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INTEGRATION OF DYE-SENSITIZED SOLAR CELLS WITH GLASSBLOCK

INTEGRACJA CZUŁYCH BARWIONYCH OGNIW SŁONECZNYCH Z BLOKIEM SZKLANYM

A b s t r a c t

Dye-sensitized Solar Cells (DSC) – based on the use of hybrid (organic/inorganic) cells – make a new frontier of the PV industry, especially for the potential of complete sustainability in terms of ecological and economical costs as well as its particular affinity with the theme of Building Integrated Photovoltaics (BIPV). This paper shows the first results of research (included in a larger work on the improvement of the performance of glassblocks in order to use them for the construction of sustainable translucent building envelopes even in Mediterranean and tropical areas) which aims at integrating glassblock with the DSC technology. Glassblock is a high-performance type of glass applied in the field of sustainable architectural claddings. Some of the performance of this new DSC-integrated kind of glassblock will be discussed in this paper in terms of efficiency, thermal transmittance, light transmission and costs.

Keywords: Dye-sensitised Solar Cell, glassblock, energy saving, translucent building envelope

S t r e s z c z e n i e

Czułe barwione ogniwa słoneczne, oparte na zastosowaniu ogniw hybrydowych (organicznych/nieorganicznych), wyznaczają nową granicę przemysłu fotowoltaicznego, szczególnie dla potencjału pełnego rozwoju zrównoważonego w kategoriach kosztów ekologicznych i ekonomicznych oraz szczególnych związków z tematem zintegrowanej fotowoltaiki budowlanej. Niniejszy artykuł prezentuje pierwsze wyniki badań (stanowiących część większego projektu dotyczącego zwiększania wydajności bloków szklanych w celu stosowania ich przy budowie zrównoważonych powłok półprzezroczystych nawet w regionach tropikalnych i śródziemnomorskich) nastawionych na integrację bloków szklanych z technologią czułych barwionych ogniw słonecznych. Blok szklany to wysokowydajny typ szkła stosowany w dziedzinie zrównoważonych powłok architektonicznych. W artykule tym przedstawiono funkcjonowanie nowego rodzaju bloku szklanego zintegrowanego z czułymi barwionymi ogniwami słonecznymi w kategoriach wydajności, transmitancji ciepła, transmisji światła oraz kosztów.

Słowa kluczowe: czułe barwione ogniwo słoneczne, blok szklany, energooszczędność, półprzezroczysta powłoka budowlana

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1. Dye-sensitised Solar Cells and glassblocks

1.1. Introduction

In this work, a study which aims at integrating Dye-sensitised Solar Cells (DSC) with glassblock for the construction of translucent photovoltaic panels will be presented. A combination of the two technological elements, the glassblock and the DSCs, enhances their own features. The final complete product is ready-made for installation, owns the qualities of glassblock and produces sustainable energy at the same time. The objective of the research being carried out at the Department of Architecture, University of Palermo is to design a glassblock which would be able to produce clean energy, would be easily integrated in building envelopes and customizable in terms of colours, transparency levels, finishing and design in order to respond to the requirements of the project (and the users/architects' wishes) and of its climatic context. The thermo-acoustic insulation of the product may be modulated according to the specific requirements of each case of installation with the use of particular modified configurations of the glassblock itself. For instance, the product may be used in multifunctional PV panels for translucent façades which can perform efficiently in all light conditions (even in diffuse light, also converting internal artificial light) that are not dependent on the angle of solar radiation and do not suffer from the high operative temperatures of functioning in accordance with the features of the DSCs. Integration of DSC modules with the glassblock makes it possible to have PV panels which coincide with the building envelope itself so that they do not need any further structures to be installed allowing, at the same time, further economy in the building construction due to the possibility of subtracting the price of a substituted building element from the price of a panel.

