Trinity College Dublin
Coláiste na Tríonóide, Baile Átha Cliath
The University of Dublin

PEARL PV

COST Action PEARL PV Conference – Enabling the PV Terawatt Transition

Advances in Luminescent devices for BIPV

Capturing diffuse light

Dr Sarah McCormack
Associate Professor

15/03/2022

European Research Council
Established by the European Commission

The EU Framework Programme for Research and Innovation
HORIZON 2020

Science Foundation Ireland
sfi
For what's next

Overview

Background to Luminescent solar concentrators

- Introduction to LSCs and limitations

Current research on Luminescent devices for BIPV

- Review of current upscaled LSC performance for BIPV

Commercial LSC for BIPV

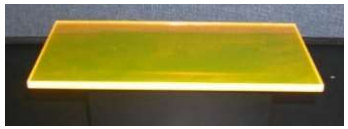
- Currently available

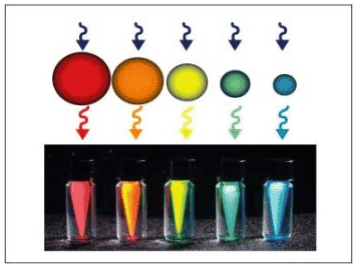
Conclusions

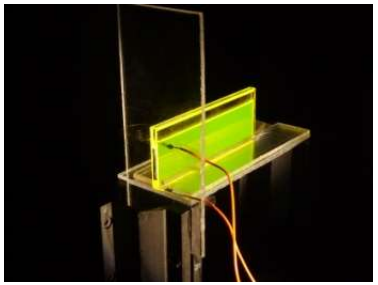
Luminescent Solar Concentrators

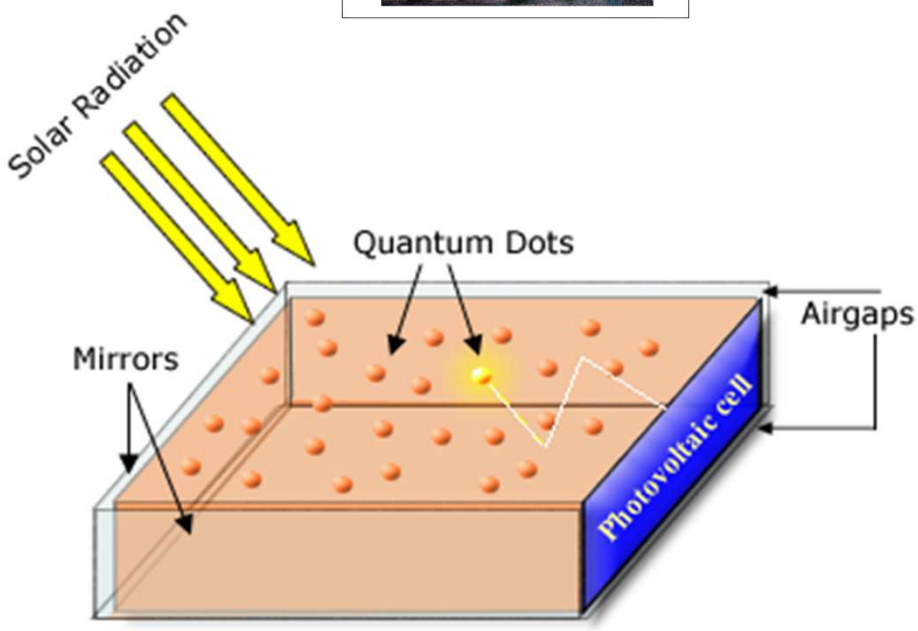
An introduction

- First conceived in the 1970's by Goetzberger & Greubel.
- Use of dyes, quantum dots, rare earth materials
- However many loss mechanisms
- Research mainly focuses on small scale
- This talk will discuss work where LSCs have been upscaled for BIPV applications



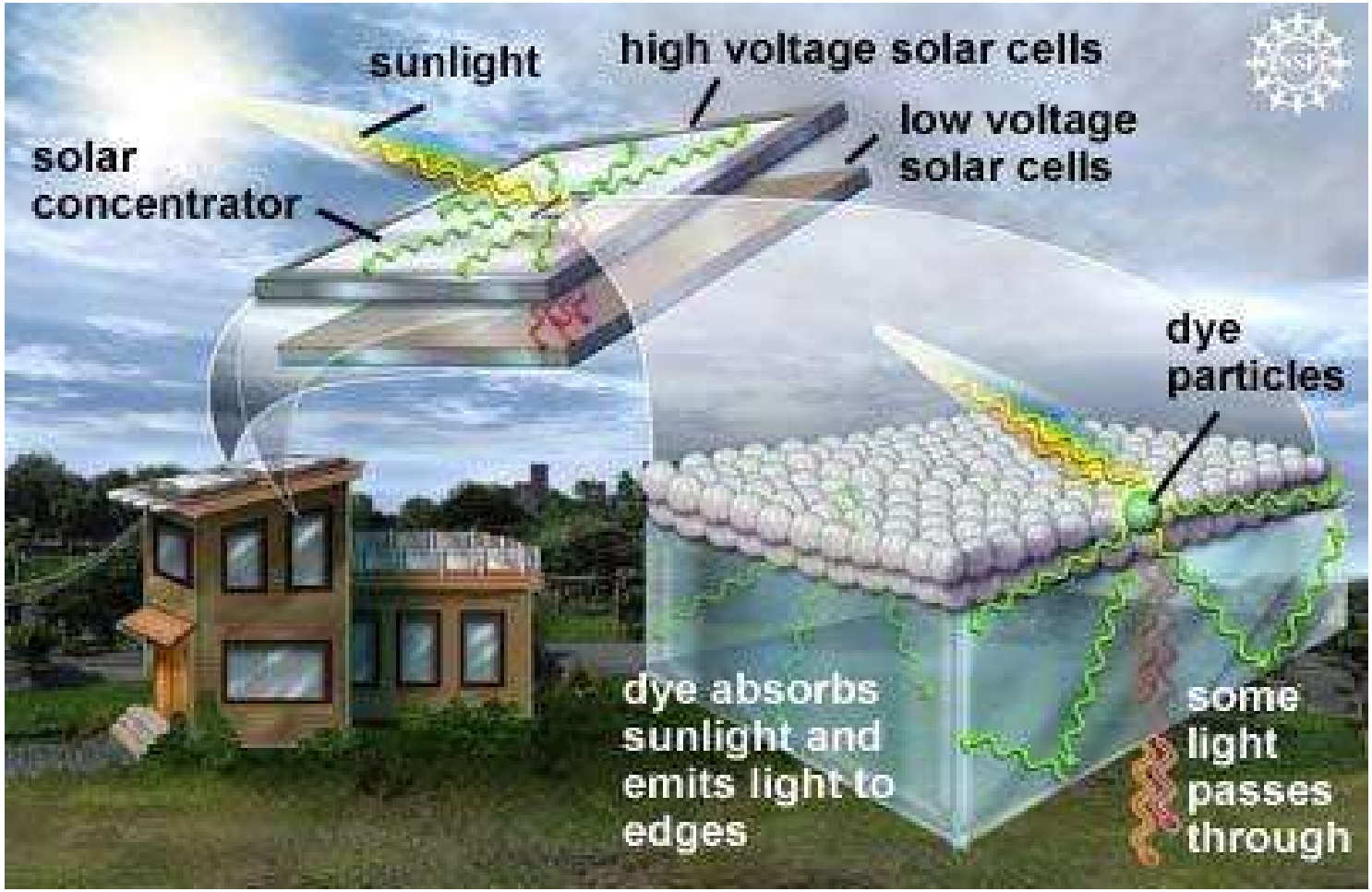






Advantages of LSC

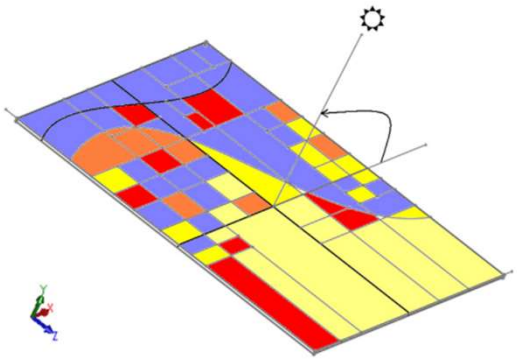
Static diffuse concentrator building elements suited to BIPV



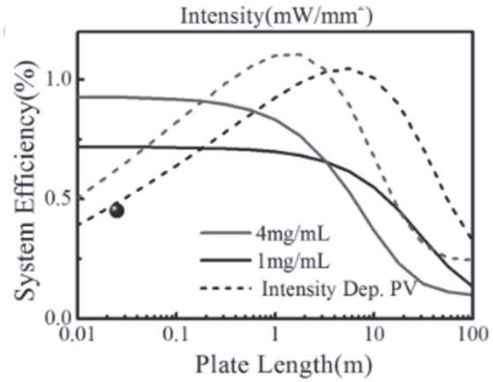
Huge amount of literature on LSCs

P A R L P V

- Excellent reviews on LSCs available – but not including large scale BIPV
- Even when included in the title – still only small scale –
- predicting consistent efficiencies up to 10 m^2
- modelling devices

