BIPV MEETS CUSTOMIZABLE GLASS: A DIALOGUE BETWEEN ENERGY EFFICIENCY AND AESTHETICS

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ABSTRACT: The realization of Building-Integrated Photovoltaics (BIPV) facades with black and blue conventional modules has represented a first step of innovation in the process of PV transfer in sustainable buildings. Nowadays, architects are looking for additional BIPV products to design active facades with novel architectural languages. For this reason, BIPV manufacturers started to customize BIPV modules in order to meet architects and clients' requirements. However, changing traditional front solar glass to obtain coloured PV, can influence the final module power output. Even though there are already investigations about the reduction of PV energy output due to the front glass aesthetical treatments, there are not yet clear correlations between alternative design options (glass treatments and colours) and their operative conditions as façade elements.

This paper is firstly aimed at providing a systematic investigation about novel mono-chromatic BIPV products in order to identify the influence of some main design options on the electro-thermal performances of modules. Specifically, this analysis is performed by evaluating, in collaboration with a Swiss industrial partner, a range of customized mono-chromatic BIPV prototypes by means of indoor measurements and outdoor tests. Furthermore, these results have been used to preliminarily assess the electro-thermal behaviour of multi-chromatic BIPV configurations both at STC and outdoor conditions. As a result, it arises that the operative condition should be carefully considered to qualify the behaviour of multi-chromatic BIPV modules with novel aesthetical designs in order to provide reliable data about the real electro-thermal behaviour.

Keywords: coloured BIPV modules, glass aesthetical customization, BIPV efficiency, BIPV operative conditions

1 INTRODUCTION

Building Integrated Photovoltaics (BIPV) provides the opportunity to contribute to the energy sustainability of the built environment since it enables building surfaces to become energy generators, still constituting a building material.

In recent years, the deployment of BIPV facades has been emerging, especially thanks to: (i) their suitability to spread the energy production through the day, when BIPV façades with different orientations are realized, and (ii) their larger surface area in comparison to roofs (in particular for multi-storey buildings), which could potentially improve the building energy target and the self-consumption. However, since building facades represent also the expression of architectural languages, architects are looking for aesthetically appealing materials for realizing active surfaces. In this context, from the collaboration between glass manufacturers and BIPV producers, novel customized BIPV modules are arising thanks to the use of different front glass treatments to obtain various colours, textures or material appearance, different reflectivity, visual/optical effects, etc [1].

If aesthetical improvements are an added value of these BIPV products to support a more and more dynamic market, there can be variations of the energy behaviour in comparison with traditional PV modules, such as the power output reduction and/or the unconventional (e.g. non uniform) operative conditions, which need to be further investigated in order to provide the market with reliable and efficient BIPV systems.

Currently PV modules are optimised, selected and sold on the basis of power produced under standard test conditions (STC). However, this metric does not always reflect real-world conditions. Especially for tailor-made BIPV components, more insight into measurement methodologies, energy rating, safety, degradation rates mechanisms and further knowledge on performances and long-term stability are now requested. On one hand the authors are contributing to develop more accurate measurement methods for emerging solar modules, for extending energy rating to modules applied to or integrated into buildings, with the goal to extend the IEC 61853 standard series with some technical specifications taking BIPV into account [2]. On the other hand, a detailed analysis of power loss and performance under real operating conditions is necessary in order to understand how the special BIPV modules (e.g. coloured, mono or multi-chromatic) behave and, consequently, to laid down a first step in defining characterisation and measurement approaches for special BIPV modules to accurately reflect the real operating environment which is still not fully understood.

Within this framework the paper focuses on analysis of energy performance of coloured modules, by introducing a systemic analysis through an indoor measurement campaign on a range of significant mono-chromatic BIPV prototypes, which take into consideration different colour types and the glass treatments, to define how these design options affect the electrical performances of BIPV modules. Furthermore, outdoor measurements have been carried out in order to also investigate and characterize how the electro-thermal performances of such a products are influenced by real operative conditions.

Besides this, the mismatch among different coloured BIPV prototypes has been analysed by considering both indoor and outdoor conditions with the aim to identify which design parameters can be optimally combined to obtain multi-chromatic BIPV modules, without significantly reducing the electrical performances.

2 APPROACH AND METHODOLOGY

Recently, some aesthetical BIPV novelties, such as coloured modules, has arisen from the encounter between the glass manufacturers and the PV manufacturers know-hows. However, the realization of a coloured coating to hide cells on BIPV modules can involve a different electro-thermal behaviour in comparison to traditional modules, that need to be assessed in order to provide market with reliable BIPV elements.

