Hidden colored Building Integrated Photovoltaics: technology overview and design challenges

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Abstract

Colored building integrated photovoltaics (BIPV) modules can hide the PV cells behind colored patterns which hinder the perception of the cells so that the PV modules appear very similar to standard construction materials. This feature represented a turning point in the social acceptance of BIPV applications and a wide range of colors is currently available on the market. This wide selection enables PV to be easily integrated in architecture, also in traditional roofs, façades, and shading systems. Nevertheless, further R&D activities are needed to improve their performance and reliability. The manufacturing of these modules is predominantly customizable for a specific installation, whereby is essential to balance aesthetic and energy aspects, and this poses challenges in the evaluation of their technical performance. This work aims at presenting the possibilities for integrating PV in the building envelope, focusing on printed, coated or finished front glass to provide additional aesthetic features to the BIPV systems. An overview of technological solutions for introducing colors in BIPV modules is provided and the design challenges for colored BIPV integration in the building stock are discussed, by presenting some exemplary case studies.

Keywords: BIPV; appealing PV; aesthetics; color; component performance; customization; cost-benefit.

1. Introduction

Transforming the building stock into nearly zero or positive energy is a key aspect to meet the decarbonization targets worldwide (United Nation Framework Convention on Climate Change in 21st Conference of the Parties 2015; Chiang et al. 2013; European Parlament 2018). In this context, building integrated photovoltaic (BIPV) technologies stand as a promising solution to harvest solar energy for on-site and diffuse energy production, contributing to the transition from fossil fuels to cleaner energy to be used in buildings (Michas *et al.*, 2019). BIPV systems are multifunctional envelope elements, which can be integrated into the building skin at three different levels: (i) aesthetic, i.e., by meeting the architectural language of the building; (ii) technological/functional, i.e., by fulfilling all the functional requirement of a standard envelope component; (iii) energy, by interacting efficiently with the energy systems of the building, increasing the share of renewables used to cover the building's energy use (Maturi and Adami, 2018). Despite their high potential, the large-scale application of BIPV has been hampered due to the difficulty of traditional photovoltaic modules in meeting the aesthetic features of conventional architectural materials (Saretta, Bonomo and Frontini, 2018). The introduction of colored BIPV modules represented a breakthrough in the spread of BIPV installations and their social acceptance ("PV Accept"; "3ENCULT: Efficient Energy for EU Cultural Heritage"; "BIPV Meets History: Value-Chain Creation for the Building Integrated Photovoltaics in the Energy Retrofit of Transnational Historic Buildings"). The aesthetic improvements of BIPV technologies may unlock the solar potential of a large set of vertical and horizontal envelope surfaces that would not be exploited otherwise, but it requires a very high customization level, concerning colors, shapes, sizes, finishing (Huang *et al.*, 2019; Lovati *et al.*, 2019). Therefore, one of the main challenges in the design of hidden colored BIPV modules is the balance between aesthetic and energy aspects, i.e., the optimization of the technical performance of highly customizable products against the real requirements of the built environment. In particular, there is the need to improve the awareness on colored BIPV technologies with regards to their multifunctional integration features, assessing their performance reliably as envelope components and as well power generation systems (Pelle *et al.*, 2020). This work aims at presenting the technological solutions for integrating PV in the building envelope, focusing on printed, coated or finished front glass used in front of a PV layer, to provide additional aesthetic features to the final product. Firstly, an overview of technological solutions exploiting colored layers to modify BIPV modules' appearance is presented, with a particular focus on the methodologies used to link aesthetic and energy features, i.e., modules' color and

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efficiency. Then, the design challenges for the multilevel integration of BIPV systems in the envelope are discussed. Specific focus is given to architectural integration, and detailed discussion on the customization possibility of products is presented, based on specific aesthetic parameters. Finally, exemplary case study collection, using colored BIPV as envelope solution, is provided.

