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# Colouring solutions for building integrated photovoltaic modules: A review

Alejandro Borja Block [a], Jordi Escarre Palou [b], Marie Courtant [a], Alessandro Virtuani [b], Gianluca Cattaneo [b], Maxime Roten [b], Heng-Yu Li [b], Matthieu Despeisse [b], Aïcha Hessler-Wyser [a], Umang Desai [a,*], Antonin Faes [a,b,*], Christophe Ballif [a,b]

[a] *École Polytechnique Fédérale de Lausanne (EPFL), Institute of Electrical and Micro Engineering (IEM), Photovoltaics and Thin-Film Electronics Laboratory (PV-Lab), Rue de la Maladière 71b, 2002 Neuchâtel, Switzerland*

[b] *CSEM, Sustainable Energy Center, Jaquet-Droz 1, 2000 Neuchâtel, Switzerland*

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ABSTRACT

As global decarbonisation requires the widespread adoption of solar photovoltaic (PV) electricity, addressing challenges related to land use has become relevant. The conflict between PV installations and other land uses, such as forestry or agriculture, highlights the urgency for alternative solutions. Integrating PV technology into the built environment is a compelling strategy to mitigate these challenges, enabling electricity generation precisely where it is needed. In the context of buildings integrated photovoltaics (BIPV), PV modules serve a dual purpose, functioning both as electricity generators and integral components of the architectural design. Therefore, the architecture requirements — specifically in terms of shape, size, and colour— become relevant for BIPV modules. This paper offers a general overview of the diverse colouring technologies employed for BIPV modules, describing their functioning, challenges, and advantages. An examination of the current landscape of coloured PV products involving considerations of pricing and power output is presented. Additionally, this work addresses the critical topics of reliability and stability in colour solutions, outlining methodologies for quantitative colour characterization. It provides foresight into the potential challenges facing installations in the future and explores the multifaceted social, economic, and environmental implications of this evolving technology.

## 1. Introduction

Temperatures on Earth have already surpassed previous records due to continuous global warming [1]. This has resulted in climate change, which is progressively endangering human safety in diverse locations. To overcome these issues, it is critical to transition to clean and renewable energy sources. The Conference of Parties (COP-28), an annual gathering held in the framework of the United Nations Framework Convention on Climate Change (UNFCCC), concluded that it is necessary to triple the renewable power capacity and double the energy efficiency by 2030 to limit the temperature increase to 1.5 °C above pre-industrial levels [2]. Because of its low cost and low environmental impact, photovoltaic (PV) energy is an important component of this transformation. Furthermore, PV technology contributes to the security of local energy supply, lowering reliance on possibly undependable international energy imports. In places where land is scarce, broad usage of PV systems competes with other land uses, including farming, forestry, and livestock [3,4,5]. Even in larger countries, the installation of substantial solar farms on land is encountering growing resistance from both national and local institutions due to conflicts with other land use [6].

Integrated PV solutions, such as agri-PV and building-integrated photovoltaic PV (BIPV), show promise in addressing land scarcity issues. In fact, to facilitate the large-scale deployment of PV systems, it becomes necessary to use various infrastructure surfaces [7,8,9]. These surfaces extend beyond mere buildings and include a wide range of visible structures, including noise barriers, bridges, road fences, harbours and more. Integrated PV solutions serve multiple purposes by generating energy, replacing building materials, and providing economic and environmental benefits [10,11]. As a result, integrated PV modules may have higher requirements for safety and aesthetics. Operational safety of the BIPVs is of a particular importance since the target buildings are usually inhabited by humans. Thus, the BIPV products should comply to the safety requirements as mandated by

* Corresponding authors at: École Polytechnique Fédérale de Lausanne (EPFL), Institute of Electrical and Micro Engineering (IEM), Photovoltaics and Thin-Film Electronics Laboratory (PV-Lab), Rue de la Maladière 71b, 2000 Neuchâtel, Switzerland (U. Desai and A. Faes).

*E-mail addresses:* umang.desai@epfl.ch (U. Desai), antonin.faes@epfl.ch (A. Faes).

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several international norms like, IEC 63092–1 [12], and should also fulfil the requirements of the fire safety norms like, EN 135011: 2018 [13], as well as safety with glass in buildings [14]. Fig. 1 depicts some examples of coloured BIPV installations. The adoption of transformative approaches – such as colouring solutions – is in fact a way to better harmonize the integration of solar PV in building and urban contexts, which may have a clear aesthetical relevance.

Architects and building owners may prefer customizable BIPV modules that can be modified in terms of shape, size, and especially colour [16,17,18]. Targeting a full transformative appearance of PV modules based on c-Si was introduced only recently [19,20]. Coloured PV technologies may in fact enhance their acceptance in the built environment, not only because they may be more visually appealing to key stakeholders in construction but also because they could comply with building codes, offering a solution to install renewable energy systems close to the end user. However, challenges associated with coloured PV exist that need to be addressed.

Concerns have been raised about coloured PV technologies' power generation, environmental effect, cost, and reliability [18,21]. To lower the carbon footprint of economically viable BIPV products, a balance must be established between the power they provide and their visual appeal [22,23]. The required appearance should be obtained while optimizing power generation. Another essential feature of coloured PV is the incorporation of additional materials (such as polymers, additives, inks, etc.) inside the modules that will interact with environmental factors including temperature, humidity, and light. Over time, these interactions have the potential to degrade both the performance and visual appearance of BIPV modules, potentially resulting in a shorter lifespan and undercutting the economic, aesthetic and environmental benefits that BIPV products are designed for.

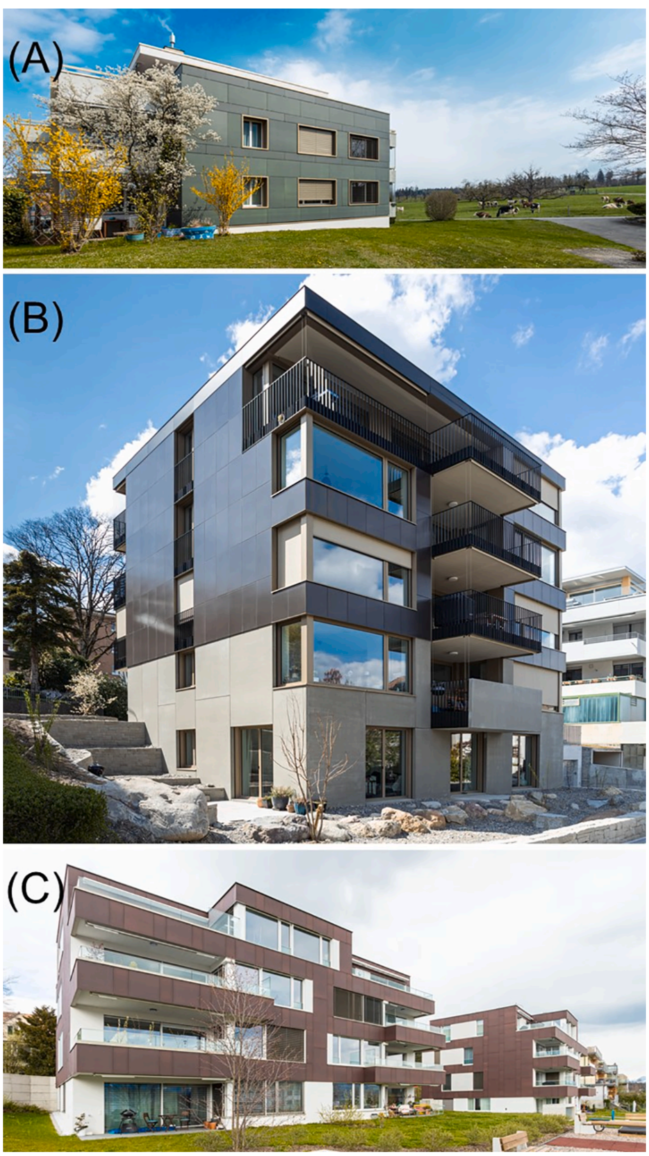


**Fig. 1.** BIPV installations from Sunage SA in Switzerland, highlighting diversity in colours. (A) Opfikon 2018. (B) Thalwil 2021. (C) Mannedorf 2019. Images courtesy of Sunage SA [15].

In this work, we offer an overview of coloured PV technologies. We focus on techniques used in conjunction with crystalline silicon cells, we explain their operation and explore key issues related to their performance. We also present cutting-edge examples of these solutions, compare them, and examine the advantages and drawbacks of coloured PV. Overall, our goal is to provide a broad and up-to-date assessment of colouring solutions for BIPV modules from an industrial perspective, covering their performance and aesthetics, while also addressing the challenges associated with these technologies.

## 2. Colouring techniques for PV

In this section, we will explore some of the common colouration technologies employed in PV modules. These technologies can be combined and integrated to specific treatments of the glass to modify their glare. They usually target at reflecting and scattering part of the visible spectrum to create a colour effect, while letting infrared light goes through. As a guideline, with standard crystalline solar cells, around half the power comes from infrared photons. Unless indicated, the examples include c-Si solar cells.

