Investigations on luminescent glazing for transparent solar windows

Mohamed Fathi*, Mahfoud Abderrezek, Farid Djahli

***Abstract*— The aim of this study is developing an efficient and practical approach for utilization in buildings of windows and façades for solar energy conversion without impeding vision through glazing. For that purpose, the glazing is processed with a luminescent coating allowing recovering of the high energy photons from the Ultra Violet (UV) spectrum. By embedding photovoltaic cells of monocrystalline silicon types into the frame of window prototype, it is verified that solar energy conversion is effective from glazing edges. The electricity generated from the edges of the luminescent windows is valuated. The photocurrent and power are increased by adding a tinting film on the backside of luminescent glazing. Experimental tests and analysis of a prototype in operation have been practiced.**

***Index Terms*— Light Concentration, Luminescence, Photovoltaics, Solar Energy, Sun Spectrum Downshift.**

I. Introduction

THE Photovoltaic (PV) panels are more and more used for the production of green electrical energy in a centralized approach as like in large power plants but also by a distributed approach at the level of homes building or other infrastructure in urban or rural areas [1, 2, 3]. The use of these solar panels in the case of the distributed approach requires their installation on roofs or facades of buildings according to known technology of BIPV (Building Integrated Photovoltaic) or BAPV (Building Added Photovoltaic) [4, 5, 6]. The BIPV panels are quite expensive panels and do not allow a clear view of the surrounding landscape through the glass as either in the window or in opening roof (Sky Light) [7, 8, 9]. Furthermore, the orientation and tilt are critical to the performance index of the system made with BIPV and BAPV or Sky Light modules [10, 11, 12].

In this work, an interesting approach is demonstrated according to the technology of Luminescent Solar Concentrator (LSC) that allows producing energy from luminescent glass. For that purpose, Fig. 1 shows the difference between LSC and BIPV approach. A simplified process of dip coating is investigated [13, 14, 15], in order to facilitate the integration of the LSC technology in the manufacturing process of glazing and windows.

The LSC device is based on the combining of luminescent coatings on glass and the spectrum down shift phenomenon that will transform the high energy photons into lower energy photons in the visible wavelengths that get out from the edges of glazing [16, 17, 18, 19]; where solar cells will be positioned to make the photovoltaic conversion. This gives transparent windows that allow visual comfort without the drawback of obstructing the passage of light from PV cells comparatively to BIPV devices where cells are incorporated in the backside of the glass [20, 21]. By the application of LSC windows, the integration into architecture and environment seems to be more appropriate to be adapted to any orientation and low radiation [22, 23, 24]. Because this kind of technology does not require a specific tilt angle, it is increasingly sought for areas with low radiation as like northern Europe [25, 26].

Through this work, luminescent glazing synthesis is experimented by means of a simplified process of dip coating that has been tested and developed at laboratory scale. Achieving a first laboratory prototype permits the study of feasibility and shows the proof of the concept for PV cells monocrystalline silicon type imbedded in the frame borders of the luminescent glass. The various optoelectronic analyses, performed by spectrophotometry and by spectral radiation analysis of light output from edges of the luminescent glazing, helped to understand and highlight the operation of such devices. Furthermore, with varying the light transmission level by adding a tinting film on the backside of LSC window, the conversion efficiency should be enhanced according to the light trapping in the luminescent glazing windows.

This paper was submitted on 26 March 2017. This work was supported by the General Directorate of Scientific Research and Technological Development (DGRSDT) Affiliated to The Higher Education and Scientific Research Ministry (MESRS) of Algeria.