Some of these mono-chromatic BIPV modules have been already installed in building facades, such as in lighthouse buildings which have become icons of solar architecture. If BIPV modules would become façade elements, it should also offer the option to be customized so that architects and façade engineers can also envision multi-chromatic BIPV modules to develop their own façade designs. Since multi-chromatic modules are not yet in the market as standard products, this till requires glass and PV manufacturers to develop tailor-mades products with specific and complex manufacturing and qualification processes. In order to support the development of custom BIPV products, it would be convenient to investigate "a priori" the main design options and define the most sensitive parameters of customization for ensuring energy efficiency, reliability, in order to avoid time and cost savings.

In this perspective, this paper provides a systematic investigation about some mono-chromatic BIPV prototypes in order to identify the influence of some design aspects (colours and front glass types) on the electro-thermal performances of the module. This analysis has been carried out by means of both indoor and outdoor measurements. Then, on the path to the development of multi-chromatic BIPV modules, the evaluation of the mismatch among different coloured BIPV modules has been performed with the goal to preliminarily assess the electro-thermal behaviour of multi-chromatic BIPV modules both at STC and outdoor conditions.

2.1 Prototypes

All the prototypes are glass/glass modules made of 4 mono c-Si cells connected in series and laminated within two glass panes of 3mm thickness each.

Table 1: Characteristics of the BIPV prototypes and their ID code

Colour	*Satin*	*Float*		*Colour degree [%]*
	Position 2	*Position 1*	*Position 2*	
No colour	C1	C2		-
Blue	D1	D3	D2	10
Green	E2	E1	-	10
Light grey	A1	A3	A2	10
Dark grey	B2	B3	B1	10
Terracotta	F3	F2	F1	10

In detail, the front glass of the prototypes has been customized by combining three main design options: the glass type (float/satin finish), the positioning of the colour (outer side – position 1 / inner side – position 2), and the type of colour, as shown in Table 1. For all the prototypes, the coating technique before the glass tempering process has been used for the colour application.

2.2 Methodology

If on one hand front glass treatments can improve the aesthetical perception of BIPV modules by hiding the solar cells, on the other hand they can affect the electrical performances, in comparison to traditional PV modules.

In order to investigate such aspects, this research study has been articulated into two main phases. The first phase regarded the indoor characterization of mono-chromatic BIPV prototypes. In this we evaluated the influences on the electrical parameters of the type of front glass and the type of colour with the aim to compare the coloured modules with reference modules, as well as among each other. Since real operating conditions can affect the electrical behaviour of coloured modules [3], a second phase has been envisioned to characterize the operative thermo-electrical characteristics of the prototypes. Therefore, a group of BIPV prototypes have been exposed in the outdoor test facilities in order to investigate the colour influence on the modules' operative temperature and power output.

The second phase involved the investigation of a set of coloured BIPV prototypes to evaluate how they perform when they are combined in series, in order to preliminarily identify which design options are compatible to form a multi-chromatic BIPV module. Hence, not only theoretical calculations have been carried out, but also indoor and outdoor measurements have been performed with the aim to assess the validity of the method adopted.

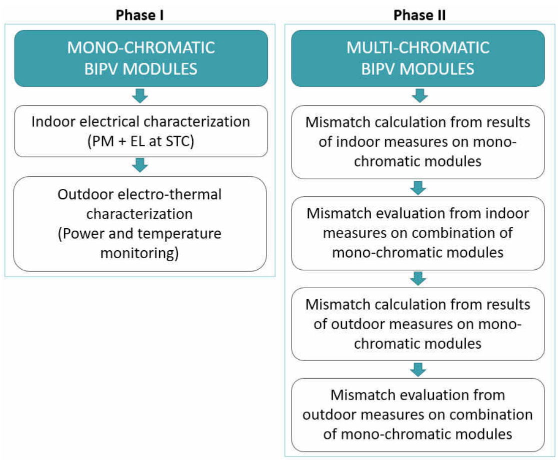

Figure 1: Methodology implemented in the study for the evaluation of the electro-thermal behaviour of mono-chromatic and multi-chromatic BIPV modules.

2.2.1 Indoor characterization

Indoor characterization tests for mono-chromatic modules have been performed in the laboratory of ISAAC-SUPSI with the aim to assess the influence of both the types of glass and the colours on the power parameters at STC. Moreover, electroluminescence (EL) was performed to evaluate the quality of the cells.

