Applications of Organic Cells in Buildings: Integrated Photovoltaic Systems

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Abstract: In this paper the use of organic cells with the aim of implementing them in urban environment for indoor and outdoor building-integrated systems is analyzed. Window systems with organic cells are presented as well as a methodology for finding their optimal parameters. A comparison of organic windows with regular windows is performed using the presented methodology to show the potential of organic cells.

***Keywords*—solar energy. photovoltaic. organic cell building. efficiency. windows.**

I. Introduction

THERE is currently general agreement that the world must evolve towards developing an energy infrastructure based on renewable energy as low polluting as possible. In fact, this transformation is considered a necessity for the future of our planet. Population growth and the need to provide electrical energy to all the people in the world as well as the urgent need to reverse the ecological impact of modern society make it evident that the development of technologies that help to achieve the objective of a sustainable global energy infrastructure must be devised now.

Among the renewable energies, solar energy occupies a central place but its generation cost is still high. The high cost and complexity of production of silicon cell-based photovoltaic systems is the biggest impediment to the deployment of solar power on a global scale..

Organic solar cells, called Dye Sensitized Solar Cell (DSSC) present an alternative to the classical inorganic silicon cells. These cells have organic molecules that help the absorption of photons through an electrochemical reaction. Their low cost, ease of manufacture, non-polluting materials and structural versatility make them a great option to be implemented in building's window systems.

The purpose of this paper is to delve into DSSC technology and their application to make solar energy economical. The discussion begins by presenting world numbers in terms of energy production. After this, the operating characteristics of an organic cell, their fundamental parameters of efficiency and transparency, as well as a methodology by software simulation to find the optimal relationship of these parameters with the efficiency of the entire system in which they are integrated will be explored.

A final section in this work introduces the Changeable Semitransparent Organic Window (COSW) system by [6] and the Switchable PV Window by [11]. This are windows capable of changing their transparency automatically, being

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able not only to generate electricity but also to reduce the demand of energy in lighting and heating.

II SOLAR ENERGY PRODUCTION WORLDWIDE

According to the annual reports from IRENA [3] and the Fraunhofer Institute for Solar Energy [2] published in 2020 the photovoltaic power generation worldwide up to 2018 was 585-Terawatt per hour, which is only 2.2% of the total electric energy generation. Coal and gas are still the most used resources, adding up more than 60% of the total production. These data are displayed as a circular chart in Fig. 1.

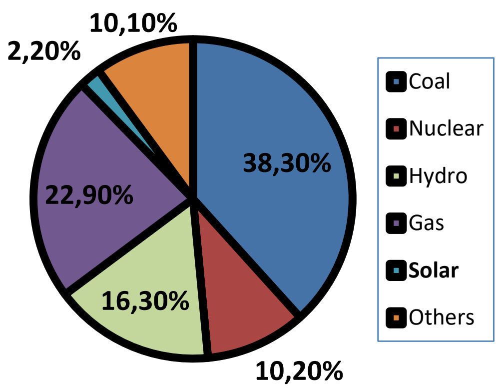

Fig. 1. Global electricity production by source

In terms of geographic zones China is the leading country for solar energy generation with 36% of the global share. Its followed by Europe with 15% and North America with 12%. Concerning PV module production in 2019, China is also the leading country with a share of 66%. The second largest productor is the rest of Asia with 18%. Europe contributed with a share of 3%; and the USA and Canada with 4%.

Solar energy production has grown steadily for the past two decades. The worldwide growth has been close to exponential, with values between 20% and 30% depending on the year, and the increase in 2019 was 22%. In economics terms, the global weighted-average total installed cost, which measures the cost in US Dollars of an installation capable of generating 1 Kilowatt of photovoltaic energy, has declined more than 80% in the last 20 years and 13% in 2019.

Despite all these improvements, the cost of production of solar energy is still high compared to the cost of production of non-renewable sources. The high cost and complexity of production of silicon solar cells is the greatest limitation to overcome in order to achieve the objective of making solar energy economically viable on a global scale.

