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Energy optimization of BIPV glass blocks: a multi-software study

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Abstract

The aim of this paper is to show the results of the performance analyses carried out on four patented glass block configurations integrated with third-generation Dye-sensitized Solar Cell (DSC) modules. The analyses take into account the thermal, optical and electrical performance by using three different software (COMSOL Multiphysics, WINDOW, Zemax), also enabling to take into consideration the peculiar three-dimensional geometry of this innovative glazed product. Starting from these results, new configurations improved as for the thermal insulation, are also introduced and studied, in order to make further considerations about the applicability of this building component for the construction of energy-saving and generating building envelopes.

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Keywords: Building Integrated Photovoltaics; Thermal and optical analyses; Building envelope; Glass Block, Dye-sensitized Solar Cells (DSC)

1. Introduction

The glass block is a well-known building product, which has been widely employed for the construction of spatial dividers and building envelopes, both in modern and contemporary architecture. In the last decades, the necessity to optimize its energy performance according to the stricter and stricter energy efficiency regulations, as well as to make it more competitive is driving several efforts for the optimization of its thermal insulation, solar and optical properties, but also for the optimization of conventional “wet” assembly systems for both internal and external installations, based on the use of concrete.

A standard glass block is characterized by a thermal transmittance (U value) slightly below 3.0 W/m^2K as well as high solar factor and light transmission values, respectively equal to 79.7% and to 79.5% [1]. Its use for envelope

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applications has been limited in the last few years due to its poor thermal insulation performance, unable to respond to the maximum acceptable U values imposed by recent regulations for glazed building components. Moreover, in some installations, the use of this product for the construction of transparent or translucent building envelopes — in absence of other measures for the reduction of solar gain and light transmission — may origin thermal and visual discomfort inside the buildings. For example, in case of high levels of solar radiation, the use of colored and/or diffusing glass blocks has been suggested for building envelope applications in order to avoid phenomena of visual discomfort [2]. As in all glazed building components, solar gain and light transmission values should be carefully studied according to the features of each project. These could indeed represent significant issues especially in warm climate areas, due to high temperatures and solar radiation levels during the year. Hence, measures to enable glass block to respond to diversified requirements also in terms of daylighting and solar gain should also be undertaken.

In the light of the above considerations, a novel, multifunctional and translucent building component for Building Integrated Photovoltaics (BIPV) has been developed by the authors at the University of Palermo. The component is a precast and pre-stressed panel made of innovative glass blocks, dry-assembled by means of a supporting structure in plastic material, optimized as regards their thermal insulation (through the use of a plastic sub-component, the so-called "thermal belt") and integrated with third-generation Dye-sensitized Solar Cells (DSC) [3]. The development and commercialization of this building component is the main objective of the technological start-up company and spin-off of the University of Palermo, SBskin. Smart Building Skin s.r.l. [4]. Besides the obvious advantages linked to the PV performance, the integration with DSCs could have also positive relapses in terms of visual and thermal indoor comfort conditions, since a wide range of light transmission and solar gain performance could derive from the integration of the glass block with different types of DSC devices. Clearly, such integration has also an impact on product's appearance, resulting in a great variety of possible results in terms of colour, transparency, design of the building envelope (either a roof or a façade). In this sense, the peculiar modularity of the glass block represents an added value that could be exploited for the definition of larger drawings.

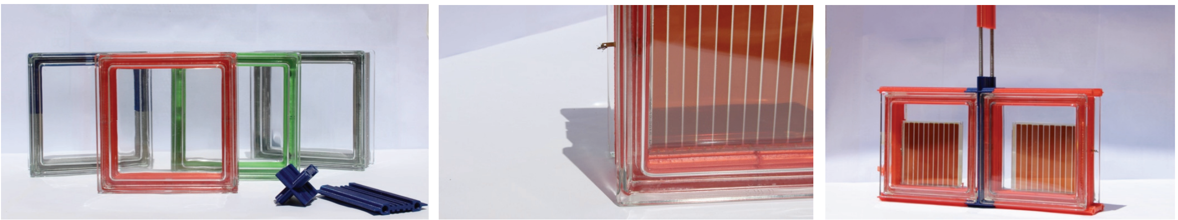


Fig. 1. Prototypes of the novel glass block configurations, with thermal belts in various colors, DSC samples and plastic supporting structure

2. Multi-software Energy Performance Analysis of the DSC-integrated Glass Blocks

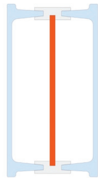
Due to the peculiarities of this BIPV product, a multi-software methodology was defined and used in order to fully assess the main indicators of the thermal, optical, and electrical performance of the DSC-integrated glass blocks. In particular, three different software (COMSOL Multiphysics, WINDOW, Zemax) were used, that allowed taking into consideration the peculiar three-dimensional geometry of this glazed product.