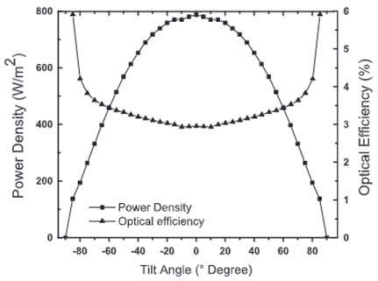


The stained glass window design modelled using five Lumogen dye colours



(2.5cm *x* 2.5cm *x* 0.1cm)

Power density and optical efficiency of a square stained glass window(47 cm 58 cm 0.5 cm) for varying the tilt angle



Optics Express Vol. 16, Issue 26, pp. 21773-21792 (2008) • https://doi.org/10.1364/OE.16.021773

OPTICA PUBLISHING GROUP

Luminescent Solar Concentrators - A review of recent results

Wilfried G.J.H.M. van Sark, Keith W.J. Barnham, Lenneke H. Slooff, Amanda J. Chatten, Andreas Büchtemann, Andreas Meyer, Sarah J. McCormack, Rolf Koole, Daniel J. Farrell, Rahul Bose, Evert E. Bende, Antonius R. Burgers, Tristram Budel, Jana Quilitz, Manus Kennedy, Toby Meyer, C. De Mello Donegá, Andries Meijerink, and Daniel Vanmaekelbergh

Author Information • Find other works by these authors •

ADVANCED ENERGY MATERIALS www.advenergymat.de

Materials Views www.MaterialsViews.com

Thirty Years of Luminescent Solar Concentrator Research: Solar Energy for the Built Environment

Michael G. Debije and Paul P. C. Verbunt*

Materials Views www.MaterialsViews.com

ADVANCED ENERGY MATERIALS www.advenergymat.de

Transparent Luminescent Solar Concentrators for Large-Area Solar Windows Enabled by Massive Stokes-Shift Nanocluster Phosphors

*Yimu Zhao and Richard R. Lunt**

ELSEVIER

Contents lists available at ScienceDirect

Solar Energy Materials & Solar Cells

journal homepage: www.elsevier.com/locate/solmat

Luminescent solar concentrators: From experimental validation of 3D ray-tracing simulations to coloured stained-glass windows for BIPV

CrossMark

A. Kerrouche, D.A. Hardy, D. Ross, B.S. Richards *

School of Engineering and Physical Sciences, Heriot-Watt University, Edinburgh, EH14 4AS, United Kingdom

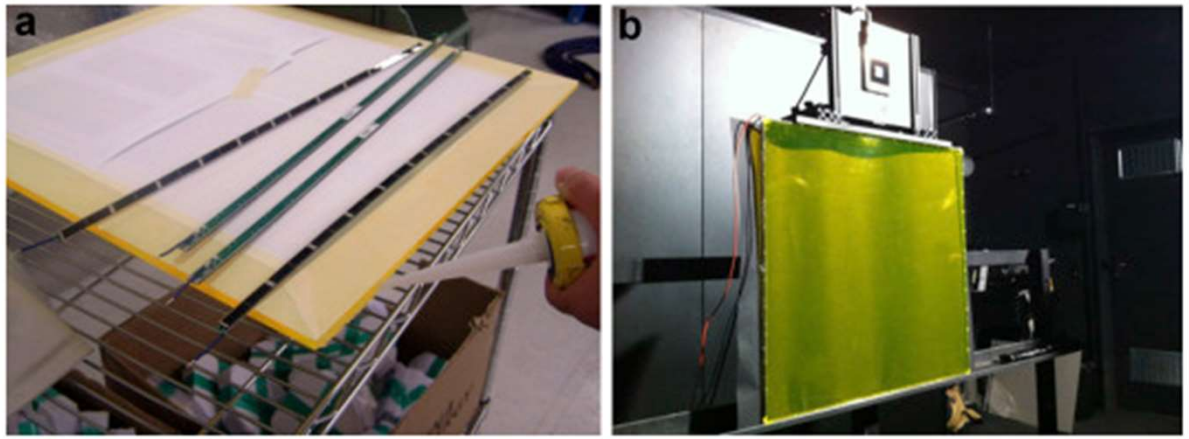
Large LSC module performance

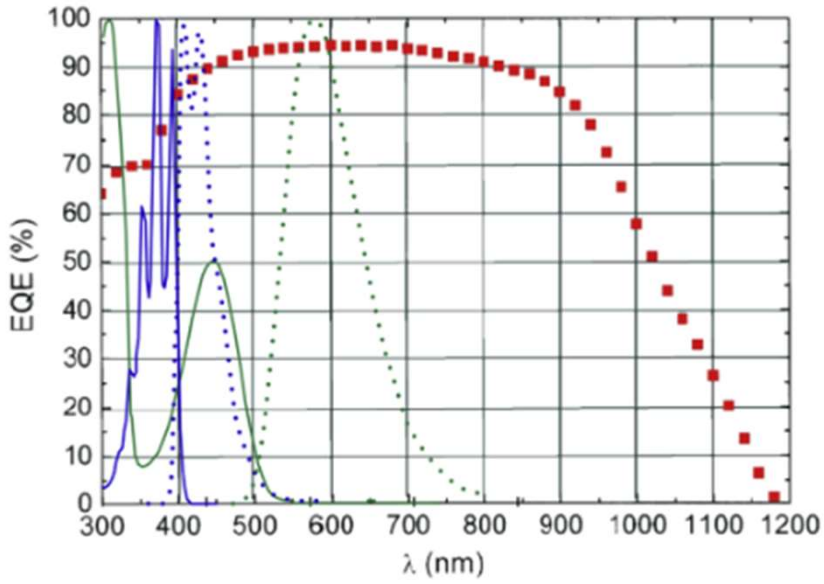
Aste et al., 2015

Aste at al., describe the first operating measurements carried out on an LSC prototype

PV Test Facility of the Politecnico di Milano, Italy.

- PMMA plates (6mm) doped with 2 in-house dyes
- 88 monocrystalline PV cells, (22 x 7 mm each, in a combined series-parallel connection,
- Six 50 x 50 cm panels in a single metal frame to realise a 108.4 x 161.8 cm LSC module.
- Total nominal power of the 528 cells installed in the module was 11.77 Wp.

