IEA-PVPS

COLOURED BIPV

Market, Research and Development

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Report IEA-PVPS T15-07: 2019

PVPS

PHOTOVOLTAIC POWER SYSTEMS PROGRAMME

INTERNATIONAL ENERGY AGENCY

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COLOURED BIPV

Market, Research and Development

IEA PVPS Task 15, Subtask E

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February 2019

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Contents

Foreword

The International Energy Agency (IEA), founded in November 1974, is an autonomous body within the framework of the Organization for Economic Co-operation and Development (OECD) which carries out a comprehensive programme of energy co-operation among its member countries.

The IEA Photovoltaic Power Systems Programme (PVPS) is one of the technological collaboration programmes (TCP's) on research and development within the International Energy Agency (IEA). IEA PVPS has been established in 1993, and participants in the programme have been conducting a variety of joint projects regarding applications of photovoltaic (PV) conversion of solar energy into electricity.

The mission of the PVPS is "…to enhance the international collaboration efforts which accelerate the development and deployment of photovoltaic solar energy as a significant and sustainable renewable energy option…". The underlying assumption is that the market for PV systems is gradually expanding from the niche-markets of remote applications and consumer products to rapidly growing ones for building-integrated and centralised PV generation systems.

Building-Integrated PV (BIPV) is seen as one of the five major tracks for large market penetration of PV, besides price decrease, efficiency improvement, lifespan and electricity storage. The IEA PVPS Task 15 focuses on the international collaboration to create an enabling framework to accelerate the penetration of BIPV products in the global market of renewables. Its aim is to create an equal playing field for BIPV products, BAPV products and regular building envelope components that careful consider mandatory requirements, aesthetics, reliability and financial aspects. To reach this objective, an approach based on 6 key developments has been established, focussed on growth from prototypes to large-scale producible and applicable products. The key developments comprise of dissemination, business modelling, regulatory issues, environmental aspects and demonstration sites.

This Task contributes to the ambition of realizing zero energy buildings and built environments. The scope of this Task covers new and existing buildings, different PV technologies, different applications, as well as scale difference from 1-family dwellings to large-scale BIPV application in offices and utility buildings.

The current members of IEA PVPS Task 15 include: Austria, Belgium, Canada, Denmark, France, Germany, Italy, Japan, Korea, Norway, The Netherlands, Spain, Sweden and Switzerland.

This report concentrates on the possibilities to aesthetically tailor BIPV elements by introducing colour in order to allow for a better integration of PV into roof scenery or townscapes. The main authors of this document are Gabriele Eder, Pierluigi Bonomo and Helen Rose Wilson.

Further information on the activities and results of the Task can be found at www.iea-pvps.org.

Michiel Ritzen, operating agent IEA PVPS Task 15

February 2019

Acknowledgements

This paper received valuable contributions from several IEA-PVPS Task 15 members and other international experts. We want to acknowledge all participants of the IEA-PVPS Task 15 for their helpful inputs and reviews.

A contribution to section 4.1 of this document was given thanks to the work done by SUPSI within the activities of the PV-Enerate research project - Advanced PV Energy Rating 1 .

1 Executive Summary

In the building sector, net-zero energy performance targets and reduction of CO_2 emissions are the main drivers for building integrated photovoltaics. Recent market studies [10,18,19] show the history and perspective of the global market in the BIPV sector and calculate a global compound annual growth rate of ~ 40 % from 2009 up to 2020.

In Europe, the BIPV market is in a transition. The past decades of a slowly emerging BIPV market have been characterized by the original dominant value of BIPV: a building that communicates an image of sustainability and innovation. Payback time or "return on investment" have not been the major parameters in the decision process for applying BIPV. This is changing now. In most European countries, the new regulations on energy performance in buildings (derived from the European Energy Performance of Buildings Directive and the Directive on energy efficiency) have been translated in national regulations/laws, stating that all new (and freshly refurbished) buildings of the EU member states should be nearly zero energy buildings (nZEBs) by 2020. Thus, the time for the regulations to become mandatory is very near. It is expected that the energy performance regulations are now taking over as the main driving factor for the BIPV market and that should have huge consequences in removing the difference between a conventional building component and a BIPV component both in aesthetical and construction terms. This has led to intensified research and development aiming to create BIPV products that come in a variety of colours and sizes, while at the same time being as close as possible to existing building components, to its requirements and how it is considered by the construction industry.

The given market overview of state-of-the-art coloured BIPV products clearly reveals that for all parts of a BIPV module (glass, polymers, PV-active layers), there are technical solutions available for colouring. Pilot projects utilizing coloured BIPV products have been built in numerous (mainly European) cities clearly demonstrating the maturity of these solutions.

The key aspect that has been slowing down the progress of implementation of these aesthetically appealing and technically sophisticated new products into a wider market are the costs. In this respect, a lot of effort has been made to improve and optimize the relationship between colour and efficiency/power generation of BIPV elements. The results of the past and on-going innovative research and intensified fundamental considerations are also summarized in this report.

Besides the colour perception of the coloured BIPV elements under solar irradiation which is essential for the acceptance of the exterior appearance of a building, also transparency and inside visual comfort of BIPV – windows and façade elements are essential for the users and inhabitants.

2 Introduction

More than a third of worldwide final energy consumption is attributable to buildings, and reducing their final energy consumption has become a major challenge. Building-integrated solar energy systems could provide electricity and/or heat to buildings and to their local environment (using photovoltaics, solar thermal or hybrids of the two). Building-integrated Photovoltaics (BIPV) can theoretically produce electricity at attractive costs by assuming both the function of energy generators and of construction materials. This is of particular interest in the context of decarbonizing energy systems, especially in densely built environments where traditional ground-mounted photovoltaic (PV) systems cannot be easily used [1,2].

Technological advances in Building-Integrated Photovoltaics have converted the building envelope into a renewable energy-based generator. The challenge however, is that architectural design objectives sometimes conflict with energy performance, such as the provision of view and daylight versus maximum power output. In innovative cases, the characteristics of conventional BIPV façades have been modified in colour and appearance to address such conflicts leading to an on-going customization trend in BIPV façade design [3]. Although research and development in the field of BIPV are very multi-disciplinary and address issues such as mounting, safety and thermodynamics, the modification and optimization of the aesthetic appearance and colour of BIPV elements is attracting increasing interest [4]. As BIPV modules determine the aesthetics of the whole building, colouring plays an important role for the acceptance of BIPV applications. So far, the colouring of PV, namely its ability to be camouflaged or "designed", has been considered an essential requirement for market acceptance of PV façades. In many recent flagship projects, the photovoltaically active part of the building envelope is not recognizable. In BIPV glass façades, the conventional PV material language can be hidden behind coloured patterns that completely disguise the original materiality of the PV cells. [5].

In the following report, the market situation of BIPV in general and coloured BIPV in particular will be reviewed, including a chapter with a detailed market overview of coloured BIPV products (state-of-art products and "Best Practice Examples" of realized projects). The second part of the report focuses on the theoretical principles and the technological implementation of colour tuning BIPV modules.

3 Market situation of Building-integrated Photovoltaics: European and global overviews

The following chapter gives an overview of the European as well as the global market situation concerning BIPV in general and coloured BIPV specifically.

3.1 Development in Europe

In 2010, the European Council announced that the countries within the European Union (EU) would have to increase energy efficiency in order to decrease energy consumption by 20 % by 2020 [7]. The council referred to the "plan of action for energy efficiency: exploit the potential" and called for rapid and extensive realisation. Reflecting the large energy-saving potential of the building sector, it is intended that the member countries of the European Union should enable and urge architects and project planners to consider the use of renewable energy sources in the building sector. In 2017 [8], PV electricity was responsible for ~10 % of the total renewable energy production within the 28 member states of the European Union (EU28).

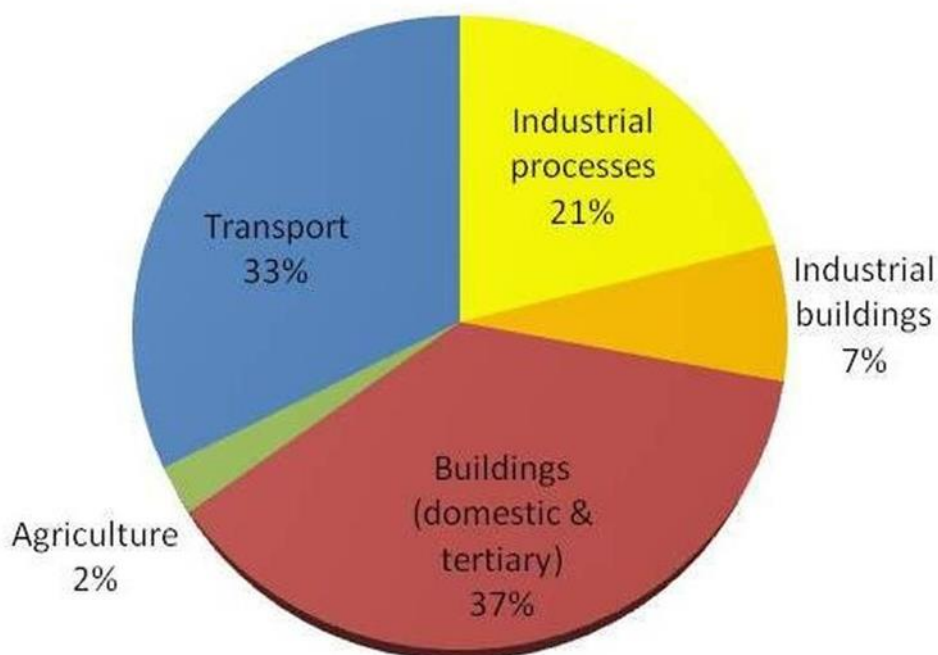*Figure 1: Share of total EU energy consumption (Energy World Magazine 02.2017, [9])*

The building sector is responsible for approximately 40 % of Europe's final energy consumption [9,10]. This share in energy consumption translates into about 20 EJ2 of energy consumed annually and therefore represents 36 % of Europe's carbon emissions (Global Industry Analysts, Inc., 2015 [10]).

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[2] EJ ≡ Exajoule ≡ 10^{18} Joule

To introduce countermeasures, to increase necessary energy saving and efficiency raisings and to reduce CO2 emissions according to the goals proclaimed by the European Council, it is important to create sustainable buildings and promote energy-relevant renovation of the building stock. To do so, buildings must be designed and constructed in a way that they do not need more energy over their entire lifetime than they can produce. Therefore, buildings must be transformed from energy consumers to energy producers. BIPV can contribute decisively toward reaching the goal of truly sustainable building design. In future households, electricity can be the only power source needed [11].
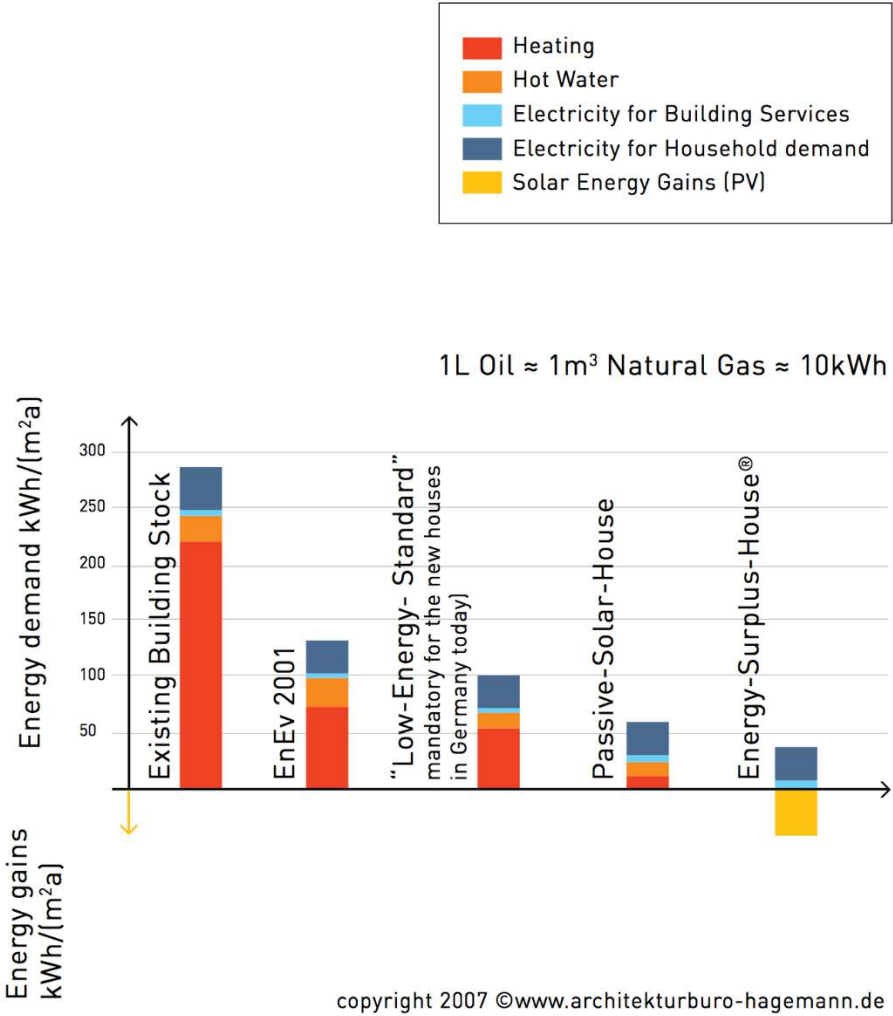
Figure 2: Energy demand in households (©Architekturbüro Hagemann [11]);

The BIPV market in Europe is estimated at 967 MW of installed capacity for the year 2015 and is projected to reach 4.8 GW by 2020, with a compound annual growth rate of about 40 % over the analysis period 2014 to 2020. Because of the lack of land area for large-scale PV plants and limited prospects for wind energy, BIPV is a promising alternative for energy supply to Europe (Global Industry Analysts, Inc., 2015 [10])

Attractive incentives and subsidies in France, Italy and Germany are the main reason why the growth of the BIPV market especially in these countries was the highest in Europe. These three countries alone made up 87 % of the market in 2014 in Europe. However, changes in the incentives and/or

boundary conditions by the national governments (see Figure 3) had a strong influence on the BIPV market in these countries as subsidized developments tend to be not financially viable when subsidies are removed [12].
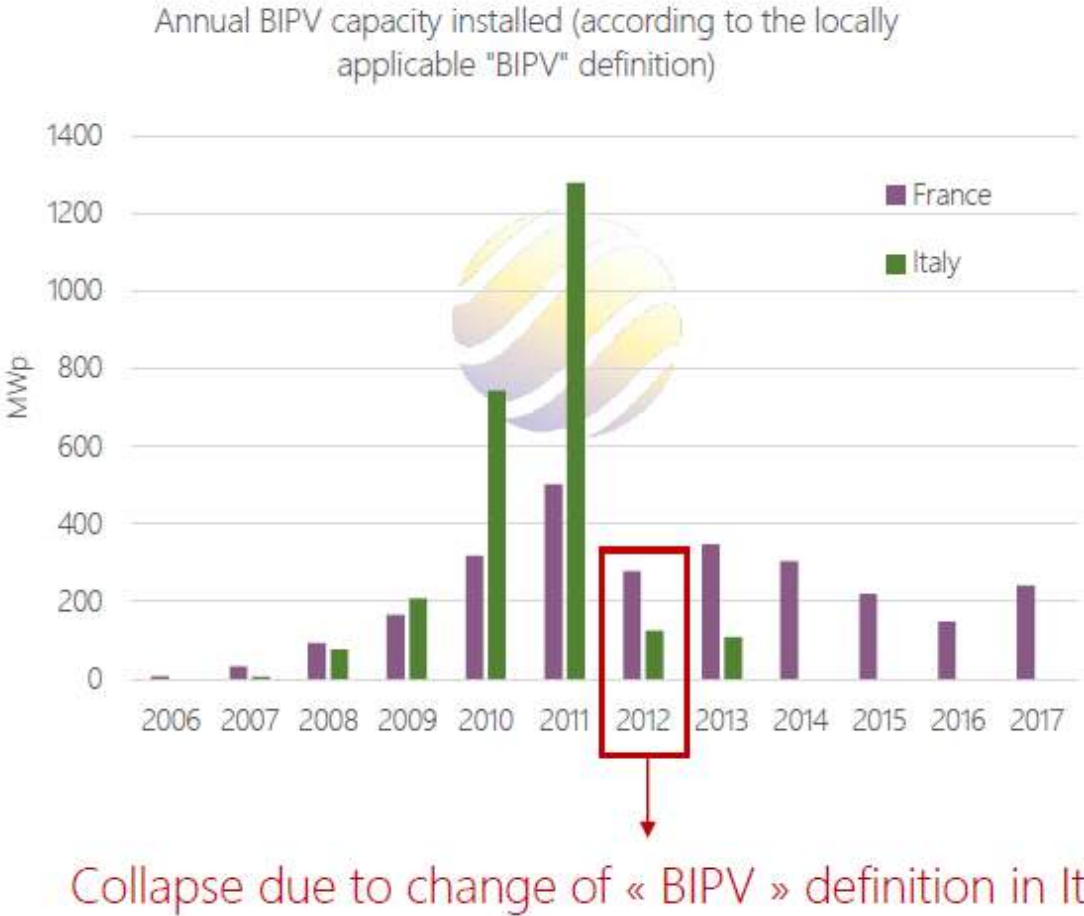
Figure 3: Development of annual BIPV capacity installed in France and Italy (Philippe Macé, Becquerel Institute 2018 [12]).