### *2.1. Coloured glass*

#### *2.1.1. Digital ceramic printing*

Digital ceramic printing (DCP) on glass offers the flexibility to modify colours using inkjet technology on either the inner or outer surface of the front glass. However, it is typically preferred to position the coated side of the glass inside the module in direct contact with the encapsulant. This approach serves the dual purpose of safeguarding the coating from degradation due to weathering and simplifying the cleaning of the front glass. While common glass printing methods, like roll or screen printing, are feasible, DCP has gained greater prominence due to the momentum generated by the inkjet technology, owing to its versatility to make different patterns at high resolution in a flexible manner.

Inkjet digital ceramic printing uses inorganic ceramic inks. These inks consist of a mixture of pigments and very fine glass particles, named frits. After the printing process on glass, the coating is fused to the glass substrate during the glass tempering steps at typical temperatures of 640–700 °C. The high temperature limits the number of pigments that can be used as The pigments used in the ink formulation must be thermally stable and not lose their optical properties upon firing. Inorganic metal oxides pigments such as chromium oxide, copper oxide, mix oxides CuCrO, titanium dioxide, red iron oxide, nickel antimony titanium rutile or cobalt aluminate blue spinel, are generally used when formulating ceramic inks. Noticeably, the process does not only enhance the glass' resistance to abrasion and chemical agents but also imparts a remarkable resilience to UV radiation.

State of the art digital ceramic printers from DipTech [24] allow to use up to six different inks which can be used together to match colours from 'Reichs-Ausschuss für Lieferbedingungen' (RAL) and Pantone templates. These digital printers allow printing in white too, and adjusting the translucency level of the printing by manipulating two main parameters:

1. The print opacity (i.e., the fraction of area covered by the inks).

2. The volume per printed dot (from 5 to 40 picolitres, relating to the size of the dots).

As an example, Glas Trösch AG [25] uses this technology with their 6-colour DipTech printer. As the DCP process by DipTech is meant for opaque colouring, the usage of the software and hardware requires some engineering skills to adapt its purpose for translucent applications like coloured PV modules [26,27]. Hochschule Luzern (HSLU) supports Glas Trösch in the engineering process of this technology. Module manufacturers like 3S Swiss Solar Solutions AG use DCP-glass to manufacture some of their coloured modules (MegaSlate Flair, see Fig. 2) [28].

Kameleon Solar and its product line ColorBlast® also uses this technology to print small hexagons with some space left between them [29]. These dotted patterns optimize the amount of light transmitted to the solar cells, provided that there is a dark background (see Fig. 3).

Understandably, the application of a coloured layer over the solar cell will reduce the absorbed light in the cell and consequently the short-circuit current and power of the module. The loss in power will depend on the printing density and ink itself. It is essential to give careful consideration to the compatibility of the coatings with not only the substrate (in this case, the glass) but also the printing technique and, in the long run, the materials within the module (such as the encapsulant). Another advantage in using DCP in lieu of conventional glass substrates is that no modification of traditional PV manufacturing lines is required. Unless a PV module maker is equipped with DCP tool and a glass tempering line, a strong disadvantage will arise about glass handling and shipping, as the module maker will have to return to the glass maker for any additional samples, with risk of colour variations, time delay, and minimum quantities required to have an acceptable price of launching a process.

### 2.1.2. Screen printing

Silk screen printing is another technique that is used to print the inner side of PV front glass covers to impart colour. The ink is applied on glass through a mesh stencil. The stencil blocks out areas of glass that should not be coated, avoiding ink to be deposited on them, creating the design. Next, when using a frit-based ink, a firing process is required to adhere the ink to glass. The result is a high print quality with high resistance to abrasion, chemical agents, and UV radiation. As an example, Viasolis can supply products with coloured silkscreen printed glass. This coloured glass is used in front or rear glasses of solar panels, and it can be combined with coloured solar cells to achieve different visual aspects [26].

Merck and Ceramic Colors Wolbring, a company specialized in the production of coloured pastes for screen printing among others, have developed a product line named Colorquant [31]. This product is based in colouring the glass, probably by screen printing, using effect pigments from Merck (see Fig. 4). Generally, these pigments are based on mica flakes coated by a thin layer of titanium dioxide, and they impart colour mainly by interference what reduces performance losses. The colour is controlled by the thickness of the titanium dioxide layer that allows a high variety of colours. Additive colour mixing rules apply when using different effect pigments in the formulation. Effect pigments can also contain layers of iron oxide, iron titanate, chromium oxide and others to reinforce the colour by absorption. Iron oxide can be used to achieve reddish tones but the price to pay is increased performance losses. The expected losses using Colorquant glasses depends on the colour, but they are below 20 %. Another advantage of this technology is that flakes can be coated on a commercial basis in aqueous suspension and expensive vacuum techniques are not required. An example that illustrates this concept can be found in [32], where an interferential based green coating is deposited in solar glass by means of screen printing. In addition, these pigments can be used to impart colour on PV modules when applied to other components than glass such for example encapsulant layers [33].

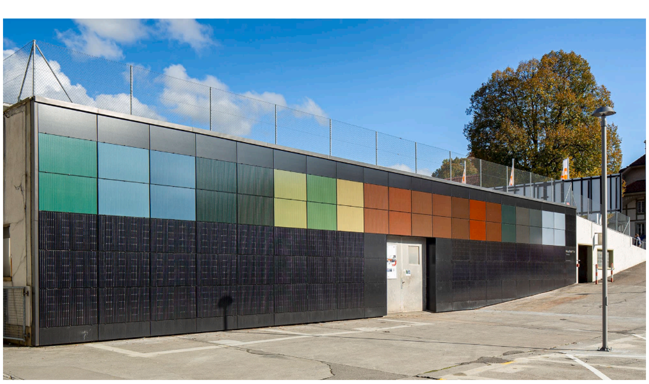

**Fig. 2.** Test installation of MegaSlate Flair DCP coloured modules in Bern with a varied range of colours. Image courtesy of 3S Swiss Solar Solutions AG [28].

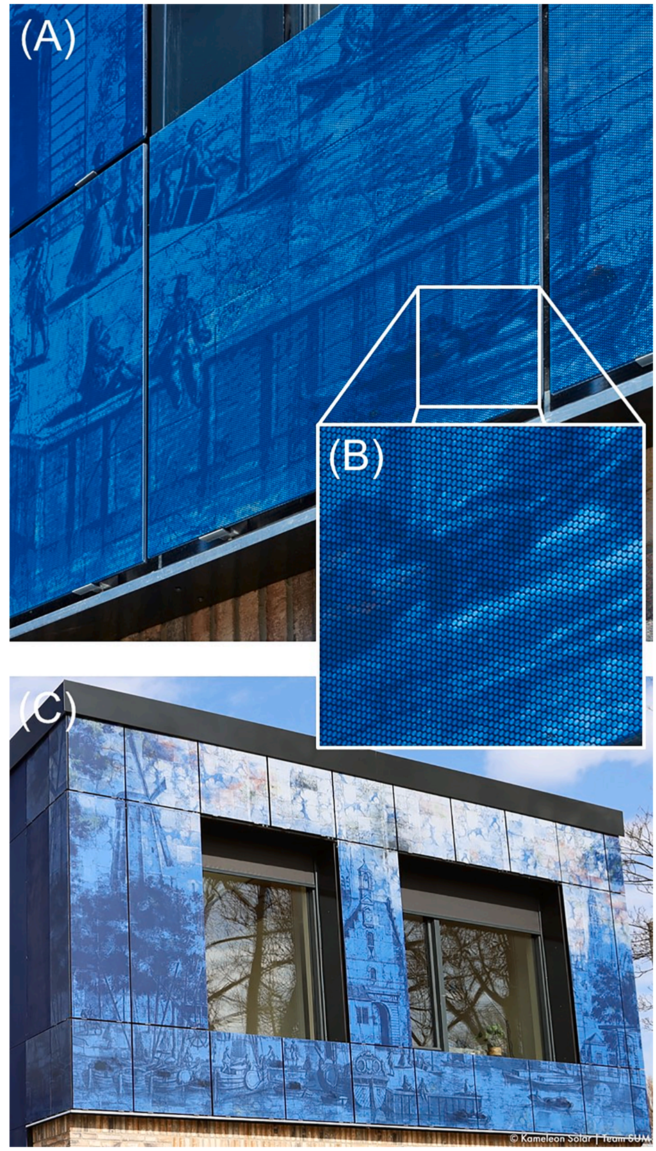


**Fig. 3.** SUM prototype from Kameleon Solar. (A) Façade. (B) Close-up of the printed small hexagons leaving space between them. (C) Full façade. Images provided by Kameleon Solar | Team SUM [30].