COMSOL Multiphysics is a software for modelling and simulating physics-based problems [5], used for a detailed calculation of the thermal transmittance (U value) of different glass block configurations, considering both two- and three-dimensional models of the product. WINDOW is a tool for the analysis of thermal and optical performance of glazing, developed at Lawrence Berkeley National Laboratory (LBNL) [6]. It was used for the evaluation of optical and solar performance (T_{vis}, T_{sol}, g-value) of the DSC-integrated glass blocks, by referring only to the so-called "vision area" of the product and not accounting for the side edge characterizing the product. It also provided the temperature distribution on each of the layers that compose a glazing system. Finally, Zemax is an optical design software [7], which was used to perform deeper optical analyses on three-dimensional models of the different DSC-integrated glass block configurations and to assess the electric power [8]. At a first stage, the study focused on four main configurations representing the main possible positions of the module inside the product: on the outer surface (Configurations 1, 2), on the inner surface (Configuration 3) of the sun exposed glass shell and inside the cavity (Configuration 4) [3].

The aim of this multi-software study is to fully assess the optical and thermal performance of different glass block configurations, plus to make some estimation regarding the photovoltaic performance. Starting from the results it is possible to optimize the performance of the components as well as to define some optimum combinations according to different needs of active building façades and requirements related to diversified climate contexts. Afterwards, when all the appropriate experimental validations are completed, this multi-software approach might also represent an accurate and easily replicable methodology for an assessment of main optical and thermal performance indicators for the PV-integrated glass blocks, also in relation to a change of the input properties of the components (e.g. color and optical properties of the incorporated DSC module).

The most significant results regarding the four basic configurations are put together and summarized in Table 1.

Table 1. Summary Table of the multi-software analyses regarding the four patented configurations

		Configuration 1	**Configuration 2**	**Configuration 3**	**Configuration 4**
					
Dimensional features					
Thickness (mm)		86	86	80	100
Module dimension (mm)		170	184	144	154
Module area percentage (%)		80.06%	93.78%	57.44%	65.70%
Thermal performance					
U value, 2D (W/m^2K)	Unframed	2.9	2.9	3.0	2.0
	Framed	2.9	2.9	3.0	2.0
U value, 3D (W/m^2K)	Unframed	2.9	2.9	3.0	1.7
	Framed	2.9	2.9	3.0	1.8
Light and Solar Properties					
T_{vis}	Vision Area	11.47%	11.47%	11.44%	10.21%
	Framed GB	8.79%	7.12%	12.39%	5.17%
T_{sol}	Vision Area	26.55%	26.55%	26.50%	24.19%
	Framed GB	15.93%	14.69%	17.90%	11.28%
g-value	Vision Area	35.10%	35.10%	35.30%	45.00%
	Framed GB	34.72%	34.98%	34.92%	40.29%
Electrical performance					
Solar radiation reaching the module (%)		100%	100%	89%	70%
Power peak (W_p)		1.44	1.69	0.83	0.54
Area needed for 1 kW_p		25.5	21.8	44.4	65.3
Temperature distribution					
DSC surface temperature (°C)		51.3	51.3	52.3	67.2
Inner surface temperature (°C)		37.4	37.4	37.8	44.3

Configurations 1 and 2 seem the most promising as for the electrical performance, due to wider module area, direct exposure of the DSC to the sun and limited warming-up of the module: fixing the conversion efficiency to 5% (i.e. based on an average of most common efficiency values of DSC commercial modules), the power peak of the glass block is equal to 1.44 and 1.69 W_p, respectively, resulting into a power per area of panel of 39 and 46 W/m^2.