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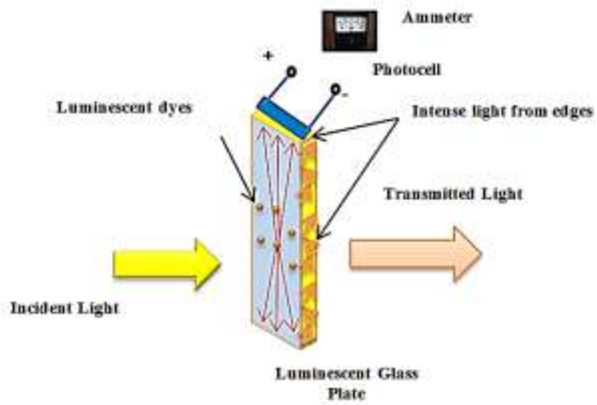
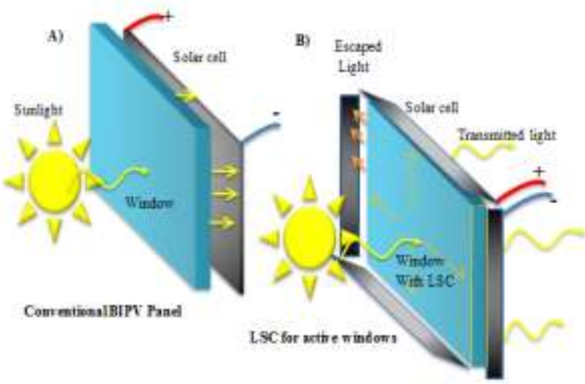


(a)



(b)

Fig. 1. Principle of Luminescent solar concentrator (LSC) for windows and façades. A - The principle, B- Difference between Luminescent solar concentrator (LSC) for active windows and BIPV panel.

II. Experimentations

A. *Simplified process for luminescent coating of glass plates*

After performing various tests, a simplified process using an orange fluorescent pigment component is developed according to the following steps; when mixed with ethanol and distilled water the orange fluorescent pigment is uniformly dissolved. Firstly, one ethanol volume is mixed with one volume of water. Then, was added a concentrated orange fluorescent compound in the form of a cartridge of 10 ml (Staedtler©-Fluorescent-Orange-92RE-14), to be diluted with the prepared solution of 250 ml (water + ethanol: 1-1). The obtained mixture is placed in a magnetic stirrer and mixed for 30 minutes.

Fig. 2. Glass windows dip coating in Luminescent orange pigment solution

By using the deposition technique of thin films by dip-coating process [27, 28], in the formed solution, the glass sample is immersed and withdrawn slowly in order to grow a luminescent thin layer on the glass plate. After removal of the glass plate immersed in the solution for 5 minutes and drying in ambient air for 20 minutes at inclined position, the glass plate is put in an oven for soft baking at 60 °C during 30 minutes. This last step is necessary to allow total evaporation of solvents and water from formed luminescent layer and improve its adhesion on the glass plate. This produces a luminescent orange glass as shown in Fig. 2 wherein it is noticed the glowing edges by LSC effect.

Steps for implementation of the luminescent window test prototype

After making the luminescent coating on a glass plate of 10 x 10 cm2, an experimental prototype is realized for optoelectronics laboratory tests indoor and outdoor as shown in figure 3.

PV Photocells are inserted in the frames of edges so as to be aligned by covering the entire edge side; a frame in black polyvinyl chloride (PVC) was used for this first laboratory prototype (see pictures of Fig. 3). The output connections (+/-) were taken by opposing sides of the frame and allow the measurement of the photocurrent and other electrical parameters of the photocell embedded in the frame. The main steps are as follows:

- A self-adhesive film is deposited, on the rear side, for several tinting and shading levels of light transmission.
- Frames made PVC are prepared and cut to the size of the lateral edges to nest there.
- Preparation of a string of silicon solar cells in series for the photo collection of concentrated light on the glass edging.
- Assembly of the PV cells string in the frame and welding of output terminations (+/-).

Fig. 3. Assembly steps for LSC window prototype

III. Estimation of Solar Electricity Generated by Luminescent Glazing in Building Windows

A. Calculation of the optical yields

For this study, it was defined the optical yield (Y_{opt}) of the LSC window face and edge by the ratio of light intensity transmitted by the backside face (E_{out}) or the edge (E_{edge}) of LSC plate to intensity of light received on the front side (E_{in}). These Y_{opt} ratios are defined in equations (1) and (2). The repartition of light intensities, for an outdoor measurement example, is represented on Fig. 4. Thereby, it is has been obtained an average value of 19.1% of the optical yield of light escaping at the edges. It is to be noticed that the optical yield output on the edge of a transparent plate LSC was compared to a neutral plate window and it has been found to be more than ten times bigger (X 10). This confirms the LSC window interest and its efficiency for power energy conversion from glazing edges. So to maximize the performance of electric power production, it is well advised to maximize the concentration of the output light intensity of borders and thus increase its optical yield ($Y_{opt\text{-}edge}$). as in