The BIPV market in Europe is in transition. The past decades of a slowly emerging BIPV market have been characterized by the original dominant value of BIPV: a building that communicates an image of sustainability and innovation. As BIPV is often more expensive than the straightforward application of a PV system on a roof (BAPV), the appropriate question is always: what is the value that justifies this additional cost? In past years, this value in most cases was: aesthetics. With this perspective, the building communicates a message that can be a message of sustainability, responsibility and even idealism. Payback time or "return on investment" have not been the major parameters in the decision process for applying BIPV. This is changing now. In most European countries, the new regulations on energy performance in buildings, derived from the European Energy Performance of Buildings Directive (EPBD) 2010/31/EU [13] and the Directive 2012/27/EU on energy efficiency [13] have been translated into national regulations/laws. The 2010 directive states that all new (and freshly refurbished) buildings of the EU member states should be nearly zero energy buildings (nZEBs) by 2020. Clearly, one possible solution to realize NZEBs is the generation of renewable electricity on-site, by means of (BI)PV [15]. This EPBD has been updated recently in the 2018/844/EU

[16] (amending [13] and [14]) in order to accelerate the process: "The new Directive has huge potential for efficiency gains in the EU building sector, the largest single energy consumer in Europe. "It includes measures that will accelerate the rate of building renovation towards more energy efficient systems and strengthen the energy performance of new buildings." (EC Europa news 2018 [17])

The time for the regulations to become mandatory is very near. It is expected that the energy performance regulations are now taking over as the main driving factor for the BIPV market and that this should have huge consequences. Instead of BIPV finding its value only in being visible and supporting a corporate image, the main value of BIPV products is now becoming invisibility. In other words, we no longer want to see the difference between a "conventional" building component and a BIPV component, both in terms of aesthetics and construction outcome.

Another dominant market factor in the new era is the fact that multi-storey buildings (such as high-rise buildings or blocks of residential units) simply do not have enough roof area to meet the energy performance requirements by using conventional PV modules. This leads the building designer naturally to the use of the façade for applying BIPV, which is a central part of the architectural concept.

This change in market drivers has led to intensified research and development aiming to create BIPV products that come in a variety of colours and sizes, while simultaneously the BIPV components ideally should be manufactured as similarly as possible to existing building components, and suit their requirements and working practices in the construction industry [5].

3.2 Global development

The need to increase energy efficiency in the building sector and to reduce CO2 emissions are main drivers for BIPV. Recent market studies ("BIPV - Market Analysis, Trends and Forecasts", 2015 [10] and 2018 [18], by the Global Industry Analysts, Inc. and "BIPV Technologies and Markets 2017-2024", 2017, by n-tech [19]) show the history and perspective of the global market in the BIPV sector. The global compound annual growth rate (CAGR) was 43 % from 2009 to 2013. The Global Industry Analysts' Projections from 2016 up to 2020 estimate a CAGR of ~40 % [18]. A perspective for the upcoming years is shown in Figure 4; also n-tech came to a comparable prediction that the market will rise by 40 %/year within the next decade [1,19]. In the outlook, Ballif [1] stated that "Amid constant technological developments and increases in the BIPV product range, BIPV project processes need to follow integrated design approaches for new construction and building retrofits. That is, the approach needs to consider the new technological possibilities, the positively evolving legal frame, the early stage information and coordination of all stakeholders, as well as strategies to increase volume and make products more popular. Indeed, recent research has granted a significant number of new assets to BIPV in terms of architectural integration, including amazing possibilities to play with colour or size, which should enable BIPV to expand beyond its current perceived status of technical constraint for architects and to become a true raw material that can be taken into account from the early stages of a project's process".
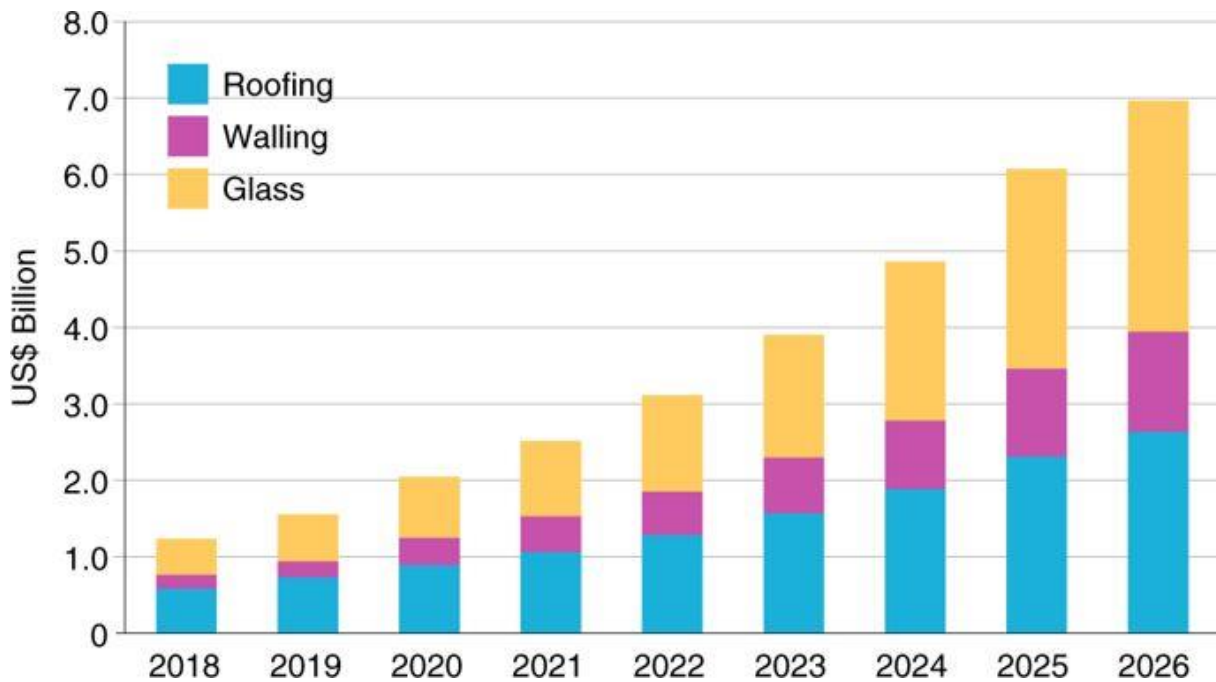
Figure 4: Global BIPV market perspective (2018 – 2026); from: Integrated thinking for photovoltaics in buildings, (Ballif et al (2018)[1]).

US, Asia-Pacific and Europe are expected to be the leading regions for a growing BIPV market. The percentage share of the global BIPV market is estimated to be 44 % in Europe, 28 % in Asia-Pacific and 16 % in the US in 2020 [10].

3.3   Building integration

For new buildings that have to meet nearly zero energy building standards, the use of the surrounding environment to harvest energy is of utmost importance, whereas solar energy is one of the most obvious sources. Building-integrated photovoltaics represent an opportunity to implement multi-functional elements efficiently into a buildings skin with respect to aesthetic, economic and technical solutions. BIPV units can replace parts of conventional building materials and components such as roofs and façades [22,20]. Generally, the BIPV market can be divided into three main categories:

- Façade: walls and windows

- Roofing: roof-integrated PV

- Others: shading, balcony railing, etc.

Architectural implementation in walls and windows will play a major role in the future of BIPV. This means that technological improvement and research has to be conducted in this field, especially for new, emerging technologies [10,18].

Based on possible applications, BIPV products for roofs can be classified into products for pitched roofs and flat & curved roofs [5]. For pitched roofs, mostly mounted systems (in roof mounting), full

roof solutions, solar tiles or shingles [21] are applied. Lightweight, self-bearing systems and prefabricated systems are often the solution for flat or curved roofs. In the façade of the building envelope, BIPV often replaces opaque façade elements (e.g. façade cladding or curtain walls) or transparent solar glazing or windows (thermally insulated façade). Furthermore, BIPV is used as elements in overhead atrium covers, skylights, shading structures and solar-shading devices.
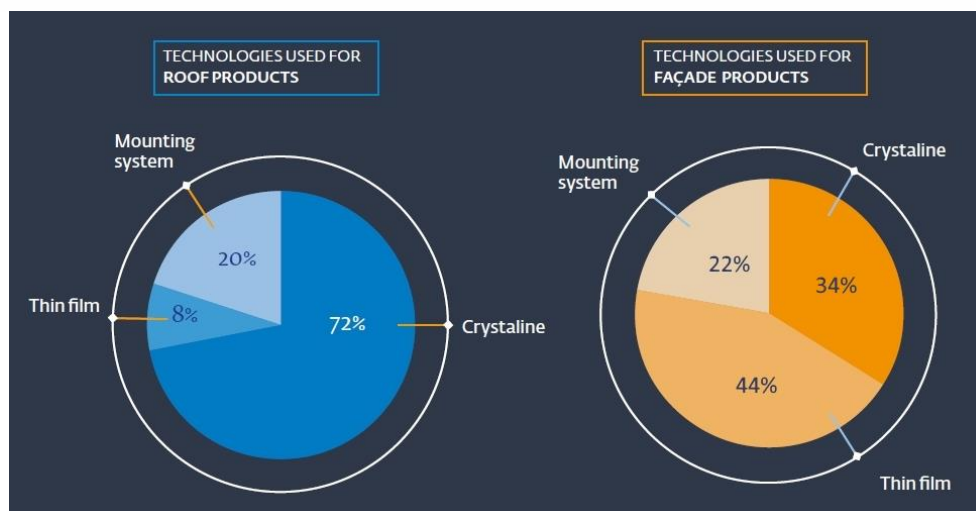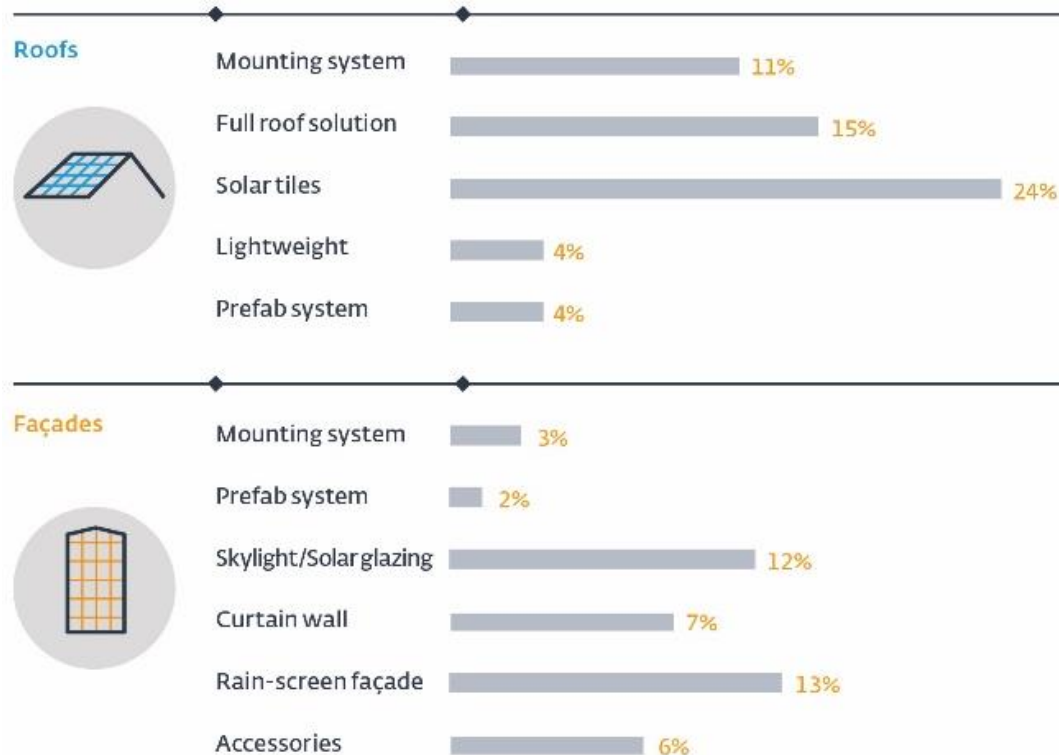
Figure 5: top: results of the market survey presented in terms of the occurrence of product groups; Distribution of BIPV products according to different categories; bottom: pie charts of the technology used in the roof (top) and façade (bottom) BIPV application areas (P. Bonomo 2017 [6])

The most common product group is that of solar tiles (any size), immediately followed by the full roof solution [6]. In 2015, this trend was already visible although full roof systems were slightly more common than solar tiles. Products for rain-screen façades, where the photovoltaic module is used as

building cladding, and skylight/solar glazing follow with a significantly lower percentage. Products for roofs are much more numerous than those for façades, indicating that the roof market is currently wider than the façade market. It should be noted that products described as solar glazing for roofs are generally marketed also with a curtain wall variant. 8% of the BIPV products for roofs and 44% of the BIPV products for façades use thin-film technology.

Summarizing the considerations obtained through a price survey made by SUPSI (Switzerland) and SEAC (The Netherlands), it emerges that standardized prices per square meter exist neither in the construction nor in BIPV industry. Also, suppliers are generally unwilling to share pricing information apart from very specific price quotations. Nonetheless, thanks to the participation of approximately 35 companies, we can conclude that BIPV is affordable and that the extra costs compared to a wide range of conventional building materials, especially in the high-end spectrum, are limited and affordable.

Overall, the BIPV sector is in healthy shape. Many attractive products are available, reliable and offered at a competitive price. Good examples of aesthetically pleasing and affordable BIPV buildings can be found increasingly in the ordinary building stock. Normative approaches for product qualification are improving as well. It is time for the demand side to catch up and allow the suppliers of BIPV products to expand their market and realize economies of scale [6,5].

3.4   Coloured BIPV

The preceding sections describe the general BIPV market developments. In the next chapter, the focus will turn to coloured BIPV modules which are predicted to have a potential market in solar integration in sensitive urban areas or within protected heritage buildings. Coloured BIPV elements are better suited to increase the acceptance of solar solutions in the energy renovation of old existing buildings within complex urban settlements [24,25]. Coloured BIPV solutions could be adapted to the variety of materials, colours and shapes that can be seen today in the centre of cities, where a diversity of buildings from different eras and construction solutions coexist with each other [26, e.g. LED use with PV to colour façades at night 23].

