



Feasibility assessment of methods to produce coloured PV modules for building integration

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Summary

This report focuses on assessing the feasibility of different methods to produce coloured modules for building integrated photovoltaics (BIPV). In general, the improved aesthetic properties of coloured BIPV comes with a reduced power conversion efficiency, and an increased technological complexity and cost.

The colouring layer can be incorporated in the PV module in several ways: colouring of the bulk or surface of the glass, inserted as a separate foil, mixed with the encapsulant or applied directly to the solar cell. The most frequently used solution seems to be thin films or pigmented coatings on the inner surface of the front glass.

In order to be commercially relevant; the colouring method must be available for large areas with a low cost. The colouring method must also provide aesthetically pleasing modules, and result in low losses in electricity generation compared to a module that has not been intentionally coloured.

In the literature, several figures of merit have been proposed to assess and compare different colouring technologies with respect to their influence on power conversion efficiency. The “Colour Performance Index” is a figure of merit that can be used to understand and compare different colouring technologies with respect to the expected power losses resulting from colours with different lightness.

The two main approaches for colouring are based on the use of interference coatings and the use of inorganic colour pigments. Using pigments has the lowest cost, while using interference with dielectric films introduces less losses and provides modules with higher efficiency.

The use of pearlescent interference pigments is a less common, but emerging option, that has been recently introduced. This colouring technology aims to combine advantages of interference coatings with those of conventional inorganic pigments. The use of pearlescent interference pigments may provide aesthetically attractive colours with limited losses, while keeping the cost and complexity low.

An overview of suppliers and products are given in Table 1, together with available data of their key performance characteristics. Relevant products available on the market are both complete coloured modules, components such as coloured glass or foils, and colouring materials such as pigments.

Key findings from the feasibility assessment are summarized in Table 3, covering the most relevant colouring technologies. Recommendations are given for companies that are developing coloured PV modules for building integration, as well as for those that wish to bring coloured PV modules to the market.

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1 Introduction

Solar photovoltaics (PV) is the fastest growing energy technology worldwide with respect to installed electric power capacity [1]. Distributed solar PV, such as photovoltaics on buildings, is expected to account for almost half of the annual additions in capacity within solar PV. Annual additions in distributed PV applications are expected to reach almost 170 GW by 2027 [1].

The majority of the inclusion of PV in buildings is still in the rooftops with standard PV modules that are attached to the roof and supported by additional mounting structures. This approach is labelled as building attached photovoltaics (BAPV). It represents an add-on to the building, in which the only objective is to generate electricity. BAPV solutions do not merge in the building envelope and are often not aesthetically adequate.

Even though the addition of PV systems using the BAPV approach already represents an advancement in buildings operation, there is a large potential to be explored with the possibilities of integration in the building system starting from the early stages of design. In this scenario, building integrated photovoltaics (BIPV) is the PV technology that advances in terms of integration within the building [2].

The main advantages of BIPV in comparison to BAPV revolves around the integrative benefits of the system and improved aesthetics. With integration, extra loads of supporting structures in which the PV panels are attached to the building are non-existent. Additionally, the costs of installation aggregate all the functions performed by the BIPV besides the generation of electricity [2].

When PV modules are utilised as building elements, aesthetic aspects, including colour, become critical in addition to the energy performance [3].

The colour of a PV module is described by the visual parameters *lightness*, *chroma* and *hue*, each of which may be altered when colour is added to a conventional uncoloured module. Adding colour to a mono-facial black PV module requires that light is reflected from the module, which will result in a loss in electricity generation. In addition to losses due to reflected light, there may also be losses caused by unwanted absorption in the colouring layer. Different contributions to the losses in a coloured PV module are illustrated in Figure 1.

In the visible (VIS) range ($\lambda = 400\text{-}700\text{ nm}$) any reflection from the colouring material will add to the colour, and at the same time reduce the power conversion efficiency (PCE) of the module. In addition, any absorption of visible light will reduce the efficiency without contributing to the colour and should therefore be avoided. Any additional reflectance or absorption in the near infrared (NIR) range ($\lambda = 700\text{-}1100\text{ nm}$) will also reduce efficiency without contributing to the colour.

Figure 1 also illustrates the conflict between the need for high reflectance as well as high transmittance. High reflectance is needed to obtain bright colours, while high transmittance is desired in order to achieve high power conversion efficiency.

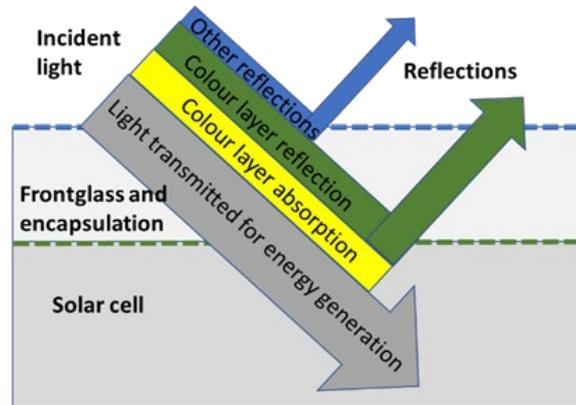


Figure 1: Schematic of reflected, absorbed, and transmitted light in a PV module [5].

Based on the results from previous activities in FME SuSolTech [4-8], we will assess the feasibility of different methods to produce coloured PV modules for integration into the façade or the roof of a building.

The target audience for this report are persons or companies that wish to bring coloured PV modules to the market, and our aim is to provide up-to-date information and guidance related to the different colouring technologies.

The feasibility assessment is limited to techniques and products that are relevant for opaque silicon-based modules, since the PV market is dominated by this technology. Colouring technologies that are less mature, such as metasurfaces, quantum dots and plasmonic pigments, are not included.

The assessment will focus on the technical, aesthetic, and commercial aspects of the technology. This report builds on a previous report by the same authors, that was limited to colouring of PV by interference-based methods [9].

2 Placement of colourants in PV modules

The different components of a conventional PV module are shown in Figure 2. The solar cells are encapsulated in a transparent polymeric material, often made from ethylene-vinyl acetate (EVA), and laminated to a back sheet or glass and a front glass cover to protect the solar cells from environmental stresses. The aluminium frame provides structural support for the module and allows for mounting onto a structure, whereas the junction box, which is attached to the back of the module, contains the electrical connections. An anti-reflective thin film coating is commonly applied to the surface of the solar cells, and this results in a black or dark blue colour. High electrical performance can be achieved for such PV modules because they typically reflect a relatively small portion of the incoming light.

In order to modify the colour of the PV module, colouring elements can be applied to the surface or bulk of different components of the PV module, including the front glass cover, the encapsulant (laminant), or the solar cells. Colour can also be applied by the use of an additional coloured polymer foil which can be introduced between layers in the stack or retrofitted to the PV module by mounting onto the outer side of the front glass.