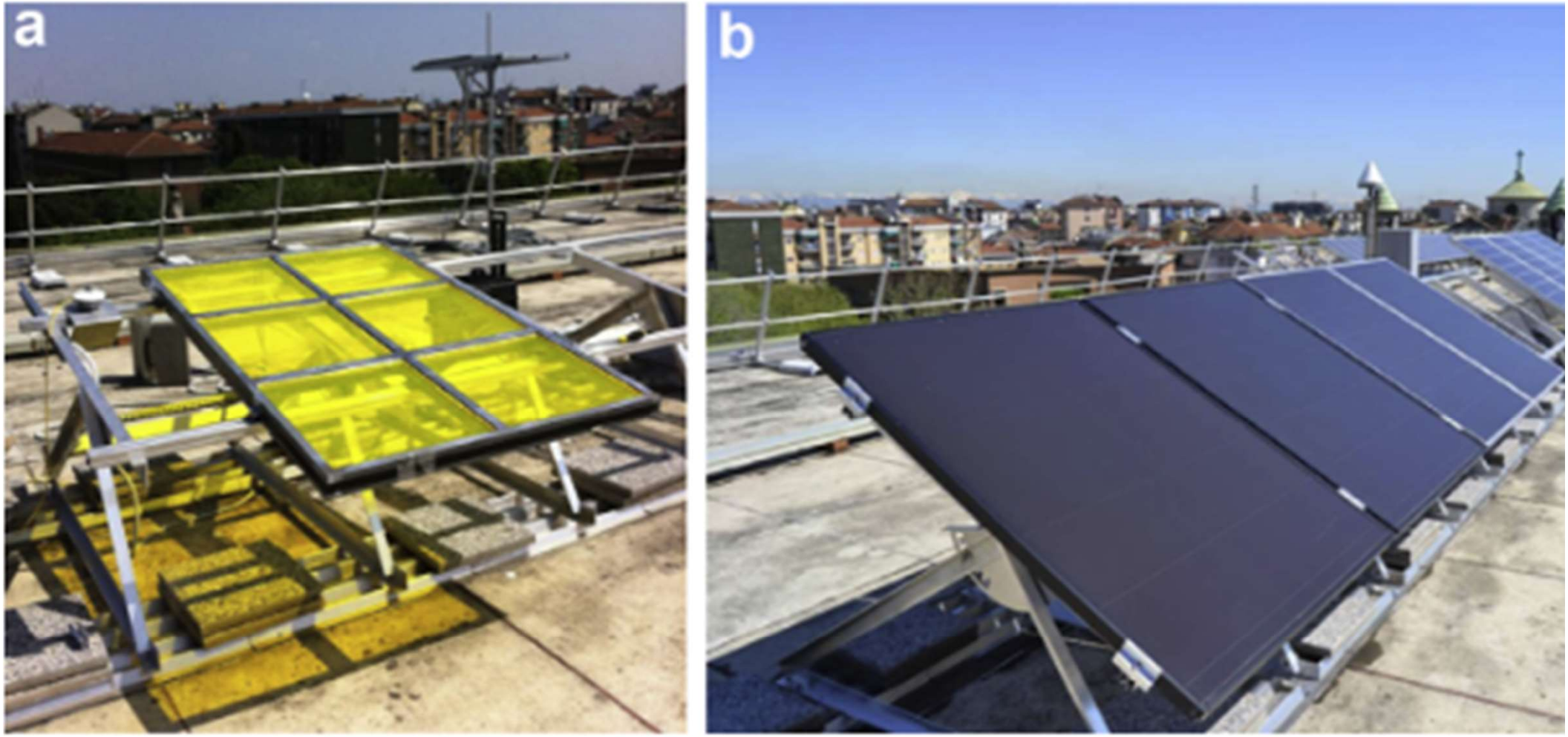




https://doi.org/10.1016/j.renene.2014.11.026

Large LSC performance

Aste et al., 2015

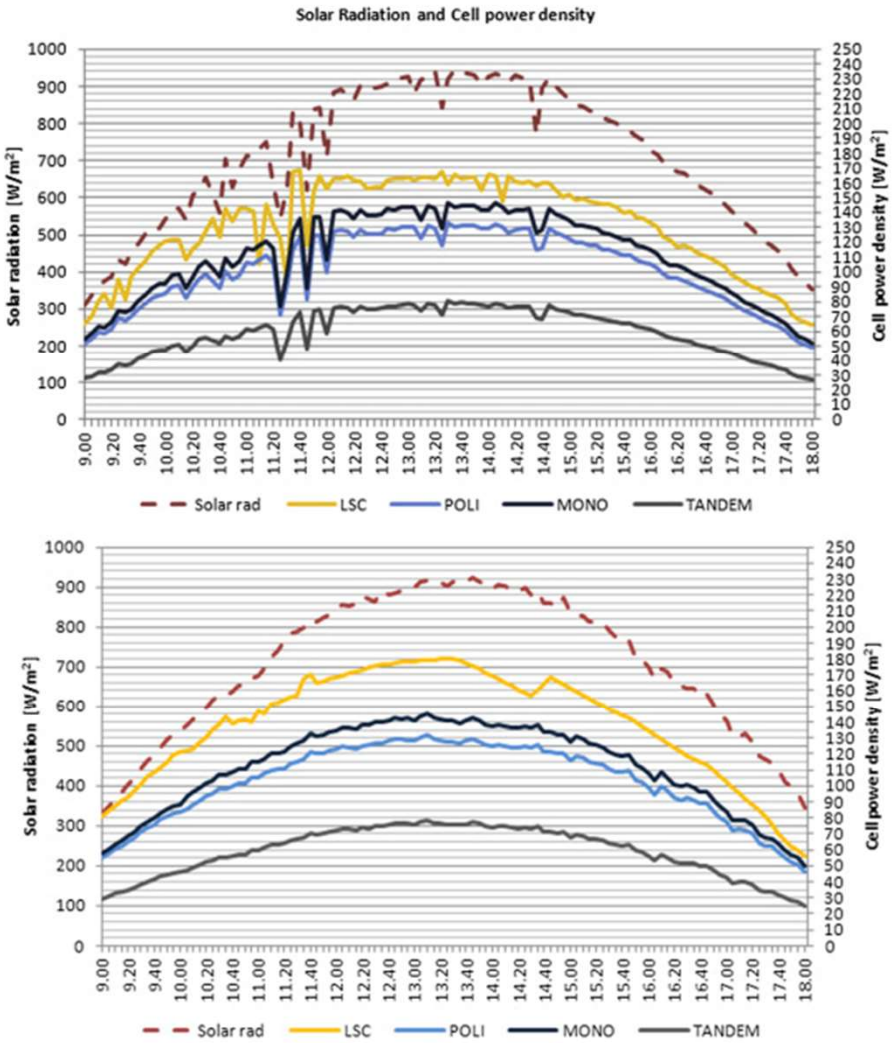


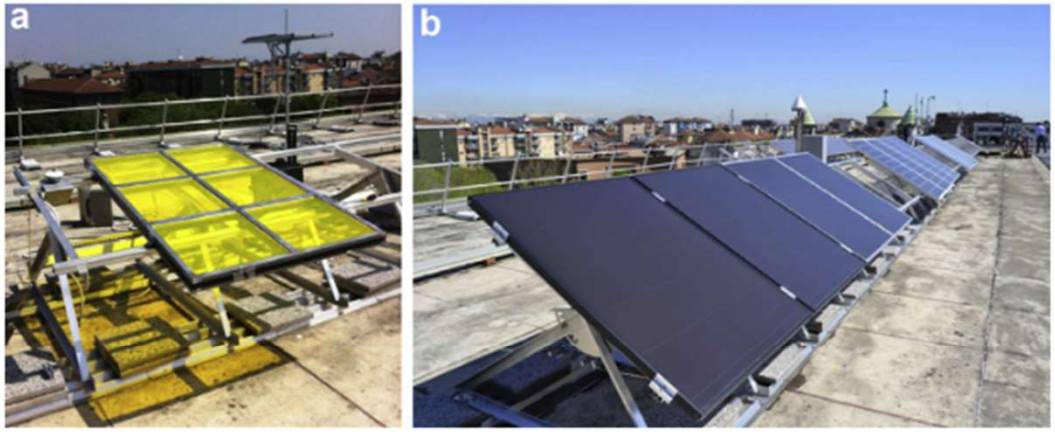
(a) ENI module and (b) standard photovoltaic modules at the PV Test Facility of the Politecnico di M

https://doi.org/10.1016/j.renene.2014.11.026

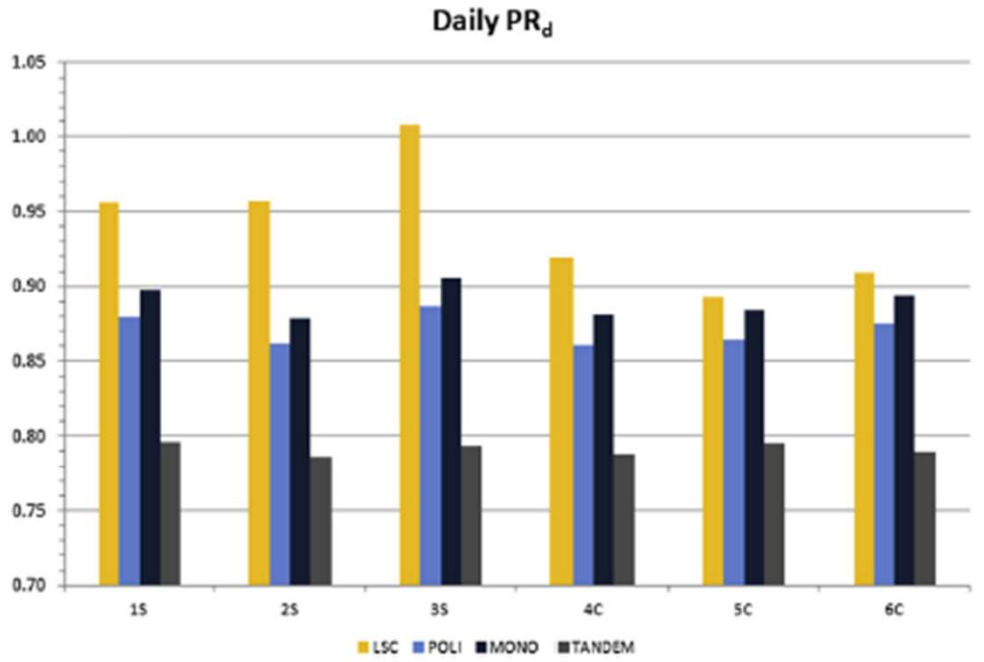
Large LSC performance

Aste et al., 2015





(a) ENI module and (b) standard photovoltaic modules at the PV Test Facility of the Politecnico di Milano University, Italy.

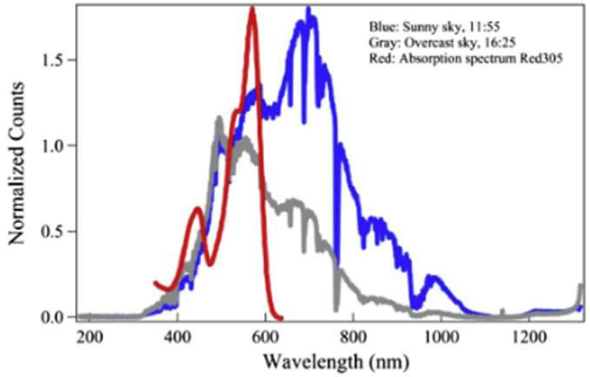


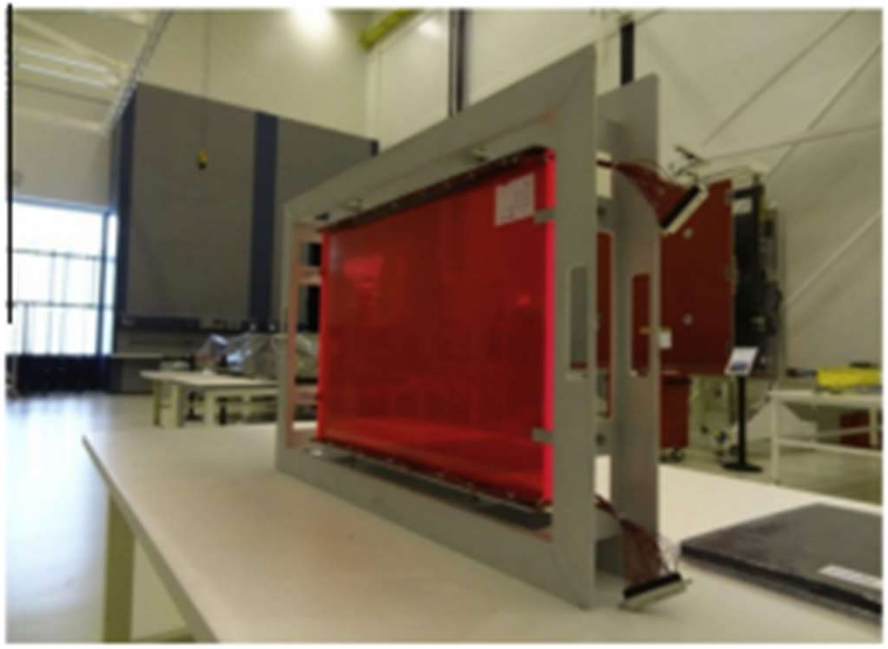
Daily performance ratio related the ENI module and the standard PV modules. S = sunny days; C = partially cloudy days.