2. Technological solution for hidden colored PV modules

High customizable BIPV technologies guarantee larger aesthetical possibilities, required by architectural applications to ensure flexibility in the design (Pelle *et al.*, 2020). The ability of BIPV products to match the architectural language and composition of buildings, through different shapes, dimensions, colors, and textures represent a clear advantage for BIPV integration in the building envelope (A. Scognamiglio, A. Berni, F. Frontini and Maturi, 2012; Farkas *et al.*, 2012; Franco and Magrini, 2017). Large possibilities for customization constitute on one hand the strength and the uniqueness of BIPV products in the PV scene, but on the other hand, it could also represent a limit for industrial production and cost reduction (Gewohn *et al.*, 2021). Different customization techniques to obtain colored or textured BIPV modules are currently used. They mainly differ from the position and kind of colored layer used for manufacturing (Grobe, Terwilliger and Wittkopf, 2020). Colored layers can be introduced as part of the active layer or added to the module's assembly, as a further component of the module stuck, behind or in front of the active layers (Eder *et al.*, 2019). The introduction of a colored layer behind the active components of the PV module does not interfere with the conversion of solar radiation into electricity, thus it does not affect the energy yield of the system. Whereas, when colored layers are interposed between the active layer and the light source, or it is integrated within the active layer, it modifies the spectral power distribution of the solar radiation available for power conversion, since part of it is reflected, in the visible spectrum, to display colors (Peharz and Ulm, 2018; Halme and Mäkinen, 2019; Røyset, Kolås and Jelle, 2020). Integrating the color in the active layer of PV technologies means that the color is introduced in the manufacturing process of the PV cells, within the active layers. This is possible, for example, by including different dyes in the production of perovskite solar cells, dye-sensitized solar cells (DSSCs) or luminescent solar concentrator (LSC) or employing active materials that exhibit different absorption spectra in semitransparent organic photovoltaic cells (OPVs) (Kuhn *et al.*, 2021). The BIPV modules produced with such a technique present a uniform, semitransparent colored appearance. Another possibility is to optimize the thickness and the refractive index of the passivation or anti-reflection coating (ARC) of silicon or CIGS PV cells (Pascual-San José *et al.*, 2018; Ji *et al.*, 2019). This process results in different colored cells, according to the coating typology and thickness. Interposing a solar layer between the active layer and the light source means that an additional colored layer is added to the modules stuck, during the lamination process, without interfering with the manufacturing of the active layer. The colored layer can be added in interlayers or encapsulant films or through the modification of the front glass, that can be printed, coated or textured, according to the architectural needs. Colored additional layers can be used in the lamination of several BIPV technologies, including crystalline and amorphous silicon, thin-film, perovskite (Kuhn *et al.*, 2021). Among interposed colored layers, some present almost endless customization possibilities, such as BIPV modules with printed, coated or finished front glass, polymeric interlayer or textile additional layers that can be digitally printed. In the following, the focus is given on this kind of technology, which can guarantee a higher level of flexibility in the design choices, while relaying on robust and efficient technology, such as c-Si PV cells as active layer. In particular, the design challenges to be addressed for a correct multilevel integration of BIPV systems in envelope are highlighted, and the possibility for customization presented.

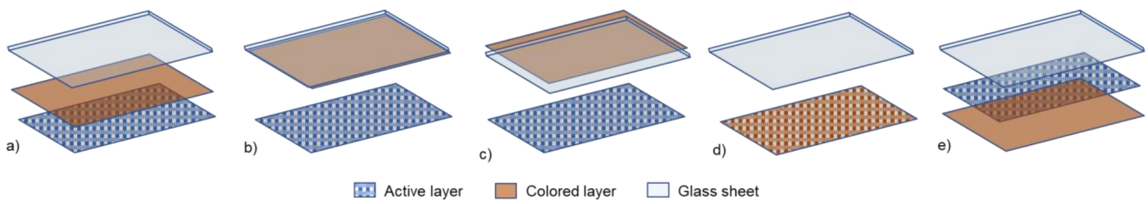


Fig. 1. Schematization of the customization techniques to obtain colored or textured BIPV modules: a) colored interlayer or encapsulant; b) colored coated front glass; c) colored layer on top of the front glass; d) colored or coated active layer; e) colored back sheet.