Configuration 4 seems the least promising due to notable overheating phenomenon inside the glass block due to high energy absorption, lower amount of sunlight striking on module surface (i.e. 70% of the incident solar radiation, leading to lowest electrical power), smallest visible and solar transmission values. The important overheating is due to the fact that the module is positioned in the middle of glass block cavity, thus resulting not ventilated and insulated from the external environment. This can generate a drop in the electrical and thermal performance of the product as well as expose it to thermal stresses. The drop in the electricity conversion become even more significant if we also consider the possibility of self-shading on the solar device, when sun is not striking perpendicularly on the surface of the glass block in real installation conditions. The position of the module inside the glass block as well as the presence of the plastic thermal belt have the advantage to provide Configuration 4 with the best thermal transmittance, but all other issues related to the DSC module performance lead to have it excluded.

The optical performance of the so-called vision area is rather low and very close among the various configurations, since this parameter depends mainly on the characteristics of the DSC module more than on its position. Such differences increase when considering the transmittance of the whole product, accounted for by means of Zemax software, which includes in the optical study also glass block border and supporting profiles. In particular, in this study, Configuration 3 has been assessed as the one providing the highest optical transmittance, whereas also the lowest module area percentage (these two features are in actual facts directly related). This aspect, related to the particular shape of the glass shell, represents a downside for the electricity production as also does the presence of the glass shell in front of the module reducing, even if quite limitedly, the amount of energy striking its surface (i.e. 89% of the incident solar radiation). On the other hand, the fact that the module is located inside the product may represent a relevant advantage for reasons related to the easier electrical connection of the DSC-integrated glass blocks and also because of the protection that the glass shell might provide to the PV device.

Looking at the thermal transmittance (U value), the four basic configurations are not sufficiently insulating, at least not in all climate zones. For example, if we look at the Italian Context, the Legislative Decree 311/2006 provided stricter thermal transmittance limits for glazing and window components and, depending on the climate zone, the minimum acceptable U value for windows (including both glazing and frame) ranges from 2.0-4.7 W/m^2K. In other countries, the transmittance limits are even more restrictive: for example, in Switzerland, the U value of a glazing (i.e. corresponding to the centre of the glazing U value, not accounting for edge effects) cannot be higher than 1.3 W/m^2K; the limit for the U value of a window, including both frame and glazing, is instead 1.6 W/m^2K [9]. Same applies, e.g., for the UK, where according to the Building Regulations [10] acceptable U values for windows are below 1.6 W/m^2K, given a percentage of the window area with respect to the floor area equal to 25%. Such U value (1.6 W/m^2K) is chosen as benchmark in this work.

Having said that, further operations should be considered in order to improve product thermal transmittance, starting from the considerations made in previous works [11]. Here, the analyses completed on thermally optimized glass block configurations demonstrated the possibility of increasing the energy performance of the product up to very efficient U values. Integrating such better insulating configurations with DSC modules can allow for the attainment of efficient thermal transmittance values, while also adding the plus-value of energy production. In these cases, the main challenges are how to maintain efficient solar factors and appropriate light transmission values according to building requirements and optimum PV production levels, while guaranteeing the highest durability and ease of manufacturing to the assembled product.

In this sense, Configuration 3 provides the best balance among these requirements and therefore has been selected for the subsequent analyses involving new thermally-optimized and DSC-integrated glass block configurations. Some operations are being considered in order to optimize further the photovoltaic performance of Configuration 3, such as increasing the module area by intervening on the shape of the glass shells and reducing the reflection on the outer glass shell e.g. by means of specific treatments (such as anti-reflection coatings).

2.1. Preliminary Considerations on the Optical Performance of the DSC Modules

Before going in deep with the study of new configurations, it is worth to underline some aspects that can be deducted from the previous analyses. As already highlighted, all configurations show low values of solar and visible transmittance, due to the optical characteristics of the module used for the simulations, deeply described in literature [12]. However, DSC modules can easily be designed with higher transparency values, although this is often linked with a certain reduction in the conversion efficiency. It should also be noted that, in the DSC module used for the above-reported analyses, the whole area of DSC module is considered as active while, in actual fact, the typical configuration of DSC modules is not fully covered with solar cells; indeed, for electric productivity purposes – and in particular to avoid internal resistance losses – DSC modules are normally characterized by a series of rectangular narrow cells with highly transparent non-PV spaces between them (as it is possible to see in Fig. 1). This means that an increase in devices' solar and visible transmittance as well as a decrease in STC power density can be expected.

