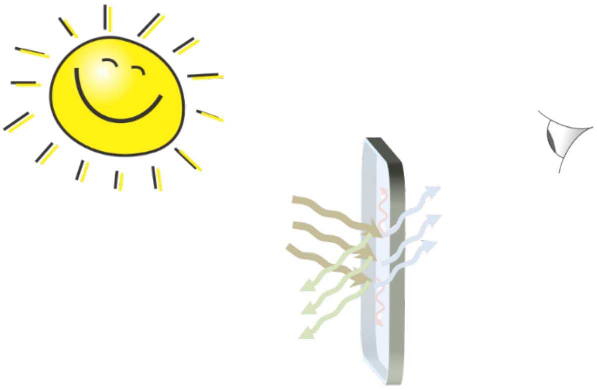

Figure 3 Interaction of ***incident light*** *with a transparent object (for ex. a glass sheet):* ***incoming light*** *is* ***reflected****,* ***absorbed*** *and* ***transmitted****.*

2 How does a solar cell work?

2.1 The Photoelectric effect

A solar cell is used to convert solar energy into electricity (Figure 4). The light hits the surface of the solar cell, a semiconducting material, and knocks out released electrons. These electrons take different paths inside the solar cell until they are collected at the plug-in as Direct Current (DC). The phenomenon of ejecting electrons from a semiconducting material by the energy of solar radiation is called the *photoelectric effect*. The photoelectric effect was explained successfully by Albert Einstein (1921) for which he was awarded Nobel prize the following year.

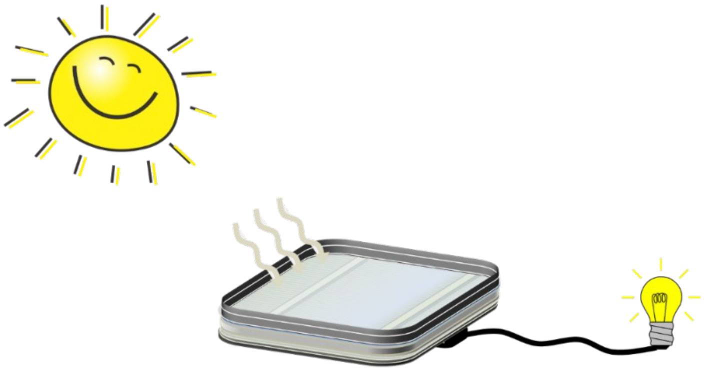

Figure 4 *A solar cell harvests solar energy in form of (DC) electricity.*

Most of our modern electrical gadgets and appliances are designed to use Alternating Current (AC). The difference of DC and AC is the direction of the current, for DC the direction is constant while for AC it periodically reverses direction. Therefore, it is necessary to use an inverter to feed the user or the grid with AC electricity.

3 Anatomy of a solar cell

There are different types of solar cell based on what semiconductor material we use. Changing the semiconducting material means changing the type of solar cell which in turn has a profound impact on the production scheme, price, generated power, type and form of the electrodes, appearance and color of the solar cell, its weight and finally the physics governing it. A very simple classification of various solar cells is seen in Figure 5.

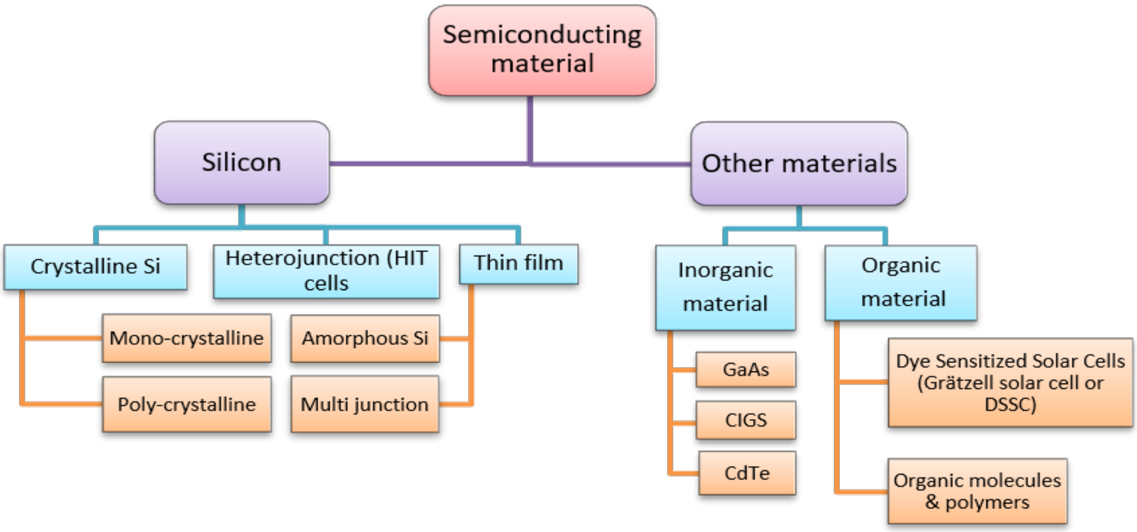

Figure 5 Based on the type of the semiconductor material being applied in the cell structure, there are various types of solar cells with different mechanism of generating electricity.