To summarise, colour can most typically be introduced in the form of:

- Coloured coatings on the outer surface of the front glass (exposed to weather)
- Additional coloured foil on the outer glass surface (exposed to weather)
- Coloured materials in the bulk of the front glass
- Coloured coatings on internal surfaces
- Coloured materials in the bulk of the encapsulants
- Additional coloured foil placed between layers
- Coloured solar cells, e.g., by the use of interference coatings

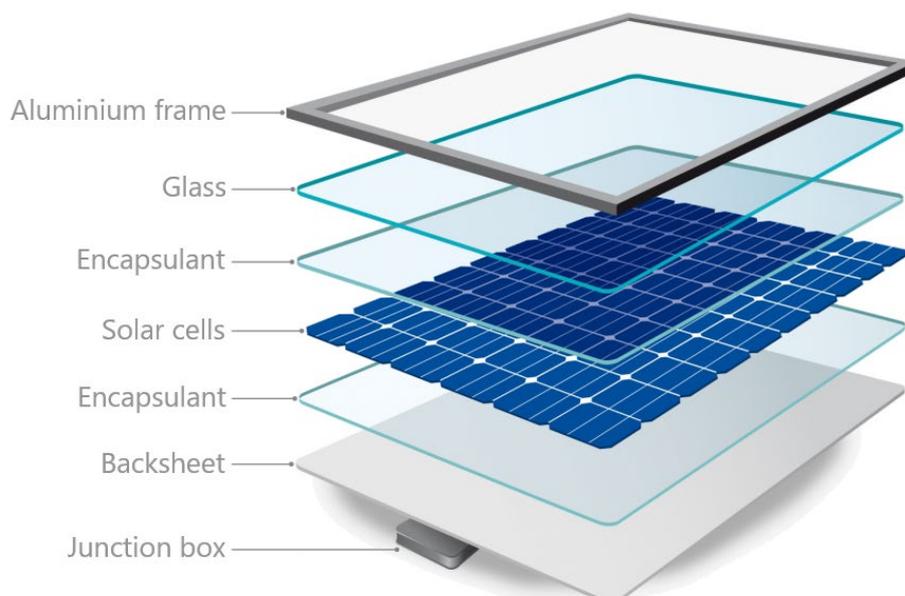


Figure 2: Layered structure of a conventional PV module.

3 Materials and methods for introduction of colour

Colour can be introduced in PV modules in many different ways, and in the following a brief description of the most common methods is given. A more detailed review of various colouring techniques is given in [10-12]. Common for all techniques is the desire to reflect a specific portion of the VIS light, with minimal reflectance of the NIR light, and with minimal absorption losses resulting from the colouring.

To reduce losses for colouring solutions based on pigments, spectrally selective pigments that transmit near infrared radiation may be preferred.

3.1 Digital ceramic and screen printing

In digital ceramic printing on glass, inorganic (ceramic) pigments [13] are applied to the glass by a printer and subsequently fired to fuse permanently with the glass surface. The typical size of inorganic pigments is 100 to 1000 nm. Dip Tech Machinery is an example of a manufacturer of equipment for printing on glass.

The printer controls how large fraction of the surface that is covered by pigments and thereby the transmittance, scattering and reflectance of the coating.

Some of the most commonly used inorganic pigments are chromium oxide (green), cobalt oxide (blue), cadmium sulphide (yellow), iron oxide (red, brown, black), and tin oxide (white).

Screen printing is similar to digital ceramic printing, except that the position of the pigments is controlled by applying the pigments through a fine mesh screen. The open areas define the areas covered with pigments. The open areas are typical in the order of 100 μm and are therefore not visible from a distance.

Both digital printing and screen printing opens the possibility to introduce patterns or images for aesthetic purposes, as illustrated in Figure 3.



Figure 3: Two examples of printed solar cells used as decorative façade elements. Photos by Helge Tvedten, NRK. Reprinted with permission from [14].

3.2 Mass-coloured glass

The front glass can be coloured by adding pigments that are dispersed throughout the glass matrix during melting. Common pigments used here are chromium oxide (green), cobalt oxide (blue), cadmium sulphide (yellow), and tin oxide (white). Glass can also be coloured by adding dyes that are soluble in the glass, but dyes are generally more prone to degradation over time.

3.3 Coloured encapsulant

In PV module fabrication, the solar cell is laminated to the glass with an encapsulation layer between the cell and glass. This layer is a polymer-based film, like EVA or polyolefin elastomer (POE), and can be coloured by adding pigments or dyes to the bulk of the encapsulant.

3.4 Coloured foils as additional component

Coloured polymer foils that add an extra layer to the module can be used to achieve the desired colour. The foil can be added to the outer surface of the front glass or, alternatively, between layers in the stack. Between layers it will act like an additional encapsulation layer. If the foil is added to the outer surface of the glass, it must be sufficiently robust to handle the impact of wear and weather exposure.

The advantage of a foil on the outer surface of the glass is the possibility to add colours to a PV module without interfering with module production process, or by retrofitting on existing buildings.

The foil can be coloured by adding pigments to the surface or pigments or dyes to the bulk of the foil. This will be very similar to the methods outlined above for the case of glass or encapsulant.

An additional foil can also be coloured by optical interference coatings, as described in chapter 3.6.

3.5 Pigments based on optical interference

All the above-mentioned colouring methods based on pigments (or dyes) requires that the pigment reflects the desired spectral range. This reflectance is often accompanied with optical absorption that neither contributes to the observed colour, or current generation in the solar cell. A recent method that may give a higher transmittance to the cell with minimal loss is to use interference-based pigments (also called pearlescent pigments) [15-17]. These pigments are typically based on small thin mica flakes (5-50 μm diameter) with an additional TiO_2 coating (50-200 nm thickness). The mica flakes have a high transmittance and act as a substrate for the TiO_2 coating. The thickness of the TiO_2 coating determines the reflectance spectrum and the resulting colour. Synthetic oxides may be used as alternative to mica and iron oxide as an alternative to TiO_2 .

3.6 Optical interference coatings

An alternative to the application of pigments or dyes to produce a coloured glass is the application of thin interference films to the glass [18]. These films cover the entire glass surface and are typically applied by vacuum coating technology such as sputtering. Each film layer is thin, usually 50-200 nm, and is made of optically transparent materials such as silicon oxide (SiO_2), silicon nitride (Si_3N_4), and titanium oxide (TiO_2). This results in very low optical absorption losses. The optical reflection is caused by refractive index contrast at the film interfaces. The light from different interfaces results in constructive or destructive interference determined by the film thicknesses and optical wavelength. Thus, a well-designed interference coating will reflect the desired part of the visible spectrum, with minimal loss, and with minimal reflection in the NIR part of the spectrum.

In general, optical interference coatings make it possible to achieve saturated and bright colours while maintaining an acceptable power conversion efficiency for the solar cell module, i.e., the decrease in overall power output for a PV module coloured by optical interference coatings is relatively low compared to other colouring technologies. This is the case for both light and dark colours. However, the colour produced by optical interference coatings can vary depending on the angle of incidence of the light. This unique property can offer aesthetic opportunities, but for some architectural applications it may also be considered undesirable.

An alternative to applying the interference coating on the glass is to apply interference coatings directly onto the solar cell [19-20]. In a standard PV module, an antireflection (AR) coating is applied to the surface of the silicon to reduce unwanted optical reflection at this interface. This AR coating consist typically of a 70 nm Si_3N_4 layer that is optimised to maximise power generation and has therefore a reflectance minimum in the red part of the spectrum. This is the reason for the dark blue tint of a standard PV module. Other colours can be introduced by changing the thickness of the single layer AR coating or by adding further layers. A challenge in controlling the colours is the surface topography of the silicon surface, typically very steep pyramids that are designed to minimize reflectance. Bright colours will therefore be difficult to achieve.

4 Visual properties of coloured PV modules

In this chapter the visual properties included in the term *colour* are described. This includes parameters such as lightness, chroma and hue, as well as the angular dependence of colour.

In addition, other visual characteristics that could be very important for the aesthetics of PV modules are also briefly described. These secondary visual characteristics include gloss, uniformity, glitter effects and printed patterns. For these visual characteristics the emphasis is on how they relate to colour and colouring technology.

4.1 Lightness, chroma, and hue

In the CIELab colour space the main parameters are L^* , a^* , and b^* , and together they form a three-dimensional colour space [21]. All three parameters range from 0 to 100. The 3-dimensional colour space is illustrated in Figure 4.