### 2.1.3. Mass-coloured glass

In the PV industry, low-iron flat glass is employed to optimize light transmission. However, manufacturers have the flexibility to introduce

**Fig. 4.** A portfolio of Colorquant product samples from Ceramic Colors Wolbring. Image provided by Ceramic Colors Wolbring GmbH [34].

colouring agents into the glass during the production process, resulting in what is known as mass-coloured glass. Unlike printed glass, for which coloured is applied to a surface, mass-coloured glass undergoes a transformation throughout its entire volume, allowing for the creation of a colour that strikes a balance between transparency and saturation [18]. Colours in glass could be adapted by adding powdered oxide, sulphide, or other compound of metals to the glass while it is in molten stage, e.g., cadmium sulphide, gold chloride and cobalt oxide are added to get yellow, red and blue-violet colours, respectively [35].

### 2.2. Coloured encapsulant

Coloured encapsulant is produced by a standard polymer extrusion process. Organic or inorganic pigments of colours and other necessary additives like UV absorbers, anti-oxidants, etc, are added to a base resin. Extrusion process is suitable for the high-volume manufacturing process as are typical PV encapsulant. Foil translucency can be tweaked by either adjusting the thickness of the films or the concentration of the colourizing material. Typical processing temperature remain below 200°, putting less stringent requirements on the dyes that in in DCP process for which the choice of pigments is narrowed down.

Interferential pigments such the ones commercialized by Merck or Basf, among others, can be used to produce colour encapsulant. Interferential pigments modify light reflection, instead of providing colour by a selective absorption of visible light, being able to create brilliant interference colours in PV modules with performance losses well below 20 %. The downside being a higher colour angular sensitivity, which is not the case when using absorbing pigments. Luminescent dyes are also compatible with extrusion, and can be incorporated in the formulation of a coloured encapsulant [36].

Coloured encapsulant can present a high resistance to UV radiation. Different factors may affect the UV resistance such as the types of pigments and additives used in the formulation, the base resin, and the environmental conditions such as temperature and the amount of oxygen absorbed by the encapsulant over its service lifetime. For example, under anaerobic conditions a titanium dioxide pigmented foil can show a fast darkening while under the presence of oxygen its colour can remain stable.

Freesuns, a Swiss BIPV company, specialize in solar tile products designed to seamlessly integrate into buildings, including heritage roofs architectures, even in terracotta colours. These tiles, available in various hues, may contribute in preserving the unique aesthetics typically associated with traditional buildings (see Fig. 5).

Currently, Solaxess, a pioneer company in colored BIPV solution, brings a new generation of products is commercializing coloured encapsulant films for BIPV applications [38]. The coloured polymeric foils produced by Solaxess are meant to be sandwiched inside any

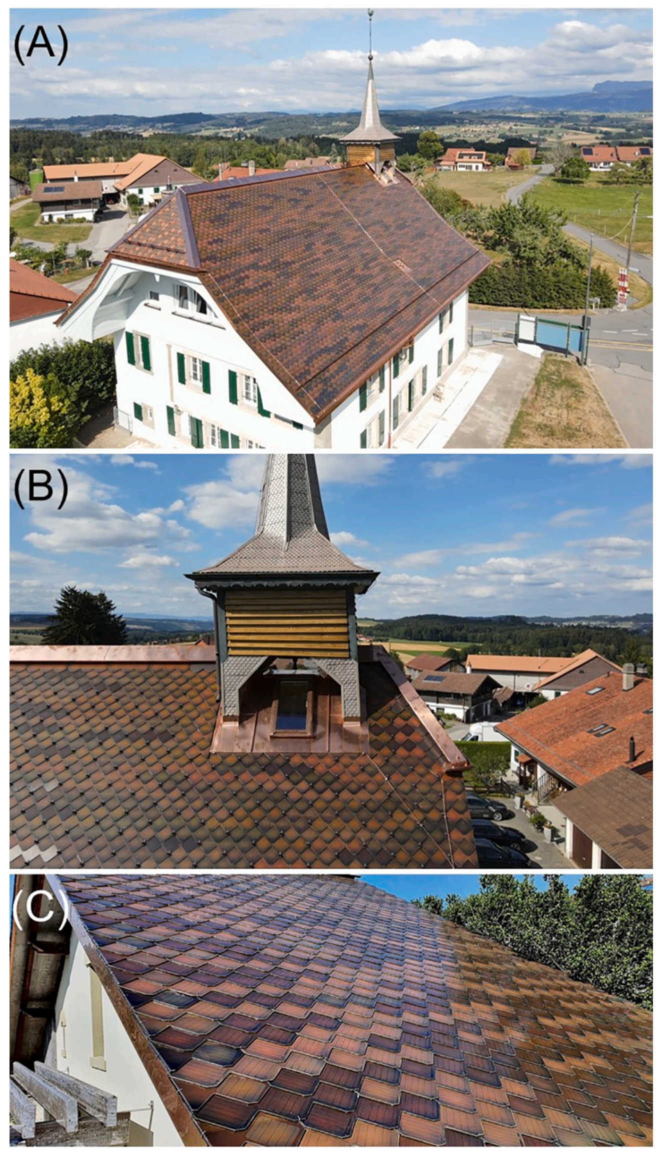


**Fig. 5.** Freesuns project in Ferlens, Switzerland, with different tones of terracotta solar tiles. (A) Distant perspective. (B) Near perspective. (C) Close-up view. Images courtesy of Freesuns [37].

crystalline silicon modules, as a quasi-drop in the manufacturing process of PV modules to produce the desired coloured appearance. Some examples of installations with Solaxess foils are shown in Fig. 6.

Vanceva [40] and Trosifol [41] products are coloured encapsulant interlayers based on Polyvinyl butyral (PVB), a polymer commonly used to manufacture laminated safety glass for architectural applications.

Slooff et al. [42] investigated another colouring approach used by Solar Visuals in which a coloured foil is incorporated between two front layers of encapsulant at the top of the solar cells. This approach is quite flexible in adapting different colours as well as dot patterns to get impressions of leaves. The reliability of these foils in the form of modules was also studied, showing non-significant degradation during 500 h of accelerated UV testing, 1500 h of accelerated damp-heat ageing, 400 thermal cycling and outdoor exposure for one year in the Netherlands [42].

### 2.3. Coloured semi-transparent PV-active layers

Another possibility of colouring the BIPV products rests in using the semi-transparency of the amorphous silicon PV modules (a-Si), wherein the active layer is partially removed to improve the transparency (Figs. 7 and 8). For example, Onyx solar [43] uses coloured PVB encapsulants from Vanceva to laminate semi-transparent amorphous silicon thin film modules to a rear glass (Fig. 7). This results in coloured translucent laminates with a homogeneous aspect that can generate electricity. As the colour layer is applied on the rear side of the BIPV unit, performance losses due to the application colour are minimized. The aspect can be further tuned by controlling the degree of transparency. Such a product can be most suitable for a potential application in the façades as an exceptional case where the priority is given to semi-transparency over the power conversion efficiency. The downside of this technology is the low conversion efficiency of amorphous silicon thin film modules as compared to modules containing crystalline silicon cells.

Advanced Solar Power is a Chinese manufacturer of cadmium telluride (CdTe) thin film modules [44]. This company offers coloured translucent solar panels based on CdTe using the same concept as Onyx solar. This type of modules has been used by the Swedish company Soltech Energy to build advanced active facades [45].

### 2.4. Interferential coatings

In this process at least two different transparent materials are deposited alternatively over a glass or a polymer foil to control the amount of visible light reflected by forming an interferential multilayer structure. A low-pressure plasma process is generally required to deposit the materials what makes this technology relatively expensive. Care is needed on the design to minimize angular dependencies. Examples of this approach are the MorphoColor concept from Fraunhofer ISE, the Kromatix$^{TM}$ technology from Swissinso, or the Solaxess first generation of white colour foil.