Assembling a solar cell requires not only the semiconducting material but also protection of the semiconducting material towards humidity, oxygen, wind, snow, static or ice loads. Materials that are used to shield the solar cell against physical, chemical and mechanical damages are known as encapsulants. Encapsulants enclose the solar cell on both front and rear and consists of following:

- Glass or plastic sheet
- Encapsulant/adhesive layer

The front side of the solar cell is covered by glass or plastic materials[3]. A front sheet is laminated, i.e., adhered to semiconducting material by applying Ethylene Vinyl Acetate films, generally known as EVA, on both top of and beneath it. The back sheet could also be glass or polymer. Then the whole package of back sheet/EVA/semiconducting material/EVA/front cover will be heated. Because of heating, the EVA film will be melted and adhere the front and rear covers of semiconducting material to it. To better understand the general structure of a solar cell, please see Figure 6.

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[3] *https://www.m-chemical.co.jp/en/news/mpi/201201250470.html*

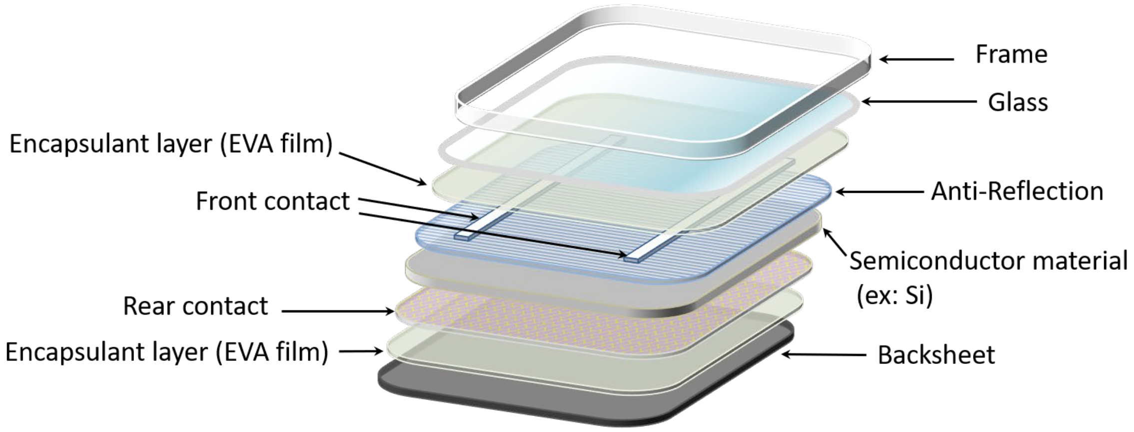

Figure 6 Different components of a silicon solar cells device. Please notice the Anti-Reflection (AR) layer directly on top of Si semiconductor.

4 Modification of color: different approaches

As previously mentioned in the preface of this report, the color of a solar cell can be modified by different techniques based on modifying different components:

- Modification of AR-layer thickness,
- Changing semiconducting material,
- Modifying the top glass cover,
- Alteration of encapsulant

4.1 Modification of Anti-Reflection (AR) thickness

In some cases, the surface of the semiconducting material is very reflective based on its refractive index. Reflection prevents solar light striking the semiconducting material, so it is a source of loss. To decrease the loss, the surface of the semiconducting is often covered by Anti-Reflecting (AR) material(s). The thickness of the AR-layer affects the color the solar cell will have. Crystalline silicon-based semiconductors, both monocrystalline and polycrystalline, are frequently covered by AR-layer. Solar cells with modified color of the semiconducting layer can be purchased directly from the solar cell producer. Although modification of the AR-layer thickness is possible, it is not completely without any hitch. In plain text, the alteration of AR-layer thickness entails an increased price. The other aspect to consider is the impact of modified AR-layer thickness on generated power. The thickness of the AR-layer is optimized to minimize the reflections from the surface of crystalline silicon. This optimized AR-layer thickness leads to various shades of blue of crystalline silicon solar cells (see Figure 7). Modification of the optimized AR-layer thickness, lowers the cell efficiency. However, it can be worth it depending on the value of the aesthetics. As an example, it is possible to generate a reddish/brownish/golden color of the flakes of crystalline Si recognizable by their glittery surface (see Figure 7).

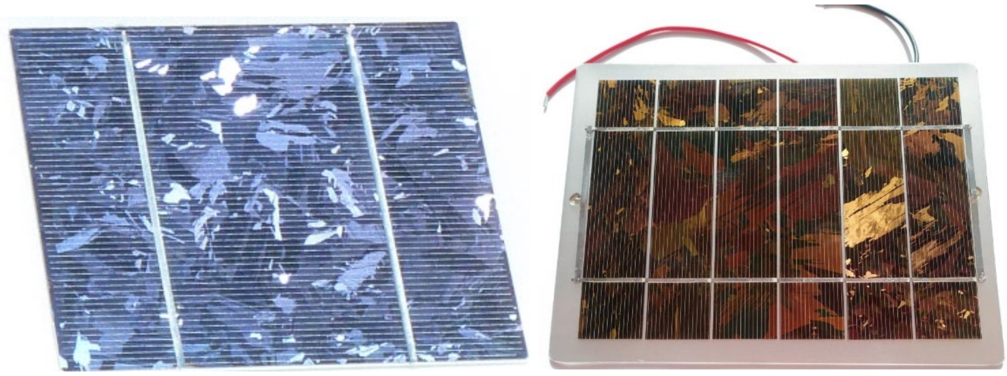

Figure 7 Left) Polycrystalline Si solar cell in its original color, Right) Polycrystalline Si solar cell with modified thickness of AR-layer (on top of semiconducting material) from Solar Capture Technologies[4].