In 2001, these issues were investigated in depth under the European PV ACCEPT (2001-2004) project [25], which highlighted that innovative design of solar modules would enable new possibilities for integration into old buildings, historical sites, the urban space and landscapes. In the results of the project, the importance of an aesthetic and creative module design to increase social acceptance was stressed, but also the financial and technological feasibility of the solutions [25]. The project succeeded in developing photovoltaic modules with innovative features concerning formats, colours and surfaces (e.g. matt and structured surfaces or covered with regular or irregular patterns), anticipating the solutions that are now market-available. The solutions were installed in different buildings, some of them historical, as well as in landscapes, proving that modern technological elements are not necessarily in contradiction to heritage preservation.

Also in the Austrian Projects, PV@graz [26] and PV@facade [27], BIPV elements with coloured glass surfaces (coated and printed) were developed to allow integration of photovoltaics into heritage roofing landscapes of old cities. Improving energy efficiency by using solar systems in heritage buildings is not a new topic [24] but it has recently gained more attention within the international research community (e.g. the recent IEA SHC Task 59 activities [28]) and the activities of EPFL [29].

The focus is on finding conservation-compatible energy retrofit for existing buildings which allow historic and aesthetic values to be preserved, while also considering solar system integration.

Generally speaking, coloured BIPV can be applied in all the segments mentioned in chapter 3.3, namely façade, roofing, as well as shading, balcony glazing, etc. However, one can draw a most likely path of steps for market adoption of coloured BIPV. These steps are:

1. Coloured BIPV façades for representative office and/or public buildings. Most often, unique products are required on a project-to-project basis (depending on typology and construction). No particular price pressure.

2. Coloured BIPV façades for residential high-rise buildings. For this application, preferably standardized products are required in various colours, with a preference for white/greyish colours. Medium price pressure.

3. Coloured BIPV roofs for residential low-rise buildings. The aim is to "hide" the PV functionality and thus terracotta colour and other "roof colours" are preferred. Strong price pressure.

A number of arguments point toward high-rise buildings (mostly office or prestigious public buildings) as the number-one target market for coloured BIPV.

Figure 6: Black BIPV façade with laminated glass on a public building (children's day-care centre in Marburg); project realized by ertex-solar (www.ertex-solar.at/produkte/referenzen) Opus Architekten © Eibe Sönnecken

Figure 7: Technical University of Vienna, public high-rise building with BIPV façade; Plus-energy building (Photo ©Schöberl & Pöll GmbH, www.schoeberlpoell.at/en/projects/plus-energy-buildings).

First of all, there is a strong trend toward energy-neutral offices. Building rating methodologies such as BREEAM and LEED promote the use of PV on office buildings. In particular, the nZEB (nearly Zero Energy Building) regulations are being applied from 2018 onwards for public office buildings in many European countries (EPBD, 2018/844/EU [16]. For most office buildings, rooftop PV alone is not enough to achieve nZEB, as the energy demand of offices is simply too high, the roof space is too small, and parts of the roof are already occupied for other purposes such as technical installations and increasingly also for vegetation. This forces a large part of the required PV installation onto the façade. The façade is the part of the building envelope which has a high architectural value, can be used actively for communication purposes and gives the building a distinctive appearance, attractiveness and image. Coloured and textured PV in many different forms will give each building a unique appearance and design, and thus improve the satisfaction level of stakeholders such as residents, tenants and end users [30].

The arguments described above lead to high potential for coloured BIPV in high-rise (representative office and/or public) buildings, starting at the high-end segment and slowly evolving to the lower-end offices.

For residential high-rise buildings, similar arguments apply. Also here, the nearly Zero Energy Building requirements are rapidly coming into force (by 2020) and the roof alone is not large enough to supply the required renewable energy. This market will become established after the office market, differing from it as tighter requirements on price pressure and available budget exist. It is expected that once coloured BIPV façades have established themselves in the office market, more standardized products will be available and the prices will have dropped somewhat, allowing the residential high-rise market to take up. The largest market demand is expected to follow

conventional material choice for white and grey modules, but BIPV products in all available colours and appearances will find their way into façade applications.

Furthermore, also an application of coloured BIPV products in the market for residential roofs has to be considered. A certain fraction of houses is perfectly suited for an all-black roof, for which a coloured panel has little added value. However, there are large regions of Europe and the world where houses are equipped with terracotta roofs. Red or terracotta coloured PV panels will fit perfectly to this type of house and the market for this application will start once the price levels become competitive [30].

4   Market Overview of coloured BIPV Products

The process of integrating photovoltaics into buildings ranges between novel installations and traditional systems implemented as elements of existing buildings. In architecture, the replacement of an existing material by a new one is usually accompanied by the permanence of tradition with regard to both architectural languages and technical systems. This slow process of innovation is linked to both new technology and new design models which can be related to morphological aspects, building envelope image or construction.

Regarding the building envelope, for example, the physical flexibility and lightness of thin films permit PV to be incorporated into ultrathin and lightweight skins or membranes. Such innovative trends as new technologies (e.g. dye-sensitized solar cells - DSSC, organic PV) or special appearance treatments for glass are opening the scenario of a new language of photoactive technologies towards a coloured or "invisible" PV.

The technological transfer of PV to the architectural sector is changing building skin design approaches and opening new challenges. The industry makes plenty of products for building application available: multi-functionality, cost-effectiveness, mass customization and other paradigms are ensuring a growing penetration of the real market. Thus, along with functional and construction aspects, today BIPV is definitely one of the new fundamentals for contemporary innovation in architecture [6]. The use of a material in architecture, in the course of building history, has always been enriched with something other than simple technological innovation, including a symbolic spirit, expressing its own linguistic value, change and design power. In the common imagery, for example, glass is the material that can express a sense of constructive and perceptual lightness, which result in the physical dematerialization of the architectural object and perceptual and psychological transparency. When we hear about photovoltaics, however, the image that is invoked in our mind is a blue or black element that usually seems to "overload" the aesthetic image of a building. Even though a PV element has the fundamental role of generating energy from renewable sources, this is not the main aspect concerning the "innovation in architecture". The combination of glass and photovoltaics, despite their different appearance and materiality, seems to match well in terms of both aesthetics and functionality of the building envelope. Moreover, both in architecture and research perspectives, there are many products, flagship buildings, research projects and some emerging innovative trends that are drivers for successful transfer of BIPV glazing into the real built environment. Since many requirements have to be met for a high-quality architectural project which is also compliant with challenging energy standards, these "innovation trends" can be interpreted as the "meeting points" between different fields: architecture,

construction products, glass façades and energy. Coloured modules are an example for this innovation path [31].

4.1 Coloured BIPV modules: Overview of state-of-art products and realized projects

The increased attention to solar buildings has created an interest in the new role of BIPV façades as active elements of the building envelope. To allow architects new design opportunities for the aesthetic language of PV, researchers and module manufacturers are developing customized BIPV glass modules in terms of performance and appearance. For example, PV cells can be camouflaged behind coloured patterns that completely disguise the original materiality of the PV cells. However, this generally involves a "shadow" (or irradiance mismatch) over the PV cells and a consequent reduction of the energy production that needs to be carefully optimized in order to obtain energy-efficient customization of the BIPV modules and also to avoid reducing the reliability and durability of the BIPV modules. The challenge to optimally balance the aesthetic quality with the energy and electrical efficiency, reliability and safety is one of the drivers of innovation today. Different customization techniques can be identified in the current developments to obtain coloured or textured BIPV modules [31] and will be described in detail in the following sections (including best-practice examples).

(a) Anti-reflection coatings on solar cells

(b) Coloured and or semi-transparent PV-active layers

(c) Special solar filters as layers, coatings or interlayers with colours or patterns

(d) Coloured polymeric encapsulant films

(e) Modified front glass by printing, coating or alternative finishing

4.1.1 Products with coloured anti-reflective coatings on solar cells (c-Si)

As bare crystalline silicon (c-Si) presents high reflectance values (around 30 %), both monocrystalline and multicrystalline PV cells include antireflective (AR) coatings on their surfaces, having a coating thickness optimized to increase the efficiency conversion. The optimized AR coating gives the cells their typical blue colour, which can be better appreciated if the cell is not texturized (see Figure 8), as commonly occurs in multicrystalline PV cells (monocrystalline PV cells present a darker appearance because of their surface texturization). Variations on the AR coating thickness shift the blue to other colours, having an impact on the PV cell efficiency also. Solar cells with modified colour based on the anti-reflective coating can be purchased directly from the cell manufacturer. Colours such as blue, green, yellow, orange, and pink can be obtained by changing the coating thickness, leading to a shift in the reflection minimum to the near-infrared range, and boosting the reflection in the visible spectrum. As cell manufacturers, unfortunately, are typically incapable of producing small batches for specific customers at acceptable price levels, this solution is not very widespread today. A typical

example of achievable colours such as that offered by the company Iofsolar [32] is shown in Figure 9, a realized project using green coloured cells is illustrated in Figure 10.

Figure 8: Left: multicrystalline Si solar cell in its original colour; right: multicrystalline Si solar cell with modified thickness of AR COATING (on top of semiconducting material) from Solar Capture Technologies (www.solarcapturetechnologies.com).

Figure 9: Achievable colours of c-Si cells as offered by lofsolar (www.lofsolar.com)[32]

Figure 10: Building with BIPV façade with coloured c-Si cells (LOF), project Fondation Abbé Pierre in Paris (www.ertex-solar.at/produkte/referenzen);©ertex-solar

4.1.2 Products with coloured and/or semi-transparent PV-active layers (thin film, OPV)

Semi-transparency of PV layers can be obtained for example for amorphous silicon PV modules (a-Si) thanks to laser treatment of the active layer that is partially removed in order to increase the light transparency (see Figure 11). A possible application can be seen in fully glazed buildings where the available surface to implement BIPV is very large, so there is no need for high power solutions.

Figure 11: Semi-transparent coloured amorphous silicon BIPV modules used in the refurbishment of the buildings of the Terina Mediterranean Foundation in Calabria (Italy). (Source: www.onyxsolar.com/mediterranean-foundation-terina).

Different degrees of transparency can also be obtained with cadmium telluride (CdTe) technology (Figure 12, SolTech Energy). With these products, shading and power generation can be combined in one window or façade panel. For copper indium gallium selenide (CIGS) solar cells, Solibro Research has experimented with partial removal of the semiconductor layer by both water-jet polishing and dry sand-blasting by using screen printing as a mask; the latter approach was found to be better. A semi-transparency of 40% can be achieved while the PV module efficiency is reduced by 45-50% due to additional edge effects from the removal. The developed removal process with dry sand-blasting is versatile and can virtually produce any pattern as long as the semiconductor is connected such that current can pass through (Figure 13).

Figure 12: Semi-transparent CdTe modules used for shading and energy production in the façade (Source: www.soltechenergy.com)

Figure 13: CIGS solar cell with removed semiconductor material using dry sand-blasting achieving 40% transparency - this is not yet a certified product (Source: Neretnieks, P. Utveckling av semitransparenta solpaneler. in Solforum. 2017. Västerås, Sweden.)

Another opportunity is offered by PV modules based on organic PV cells (OPV) or dye-sensitized solar cells (DSSC) modules. Thanks to these new materials used to convert the solar light into electricity, it is possible to obtain modules in different colours and transparency.

The technology of dye-sensitized solar cells is often referred to as artificial photosynthesis, analogous to chlorophyll in leaves, where a sensitized dye absorbs light and generates excited electrons. These electrons are injected into and transported via the conduction band of a porous semiconductor with a large surface area. These cells are thin film devices that use a nano-crystalline carrier layer made of titanium dioxide (TiO_2), onto which a monolayer of light-absorbing dye molecules is chemically bonded. A small amount of gel electrolyte is used for the transport of the carriers (Figure 14). The technology, developed by EPFL (Prof M. Grätzel [32]), has matured after 20 years of development and different licenses distributed worldwide by EPFL. So far, the stability of DSSC has been hindered by poor polymer sealing. Recently, some industries have been able to develop an industrial process for improved, reliable glass sealing of DSSC [35].

Figure 14: H-glass (former G2E), coloured a-Si modules, charging station in Switzerland

In fact, third-generation technologies (i.e. organic solar cells OPV and emerging photovoltaic technologies based on dye-sensitized solar cells DSSCs, perovskite materials, etc.) and luminescent solar concentrators (LSCs) are still a niche market today. However, they can offer promising solutions for BIPV [33]. Their promise is to be less expensive and more easily integrated into the building context than traditional silicon solar cells. Until now they have remained at the stage of scientific research, with only some flagships projects effectively realized (see Figure 15 and Figure 16 for examples). Some points, such as their durability and stability over time, still remain open for future investigation [35, 37].

Figure 15: Example of leaf-integrated OPV modules, pioneering organic photovoltaic technology in the German pavilion, Schmidhuber Architects, Expo Milan 2015, Italy (left and centre:© Cristina Polo López). The OPV Solar Trees now stand in the redesigned entrance area of Merck KGaA in Darmstadt (right © Merck KGaA)
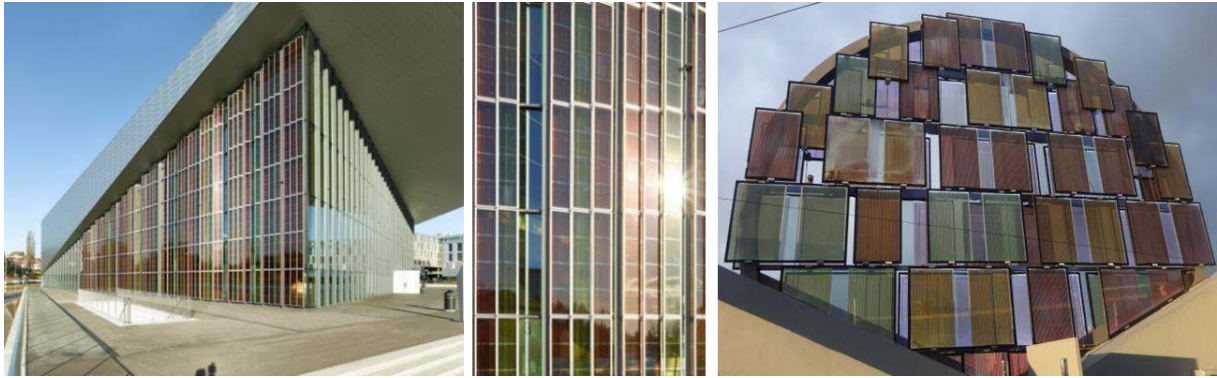
Figure 16: Example of DSSC technology: a) SwissTech convention centre at EPFL campus, Lausanne Switzerland (Source: BFE-SUPSI); b) Austrian pavilion Expo Milan 2015, Italy (©Francesco Frontini).

In the past two decades, the efficiency of dye-sensitized solar cells (DSSCs) has increased progressively (from ~7% to ~14%). At the same time, to become more competitive, various organic materials are being investigated to improve the cell efficiency, enhance the cell durability, and reduce the cost of production [38]. Despite the low efficiency compared to silicon solar cells, some studies have highlighted other advantages of organic dye-sensitized solar cells using natural pigments, such as a wide selection of coloured and transparent cells to improve aesthetics and the variability of design, as well as optical properties, such as their specific dependence of energy generation on the angle of incidence and the intensity of sunlight [39,40]. Other advantageous aspects are the easier and less expensive manufacturing process applying simple screen-printing, their lighter mass that allows them to be used over flexible systems with thin structures, as well as concepts for an environmentally sound product, such as a design and production process which facilitates recycling [41,42]. This potential for versatile applications, as flexible or light-weight products, with unique features when compared to other solar technologies make DSSCs suitable for multiple applications such as: solar-control fins and louvers, sun-shading canopies, as cladding for curtain wall façades and rear-ventilated façades, semi-transparent windows, sliding shutters or street furniture [42]. One example of new solutions based on ETFE membranes being used as solar energy façades is shown in Figure 17.