An active area percentage (AA%) can be defined in each DSC module: it is represented by the ratio of the active area (i.e. the surface effectively occupied by dye-sensitized solar cells) and the total area of the module (inactive spaces included), as indicated in the following equation:

$$AA\% = \frac{A_{active}}{A_{module}} \qquad (1)$$

The percentage of the active area (AA%) in DSC modules is equal for all PV-integrated glass block configurations and depends only on DSC module characteristics. This value can vary significantly from one manufacturer of DSC modules to the other and basically depends on the module design and manufacturing processes. Different designs of the module, due to e.g. visual as well as aesthetic requirements, can result in different values of active area percentage and, subsequently, in different optical and electrical performance.

In order to account for the active area percentage and its potential relapses on both PV, thermal and optical performance, an average 75% value was taken as reference in the analyses. In particular, a "new" DSC module was created in Optics [13] with the already presented methodology [11], simply by weighing the properties of the DSC module with those of the highly transparent non-active area, characterized by the juxtaposition of three layers:

- a layer of highly transparent TCO glass (glazing coated with a transparent film of a conductive oxide, e.g. SnO_2);
- an interlayer of encapsulant to enclose the cells and keep the two glazed substrates together in the DSC sandwich;
- a layer of highly transparent glass.

In particular, the commercially available Tech15 glass (3-mm thick, manufactured by the Company Libbey Owens Ford and deeply analyzed in literature [14]) was used for the assessment. The spectral data (transmittance and reflectance over a spectrum from 290-2500 nm) were input in Optics. Then, a new laminate was created by putting together this layer of TCO glass (3 mm) with highly transparent interlayer (0.38 mm) and glass (3.5 mm), both available in Optics library. The detailed spectral data related to this new laminate, useful to simulate the non-active spaces among the cells in the typical striped configuration of DSC module, were extracted in the form of a text file. Subsequently, the detailed spectral properties (transmittance and reflectance) of the active and non-active part in DSC module were weighted considering 75% active area percentage for the DSC module. Any kind of module area percentage and, thus, of module design could be easily assessed by using this methodology.

In Table 2, the main optical properties related to the Wenger's DSC module with 75% active area and 25% highly transparent non-active area are reported and compared with those of the wholly active Wenger's DSC device. In parallel, a green DSC module, manufactured by a Swiss company, was also accounted for in the evaluations, starting from experimental measurements provided by the manufacturer itself and performed on samples through the use of an UV/Vis/NIR spectrophotometer equipped with an integrating sphere.

The main optical properties of this green module are also summarized in Table 2, considering both 100% and 75% active module configurations. The study of two devices allows providing a wider spectrum of results and making some consideration about the applicability of this product for the construction of energy-saving and producing building envelopes. As expected, the light transmission performance of the DSC modules (with 75% active area percentage) increases compared to the "initial" 100%-active device: the visible transmittance goes from 12.8% up to 29.4% in Wenger's red device; and from 29.2% to 36.1% in the green one. This is an interesting aspect to consider, especially in building integrated applications. Solar transmittance also increases, but not as significantly. Overall, accounting the active area percentage causes an increase of the optical performance indicators of the solar devices, although obviously leading to a decrease in the PV performance due to the reduction of the active portion of the solar device per unit area.

Table 2. Summary table of the main properties of the modules used for the analyses.

	Wenger's DSC (100% active)	Wenger's DSC (75% active)	Green DSC module (100% active)	Green DSC module (75% active)
Thickness (mm)	6.125		6.5	
Thermal Conductivity (W/mK)	1		1	
Solar Transmittance	0.357	0.420	0.308	0.384
Solar Reflectance, front	0.100	0.112	0.091	0.092
Solar Reflectance, back	0.100	0.112	0.091	0.092
Visible Transmittance	0.128	0.294	0.292	0.361
Visible Reflectance, front	0.084	0.085	0.084	0.091
Visible Reflectance, back	0.084	0.085	0.084	0.091
Color Rendering Index (CRI)	0.98	59.53	80.31	91.83

Besides the aspects concerning the appearance of the glass block, the color difference of the two devices result in significantly different color rendering performance, as it is possible to see in the last row of Table 2, where the Colour Rendering Index (CRI) of the two DSC devices is reported. The CRI of a glazing is an indicator of the ability of transmitted daylight through the glazing to portray a variety of colors compared to those seen under daylight without the glazing. In principle, the higher the CRI — whose maximum value possible is equal to 100 — the better; this indeed means that the perception of colors inside the building is as natural as possible and that colours are perfectly reproduced. The analytical procedure for the calculation of CRI is indicated in EN 410:1998 [15]. Looking at the CRI values derived from the analysis of the spectral behavior of the two DSC devices by means of Optics, it is possible to make some considerations about the applicability of the studied devices, according to the regulatory indication provided in the standard UNI EN 12464-1:2011 focusing on the lighting of indoor work places [16].