II. ORGANIC CELLS

In [4, Fig 2] a schematic representation of the Dye-Sensitized Solar Cell (DSSC) is presented.

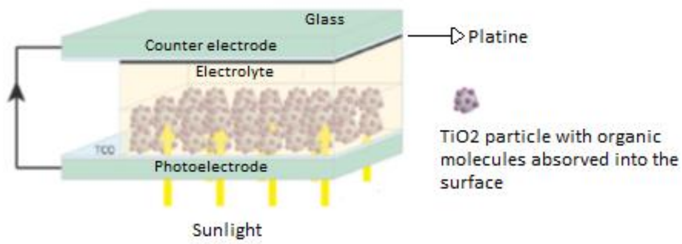

Fig. 2. DSSC Schematic Diagram

This kind of cell is a photo-electrochemical system composed of five basic components:

- A mechanical support coated with transparent conductive oxides.
- A semiconductor film, usually Titanium Dioxide (TiO_2).
- A sensitizer adsorbed onto the surface of the semiconductor.
- An electrolyte containing a redox mediator.
- A counter electrode capable of regenerating the redox mediator.

A schematic representation of the DSSC process is shown in [5, Fig. 3].

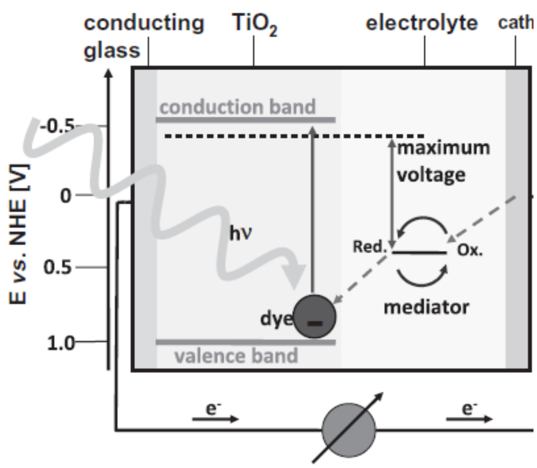

Fig. 3. DSSC Electrochemical process.

The working principle is described by [8] as follows: in the first step the dye sensitizer acts like an electron donor absorbing a photon, thus leading to the excited dye sensitizer to inject an electron into the conduction band of the semiconductor, leaving the sensitizer in an oxidized state. Then the injected electron flows through the semiconductor's network to arrive at the TCO back contact and then through the external load to the counter electrode to reduce the redox mediator. The redox, commonly an iodine base electrolyte, in turn regenerates the sensitizer, completing the electro-chemical circuit.

III. Applications of Organic Cells in Buildings

A. Building Integrated Photovoltaics

Silicon solar cells have a rigid structure and this imposes limitations on their potential for their implementation in urban environments, being mostly limited to installations in roofs. Organic cells, because of their great structural versatility, have the potential to solve these problems. According to Hiramoto and Shinmura [9], from the Institute for Molecular Science (Okazaki, Japan),organic cells have the following structural advantages:

- They are flexible
- They are printable
- They have light weight
- They are low cost
- They can be fashionably designed
- They can be fabricated by roll-to-roll production
- They can be attached to the roofs, windows, and walls of houses and buildings.

Building integrated photovoltaics (BIPV) are photovoltaic panels used to replace the traditional building materials. They are integrated into the building roof, skylights, and facades of the building during the construction process.

After a thorough energetic and economic analysis, Oliver and Jackson [10] show that many of the high costs of solar energy can be reduced if they are implemented as integrated systems in the construction of buildings as shown in [10, Fig. 4]

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Fig. 4. a) Semi-transparent organic cell b) Building using DSSC windows panels.

B. Efficiency and Transparency

The ability of the organic solar cell to convert light into electricity is directly related to the interaction of the organic material with photons from sunlight. The greater the thickness of the organic substrate, the greater the current density and the efficiency of the cell will be. However, as the organic substrate layer grows, the transparency of the cell decreases, blocking the passage of sunlight into the interior of the building. This leads to a loss of natural lighting inside the rooms, increasing the need to use artificial light and heating.