Figure 17: Energy-efficient ETFE-based membrane façade installed using printed Organic Photovoltaic OPVIUS Energizing Surfaces. Source: OPVIUS GmbH and Taiyo Europe GmbH. Press release 29 May 2018, Images: Merck KGaA.

Luminescent solar concentrator (LSC) technologies can also be used as decorative and colourful element for harvesting solar energy. However, they still remain in a prototype phase. An example is the "Electric Mondrian" demonstration case study (Figure 18), inspired by the colourful works of the Dutch artist Piet Mondrian, that is based on commercially available luminescent concentrators ("Perspex" (PMMA) elements) standard c-Si solar cells attached to each side [43].
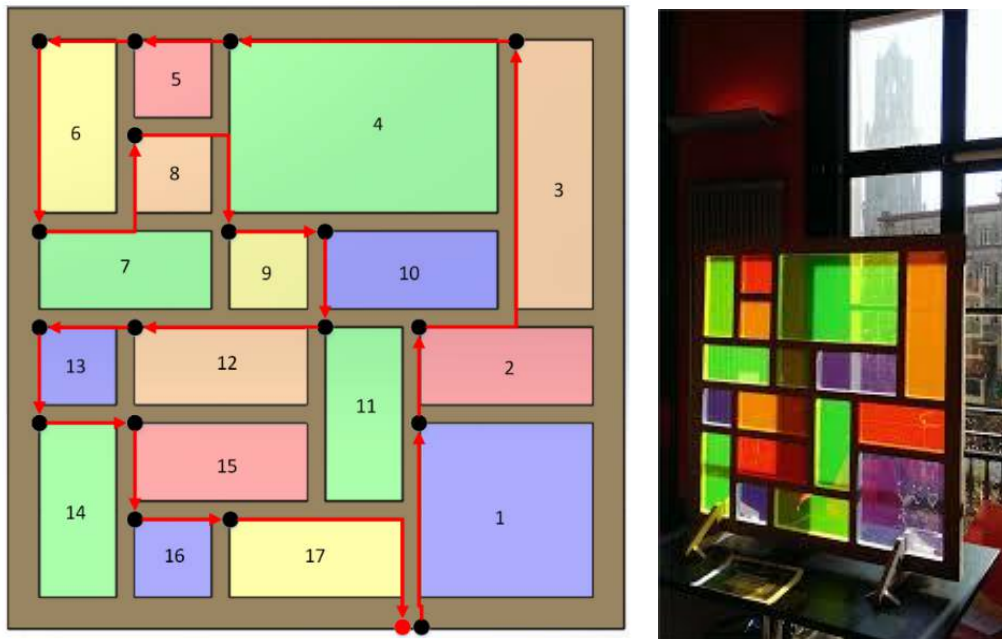

Figure 18: Inspired by the works of the Dutch artist Piet Mondrian, an Electric Mondrian Prototype design has been developed with LSC technology (Source: W. van Sark, 2017 [43]).

Although, as already mentioned above, there are still several factors that limit the practical use of these technologies, research is focusing its efforts on optimizing the solutions to obtain better performance results and improved the durability. This will probably result in greater commercialization of these products in the next few years.

4.1.3 Products with coloured/patterned interlayers and/or special solar filters

Interlayers with colours/patterns: An interlayer with a certain colour/pattern can be laminated inside the module as an additional encapsulant sheet or the encapsulant/backsheet itself can be coloured resulting in quite an economical solution that does not require special treatment. Conventional film printing techniques from the graphics industry or semi-transparent inks that allow light to pass through can be used. Due to these key advantages, this technique could reach a large market share in the foreseeable future. Extra layers added to an existing module usually mean that the need for product re-testing according to IEC guidelines must be checked. Special solar filters: Scattering and reflection filters: One of these techniques has been developed by CSEM [44], the Centre Suisse d'Electronique et de Microtechnique commercialized by Solaxess SA. A elective filter is applied to the

front of the glass cover. This filter reflects and diffuses solar radiation within the visible spectrum, providing a white appearance (Figure 19 left), while the infrared part is transmitted and converted into electricity. In this way, there is an efficiency reduction of about 40% in comparison to a traditional module.

- Hi-res photos: CSEM as well Kaleo-Solar developed (Figure 19 right) a technological solution for integrating high-definition images into solar panels. A high-resolution photo printed on a film with special inks is laminated between cells and the cover glass. After the module is laminated, only the printed photo can be seen on the surface while solar cells behind are no longer visible.

Figure 19: BIPV products that use special solar filters: left: "White" PV and coloured modules (Source: CSEM, http://www.csem.ch); right: Kaleo Solar PV module (Source: ©briefcom/bcn/csem; www.kaleo-solar.ch)

4.1.4 Products with coloured polymer films (encapsulant, backsheet)

Amorphous silicon technology can be combined with coloured polyvinyl butyral (PVB) as the back encapsulant to obtain PV coloured glass with various degrees of transparency. Customized and standard PV glazing products are offered by the manufacturer Onyx Solar, showing different mechanical, thermal, optical and electrical characteristics. There are examples of skylights, façades, canopies, flooring and walkways with these products. Coloured encapsulants are also used in combination with thin film technologies. In Figure 22, glass elements with CdTe technology are shown in the façade of a building (SolTech Energy). As the photovoltaic thin film is sputtered onto the front glass cover during production, the energy output is not affected by the coloured encapsulant behind it.

Figure 20: Flooring BIPV products made of amorphous silicon with coloured PVB. (Source: https://www.onyxsolar.com)

Figure 21: Left: Semi-transparent BIPV products made of amorphous silicon with coloured PVB. Right: Colour palette of amorphous silicon BIPV with coloured PVB. (Source: https://www.onyxsolar.com)

Figure 22: Façade elements with coloured encapsulants using a CdTe active layer (Source: www.soltechenergy.com).

4.1.5 Products with coated, printed, specially finished or coloured front glass covers

Front glass surface techniques: A strong new trend is to use different surface treatments applied to the front glass cover, as are usual in the building sector. Different methods exist:

- Spectrally selective coating: Thanks to a special sputtering process, SwissINSO SA obtained coloured BIPV glass modules. KromatixTM technology, developed by SwissINSO SA in partnership with EPFL (Swiss Polytechnic Institute), uses a multi-layer reflective coating on the glass and spectrally selective coatings that exploit specific sputtering nano-deposition technology for the colour coating of solar glass for photovoltaic and thermal panel applications. The conversion efficiency of these modules with a white coating is 11.4%, instead of 19.1% for standard modules [45]. Different colours such as grey, terracotta, blue, bluish-green, green and yellow can be realized.

Figure 23: BIPV amorphous silicon (top) and crystalline silicon (bottom) modules manufactured with Kromatix™ glass as the front glass cover, laminated at Onyx Solar factory. (Source: https://www.onyxsolar.com)

Figure 24: Colourful printed custom-size solar panels for façades applying SwissINSO KromatixTM. Demonstration BIPV projects: a) Solar Silo "Kohlesilo", Basel (CH). Industrial building placed in the cultural Gundeldingen area; awarded the Swiss Solar Prize in 2015. (Source: SUPSI; http://www.bipv.ch)

- Coloured enamelled (or fritted) glass: A ceramic paste is applied to the glass prior to tempering of the glass. The additives bake out and the ceramic paste bonds strongly to the glass. By printing a dotted pattern, sufficient light can reach the cells; another example of multi-coloured ceramic digital printing on BIPV glass has been developed by the Lucerne University of Applied Sciences (Figure 25), where a specially developed method ensures that despite the use of different colours, no inhomogeneous shading and losses of more than 20% result [45].

Figure 25: Energy Challenge 2016 temporary exhibition launched by EnergieSchweiz (CH), BIPV modules developed by the University of Lucerne (source: Envelopes and Solar Energy Competence Centre within the Hochschule Luzern)

A special solution has been used by Huggenbergerfries Architekten Studio in the multi-family building "Wohnhaus Solaris" (Figure 26), Zürich, Switzerland. The red/brown BIPV glass elements were used

as cladding and tiles. The BIPV component uses digital ceramic printing to hide the PV cells and the front glass cover is finished with a rough structured surface with a good appearance and aesthetics.

Figure 26: Digital ceramic print on glass/glass BIPV modules with various dimensions developed by ertex solar GmbH. Multi-family building Wohnhaus Solaris, Zürich (CH) (Source: HBF AG)

- Sandblasting: A technique that consists of spraying sand at high velocities onto the front glass surface, creating milky white patterns. Within the EU project ConstructPV [47], some initial prototypes of BIPV glass covers were designed and realized with this technique (Figure 27), paying attention to the balance between costs, energy output and visual effects. Other examples of BIPV glass modules realized with sandblasting are the ones designed by SolarGlasLabor where additional colouring techniques are used [50].

Figure 27: Façade mock-up developed within the EU-funded Construct-PV FP7 project (http://www.constructpv.eu). The mock-up demonstrates variants and possibilities in terms of architectural and technological design/manufacturing of BIPV systems for the building envelope (Source: SUPSI)

- Digital glass printing: A process that allows printing special ink onto the glass surfaces in order to obtain a drawing (Figure 28). In the framework of the EU-funded SmartFlex project [51], a novel digital ceramic-based printing process was developed, enabling high-definition pictures (up to 720 dpi) to be printed on the glass.

Figure 28: SmartFlex modules, www.smartflex-solarfacades.eu/project, (Source: SUPSI, modules manufactured by Viasolis and Glassbel)

- Satin finish and glass printing: A satin finish on the outer glass surface is sometimes combined with screen-printing on the inner side. Therefore, there is a reduction of the glass transparency and a resulting coloured matt surface; Examples of this technology were used in different pilot projects (Figure 29).

Figure 29: Project Pilot Plus-Energy Building Renovation – Zürich. Coloured frameless BIPV glass modules treated to obtain an anti-reflective and matt surface have been used to cover the whole building envelope [30] (Source: Viridén + Partner AG).

- Mineral coating: Coloured BIPV modules can be produced by the SUNCOL technology [50] in the four most commonly used colours: brown, terracotta, musk green, slate gray (Figure 30). They are available in the version "Laminate without frame" and "Framed" with a 40 mm coloured frame in the same colour as the laminate. In the fabrication of the SUNCOL modules, a new mineral coating process is used which is stabilized on the glass surface at a very high temperature, thus being structurally bonded to the glass itself.
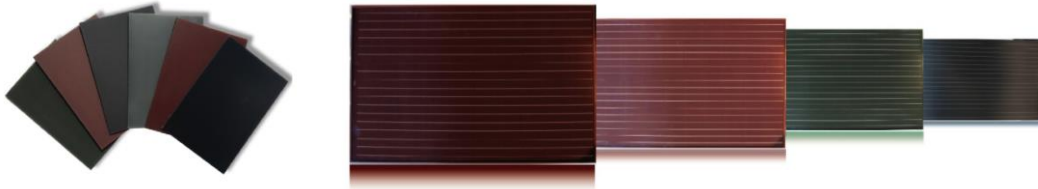

Figure 30: Sunage SUNCOL standard BIPV modules (Source: Sunage SA; www.sunage.ch)

Figure 31: Mass-coloured glass BIPV modules; Balenciaga store in Miami with a coloured BIPV façade. The modules are made of multi-crystalline PV cells and have blue, mass-coloured glass as the front cover.www.onyxsolar.com/projects/23-projects/photovoltaic-curtain-wall/357-balenciaga-store-miami.

- Mass coloured glass: Mass-coloured glass can be used as the front cover in any PV technology; the result is semi-transparent BIPV modules with different sizes and colours. The colour and transparency can be designed to optimize the solar factor, enhancing the thermal comfort inside the building.

These new BIPV developments open up new fields of interest for research, in particular regarding the power output reduction due to the "price of aesthetics" and the effective energy yield of these systems in real operating conditions (integrated into the building envelope). In addition, possible effects of these surface treatments on the electrical behaviour of PV technologies have to be considered (e.g. possible localized hot spots, potential mismatch effects, optical reflections, different incidence angles of radiation, light spectrum or temperature variation over the back of the modules, etc.) [51].

All of these techniques aim to optimize the visual effect and the efficiency of the photovoltaic electricity generation, since there is a reduction of the incident light on the PV cells. It is interesting to note a double approach: on one hand, a high-tech development has created new techniques and materials (mainly transferring them from high-tech research fields such as materials science or physics and optics), and on the other hand, techniques already used in the building industry have been adapted to customize the front glass cover. It is also relevant to consider that, in some cases, aspects such as design/production flexibility, building performance, production flexibility and cost-effectiveness still remain challenges to be overcome in order to ensure market penetration. What is important to highlight is that some of the above-mentioned customizable BIPV glass have already been implemented in real buildings. In various cases, these are lighthouse projects but also some private projects in Switzerland are emerging, as proof of a nascent market for customizable BIPV glass which is cost-effective and affordable [31].

5 Colour tuning of BIPV Modules (theoretical principles and technological implementation)

5.1 Fundamental principles and limits of colour perception

The PV market was and is dominated by c-Si solar cell technology. Although alternative technologies have intrinsic advantages in terms of aesthetic appearance, also the BIPV marketed is dominated by c-Si solar cells. The demand for alternative colours and designs in the BIPV market is addressed by colour tuning of c-Si PV products. In section 5.3 an overview of the state of the art concerning colour tuning of c-Si is provided. Unfortunately, colouring of c-Si PV products is usually related to additional costs and colouring decreases the power output of c-Si PV modules. This negative impact of colour on the performance of PV products is related to fundamental optical and physical principles, which are presented below.

5.1.1 Colour perception under solar irradiation

Solar radiation on earth has a spectral distribution ranging from wavelengths (λ) of 300 nm to 2500 nm. The solar radiation can be divided into three spectral regions: ultraviolet (UV), visible (VIS) and near infrared (NIR). The part of the solar radiation which is visible to the human eye (VIS) covers a spectral range from 380 nm to 780 nm. In Figure 32, a terrestrial solar spectrum is plotted and the visible (VIS) sunlight is shown in grey. The visible part of the solar irradiation contributes about half of the total intensity of the plotted solar spectrum. A solar cell made of c-Si material can exploit wavelengths < 1150 nm and consequently c-Si PV converts sunlight plus ultra-violet (UV) irradiation and parts of the near-infrared (NIR) solar spectrum.
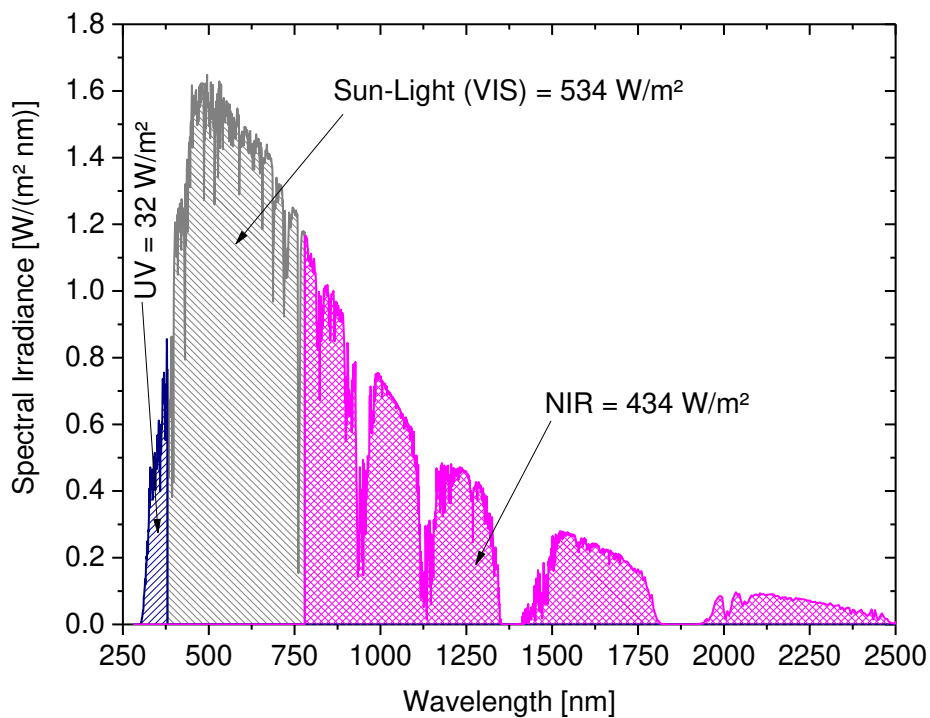

Figure 32: The ASTM G173-03 AM 1.5 g reference spectrum is plotted. The total (integral) intensity of that spectrum is 1000 W/m² (© Gerhard Peharz)

The colour of an opaque object illuminated with solar irradiation is determined by the spectrum of the reflected light. That reflected light can be detected by a human eye which sends signals to the human brain where the colour perception of the object is created. For instance, the perception of a highly absorbing and low-reflecting object such as a highly efficient PV module is always dark or black. If the perception of that PV module is requested to be changed to snow white, the reflection of the sunlight by the module has to be increased substantially in the total visible spectrum (VIS). Since the reflected light is per definition not absorbed by the coloured module, less solar radiation power can be converted into electrical current and the performance of the module is substantially decreased. In addition, radiation which is absorbed by coloured pigments in front of the photovoltaic elements is also unavailable for conversion to electricity.