In this sense, a big difference can be evidenced between Wenger's red device and the green one. Indeed, the first one is characterized by very low CRI (i.e. close to 0) in the 100%-active module, which is also rather opaque to visible light. This would limit the applicability of this module for the construction of semitransparent elements of glazed façades/roofs, despite all other related benefits. Contrarily, the green module is characterized by a notably higher visible transmittance and by a significantly higher CRI, slightly above 80 in its active part.

However, having weighted the properties of active and non-active spaces according to an average active area percentage of 75% and 25% respectively, different results have been obtained not only in terms of visible and solar transmittance, but also in terms of color rendering performance. In 75%-active red module CRI grows up to 59.5, close to 60. This is still not sufficient for several building spaces and activities, but it is enough for circulation areas and other rooms. Considering a lower than 75% active area percentage could be a way to increase global CRI and allow for the studied red module to be used for other types of spaces; however, this would generate a decrease in the active area and thus in the electricity performance of the DSC-integrated glass block. Otherwise, for example, coupling highly transparent surfaces (such as non-PV glass blocks or clear glass systems) with DSC-integrated glass blocks could produce an overall increase of the CRI related to the light transmitted across the building envelope. Even in this case, this implies a lower available surface for PV. Different red tones for DSC module and diverse transparency values (depending on the nano-structure of the DSC device) could also have an influence on the CRI.

Differently, the green module is already provided with a very good color rendering performance but, considering an active area of 75%, a clear and highly transparent non-PV area of 25% and weighing the respective spectral properties accordingly, CRI reaches very good overall 91.8 value, which would allow using it in any of the situations indicated in the reference standard [16], i.e. also where optimal visual comfort conditions are required.

2.2. New Thermally-optimized and DSC-integrated Glass Block Configurations

After having defined and discussed the optical and solar characteristics of the DSC modules used for the analyses, a series of new thermally-optimized configurations of the glass block DSC-integrated have been designed and analysed, starting from the considerations made in the previous assessments. The aim is to improve the thermal transmittance of this BIPV product and enable its use in a wider variety of climate contexts. For this purpose, one or more of the following operations has been considered:

- the insertion, inside of the cavity, of one or more sheets of glass (clear or low-emissive);
- the use of a plastic sub-component, the so-called "thermal belt", for the interruption of the thermal bridge between the two glass shells constituting the glass block;
- the evacuation of the cavity.

As stated previously, these additional analyses consider the module integrated according to the Configuration 3, i.e. glued onto the inner surface of the glass shell exposed to the sun. The new configurations are aimed at improving the U value of the product, without compromising its visible light transmission performance.

The thermal belt, which is needed to simplify the assembly of the glass block and to guarantee a higher mechanical tightness to the whole product, does not have a relevant effect on the global optical performance of the "framed" product, as already underlined from Zemax simulations on three-dimensional models of the product [8], and it has no effect on the performance vision area of the product. It is also a solution to further reduce the U value of the product due to the provided thermal break between the outer and inner glass shells, but its use alone is not sufficient for a relevant drop of the U values. Therefore, the thermal belt has been coupled with other subcomponents (i.e. glass, low-e glass). The insertion of a glass sheet inside the cavity of the product has already been individuated as a possible solution for the improvement of the U value of the product, but for further decrease of the thermal transmittance the use of a low emissive glazed sheet could be pursued. For this scope, among the very wide choice of commercial products belonging to the IGDB, the low-emissive "ClimaGuard Premium on Float ExtraClear Glass" manufactured by Guardian Europe and characterized by extra clear appearance was selected for the analyses. This is of great relevance to compensate to the low visible transmittance of the DSC devices. In addition, the emissivity (ε) of one of the two surfaces of the glass is very low (ε=0.038) and this helps reduce winter thermal losses (lower U value) and summer heat gains as well; solar transmittance is clearly lower than that of a clear glass, due to increased solar reflectance, but yet it remains close to 60%. The objective of improving the thermal insulation without reducing the visible transmittance significantly is thus achieved with the insertion of this glass product; however, different requirements as regards the optical transmittance of the glass block might lead to the use of other types of glazing, depending on the needs of different installations and climate conditions.