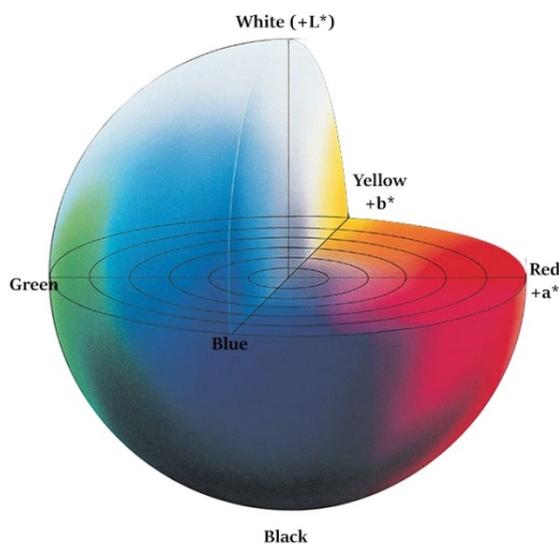


Figure 4. The 3-dimensional CIELab colour space. Illustration reprinted with permission from [22].

L is the lightness and is a function of the luminous reflectance factor Y . The relation between L^* and Y can be expressed as $L^* = 116Y^{1/3} - 16$.

Y is the reflectance weighted with the photopic luminosity function. A medium lightness surface with $L = 50$ corresponds to $Y = 0.18$, while a glass surface with 4% reflectance ($Y = 0.04$) corresponds to $L = 26$.

The parameters a^* and b^* can alternatively be expressed by chroma C^* and hue h° , related by $C^* = (a^{*2} + b^{*2})^{0.5}$, and $h^\circ = \arctan(b^*/a^*)$. Chroma describes how saturated the colour is, while hue represents the dominant wavelength where red, green and blue are approximately 0, 120 and 240 degrees.

Different colouring methods have different limitations in how large portion of the colour space that can be achieved. Interference based methods that can reflect a narrow portion of the spectrum has the potential to achieve high chroma (> 30).

High lightness requires high reflectance, which has to be compromised with resulting reductions in power conversion efficiency.

4.2 Gloss

The gloss (specularity) of a surface is an important aesthetic characteristic. A flat and reflecting surface, such as a glass surface, will result in high gloss, while a rougher surface leads to more diffusely reflected light resulting in lower gloss.

The roughness of interfaces between layers, as well as pigments or other elements that scatter light within the bulk of a material, may also contribute to lower gloss levels, but the outermost surface is the most important.

This holds true also for a standard PV module, where the gloss is mainly determined by the roughness of the outer surface of the front glass.

Typically, a surface texture is added to the front surface to reduce gloss, but also to reduce reflectance of the glass surface. The light scattering from a texturized surface may influence the appearance introduced by the colouring layers. An example is when an interference film is reflecting light from a flat backside of the front glass. This specular reflection can be made more diffuse by a front surface roughness.

The preferred gloss may be influenced by the surroundings of the BIPV installation, exemplified by high gloss high-rise buildings with glass facades, or low gloss brick buildings. We propose that manufacturers and suppliers of BIPV modules provide information regarding the gloss levels their products.

4.3 Uniformity, glitter effect, and printed patterns

A conventional uncoloured PV module has a characteristic look caused by the black or dark blue colour of the solar cells and the appearance of the electrical contacts. From an aesthetic point of view, it may be desirable that the colouring makes the electrical contacts (i.e., fingers, busbars and ribbons) and the solar cells less visible, providing a more uniform appearance. Such hiding can most easily be achieved with highly reflecting light colours, or with coating layers with high scattering. Good hiding can also be achieved by absorbing pigments, but this will result in significant reductions in efficiency.

Another aspect of uniformity is that the colour may have unwanted variation across a PV module, or between PV modules. This may be caused by variation in uniformity of coating thicknesses.

Non-uniform PV modules may be a desired feature, which can be obtained if the colour is created with printing techniques. Patterns or images can then be applied to the PV module.

The appearance of these uniformity variations will strongly depend on observation distance. Small patterns or variations will only be observable close-up, while module to module variations will be visible on long distances.

Another visual feature that can be obtained with interference pigments (pearlescent) is a metallic or glitter effect similar to that of a metallic automobile car paint.

4.4 Angular colour dependence

When the colour is introduced by interference, the colour will depend on the observation angle. The angular dependence of the colour can be quantified in terms of the colour difference ΔE between angles 1 and 2 and can be calculated as the distance between two colours in the $L^*a^*b^*$ colour space as [7, 21]:

$$\Delta E = \sqrt{(L_1^* - L_2^*)^2 + (a_1^* - a_2^*)^2 + (b_1^* - b_2^*)^2}$$

A value of ΔE close to zero would indicate a colour with low angular dependence, and colouring technologies using, for example, pigments or dyes will typically have ΔE values close to zero. For optical interference coatings deposited on non-textured (planar) glass, we have previously shown that ΔE can vary between 2 to 70, depending on the coating design parameters [7]. $\Delta E \approx 2.3$ corresponds to a colour difference which is barely perceptible by a human.

One strategy for reducing the angular dependence of the colour can be to apply the optical interference coating onto a surface with a micro-scale texture. Such textures create scattering that reflect light more uniformly across different angles, which helps in maintaining consistent colour regardless of the viewing angle. Another approach to mitigate the angular colour dependence can involve optimising the multilayer design (e.g., the number of layers and the layer thicknesses) and selecting thin film materials with high refractive index (e.g., silicon nitride and titanium oxide) [18, 22].

5 Properties related to power conversion efficiency

In this chapter, the most important properties related to power conversion efficiency of coloured PV modules are described.

5.1 Factors affecting power conversion efficiency

The power conversion efficiency (PCE) of a coloured PV module will be reduced due to added optical reflectance and absorption, as illustrated in Figure 1. In the VIS range (400-700 nm) any reflection from the colouring material of the layer will add to the colour, and at the same time reduce the PCE. Any absorption of visible light will reduce the efficiency without contributing to the colour and should therefore be avoided. Any additional reflectance or absorption in the NIR range (700-1100 nm) will also reduce efficiency without contributing to the colour.

Colouring techniques that provide a reflectance in the required colour spectral band, combined with no optical absorption are therefore well suited to obtain a good compromise between lightness and efficiency. In the case of no or little absorption, it is the lightness that is the main parameter contributing to reduced efficiency. A high lightness may be desired from an aesthetic point of view, creating a conflict between aesthetic desires and the desire for high efficiency.

5.2 Colour Performance Index and other methods for comparisons

For available products with colours based on different colouring technologies, it is useful to compare the electrical and visual performance.

Three frequently used indicators of the electrical performance of the PV module are power conversion efficiency PCE [%], relative loss ΔP [%], and power density [W_p/m^2]:

- Power conversion efficiency (PCE) is the fraction of incoming solar radiation that is converted to electrical power.
- The relative loss (ΔP) quantifies the relative loss in electric power compared to an ideal black reference with zero reflectance. Relative loss may be calculated from the PCE values for a coloured module and an ideal black reference module, expressed as $\Delta P = (PCE - PCE_{reference}) / PCE_{reference}$.
- The power density quantifies how much electrical power a module can generate for every square meter of its surface.

In the comparison between technologies and products, both the electrical and the visual performance must be considered. The main visual performance parameters are L^* , a^* and b^* , or the luminous reflectance factor Y as an alternative to the lightness parameter L^* .

In a previous study, the dependence between colour and the resulting loss in power generation has been studied [4]. It was found that the lightness was the main parameter that influenced power conversion efficiency, while hue and chroma had a smaller influence on the efficiency, with green hues performing better than red or blue.

It is therefore important to take the colour, and particularly the lightness, into account when technologies and products are compared. Røyset et al. [4] proposed the use of a *Colour Performance Index* (CPI) as a figure of merit, given as $CPI = Y/\Delta P$. A given lightness achieved with minimal reflectance and absorption results in a high CPI.