$$Y_{opt-face} = \left(E_{out}/E_{in}\right) \times 100 \quad (1)$$

$$Y_{opt-edge} = \left(E_{edge}/E_{in}\right) \times 100 \quad (2)$$

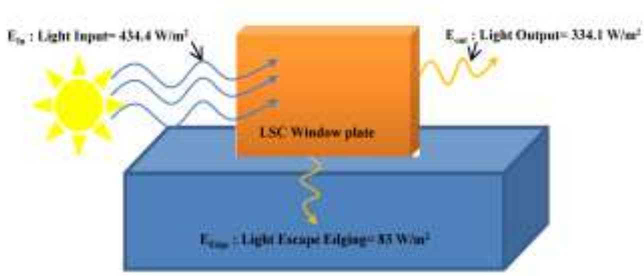


Fig. 4. Example of defining the optical yield (Yopt) of light intensity distribution in the LSC window.

To calculate the optical yield (Yopt) of the LSC system which performs in outdoor condition, the assemblies shown in Fig.5 were realized in order to measure the irradiance intensities values relative to the three positions (a), (b) and (c). These positions corresponds to the irradiance received by the front side of LSC plate (E_{in}), transmitted by the LSC glazing (E_{out}) and by one of its four edges (E_{edge}). Then, several measurements with variable input irradiance has been done and reported in Table 1. These results are reported on curves of Fig. 6, where we notice an average optical edge yield (Yopt-edge) of 20% when irradiance input (E_{in}) is superior to 200 W/m^2. This result proves that the estimation of energy potential production is possible for future sizing of LSC windows integrated to buildings [29].

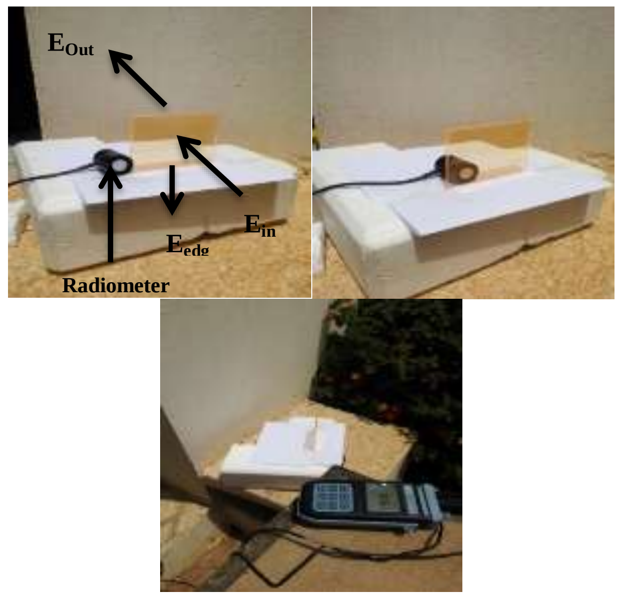


Fig. 5. Outdoor measurements of the optical yield (Y_{opt}) with the three positions of the radiometer. a- Input light intensity (E_{in}), b- Output light intensity from LSC plate backside (E_{out}), c- Output light intensity by edging (E_{edge}).

Table 1: Outdoor measurements with calculation of the optical yields.

E_{in} (W/m2)	E_{out} (W/m^2)	E_{edge} (W/m^2)	$Y_{opt\text{-}face}$ (W/m^2)	$Y_{opt\text{-}edge}$ (W/m^2)
176	128	51	72,73	28,98
250	138	59	55,20	23,60
258	153	63	59,30	24,42
317	182	67	57,41	21,14

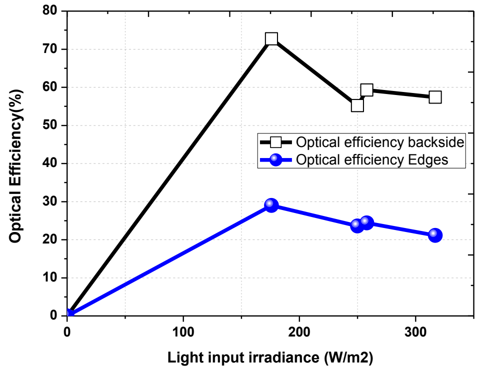
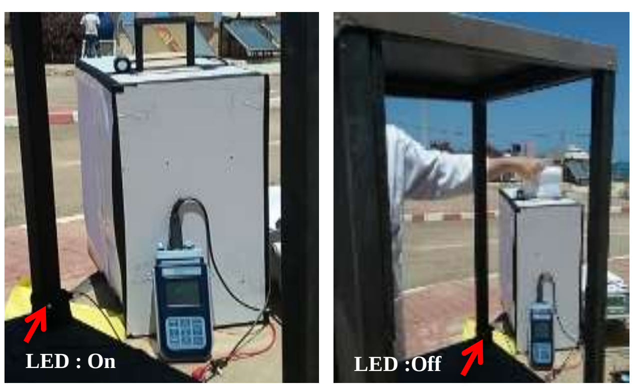