1.2. Dye-sensitized Solar Cells

Dye-sensitized Solar Cells (DSC), invented in the early 1990s by Michael Grätzel and Brian O'Reagan [1], are characterized by a sandwich structure composed of a transparent substrate (e.g. glass) conductive with a thin layer of transparent conductive oxide TCO (e.g. FTO – Fluorine-doped Tin Oxide) and then coated with a mesoporous film of a semiconductor material, commonly a-toxic and biocompatible TiO_2 titanium dioxide (or, more simply, titania). The photoactive dye molecules are absorbed onto the TiO_2 surface to create the photoanode of the DSC device, then the cell is closed with a counter electrode of a conductive – not necessarily transparent – substrate coated with a platinum nanometric film with the function of a catalyst. Finally, the device is hermetically closed by a sealant and filled with an electrolyte solution which fulfils the function of completing the cell and starting the mechanism [2].

The efficiency of the dye-sensitised technology, different from the high-purity crystalline silicon technology, does not suffer from impurities in the materials. Consequently, the costs of raw materials and their processing are much lower. It is not necessary to work in high-vacuum conditions, and the temperatures of the processes are relatively low. Moreover, the possibility of using highly productive and low-cost processes, creating small quantities of manufacturing wastes taken from the field of printing – such as screen, ink-jet and roll-to-roll – turns the DSC into one of the most economical and sustainable PV technologies [3].

One of the features of DSCs is their response in terms of electricity production under various light conditions. DSCs show high efficiency in low and diffused light (for example, in the early morning, on a cloudy day or even in artificial light), too. In fact, such companies as Sony and Sharp, active in the field of the industrialisation and commercialisation of this technology, see an important direction of development in its indoor use. Moreover, the efficiency of a DSC shows its peak in a light intensity of 200 W/m^2, i.e. 1/5 of the intensity of sunlight (1000 W/m^2). Therefore, the method of evaluating a solar module peak power, measured in Wp (Watt-peak) and referred to the Standard Test Conditions (STC), rarely corresponding to the real operative conditions, can lead to an underestimation of the effective energy performance of this "3rd generation" technology.

Differently from the first generation silicon-based panels, DSC panels do not necessarily need an oriented installation facing the sun as they produce high proportional levels of power from "global" radiation – reflected and diffused light – with intuitive and notable advantages in terms of façade integration [4].

DSCs do not suffer from high operative temperatures as the first generation technology does: this guarantees a wider market including countries in diverse climate areas consisting in an advantage in terms of architectural integration.

Because of all these considerations, despite the relatively lower nominal efficiency of the DSCs in comparison with the other technologies, if we consider the energy (kWh) yearly produced by DSC and a crystalline silicon PV plant working in real open-air conditions and installed with the same peak-power, it has been proved that the 3rd generation technology produces 10–15% more energy than the other [5].

The Japanese company Fujikura has also done some important outdoor tests studying the behaviour of two plants: one of DSC panels, the other of polycrystalline silicon (p-Si) panels demonstrating that – being the output power installed at the same 10 kW – the electricity produced by DSC panels in the course of a year under real operative conditions is bigger than the electricity produced by the p-Si plant (Fig. 1). This difference increases when the panels go from the south-oriented and 30°-inclined position to a more "disadvantaged" one in terms of direct irradiation, such as the north wall: in this position, the DSC panels produced 1.6 times more energy than the p-Si ones [6].

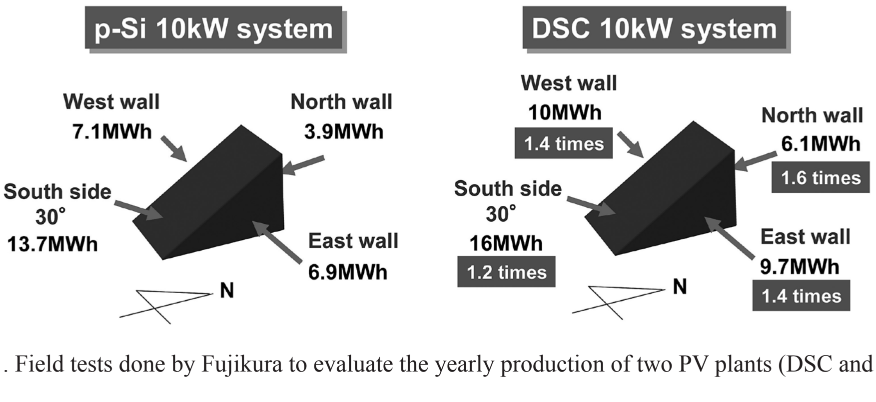

Fig. 1. Field tests done by Fujikura to evaluate the yearly production of two PV plants (DSC and p-Si)