https://doi.org/10.1016/j.renene.2014.11.026

Performance under changing light conditions

Debije & Rajkumar (2015)





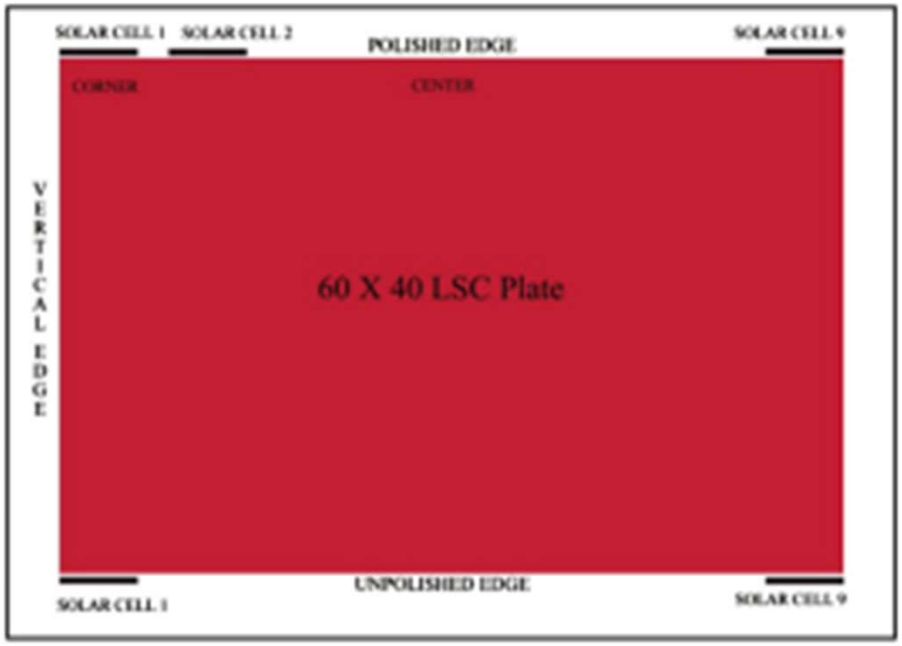


Fig. 1. (Left) the luminescent solar concentrator prototype, (right) depiction of solar cell placement.

https://doi.org/10.1016/j.solener.2015.08.036

Performance under changing light conditions

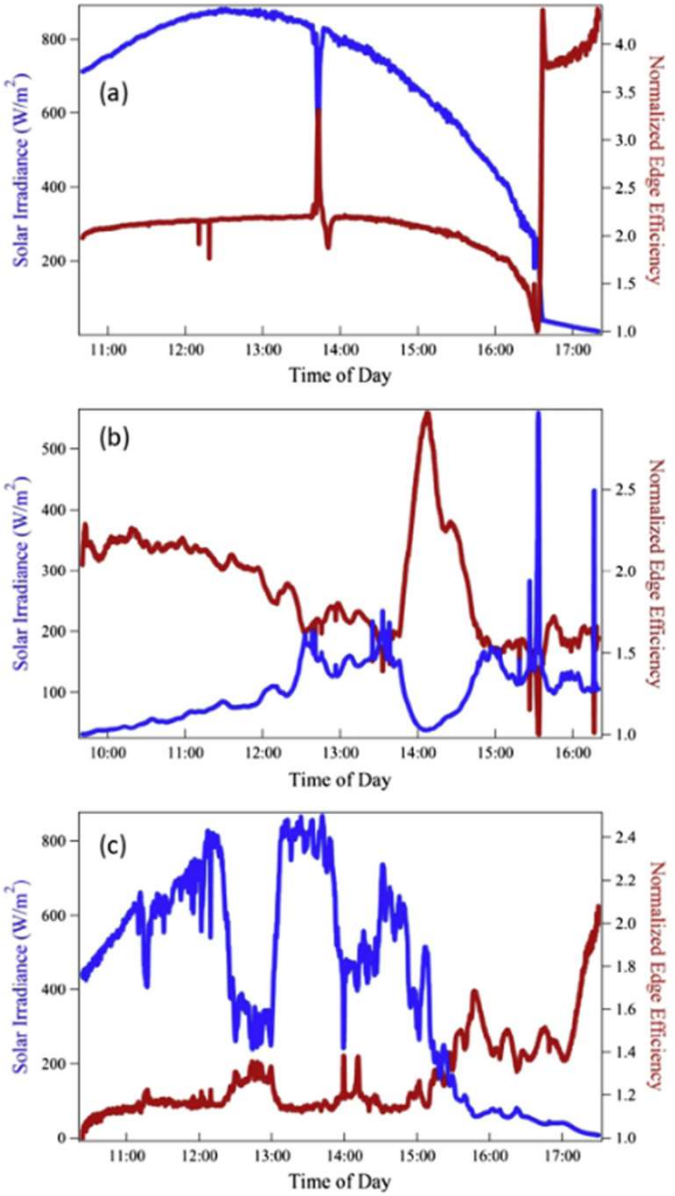
Debije & Rajkumar (2015)

Calculated normalized electrical edge efficiency (red) and global vertical solar irradiance (blue) plotted as a function of time for 3 different days

Generally PV efficiency decreases with decreased irradiance

Drop in solar irradiance (a) led to a spike in edge efficiency

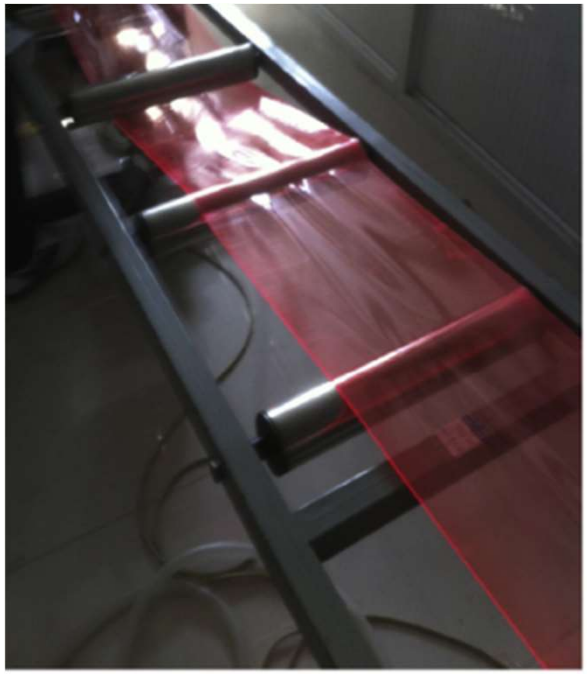
LSC efficiency improved under cloudy and diffuse light conditions

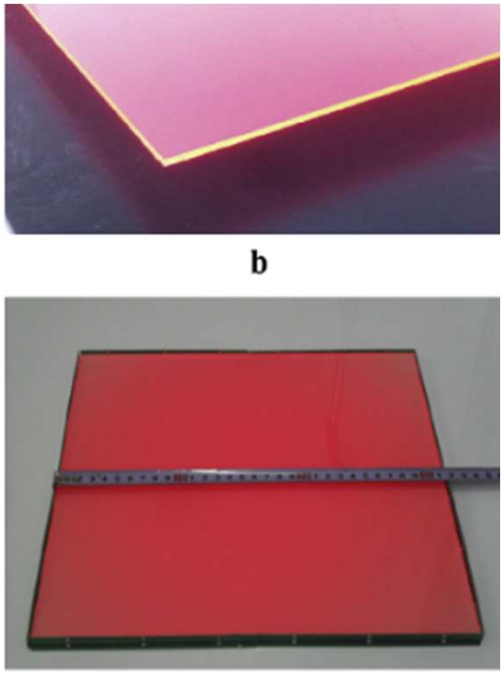


https://doi.org/10.1016/j.solener.2015.08.036

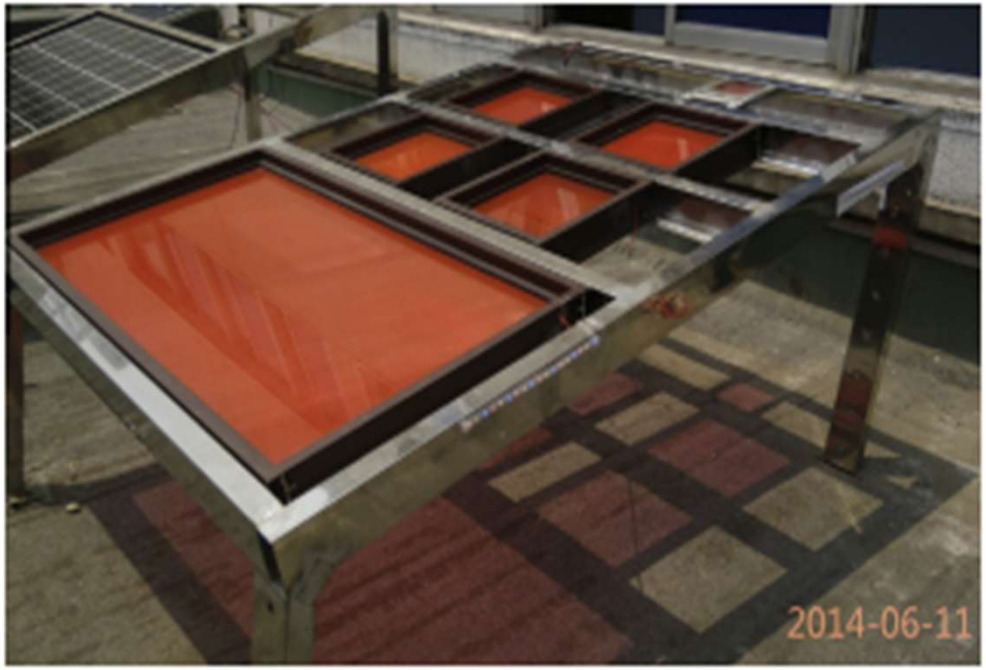
Large area glass laminate LSCs

Zhang et al., 2015





b



In this study, different size glass laminated luminescent solar concentrators (GL-LSCs) of