As an example, a grey module with 10% reflectance across the whole spectrum, will have $Y = 0.1$, and relative loss $\Delta P = 10\%$, compared to an ideal black reference module with 0% reflectance. For the grey module, the resulting $CPI = 1$.

An improvement can be made if the grey reflectance outside the VIS region is zero, resulting in the same Y , while relative loss ΔP is reduced to 4.7%. The colour is here identical to the grey module in the example above, but the Colour Performance Index is higher, with $CPI = 2.13$.

The Colour Performance Index can be further increased by having a narrower spectral band where the eye sensitivity is highest, resulting in a green hue. The maximum theoretical CPI is about 5.3 for a crystalline silicon-based PV module.

The Colour Performance Index proposed by Røyset et al. [4] is a very useful parameter for comparing PV modules with different lightness. It is unfortunate that only a few producers specify both the lightness and the relative loss and thereby making the calculation of CPI straightforward.

As an alternative to the CPI by Røyset et al., the relative loss could be compared to the lightness L^* instead of Y . However, since ΔP is not linear with increasing L^* , it can be argued that this metric would be less intuitive and therefore less useful.

Perhaps a more useful option is to compare different colouring technologies in a ΔP versus L^* plot. Such plots can be found in [4] and [12].

To visualise the performance plots of PCE versus L^* are also seen [12]. Such plots are useful for comparison of products with different cell technologies, or in the cases where no reference module is available for comparison.

Chen et al. [17] proposed a slightly different figure of merit, $C_{eff} = \Delta P/\Delta E$, where the colour difference (ΔE) between the coloured module and the reference module is emphasised. In addition to changes in lightness, this metric also value colour changes that result in saturated colours with high chroma,

6 Products and suppliers

In this chapter, companies with colouring technologies for PV modules available on the market are presented. They are also listed in Table 1, including key performance parameters of the different products.

Glas Trösch [24] offers coloured glass that is coloured using a digital ceramic printer. It is marketed as Swisspanel Solar glass. They have been collaborating with 3S Swiss Solar Solutions who have manufactured the modules.

Kameleon Solar [25] and its product line ColorBlast® also uses digital printing technology to print small hexagons with some space left between them. The density of the dotted patterns determines the amount of light transmitted to the solar cells. At distances, these hexagonal patterns will not be distinguished by eye and appears to be homogeneous.

Coloured glass is offered by **Sunage** [26] both for roof and facade applications. In a previous study [4], it was found that the colours that were offered at that time were relatively dark, with low chroma, whereas the NIR reflectance was higher compared to the results for interference coatings on glass.

Onyx Solar [27] offers coloured glass in a wide range of colours. Their product portfolio includes ventilated facades, skylights, canopies, louvers, walkable floors/roofs, balconies, roof tiles, and acoustic barriers.

Freesuns [28] offers solar tile products designed to seamlessly integrate into buildings. These tiles, available in various hues, may contribute to preserving the unique aesthetics typically associated with traditional buildings.

Solaxess [29] has developed coloured foils to be used between layers in coloured modules. The solutions from Solaxess have been used by several module manufacturers, such as e.g. **3S Swiss Solar Solutions AG** (Switzerland).

Sistine Solar [30] offers SolarSkin, a printed foil that can be applied on top of existing solar modules. This offers the possibility to alter the visual appearance of standard PV modules after their fabrication. They claim a durability of 30 years and self-cleaning and anti-glare properties. They cooperate with LG, Solaria, Canadian Solar, Samsung, and QCells.

Two companies offer colouring technology based on semi-transparent ceramic interference pigments. **Ceramic Colors Wolbring** [31] has developed a product line of coated glass where the ceramic pigments are added as a layer on the glass surface. **Lenzing-Plastics** offers polymer foils containing interference pigments [32]. Both are based on the Colorquant pigments developed by **Merck** [33]. The pigments are probably based on mica flakes coated with TiO₂. A wide range of colours are available. As for interference coatings, these solutions offer the potential for low absorption and low NIR reflectance. **BASF** is another company that offers interference pigments.

The German research institute Fraunhofer Institute for Solar Energy Systems (ISE) has developed an approach for colouring PV modules using optical interference coatings based on their patented MorphoColor® technology, which is inspired by the three-dimensional photonic structures found on the wings of the Morpho butterfly [18, 23]. By applying a similar surface structure on the back of the front module glass cover prior to depositing the multi-layer interference coating, this method allows for the creation of saturated and stable colours at different view angles with low loss of light transmission. **Megasol Energie AG** is a Swiss producer of solar panels currently offering coloured PV modules utilising Fraunhofer ISE's patented MorphoColor® technology. In 2023, Megasol was granted a license to produce and market coloured PV modules incorporating the MorphoColor® technology. Megasol currently offers BIPV products with different design dimensions, including glass surfaces and structures in all sizes and shapes.

In 2024, Fraunhofer ISE introduced the MorphoFlex concept at the 41st European Photovoltaic Solar Energy Conference and Exhibition in Vienna, Austria [34]. The new concept is based on applying the MorphoColor® interface on a polymeric film, which can be integrated into both flat and curved rigid PV modules as well as flexible PV modules. The desired surface structure is transferred to the polymer film from a master structure that has been made using interference lithography and roll-to-roll ultra-violet (UV) nanoimprint, in collaboration with **Temicon GmbH**. The optical interference coating is deposited onto the structured surface of the polymer film using roll-to-roll sputter coating, which is done in collaboration with **ROWO Coating GmbH** in Germany. During lamination of the PV module, the coloured polymeric foil is placed on top of the solar cells between two layers of conventional encapsulant. PV modules coloured with MorphoFlex polymeric foils can achieve electrical performance and colour saturation comparable to that of PV modules with MorphoColor® coating applied directly on glass. Currently, Fraunhofer has not published details related to the series production of commercial products based on MorphoFlex, but in 2023, they presented in a press release a solar cell-covered car with MorphoColor lamination [34].

Kromatix SA [35] is a Swiss company, established in 2008 as a spin-off from the Swiss Federal Polytechnique Institute (EPFL), producing coloured glass for PV modules and photovoltaic-thermal (PVT) collectors. Their patented technology, called Kromatix™, is based on a multilayered interference coating that is deposited on the back of the front glass cover using low-pressure plasma processes. This approach has many similarities with Fraunhofer's MorphoColor® technology and provides flexibility for the module producers, since the solar cell design does not need to be altered, i.e. mass-produced (and cost-effective) solar cells can be used in the PV module. The optical interference coatings can be introduced at the module fabrication stage, independent of the solar cell architecture. The outer surface of the front glass cover is texturized, resulting in diffuse reflection, which prevents glare and masks the appearance of the solar cells inside the PV module. Companies such as **3S Swiss Solar Solutions AG** (Switzerland) and **SolarLab** (Denmark) have been producing coloured BIPV modules based on Kromatix™ coloured glass.

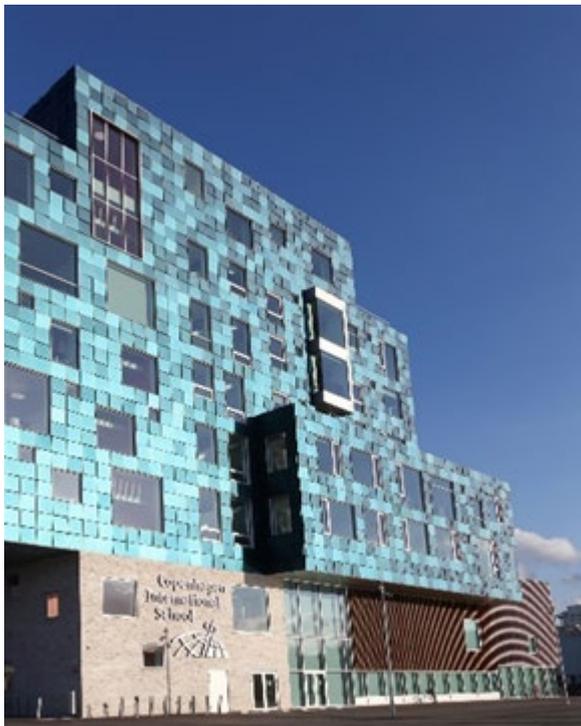
LOF Solar is a Taiwanese company established in 2008 that produces coloured PV modules based on coloured solar cells. Their colouring technology is to apply optical

interference coatings on the front side of the solar cell [36]. LOF Solar offers solar cells in more than 10 different colours.