4.2 Altering semiconducting material

Different semiconducting material have different generated power, price, appearance, color and weight. However, the discrepancy between different types of solar cell gives a versatile tool to architects and end users to be able to integrate solar cells in various building units. From the point of view of possibility of aesthetical integration of solar cells in buildings, the following advantages can be listed:

- Flexibility
- Low weight
- Colors
- Transparency/ semi-transparency
- Replacement of other material

For companies investing in aesthetically pleasing solar cells the following benefits are encountered:

- Environmental benefits
- Replacement of other material
- Positive image
- Innovativeness and competitiveness

These properties facilitate integrating solar cells with glass elements such as windows, skylight and facades. Since the color is rather easily adjustable, the price alteration is comparatively reasonable. Another distinctive aspect that should be mentioned in here is the potential of using Grätzel cells for indoor applications which paves the way for exotic wallpapers and similar out-of-the-box utilizations, see Figure 8. Albeit, everything comes at a price. Aesthetics, transparency/semitransparency, flexibility, vivid colors and comparative prices are counterbalanced by lower efficiency and shorter lifespan. Therefore, adopting flexible, thin film solar cells in the architecture of buildings is a tradeoff between expenses, lifetime and aesthetical expressions.

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[4] *https://www.solarcapturetechnologies.com/*

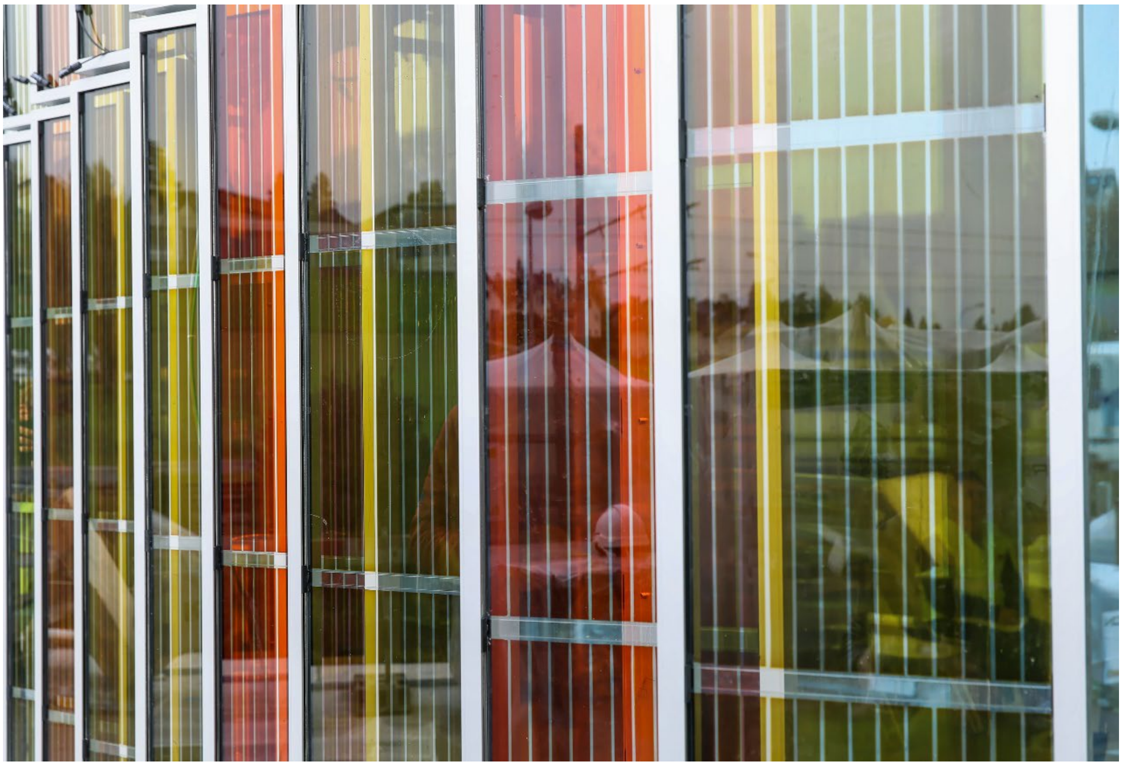

Figure 8: Vivid colors of Grätzel cells are seen clearly in this photo. Photo: © Alain Herzog / EPFL

4.3 Modifying the top glass cover

4.3.1 The inherent color of glass

Industrially produced flat glass is in principle in some way always colored due to impurities [4]. The impurities originate from the raw materials, most commonly, sand. Iron oxide is the most conventional impurity and gives the glass a greenish color. The green color is in fact a mixture of yellow and blue that we perceive as green, the yellow color is due to a narrow absorption band of Fe^{3+} in near UV-region while the blue color is due to a very broad absorption band of Fe^{2+}in the near-infrared region that partly absorbs light in the range 600-700 nm in the visible region. Iron oxide is not only an unwanted impurity but also valuable for controlling the UV and IR transmission of the glass which have important properties in a variety of products such as for instance architectural windows and car windscreens [4]. A lot of work has been carried out in sourcing sand having a naturally low iron but also nickel content. Ni^{2+} is another metal oxide that most commonly give a brown-grey or purple color. It was quite a common color for the first pieces of manmade glass.