7.8 x7.8 cm^2 ,

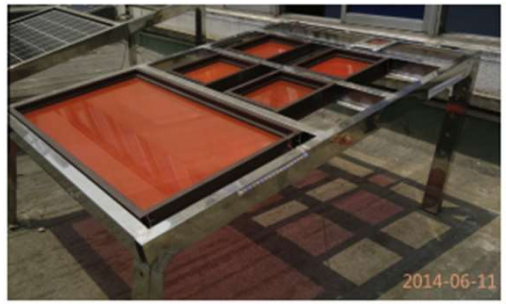
15.6x 15.6 cm^2 ,

31.2 31.2 cm^2 and 61 x 122 cm^2 were fabricated by using fluorescent dyes Lumogen Red 305 and Yellow 083, ultra-white glass and commercial mono-crystalline silicon solar cells.

https://doi.org/10.1016/j.solener.2015.05.004

Large area glass laminate LSCs

Zhang et al., 2015



As size increase, output power of GL-LSCs increases, but power conversion efficiency (PCE) decreases

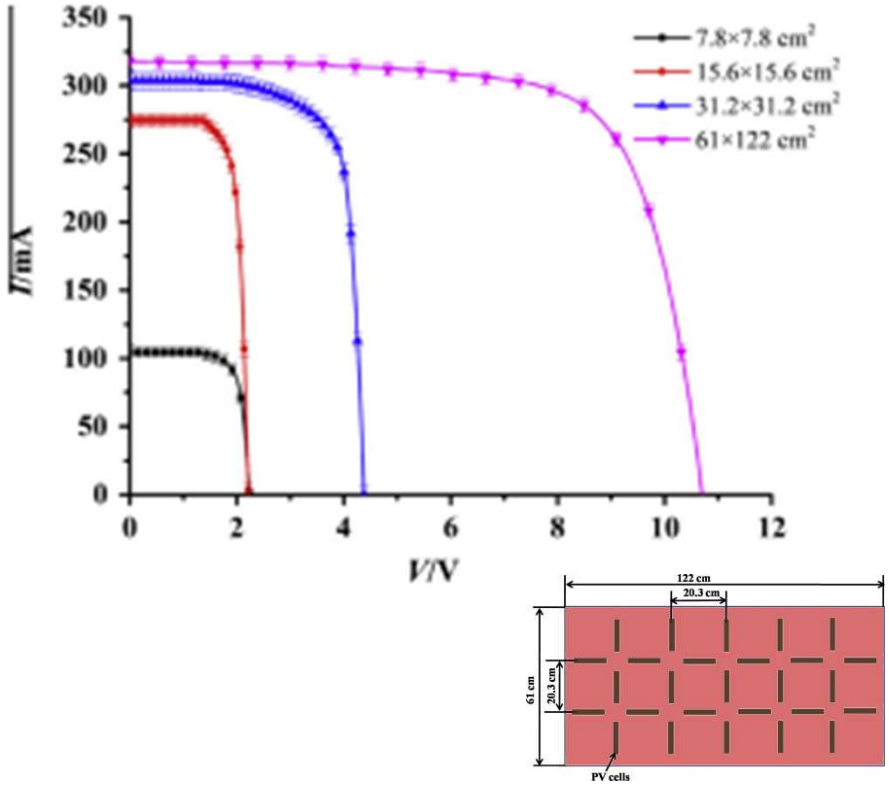
A series of GL-LSCs with bottom-mounted PV cells were fabricated.

The relationship between the area of luminescent waveguide and the gain of the bottom-mounted PV cells was investigated for the optimization of the GL-LSCs performance.

A highest gain of 1.38 was achieved in power over the bare PV cells was obtained with PV cell coverage of 4.54%.

A highest PCE of 2.28% was achieved with PV cell coverage of 11.32%.

It was found that the design with PV cell coverage of 9.07% have the lowest cost of $ 1.25/WP with a PCE of 2.02% and a gain of 1.27.



Performance and cost per W_P for all bottom-mounted PV cells GL-LSCs with a white reflector.

PV cell size (cm^2)	PV cell coverage (%)	η_{lsc} (%)	Gain	p^a (W_P)
15.6 × 2.0	11.32	2.28	1.15	$ 1.27
15.6 × 1.0	5.66	1.36	1.37	$ 1.47
12.5 × 2.0	9.07	2.02	1.27	$ 1.25
12.5 × 1.0	4.54	1.10	1.38	$ 1.65

https://doi.org/10.1016/j.solener.2015.05.004

Liv-Lib project

Zarcone et al 2016 - Université Paris-Est & University of Ferrara

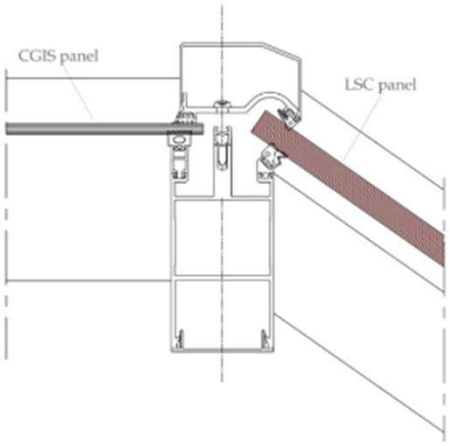
A solar canopy specially designed for Liv-lib' project at Solar Decathlon Europe 2014 (SDE2014) in Versailles, integrating an innovative system for energy production, LSC jointly with Copper Indium Gallium diSelenide (CIGS) solar cells.

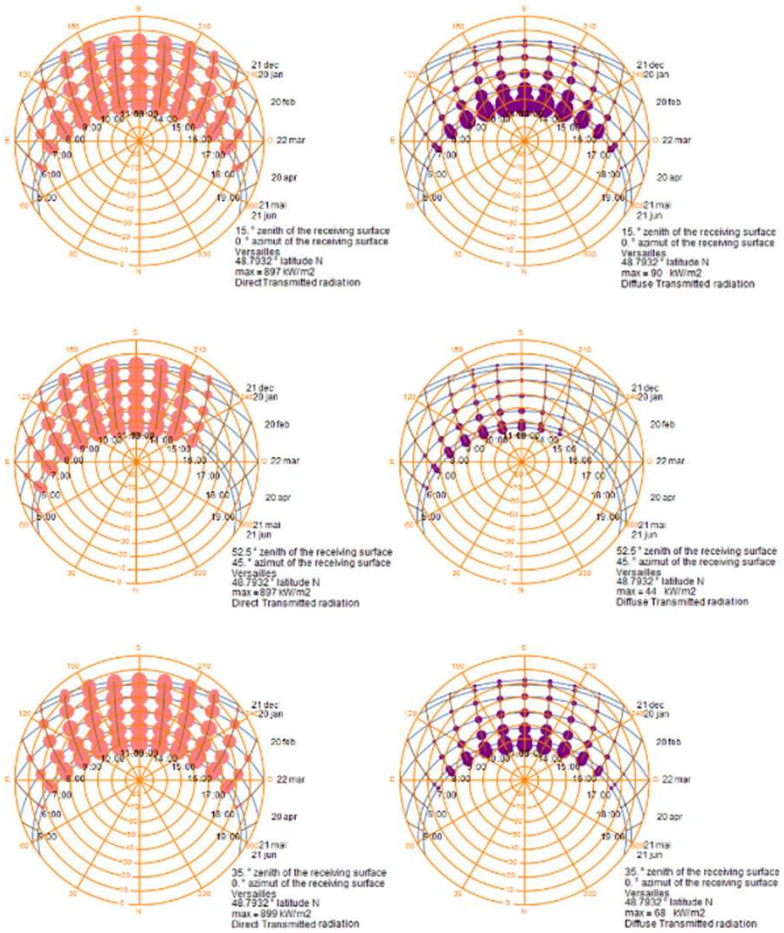
Night view of the Liv-lib during the SDE 2014 competition, showing; (b) The LSC panels stand out on the roof; (c) Under the canopy the light gets a red hue caused by the re-emitted light that doesn't undergo total internal reflection