To reduce energy consumption to a minimum, the optimal balance must be found between the efficiency of the cell, (how much electricity it generates) and its transparency (how much sunlight passes through it).

In the following graphs the results relating to the efficiency as a function of the thickness of the organic layer, obtained by [7] in an experimental way are presented.

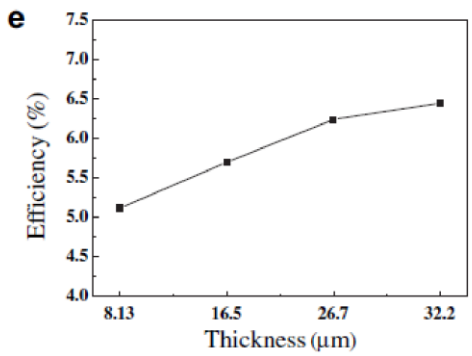

Fig. 5. Cell Effiency vs Thickness of organic layer

With these experimental data [7] performed a simulation to evaluate the efficiency of a room with a 30m x 30m floor and 3.9m high walls. Two situations were simulated: with walls in the room with regular windows and with windows with organic solar cells. In both cases the walls faced Northwest, Northeast, Southwest, and Southeast with a window-to-wall ratio of 50%, which is a standard value used in modeling. The results show the energy consumption in the room for the period of one year for different transparency levels of the cells. The four compass points are take into account as the solar radiation is not the same in different cardinal directions.

In the figures [7, Fig 6] and [7, Fig 7] the energy consumption, by year, measured in kW/m^2, for regular windows and for DSSC is presented.

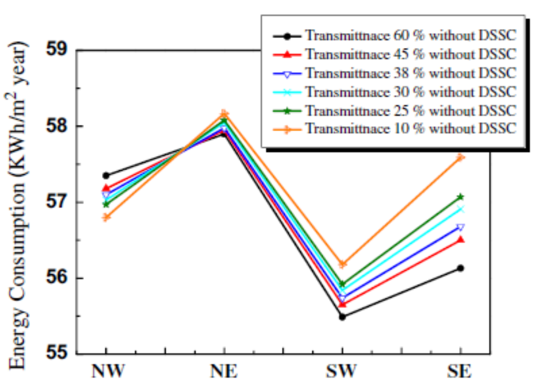

Fig. 6. Regular window yearly energy consumption

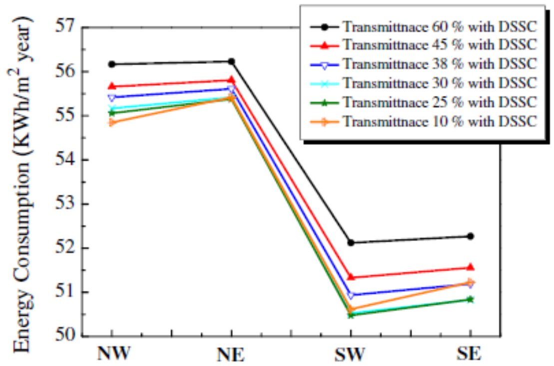

Fig. 7. DSSC window yearly energy consumption

The difference in annual consumption for a regular window system and a window system with DSSC cells for different levels of transparency is shown in [7, Fig 8].

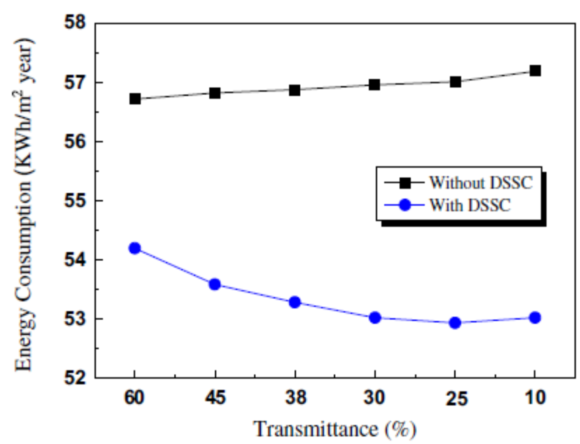

Fig. 8. Total energy consumption by year vs transparency with DSSC

The lowest energy consumption is achieved when the transmittance is 25%, which corresponds to 11.6% in energy saving. According to the authors, this is due to the excess of electricity production from DSSC compared to the energy use when transmittance is between 60% and 25%.