Glass is a transparent material. This mean that the intensity of the color follows Lambert-Beers law, in other words depend on the thickness of glass, the concentration and the glass composition (its extinction coefficient) [5]. Most flat glasses applied as cover glass for PV modules are of soda-lime silicate type i.e. have a similar extinction coefficient. So, the concentration and the thickness are the primary parameters of importance for coloring the cover glass. The thickness of the glass has a profound impact on the resulting color and the effect can be easily observed when viewing from the cross-section of a flat glass instead of through a window glass. The concentration of coloring agents such as iron oxide can also be tuned for different purposes, hence, for cover glass for PV modules so-called low-iron glass is commonly used mainly for increasing the efficiency of the PV module [6].

The color of glasses is measured using the CIE (Commission Internationale de l'Eclarairage) Lab-system [7]. In the CIE the amount of light that passes through the sample is measured and then plotted in a x,y-graph which can be extended to a x,y,z-graph giving a color sphere where the z-axis is the brightness of the color. The positive side of the x-axis corresponds to red and the negative side to green. Similarly, the positive side of the y-axis corresponds to yellow and the negative side to blue. All other colors will then be inside the area made up by the complementary colors.

4.3.2 Coloring agents of glasses

Glasses are mostly colored using additions of metal oxides to the glass melt, for more rigorous description of colors in glass please find ref [7]. The most common coloring agents are iron oxide (green), chromium oxide (green), cobalt oxide (blue), copper oxide (turquoise blue), manganese oxide (purple), nickel oxide (violet/brown) and titanium oxide (yellow). Cr^{3+} in chromium oxide provides an intense emerald green color that frequently can be observed in champagne bottles. Cr^{3+} have two strong absorption bands at 450 nm and 650 nm. Co^{2+} strongly colors the glass blue and is frequently known as cobalt-blue, it gives three absorption peaks of about 530, 590 and 650 nm. Cu^{2+} colors the glass quite strongly turquoise due to a broad absorption peak at about 750 nm. Mn^{3+} gives a purple amethyst color. Ni^{2+} gives a brown-grey color in conventional soda-lime silicate glass [8]. Ti^{4+} provides a quite weakly colored yellow glass by absorption in the near UV-region [9], about 380 nm.

Besides the addition of metal oxides to the glass melts there are so-called semiconductor-colored glasses, however, as these are more rarely used due to their toxicity they will not be overviewed here. There are also so-called striking colors that gives a color due to scattering light. These are commonly based on metal nanoparticles of copper (yellow-red), silver (yellow-brown) or gold (red) [7].

Colored flat glasses are not as common as conventional clear flat glass, but all larger flat glass manufacturers offer some colored flat glasses. The coloring agents are added in the glass melting process to achieve specific colors. For instance, additional iron is added to produce green tint, cobalt and iron for blue tints and iron, cobalt and selenium for bronze or grey tints. The colors are perceived as weakly colored when viewed in transmitted light and do not give significant colored reflectance's. The exterior visual appearance is a lower light transmittance, i.e. solar shading effect, in combination with their color appearance. For a range of products offered by the flat glass manufacturer AGC, see Figure 9.

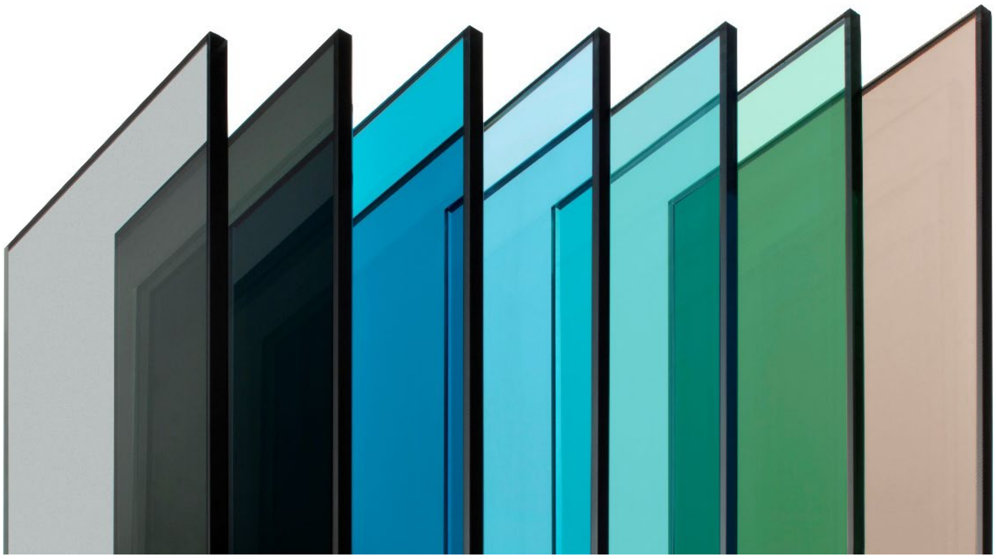

Figure 9: Planibel Colored product range by AGC; grey, dark grey, privablue, dark blue, azur, green and bronze. Image used with permission of AGC Glass Europe.

4.3.3 Surface coloration of glass

Surface coloration is another route to make versatile colored flat glass in smaller quantities. A slow and so far not so industrialized route for surface coloration is via ion exchange by immersion in a salt bath containing silver or copper ions for coloration yellow-brown or red-brown respectively [10, 11]. In the past an electrofloat process was also developed for coloring flat glass using lead and copper nanoparticles giving a bronze appearance of the glass [12].

A more industrial process for surface coloration is the application of coloring agents in a burner e.g. using Beneq Oy's nHalo™ equipment (not marketed anymore). A wide variety of colors using different coloring agents for glass can be produced. The burner and flame help to make the aerosol metal or metal oxide particles and makes the glass susceptible for doping of the glass surface, see ref [13] for more details.