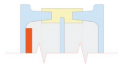
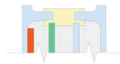
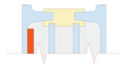
The analysed configurations are illustrated in Table 3 and are all characterized by the use of a Nylon (PA6) thermal belt, that allows for a 10-mm interruption of the thermal bridge between the glass shells composing the glass block as well as for the insertion of one or more sheets of clear and/or low-emissive glass. Regardless of the presence of the thermal belt between the two glass shells, all configurations are characterized by the same 80-mm thickness as "standard" glass blocks. In order to maintain the "standard" 80-mm thickness of the product unvaried, a 5-mm reduction in the thickness of each glass shell is considered. The increase of standard glass block thickness, due to the insertion of the thermal belt, may indeed result in higher manufacturing costs and represent a sensitive change in the consolidated configuration of the product. Moreover, maintaining the thickness unvaried is also useful for standardization purposes, since 80-mm thick glass block with thermal belt could be installed by using the same supporting elements patented by SBskin also for assembling "standard" glass blocks.

Analyses with COMSOL Multiphysics and WINDOW have been executed to identify the main parameters related to product optical and thermal performance, by considering both air-filled and evacuated cavity/ies. The considerations made on the electrical power are not expected to change from what assessed previously and reported in Table 1. Simulations have been run by taking into account Wenger's and green modules in both 100% and 75%-active configurations and by considering both air-filled and evacuated cavity/ies, in order to obtain a wider spectrum of results. The U value has been calculated by means of COMSOL in a 2D environment, where the new glass block configurations have been simulated both framed by the supporting structure in plastic profiles and unframed.

2.3. Discussion of the Results and optimization of sub-components

Results are illustrated in the Graph in Table 3 and summarized (as for the air-filled configurations) in Figure 2.

Table 3. Main performance parameters of the thermally optimized glass block configurations integrated with Wenger's and green DSC modules.

			3.01		**3.02**		**3.03**		**3.04**	
			 PA6 thermal belt, two cavities, and one 4-mm sheet of low-e glass		 PA6 thermal belt, two cavities and one 4-mm clear glass sheet		 PA6 thermal belt, three cavities, 4-mm clear and low-e glass sheets		 PA6 thermal belt, three cavities and two 4-mm clear glass sheets	
Thermal performance			*Vacuum*	*Air*	*Vacuum*	*Air*	*Vacuum*	*Air*	*Vacuum*	*Air*
U value 2D (W/m²K)		Framed	1.3	1.7	2.0	2.2	1.4	1.6	1.7	1.9
		Unframed	1.2	1.7	2.0	2.2	1.3	1.6	1.7	1.8
Light and Solar Properties										
Red (Wenger's DSC)	T_{vis}	100%	9.99%		10.31%		9.03%		9.33%	
		75%	23.50%		24.09%		21.39%		21.97%	
	T_{sol}	100%	15.21%		22.43%		13.16%		19.07%	
		75%	20.19%		27.47%		17.71%		23.70%	
	g-value	100%	20.90%	23.60%	31.70%	32.90%	20.00%	21.20%	27.80%	28.80%
		75%	26.50%	29.10%	37.00%	38.30%	25.20%	26.30%	32.80%	33.80%
Green DSC	T_{vis}	100%	17.79%		18.18%		16.24%		16.62%	
		75%	29.35%		30.01%		26.81%		27.46%	
	T_{sol}	100%	14.11%		18.99%		12.32%		16.27%	
		75%	19.36%		24.88%		17.07%		21.59%	
	g-value	100%	19.10%	22.90%	28.80%	30.50%	18.20%	20.20%	25.10%	30.00%
		75%	25.00%	28.10%	34.30%	35.70%	23.80%	25.30%	30.30%	31.40%

Looking at the results, U values up to 1.2 W/m²K can be achieved in new configurations with evacuated cavities. However, creating and maintaining vacuum is a complex issue, especially inside such thick cavities. Considering the air-filled configurations, only one allows achieving a U value below 1.6 W/m²K, set as benchmark: i.e. 3.03 where two 4-mm glass sheets, one of which low-e, are located inside glass block cavity by means of the thermal belt. On the other hand, the use of two glass sheets, increasing the cost and weight of the product, is considered as a disadvantage that does not seem to be compensated by the limited reduction of the U value compared to that of 3.01.