Figure 5 shows examples of products and BIPV solutions offered by some of the companies mentioned above. In Table 1 in the next chapter, we provide a summary of the colouring technology utilized by companies, along with the typical performance of the products they offer in the market. The performance numbers are mainly taken from [4, 10, 37].



Left: Swisspanel Solar glass from Glas Trösch, reprinted from [24]. Right: Façade with ColorBlast from Kameleon Solar. Reprinted with permission from [25].



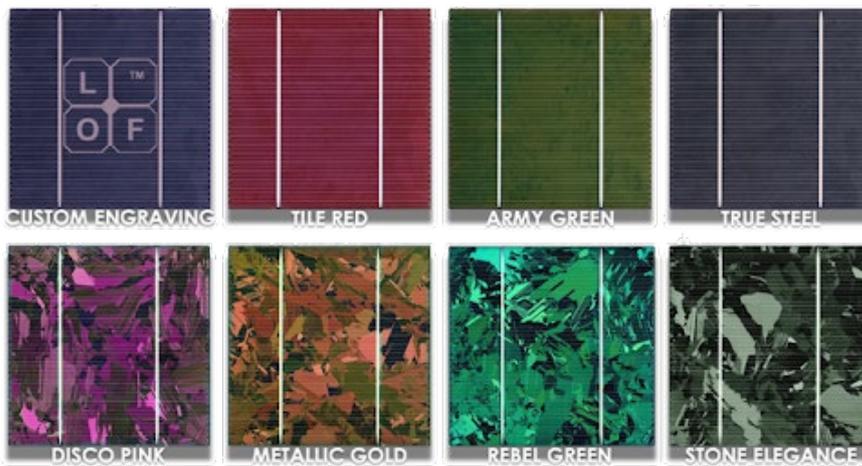
Left: Copenhagen International School with Kromatix coloured glass. Reprinted with permission from [35]. Right: Roof tiles from Freesuns. Reprinted with permission from [28].



MorphoColor samples from Fraunhofer ISE. Reprinted under licence CC BY 4.0 [18].



Facade with Suncol modules from Sunage. Reprinted with permission from [26].



A selection of coloured solar cells from LOF Solar, reprinted from [36].

Figure 5: Examples of coloured PV from different suppliers.

7 Comparison of products and colouring technologies

As we have discussed earlier, both electrical and visual parameters are needed to carry out a detailed comparison of different products and colouring technologies.

For electrical performance, power conversion efficiency (PCE) and power density are useful parameters, as well as relative loss (ΔP) compared to an ideal black reference module. For visual performance, L^* , a^* , b^* , are useful parameters, both for a coloured module as well as for a conventional uncoloured module.

If all of these parameters were available, it would make it easy to compare different products and colouring technologies. Unfortunately, in product datasheets as well as in the scientific literature, usually only a few of these parameters are given. This lack of relevant information makes comparisons more challenging.

Kutter et al. [37] provides one of the few examples in the literature where both electrical performance data as well as visual performance data is provided, for samples with three different colouring technologies and three different colours (red, green and blue). However, the samples were all prepared in the laboratory, and the optical properties of pigments and materials used are not clearly specified.

Kuhn et al. [38] provides an overview of different options to realise coloured BIPV modules, and comments on durability, design freedom and relative losses for the different options. However, since the colours are not clearly specified, it is not straightforward to compare the different options with respect to colour performance.

Block et al. [10] provided a summary of some of the current coloured BIPV solutions available on the market, regrouped according to the colouring technology. The summary includes data on power densities and relative power losses, as well as some information regarding visual characteristics. However, as indicated by the authors, the information from some manufacturers is not (or only partly) available, and the content of the summary is therefore purely indicative.

Røyset et al. [4] compared different products by measuring the spectral reflectance and calculating relative loss P and idealised CPI based on the assumption of no optical absorption losses in the colouring layers. See illustrations in Figure 6.

Li et al. [12] compared different colouring technologies and plotted PCE and relative loss versus lightness L^* . They also presented a table with visual parameters (L^* , a^* , b^*) and power conversion efficiencies for several coloured PV modules based on different colouring technologies. They compared modules based on inorganic pigments, multilayer thin films, and interference pigments. Modules with interference coatings and interference pigments had a similar PCE, while modules with inorganic pigments had a lower PCE. See illustrations in Figure 7.

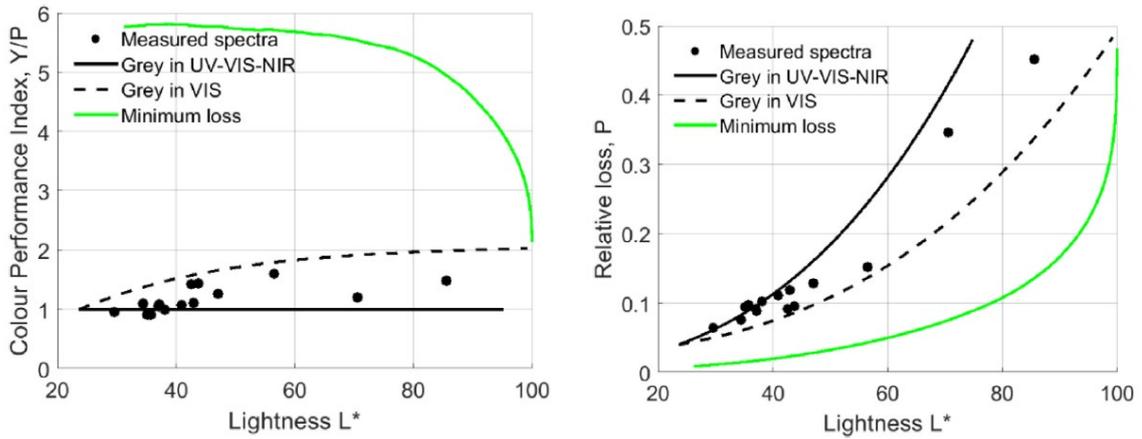


Figure 6: Colour Performance index and relative loss versus lightness. Illustrations reprinted with permission from [4].

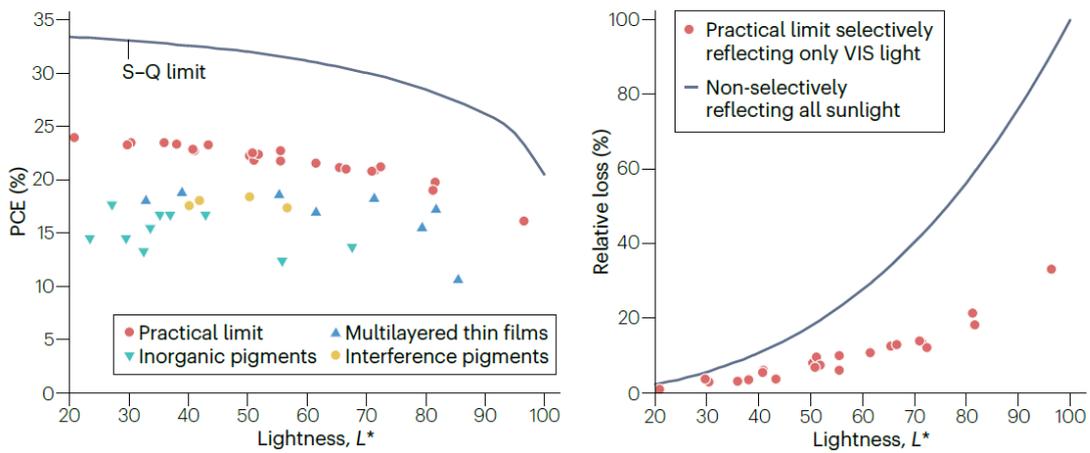


Figure 7: Power conversion efficiency and relative loss versus lightness. Illustrations reprinted with permission from [12].