4.3.4 Other methods to color glass

There are a variety of other methods to color the glass [7]. There are both inorganic and organic color paints. Inorganic color paints are annealed at about 500 °C while organic are annealed at about 180 °C. Organic color paints are less chemically stable. Inorganic color paints can either be applied using spray, brush or by screen-printing [14, 15]. Screen-printing is widely used in the container glass industry.

Another alternative is to provide structural coloration of the PV module. Structural coloration is widely used by insects, flowers or birds for generating strong colors e.g. a butterfly. The structural coloration effect is generated by optical interference of reflected light [16]. This can be added to glass by nanostructuring the glass surface by applying a coating, something which is reported in the following ref [17] for BIPV purposes.

4.4 Inserting colored laminate film

4.4.1 Structure of laminates

Semiconducting material must be protected from the environment in order to keep being functional for a long time. One process for securing a tight seal between the top glass cover and the backsheet is done via a lamination process. The lamination process entails putting a polymer material, laminate film, between the semiconducting component and its top and bottom cover (c.f. Figure 6). Then the complete system of semiconducting material, two laminates (one on top of the semiconducting material and one beneath it) and the top and bottom covers will be heated in an oven. The laminating film melts and turns upon cooling into a transparent glue which adheres to the semiconducting components and to the front and back cover and thereby seal the system from the environment. Until now the most utilized laminate film for PV applications are films based on Ethylene Vinyl Acetate, generally known by its abbreviation EVA. There is another laminate film being used primarily in architectural glazing's which is based on the Polyvinyl Butyral (PVB)-polymer. There are also several films based on other types of polymers, but they are often developed for specific tasks and not as general as EVA and PVB.

Both two laminate films are polymers. A polymer is a material consisting of long chains of repeating units called monomers. PVB has only one monomer (Figure 10) and is called a *polymer*. EVA constitutes from 2 different monomers and therefore is called a *co-polymer*. It is easier to produce a polymer than a co-polymer, but with careful selection of the monomers and the reaction properties it is possible to minimize the production effort.

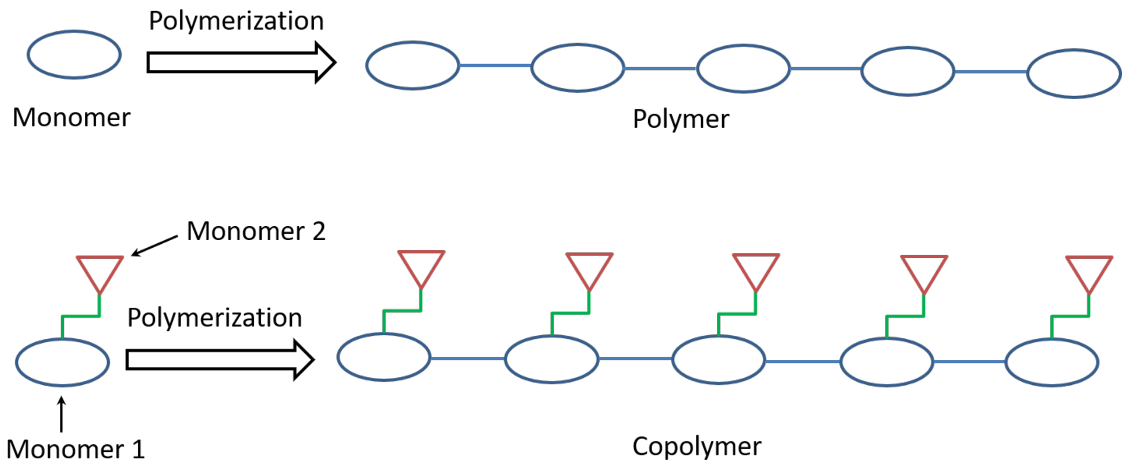

Figure 10: Difference between polymer and copolymer.

Both EVA and PVB are flexible and elastic at room temperature, but during lamination they undergo two different type of reactions. The exerted heat of lamination causes EVA film to start crosslink (Figure 11) with itself and the surfaces of the materials on each side of the film, the glass and the solar cell. Crosslinking implies various chains of the copolymer to start linking to each other. The resulting structure is not possible to melt. At a high enough temperature, the film decomposes rather than melting. PVB, on the other hand, does not exhibit crosslinking which suggest that the material can be melted even after the lamination process. This is an important factor as PV modules get warm (as high as ~65°C) during operation. Constant re-melting of laminate could potentially alter the panel durability and ultimately the lifetime. Both these laminates differ from each other in their properties. EVA is more resistant to humidity as opposed to PVB which requires drying prior to the lamination process.

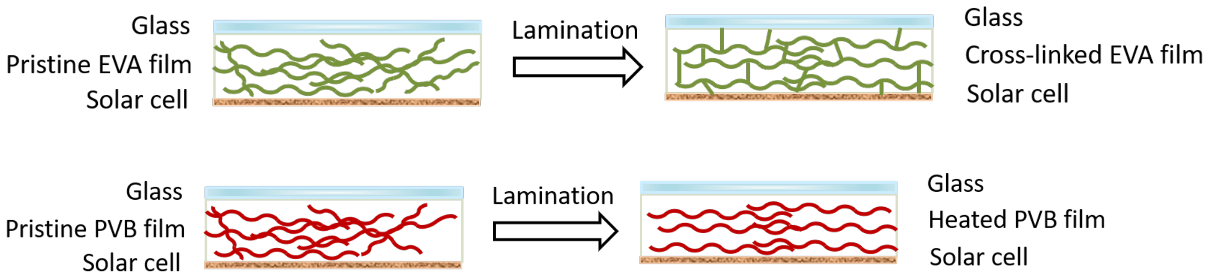

Figure 11 Lamination process: due to heat both PVB and EVA chains straightens up which leads to the transparency of the films after lamination process. EVA chains link to each other, to glass surface and to solar cell.