Fig. 6. Optical yields plotting for edge and face from outdoor measurements of LSC window.

B. Electricity generation measurement from illuminated luminescent window plates

Outdoor measurements were made at 250 W/m^2, 138 W/m^2 and 59 W/m^2, respectively for light input irradiance (E_{in}), light output irradiance at backside (E_{out}) and light output irradiance at edge (E_{edge}). A voltage of 4.111 volts and a current of 652 µA have been measured on mono-Si PV cell of 85 X 6 mm^2. Also, to proof the concept of energy production, the power supply of a LED (from a cell integrated into the edge of the light window) has been successfully demonstrated, as shown on pictures of Fig. 7.



(a) (b)

Fig. 7. A LSC window as power supply of a LED : proof of the concept. a- LED supply « On » from illuminated LSC window, b- LED supply « off » when LSC window is masked.

This is the proof of the concept as shown in picture of Fig. 7. The energy calculation shows that we can produce 1.07 W per m^2 from the four edges of the LSC glass in these irradiation input conditions (E_{in}) and up to 4.28 W per m^2, in STC (1000 W / m^2). According to the worst month in our locality (Algiers), where 3.2 hours of STC by day are available, 13.7 Wh per m^2 of window can be produced per day. That is, for an annual radiation of 2000 hours STC, a square meter of LSC glass will produce 8.56 KWh per year. When assuming a traditional house of F4 type (120 m^2 of floor area) with 20 m^2 of glazed window, a quantity of 171 KWh is cumulative over the year. However, with 20 m^2 of LSC glazing, we can produce 272Wh/day, for the equivalent of F4 type house; this could meet the lighting needs or power loading for USB electronic devices (phone, camera, etc).

C. Application of luminescent windows in building integrated lighting

This interesting result of power supplies from LSC window in distributed energy production was firstly applied in assuring standalone lighting and USB electronic devices loading. For that, a new prototype concept have been developed and realized in this work. As shown on Fig. 8, an LSC active window (consisting of 3 assembled glazing plates of 10 X 10 cm^2) has permitted to power supply of a string matrix of 6 LEDs (6 X 0.1 W) and a USB port plugged to a cell phone.

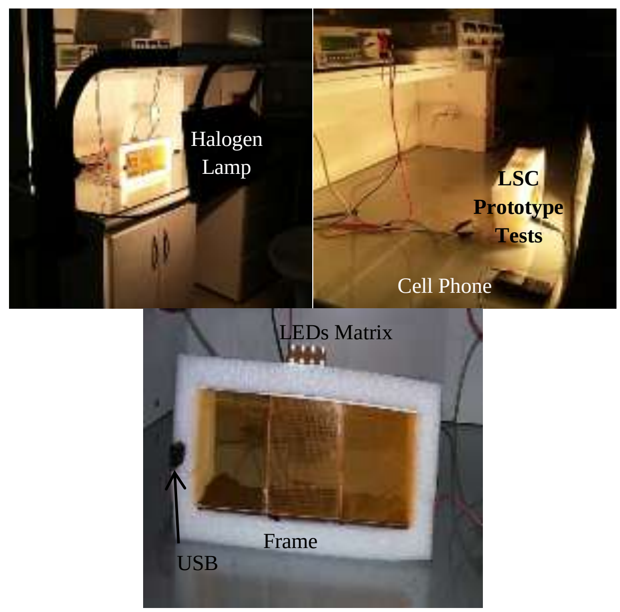


Fig. 8. Prototype of luminescent window for power supply of LEDs lighting and USB port.