IV. CHANGEABLE ORGANIC SEMI TRANSPARENT SOLAR CELL WINDOW

Tak et al. [6] introduce a Changeable Organic Solar Window (COSW), capable of automatically changing its transparency with the purpose of finding the right balance that allows to maximize the generation of electricity at the same time it takes advantage of natural lighting to achieve the right level of lighting and thermal comfort for a room. A Schematic diagram of the window is shown in [6, Fig. 9]

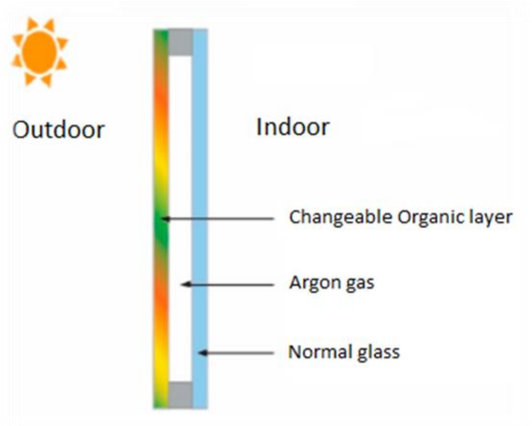

Fig. 9. Schematic representation of the COSW

The system consists of a double-glazed window, (which are closed units made using two pieces of glass which are separated by an air gap) where the polymer-based organic solar cell is utilized as the outer layer to maximize the electricity production and modulation range. The space between the solar cell and a 3mm-thick common transparent glass of the interior layer is filled with argon gas. This ensures adequate thermal insulation

In [6] the optical proprieties of the window were simulated with software used to design and study glazing systems. The COSW was configured with a transmittance between 0.536 and 0.603 for visible light and between 0.479 and 0.493 for solar heat gain coefficient. The electric properties of the photovoltaic layer of the window were configured with the values of 0.58 V for the open-circuit voltage and 9.696 mA/cm^2 for the short-circuit density current. The system can go through 5 states, modifying its transparency and Solar Heat Gain Coefficient.

The goal of the simulation was to examine the total energy conservation, which is the sum of the electricity generation from the photovoltaic system and the energy savings. The results are compared with those obtained for a normal double-glazed Low E window under the same conditions. Double-glazed Low E windows are regular windows consisting in two pieces of glass which are separated by an air gap and a thin layer on the outer glass, provided to limit heat transfer and UV rays. The room is a square module with a 6m x 6m floor and 4m high walls, with a window only on one wall. (50% window-wall relationship) for the cardinal directions North, South, East and West.

According to Tak et. al. [6] the results, considering only the energy savings (without considering the PV generation), were 9.24kW/m^2, 7.56 kW/m^2 and 11.39 kW/m^2 for a south-facing, east-facing, and west-facing facades, respectively in a period of one year. For the north-facing façade however, the COSW was less useful because it consumed more energy than the regular double-glazed Low-E window, and produced only a small amount of electricity.

The electricity production from the COSW was 5.56 kW/m^2, 3.96 kW/m^2, 3.63 kW/m^2, and 2.31kW/m^2 for the south-facing, east-facing, west-facing, and north-facing facades, respectively. However, the results also showed that the COSW consumes more energy for the north-facing windows than the conventional window system, being this the only drawback found.

The total reduction in energy consumption considering the electricity production from the solar cell deducted from the total energy consumption was approximately 14.80 kW/m^2 for the south-facing facade, 11.51 kW/m^2 for the east-facing facade, and 15.02 kW/m^2 for the west-facing facade. In order to have a practical reference this numbers can be better visualized as percentage.