Both EVA and PVB can be manufactured in many different colors and shades. The color of the laminating foil can control the appearance of the PV module. By using different colors, it is possible to make patterns. For PVB foils a wide variety of colors and shades can be produced. EVA appears to have fewer colors in the palette, instead the colors are made up by combining foils. The foils can be opaque or translucent and be suitable for either indoor or outdoor climate. But, by using colored foils there will be a reduction in the amount of solar radiation that can be transferred to energy in the PV module. A leaf on a tree appears to be green during the summer since it absorbs the red and blue light but reflects the green part of the sunlight. The green light hits our eyes and the leaf looks green. The same thing is happening in the laminating foil when it is colored. In order to maximize the amount of sunlight that can be transferred to electric energy it is best to use a piece of laminating foil that does not absorb any visible light from the sun. This will make all PV modules look like the color of the semiconductor. In other words. The freedom to choose color must be weighed against reduction of the efficiency of the PV module.

All organic molecules are affected by sunlight. Organic molecules are made up of carbon and hydrogen, in some cases also oxygen and nitrogen as well as other substances in minor quantities. The highly energetic UV light from the sun causes polymer foils to degrade. Eventually it will degrade so much that water will leak in and make the cell cease functioning. In the foil there are some substances that work as preservatives so that the preservative reacts with the sunlight instead of the EVA/PVB and thus extend the life expectancy of the cell. EVA and PVB are large molecules, consisting of many atoms, and due to the way, the atoms are fitted in the molecules, they cannot easily be stacked molecules after molecules in a symmetrical way. Polymer materials that CAN be stacked in a symmetrical way (crystals) are very often opaque and non-stackable (amorphous) transparent PVB was the first laminating film that was used for solar cells and is a good material for solar cells. EVA has though become the dominant laminate for PV modules as it attaches better to the glass and is much less affected by water than PVB.

5 Aesthetically pleasing examples of PV modules

5.1 SolTech Energy Sweden

SolTech Energy is a Swedish company that develop and sell BIPV products. SolTech Energy has put a lot of effort into aesthetically pleasing PV. For BIPV-roof solutions SolTech Energy have developed SolTech RooF and SolTech ShingEl. Both can be fully integrated with Benders roofing system Carisma, see figure 12. Semi-transparent CdTe thin film PV modules (SolTech ST) have also been developed using colored encapsulants, see figure 13. The active CdTe is sputtered onto the front glass so that the energy output is not significantly affected by the colored encapsulant. SolTech Energy have also developed a Façade PV system with the help of Sapa Building Systems, SolTech Façade (see figure 14). According to SolTech Energy, BIPV and colored BIPV, will be possible to get cost-effective and they believe that it will be a conventional solution in the future. In principle, they consider it to be a question of mindset about environmental sustainability by replacing building materials that are not sustainable with materials that can generate electricity. The challenges of BIPV and colored PV is the aesthetics especially for refurbishment of buildings – for new buildings it is easier to adapt the BIPV solutions. In general, SolTech Energy acknowledge that there is a great interest in BIPV now.

Figure 12: Installations of Left: SolTech RooF and Right: SolTech ShingEl.
http://www.soltechenergy.com/en/products/12186/
http://www.soltechenergy.com/en/products/soltech-shingel-2/

Figure 13: SolTech ST installation at Flustret, Linköping in Sweden.
http://www.soltechenergy.com/en/products/soltech-supreme-st-en/

Figure 14: SolTech Façade architectural image giving 100-123 W_p/m^2.
http://www.soltechenergy.com/en/products/soltech-facade/

5.2 SolarLab DK

SolarLab is a company that provides aesthetically pleasing façades with integrated PV – see figure 15-17 for some examples. The glass is a low iron glass with a frosted front-surface and an applied nanostructured coating on the rear-side that provides a disruptive optical interference. The structuring thus provides a structural color (meaning a color based on structural interference of reflections) similar to what many colorful insects have. The coating is developed and marketed as Kromatix™ by the Swiss company Swiss Inso [17]. The structural color inflicts a shortfall of 8-15% (relative) in the efficiency of the PV. SolarLab exclusively uses monocrystalline Si as PV material. The glass is typically 3.2 mm thin but, in some cases, also 4-6 mm thick depending on the type of building. As laminate EVA is used. SolarLab do not provide any standard product but is working with custom designed buildings and are optimizing their BIPV façade for each specific case. The BIPV façade does not inflict any extra costs compared to a moderately expensive façade material. To give an example for a standard type of building where two thirds of the façade is covered with BIPV and the remaining third is covered with a passive façade (typically facing north) – the cost for a BIPV façade is approximately a factor of 2-3 more expensive than the cheapest alternative: sheet metal. On the other hand, compared to an expensive façade such as rocks or ceramics the prices for a BIPV façade can be a factor of 0.5, thus giving a priceworthy and aesthetically pleasing alternative that also generates electricity. The service lifetime of SolarLabs BIPV façade is claimed to be about 50 years. For BIPV it is important to note that there are other requirements when applying PV integrated in a façade than for PV in a PV park or as BAPV – building regulations also apply if it is an integrated part of the building.