https://doi.org/10.1016/j.egypro.2016.06.255

Liv-Lib project

Zarcone et al 2016





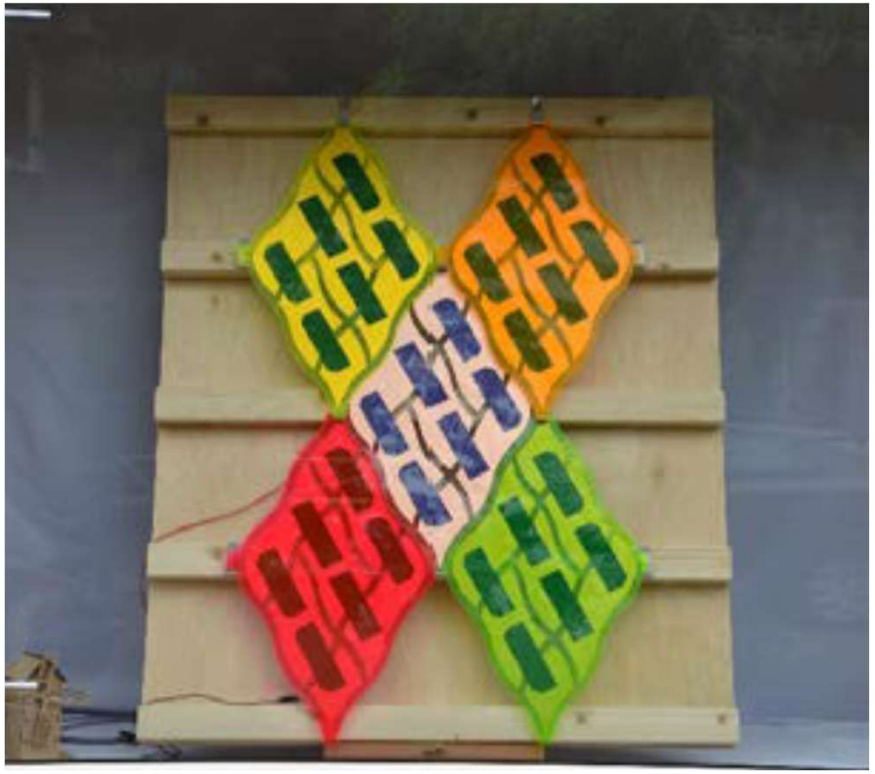
The photovoltaic electricity demand of the house is satisfied through 30 thin film CIGS solar panels (21.6 m2 at 120 Wp/m2 giving 2.6 kWp) and 25 LSC panels (23.0 m2 at 16 Wp/m2, giving 370Wp) for a total power of 2.97 kWp installed.

https://doi.org/10.1016/j.egypro.2016.06.255

Leaf Roof Tiles

Reinders et al 2016

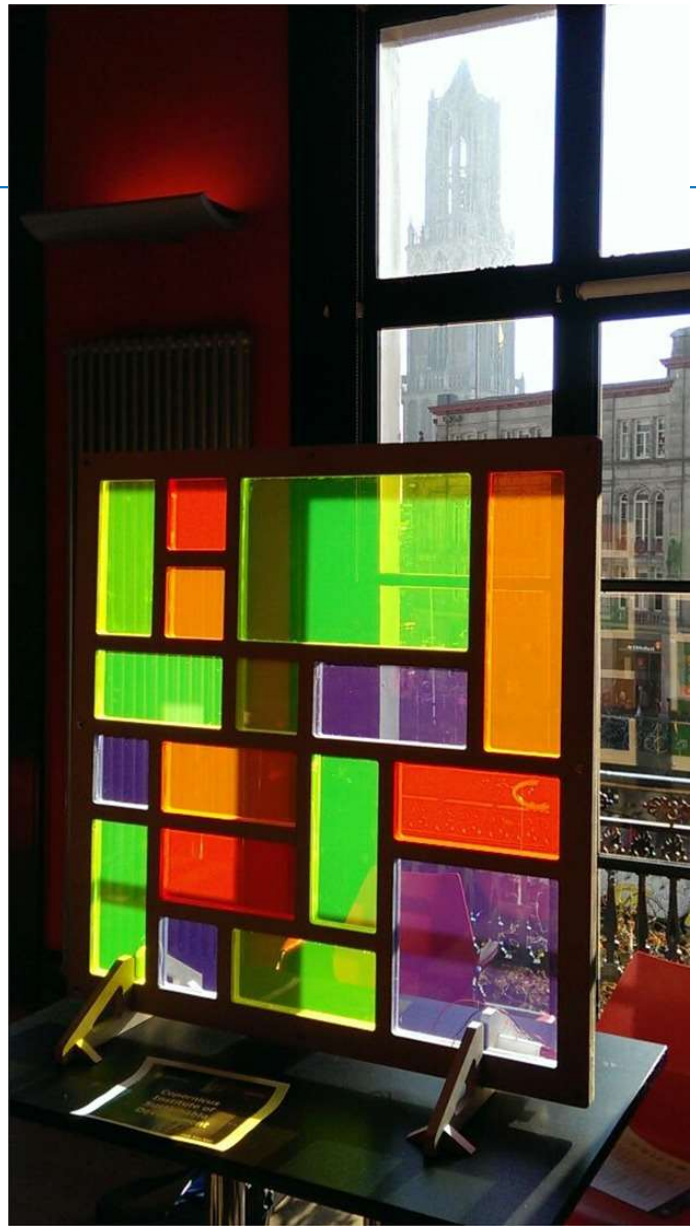
- A Leaf Roof tile, shown in consists of a 5 mm thick LSC waveguide of PMMA containing 80 ppm of Lumogen® F Red 305 dye.
- It is equipped with SunPower™ C60 solar cells, cell wiring and a metallic back reflector made from copper.
- The total area of the front surface of the Leaf Roof element is 0.11 m2, leading to a theoretical efficiency of 4,4% with an Impp of 1,39 A and a Vmpp of 3,49 V, without encapsulation with the PMMA waveguide.
- For the prototype design, a tile configuration consisting of 6 PV cells with a customized size of 52 cm^2 (resulting from cutting complete cells in 3 slices) has been chosen. The total area covered by PV cells is therefore 312 cm^2.
- It has shown an energy yield which is 9 % higher compared to a reference prototype with a transparent PMMA waveguide (without dyes).



https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=7750307

Electric Mondrian

Moraitis et al., 2018



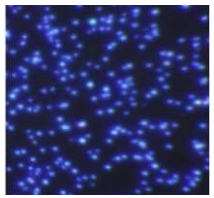
Inspired by the painting style of Piet Mondrian.

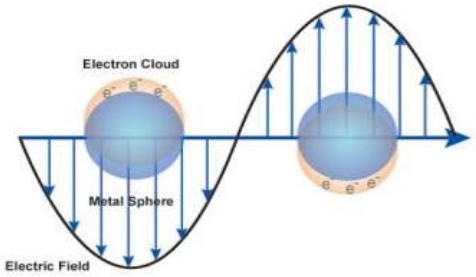
Colourful LSC plates embedded with Lumogen dyes were used to create a decorative element that could serve as a stand-alone charging point for mobile devices

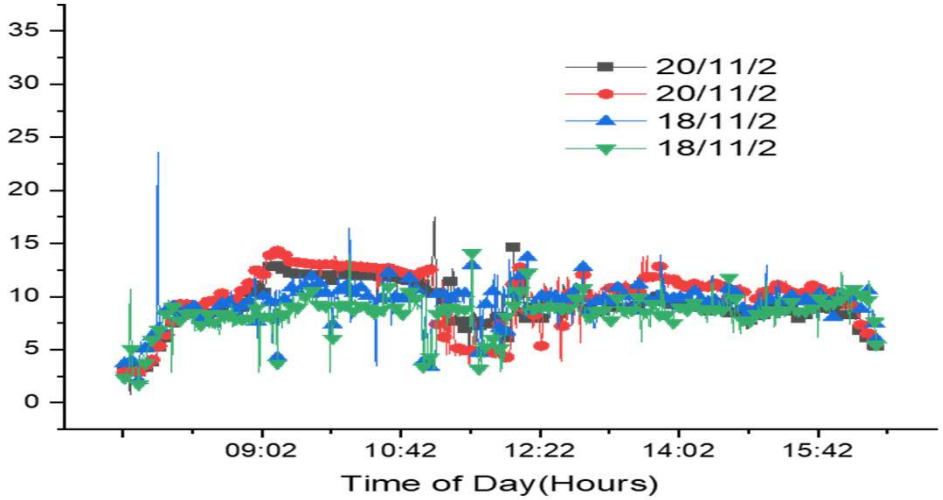
This is the first attempt to create an actual LSC as part of a window. The small size of the device, approximately $1m^2$, would not cause color distortion in the living space of the room behind it and the modularity of the system would allow larger or smaller areas to be covered.