IV. Conclusion

This study investigated on luminescent glazing application for achievement of energy power conversion from solar irradiation. For that purpose, PV cells of monocrystalline silicon type are embedded into the frame of luminescent glazing. This configuration allows better integration of photovoltaic in building for energy generation, by assuring in same time an open view through windows and façades. Prototypes based on chemical dip coating process are made at laboratory scale. These prototypes allowed measurements of voltage and current outputs in order to estimate the power supply potential of luminescent windows. The energy calculation shows that we can produce 1.07 W/m^2 from the four edges of the luminescent window at low irradiance input (Ein) conditions of 250 W/m^2 and up to 4.28 W/m^2 in Standard Test Conditions (STC, E_{in} = 1000 W/m^2). The daily solar electricity generation was estimated at an average of 450 Wh/day from 20 m^2 of luminescent glazing surface for typical houses in a North African site (Algiers). This concept of a luminescent glazing window was concretized by the realization of a prototype at laboratory scale. Outdoor testing allowed validation of the solar energy conversion concept by luminescent glazing to satisfy energy needs for lighting (LEDs) and power supply devices (USB).

References

[1] Almada J.B, Leão R.P.S, Sampaio R.F, Barroso G.C. A centralized and heuristic approach for energy; 2016.

[2] Panguloori R, Mishra P, Kumar S. Power distribution architectures to improve system efficiency of centralized medium scale PV street lighting system. Solar Energy 2013; 97: 405–413. http://dx.doi.org/10.1016/j.solener.2013.08.034.

[3] Fathi M, Abderrezek M, Friedrich M. Reducing dust effects on photovoltaic panels by hydrophobic coating. CleanTechn Environ Policy 2016; DOI 10.1007/s10098-016-1233-9.

[4] Zomer C. D, Costa M. R, Nobre A, Rüther R. Performance compromises of building-integrated and buildingapplied photovoltaics (BIPV and BAPV) in Brazilian airports. Energy and Buildings 2013; 66: 607–615.

[5] http://dx.doi.org/10.1016/j.enbuild.2013.07.076.

[6] Santos Í. P. d, Rüther R. The potential of building-integrated (BIPV) and building-applied photovoltaics (BAPV)in single-family. urban residences at low latitudes in Brazil. Energy and Buildings 2012; 50: 290–297. http://dx.doi.org/10.1016/j.enbuild.2012.03.052.

[7] Young Tae Chae, Jeehwan Kim, Hongsik Park, Byungha Shin. Building energy performance evaluation of building integrated photovoltaic (BIPV) window with semi-transparent solar cells. Applied Energy 2014; 129: 217-227.

[8] http://dx.doi.org/10.1016/j.apenergy.2014.04.106.

[9] Olivieri L. Performance of Semi-transparent Photovoltaic Façades. Springer International Publishing, Chaptern :Nano and Biotech Based Materials for Energy Building Efficiency; 2016, 279-320.

[10] Pravettoni M, Strepparava D, Cereghetti N, Klett S, Steiger M. Indoor calibration of Sky Quality Meters:Linearity, spectral responsivity and uncertainty analysis. Journal of Quantitative Spectroscopy and Radiative Transfer 2016; 181:74–86. http://dx.doi.org/10.1016/j.jqsrt.2016.03.015.

[11] Sudip Kumar Pal, Kari Alanne, Juha Jokisalo, Kai Siren. Energy performance and economic viability of advanced window technologies for a new Finnish townhouse concept. Applied Energy 2016; 162:11–20. http://dx.doi.org/10.1016/j.apenergy.2015.10.056.

[12] Charles S. S. J, Cheng C.L. Verification of Optimal Angle for South Orientated Tilted Plans According to theLatitude, Concept for BIPV. Springer Berlin Heidelberg, Proceedings of ISES World Congress 2007; 1:1059-1063. DOI 10.1007/978-3-540-75997-3_206.

[13] Cuce E, Cuce P. M. Tilt Angle Optimization and Passive Cooling of Building-Integrated Photovoltaics (BIPVs)for Better Electrical Performance. Arabian Journal for Science and Engineering 2014; 39: 8199-8207. DOI: 10.1007/s13369-014-1394-y.

[14] Anatoli Chatzipanagi, Francesco Frontini, Alessandro Virtuani. BIPV-temp: A demonstrative Building Integrated Photovoltaic installation. Applied Energy 2016; 173: 1-12. http://dx.doi.org/10.1016/j.apenergy.2016.03.097.