Figure 15: BIPV façade on RISE Awitar Building in Borås. Photo and installation provided by www.SolarLab.dk.

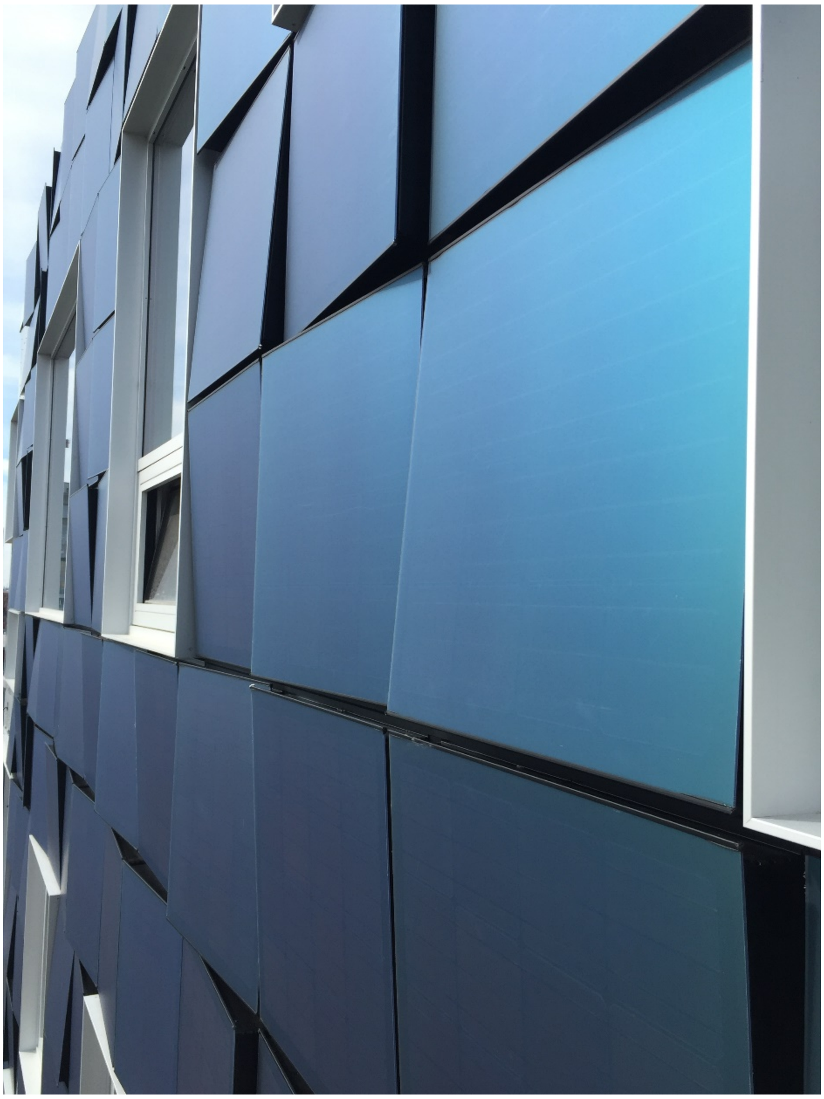

Figure 16: BIPV façade on Copenhagen International School (CIS) in Nordhavn, Copenhagen. Photo and installation provided by www.SolarLab.dk.

Figure 17: BIPV façade on Bornholms Hospital in Rønne, Bornholm. Photo and installation provided by www.SolarLab.dk.

5.3 Solibro Research

Solibro is a world leading developer of CIGS thin film coatings for PV modules. Solibro are also part of the Hanergy group whose PV modules are based on CIGS which is sputtered onto a conventional float glass using PVD and laminated with a front with tempered low-iron float. Solibro has done several R&D projects with both colored and semi-transparent PV modules. The semi-transparent PV panels were made by removing the CIGS-coating off the substrate glass using a type of sand-blasting method [18]. Water-polishing has also been tried, however, was found not to be suitable. With the sandblasting method it is possible to get a maximum transparency of 70-80% and the loss in the efficiency is somewhat more than the removed CIGS due to edge-effects. Colored PVB-foil on the rear-side has been tried – a wide variety of colors can be applied, see figure 18 as an example of what is possible to achieve. The cost for colored PV, colored BIPV or BIPV is generally too high – this will in the end affect the electricity price and the effective payback time. This is normally not acceptable for contractors. So Solibro has not yet launched any products with colored PV. Unless there will be any large contract Solibro does not foresee to launch any product either. An example of a BIPV façade with CIGS PV modules is shown in figure 19.

Figure 18: Examples of colored semi-transparent CIGS PV modules developed by Solibro Research [18]. The PV modules are seen from the inside to out.

Figure 19: Example of a façade of CIGS PV modules from Solibro, located at the full-scale building prototype of the Innovation Environment Smart Housing Småland www.smarthousing.nu in Växjö.

5.4 Other commercial alternatives of aesthetic PV modules

Racell® is a Danish company that manufactures customized solar panels for specific architectural projects. For more detailed information about their product portfolio and architectural projects: http://racell.dk/.