3. Design challenges for BIPV architectural integration

Aesthetical integration of BIPV is crucial for boosting the spread of BIPV technologies. Highly customizable products allow designers to study and select freely the best integration features of BIPV modules in their projects. But it is always important to keep in mind the multifunctionality of BIPV modules as technological envelope elements. To guarantee the complete freedom of expression for designers, there must be a sufficient range of modules, colors, and finishing, so that it is possible to design using these elements as traditional building materials, as stone, metal, and glass. Existing BIPV modules can be produced in a wide range of sizes or shapes, but consideration should be given to the required electrical system, consisting of PV cells and electrical connections. Therefore, the architectural and technical design must be addressed simultaneously. To obtain the best results out of BIPV installation, designers must consider the energy generated by the modules as a part of an integrated design process, that includes architectural, technological and energy aspects. Moreover, since every building is different, in terms of shape, landscape context, size, function, etc., the design of BIPV systems should also consider the context in which the PV modules are applied. For example, the integration of BIPV modules with a shining finish on the façade of a building could cause glare problems to the surroundings, and this is particularly critical in dense urban environments and in presence of high traffic streets. Nowadays market provides a wide range of possibilities to customize BIPV installation, but the multifaced available technical solutions could make module selection complex for the designer, who needs proper information to support the design choices on the three integration aspects. In (Pelle *et al.*, 2020), a methodology is provided, for the evaluation and selection of the most suited BIPV technology to be used in a specific project. The study identifies the specific parameters needed to better assess BIPV integration features. From a technological integration point of view, BIPV technologies that provide multifunctionality, i.e., the possibility to be used in different envelope positions by choosing the appropriate mounting system (e.g., as façade rain-screen and as a roof tile) facilitates the standardization of the products manufacturing and the procurement design. From the energy integration point of view, it is always fundamental to consider the efficiency and nominal power of the specific product. The most challenging aspects to be considered are the ones related to aesthetic integration, which, as said, could affect all the design levels. Among these, shape, and dimension, color, which affects the modules' efficiency, and the finishing, which influences the modules' reflectance, are identified as crucial information for the system design. Hereafter, a detailed overview of these design parameters for BIPV technology is provided.

3.1 Dimension

The use of standard single-sized BIPV modules on building facades is prevented by numerous obstacles such as windows, doors, roof pitches, etc. For this reason, the BIPV modules must adapt to the geometry of the façade. Most of BIPV modules can be customized in shape and size. In the case of new buildings, priority is given to making the module size as homogeneous as possible, but this is not always achievable. In the case of renovations, however, the BIPV modules always have to adapt to the geometry of the existing façade. Consideration should be given to the required electrical system consisting of PV cells and electrical connections. Currently, standard BIPV modules based on silicon PV cells use cells of size 156.75 x 156.75 mm or 158.75 x 158.75 mm, although the current market is moving towards larger cells. The modules' electrical components must adhere to specific regulations (IEC 61215, IEC 61730, LU1703) to guarantee optimal functioning and safety. For example, all active elements within the module must be spaced at least 8 mm away from the edge of the glass, and distances of up to 20 mm are possible for safety reasons. As a consequence, if the architectural design requires module dimensions that are too small to accommodate the circuit board with the PV cells while complying with the specific standard (the minimum size for an active module accommodating standard c-SI cells is 360x360 mm), dummy modules, i.e., passive PV modules that are aesthetically identical to active modules but without PV cells must be manufactured, to guarantee chromatic and materic uniformity to the façade. The introduction of passive façade components has an impact also on the energy integration of the BIPV system since it implies a smaller surface available for energy production.

3.2 Finishings

In addition to the dimension, architects and designers can also customize the finish of the front glass. Solar glass, which has a microstructure that allows the best performance of the module in terms of efficiency, is mostly used for roof-integrated modules. Shining glass is mainly used for PV modules that can be integrated into facades or balconies. Nonetheless, the integration with this glass type must be carefully considered because of its high reflectance that may cause glare in the surrounding area. On the contrary, sating glass provide antireflective feature allowing an easier integration into all vertical and horizontal surfaces of the building. One of the latest innovations in the BIPV scene is structured glass. In this case, the front glass sheet of the BIPV module is provided with tridimensional patterns. There are different possibilities for structured glass customization, including vertical and/or horizontal lines or sanding, that allows the BIPV module to better mimic the texture of a traditional building material (Fig. 2).