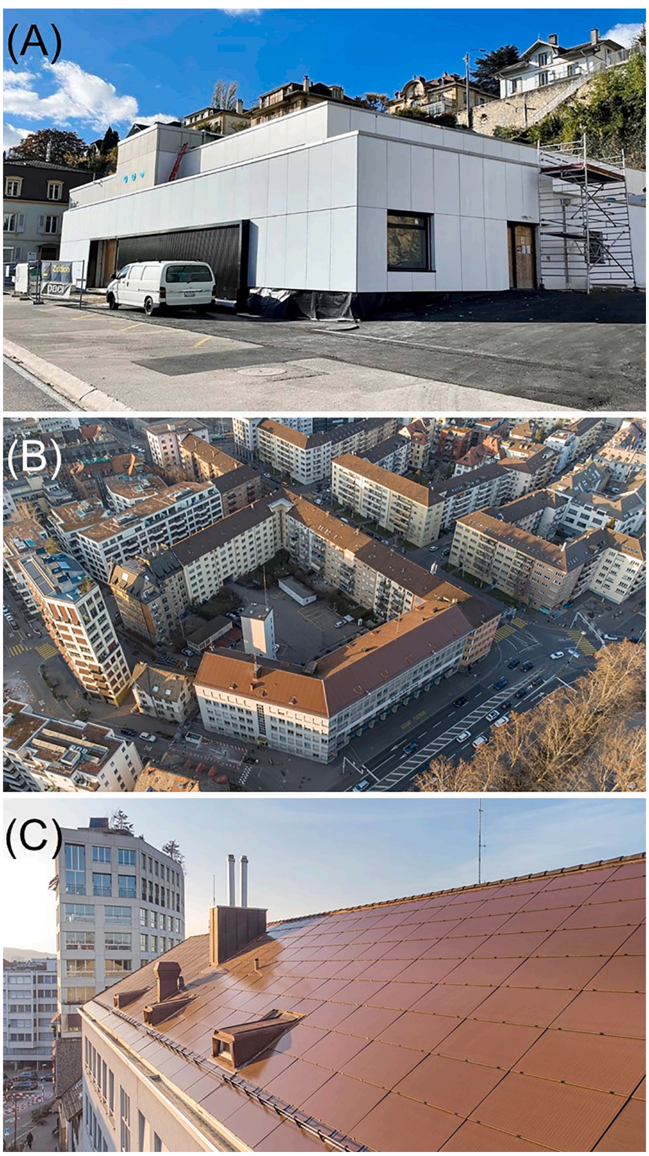


**Fig. 6.** (A) BIPV building made with a Solaxess nanotechnology white film. Image courtesy of Solaxess [39]. (B) and (C) Building in Zürich, Switzerland, with terracotta foil. Images provided 3S Swiss Solar Solutions AG [28].

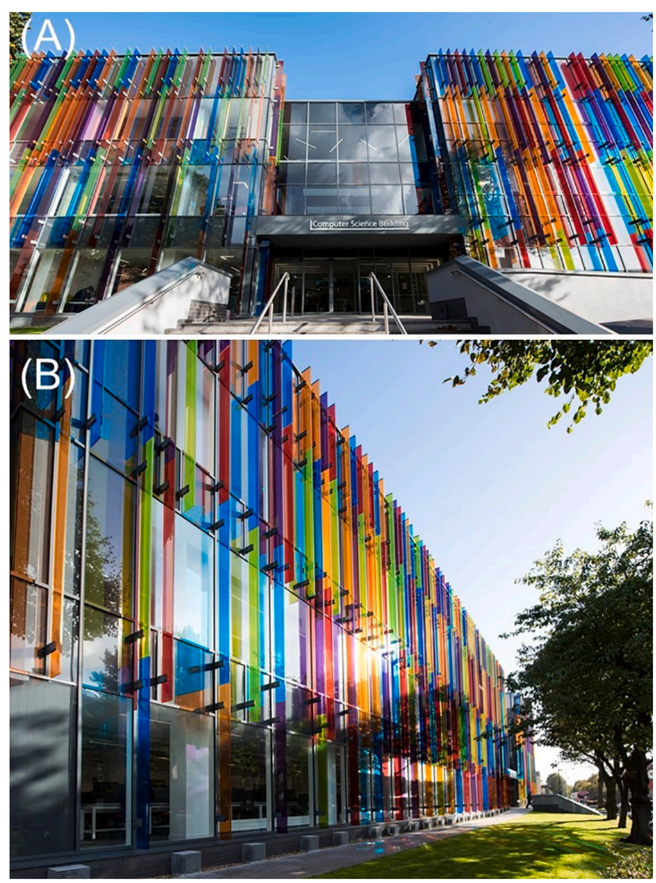


**Fig. 7.** (A and B) Computer Science Building of the University of Belfast with Vanceva coloured foils. (A) Main entrance. (B) Façade. Images courtesy of Vanceva [40].

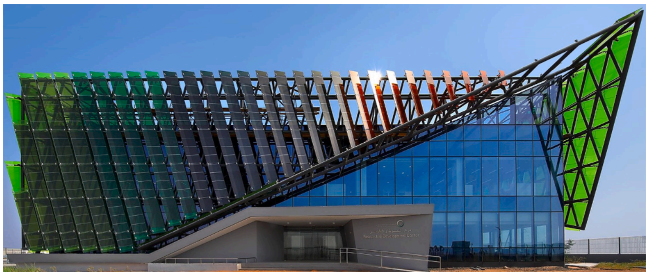

**Fig. 8.** Project for DEWA R&D from Onyx solar employing see-through coloured a-Si. Image provided by Onyx solar [43].

The MorphoColor concept is inspired by complex 3D photonic assemblies found in nature that allow highly saturated colours with low angular dependencies [46]. A corrugated interferential multilayer structure is used to mimic these structures. Corrugation is described as the key feature to reduce angular dependency. In practice, it is achieved by depositing the interferential multilayer over a textured substrate, such as glass previously etched in a hexafluoric acid-based solution. MorphoColor coatings are highly transparent, and the desired colour is produced by tuning the interferential multilayer structure to reflect the desired light. When MorphoColor coatings are applied in PV modules, performance losses below 6 % are claimed for blue, green, and red colours when compared to a black reference. The extra cost of PV modules when adding the MorphoColor concept is estimated in 30–100 Euros/$m^2$ [47].

The Kromatix concept is based on the deposition of an interferential multilayer stack on the inner side of the PV front glass by radio frequency sputtering deposition. The interferential multilayer used in Kromatix products is designed to minimize the angular dependency of the colour [48]. For this purpose, the reflection of the stack needs to be composed of at least two peaks. Multi-peak reflection curves allow to define a dominant colour which will depend on both wavelength and intensity of the peaks. When increasing angle of observation, the position of the peaks will be shifted towards lower wavelengths, but dominant colour must remain. The complexity in the design makes difficult to achieve a large variety of colours and currently ten Kromatix colours are commercially available. In Kromatix technology, the outer surface of the glass can be textured to reduce glare and improve aesthetics. As for the MorphoColor concept, no pigment or dyes are used in Kromatix technology, thus avoiding significant performance losses. Swissinso claims performance losses between 2 % and 8 % depending on the colour chosen [49]. Fig. 9 showcases two BIPV examples with Kromatix technology.

Solaxess 1st generation of white colour foil is also based on an interferential multilayer structure designed to highly reflect visible light while maximizing infra-red transmittance [51]. To avoid a mirror-like appearance, the interferential multilayer can be either corrugated or a diffusing layer can be coated over it [52]. The foil is laminated in the front of standard PV panels to produce a white appearance. The aesthetics-performance trade-off can be optimized by playing with the interferential multilayer design in two distinct ways:

1) The interferential multilayer can be tuned to control the wavelength that separates the high from low reflectance regions. This wavelength is generally set close to 800 nm. Moving this wavelength closer towards the visible decreases performance losses but increases colour angular dependencies.
2) The interferential multilayer can be designed to transmit a higher amount of visible light what will reduce performance losses but also the whiteness of the module. Generally, around 30 % of visible light will pass through the interferential multilayer arriving to the active cells of the panel. This amount of visible light is claimed to maximize efficiency while keeping details of the panel invisible to observers [53].

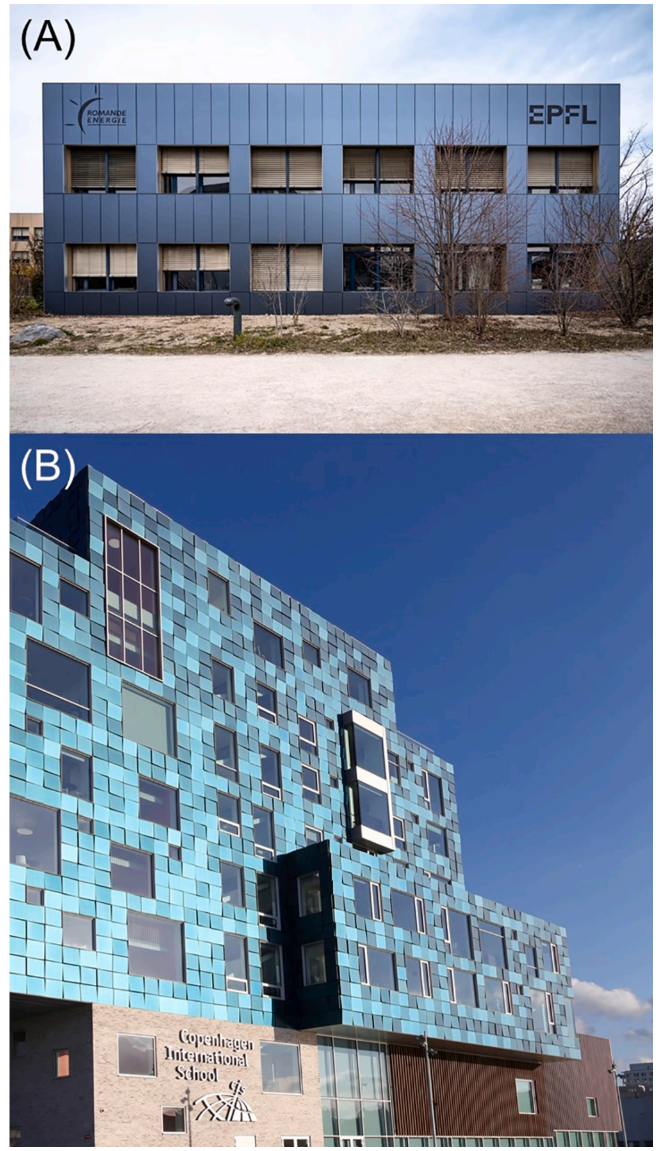


**Fig. 9.** (A) First building equipped with Kromatix technology at EPFL main campus. (B) Iconic BIPV building of the Copenhagen International School with blue green Kromatix glass. Images courtesy of Kromatix™ SA [50]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