Grounding on the resulting IV curves, mismatches among different mono-chromatic prototypes have been calculated. As a consequence, modules with similar electrical characteristics have been combined in series and subjected to power measurements at STC in order to check their electrical compatibility for the development of multi-chromatic modules.

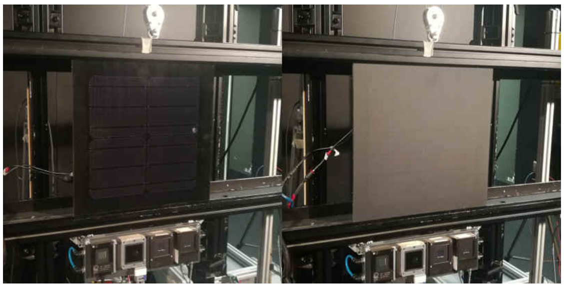

Figure 2: BIPV prototypes. Left picture: PM on reference module “C2”. Right picture: PM on satin finish dark grey module “B2”.

2.2.2 Outdoor characterization

A group of coloured BIPV prototypes have been selected to be exposed in the outdoor test facilities of ISAAC-SUPSI in Lugano (Switzerland) to evaluate their electro-thermal behaviour in real operative conditions. The prototypes have been installed as façade elements and have been equipped with Maximum Power Point Trackers developed by SUPSI, which have been adapted to their voltages and current ranges. Moreover, a pyranometer has been installed to record global irradiance at 90°, and also wind speed and ambient temperature have been monitored. In order to achieve a high level of reliability in the inter-comparison, improved data quality control and an advanced data analysis procedure were used [4]. In addition to electrical parameters, also temperatures have been tracked by means of temperature PT100 sensors placed on the back glass of the prototypes.

Finally, power and temperature measurements have been performed on a couple of mono-chromatic BIPV modules in order to assess their combination in-series.

Figure 3: prototypes installed at ISAAC-SUPSI outdoor test facility in Lugano (Switzerland).

3 MONO-CHROMATIC BIPV MODULES CHARACTERIZATION

3.1 Indoor characterization

As a preliminary step, all the prototypes have been subjected to electroluminescence tests to evaluate the presence of damaged cells that can affect the efficiency. From the emerging results, it arises that there are not relevant damages, hence the power measurement tests at STC have been performed. In detail, the results have been analysed in order to identify the main influencing aspects on the power output of the modules.

When the power output results are analysed for the same colours and different glass types (Figure 4), it arises that differences are in the range between a minimum of 0.3% for the green prototype and 3.3% for the dark grey prototype. Moreover, there is no evidence of efficiency variations when the colour is applied in position 1 or position 2. What is interesting to note is that the satin finish effect of the front glass does not affect significantly the power output of the prototypes. Indeed, in the case of reference, blue and terracotta prototypes, the satin finish modules have a higher power in comparison to float glass modules.

On the other side of the coin, analysing the prototypes with the same front glass treatment (Figure 5), it emerges that the colour type significantly affects the power output. As a result, among the coloured modules, the blue prototypes show less power reduction in comparison to the reference module, while the dark grey prototypes performs the maximum power losses, independently from the glass type.

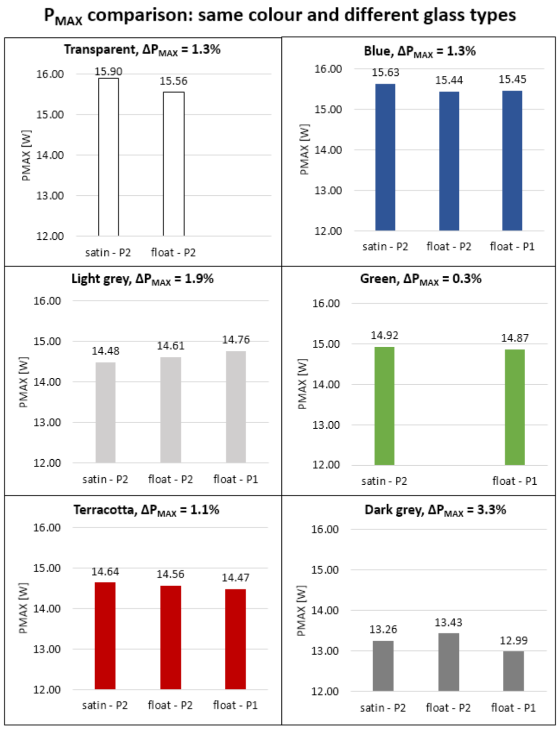

Figure 4: Comparison of the power output for prototypes with the same colour type to analyse the influence of different glass types and colour positioning.