[15] Varga B. O, Iclodean C, Mariasiu F. Electric and Hybrid Buses for Urban Transport. Springer International Publishing; 2016.

[16] Berman E, Wildes P. D. Luminescent Solar Concentrators (LSC); Technical and Economic Requirements for a Residential System. Springer Netherlands, Chapter :Fourth E.C. Photovoltaic Solar Energy Conference 1982; 606-610.

[17] Marco Carlotti, Elisabetta Fanizza, Annamaria Panniello, Andrea Pucci. A fast and effective procedure for the optical efficiency determination of luminescent solar. Solar Energy 2015; 119: 452-460. http://dx.doi.org/10.1016/j.solener.2015.05.031.

[18] Abderrezek M, Fathi M, Djahli F, Ayad M. Study of the effect of luminescence down-shifting on GaAs solarcells with several optical windows layers. J. Sol. Energy Eng 2013; 136: 011014-1.011014-5. doi: 10.1115/1.4025593.

[19] Yilin Li, Joseph Olsen, Kenny Nunez-Ortega, Wen-Ji Dong. A structurally modified perylene dye for efficient luminescent solar concentrators. Solar Energy 2016; 136: 668–674. http://dx.doi.org/10.1016/j.solener.2016.07.051.

[20] Danos L, Parel T, Markvart T, Barrioz V, Brooks W.S.M., Irvine S.J.C. Increased efficiencies on CdTe solarcells via luminescence down-shifting with excitation energy transfer between dyes. Solar Energy Materials and SolarCells 2012; 98: 486–490. http://dx.doi.org/10.1016/j.solmat.2011.11.009.

[21] Xin Wang, Tongxin Wang, Xiujie Tian, Lijuan Wang, Wenxuan Wu, Yanhua Luo, Qijin Zhang. Europium complex doped luminescent solar concentrators with extended absorption range from UV to visible region. Solar Energy 2011; 85: 2179-2184. http://dx.doi.org/10.1016/j.solener.2011.06.007.

[22] Debije M. G, Verbunt P. P. C. Thirty Years of Luminescent Solar Concentrator Research: Solar Energy for the Built Environment. Adv. Energy Mater 2012; 2: 12–35. DOI: 10.1002/aenm.201100554.

[23] Baig H, Sellami N, Mallick T. K. Performance modeling and testing of a Building Integrated ConcentratingPhotovoltaic (BICPV) system. Solar Energy Materials and Solar Cells 2015; 134: 29–44. http://dx.doi.org/10.1016/j.solmat.2014.11.019.

[24] Meinardi F et al. Highly efficient large-area colourless luminescent solar concentrators using heavy-metal-free colloidal quantum dots. Nature Nanotechnology 2015; 178: 878–885. doi:10.1038/nnano.2015.178.

[25] Vishwanathan B, Reinders A. H. M. E, de Boer D.K.G , Desmet L, Ras A. J. M, Zahn F. H, Debije M. G A. comparison of performance of flat and bent photovoltaic luminescent solar concentrators. Solar Energy 2015; 112: 120-127. http://dx.doi.org/10.1016/j.solener.2014.12.001.

[26] M. Sabry, P.C. Eames, H. Singh, Y. Wu. Smart windows: thermal modelling and evaluation. Sol Energy 2014; 103: 200–209. http://dx.doi.org/10.1016/j.solener.2014.02.016.

[27] Bougiatioti F, Michael A. The architectural integration of active solar systems. Building applications in the Eastern Mediterranean region. Renewable and Sustainable Energy Reviews 2015; 47: 966–982. http://dx.doi.org/10.1016/j.rser.2015.03.030.

[28] Kannan N, Vakeesan D. Solar energy for future world: - A review. Renewable and Sustainable Energy Reviews 2016; 62:1092–1105. http://dx.doi.org/10.1016/j.rser.2016.05.022.

[29] Sabry M, Eames P.C, Singh H, Wu Y. Reduced energy consumption and enhanced comfort with smart windows: Comparison between quasi-optimal, predictive and rule-based control strategies. Energy and Buildings 2016; 127: 680–691. http://dx.doi.org/10.1016/j.enbuild.2016.06.024.

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