In this technology, like for the Kromatix or the MorphoColor concepts, no light is absorbed to produce colour. However, due to the nature of the white colour (i.e., a superposition of light with different wavelengths), larger amounts of visible light need to be reflected resulting in performance losses close to 48 %. This value is estimated for collimated normal incident light. When measuring in non-collimated LEDs based sun simulators, losses are reduced to 41 %. Performance losses are highly dependent on the incident angle of light.

Currently, this Solaxess technology is the best suited to produce high luminosity white colours with the lowest performance losses [54].

Modules with metallic appearances can also be achieved using Solaxess technology by tuning either the corrugation of the interferential multilayer or the over-coated diffuser layer. Other colours than white are also possible by adding an extra-coloured layer on top.

Noticeably for interference filters directly deposited on glass, the same challenges of glass handling, shipping, and small volumes costs, will appear as for DCP.

### 2.5. Coloured cells

Solar cells are engineered for optimal light absorption, resulting in a distinctive dark blue or black appearance when observed. Both monocrystalline and polycrystalline silicon solar cells are equipped with a top-layer anti-reflective coating, usually composed of silicon–nitride (SiN), strategically employed to enhance overall efficiency. Notably, the colour of the cell can be adjusted by varying the thickness of this coating. However, this customization comes at a trade-off; the heightened reflectivity leads to an efficiency decline ranging between 15–30 %, dependent on the chosen colour. While these custom-coloured cells are commercially available from manufacturers, their relatively high prices, driven by limited demand, obstruct a broader adoption of this solution. As an example, Lofsolar is a company that offers both monocrystalline and polycrystalline silicon-coloured solar cells [55]. Colours like golden brown, steel, red, forest green, lavender or terracotta appear on their product portfolio. It is also possible to acquire modules assembled with their coloured cells.

Another possibility is to modify the colour of standard commercial solar cells after its fabrication. For that purpose, an option is to apply on top of the cell a photonic glass coating, using monodispersed dielectric microspheres with a diameter of 0.2, 0.25 or 0.3 µm with a high refractive index such as zinc sulfide (ZnS) [56]. The colour is generated due to a selective reflection of visible light after interacting with the photonic glass. This self-assembled structure is not purely periodic what results in less saturated colours than the ones obtained from purely periodic structures (photonic crystal). As colour is produced by light scattering, the reflectivity is better tuned as compared to pigment therefore performance losses are expected to be lower [56]. Losses will depend on colour and its brightness, but in general they will be lower than 15 %. In this technology, the colour is controlled by the diameter of the microspheres. Increasing diameter, the colour will shift from blue to red tones. Brightness of the colour will increase with the thickness of the structure, but the colour will be less saturated. Another advantage is the low-cost deposition process that is flexible, can be scaled up, and allows to deposit both homogeneously and forming coloured patterns.

Plasmonic colouring is another option to change the visual aspect of solar cells after its fabrication. The interaction of light with metal nanoparticles is wavelength dependent. Colour is produced by an increased scattering of light with wavelengths close to the plasmonic resonance frequency of the metal nanoparticles. In the work of G. Peharz et al. [57], silver-based nanoparticles with diameters comprised between 50 to 150 nm were generated on top of silicon solar cells. The nanoparticles were formed by annealing at 300 °C a thin layer of silver previously deposited by sputtering. The resulting silver nanoparticles have a plasmonic resonance frequency at around 500 nm, what gives cells a green colour. The colour produced is insensitive to the angle of observation and performance losses are around 10 %. The authors suggest using gold instead of silver to achieve reddish colours, while smaller particles would shift colour towards blue. In their view, alternative process to generate the nanoparticles should be investigated to increase versatility and reduce the cost of applying this technique.

Yet another possibility is active material-intrinsic colouring, which is possible when working with organic PV cells (OPV) [58], Perovskite [59], and dye-sensitized solar cells (DSSC) [60]. When using these materials, it is possible to vary colour and transparency. However, the common downside for all these technologies is a lower efficiency relative to crystalline silicon modules and shorter lifetime.

ASCA is a manufacturer of coloured OPV modules [61]. The company prints organic materials on flexible PET foils, and currently offers four different colours: blue, green, red, and grey. Translucency allows to combine the modules with other coloured materials to achieve a large colour palette. The technology allows for flexible and lightweight (<500 g/m2) modules that are also recommended for indoor applications.

### 2.6. Luminescent solar Concentrator PV

Luminescent Solar Concentrator (LSC) are composed by a transparent or semi-transparent window that absorbs, reemits, and concentrates the incident light. This is possible due to the inclusion of particles of luminescent material embedded in a transparent host matrix (polymer or glass) with a high refractive index acting as an optical waveguide for the light due to total internal reflection in the material [62]. The "window" is then coupled with solar cells that are placed on its edges and collect the remitted light guided through the waveguide. LSCs is a promising technology for BIPV due to the tunability of their colour and translucency. For instance, Glass2Power and ClearVuePV offer transparent windows (see Fig. 10), as well as coloured artistic displays and advertising panels with self-powered lighting for the latter [63,64]. ENI is also developing coloured LSC using fluorescent colour dyes [65]. For BIPV purposes, the host matrix is sandwiched between two layers of glass. The internal glass is coated with a spectrally selective low-emissivity thin film at the interface with the matrix to transmit only the visible part of the solar radiation spectrum and reflect the UV and IR back into the matrix layer. Through the photoluminescence process, the luminophores convert and re-emit the high-energy photons at longer wavelengths (UV-downshifting). The conversion efficiency is between 1 and 7 % depending on the surface, luminescent material and the PV cell

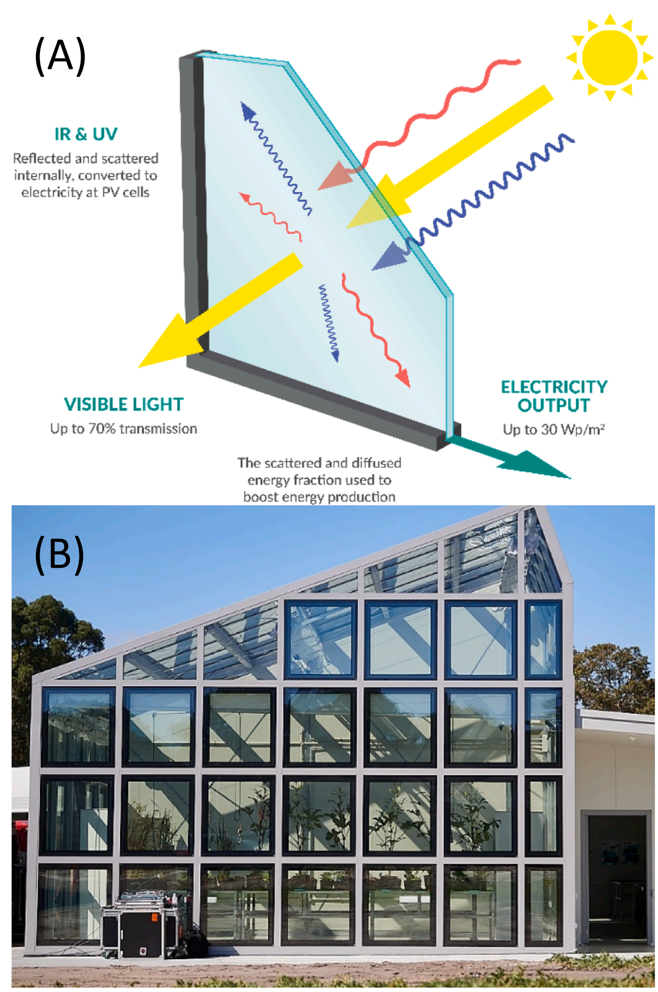


**Fig. 10.** ClearVuePV LSC transparent window. (A) Explanatory schematic and (B) Murdoch University Greenhouse with ClearVuePV windows. Images courtesy of ClearVuePV [71].

technology used [66]. The principle of luminescent downshifting has also been applied as a coating on the cell or the glass in standard PV modules to enhance their solar conversion efficiency [67,68] as well as for encapsulants by Singh et al. [69], wherein increase in efficiency by 6.8 to 9 % has been reported. Although LSC have been researched for multiple decades, their application for IPV is only emerging. This technology belongs to a niche market for now, and is limited by the lack of standards for performance and degradation evaluation [70].