Solaxess is a Swiss company that has developed a white PV panel based on a colored film which reflects the visible and transmits the infrared light to the PV modules. For more detailed information about their product portfolio and architectural projects: www.solaxess.ch/en

Svea Solar is a Swedish company that installs building integrated PV panels. They have complete packages for installation of solar panels both as BIPV and BAPV. For more detailed information about their product portfolio and architectural projects: https://sveasolar.se/

Clix by Midsummer is a BIPV roof system based on CIGS PV modules developed by Midsummer, a Swedish supplier of equipment for cost-effective manufacturing of CIGS PV cells. Their system Clix is developed to be quick and easy to install and is reported to have a very competitive price. The following colors are available: black, silver, red, dark grey and Aluzinc. More can be read at: https://clixbymidsummer.se/en/

Besides the few mentioned above a range of others exist categorized by the roof or façade system as listed in ref [19] and in Appendix 1.

6 Challenges of aesthetically pleasing PV

The greatest challenge for aesthetically pleasing PV such as BIPV and colored BIPV is the cost. However, it is possible to make it cost-effective, but it depends on the cost of the building materials that is being replaced. In general, knowledge is often missing, and the planning of the PV comes too late. Sometimes it is required to have someone that can mediate between the architect and PV supplier. Someone who knows the technical limitations but still can see the possibilities and possess the know how to make cost-effective solutions for each specific project. Most important is that the PV comes into the planning at an early stage before details are fixed. Another challenge is to make simple PV installations that are cost-effective and that generates electricity with a viable price. Aesthetic PV modules can be made simple and elegant as well. The construction company ask for technical help in PV installations while architects less often ask for technical assistance. In most cases BIPV is more cost-effective and easier for newly built buildings than for refurbishment. For the latter BAPV can be simple, cost-effective and still aesthetically pleasing.

Regarding aesthetically pleasantness vs. PV efficiency, transparent PV modules will never have a good efficiency as about roughly 50% of the solar irradiance comes in the visible wavelength range. Every percentage of the transparency is a direct loss of the efficiency. Same for colored PV as these either absorb, reflect or scatter light in the visible spectrum. For pale coloration are the routes colored encapsulant and colored glass versatile and cost-effective alternatives. The PV power loss is typically least for colors absorbing/reflecting in the shorter visible wavelengths e.g. half power loss in the blue range (400-450 nm) as compared to red (600-750 nm) and green (500-550 nm) [20]. This is basically a result of the semiconductor, e.g. c-Si do not convert as much of the blue light as for the green and red light. In addition, sun irradiates most energy in the wavelengths around 500 nm. If the color perception of the human eye is considered, we perceive green color the strongest, an alternative figure of merit therefore give that blue light (about 450 nm) is still most efficient while orange light (about 575 nm) is the 2nd most efficient for coloration of PV [20]. For strong color perception by humans the color must be caused by reflections. The most efficient route for this is through structural coloration [21] i.e. structural interference of reflected light. Structural coloration is most effectively achieved by the application of thin films on the cover glass and secondly on the semiconductor material. For structural colors the efficiency loss is theoretically in the range of 3-8% depending on the wavelengths that are being reflected, 3% for blue light at 400 nm while 8% for red light at 650-700 nm. Examples of structural colored PV are Kromatix™ and recently developed colors by Fraunhofer [16].

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Appendix 1

Roof PV systems:

https://aerspire.com/en/

https://beausolar.eu/

http://www.brandonisolare.com/en/

https://www.emergo.nl/

https://www.ertex-solar.at/en/

https://www.solarcarporte.de/en/solarterraceroof/

https://www.kalzip.com/en/

https://energyglass.gruppostg.com/en/

https://www.eternit.ch/

https://exasun.com/en/

http://www.designergy.ch/index/

https://www.ernstschweizer.ch/en/

http://www.globalsolar.com/

http://www.cottopossagno.com/index.php?lang=en

http://www.fornacefonti.it/en

http://www.lofsolar.com/

http://www.galaxy-energy.com/en/

https://en.irfts.com/

http://www.marcegaglia.com/officialwebsite/

http://www.kaneka-solar.com/

http://www.mecosun.fr/en

https://www.giellenergy-tile.eu/giellenergy-tile-tegola-fotovoltaica/

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http://www.smartroof.be/en

https://www.solarmarkt.ch/

https://www.solarworld.de/en/home/

http://www.solterra.ch/

https://www.sunstyle.com/SolaireSuisse.html&sp=EN

http://www.solarstone.ee/en

https://www.solinso.nl/en/

https://stafiersolar.com/

https://www.solarteg.it/

https://solstis.ch/fr/

https://www.solarcentury.com/

http://www.solartechniken.de/

http://www.starunity.ch/

http://www.solteq.uk/

http://www.sunage.ch/

http://www.sun-integration.com/

http://www.gseintegration.com/en/

https://userhuus.ch/

http://www.tegolacanadese.com/?lang=en

https://www.vindosolar.com/en/

https://www.tesla.com/en_EU/energy

http://www.tritec-energy.com/en

http://www.gseintegration.com/en/default.html

https://www.tulipps.com/nl/

https://www.zepbv.nl/

https://www.agc-yourglass.com/am/en/brands/sunewat

Façade systems:

https://www.eigenenergie.net/

https://www.ertex-solar.at/en/

https://alwitra.de/en/

https://aerspire.com/en/

https://www.solarcarporte.de/en/solarterraceroof/

https://energyglass.gruppostg.com/en/

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http://www.wyssaluhit.ch/

https://www.agc-yourglass.com/am/en/brands/sunewat