According to [12] the expected energy consumption for a normal commercial building in France for 2020 under the EU regulations is ~ 175 kW/m^2. Taking the previous result of 15.02 kW/m^2 in consumption reduction for the COSW this means 8.6% in energy saving for the year.

V. SWITCHABLE PHOTOVOLTAIC WINDOW

Wheeler et. Al. [11] proposes a switchable PV window that adapts its absorption properties to solar conditions. It works by changing the chemical composition of one of its layers by solar thermal heating. The change in transparency is enabled by a chemical reaction in the absorber layer; this layer is composed of a metal halide perovskite methylamine complex of formulae $CH_3NH_3PbI_3$.

Perovskite is a mineral which consists of calcium titanium oxide, with chemical formula $CaTiO_3$; by extension any material that shares this crystalline structure of the form ABX_3 , where A and B have net positive charge and X has net negative charge is called perovskite material. The reversible dissociation of a methylamine complex (CH_3NH_2), which is an organic compound, from the perovskite crystalline type structure switches the device from its transparent state to its opaque state.

The device is sealed in argon and returns to its transparent state upon removing the solar irradiation and after cooling. This reaction, along with the different layers of the cell, is shown in [11, Fig 4].

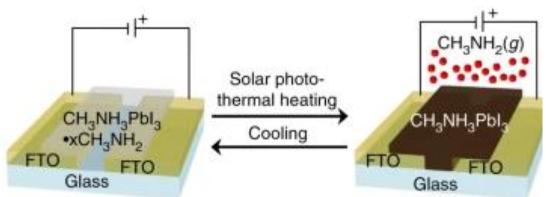

Fig. 10. Schematic representation of the chemical reaction

In [11, Fig 1b] the different levels of transparency can be seen as a function of the wavelength of the solar radiation.

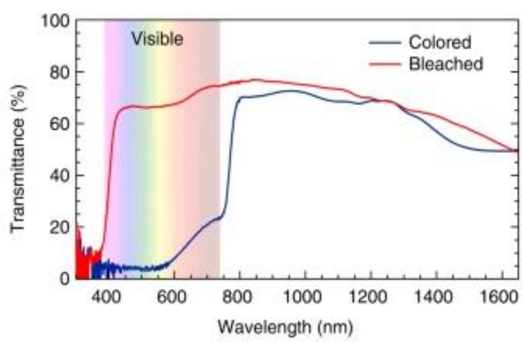

Fig. 11. Transmittance vs Wavelength

In [11, Fig 1d] and [11, Fig 1e] the current generation is shown as a function of time and illumination.

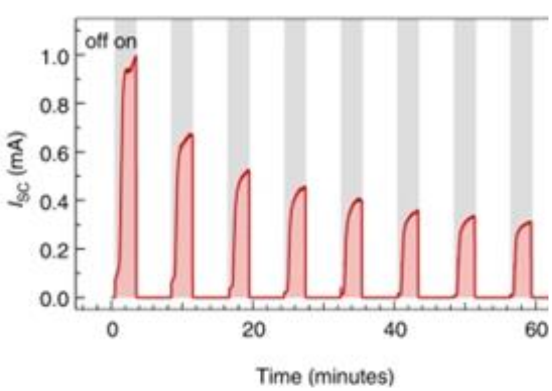

Fig. 12. Current for dark and light intervals

The grey ”on” section represent 3 minutes of lighting showing the peak in current generation; the white ”off” section represent 5 minutes of cooling without light, showing no current generation. Each peak represents a cycle through which the device passes.

According to the authors the device is highly absorbing in the visible light part of the spectrum when it is in the opaque state, with an average transmittance of 3%. The visible light transmittance increases to 68% when it is in the transparent state. The range of reduction in transparency is important for the thermal performance of the window. The device reached power conversion efficiency (the ratio between the useful output energy and the input energy) of 11.3%, passing over 20 cycles, and with switching times of less than 3 min.