### 2.7. Post-manufacturing colouring

Visual aspect of standard solar panels can also be modified after their fabrication by applying on top a coloured coating or foil. A commercial example is SolarSkin (see Fig. 11), a product commercialized by the company Sistine Solar. SolarSkin is a printed foil that can be applied on top of existing solar modules.

This is also the approach of Compáz, a company that mix technology and art to produce artistic images on top of existing solar modules. Compáz foil consists of a high-resolution printing combined with a selective reflective background, that mainly reflects visible light, and it is necessary to perceive the colour of the printing in reflection. Performance losses are reduced by using inks transparent in the infrared.

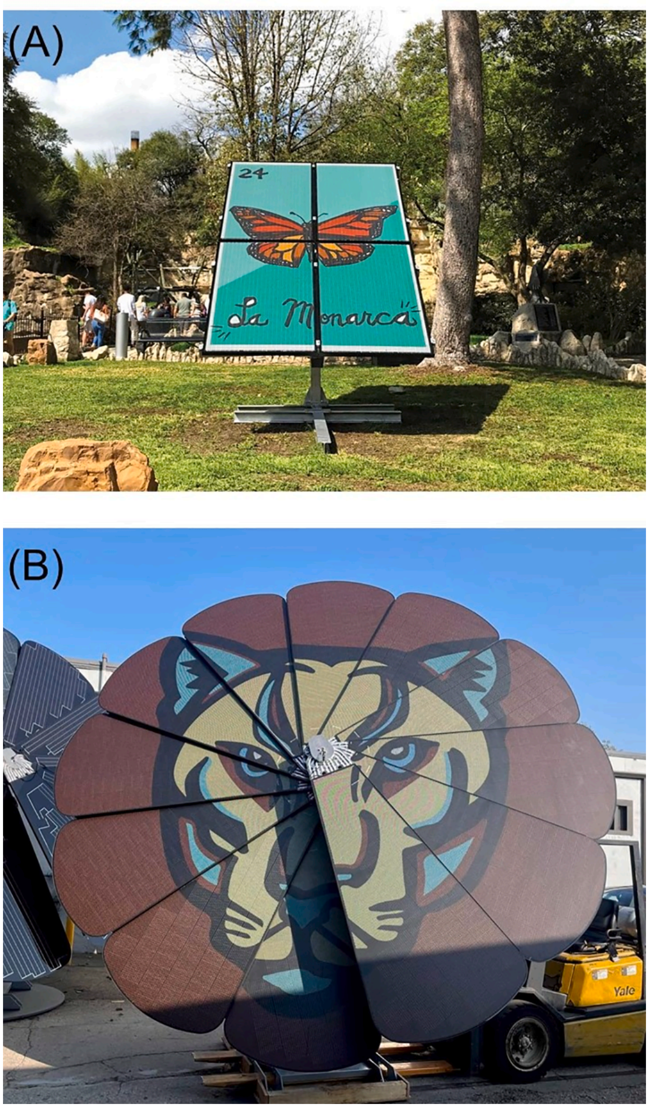


**Fig. 11.** Sistine Solar projects. (A) La Monarch mural and (B) Solar flower at Southeast New Mexico College. Images provided by Sistine Solar [72].

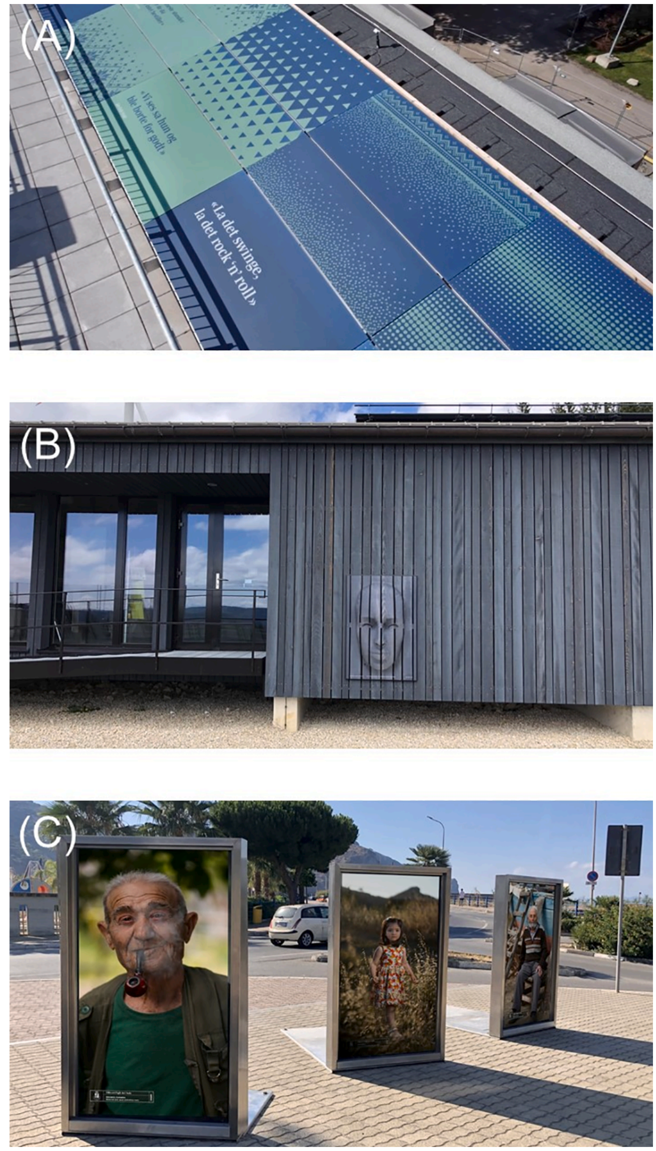


**Fig. 12.** Examples of realizations using coloured PV modules by Compáz. Images courtesy of Association Compáz [73].

Fig. 12 depicts some projects performed by Compáz.

Despite the fact that no information is available for these solutions, the lifetime of these latter products may be limited, since the foil is applied directly on the outer side of the glass front cover and is not protected by environmental agents. On the other hand, potentially these foils may be removed easily and replaced with a similar foil or by a foil with a different pattern and/or colour, at a relatively moderate cost. This opens up the possibility to use solar PV panels as advertising boards in special settings or to change the visual appearance of a solar façade or installation, which is consequently not locked up for 20 to 30 years.

Lamination of coloured textiles on top of existing solar modules is another option that can be found in the literature to modify their visual appearance [74].

## 3. The price for aesthetics and performance

The decision-making process in selecting coloured BIPV solutions poses a challenge given the diverse range of possibilities and the inherent customization and project-specific nature of BIPV solutions. Table 1 gives an attempt at comparing the main colour solutions for BIPV by providing industrial examples —many of which having been

**Table 1**
Summary of some of the current BIPV coloured solutions available on the market, regrouped according to the colouring technology. The information from some manufacturers is not (or only partly) available. The content of the table is purely indicative, with numbers either sourced directly from the manufacturers, or found in literature, but often missing entirely. The review of companies may be incomplete.