A PV product which is optimized for maximum conversion of solar radiation has a pre-defined colour (black). A coloured PV element is synonymous with partial reflection of the irradiation in the visible

region. Consequently, in a coloured PV element, the amount of solar power which can be converted into electricity is reduced compared to a black product. Colour perception and power conversion of c-Si solar cells can be calculated on a fundamental basis. Thus, it is possible to derive fundamental principles on the impact of colour on the performance loss of c-Si PV.

5.1.2 Relationship between colour and efficiency/power generation

The colour perception of humans is determined by the cone cells in the human eye which differ in their spectral sensitivity. In particular, three different types of cone cells are found in the human eye and the stimulus which they send to the brain depends on the spectral distribution of the impinging light. In the human brain, the stimulus signals are processed to perception of colour. Consequently, colour perception depends on the spectral responses and subjective post-processing. The standardization of colour metrics is based on a statistical analysis of surveys of test persons under controlled conditions. The International Commission on Illumination (CIE) defines colour matching functions $\overline{x}(\lambda), \overline{y}(\lambda)$ and $\overline{z}(\lambda)$ for an average human observer [52]. Such colour-matching functions are plotted in Figure 33.
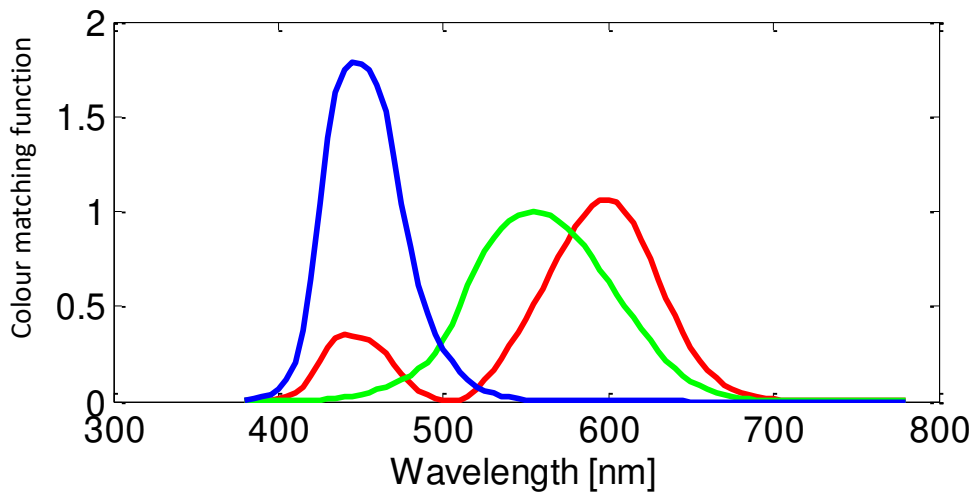
Figure 33: CIE colour-matching functions 1931 2°: $\overline{x}(\lambda)$ in red, $\overline{y}(\lambda)$ in green and $\overline{z}(\lambda)$ in blue [52]

The colour-matching functions enable a mapping of colours based on irradiation spectra impinging on the human eye (intensity$_{eye}$ (λ)). In particular, every spectrum is mapped to a set of X,Y,Z colour coordinates: The colour-matching functions enable a numerical description of colours based on reflectance spectra R(λ) and the illuminant spectrum S(λ) by tristimulus values:

$$X = \text{K/N} \int_\lambda R(\lambda) * S(\lambda) * \overline{x}(\lambda) \ d\lambda \qquad \text{Equation 1}$$

$$Y = \text{K/N} \int_\lambda R(\lambda) * S(\lambda) * \overline{y}(\lambda) \ d\lambda \qquad \text{Equation 2}$$

$$Z = \text{K/N} \int_\lambda R(\lambda) * S(\lambda) * \overline{z}(\lambda) \ d\lambda \qquad \text{Equation 3}$$

Where N $= \int_\lambda S(\lambda) * \overline{y}(\lambda)\ d\lambda$

and K is a normalisation factor, usually 1 or 100.

Assuming that no transmission of radiation takes place and that no radiation is absorbed by the coloured coating itself, which usually is a valid assumption for the interference-based stacks of dielectric films, the spectrum absorbed by a BIPV element (intensityabsorbed(λ)) is the difference between the incident solar and reflected spectrum:

$$intensity_{absorbed}(\lambda) = \left(1 - R(\lambda)\right) * intensity_{\text{solar}}(\lambda) \qquad \text{Equation 4}$$

For the special case of non-absorbing coatings, e.g. monochromatic colours, the photocurrent of a solar cell (BIPV) element can be derived from the intensity absorbed and the spectral response of the cell. In an ideal case, the spectral response of a cell is determined only by the band-gap (Eg) of the solar cell material (e.g. 1.1 eV for c-Si). In particular, Eg defines the cut-off wavelengths of an ideal spectral response (spectral responseideal)[52]:

$$spectral\ response_{ideal}(\lambda) = \begin{cases} \lambda/(h*c) & for\ \lambda \leq \lambda_{cut\ off} \\[2mm] 0 & for\ \lambda > \lambda_{cut\ off} \end{cases} \qquad \text{Equation 5}$$

$$\lambda_{cut\ off} = h*c/E_g \qquad \text{Equation 6}$$

where h denotes the Planck constant and c the speed of light in vacuum. The photocurrent density (Jphoto) of an ideal cell is derived from the following equation:

$$J_{photo} = \int_\lambda intensity_{absorbed}(\lambda) * spectral\ response_{ideal}(\lambda)\ d\lambda \qquad \text{Equation 7}$$

The photocurrent (Iphoto) is calculated as the product of the solar cell area and (JPhoto). The current-voltage (IV) curve of a solar cell can be calculated by applying Shockley diode equations. For c-Si solar cell applications, the so-called two-diode model is well established for simulating and calculating the corresponding IV curves [52]:

$$I = I_{photo} - I_{01} * \left(e^{\frac{(V + I * R_s) * q}{n_1 * k * T}} - 1 \right) - I_{02} * \left(e^{\frac{(V + I * R_s) * q}{n_2 * k * T}} - 1 \right) - \frac{(V + I * R_s)}{R_p} \qquad \text{Equation 8}$$

Where:
I_{photo} ....Light-generated current
I_{01} ....Dark saturation current in the n-doped and p-doped regions
I_{02} ....Dark saturation current in the depletion region (space-charge region)
n_1 ....Ideality factor (<1) in the n-doped and p-doped regions
n_2 ....Ideality factor (<2) in the depletion region (space-charge region)
R_s ....Series resistance
R_p ....Shunt resistance

T ....Temperature
k ....Boltzmann constant
q ....Elementary charge

The open circuit voltage (V) is derived from the IV curve at zero current. The IV curve allows the power-voltage (PV) curve and the maximum power Pmpp to be determined. The input parameters for the calculation of photovoltaic performance are listed in Table 1. In particular, the dark saturation currents were derived from a fit to dark IV curve measurements of an industrial c-Si solar cell. Also, the band gap corresponds to that of c-Si; the remaining parameters were chosen to be ideal.

Table 1: Input parameters used for the simulation of the photovoltaic performance [52]

Parameter	Abbr.	Value	Unit
Band gap	E_G	1.12	eV
Dark saturation current in the n-doped and p-doped regions	j_{01}	0.717 * 10-12	A
Dark saturation current in the depletion region	j_{02}	2.550 * 10-8	A
Ideality factor (≤1) in the bulk material	n_1	1	[]
Ideality factor (≤2) in the depletion region	n_2	2	[]
Series resistance	R_S	0	Ω
Shunt resistance	R_p	infinite	Ω
Temperature	T	300	K

In summary, the considerations shown above enable the calculation of colour coordinates and the power of a c-Si solar cell device for a given reflectance spectrum (reflectance(λ)) for non-absorbing coatings. Consequently, the impact of colours on the power output of a c-Si based BIPV element can be calculated if the colours are achieved by use of non-absorbing coatins. In particular, the power loss is derived by comparing the maximum power of a coloured c-Si BIPV device (Pmpp,colour) and a reference power (Pmpp,ref):

$$\text{Power loss due to non} - \text{absorbing layers}$$
$$= \frac{P_{\text{mpp,ref}} - P_{mpp,color}}{P_{\text{mpp,ref}}} \cdot 100\%$$

Equation 9

Monochromatic colours: Monochromatic colours are the result of relatively narrow reflection spectra. Experimentally, such narrow band reflection spectra can be created by dielectric layer stacks [32]. For BIPV applications, narrow reflectance spectra are of advantage since the power losses are relatively low. Thus, A series of pill boxes with varying height in reflectivity and spectral width were defined. In particular pill box spectra with a spectral width of 40nm were generated. The pill box height of the reflectivity was varied between 0.1 and 1 (step size 0.1) and the centre wavelength was

shifted from 400nm to 700nm (step size 10 nm). It was found out that reflectance spectra of pill boxes with a wavelength width of 40 nm and reflection of 100% are sufficient to create highly saturated monochromatic colours from sunlight. The calculated power losses due to such narrowband reflection are significantly below 10%. In Figure 34, the power loss of c-Si devices calculated for reflectance spectra of pill boxes (40 nm width) is plotted for different centre wavelengths in the visible spectrum.
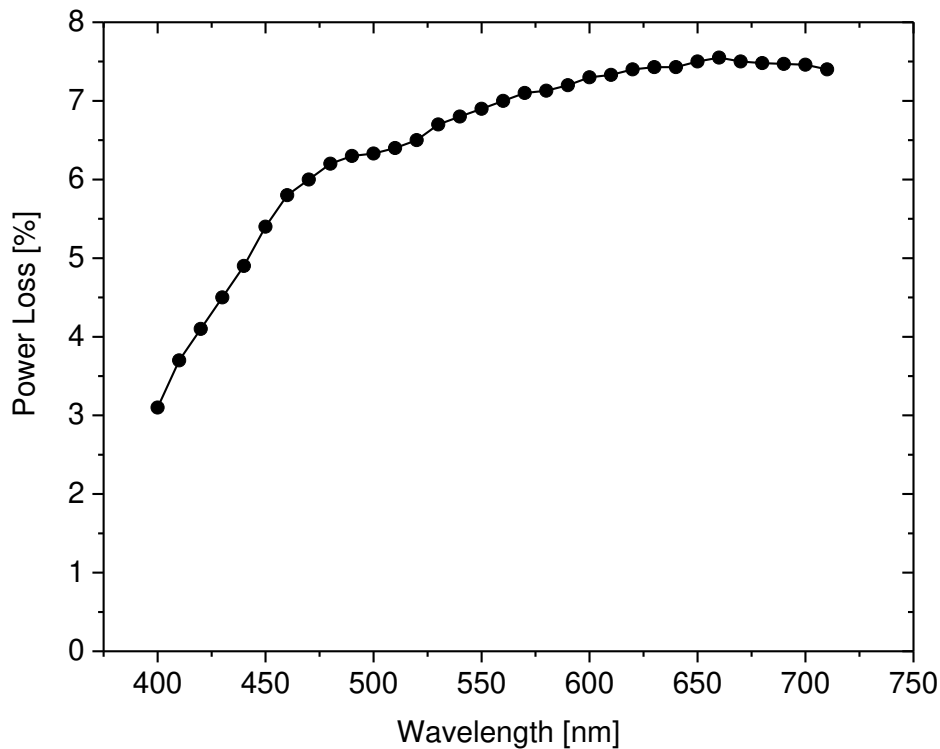

Figure 34: The calculated power loss for a c-Si device is plotted for reflectance spectra of pill boxes having a width of 40 nm.

It is evident that the power loss increases with increasing centre wavelength of the reflectance spectra. Consequently, in terms of monochromatic colours, blue (400 – 450) causes about half the power loss of red (600 -750 nm) and green (500 – 550 nm) is slightly less demanding than red. This wavelength dependence of the power loss is determined by the solar spectrum (see Figure 34) and by the spectral response of the c-Si solar cell. Even an ideal c-Si solar cell generates only a relatively small fraction of its photocurrent from light in the blue spectral range. By contrast, the maximum current is generated between 600 and 700 nm (red spectral range).

Real colours (RAL colours): As described above, even highly saturated monochromatic colours cause rather low power loss of less than 10%. However, those colours cover only a small fraction of the real colour space. In architecture and the construction sector, standardized colours are used which are defined in colour samples (see Figure 35 left). For instance, the Natural Colour System (NCS) or RAL colours are frequently applied [47]. The colour of BIPV elements can be matched to standard colours – for example by printing ceramic inks onto the cover glass or other methods described in the following (see chapter 5.3.).
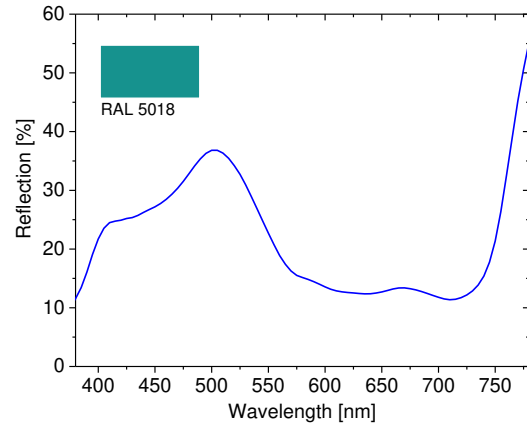
Figure 35: Left: photo of a RAL colour catalogue (Source: www.ral-shop.com). Right: Reflectance spectrum of RAL 5018

The reflectance spectra of the 218 classic RAL colours were measured in the visible spectral range (380 to 780 nm). As an example, the reflectance spectrum of RAL 5018 is plotted in Figure 35 right.

5.1.3 Theoretical colour efficiency

Since many more buildings are white or light grey than black or dark grey, one could conclude that white is more popular than black and consequently white has a higher aesthetic "value" than black in the context of building applications. The question of quantifying the value of colours is interesting for BIPV applications, since a highly valuable colour would justify higher power losses than a low-value colour.

A first approach to quantifying the value of colours is to use the "Lightness" value of the CIE L,a,b colour coordinates. The L,a,b colour space is derived from the X,Y,Z colour coordinates described above by applying the following equations [52]:

$$L = 116 * Y_{dist} - 16$$

Equation 10

$$a = 500 * (X_{dist} - Y_{dist})$$

Equation 11

$$b = 200 * (Y_{dist} - Z_{dist})$$

Equation 12

Where:

$$Y_{dist} = \begin{cases} \sqrt[3]{Y/Y\_ref} & for\ Y/Y\_ref > 0.008856 \\ 7.787 * Y/Y\_ref + 16/116 & for\ Y/Y\_ref \leq 0.008856 \end{cases}$$

Equation 13

To calculate X_{dist} replace Y by X and Y_{ref} by X_{ref} in Equation 13. To calculate Z_{dist} replace Y by Z and Y_{ref} by Z_{ref} in Equation 13. The reference values X_{ref}, Y_{ref} and Z_{ref} depend on the observer

model and on the illuminant. In the example above, the values were based on the standard illuminant D 65 and a 2° standard observer.