Rys. 1. Próby przeprowadzone w warunkach naturalnych przez Fujikura dla oceny rocznej produkcji dwóch zakładów PV (DSC oraz p-Si)

What makes DSCs really competitive, besides the simplicity of their production and their low costs both in ecological and economical terms, is their great versatility and potential in terms of Building Integrated Photovoltaics (BIPV). DSC modules can be printed on rigid or flexible substrates from stainless steel to glass and plastic polymers. Moreover, using specific dye molecules, particular formulations of the TiO_2 paste and deposition techniques which only allow printing on certain areas of the substrate, it is possible to obtain solar cells responding to particular aesthetical or formal needs (some examples of the possible multiplicity of colours and designs for DSC are shown in Fig. 2, 3). DSCs facilitate a large range of products to be manufactured from the same line: for instance, it is possible to tune the transparency of DSC devices in virtually unlimited combinations through adjustments of the thickness and type of TiO_2 films as well as of the nature of a dye without requiring any additional manufacturing hardware [7, 8].

The result can be the loss of some percentage of efficiency but it has to consider the overall reduction of the energy consumption of a building as well as the indoor light levels required to understand which manner (the most efficient/the most transparent) is the best to undertake according to the context of application etc. Moreover, as stated before, the application of DSC panels as components of glazing façades will also make it possible, thanks to their quality of being bifacial, to convert both the solar radiation coming from the outside of a building and the artificial light coming from the indoor environment to electricity allowing for further enhancements of the performance of conversion. For all these reasons, many people see the dye-sensitized technology as ideal for BIPV, particularly for glazing.

Nowadays, twenty years after the invention, dye-sensitized solar cells, owing to some innovations in research and the first developments in industrial production, give important results in terms of conversion efficiency (13% for lab cells and 8% for commercial modules)

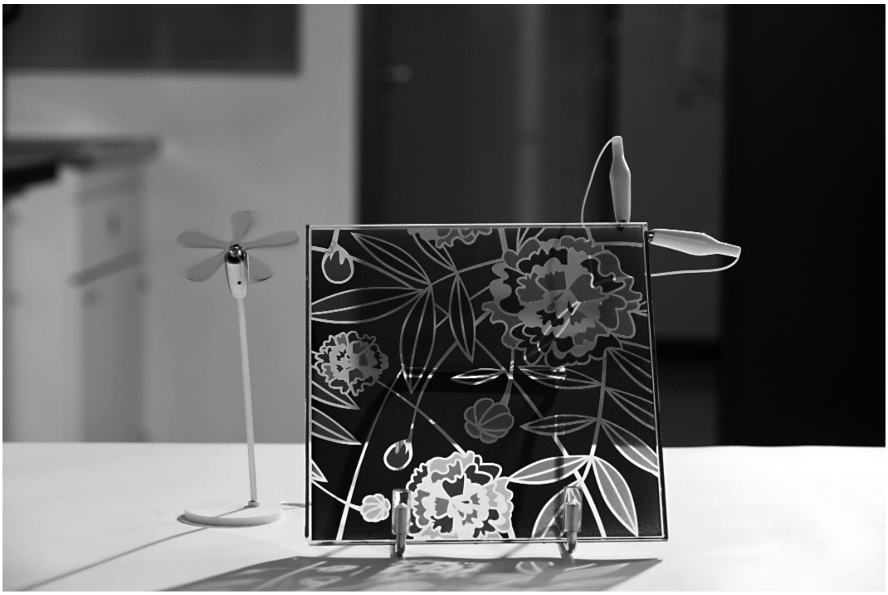

Fig. 3. DSC module manufactured by Sony Co. Ltd.