3.3 Colors and patterns

To provide better integration of PV modules in all environmental contexts and building types, architects and designers have the opportunity to customize the front glass of the BIPV module. The customization can provide uniform colors and reproduce an image or texture on the front glass (Fig. 3). For example, it is possible to reproduce the pattern or a high-resolution photograph of traditional building materials, so that the modules can be perfectly integrated into the surrounding traditional landscape. In cases of renovation of an existing building, the exact texture of the original material can be replicated on the BIPV modules. This solution is mainly adopted where landscape constraints for the integration of BIPV modules are present. The color shades or the pattern can be chosen from a standard palette, but it is also possible to customize modules design depending on the project requirements. As explained before, each color has a different effect on the efficiency of the PV modules. For standard colors (e.g., traffic white, terracotta, brown, greyish blue, green) the electrical specifications are determined, whereas in customized colors they are usually determined by post-production tests.

Fig. 2. Examples of modules' size customization for adapting the BIPV system to the façade geometry. On the left; Wohnüberbauung Männedorf Project, Männedorf, Switzerland (2020-2021) on the right: Opfikon Project, Opfikon, Switzerland (2018). Images courtesy of SUNAGE sa.

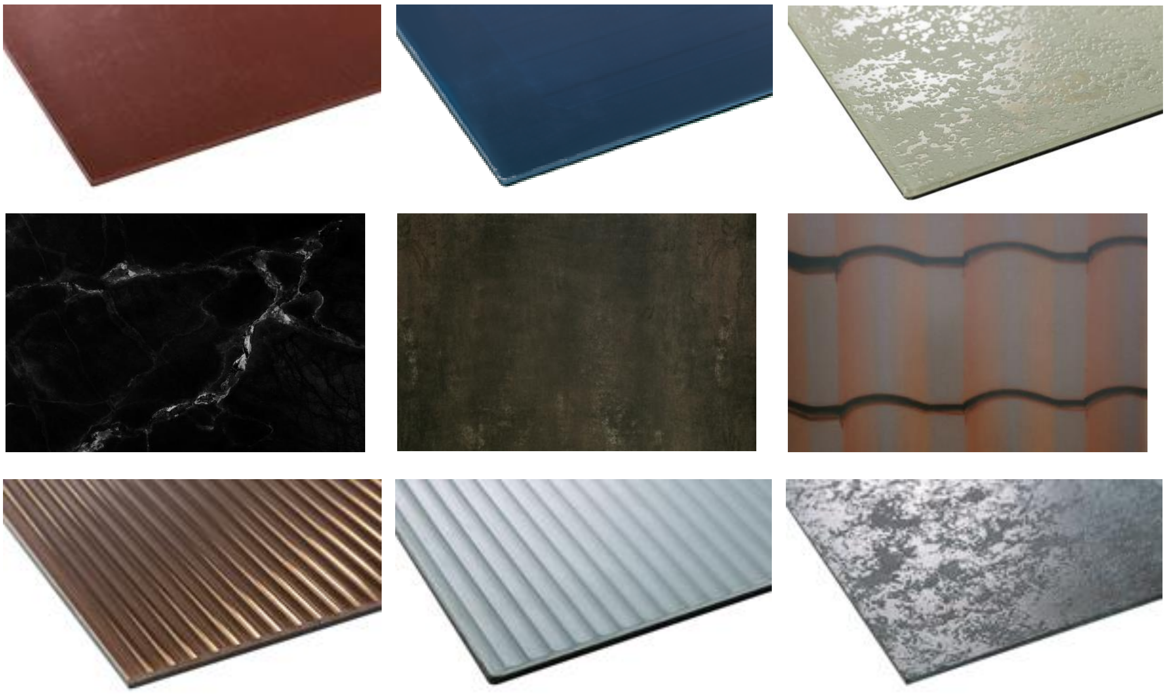


Fig. 3. Examples of customized colors and patterns. From the top left: terracotta color, grayish-blue color, sanded light green, marble pattern, cortex pattern, roof tiles pattern, vertical lines bronze, vertical line grey and sanding. Images courtesy of SUNAGE.