Colours with high lightness value (L) correspond to "lighter" colours than those with the same a and b coordinates and a lower L. Assuming that "lighter" colours are more valuable than dark colours, one can define a colour efficiency by dividing the L value by the corresponding power loss of a certain colour. In Figure 36 such "L-efficiencies" are plotted for monochromatic colours derived from 40 nm / 100 % pill box reflectance spectra (same as shown in Figure 34).
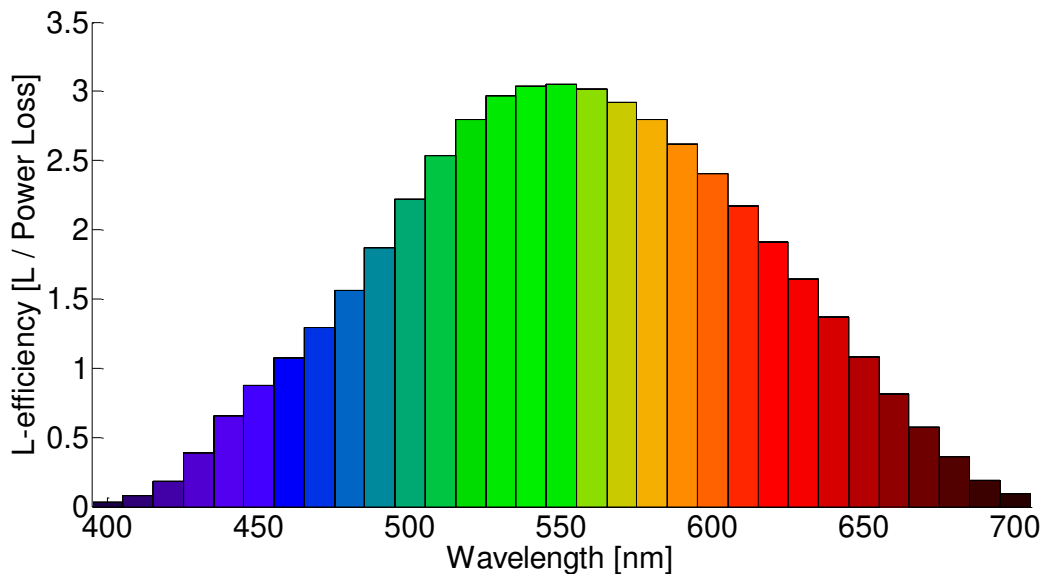

Figure 36: Ratio of lightness value L and Power loss for monochromatic colours (derived from pill-box reflectance spectra with width = 40 nm and height = 100)

Obviously the most efficient monochromatic colour is green, when using L for quantifying the colour-value. In contrast, blue and red are much less efficient for that definition of colour efficiency. The spectral dependence of the L-efficiency as shown above is determined by the definition of the L-value. As described in Equation 10, L is derived only from Y, which further is calculated by applying Equation 2. Since Y is derived from $\overline{y}(\lambda)$, wavelengths around 550 nm result in substantially higher L-values than those < 450 nm or > 600 nm (see Figure 36).

$\overline{y}(\lambda)$ defines the absolute spectral sensitivity of the human eye, which is much more sensitive in the green spectral region than in the red or the blue part. For lighting issues, this quantity plays an important role and explains why green LEDs appear much brighter than red ones when both are emitting the same intensity. As already described above, the colour perception is determined by the (wavelength-dependent) stimulus of the human eye and post-processing in the human brain. Thus,

"colour corrections" of the human colour perception are taken into account when defining the colour-matching functions (see Figure 37).

The ratio of the colour value sum and the power loss enables the definition of an alternative figure of merit for the colour efficiency. A general definition of colour efficiency (Ceff) can be defined as follows:

$$C_{eff} = \frac{X_{color} + Y_{color} + Z_{color}}{J_{photo,ref} - J_{photo,color}}$$

Here, Xcolour, Ycolour and Zcolour are the XYZ values derived from a given reflectance spectrum when illuminated with solar irradiation which defines the colour of an object. This approach is restricted to interference-based monochromatic colours based on non-absorbing dielectric coating stacks. Jphoto,ref is the reference photocurrent density (no reflection) and Jphoto,colour is the photocurrent density for the reflectance spectrum used to calculate Xcolour, Ycolour and Zcolour and is derived from intensityremaining.

In Figure 37, Ceff is plotted for monochromatic colours derived from 100 % pill box spectra with a 40 nm bandwidth (same colour data as used for Figure 34 and Figure 36). The most efficient monochromatic colour corresponds to a center wavelength of about 450 nm (blue). In particular, blue seems to be about twice as efficient as green and red. Interestingly at about 500 nm Ceff has a local minimum which corresponds to bluish-green. The spectral distribution of Ceff results mainly from a sum of the colour matching functions and the fact that the losses for solar cell devices are significantly lower when reflecting sunlight at wavelengths < 450 nm (see Figure 34). In conclusion, the most efficient trade-off of strong colour and low losses is obtained for a monochromatic colour with a center wavelength of about 450 nm.
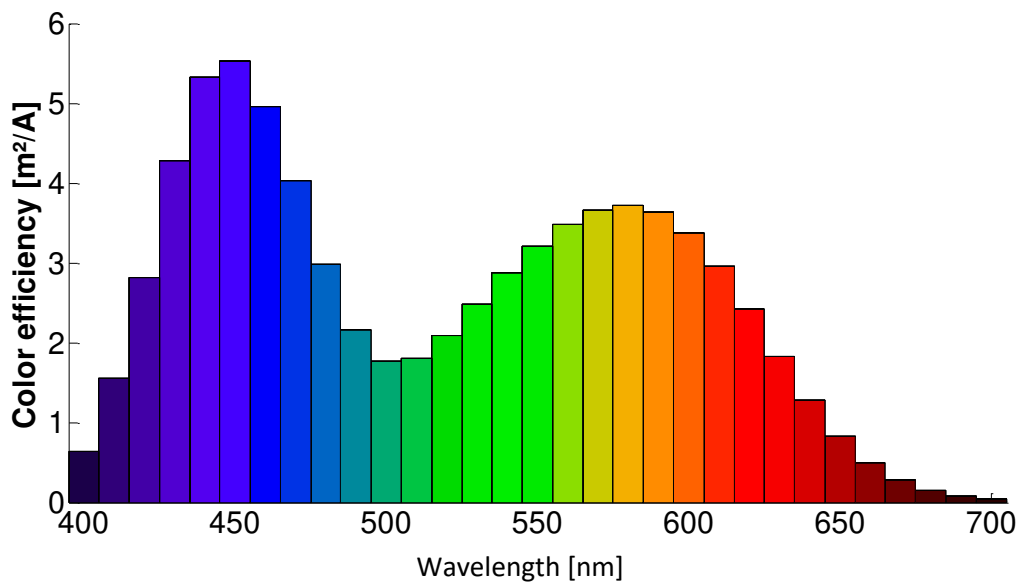

Figure 37: Ceff for monochromatic colours derived from pill-box reflectance spectra (width = 40 nm and height = 100%) [52].

5.1.4 Visual comfort of coloured BIPV (indoors and outdoors)

The advances in BIPV technologies have expanded the possibilities in aesthetic aspects reflected by colour, materials, texture and transparency. While transparency could be achieved by varying gaps between opaque cells of the 1st generation, only 2nd and 3rd generation solar cells allowed the transparency and colour of the PV cells themselves to be changed. Thin-film PV modules of the 2nd generation are based on amorphous silicon (a-Si) thin-film solar cells and their colour is neutral, meaning their colour is represented in a monochrome grey scale. Another technology is micromorphous silicon (a-Si:μc-Si) thin-film solar cells, that can represent colour and variable

transparency, mostly in red, green or blue. Third generation PV, such as organic photovoltaics - OPV, dye-sensitized solar cells - DSSC, luminescent solar concentrators - LSC and recently perovskites have a wider spectrum of colours and transparency ranges that could fit specific aesthetic requirements. These technologies are particularly applicable to façades as transparency and colour variations are one of the most important requirements for aesthetics and human comfort. However, applying semi-transparent coloured BIPV to façades or external shades could cause a spectral shift of the daylight, resulting in unpleasant effects and poor human visual comfort.

To avoid such effects and assess the visual comfort of semi-transparent coloured BIPV, the BIPV scientific community adopted established approaches for characterizing light sources and illuminants using parameters such as correlated colour temperature (CCT) and colour rendering index (CRI) [54],. These parameters define how and to what extent daylight with a spectral power distribution (SPD) in the visible range of 380 nm to 780 nm is filtered by a semi-transparent coloured BIPV façade. CCT is measured in the unit of absolute temperature, the Kelvin (K). Therefore, the CRI is a dimensionless, relative metric that defines difference of colour appearance, or degree of colour matching, between an object that is illuminated with a tested illuminant and the same object illuminated with a reference illuminant. Regarding indoor comfort, the international standard on lighting in working spaces [58] defined specific ranges of values for luminance, CCT and CRI. The recommended CCT ranges between 3000 K and 5300 K (i.e. warm and intermediate white light). CRI values above 90 are considered ideal, while a threshold of 80 is used to define accepted spectral colour shift. Values lower than 80 are generally avoided as these illuminants, or in this case the changed illuminant spectrum caused by the transmittance spectrum of the BIPV element, renders significantly different colours that may cause visual discomfort.

When defining visual comfort of semi-transparent coloured BIPV, the CRI can be assessed by referencing to natural light or artificial illuminants. Some studies, like [60] used both methods to assess the CRI of thin-film BIPV. The study found that 6 samples of gray scale and coloured a-Si all obtained CRI above 90, demonstrating that the light transmitted by these BIPV modules renders colours well, both under laboratory conditions with artificial illuminants and outdoors with daylight. One study [62] even demonstrated that a façade covered 25% by an LSC was judged favourably compared to a normal, clear glass window. However, a percentage of coloured glazing larger than 25% is perceived unfavourably, suggesting 25% LSC coverage in the upper zone of the glazing is the functional tolerance maximum. Another study, on electrochromic glazing but comparable to BIPV regarding visual comfort [61], tested the hypothesis that occupants prefer un-tinted window panes in their sight-line, except in the case of direct sunlight coming through these panes. The study found that only a small portion of clear glazing, roughly 10%, may compensate a large portion of blue tinted glazing, providing that the illumination spectrum contains a significant portion of sunlight. On the other hand, a research paper [57] analyzed the CRI of a yellow LSC under two dominant daylight conditions and showed that the LSC increases illuminance levels under the tested sunny conditions and reduces the CCT, whereas the CRI showed variable levels and has to be carefully assessed for specific working tasks. Another study [56] used different metrics to show that the specific colour tint has to be taken into account when assessing visual comfort, as bronze or a warmer shift in glazing colour may enhance the perception of brightness by the occupants and increase the level of arousal, while blue glazing may decrease it.

In conclusion, designing with semi-transparent BIPV is still a challenging domain regarding visual comfort, since different technologies, colours and levels of transparency under different daylighting

conditions may cause highly specific visual comfort levels. Therefore, as described, general recommendations may be followed, but it is still advisable to verify visual comfort for specific cases to avoid possible visual discomfort.

5.1.5 Transparency

As defined by the response of the human eye, the wavelength region of visible light ranges from approximately 380 to about 700 nm. Visible light in its collected form is sometimes called white light but visible light actually consists of all colours in the rainbow (c.f. Fig. 36 in chapter 5.1.3 as an example). The rainbow is a naturally occurring phenomenon of refraction where water droplets behave like small prisms refracting the visible light into all its colour components. Refraction in materials depends on the refractive index and the angle of incidence. As light interacts with materials it can either be absorbed (A), reflected (R) or transmitted (T) by the material. Here, only specular reflectance and direct transmittance are considered. Some of the light may also be scattered (S), i.e. deflected from its original trajectory line, as a result of inhomogeneities in the material. The total sum of these light-matter interactions can be described by A+R+T+S = 1.

Most materials are not transparent, since they absorb radiation in the visible part of the spectrum as a result of electronic interactions in the material and convert it to other forms of energy. One of these electronic transitions is in fact the photoelectric effect which is used in PV cells and is the simple reason why most efficient PV cells are not transparent in the visible part of the spectrum, which accounts for about 50 % of incident solar energy (see Figure 32).

Another reason for materials not being transparent is light scattering due to inhomogeneities of the material such as grain boundaries in crystalline materials or phase separation as in milk. Transparent materials can also be coloured and the simple reason for that is that they only interact with some wavelengths within the visible spectrum through absorption or scattering of light. Red ruby glass is an example of spectrally selective scattering by dispersed metal nanoparticles. Transparent material that absorbs significant amounts of the visible spectrum appear coloured, whereby the colours in transmission and reflection may differ. The colour of opaque materials is dominated by reflection.; White materials reflect all wavelengths in the visible spectrum while blue materials reflect wavelengths in the blue part of the visible spectrum.

Constructive interference of the light reflected at specific wavelengths by stacks of transparent material layers can result in strong perceived colours while light is still transmitted. The phenomenon of destructive interference is used to achieve anti-reflective properties.

5.2   Colour efficiency in experimental measurements

Apart from a pleasant aesthetic result, the customization of BIPV modules by colouring techniques should guarantee reliable power output throughout the life-cycle, even though – and especially because – a "mask" is applied in front of the PV cells. For this reason, experimental measurements are needed to assess the electrical behaviour of coloured BIPV elements. Such measurements are not only significant when they are performed at Standard Test Conditions (STC) but also at outdoor test conditions. In the following, the experimental activities carried out at several research institutions

(SUPSI/CH [49], SEAC-TNO/NL [63,64] and an Austrian Consortium within the research project PV@facade [27,65] for BIPV modules with coloured with different techniques are presented:

(a) Coloured modules with digital glass printing

(b) Coloured modules with a mineral coating

5.2.1 Coloured modules with digital glass printing

Individual coloured designs for BIPV elements can be realized by printing on the front glass of the modules. The advantage of flexibility in the aesthetic appearance has to be evaluated versus the loss in electrical performance of printed BIPV elements. Within the Austrian R&D project PV@facade [27], simulations and experimental evaluation of different print approaches were performed with respect to the effect of (i) the print coverage (fraction of printed versus unprinted area), (ii) print pattern (breadboard and chessboard patterns) and (iii) plane of printing for two series of test modules (see Figure 38).

Zoom of the printing pattern

Chessboard pattern:
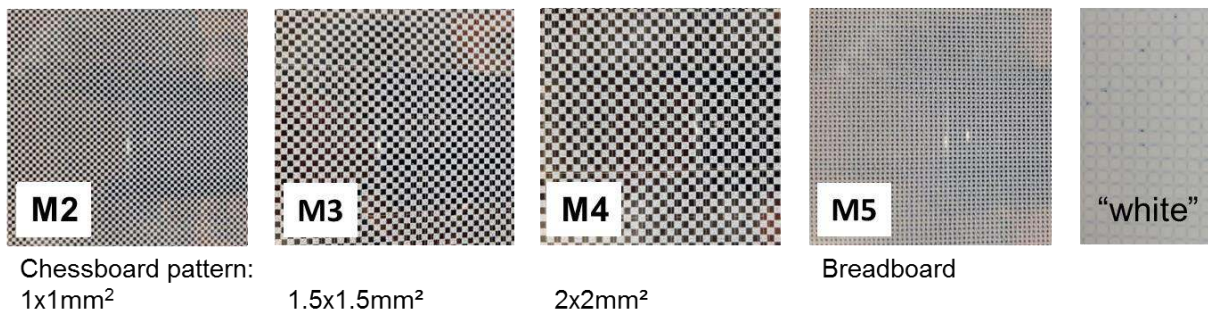1x1mm²   1.5x1.5mm²   2x2mm²   Breadboard

Figure 38: Details of test modules with a white print on the glass covers with differing degrees of coverage and print pattern (M2-M5) and nearly continuous covering with white ink (right) [65]

The influence of the installation situation (vertical façade = 90°, roof = 30°) on the performance was measured in an outdoor test site. The energy yield determined for the test modules under real life conditions was determined in dependence on the angle of incidence (season, course of a day). Furthermore, the outdoor performance was compared to the data obtained in the laboratory under Standard Test Conditions (STC) and in simulation results. The efficiencies measured under STC conditions of the test modules were found to be between 50-90 % compared to that of the reference module without printing on the glass surface (see Figure 39 and Table 2).