Rys. 3. Moduł DSC wyprodukowany przez Sony and stability (from 26 years in Southern Europe to 44 years in Central Europe) [9]. Other improvements are expected to come, both in terms of the performance and optimization of processes and costs, focusing – for example – on advanced nanostructures of the TiO_2 paste, new innovative dyes and the introduction of novel nanocomposite solid electrolytes [10]. DSC is one of the few PV technologies with the potential to launch products up to the TWh scale over the oncoming decades. In fact, although it is right now at a pre- or early industrial phase, DSC technology may soon find a wide application and become fully competitive allowing us to spread the spectrum of PV applications to a variety of customer-related sectors where traditional silicon-based technologies are not adaptable.

1.3. The Market of Dye-sensitized Solar Cells

At the moment, thirty-one companies and/or laboratories of applied industrial research working in the field of prototyping, testing and producing DSC modules are catalogued in the domain of the research we are carrying out with the purpose of defining a general picture of the state-of-the-art processes of the scale-up and industrialization of DSC for large-scale development and commercialisation and of deducting potential distribution of the DSC market according to the activities of the firms under analysis. 24 out of the 31 companies are involved – even if not exclusively – in the design of DSC modules or panels for BIP: more precisely, 20 of them chose glass as the substrate for the integration of the building envelopes pursuing transparency coupled with the constructional qualities that glass can provide as a substrate; 8 companies chose flexible transparent substrates for BIPV and 3 of them also work on indoor applications; 5 companies chose flexible stainless steel substrates instead.

Fig. 2. Transparent DSC panel manufactured by ETRI and installed in one of its venues in Korea

Rys. 2. Przejrzysty panel DSC wyprodukowany przez ETRI i zainstalowany w Korei

The tendency to build integration shows the importance that is acknowledged for the affirmation of the DSC technology to its possibility of defining buildings in formal and aesthetical terms as well: this becomes even more evident if we consider the fact that almost half of the analysed companies decided to point at the manufacturing of artistically designed DSC devices which makes a unique quality of DSCs. Besides BIPV, other types of applications are pursued by a relevant number of the analysed companies: more precisely, those applications are ones where transparency, lightness, colour and design are important, e.g. portable devices and industrial remote applications which interest 23.3% and 13.3% of the global number of the analysed companies respectively.

1.4. Building Integrated Photovoltaics

Great progress reached in the field of PV technologies made it possible to reduce the costs of the production of modules on the one hand and to manufacture products with new features, such as lightness, semitransparency, flexibility, a variety of colours or insulation, on the other hand. Obviously, it had a huge impact on the BIPV sector which, having represented a niche sector in the PV industry some time ago, nowadays is considered by many analysts as the actual future of PV industry with a two-billion-euro market expected to reach 8.7 billion euros in 2016. Its advantages are related to the possibility of reducing the cost of PV installation by scaling the price of a substituted building element from the price of a module. There are no further costs related to panel structures because they often coincide with the structure of the element they substitute. Integrating PV in the building façades would offer a more active area for PV installations as well as new possibilities in terms of design and composition. For optimal integration, the concept of photovoltaic installation has to become part of the design of a building to represent an irreplaceable power point of the entire project.

1.5. Glassblock

The glassblock has a series of technical characteristics that are typical of other materials and offers a positive response to two very important requirements of building construction: energy saving and security. In recent years, in fact, the glassblock – particularly used for internal partitions – has found an increasingly wide application for the construction of “sustainable” translucent envelopes.

The glassblock is composed of two shells obtained by pressing a drop of fused glass on a stamp and joined together through hot or cold gluing processes creating an internal cavity. Glassblocks facilitate the passage of light in various percentages depending on the colour of glass and the finishing of the faces of the shells. The glassblock may be preferred to traditional flat glass for its better performance in terms of thermal and acoustic insulation, fire resistance (due to the presence of the cavity), light transmission and modularity. The global annual glassblock market includes about 114 million items; 29.5 million are used in Europe. About half of this number –16.2 million – is used for external envelopes and, more precisely, the market is migrating towards energy-optimized kinds of glassblocks trying to respond to the strict rules and laws on energy efficiency in building construction. Compared to common glazed surfaces, the glassblock is more efficient in terms of thermal resistance because of its thickness. However, its thermal performance is still generally lower than that of opaque claddings which is mostly caused by heat transmission through glazed surfaces causing heat loss in winter and heat accumulation in summer. For these reasons, it could be necessary to reduce the thermal transmittance (or U-Value, W/m^2K) of the glassblock in order to facilitate its use for the design and construction of translucent building envelopes in any kind of climate context able to reduce building consumption maintaining high levels of indoor comfort.