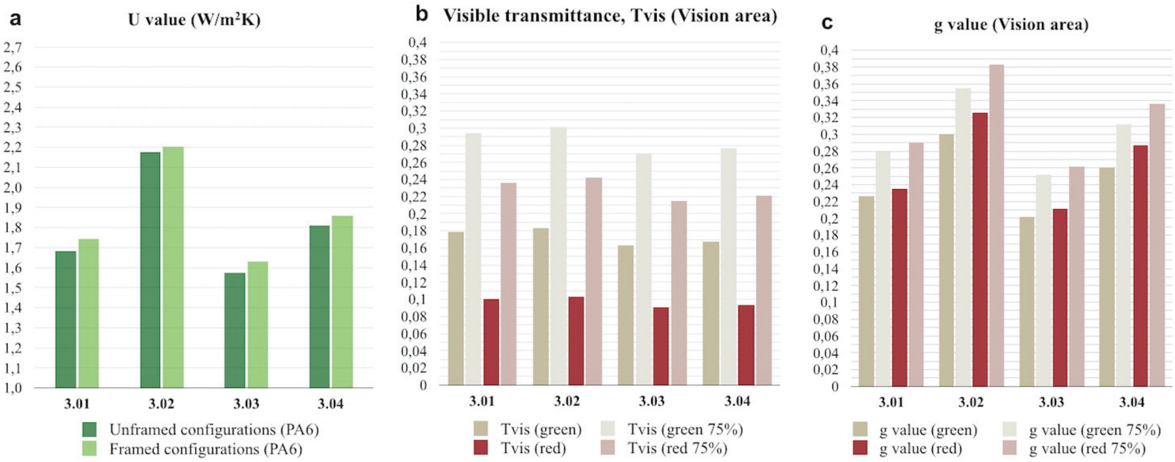


Fig. 2. Results on the new thermally-optimized glass block air-filled configurations: (a) U value; (b) visible transmittance; (c) g value

Further optimization of product U value is possible by intervening on the material characteristics and design of the thermal belt and of the profiles. For example, PLA (Polylactide), which has been used for the realization by means of 3D printing of the prototypes in Fig. 1, is characterized by a lower thermal conductivity (0.13 W/mK) than Nylon PA6 (0.25 W/mK). Therefore, its use could further enhance the thermal insulation performance of the glass block, when used for the thermal belt and for the supporting profiles. In addition, the design of the thermal belt has been optimized, by introducing a central cavity that, besides reducing its weight, is expected to improve its insulation performance. Indeed, the equivalent thermal conductivity of these cavities, calculated according to the process indicated in the standard ISO 15099 [17], is lower than that of the plastic constituting the thermal belt.

The same principle has been considered for the profiles that constitute the supporting and framing structure of the glass block components. These have been re-configured by adding a series of small cavities and computed either as PA6 or PLA elements. The related relapses on the thermal transmittance of the glass block have been analysed and, indeed, improvements of over 2 decimal points of the glass block U value has been detected, as shown in Figure 3.