Figure 39: Test modules with white printed glass covers with differing degrees of coverage and print patterns (M2-M5) [65]

Table 2: Electrical characterisation data of the test modules under STC conditions

	VOC [V]	ISC [A]	Fill Factor [%]	Pmax [W]	Prel @MPP [%]
reference	2,55	8,07	75,72	15,58	100,0
M2	2,53	7,25	76,09	13,96	89,6
M3	2,53	7,29	76,02	14,02	90,0
M4	2,53	7,30	76,05	14,04	90,1
M5	2,53	7,01	76,20	13,50	86,6
white	2,43	4,23	78,43	8,05	50,9

In particular, the short circuit current decreased with increasing print coverage, while the voltage and fill factor remained almost constant. Optical ray-tracing simulations have been conducted in order to investigate the impact of the printing pattern on the performance of the modules in more detail. The number of rays absorbed within the silicon bulk material was used as a figure of merit for comparing different printing patterns versus an uncoated reference module). The ratios of absorbed light for printed in comparison to uncoated glass were found to be always equal for the chessboard patterns of the printed glass covers M2, M3 and M4 (only differing in square size), resulting in equal efficiencies of ~90 % compared to the 100 % reference sample without print. The breadboard pattern of sample M5 has a larger coated area and consequently gave a reduced efficiency (86,6 %). The simulations resulted in losses in efficiency due to the printing patterns on the front cover as shown for M2-M5 in the range from 11.1 to 17.9 % (depending on the particular pattern), which is in good agreement with the measurement results (9.9 – 13.4 %) [65].

One of the goals of the European Smart-FLEX project [49] was to customize BIPV glass-glass modules in order to provide new design options for designing solar façades. In the framework of this project, several prototypes were developed to assess the influence of customization options on the "behaviour" of PV cells. In detail, the investigation on prototypes has involved glass-glass modules made of multi-crystalline cells laminated between two glass panes, where the front glass pane has been customized. Different colours were applied as small dots by a digital ceramic-based printing technique that also allows high-resolution pictures (720 dpi) to be printed. Specifically, coloured small dots were digitally printed on the inner surface of the front glass pane, with three different colour types (white, black and green) and with different printing degrees (ranging from 0 % colour to 100 %, see Figure 40). To analyse the influence of the various customization options, a measurement campaign has been carried out in the laboratory of SUPSI-LAB and published by Frontini et al. [66].

Power Measurement at STC: Power measurement tests were performed at STC for the different prototypes (see Figure 41) in order to evaluate the influence of the presence of coloured dots on the electrical behaviour of PV cells. The results show that there is an almost linear reduction trend of the power output when the printing degree of coloured dots increases, that is mainly due to the increasing "coverage" of the PV cells which, thus, receive less irradiation.

Spectral Responsivity: Spectral responsivity measurements allow the "behaviour" of the PV cells to be evaluated in a specific wavelength range (see Figure 40). From these results, it is evident that the

module with black dots absorbs radiation with wavelengths corresponding to both the visible and the infrared radiation, the module with green dots absorbs at wavelengths corresponding to the blue and red colours and the module with white dots reflects and transmits light over the complete spectrum.
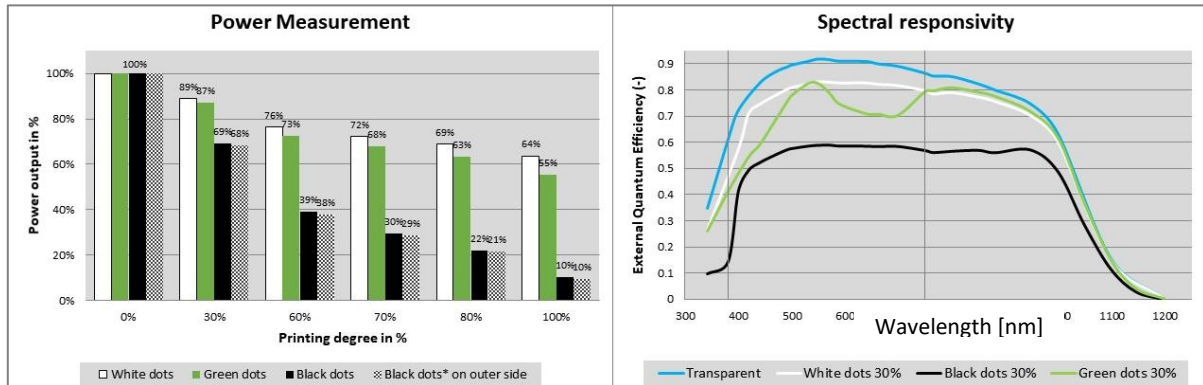

Figure 40: Left picture: Comparison of the power output (calculation performed on a single cell) among the different coloured modules and the different printing degrees. Right picture: External quantum efficiency of the modules with coloured dots with 30 % of printing degree.

Temperature Coefficient Measurement: With the aim to investigate whether the colour application on the front glass cover and the colour type affect the module temperature (and thus the final yield), the modules have been subjected to temperature coefficient measurements in accordance to IEC 60891. However, these results indicate that the presence of the colour and the colour type on the front glass does not influence the temperature of the PV modules significantly.

Outdoor Power and Temperature Monitoring: The real energy-converting behaviour of the prototypes was investigated by outdoor testing. The influence of real operating conditions on the energy output was analysed. In particular, the reference module and the black, green and white coloured modules were mounted in the outdoor testing facilities in Lugano (CH) to monitor both the power output and the temperature of each single module. The monitored data shows that, similarly to the power output of the test modules at STC, the white module performs better than the green one, while the black one is performing worst. However, also when installed in real conditions, the white and green coloured prototypes with a printing degree of 30 % have daily energy losses lower than 15 % in comparison to the reference module, for the black coloured prototypes the losses were close to 30%.
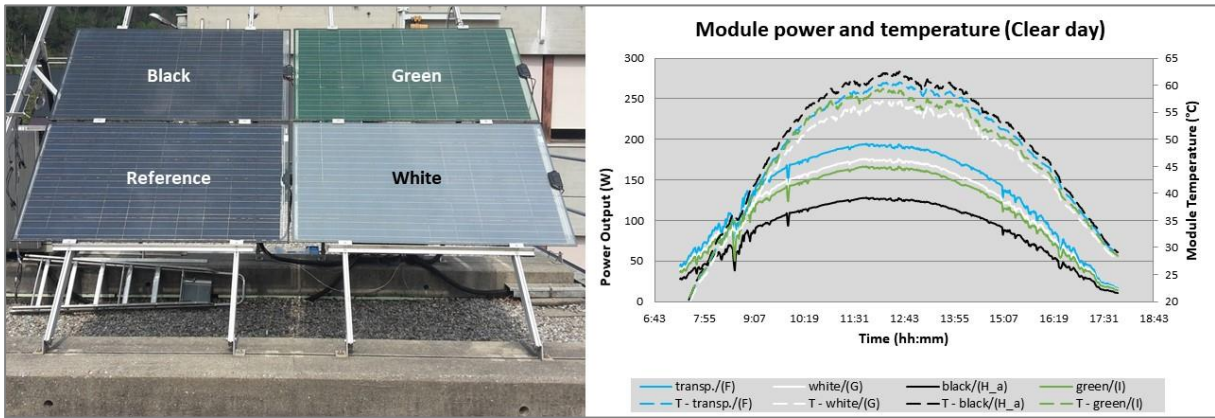
Figure 41: Left: Reference module and coloured prototypes installed at outdoor test facilities of SUPSI-ISAAC in Lugano (CH). Right: Power output and temperatures of the modules for a clear day in Lugano.

Figure 42: Test façade of innovative BIPV elements developed within project PV@facade with variable back covers, with terracotta coated glass [26], printed glass and coloured Si cells [27];

Comparable test façades were also installed in Stallhofen, Austria [27] and Eindhoven, The Netherlands [63, 64], as shown in Figures 42 and 43, respectively.

Figure 43: Top: Outdoor demonstrator of a coloured and textured PV façade installed at SolarBEAT, Eindhoven; Bottom: Cumulative DC Performance Ratio differences [63, 64]

5.2.2 Coloured modules with mineral coating

As already introduced in paragraph 4.1, there are several design options to obtain coloured BIPV modules. One of them is to colour the front glass cover of the module by means of a mineral coating process. In particular, depending on the glass type (e.g. float, satin) and the colour type, different power output results can be obtained, as investigated in the framework of a Swiss CTI Project [67] carried out in collaboration with a Swiss industrial partner. To analyse the influence of this specific colouring technique, a set of measurements has been performed, both at STC and under outdoor test conditions [51]. In detail, several prototypes have been manufactured by applying a specific amount of minerals onto different glass types (float and satin finish) before the tempering process to obtain various front glass covers with a very thin coloured layer and, then, by laminating them with PV cells and back glass panes. Specifically, the coloured prototypes are characterized by:

(a) Satin finish glass with colour applied onto the inner surface (position 2) of the front glass pane (transparent, blue, green, light grey, dark grey and terracotta),

(b) Float glass with colour applied onto the inner surface (position 2) of the front glass pane (transparent, blue, light grey, dark grey and terracotta), and

(c) Float glass with colour applied onto the outer surface (position 1) of the front glass pane (transparent, blue, green, light grey, dark grey and terracotta).

Power Measurement at STC: In order to assess the effect of the customization process, the power output at STC was measured, after positive results of the electro-luminescence tests had been obtained. The results show that the colouring technique does not significantly affect the efficiency, considering that the maximum power loss is about 17% even for the satin finish dark grey module (see Figure 44). There is no evidence of efficiency variations when the colour is applied on the outer or inner surface of the front glass.

Outdoor Power and Temperature Monitoring: From the analysis of the power output data recorded from the outdoor monitoring, it was determined that prototypes have similar electrical behaviours in comparison to the behaviour analysed under indoor test conditions. Interestingly, the reference prototype (transparent, non-coloured front glass) always performs better than other prototypes even though it shows a higher operative temperature (see Figure 45). Moreover, from the comparison of the daily energy yield with the reference module, it was determined that the blue module has lower losses (~5%) than the terracotta (~8%) and the light grey (10.5%) modules.
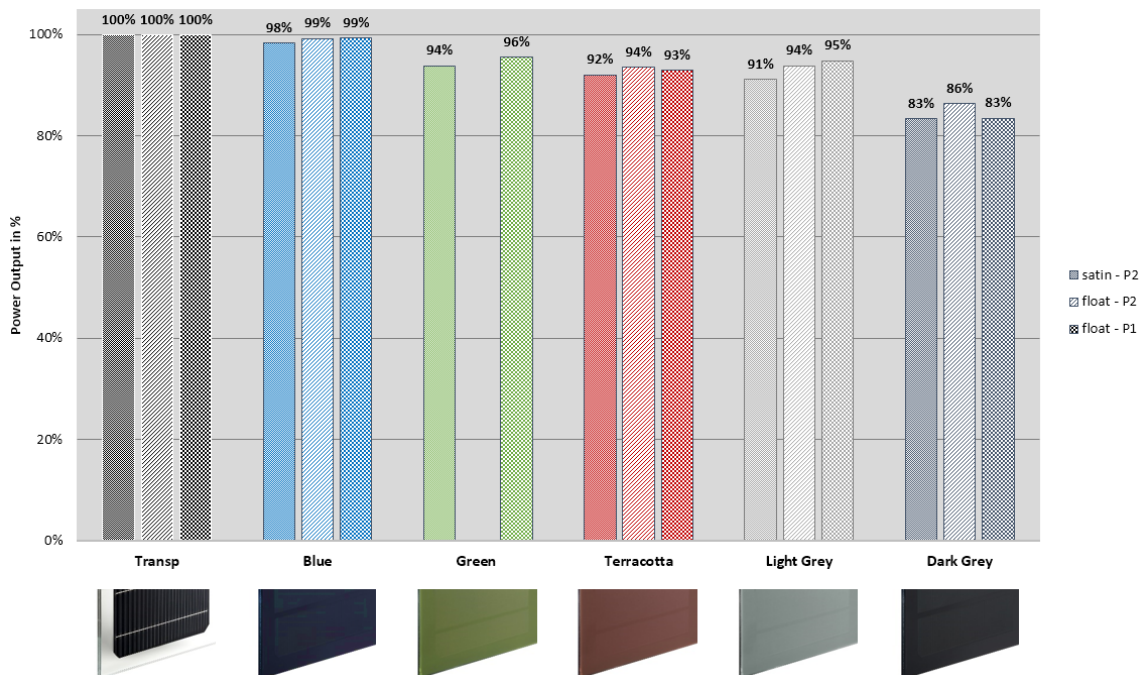

Figure 44: Power output of the different coloured modules, as a function of colour, glass surface finish and position of the mineral layer.
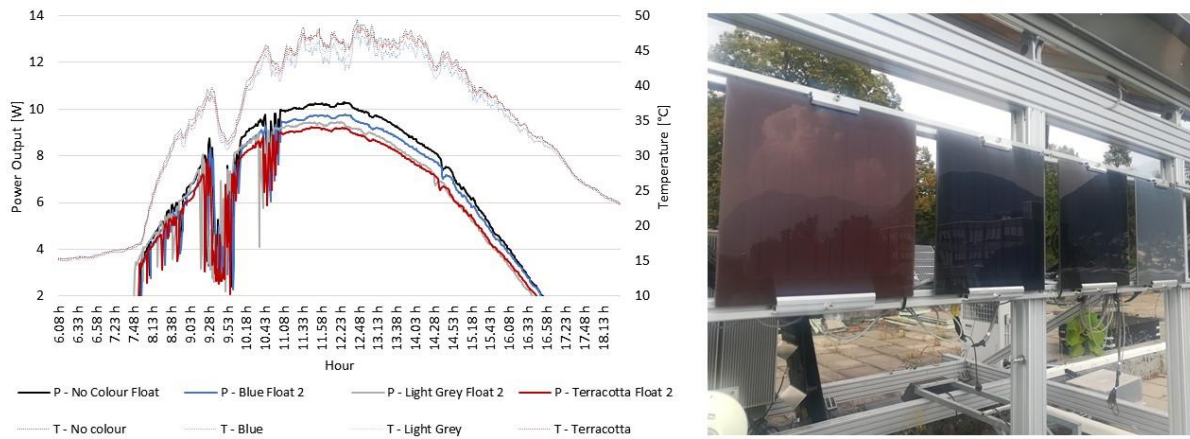
Figure 45: Left: Power output and temperature of the prototype with float glass and colour applied to position 2 (data recorded over one day in Lugano). Right: Prototypes installed at outdoor test facilities of SUPSI-ISAAC in Lugano (CH).