In Table 1 we have summarised and listed key performance parameters of available products in the market, but only a few of them can be assigned with a CPI since the lightness parameters are often missing.

Table 1. Overview of companies and product performance for different technologies for colouring PV modules [4, 10, 37].

Colouring technology	Company	Colour	PCE [%]	Power density [W_p/m^2]	Y	Relative loss, ΔP [%]	CPI (Y/P)
Print on glass	Glas Trösch	-	-	-	-	< 25	-
		White	-	-	-	45	-
Print on glass	Kameleon	-	-	80-150	-	10-50	-
Coloured glass	Sunage	Anthracite	-	-	0.06	6.4	0.96
		Terracotta	-	157.5	0.09	9.4	0.91
		Green Moss	-	-	0.09	9.1	1.05
		Light Grey	-	-	0.12	11.8	1.11
Coloured glass	3S Swiss Solar Solutions AG	Gray gneiss	-	-	-	11	-
		White-grey	-	-	-	28	-
Coloured glass	Onyx Solar	-	-	70-150	-	-	-
Coloured encapsulant	Freesuns	Terracotta	-	97	-	-	-
		Matt grey	-	138	-	-	-
		Black	-	144	-	-	-
Coloured encapsulant	3S Swiss Solar Solutions	White	-	-	-	45	-
		Beige	-	114	-	32	-
		Light grey	-	-	-	25	-
		Dark grey	-	-	-	10	-
Pigments printed on foil	Sistine Solar	-	-	-	-	12-15	-
Interference pigment in coating	Ceramics Colors Wolbring, Colorquant	-	-	-	-	< 20	-
Interference pigment in polymer sheet	Lenzing-Plastics, Colorquant	-	-	-	-	-	-
Interference coating on solar cells	LOF Solar	True Steel	17.4	103 – 178	0.08	7.5	1.09
		Forest	17.4		0.14	9.5	1.44
		Green	17.2		0.12	11.1	1.07
		Lavender	17.2		0.10	10.2	0.99
		Tile Red	-		-	-	-
Interference coating on front glass	Megasol Energie AG	Blue	-	-	0.11	3.0	1.33*
		Green	-	-	0.23	4.0	2.58*
		Red	-	-	0.07	7.2	0.61*
Interference coating on front glass (Kromatix™)	3S Swiss Solar Solutions AG	Gold	-	148.9	-	13.4	-
		Dark Grey	-	163.6	-	4.9	-
		Green	-	-	0.24	15.2	1.60

* We have assumed a reflectance of 5% for the uncoloured cell used as a reference.

8 Feasibility assessment

8.1 Visual appearance

The results in [4, 10, 37] implies that most colouring techniques can achieve colours with high lightness ($L > 40$). High chroma ($C > 40$) can also be achieved, in particular for optical interference coatings, while colouring with pigments typically achieve lower chroma. A wide range of hues can also be covered. With optical interference coatings, high chroma is available for all hues, while for pigmented coatings, the availability of high chroma may vary more for different hues.

The choice of hue may limit the possibility of keeping the NIR reflectance low. This is particularly the case for red colours where both optical interference coatings and pigments may have a strong reflectance also in the NIR range.

For dark colours ($L < 40$), the reflection of the outer glass surface (up to 4%) may contribute to a reduced chroma.

If white or grey colours are desired (low chroma), the use of white pigments may provide the desired lightness, but at the cost of high spectral reflectance in NIR. Optical interference coatings have more possibilities to achieve both white colours with high VIS reflectance and low NIR reflectance at the same time.

The gloss of the module will in most cases be determined by the reflectance and roughness of the outer surface of the front glass. Colouring techniques that involve altering the outer glass surface will have an impact on the gloss level. Modifications of the outer glass surface may be done in order to obtain anti-reflective properties or to increase angular colour stability (see below). Such modifications may introduce a surface roughness that also can affect the gloss.

Digital ceramic printing has the highest design freedom of all the colouring technologies covered in this study. This approach allows for BIPV facades with photorealistic images, branding, artwork, etc. (Figure 3). Coloured foils can to a certain extent also allow for high design freedom, by putting pieces of foils with different colours together to create a decorative facade.

The angular stability of the colour is a distinct feature of PV modules with optical interference coatings. By structuring the substrate surface prior to application of the optical interference coating and using thin film materials with high refractive index the angular stability of the colour can be modified and controlled to a certain extent, but this will not fully conceal the phenomenon. It is not clear how architects will evaluate this feature. For some BIPV projects, the angular dependency of the colour has been utilized by the architects to give the building facade a pixelated appearance. An example of this is the Copenhagen International School where the PV modules are mounted to the building walls at slightly different angles, as shown in Figure 5.

Furthermore, Fraunhofer has recently shown that the MorphoFlex approach can allow for a large degree of flexibility when it comes to designing PV modules with coloured

patterns and decorations [34]. Colours based on printing on glass surface also provide possibilities to add patterns and decorations [17].

8.2 Power conversion efficiency (PCE)

Coloured PV modules will have a reduction in PCE that mainly depends on the lightness of the module. A PV module with a moderate lightness of $L^* = 40$, $Y = 11\%$, will have a relative loss (ΔP) of about 5-10%, depending on the colouring technology. The results in Table 1 and references [4, 10, 37] show that PV modules with optical interference coatings have lower loss than PV modules based on other colouring technologies. However, the option of pearlescent pigments based on optical interference have demonstrated PCE comparable to optical interference coatings [12].

Compared to the lightness, the choice of hue and chroma has less influence on the PCE. For a given lightness ($L^* = 40$), the results in [4] show that a high chroma green colour gives a relative loss of 6.5 %, while a grey colour gives a relative loss of 9.5 %.

8.3 Cost of production

In a study published by Fraunhofer ISE in 2018, the electrical performance, colour appearance, and production costs of three different colouring technologies for BIPV modules were evaluated [37]. The findings from this study are summarised in Table 2. We have not been able to find more recent studies and cost analysis comparing different technologies for colouring PV modules.

Table 2: Comparison of PV module power loss, colour saturation, and production cost for different colouring technologies [37].

Colouring technology	Power loss*	Colour saturation	Production cost
Optical interference coatings	3 – 7%	High	0.49 – 0.91 €/W**
Coloured glass using ceramic print***	9 – 31%	Medium	0.57 – 0.75 €/W**
Coloured encapsulant	6 – 20%	Low	0.41 – 0.48 €/W**
Uncoloured (reference)	-	None	0.27 €/W

*Relative power loss for various colours compared to reference module (typically black).