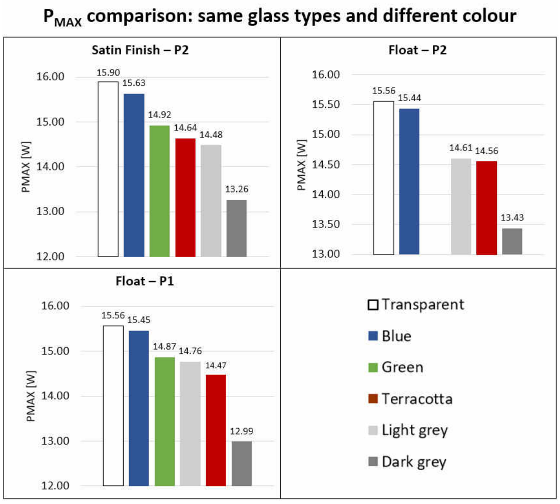

Figure 5: Comparison of the power output for prototypes with the same glass types and colour positioning to analyse the influence of the colour types.

3.2 Outdoor characterization

The outdoor tests have been performed on the mono-chromatic modules with float glass and colour applied in position 2, internally. Specifically, the following prototypes have been mounted in vertical position as façade elements: reference, blue, light grey and terracotta. The power output and temperatures of the prototypes recorded over one day are shown in Figure 6.

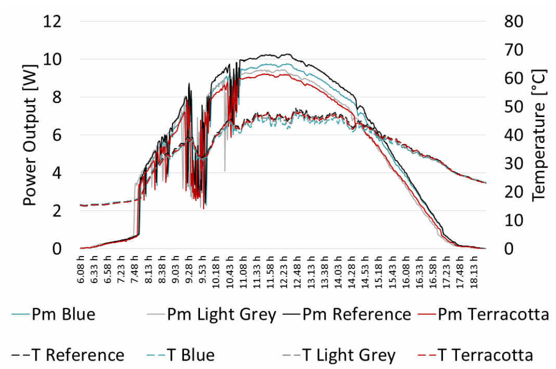

Figure 6: Power output and temperature of the prototype with float glass and colour applied in position 2, internally (data recorded over one day in Lugano)

From the analysis of the power output monitoring, it arises that prototypes have the same electrical behaviour of the indoor measurements. The reference prototype (transparent, non-coloured front glass) performs always better than other prototypes even though it shows higher operative temperature. Among coloured modules, the blue one has a higher power output, while the terracotta and the light grey prototypes are performing worst. In detail, the daily energy losses in comparison to the reference prototype are in the amount of:

- 4.9% for the blue prototype;
- 8.1% for the blue prototype;
- 10.5% for the light grey prototype.

From the evaluation of the recorded data it arises that operating temperature seems to do not significantly affect the modules behaviour since the temperature difference is in the maximum amount of 2 degrees and this is probably due to the low amount of colour that has been applied on the front glass. In detail, this colour degree allows to obtain an aesthetical effect on modules, without affecting in a relevant way their electro-thermal behaviour.

4 MULTI-CHROMATIC BIPV MODULES CHARACTERIZATION

Besides the evaluation of the mono-chromatic BIPV modules, this study is also aimed at investigating how different colored BIPV prototypes can be combined in series for envisioning the design of a multi-chromatic module. For this reason, a calculation method has been defined to evaluate if it is possible to preliminarily identify which design options are compatible to form an efficient multi-chromatic BIPV module. Specifically, this methodology consists of two steps:

- 1st step: evaluation of the mismatch among different mono-chromatic modules, by using data arising from indoor measurements;
- 2nd step: evaluation of the mismatch among different mono-chromatic modules, by the assessment of data retrieved from outdoor monitoring.

4.1 Evaluation of the mismatch using data from indoor measurements

Thanks to the IV curves collected from PM measurements at STC, the mismatch among some mono-chromatic modules has been evaluated starting by plotting the IV curves as shown in Figures 7.