5.3 State-of-the-art colour implementation technologies

5.3.1 Plasmonic coatings on PV-active layers (crystalline Si cells)

In particular, for façade-integrated modules with crystalline Silicon (c-Si) solar cells, alternative colours are demanded. One approach for tuning the colour of standard c-Si solar cells relies on plasmonic colouring. Metallic (Ag) nano-particles with a diameter of around 100 nm were created on the surface of standard c-Si solar cells [4]. Plasmonic scattering by those nano-particles at around 450 to 550 nm causes a colour change from blue to green. The green colour results from plasmonic scattering and is found to be insensitive to the angle of observation.
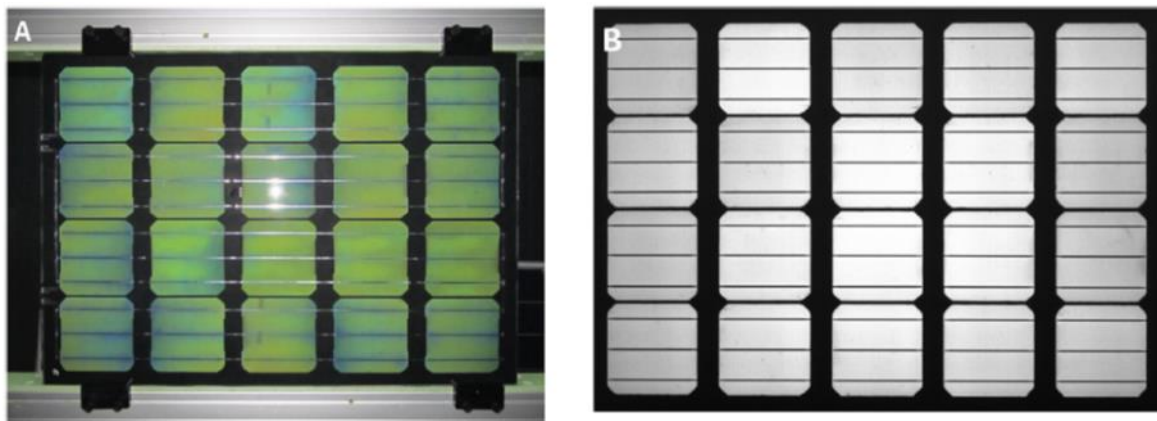
Figure 46: Left: Photo of the first module made of c-Si cells coated with Ag nano-particles. Right: Electroluminescence image of the module (no issues related to shunts or contacting) [4].

A performance analysis of the c-Si cells before and after coating shows that the power of the cells is decreased by less than 10% when the plasmonic coating is applied. A first test module consisting of plasmonic-green c-Si cells was carefully characterized and mounted in a test façade for building-integrated modules in order to generate data for the targeted field of application. The first results of

the test module demonstrate that plasmonic colouring is a feasible approach to tune the colour of standard c-Si solar cells for application in building-integrated photovoltaics, showing a reduced power of only 15%.

5.3.2 Coloured cover glasses

Conventional flat glass is normally coloured slightly green due to iron oxide impurities, as can easily be perceived when a glass pane is viewed through its edges. For PV applications, it is common to use flat glass with a lower amount of impurity, so-called low-iron flat glass, to optimize the light transmittance of the flat glass. However, additional constituents can be added to the glass composition to produce other specific colours. For example, additional iron can be used to produce a green colour, cobalt and iron for a blue colour, cobalt and selenium for a bronze or grey colour. The produced colour is perceived as being weakly coloured in transmission and the coloured glass does not exhibit significantly coloured reflection (see Figure 47). All major flat glass producers offer several body-tinted flat glass products i.e. by adding colouring agents to the glass melting process.
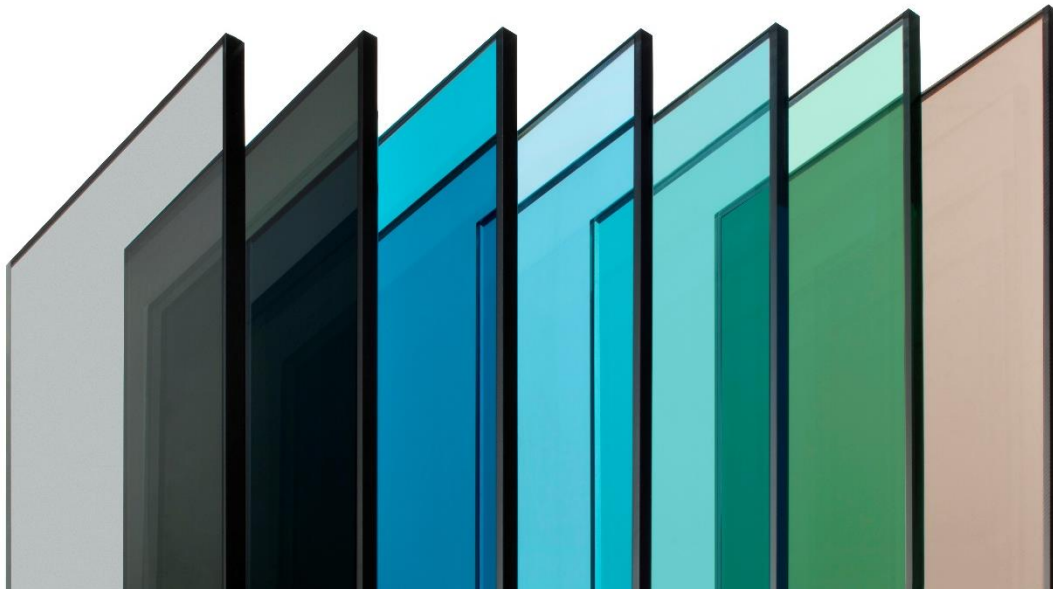

Figure 47: Examples of AGC Planibel Coloured: Grey, dark-grey, privablue, dark blue, azur, green and bronze. (Used with permission from AGC Glass Europe)

5.3.3 Printing and thin film coatings on cover glass

The cover for a BIPV module is usually made of low-iron glass featuring high transmittance. However, it can also be used as the substrate for a coloured ceramic coating, which is designed to disguise the underlying photovoltaic components of the module or to introduce new design elements. In principle, different methods are available to apply the ceramic material to the glass substrate, including digital printing, screen printing, roller coating, "curtain" coating and spraying. These are reviewed briefly in [68]. In practice, screen printing is a commonly used method for coating the glass cover of BIPV modules.

Screen-printed ceramic frits: In this method, a paste containing the ceramic pigment and matrix particles is distributed over and pressed through a framed screen onto the glass pane immediately below it. The geometrical parameters of the mesh constituting the screen and the viscosity of the paste are essential in determining the thickness of the applied coating. Either the entire surface of the glass substrate can be coated or a mask can be applied to the printing screen, such that partial printing with patterns such as spots, stripes or free forms can be achieved. After printing and drying, the enamel coating is fused onto the glass substrate by firing in a furnace. Simultaneously, this step is also part of the thermal toughening process for the glass substrate. Depending on the processing parameters, the thickness of screen-printed fritted (or enamel) coatings is typically between 25 μm und 35 μm [69].

In the PV module, the screen-printed glass cover is usually oriented such that the enamel coating is adjacent to the encapsulant layer, i.e. on the inner surface of the glass cover. The outdoor surface is thus the optically homogeneous, uncoated glass surface, which is also easier to clean than the enamelled surface.

The perceived colour is determined by properties of the pigment particles in the ceramic coating, namely their size, type and optical density. White coatings contain titanium dioxide particles which scatter radiation over the whole solar spectral range without significant absorption, whereas black pigments absorb strongly at least in the visible range of the spectrum. Coloured pigments absorb in some parts of the visible spectrum and reflect the remaining wavelengths. As the enamel consists not only of the pigments but also transparent glass matrix, the relative amounts of transmitted, absorbed and reflected radiation also vary strongly with the concentration of pigment particles in the matrix.

Clearly, if radiation in the spectral range which the solar cells can convert to electricity is removed by reflection or absorption in the ceramic coating, the photovoltaic power output will be reduced in comparison to the same cells with an uncoated glass cover. Transmittance measurements of the printed glass covers in air provide an initial indication of the maximum power loss that the cover can cause. In making such measurements, however, it is essential that all of the forward-scattered radiation actually be captured by the measurement equipment, which typically includes an integrating sphere [68]. Figure 48 shows the transmittance spectra for 6 mm low-iron glass substrates completely covered with white, grey and black screen-printed coatings, as determined with a sufficiently large integrating sphere (620 mm) and with one which is too small (220mm) for this measurement task. The measurement results obtained with the "small" integrating sphere are significantly too low in the cases of the white and grey fritted glass. In the case of the black fritted pane, the results obtained with the two spheres are almost identical.
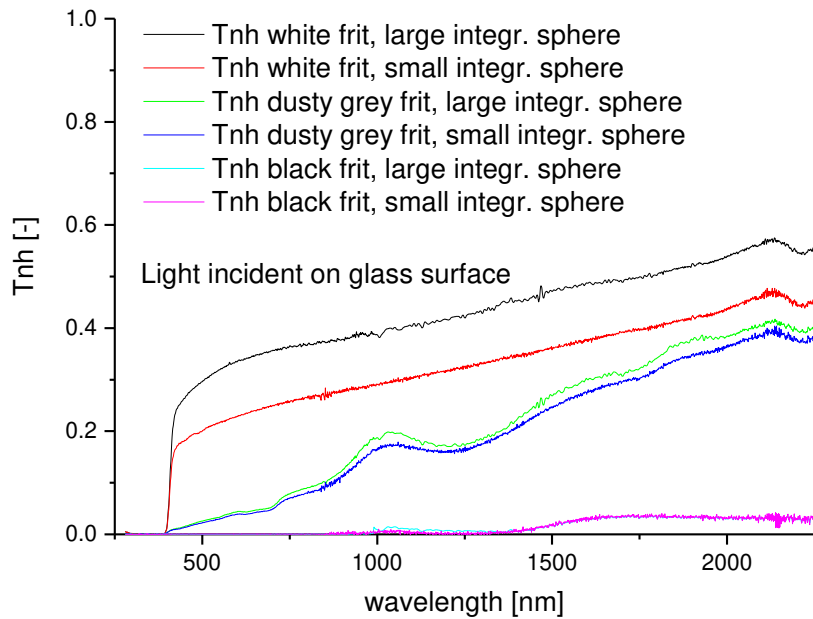
Figure 48: Normal-hemispherical transmittance (Tnh) spectra for 6 mm low-iron glass panes screen-printed with white, dusty grey and black frits over the whole surface [68]

For partial coverage of the glass pane with a printed pattern, the transmittance of the glass pane in air can be determined by measuring the transmittance of one pane with complete coverage, corresponding to the spectra presented in Figure 48, and the transmittance of an uncoated pane, and calculating an area-weighted average according to the proportion of printed and unprinted areas [70].

However, the ratio of transmittance measured in air for a printed glass cover to that of a "naked" glass cover will overestimate the power loss caused by the printed cover of a PV module. This is primarily due to the fact that in the PV module, the glass cover is optically coupled by the encapsulant to the absorbing solar cell, so that reflection losses from the second glass surface are considerably reduced compared to the measurement situation in air. This is demonstrated in [71] for glass covers with up to 40 % coverage of white, screen-printed dots (Figure 49), where the transmittance of the glass panes is compared to the short-circuit current generated by PV modules manufactured with these printed glass covers. For 40 % area coverage with the print, the transmittance loss of the glass pane measured in air relative to the unprinted glass substrate was 33 %, whereas the decrease in short-circuit current was only 18 %. This result is comparable to those reported in Section 5.2.1 of this report. These results demonstrate the necessity either to create and apply optically correct models of the PV module, including the scattering and optically coupling properties of its components [72], or to determine the power output directly from electrical measurements on PV modules manufactured with the relevant, printed glass cover [73].
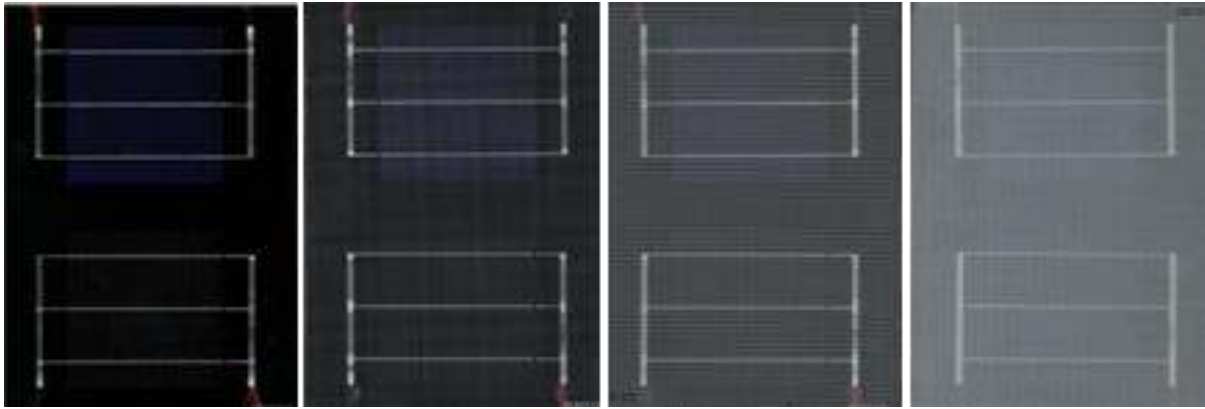
Figure 49: Photographs of mini-modules with covers made of digitally printed glass samples with different coverage ratios and the reference glass pane. From left to right: Reference glass, 10% coverage ratio, 20% coverage ratio, 40% coverage ratio; printed pattern consists of small dots [71]

Thin films on glass: In order to support acceptance and attractiveness of building-integrated PV (BIPV), there is a high demand for coloured PV modules. Architects, building planners and investors have special interest to design the building envelope e.g. with an individual colour choice, saturated colours, a homogeneous appearance for all angles of incidence and at the same time a high module efficiency.

Thin film technologies like physical vapour deposition (PVD) and chemical vapour deposition (CVD) allow a new approach to generate colours with interference coatings for PV modules with high colour saturation and homogeneity and a low power impact. Both mentioned thin-film technologies are widely used in the glazing industry for other type of coatings.

Interference coatings on glass: The basic principle found e.g. in nature on the wings of Morpho butterflies is a combination of thin-film interference effects and structure effects in one three-dimensional photonic structure [74, 75]. Due to the complex interactions in this functional layer, the angular dependence that is inherent to planar multilayer stacks can be compensated. The requirements for the filter function are high colour saturation and at the same time a high transmittance. This can be achieved by a spectrally narrow reflectance peak. The functional layer is applied to the rear surface of the module glass cover to protect this layer against weathering effects. It is manufactured by a combination of structuring and sputter coating technology. In a standard laminated module, it therefore is situated between the glass and the encapsulation layer (Figure 50).
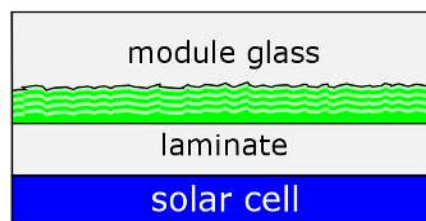

Figure 50: Sketch of the coloured module concept: the functional layer (green) is at the back of the glass cover and in contact with the laminate. Source: Fraunhofer ISE

For large-area demonstration, the functional layer was applied to glass panes of the format 1.09 x 1.12 m2. With these glass panes, PV module lamination was done at ertex solar GmbH. To provide a homogeneous black layer as a base for the colour, back-contact solar cells from Sunpower Corp. and a black backsheet and black interconnectors were used in order to achieve a homogeneous colour appearance with very high saturation (Figure 51). In order to enhance the colour tolerance and to decrease the given angular dependence, a texture may be applied on the front surface of the module glass.

To determine the influence of different coloured layers on module power output, three coloured PV modules (blue, green, red) were manufactured at Fraunhofer ISE. To compare the power output, two black reference modules were produced with the same module configuration. Power rating measurements at Fraunhofer ISE CalLab PV Modules showed an extremely low colour-induced efficiency loss. Compared to a PV module with an uncoated glass cover, the relative loss of generated solar power for the coloured modules is approximately 7%. The power loss is in the same range for all three colours [76].

In general, all colours can be produced by applying this interference layer technology. According to further spectroscopic measurements, the impact on the power output can differ depending on the selected colour.

Figure 51: Photograph of the large-area demonstration modules with the colours blue, green and red. Source: Fraunhofer ISE

6 References

All reference – weblinks were given after access in November 2018

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