| Colour technology | Company | Power density | Losses | Source |
|---|---|---|---|---|
| **Coloured glass** | **Glas Trösch** | – | **Power losses:** ≤ 25% for all colours (print opacity varies depending on the colour: more opaque for brighter colours compared to darker ones)<br>White: 45% | [77,78] |
| | **3S Swiss Solar Solution** | – | **Power losses** (for module size L: 40 cells, 1300 x 875 x 6,5 mm): 10 colours, with losses ranging from 11% (Gray gneiss) to 28% (white-grey / Green). | [79,80] |
| | **Sunage** | • **Tiles:** 157.5 $W_p/m^2$ (e.g., Terracotta), 180 $W_p/m^2$ (e.g., Black)<br>• **Facade**: 120 $W_p/m^2$ (e.g., Grey) – 149 $W_p/m^2$ (e.g., Greens)<br>*(Information based on specific projects)* | **Power losses:**<br>• Dark range: 11%<br>• Middle range: 18% | [81–84] |
| | **Kameleon Solar** *(ColarBlast)* | 80 – 150 $W_p/m^2$ (depending on colour, coverage, and available cell space) | **Efficiency losses:**<br>• ColorBlast:<br>o Darker range: 10% – 15%<br>o Mid-range colours: 20% – 30%<br>o Brighter range: up to 40% – 50%<br>• Metalliq: 10% – 18%<br>• Royal Glam: 10% – 25%<br>• Mystica: 10% – 25% | [85–88] |
| | **Onyx solar** *(c-Si – Hidden PV)* | From 70 $W_p/m^2$ to 150 $W_p/m^2$<br>Available in 17 colours with different power densities | – | [89] |
| **Coloured encapsulant** | **Freesuns** | Up to:<br>• 97 $W_p/m^2$ (Solaris Vdiamond Terracotta: earth tone colours - terracotta, brown, red)<br>• 138 $W_p/m^2$ (Solaris Heritage: matt grey with no visible lines)<br>• 144 $W_p/m^2$ (Solaris Premium Black: glossy black with no visible lines)<br>150 $W_p/m^2$ (Solaris Classic: glossy black with visible silver lines) | - | [37,75,76] |
| | **Solaxess / 3S Swiss Solar Solution** | From 110 $W_p/m^2$ to 180 $W_p/m^2$, depending on the colour.<br><br>White = 114 $W_p/m^2$ (conventional module: 191 $W_p/m^2$) | **Power losses:**<br>• 14 colours: from 10% (e.g., Dark Grey) to 45% (e.g., White)<br>• 3S modules film nano (8/14 colour foil):<br>o 40 – 45% White<br>o 32% Beige<br>o 10% (e.g., Dark grey) – 25% (e.g., Light grey) | [90–92] |
| | **Advanced Solar Power** | Example of the ASP-LAM2 (L1200*W600*D7.0mm) modules, for various transparency level (40%, 20%, 10%):<br>• ASP-LAM2-T40-57: 79.17 $W_p/m^2$<br>• ASP-LAM2-T20-76: 105.55 $W_p/m^2$<br>• ASP-LAM2-T10-85: 118.06 $W_p/m^2$ | – | [93–95] |
| **Interferential coatings** | **Merck and Ceramic Colors Wolbring** *(Colorquant)* | – | **Efficiency losses:** ≤ 20% (depends on the colour of the module and chosen glass) | [34] |
| | **Megasol** *(MorphoColor)* | ≥ 90%, compared to an uncoated module<br>Up to ≈ 94% of the efficiency of a conventional black module. | **Power losses Pmpp:**<br>• 3% (blue)<br>• 4% (green)<br>• 7.2% (red) | [96,47] |
| | **Kromatix / 3S Swiss Solar Solution** | 10 colours: from 148.9 $W_p/m^2$ (Gold) to 163.6 $W_p/m^2$ (Dark-grey) | **Power losses** compared to:<br>• Standard black module (visible ribbons) of 178 $W_p/m^2$: -8.09% (dark grey) – 16.35% (gold)<br>• Full black (invisible ribbons) of 172 $W_p/m^2$:-4.88% (dark grey) – 13.43% (gold) | [97–100] |
| **Coloured cells** | **LofSolar** | • C-Cell technology:<br>o ≥ 150 $W_p/m^2$ (technical datasheet: range 145 $W_p/m^2$ – 167 $W_p/m^2$)<br>o Example of 8 coloured cell in [X]: 150 $W_p/m^2$ – 178 $W_p/m^2$<br>• 6x6 BIPV module:<br>o 135W: 115 $W_p/m^{2s}$<br>o 130W: 111 $W_p/m^2$<br>o 125W: 107 $W_p/m^2$<br>o 120W: 103 $W_p/m^2$ | – | [101,102,54,103] |

(continued on next page)

**Table 1** (*continued*)

| Colour technology | Company | Power density | Losses | Source |
|---|---|---|---|---|
| **Amorphous Silicon** | **Onyx Solar** | Dependent on the transparency level:<br>• DARK (0%): 58 $W_p/m^2$<br>• M VISION (10%): 40 $W_p/m^2$<br>• L VISION (20%): 34 $W_p/m^2$<br>• XL VISION (30%): 28 $W_p/m^2$ | – | [104–106,89] |
| **OPV** | **ASCA** | 17.5 $W_p$ at STC for a 20-cell module with an active area of 0.519 $m^2$ → 34 – 38 $W_p/m^2$ | – | [107,108] |
| **Post-manufacturing colouring** | **Sistine Solar** *(Solarskin)* | – | **Efficiency losses:** 12% – 15% per panel | [109] |

mentioned in the previous section. The parameters involved in the present comparison are the power density ($W_p/m^2$) (which is directly linked with the power conversion efficiency) and the performance losses (%) —in either power density or efficiency— of the module compared to a conventional one. The indications on performances are always colour-dependent and case-specific for a given technology and industry. Even so, the content of many cells remains empty as the information is unknown at the time of writing. This is mostly due to the fact that BIPV solutions are highly customizable and project-dependent. Therefore, providing a general estimate on the performance of a given technology is not always possible. The same issue is encountered when attempting to give cost estimates.

Present day "typical" commercial PV module, of conventional architecture, mass-manufactured in China can cost around 30–40 €/$m^2$ on the wholesale market (for 20 % efficiency modules at a price of 0.15 €/$W_{p,}$ end 2023 prices). This prices, however, will easily be 2 to 3 times higher (or even higher) for the end customer for small-scale residential systems. Based on the current market price, the European average estimated cost-range for specialty BIPV products, including the colouring solution of choice, can vary from 100 to 400 €/$m^2$ and depends on parameters such as the product type, the size, the materials used (e.g., the glass thickness), and the relatively small manufacturing volumes of BIPV companies: in the range of 10–100 + MWp/y (compared to the volumes of manufacturers of mainstream products: ~10 + GWp/y) with e.g., several different products and colours. As most of the BIPV projects are customized, costs can vary greatly. Some products could cost less, but others, for instance super-bespoken products such as those integrated in iconic architectural/BIPV installation, may cost even up to 800 €/$m^2$. Most of these technologies are still serving a niche market and manufacturing volumes are low. With the expected increase of the BIPV market and suppliers scaling up their volumes (i.e., corresponding to PV manufacturing volumes of 100–1000 MW/y) the manufacturing cost of all the BIPV solutions will decrease in the next couple of years. The total cost of a BAPV residential rooftop system in Europe realised with mainstream Chinese products is estimated to be around 200–600 €/$m^2$. Calculating the price of a BIPV system, whether it is a rooftop or façade, is not as straightforward as it needs to offset the cost of the building elements being replaced by the BIPV ones. The additional material needed beside the module (e.g., hooks, profile, rain drainage, screws, etc.) cost around 10–20 % of the module price per sqm. Despite the higher price of BIPV modules compared to standard BAPV ones, they remain in range of classic cladding materials used by the building industry, with the additional benefit of solar panels being an active element (i.e., electricity generation) [47]. Depending on the standardization of size and colour, the price of the colour BIPV module can be strongly reduced compared to today's situation. Additionally, since the low manufacturing volumes of these niche technologies currently contribute to high costs, the anticipated increase in production and broader technology adoption in the coming years may result in cost reduction.

## 4. Reliability and stability of colouring solutions over time

The assessment of reliability and stability in coloured PV modules diverges from the conventional evaluation criteria applied to typical PV modules. While the primary parameter of concern for traditional PV modules revolves around power performance, with warranties stipulating performance loss over a given time span, coloured PV modules gives similar importance to an additional dimension – aesthetics. Beyond power output considerations, the visual appeal of coloured PV modules holds an important role, as any alteration in their appearance could lead to customer complaints.

Numerous considerations arise when dealing with coloured PV modules. The introduction of novel materials, such as coatings, coloured encapsulants, and inks, into PV modules for aesthetic modifications needs thorough testing to evaluate the stability and potential interactions of these materials with the other materials contained in the sandwich.

Presently, there is scarcity of well-documented, long-term installations of coloured PV, impeding a complete understanding and in-depth study of the possible outcomes associated with these innovative materials. Nonetheless, it is recognized that the design of coloured PV demands careful design, acknowledging the potential effects arising from alterations to the modules' visual appearance, which could involve colour changes induced by weather stressors or other degradation modes. For example, previous research has shown that some ultraviolet-curable inkjet inks may produce colour change and interactions with the encapsulant when laminated inside of PV modules after ultraviolet (UV) exposure [110]. Fig. 13 depicts the colour changes produced by an UV-curable inkjet ink.

Digital ceramic printing on glass allows to create coloured PV modules with a high level of design details, however it traditionally comes at the expense of reduced light transmittance, which ultimately also affects the module performance [111]. In addition, the printing of different colours onto the module front surface also leads to non-uniform shading of the series-interconnected solar cells. As a consequence, these colourful modules typically suffer from mismatch losses and are susceptible to developing hot-spots. In view of that, Saw et al. presented an innovative colourful PV module technology with mitigated mismatch losses and even completely avoids the risk of hot-spot formations [112]. By carefully selecting the spectrally matched colours and applying a repetition design across the entire front glass, all solar cells in the PV module receive the same, uniform optical irradiance. The innovative module design technology was demonstrated on colourful and patterned PV modules which are inspired by the Peranakan culture unique to Singapore and Malaysia, coined as "Peranakan PV" (see Fig. 14). The technology can also be further adapted to create other aesthetical PV modules with more complex designs such as portraits or landscape images [113]. A PCT application has been filed for this innovative solution with the Singapore Patent Registry [114]. This underscores the need for ongoing research to enhance the reliability and stability of coloured PV solutions as they continue to evolve in the solar energy landscape.