VI. CONCLUSION

In this work organic cells and their application to window systems have been presented. An analysis of their potential to be integrated into buildings has also been carried out. A simulation method has been designed to analyze the energy performance of rooms provided with this type of windows, in order to compare them with regular windows. This method allows finding the transparency value with which the highest efficiency is achieved. The COSW window system has also been introduced. A window with organic cells capable of changing its level of transparency automatically in order to achieve efficiency in energy consumption and adequate comfort level. We have also studied a Switchable PV Window based on a perovskite layer that dynamically responds to sunlight.

The results show that organic cell windows have great potential to reduce energy consumption when the proper parameters for their operation are known. Using the methodology proposed in this work, it is shown that the optimal level of transparency for windows with organic cells, in the simulated conditions, is around 25% with 11.6% saving. This level of transparency maximizes the energy efficiency. Regarding the CWOS window, the simulated analysis shows that it is capable of saving around 15.02 kW/m^2 of energy per year for each façade of the room, considering both the production of photovoltaic electricity and the savings in thermal energy, except for the north facade where the consumption of the normal window is lower due to the solar radiation in that cardinal orientation.

The experiential data of the Switchable PV Window presented in [11] shows the potential of perovskite cells for PV window technology. A range from 3% to 68% transparency levels and 11.3% of power energy conversion efficiency was achieved for the fabricated prototype.

REFERENCES

[1] J. Klaus, I. Olindo, A. Smets. R. Van Swaai, and M. Zeman. *Solar Energy. Fundamentals, technology and Systems.* Copyright Delft University of Technology, 2014

[2] Fraunhofer Institute for Solar Energy. *Photo-Voltaic ReportsSystems*. 17 june 2020- Available www.ise.fraunhofer.de

[3] IRENA (2020), Renewable Cost Database International Renewable Energy Agency.

[4] M. Gratzel *Dye-sensitized solar cells: A brief overview*. Swiss Federal institute of technology. 2011

[5] K. Sharma, V. Sharma and S. Sharma. *Dye-Sensitized Solar Cells: Fundamentals and Current Status.*

[6] S. Tak, S. Woo , J. Park and S. Park. *Effect of the Changeable Organic Semi-Transparent Solar Cell Window on Building Energy Efficiency and User Comfort.* Academic Editor: Andy van den Dobbelsteen; Published: 4 June 2017.

[7] S. Yoon , S. Tak , J. Kim, Y. Jun , K. Kang , J. Park. *Application of transparent dye-sensitized solar cells to building integrated photovoltaic systems.* Available https://www.journals.elsevier.com/building-and-environment. Accepted for publication 23 March 20.

[8] K. Nazeeruddin , E. Baranoff and M. Gratzel. *Dye-sensitized solar cells: A brief overview.* Institute of Chemical Sciences and Engineering, School of Basic Sciences, Swiss Federal Institute of Technology, CH-1015 Lausanne, Switzerland. Available online 17 March 2011. Associate Editor Hari M. Upadhyaya

[9] M. Hiramoto and Y. Shinmura. (2017) *Organic Solar Cells*. In: Kasap S., Capper P. (eds) Springer Handbook of Electronic and Photonic Materials. Springer Handbooks.Springer,Cham. Available https://doi.org/10.1007/978-3-319-48933-9_54

[10] M. Oliver and T. Jackson. *Energy and economic evaluation of building-integrated photovoltaics.*

Centre for Environmental Strategy, University of Surrey, Guildford, Surrey GU2 7XH, UK December 1999

[11] Wheeler, L.M., Moore, D.T., Ihly, R. et al. *Switchable photovoltaic windows enabled by reversible photothermal complex dissociation from methylammonium lead iodide*. Nature Communications 8, 1722 (2017). https://doi.org/10.1038/s41467-017-01842-4

[12] Anne-Solène Malidin, Clara Kayser-Bril, Nadia Maizi, Edi Assoumou, Véronique Boutin, Vincent Mazauric. *Assessing the Impact of Smart Building Techniques: a Prospective Study for France.* Conference Paper · December 2008 DOI: 10.1109/ENERGY.2008.4781017 · Source: IEEE Xplore