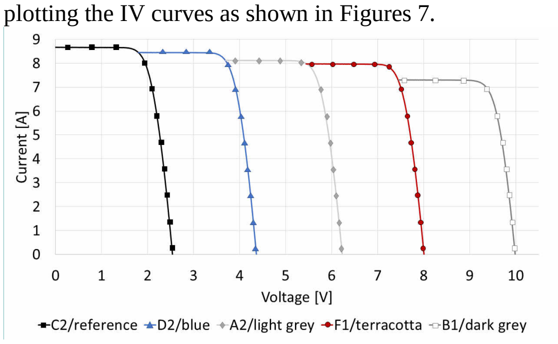

Figure 7: Float glass with colours in applied in position 2, internally. IV curves plotted to visualize better the current mismatch among different colours.

To create multi-chromatic BIPV modules, PV cells are envisioned to be connect in series and the front glass colour should be selected so that there is not a significant mismatch in terms of current intensity. Indeed, thanks to this approach, it can be possible to avoid the activation of bypass diode and avoid significant power reduction. Taking the prototypes with float glass characterized by colours applied in position 2 as examples, the mismatches are calculated by considering the maximum power point of the less performant prototype. The possible combinations for such prototypes are represented in Figure 8, where the comparison with a reference prototype is performed. From this analysis, it arises that the maximum mismatch comes out from the combination of the light grey and the terracotta prototypes, with a power loss in the amount of 6% in comparison to the references.

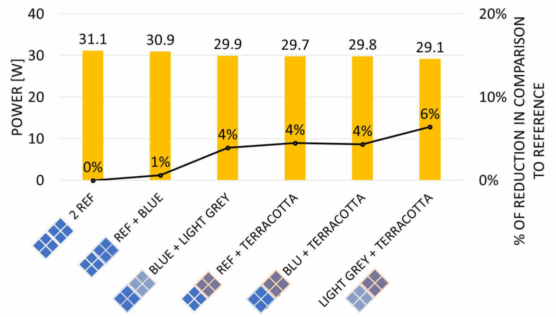

Figure 8: Mismatch calculated from IV curves retrieved from PM at STC and comparison with the two reference modules connected in series.

In order to evaluate the validity of the power output calculations for the combination of coloured BIPV prototypes, a series of prototypes has been subjected to the power measurement at STC. IV curves are shown in Figure 9 and errors are shown in Table 3.

What is interesting to note is that the errors between the calculation method and the real measures are in the range between 0.7% and 1.7%, which are very small errors considering also that the accuracy of the instruments is in the amount of 2.7%.

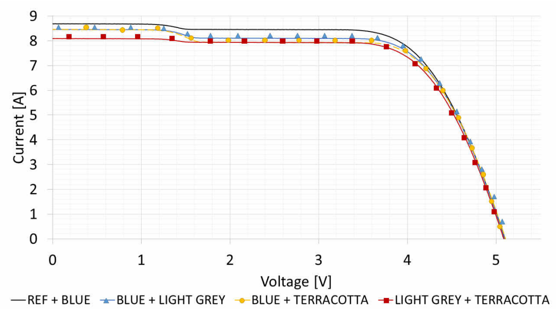

Figure 9: IV curves retrieved from PM measure on some configurations of mono-chromatic prototypes combined in series (float glass with colours in applied in position 2).

Table 3: Comparison between the calculated power output and the measured power of the combined BIPV prototypes. Float glass with colours applied internally on the front glass.

Module 1	*Module 2*	*Calculated* P_{MAX} *[W]*	*Measured* P_{MAX} *[W]*	Δ
C2 Ref	D2 Blue	30.97	31.13	+0.6%
D2 Blue	A2 Light Grey	29.93	30.26	+1.1%
D2 Blue	F1 Terracotta	29.79	30.00	+0.7%
A2 Light Grey	F1 Terracotta	28.98	29.46	+1.1%

4.2 Evaluation of the mismatch using data from outdoor measurements

Since a series of mono-chromatic BIPV prototypes has been exposed outdoor, a preliminary evaluation of the mismatch has been performed also when modules are subjected to operative conditions. Thanks to the power output monitoring and IV curves collection, the mismatch among different mono-chromatic modules has been evaluated in three relevant moments during a clear day: with low, medium and high irradiation values, respectively at 200, 400 and 730W/m^2. As shown in Figure 10, the mismatch among the combination of mono-chromatic prototypes in comparison to the reference prototypes is largely higher than the mismatch measured at STC, even though there is the same trend.