4. Colored BIPV: case study collection

In the following, some exemplary case studies that used colored and/or textured BIPV modules in the envelope (façade and/or roof) are reported and discussed. The peculiarity of each project in terms of design challenges are highlighted, describing the technical solution introduced to address them. Each case study is presented with a short introduction, a technical sheet providing information on the building type, the power installed, the efficiency of the installed BIPV modules, the BIPV installation surface, the number and type of the installed modules, their color and finishing. Then a short description of the most peculiar design features of the BIPV system are provided and a discussion on the technical solution adopted is presented.

4.1 Multi-functional Centre of Pregassona, Lugano, Switzerland (2020-2021)

Multi-functional “zero energy” building. It currently has the largest BIPV facade in Ticino and hosts:

- a medical residence for elderly people.
- a day-care center for senile dementia patients
- the new headquarters of the Municipal Social Welfare Service (SAS);
- a kindergarten.

This project was commissioned by the municipality of the city of Lugano. The project was determined by a public tender and was initially designed with a traditional white panel façade. After the project was approved and in progress, the architect and the client decided to transform the facades into an active surface by integrating BIPV modules. The building is very complex and consists of 10 different facades with different exposures. As the project was already underway, the BIPV modules had to be adapted to the existing design in terms of shape and color. Minimum efficiency of the PV system on the façade was required by the designers and the client to facilitate the investment. The color required by the architectural design was white, and it could not be changed. White color is very difficult to achieve in c-Si BIPV, as the PV cells underneath the colored layer are black. Therefore, achieving the required efficiency with the already established color was a challenge. The color design required numerous samples and tests, but in the end, the desired result was achieved. Furthermore, the size of the PV modules could not be changed from the original design. For this reason, different sizes were needed and modules up to a size of 0.9 x 2.905 m were produced. For a better energy yield, depending on the exposure of the building, irradiation models were made to study the shadows cast over the building from the surroundings. The results of these analyses have been used to determine the best configuration of the electrical circuit within the PV modules so to reduce the impact of the shadows on the global efficiency of the BIPV system.

- Type of building: Public
- Power installed: 220 kWp
- Efficiency: 13.5%
- Surface: 1’675 sqm
- Number of modules: 806
- Type of modules: Glass / Glass 4+4 mm
- Color: Light grey
- Finishing: Front satin glass

Fig. 4. Pregassona project, Switzerland: overview of the solar façade (left) and BIPV modules’ detail (in the center). On the right: project’s figures. Images courtesy of SUNAGE

4.2 Project Thalwil, Switzerland (2020)

This project has been developed by Tobler Litscher GmbH firm. The building is characterized by the brown structured glass BIPV modules on the facade, and it also includes a customized grey solar roof made with structured glass BIPV modules. The modules were produced in a uniform brown color to blend in with the surrounding landscape and to match the colors of the window frames. All facades and the roof are covered with the same type of BIPV modules. The glass front is structured in vertical lines with a shining finish. The façade modules were custom-made but are designed to be almost all the same size, to lower the production costs. The roof modules were also custom made and have different shapes to suit the shape of the four-pitch roof.

- Type of building: Residential
- Power installed: 32 kWp
- Efficiency: 12.3%
- Surface: 264 sqm
- Number of modules: 282
- Type of modules: Glass / Glass 4+4 mm
- Color: Brown (façade): Brown (roof) Finishing: Front structured shining glass type BA with vertical lines

Fig. 5. Thalwil project, Switzerland: overview of the solar façade (left) and BIPV modules' detail (in the center). On the right: project's figures. Images courtesy of SUNAGE

4.3 Solar Living Kloten Kloten, Switzerland (2020)

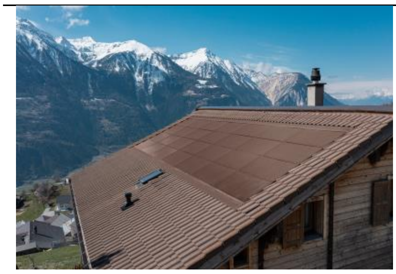
The Kloten project is a private multi-family building. The BIPV modules were designed with only 2 different sizes and in 3 different colors. The modules combined with different colors give movement to the façade, like a mosaic. The architect's stylistic choice also opted for a structured satin-finished glass with vertical lines to further mark the direction of the modules. The modules do not cover all the available surfaces of the façades, but only some vertical bands. The modules blend into the building façade with other traditional building materials.