The Task 15 of the International Energy Agency Photovoltaic Power Systems (IEA PVPS) programme are providing great effort and useful documentation regarding coloured PV, BIPV in general, and guidelines of how to assess BIPV installations from a multidimensional perspective [115]. In fact, they have recently presented a cross-sectional analysis that considers visual performance indicators such as glare,

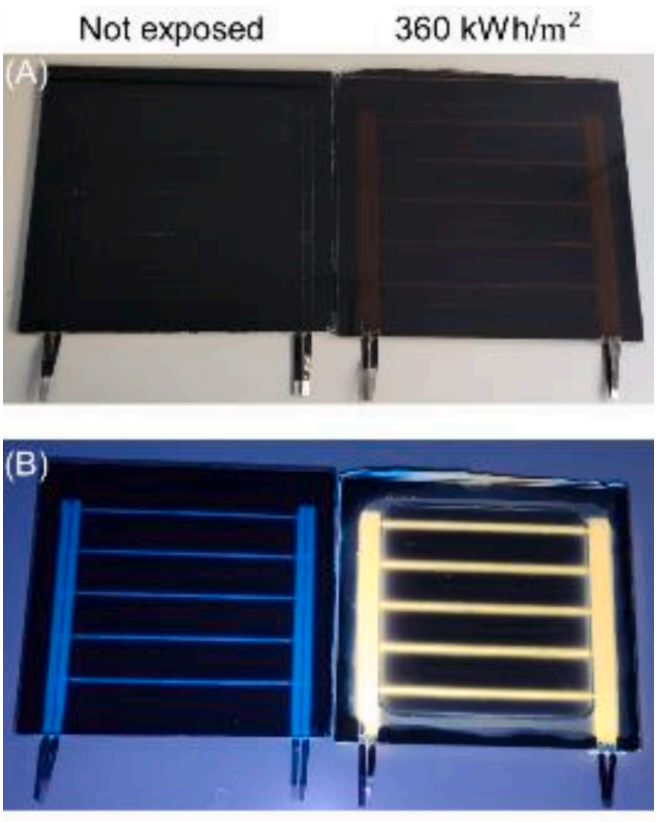


**Fig. 13.** One solar cell PV modules with coated metallic interconnects with an UV-curable inkjet ink. (A) The exposed sample appears fully black while the sample after 360 kWh/m2 of UV dose presents a colour change into brown. (B) UV-fluorescence imaging of the same samples under a 365 nm UV LED floodlight. The degraded sample produces larger noticeable fluorescence compared to the not exposed one.

**Fig. 14.** Examples of the "Peranakan PV" modules, designed and developed by Saw et al. [112]. Photo credit to SERIS, NUS.

recognisability, and colour [116]. The assessment is still qualitative, with a point score system, and relatively subjective to perform, but it is the first and important approach to assess visual appearance of BIPV installations. As of today, there are no standards to quantitatively assess colour changes over time in PV modules. Therefore, considering the relevance of aesthetics in this field, and the likelihood of visual modifications over time under weather stressors, it is important to discuss standards that seek how to assess accurately and quantitatively colour changes in PV modules.

## 5. Colour characterization for PV modules

Accurate and reproducible colour characterization is necessary all along the product chain, from colour design to manufacturing quality control and long-term colour stability assessment. The traditional colour-measuring instruments on the market (e.g., portable colorimeters) have a small-size port through which is performed spot-illumination and spot-measurement of the sample based on the reflectance value of the input light signal. However, such tools are not suited when the plane of interest –the coloured plane– is placed behind a transparent medium (i.e. glass) as the latter induces lateral displacement of the light [117]. This makes colour characterization very challenging for certain types of BIPV modules with the colouring technology located behind the front glass. The majority of the light gets displaced [117] in the glass beyond the spot-illumination area and therefore out of scope of the instrument's detection port. This leads to major losses in signal when performing spot-measurement of the reflectance at the incident location.

Using a spectrometer with an integrating sphere yields better results than a colorimeter due to the highly-Lambertian reflector coating on the internal wall of the cavity which allows for diffuse illumination and total reflectance measurements. Still, the losses remain significant and the main options explored to reduce the measurement artefacts are not suitable for PV application due to size constraints and overall impracticality (systematic manufacturing of tailored calibration reference according to the glazing type [118], placing the sample-holder inside the sphere [119], scaling-up the sphere [117,120]). An easier way to compensate the light displacement issue in the glass is to illuminate a large area around the measured spot, instead of relying on spot-illumination measurements. Thus, the light-trapping effect is isotropic and the outscattering losses in one spot are compensated by the inscattering gains of the light coming from around. This large-area illumination (LAI) method for optical measurement through glazing was first introduced by Krochmann [121] and implemented by Platzer [122,123] and Milburn [124,125].

With the recent uptake of BIPV, colour characterization tools based on reflectance spectra measured under LAI continue to be explored while other approaches based on photography are investigated [27,126] with the goal to achieve reliable colour characterization of modules. A recent study proposed an LAI setup to measure colour through glass with a change in colour perception CIE Delta E 2000 lower than 3.5 (threshold for an untrained observer [127]) when comparing the apparent colour of coloured foils laminated under glass covers of various thickness [128]. This type of system could be used to characterize colours in PV modules. Another possibility is to use digital imaging with controlled illumination, as shown by R. Schregle et al. [61].

Specific methods and standards should be implemented to perform accelerated colour stability testing for BIPV, including the definition of colour specific indices to characterize non-uniform discoloration (e.g., spots), such as the Yellowness Index [129] used in the case of encapsulant degradation.

## 6. Outlook and conclusions

BIPV will invariably play a huge role in achieving the goal of climate-resilient buildings, which is expected to become a new normal by 2030. To increase the acceptance of BIPV, especially with coloured PV modules, targeted enhancements in terms of reliability, safety, economics and environment should be considered.

The use of new materials such as encapsulants and coatings require meticulous testing. Ensuring the stability of PV modules is crucial not only to prevent colour changes or other forms of degradation but also to establish safety against fire hazards—a challenge currently being addressed by the community. To make the BIPV products safe against the fire hazard, various routes could be chosen such as, use of fire retardants in encapsulants, edge-sealants, efficient mounting of modules to stop the spread of fire from one module to the next, etc. could be tried.

Although the requirements of the building codes vary from local regions to countries to continents, it is generally found that the installation of PV modules for high-rise buildings has the most stringent requirements, which could be eased by choosing to install the modules only on structures of lower height.

Adding coloured PV in buildings may provide higher acceptance than the standard blue-cells-on-white-background building-applied PV (BAPV) devices, and fulfil construction requirements on one hand [7,130]. BAPV products such as black modules, which uses black backsheet, cells and frames are also attractive solution to increase the PV acceptance in the built environment. However, on the other hand, the addition of extra materials may impact the capital expenditure resulting on higher prices. Additionally, the variety of building geometries and need for customization could result on special mounting structured which would be also likely more expensive. Manufacturers of coloured PV have the challenge of carefully balance their costs to meet the customers' expectations of performance and visual appeal. The addition of new materials into PV modules need to be compatible with the standard processes of the production line to avoid costly extra steps.

Coloured PV would be installed in the built environment and, in many cases, at suboptimal orientations. This, coupled to the coloured layers on top of the solar cells, could result on an impact in the energy yield, consequently influencing both the return on investment and the carbon intensity of such products. Despite the potential reduction in energy yield, the overall environmental and economic advantages outweigh these challenges. This is primarily due to recent technological advancements and process optimizations achieved by the community (i. e., material usage optimization, decarbonisation of the grid, higher PV module efficiencies, etc.). Nevertheless, ongoing research and development efforts are essential to address power loss concerns associated with coloured PV.

## CRediT authorship contribution statement

**Alejandro Borja Block:** Writing – review & editing, Writing – original draft. **Jordi Escarre Palou:** Writing – review & editing, Writing – original draft, Conceptualization. **Marie Courtant:** Writing – review & editing, Writing – original draft, Conceptualization. **Alessandro Virtuani:** Conceptualization, Writing – review & editing. **Gianluca Cattaneo:** Conceptualization, Writing – review & editing. **Maxime Roten:** Writing – review & editing. **Heng-Yu Li:** Writing – review & editing. **Matthieu Despeisse:** Conceptualization, Funding acquisition, Writing – review & editing. **Aïcha Hessler-Wyser:** Writing – review & editing, Conceptualization, Funding acquisition. **Umang Desai:** Writing – review & editing, Writing – original draft. **Antonin Faes:** Writing – review & editing, Funding acquisition, Conceptualization. **Christophe Ballif:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Data will be made available on request.

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