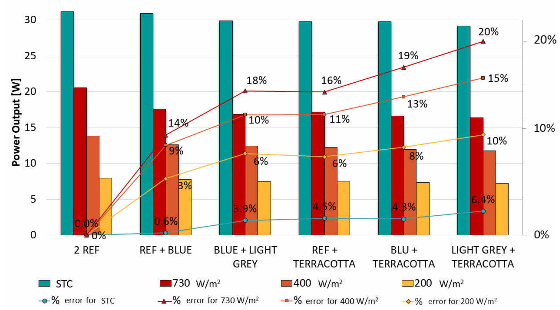

Figure 10: Mismatch calculated from IV curves retrieved from PM at operative conditions and comparison with the two reference modules.

In addition to this calculation, real outdoor measurements on two combinations of prototypes for different irradiation values have been carried out with the aim to evaluate the validity of the calculation method also for outdoor conditions. Tested combinations of prototypes (light grey/blue, and light grey/terracotta) and related errors are shown in Figures 11 and 12.

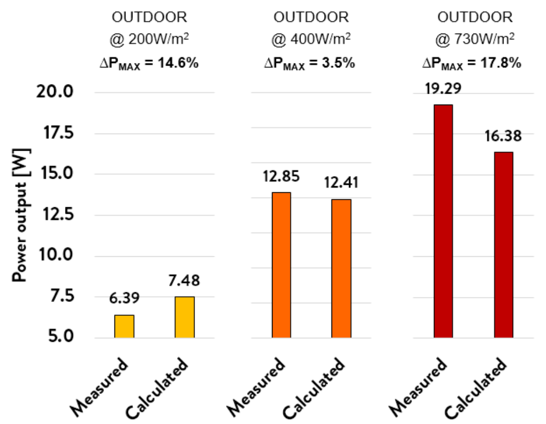

Figure 11: Comparison between the calculated power output and the measured power of the combined BIPV light grey and blue prototypes.

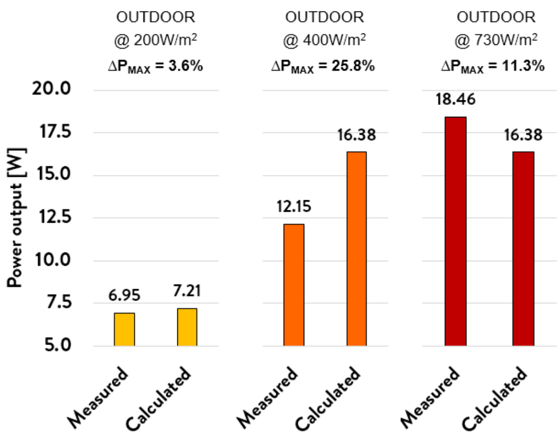

Figure 12: Comparison between the calculated power output and the measured power of the combined BIPV light grey and terracotta prototypes.

From these measures, it arises that errors of the calculation method are up to 25%. This is probably due to a combination of effects, which are not present at STC but only at outdoor conditions, such as the spectral responsivity of the different colours and the angle of incidents.

5 CONCLUSIONS AND FUTURE CHALLENGES

From the indoor and outdoor characterization on mono-chromatic BIPV prototypes, it arises that thanks to the low amount of colour coverage application (10%), the power output is not significantly affected, as well as the operative temperature. Indeed, the higher power loss results for the dark grey prototype in the amount of 17% in comparison to the reference module.

Furthermore, in order to support the development of multi-chromatic BIPV modules, this study has introduced a calculation method to assess the mismatch among two different colours and to determine the resulting power output. Thanks to this calculation method, the power output of two mono-chromatic modules combined in series can be obtained as they form a multi-chromatic element. Hence, the accuracy of this calculation method at STC has been verified by real measurements on combined prototypes. As a result, the errors of this method emerge to be very low, with a maximum error of 1.1%.

However, when the same method is applied to combined prototypes exposed at outdoor conditions, the calculation method provides errors up to 25%, since it is not able to consider real operative conditions (e.g. spectral responsivity of different colours, angle of incidence, low influence of temperature, …).

Therefore, considering such preliminary results, further investigation should be performed on combined coloured prototypes in order to gather other relevant data and develop a more detailed calculation method that can allow to obtain reliable data about multi-chromatic modules when exposed in real operating conditions. This could be useful for modules manufacturers that can rely on predesign options, thus optimizing costs for producing novel aesthetical BIPV modules. Furthermore, this study has highlighted the importance of considering outdoor conditions, besides STC, when multi-chromatic modules are developed.

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