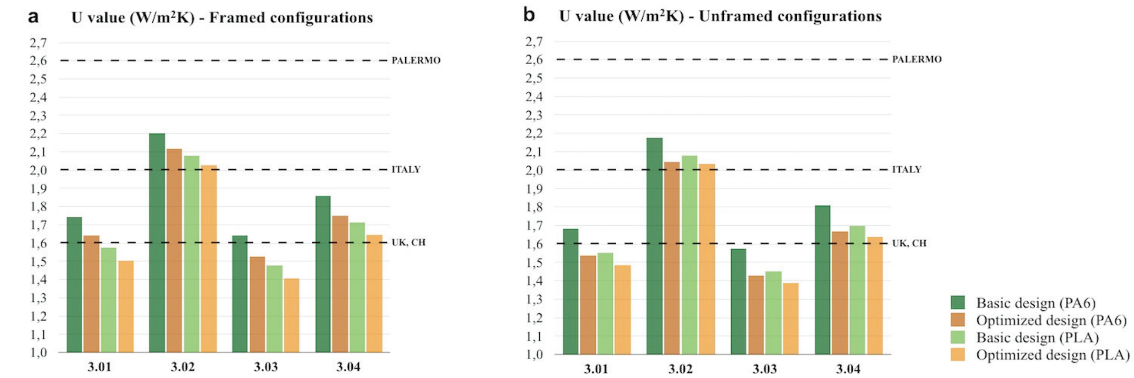


Fig. 3. COMSOL results: U values of the 4 new thermally-optimized glass blocks (3.01-3.04), air-filled, with thermal belt characterized by either "basic" or "optimized" design and made of either PA6 or PLA: (a) framed configurations; (b) unframed configurations

3. Conclusions

The here-analysed building product represents a multi-functional solution for the construction of sustainable, translucent, colourful envelopes that could save energy, while self-generating it. Many other applications are possible thanks to the energy efficiency, constructional, and aesthetic features of the DSC-integrated glass block (e.g. urban equipment, spatial dividers outside or within the building envelope in order to exploit the good response of DSCs to artificial light). In these cases, specific performance in terms of thermal insulation are not needed and the DSC-integrated glass block configurations, discussed in paragraph 2, could be used without any modification.

However, this paper has focused on the thermal optimization of the product for its use as a glazed element of the building envelope, where the thermal transmittance of any glazed product represents a fundamental parameter for the choice of one solution rather than another. As already highlighted, indeed, improving the U value of the product is also important to allow for the use of this product in diversified climate contexts: for example, in UK and Switzerland, where U value limits have been reduced only two out of the four thermally-optimized configurations (i.e. 3.01, 3.03) could be used, whereas all four could be utilized for the building envelope in the context of Palermo, Italy.

However, the thermal transmittance is not the only aspect to take into account for building envelope application. De facto, especially in northern countries, characterized by cold climate and low values of global solar radiation, it could be of relevance to maintain high solar gains and light transmission values according to building requirements, compatibly with the other parameters (PV power, thermal transmittance). In this sense, the choice of the optical characteristics of the DSC module is a fundamental part not only of the design of this innovative product but also of its best use as technical element of the building envelope. A certain variety of results, in terms of energy production, thermal, optical and aesthetic performance, can be achieved by using DSC modules with diverse combinations of transparency and colour as input for the simulations, as shown in the paper. The analyses discussed in this paper have also shown the importance to consider carefully also the characteristics of the glazing elements to be put inside glass block cavity for the optimization of its thermal insulation, since they might contribute to the attainment of specific performance levels and thus have impacts on the applicability of the product. This aspect, mixed with the versatility of DSC technology and with the modularity of the analysed product, makes it quite easy to obtain an even wider range of design possibilities, simply by assembling different glass blocks (in terms of shapes, colours, transparency level, dimensions, finishing, etc.) in potentially unlimited combinations.

Further analytical studies and laboratory tests will be carried out to further characterize the performance of this novel component for the building envelope, not only in terms of electrical, optical and thermal performance, but also as regards all essential building requirements. Experimental testing, in particular, is of great relevance also to verify the results and the validity of this analytical approach comparing the results of this study to the real behaviour of prototypes. Indeed, one of the objectives of this study has been the definition of an easily replicable and reliable methodology to quickly obtain the main energy performance indicators (i.e. thermal transmittance, visible transmittance, solar factor, electric power) of the DSC-integrated glass block components, deriving from a change in the properties of the sub-components and, especially, of the solar module selected for the integration. Given these main indicators, it is possible to select, in the design phase, the most adapted balance of all requirements with the support of building simulation tools. This approach is perfectly in line with the positions of different authors such as, e.g., Loonen et al. [18] who stated that building simulation is a useful additional tool in the development of innovative building envelope components, commonly used for supporting informed decision-making in the building design process.

Therefore, these novel multi-functional components are not only elements for the production of electricity, but also of aesthetic valorisation and technological optimization of a building, even contributing "passively" to the energy efficiency and indoor comfort. Indeed, as Semi-Transparent Photovoltaic (STPV) products installed as technical elements of the building envelope, these could be used, in place of absorbing, tinted glass or ceramic frits [19], to respond to multiple building requirements, such as: solar shading in summer to reduce cooling loads; solar gain and thermal insulation in winter to lower heating loads; daylighting to reduce artificial lighting loads; and so on…[20].

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