2. Integration of DSC with Glassblock

Four hypotheses of positioning, designing and integrating the DSCs with the glassblock have been formulated to constitute the object of Patent PA2012 A000002 entitled "Integrazione di celle fotovoltaiche ibride nel vetromattone" (authors: Rossella Corrao, Marco Morini and Luisa Pastore) and deposited in Palermo on March 6th, 2012. The first three hypotheses foresee two modalities of deposition/integration each so that the actual hypotheses become seven in total. For the time being, it is not possible to describe them in detail because the patent is under registration. The work continued with an evaluation of the effects of this integration in terms of energy production, optical and thermal performance and with an estimation of the costs of the production of these DSC-integrated glassblocks. From each DSC-integrated glassblock, two wires come out for the connection with the other glassblocks and for the creation of a dry-assembled PV panel which can be integrated in translucent façades and become a part of the envelope itself.[1] Horizontal and vertical cavities that result from the juxtaposition of contiguous glassblocks include plastic profiles containing steel bars for panel prestressing and electric interconnections. The length of the joints between the glassblocks in the panel is 2 mm.

For an approximate evaluation of the peak power of each glassblock, a range of efficiency was defined between 4% and 8% on the basis of literature: this choice makes it possible to include all the combinations of colours, "active" designs and transparencies of the DSCs in the glassblock in order to simplify a comparison between all the formulated hypotheses. Each hypothesis is characterised by a percentage of an active area per glassblock which range from 57.44% to 93.78%: this percentage is obtained by dividing the total DSC active area of the building envelope by a single glassblock (which, for the reference 19x19cm glassblock, is 0.0361 m^2). The peak power of each modified glassblock was calculated with the inverse formula of nominal efficiency for each hypothesis and for different values of nominal efficiency in the defined range. Its values range from 1.656 to 2.712 Wp per glassblock (when the efficiency is 8%):

$$\eta = \frac{P_p}{A \cdot I_{STC}} \Rightarrow P_p = \eta \cdot A \cdot I_{STC} \tag{1}$$

The valuations were also extended to a dry-assembled precast panel with 2-mm joints, consisting of 50 glassblocks, in order to be able to reason upon the scale of a building. The hypotheses that offer the highest values of an active area per glassblock – more than 80% (that is comparable to one of the other technologies integrated by flat glass owing to the fact that the interconnections and structures are integrated in the panel) – get close to the peak performance of older PV generations. This is – for clear reasons – impossible in flat glass PV semi-

1 Patent PA2012 A00003 entitled "Pannello precompresso di vetromattoni assemblati a secco per la realizzazione di involucri traslucidi", authors: Rossella Corrao, Luisa Pastore & al.

transparent façades where interconnections and structures can subtract a relevant part – almost 20% – of the active area. Moreover, it must be also considered that semi-transparency in glass-glass silicon panels is achieved by separating opaque cells so that the light can come inside through the inactive parts of the translucent façade generating a loss in the active area and, consequently, in the efficiency of modules and implying the impossibility of a translucent glassblock using the traditional Si-based technology.

If we consider that 7-11 m^2 of a photovoltaic area are required per 1 kWp of c-Si panel, whereas this value stands at about 11-13 m^2 for thin-film solar panels, hypothesis 2 – characterised by the biggest active area per glassblock (at an efficiency of 8%) – is equated to the thin-film technology with a required active area of about 13 m^2 per 1 kWp. Moreover, it must not be forgotten that DSC performance under real operative conditions – in terms of kWh/kWp – is proven better than the "1st generation technology" thanks to the particular sensitivity of DSCs to all kind of lights, their excellent behaviour with an increase in temperature and their relative independence of the angle of incidental light.