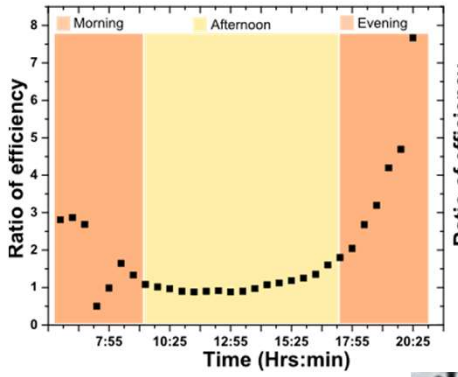
Plasmonic LSCs for Building integration

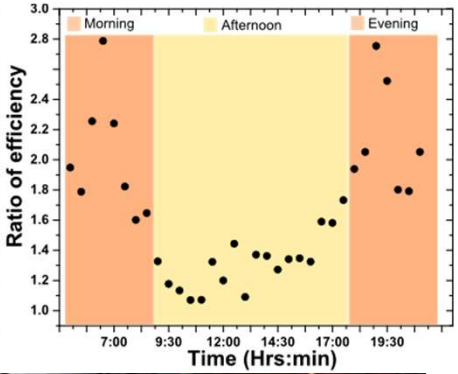
Sethi et al., 2020; 2021

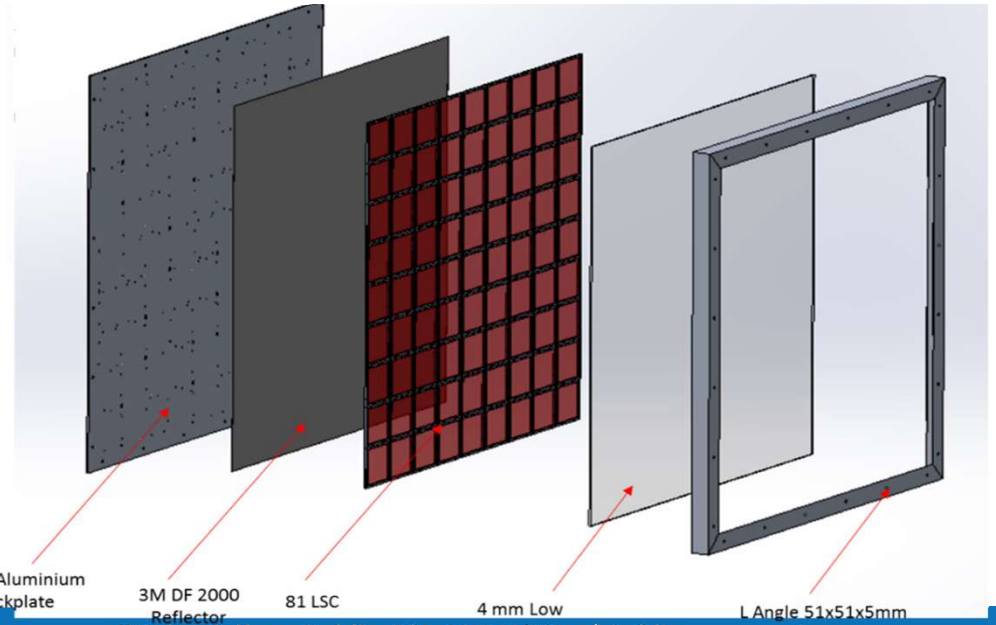


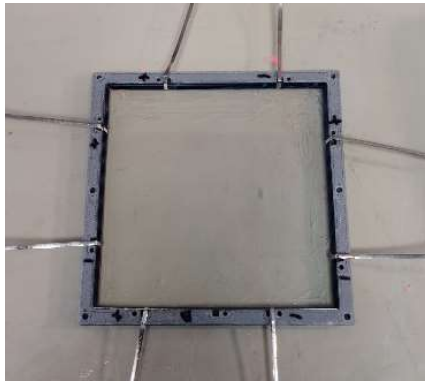


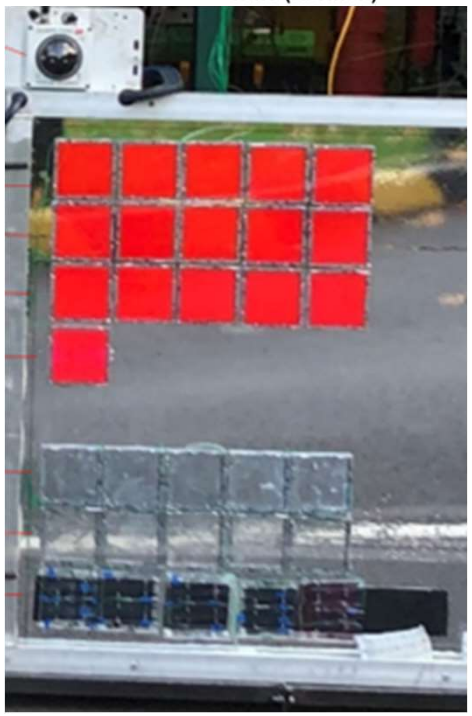












•10.1007/s11468-021-01562-y •10.1364/OE.418183 •10.1016/j.solmat.2019.110150

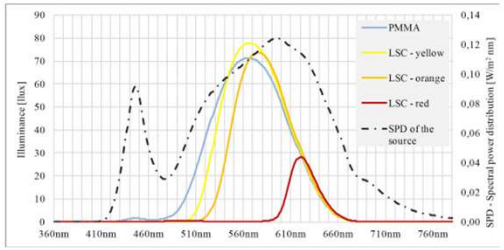
Smart windows

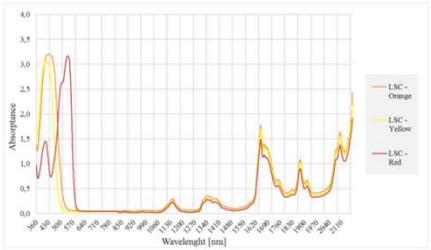
Aste et al, 2019

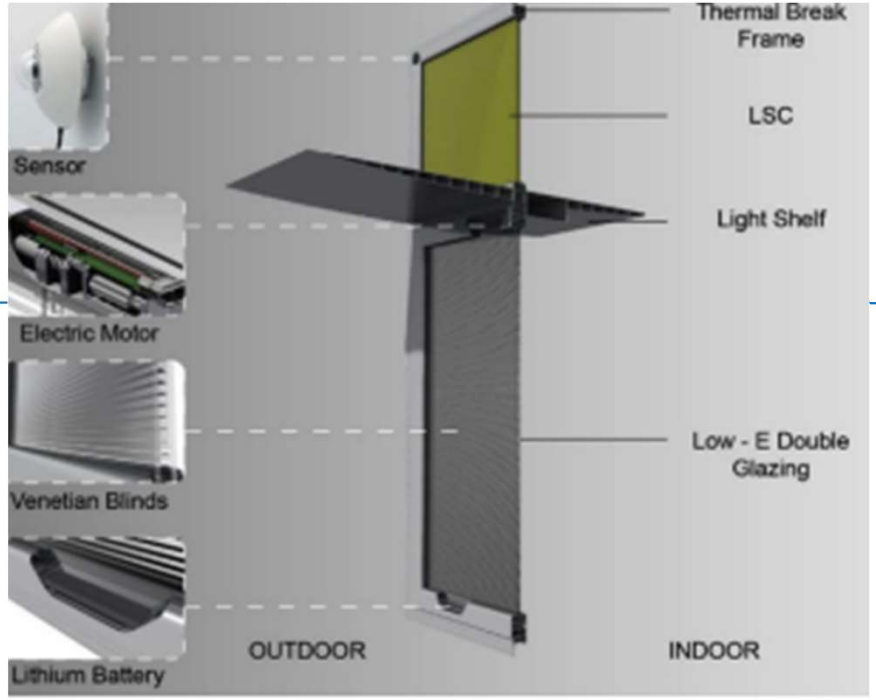
Overcoming reabsorption using derivatives of benzothiadiazole, with a large Stokes shift with tunability.

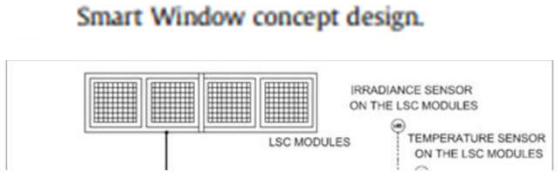
A new façade component has been developed able to exploit the multi-functionality in terms of solar electricity production, daylighting improvement and solar control.

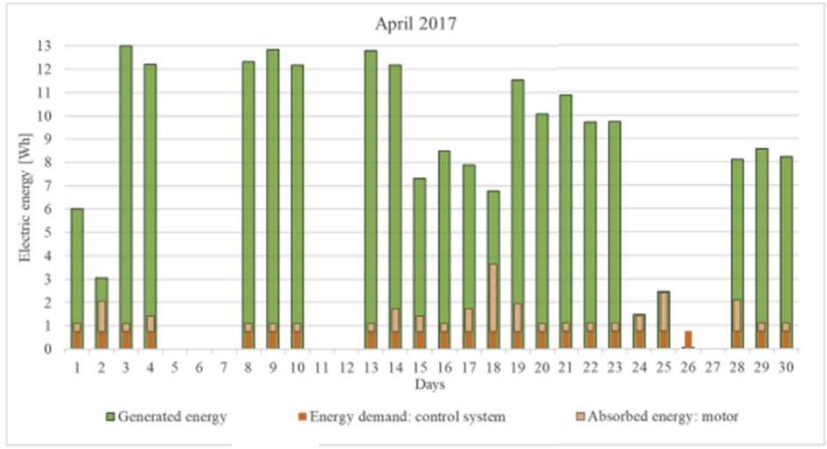
Projected: Cost €35 per 50 x 50 panel - @3% efficiency









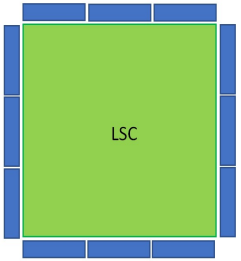


Daily energy balance of Smart Window.