- Type of building: Residential
- Power installed: 26.7 kWp
- Efficiency: 14.9%
- Surface: 223 sqm
- Number of modules: 408
- Type of modules: Glass / Glass 4+4 mm
- Color: 3 different shades of green
- Finishing: Front structured satin glass type BA with vertical lines

Fig. 6. Kloten project, Switzerland: overview of the solar façade (left) and BIPV modules' detail (in the center). On the right: project's figures. Images courtesy of SUNAGE

4.4 Erschmatt Project Erschmatt, Switzerlan (2020)

The Erschmatt project is a traditional mountain-dwelling typical of Switzerland's Alpine environment. The traditional tiles roof blends with the terracotta BIPV modules. The architects wanted to intervene on an existing traditional building by applying BIPV modules on a portion of the roof. Because of the valuable surroundings, modules were chosen to be reminiscent, in terms of color and mounting system, of the traditional tile covering which were installed on the other roof surfaces. The photovoltaic modules were applied on both sides of the roof, given the building's excellent exposure. The brown-colored modules reproduce the traditional tile roofing, provide aesthetical integration for the BIPV components into the building and the surrounding landscape.



- Type of building: Residential
- Power installed: 10.64 kWp
- Efficiency: 15.75 %
- Surface: 69.50 sqm
- Number of modules: 70
- Type of modules: Glass / Glass 3.2+3.2 mm
- Color: Terracotta
- Finishing: Front solar glass

Fig. 7. Erschmatt project, Switzerland: overview of the solar façade (left) and BIPV modules' detail (in the center). On the right: project's figures. Images courtesy of SUNAGE

5. Conclusion and future work

On-site production from renewable energy is pivotal for promoting zero energy or positive buildings and building integrating photovoltaics (BIPV) constitute a valuable solution to integrate PV technologies in the building envelope. The introduction of colored BIPV modules represented a breakthrough in spreading BIPV installations and improving their social acceptance, due to the difficulty of traditional photovoltaic modules in meeting the aesthetics features of conventional architectural materials. High customizable BIPV technologies guarantee larger aesthetical possibilities, required by architectural applications to ensure flexibility in the design. The ability of BIPV products to match the architectural language and composition of buildings, through different shapes, dimensions, colors, and textures represents a clear advantage for BIPV integration in the building envelope. Nowadays market provides a wide range of possibilities to customize BIPV installation and different customization techniques to obtain colored or textured BIPV modules are used, even if further R&D is needed to improve their performance and reliability. Among colored technologies, some guarantee a higher level of flexibility in the design choices, allowing almost endless customization possibilities while relying on robust and efficient technology, such as c-Si PV cells. This is the case of BIPV modules with printed, coated, or finished front glass, polymeric interlayer or textile additional layers that can be digitally printed. Nonetheless, architectural and technical design must be addressed simultaneously, considering that BIPV envelope components host an electrical system, consisting of PV cells and electrical connections. Therefore, the modules' energy generation should be addressed as a part of an integrated design process, that includes architectural, technological and energy aspects, to obtain the best results out of BIPV installation. The most challenging aspects to be considered are related to aesthetic integration, which could affect all the design levels. Among these, modules characteristics that are identified as crucial for a better design are (i) the shape and dimension, (ii) the color, which affects the modules' efficiency, and (iii) the finishing, which influences the modules' reflectance. In this work, these features are investigated in deep, and the challenges that they pose for a correct multilevel integration of BIPV systems in the envelope are highlighted by providing exemplary case studies. Future challenges for colored BIPV systems will deal with balancing industrialization and customization aspects, to make BIPV technologies more competitive and profitable. In fact, the use of colored front glass may result in an extra cost up to + 40%, when compared to standard glass-glass BIPV modules with transparent front glass, while using a colored and structured glass may result in an extra cost up to + 60%. A possible solution to support this process, is the development of tools that allow the prediction of the energy yield for arbitrary chosen colors or patterns. These tools would provide manufacturers with useful information on both the aesthetic appearance and on the energy performance of colored PV modules, avoiding the manufacturing and testing of prototypes for new customized products. These aspects are currently investigated within the Horizon 2020 INFINITE project ("INFINITE Building Renovation").

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