For the evaluation of its optical transmittance τ, every DSC-integrated glassblock was schematized as the stratification of three layers, each characterised by a different value of optical transmittance: the first layer is represented by the glassblock itself whose τ was previously evaluated through optical simulations by Opticad; the second is the PV layer whose value of optical transmittance was calculated considering the effective percentage of the glassblock surface occupied by DSCs (whose optical transmittance for wavelengths higher than 600 nm was deducted from literature and is 45% for 5% efficiency and 30% for 6% efficiency) [11]; the third layer is represented by the glass sheet used for closing the DSC device which is endowed in an optical transmittance of 90%. The global values of optical transmittance of the DSC-integrated glassblock, obtained through multiplication between the optical transmittance of each layer, range from 22.62 to 40.49% when the efficiency is 6%, and from 33.92 to 46.77% when the efficiency is 5%.

Undoubtedly, these values are higher than those of the first and second photovoltaic generations, while the real advantage is that the optical transmittance of the DSCs can be easily "designed" not only considering the optimal energy production but also reasoning upon the best conditions for indoor illumination in accordance with the functional destination of a building, the climatic area where it is located, the orientation of the façades available for integration, consumption in terms of electricity for heating, cooling etc.

The calculation of the costs of the DSC-integrated glassblock used prices per square metre: to be more precise, it considered an aliquot for DSC materials and one for the production, both deducted from literature [12–14]. The aliquot for the deposition/integration of the DSCs increased by a percentage relating to specific processes or complications in production introduced by integration according to each hypothesis. It also regarded the capital cost of equipment, the cost of starting the production off, which was amortized considering a ten-year period and an annual production of 500,000 DSC-integrated glassblocks, as well as the cost of the glassblock itself taken from the 2011 commercial catalogue of international companies. All the evaluations were synthesized in Table 1 presented below.

Although it is an estimation, a really important result of this evaluation is that the calculated costs – which include 30% earning both on glassblock and DSC production – do not relevantly exceed the price of the "basic" glassblock and that the difference utterly decreases when the comparison is made with other kinds of glassblock which present finishing,