**Assuming 80 MW_p 3-shift production line in Germany, using the software SCost [38].

***Ceramic enamel is printed on the inner side of the front glass cover prior to lamination.

The data suggests that the colouring technology based on optical interference coatings can achieve lower power loss and enhanced colour saturation, but with slightly higher manufacturing costs, compared to the two other colouring technologies. However, it is important to note that the difference in production cost for these three colouring technologies may play a minor role, considering that the total cost of a BIPV system will typically include the design, cabling, inverters, transport, installation, and other factors, in addition to the PV modules themselves. It is also worth noting that in this study, the estimated production cost for a coloured PV module will be at least 50% higher than that of an uncoloured (reference) module, irrespective of the colouring technology. In general, coloured PV modules will be more expensive than

conventional, mass-produced PV modules since the average total cost per unit typically decreases as production volume increases, due to the spreading of fixed costs and potential reductions in variable costs.

Another interesting finding in this study is that the manufacturing costs of coloured BIPV modules (74 – 163 €/m²), independent of the colouring technology, was in 2018 within in the range of conventional cladding materials, such as wood (50 - 180 €/m²) and bricks (60 – 100 €/m²) [37]. Consequently, when costs are comparable, selecting coloured PV modules over traditional building materials for rooftop or façade installations can offer economic advantages in terms of power generation.

8.4 Complexity of production

In general, lower complexity translates to lower equipment costs. Screen printing and coloured glass/encapsulants have generally low production complexity, whereas digital ceramic printing and coloured foils have slightly higher tooling requirements. There are several well-established manufacturers of digital ceramic printing equipment, and among the most recognized are Dip-Tech Machinery and Tecglass. These companies offer advanced printers for architectural glass, automotive, and BIPV applications. Established manufacturers of screen printers include M&R Printing Equipment and ATMA.

For bulk colouring of glass and encapsulants, the added equipment requirements will typically involve dosing systems for colorants and homogenization systems to ensure even colour distribution. Large manufacturers of glass, such as Saint-Gobain Glass and Pilkington, typically offer coloured glass for BIPV applications. The cost of clear float glass typically ranges from \$2 to \$10 per square foot, whereas coloured glass, can range from \$15 to \$50 per square foot, or more, depending on the complexity of the finish and the production volume [39]. For coloured encapsulants, the production volume will be critical for the overall cost, and consequently, there are very few prices listed for encapsulants used for colouring PV modules. However, white EVA, which is commonly used in PV modules to increase the light reflection from the gaps between the solar cells, was typically 10% more expensive than its transparent variant at the end of 2024 [40]. In general, coloured glass and encapsulants are especially attractive as a drop-in option, which does not alter the fabrication process of the PV module.

The design and fabrication processes for optical interference coatings have relatively high complexity compared to other colouring technologies. However, the vacuum coating technology required for the fabrication of high-quality optical interference coatings is an established and mature technology with many existing players. The technology is scalable and widely used in various industries, including electronics, optics, displays, automotive, and packaging. Similar types of thin film coatings have been used in solar cell fabrication for decades, employing well-known processes such as physical vapour deposition, thermal evaporation, and chemical vapour deposition. It is generally not more complicated to fabricate the different thin film layers in the optical interference coating than it is to fabricate thin film coatings for other applications. Examples of European-based companies that design and manufacture industrial vacuum coating tools include Meyer Burger Technology AG, ROWO Coating

GmbH, AGC Plasma Technology Solutions, Alca Technology S.r.l., and Sidrabe Vacuum, Ltd.

8.5 Durability

Coloured coatings or films that are placed on the top side of the front glass cover will be exposed to environmental stresses, which can gradually degrade the materials over time. For this reason, the colourants are normally placed inside the PV module and protected from direct weathering, with the exception of colourants that are retrofitted to a PV module.

Inorganic pigments are generally very durable, and the use of such pigments should enable a long service life for the module. As discussed by Kuhn et al. [41], inorganic pigments can be used in various ways in coloured coatings, coloured encapsulants and coloured front covers. Organic pigments are generally less durable and less stable than inorganic pigments and are not often used in products that are available on the market.

For digital ceramic printing and screen printing, the pigments are fused (fired) into the glass at high temperatures which results in good long-term stability. In addition, the pigments are inorganic, offering good UV-stability, but it should be ensured that no unwanted reactions occur with other components in the glass, films or encapsulants. It has been shown that TiO₂ in contact with EVA or POE encapsulants may induce significant losses due to accelerated polymer degradation [42]. The photocatalytic effect of TiO₂ may be the reason for this degradation.

Pearlescent thin film pigments is an established technology in the car industry. The pigments used are inorganic and should provide a sufficiently service long life.

Optical interference coatings are most often enclosed inside the PV module and well-protected from environmental stresses. The coloured PV modules currently offered by Megasol and LOF Solar have product guarantees that are comparable to those for conventional (uncoloured) PV modules, i.e., the electrical performance of the PV module after 25 years of operation is greater than 80% of the initial performance. Kameleon Solar offers up to 30 years power warranty, 25 years product warranty, and 50 years colour fastness. This implies that the expected lifetime for coloured PV modules is comparable to ordinary PV modules. In general, the materials used as pigments or colourants are durable and chemically stable, suggesting that the visual appearance of coloured PV modules will not change or degrade significantly over the lifetime of the product.

8.6 Environmental aspects

Depending on the coating technology, fabrication of coloured PV modules may involve complex and energy-intensive processes, which can potentially increase the carbon footprint due to higher greenhouse gas emissions during manufacturing. In addition, the reduced power conversion efficiency will also increase the carbon footprint per produced energy. In general, carbon footprint assessments of BIPV systems remain

fragmented, and often, they exclude important lifecycle stages such as material sourcing, installation, and end-of-life recycling [11].

The metal oxides and nitrides that are typically used in the optical interference coatings are abundant, non-toxic, and chemically stable materials. This implies that such coatings are a sustainable and environmentally friendly technology for colouring PV modules. The same applies for most pigments based on inorganic oxides. Pigments and substances containing toxic heavy metals, such as cadmium sulphide, should be avoided as they are harmful for living organisms and the environment.

One increasingly important aspect of PV technology is to design the products for recycling, meaning that the different components can be easily separated at end-of-life. This can involve minimizing the amount of adhesives, using reversible encapsulants, and labelling materials for easier sorting. The inclusion of colourants in PV modules can potentially affect the recyclability, and established recycling processes may need to be adapted to handle these materials effectively. For instance, the increased complexity of the material composition of the PV module could make the separation of different materials more challenging during recycling. In addition, the risk of contamination between different materials may increase, which could affect the purity of the recovered materials. This will, of course, depend on the type of thin film materials or pigments that are used, and how they are incorporated into the PV module. Coloured layers on a glass surface are expected to be easier to separate as compared to bulk colouring of glass, films or encapsulation layers.

8.7 Patents and intellectual properties

In recent years, the BIPV products offered on the market using optical interference coating for colouring seem to be based on patented technology. The patent published by SWISSINSO SA in 2014 for the Kromatix™ technology [43] and the patent published by Fraunhofer in 2018 for the MorphoColor® technology [44] are examples of this. Thus, alternative technologies for colouring PV modules that are not protected by patents may be a more viable approach for new businesses that would like to start offering BIPV products on the market. Another approach could involve the manufacturing of products under a licensing agreement where the company (licensee) is granted the rights to produce goods using patented technology. The company typically pays royalties or fees to the owner of the patented technology based on the sales or production volume. The agreement between Megasol Energie AG and Fraunhofer ISE for the MorphoColor® technology is an example of such licensed production.

Kameleon Solar (ColorBlast™) uses patented or proprietary ceramic ink printing processes for BIPV. Their patents typically cover printing patterns, ink formulations, and methods to optimize light transmission while maintaining the colour. Solaxess SA exploits 7 patents developed by the Swiss Center for Electronics and Microtechnology (CSEM) in order to industrialize and commercialize a coloured nanotechnological film. Exasun B.V. and Tesla Inc. hold patents for pigmented encapsulant layers and coloured top coatings, while Merck has patented the use of multi-coated glass-flake interference pigments for coatings and inks used in pearlescent colour layers for

architectural and BIPV applications. Sistine Solar (SolarSkin®) has a patent for graphic overlay films and methods for integrating images into PV modules.