Table 1

Synthetic table for seven hypotheses

<table>
<tr><td colspan="2">η</td><td>1 | 1a</td><td>2 | 2a</td><td>3 | 3a</td><td>4</td></tr>
<tr><td colspan="2">Active area [m^2]</td><td>0.029</td><td>0.034</td><td>0.021</td><td>0.024</td></tr>
<tr><td colspan="2">Active area per glassblock [%]</td><td>80.91[%]</td><td>93.78[%]</td><td>57.44[%]</td><td>65.70[%]</td></tr>
<tr><td colspan="2">Loss in active area per glassblock [%]</td><td>19.09[%]</td><td>6.22[%]</td><td>42.56[%]</td><td>34.30[%]</td></tr>
<tr><td colspan="2">Active area/m_2 of envelope (2-mm joints)[%]</td><td>80.06[%]</td><td>92.80[%]</td><td>56.84[%]</td><td>65.01[%]</td></tr>
<tr><td colspan="2">Loss in active area/m_2 of envelope [%]</td><td>19.94[%]</td><td>7.20[%]</td><td>43.16[%]</td><td>34.99[%]</td></tr>
<tr><td rowspan="2">$\eta_{effective,\ panel}$</td><td>4[%]</td><td>3.20[%]</td><td>3.71[%]</td><td>2.27[%]</td><td>2.60[%]</td></tr>
<tr><td>8[%]</td><td>6.40[%]</td><td>7.42[%]</td><td>4.55[%]</td><td>5.20[%]</td></tr>
<tr><td rowspan="2">Glassblock peak power (Wp)</td><td>4[%]</td><td>1.168</td><td>1.356</td><td>0.828</td><td>0.949</td></tr>
<tr><td>8[%]</td><td>2.336</td><td>2.712</td><td>1.656</td><td>1.897</td></tr>
<tr><td rowspan="2">N. of glassblock needed per 1kWp</td><td>4[%]</td><td>856</td><td>737</td><td>1.208</td><td>1.054</td></tr>
<tr><td>8[%]</td><td>428</td><td>369</td><td>604</td><td>527</td></tr>
<tr><td rowspan="2">Panel area needed per 1kWp [m^2]</td><td>4[%]</td><td>31.23</td><td>26.90</td><td>44.06</td><td>38.46</td></tr>
<tr><td>8[%]</td><td>15.62</td><td>13.45</td><td>22.03</td><td>19.23</td></tr>
<tr><td rowspan="2">Cost (€/m^2 of active area)</td><td>4[%]</td><td>€ 241.94</td><td>€ 226.76</td><td>€ 270.54</td><td>€ 260.81</td></tr>
<tr><td>8[%]</td><td>€ 274.90</td><td>€ 259.72</td><td>€ 304.44</td><td>€ 294.71</td></tr>
<tr><td rowspan="2">Cost (€/glassblock)</td><td>4[%]</td><td>€ 7.41</td><td>€ 7.79</td><td>€ 6.92</td><td>€ 7.08</td></tr>
<tr><td>8[%]</td><td>€ 8.42</td><td>€ 8.92</td><td>€ 7.79</td><td>€ 8.01</td></tr>
<tr><td rowspan="2">Cost (€/Wp)</td><td>4[%]</td><td>€ 5.45</td><td>€ 4.42</td><td>€ 8.55</td><td>€ 7.22</td></tr>
<tr><td>8[%]</td><td>€ 3.12</td><td>€ 2.55</td><td>€ 4.84</td><td>€ 4.10</td></tr>
<tr><td rowspan="2">Optical transmittance τ (λ>600 nm)</td><td>5[%]</td><td>39.07[%]</td><td>34.84[%]</td><td>46.77[%]</td><td>33.92[%]</td></tr>
<tr><td>6[%]</td><td>30.22[%]</td><td>24.59[%]</td><td>40.49[%]</td><td>22.62[%]</td></tr>
<tr><td colspan="2">Thermal transmittance (*U*-value W/m^2K)</td><td>1.57</td><td>1.57</td><td>1.57</td><td>1.27</td></tr>
</table>

colouration or specific treatments. Obviously, this happens because of the low-cost production of the DSCs but also because of the fact that the deposition of the DSCs is considered as integrated in a process normally used by the glassblock. The economic return comes not just from selling power but also from the value of a "green" building to let and the naming rights [15].

3. Conclusions and future developments

The optimization of the efficiency and stability of the cells together with the industrialization of their processes of deposition on the glassblocks will enable glassblock and PV industries to come up with a new product, both for indoor environments and external claddings, characterised by better performance. The glassblock is already an energy-efficient product, in terms of thermo-acoustic insulation and light transmission, which offers a number of different – also customizable – features according to the designers and consumers' requirements, while the possibility of integrating it with PV semitransparent and colourful cells opens brand new scenarios. The objective of the research that we are carrying out, briefly described in this paper, is to design a novel building product, a PV glassblock which maintains/improves the thermal and mechanical qualities of the original product and where the PV cells can be integrated through the design of transparency, the choice of colours and the scheme of patterns. Some particularly designed glassblocks already exist but none of them can produce PV energy: the idea is to maintain, tailor as well as refine the aesthetical characteristics of the glassblocks without adding any unsustainable costs owing to the ease of the customizability of the DSCs which both represent a unique market proposal and perfectly fit in the glassblock industry. Moreover, the use of glassblocks for indoor environments is very common – 13 million pieces are produced yearly. This number gets near 50% of the total glassblock market. The research can also have an interesting impact in this sector – in fact, a big part of energy saving could also come from internal applications where the glassblock is widely used for its aesthetical appeal and particular translucency. The low-cost DSC process, integration in the glassblock production chain and the ease of the assembly of a panel will hopefully guarantee an economically sustainable, energy-generating and aesthetically attractive PV product. Predicting a market of one million items every year, the DSC-integrated glassblock could help to reduce CO_2 emissions by about 1,000 t according to the media calculations of electric production for the four formulated hypotheses.

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