8.8 Market demand

A recent report by the International Energy Agency claims that the BIPV market in Europe ranged from 250 MW to 450 MW in 2023, indicating either moderate growth or stagnation, whereas the global BIPV market has likely surpassed 3 GW [45]. In comparison, the global PV installations reached nearly 600 GW in 2024.

According to Batista et al. [2], “the main challenges for BIPV adoption include high initial costs and information on investment payback time for decision-making and early adoption”. In addition, the relative novelty of the various colouring technologies in combination with fluctuating energy prices in recent years may have influenced the overall demand negatively due to increased financial risks. For example, the energy crisis in 2022 resulted in various governmental regulations and initiatives that created unwanted unpredictability for both building developers and consumers. In Norway, the government has recently introduced a fixed low price (“Norgespris”) for electricity for the private market. This could, in turn, reduce the general demand for BIPV and BAPV systems.

On the other hand, governments around the world are introducing new requirements to enhance the energy efficiency of buildings, which may affect the demand for BIPV systems. For example, the Energy Performance of Buildings Directive (EU/2024/1275) was adopted in May 2024 and is a legislative framework established by the European Union mandating all new residential and non-residential buildings to be *zero-emission buildings* as of 1st of January 2028 for buildings owned by public bodies and 1st of January 2030 for all other buildings. All new buildings in the EU have since 2020 been required to be *nearly-zero energy buildings*, which will be replaced by this enhanced *zero-emission buildings* requirement, where the energy needs will be covered largely by onsite and nearby renewable energy sources. This could include BIPV systems and utility-scale PV power plants.

In 2024, one of the companies that offer coloured PV modules, Kromatix SA, went into liquidation, and was later acquired by g-neration.energy AG in August 2025. Another company that filed for insolvency in 2024 was the Dutch BIPV panel producer Exasun. This may suggest that there currently is an imbalance between supply and demand for coloured PV modules. The reasons for this are not obvious. When building developers and owners consider adopting BIPV, several criteria will come into play, including aesthetics, flexibility, and return on investment (costs). Since the total energy production of a BIPV system over its lifetime can be challenging to predict (for several reasons such as system degradation, maintenance requirements, and environmental factors), the higher initial investment for BIPV products compared to conventional cladding materials might be a deterrent to building developers. In general, the construction industry is highly aware of costs.

8.9 Summary of feasibility assessment

Key findings from the feasibility assessment are summarized in Table 3.

Table 3: Summary of feasibility assessment for the different colouring technologies.

Technology ----- Topic	Print on glass	Coloured glass	Coloured encapsulant	Pigments printed on foil	Pigments based on interference	Interference coatings on glass
Visual appearance	Very high design freedom (images/patterns). Matte options. Good masking.	High uniformity. Low saturation.	High uniformity. Low saturation.	Design freedom. Can be retrofitted to standard modules. Good masking	Vivid interference effects possible. Good masking.	High saturation. Angular colour dependence . Good masking.
Power loss caused by colouring	10-50%	7-28%	10-45%	12-15%	<20%	3-15%
Cost of production	Low-moderate	Moderate.	Low. Attractive drop-in option.	Moderate.	Moderate.	High.
Complexity of production	Low-moderate.	Low.	Low.	Moderate.	Moderate. Pigments are low cost, but uniformity is non-trivial.	High. Requires advanced equipment and expertise.
Durability	High. Fused into the glass surface.	High.	Moderate. Colour retention challenges.	Moderate. Colour retention challenges.	Moderate (if inorganic). Binder governs lifetime.	High. Inorganic stacks are robust.
Environmental aspects	Heavy metal free inks are available. Penalty from added firing and PCE loss.	Affect recycling.	Additive choices (e.g. stabilizers) are critical. PCE penalty.	Added polymer mass. End-of-life separation harder.	UV-stable pigments. Choice of polymer binder matters.	No added toxicity. Low PCE penalty. Long service life.
Patents and intellectual property barriers	Low-moderate. Freedom to operate is broad.	Low.	Moderate.	Moderate.	Moderate-high.	High. Licensed / proprietary.
Market demand	Relevant for branding and artwork.	Large market outside PV.	Adoption limited by PCE loss.	Relevant for retrofitting and heritage settings.	Novel solution, unclear demand.	High initial investment. Relevant for premium facades.

9 Recommendations

One of the aims of this report is to provide up-to-date information and guidance related to the different colouring technologies, and the following recommendations are intended for those that wish to bring coloured PV modules to the market.

The main benefit of coloured PV is the possibility for improved aesthetics, and the possibility to meet local building requirements with respect to aesthetics.

However, the introduction of colour in a PV module typically comes with some drawbacks, such as (i) reduced power conversion efficiency, (ii) increased costs, and (iii) increased technological complexity.

Developing products with coloured coatings requires advanced technical infrastructure and expertise in optics, materials science, and thin-film deposition techniques, most commonly found in research institutes.

Furthermore, some of the technologies like Kromatix™ and MorphoColor® are patented, and the use of such technologies may require licensing agreements.

In this report we have focused both on visual properties as well as properties related to power conversion efficiency. In the literature, several figures of merit have been proposed to assess and compare different colouring technologies with respect to their influence on power conversion efficiency. The “Colour Performance Index” proposed by Røyset et al. [4] is a figure of merit that can be used to understand and compare different colouring technologies with respect to the expected power losses resulting from colours with different lightness.

One recommendation to manufacturers and suppliers of coloured PV is to provide data on visual characteristics such as L^* , a^* , b^* , and gloss values, in addition to electrical data such as power conversion efficiency, power density and relative loss resulting from the colouring.

The two most applied methods to introduce colour in a PV module are the use of interference coatings, and the use of coloured inorganic pigments. A third and emerging option is the use of pearlescent interference pigments.

Interference coatings are known for low losses, partly due to the use of thin films with low absorption and partly due to good transmittance in the NIR range. Interference coatings also have potential for high chroma (saturated colours). The use of interference coatings produces colours with angular colour dependence that may not be desirable. Several methods have been applied to limit the angular colour dependence, including adding roughness to the surfaces of the cover glass.

Inorganic pigments can be introduced in coatings or bulk materials with relatively low technological complexity. The use of pigments does not require vacuum coaters, and the equipment cost is typically low. In order to limit losses, spectrally selective pigments that transmit near infrared radiation should be applied. Inorganic pigments

can provide colour with no angular dependence, similar to the colours used in conventional building materials.

Pearlescent interference pigments is a less common, but emerging option, that has been recently introduced. This colouring technology aims to combine advantages of interference coatings with those of conventional inorganic pigments. The use of pearlescent interference pigments may provide aesthetically attractive colours with limited losses, while keeping the cost and complexity low.

For companies that are developing coloured PV modules for building integration the following general recommendations can be given:

- **Engage with architects:** Work closely with architects to understand their preferences and requirements and showcase how coloured PV modules can enhance building aesthetics.
- **Aesthetics versus efficiency:** Keep in mind that different colouring technologies have different performance with respect to the power loss resulting from adding colour. The “Colour Performance Index” is a figure of merit that can be used to compare different colouring technologies in this regard.
- **Navigate patent restrictions:** Investigate relevant patents and consider licensing agreements for patented technologies to avoid legal issues and leverage existing innovations.
- **Be aware of infrastructure costs:** The different colouring technologies can require access to advanced technical infrastructure and expertise, which can imply a relatively high initial investment for establishing a production line.
- **Monitor market demand:** It is important to stay informed about market trends and demand for coloured PV modules and be prepared to adapt to changes in energy prices and regulatory requirements, such as the EU's Energy Performance of Buildings Directive.

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