Large area LSC

Mateen et al., 2021

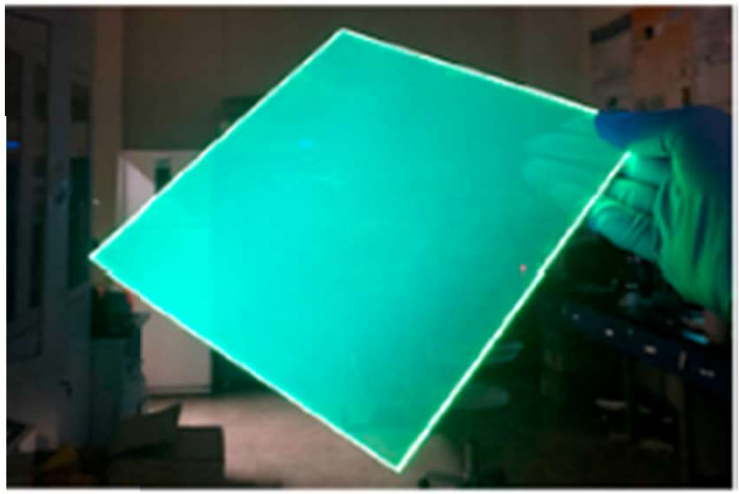
PV cells connected in parallel way

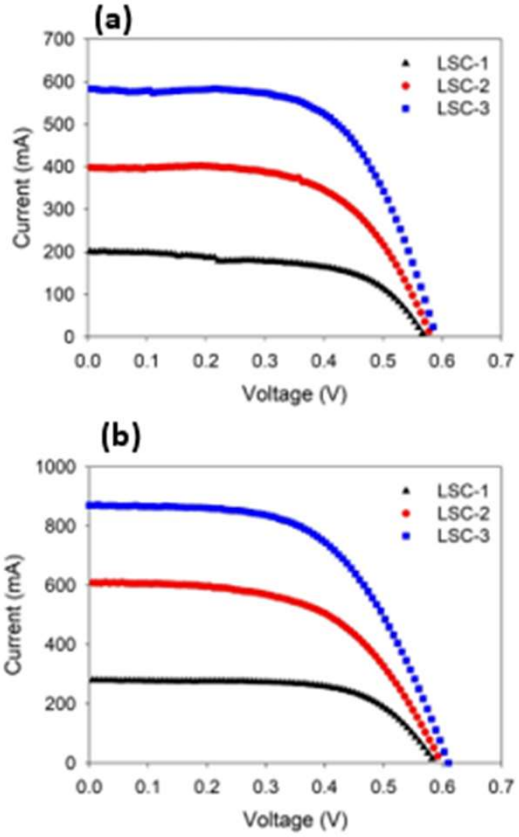


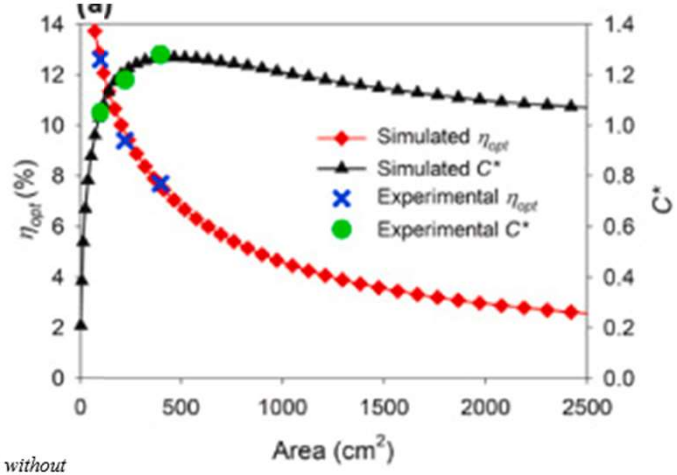
Based on new TADF based dye with large Stokes shift

Mateen et al., 2021

up to 1474.5 cm2, G = 32







Current-Voltage (IV) curves of fabricated LSC devices Illuminated with AM 1.5G spectrum (a) without backside diffuser (b) With backside diffuser. LSC-1 (10 × 10 cm²), LSC-2 (15 × 15 cm²), LSC-3 (20 × 20 cm²)

LSC Sound Barrier – SONOB project – Not BIPV!!

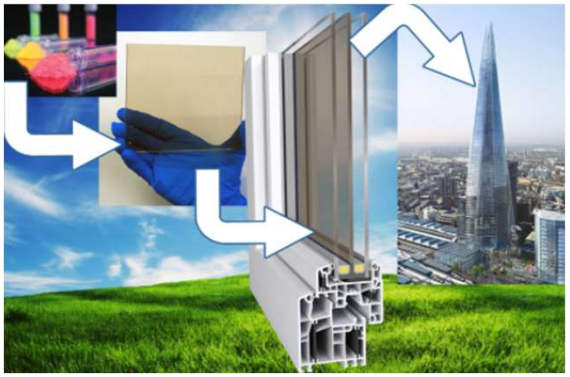
2016 - 2020

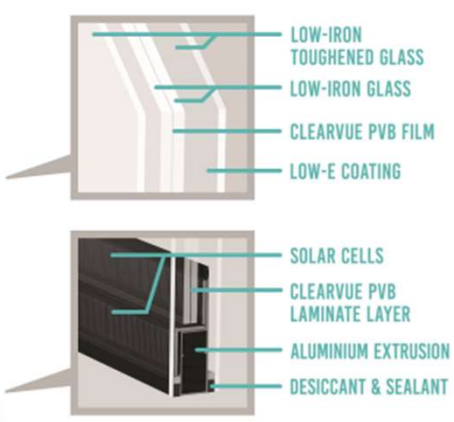
- The solar noise barrier project – a number of projects under this theme by Debije et al
- full-size (1 × 5 m^2) luminescent solar concentrator (LSC) has been constructed and the edge electric outputs from the attached photovoltaic cells monitored for a period of slightly over one year in the solar noise barrier (SONOB) “living lab” outdoor environment.

- Shading effects – street art , effects of seasonal spectral variation, cloud cover and heat distribution and modelling (Bognar et al., 2020).

https://doi.org/10.1016/j.renene.2016.10.078

LSC - Companies & Products





Future of Large scale LSC development

Products are coming

But still need for

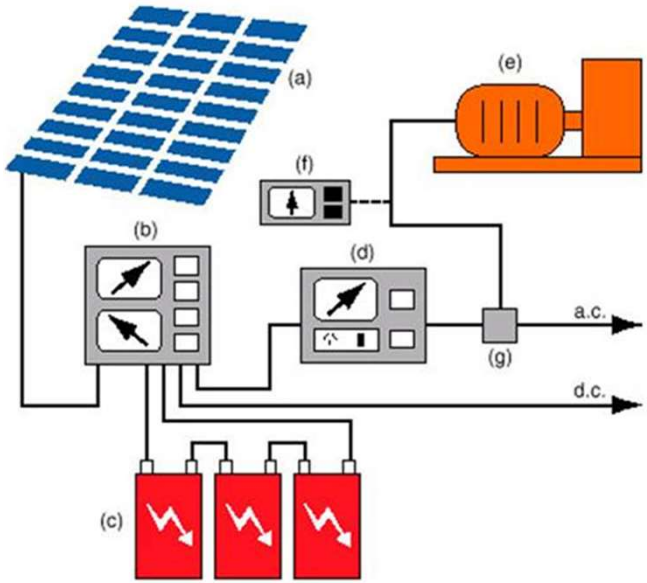
Material development

- Luminescent species (QY, stokes shift)
- Move towards green polymers – less environmental impact

Upscale not as easy as perceived

More research needed on the façade integration of these devices

Efficient and low-cost transparent solar harvesting systems can be fabricated



BIPV system diagram
Courtesy of Murdoch University Energy Research and Innovation Group

References

Goetzberger & Greubel, 1977. Solar energy conversion with fluorescent collectors, Appl. Phys., 14 (1977), pp. 123-139.

van Sark, et al, 2008, "Luminescent Solar Concentrators - A review of recent results," Opt. Express 16, 21773-21792 (2008)

Debije and Verbunt, "Thirty years of luminescent solar concentrator research: Solar energy for the built environment," Advanced Energy Materials, vol. 2, no. 1, pp. 12–35, 2012, doi: 10.1002/aenm.201100554.

Zhao and Lunt, "Transparent luminescent solar concentrators for large-area solar windows enabled by massive stokes-shift nanocluster phosphors," Advanced Energy Materials, vol. 3, no. 9, pp. 1143–1148, 2013, doi: 10.1002/aenm.201300173.

Kerrouche et al., 2014. Luminescent solar concentrators: From experimental validation of 3D ray-tracing simulations to coloured stained-glass windows for BIPV, Solar Energy Materials and Solar Cells, Vol 122, 2014, 99-106, ISSN 0927-0248, https://doi.org/10.1016/j.solmat.2013.11.026.

Aste et al., 2015, "Performance analysis of a large-area luminescent solar concentrator module," Renewable Energy, vol. 76, pp. 330–337, 2015, doi: 10.1016/j.renene.2014.11.026.

Debije & Rajkumar (2015). Direct versus indirect illumination of a prototype luminescent solar concentrator. Solar Energy, 122, 334-340. https://doi.org/10.1016/j.solener.2015.08.036

Zhang et al., "Optimization of large-size glass laminated luminescent solar concentrators," Solar Energy, vol. 117, pp. 260–267, 2015, doi: 10.1016/j.solener.2015.05.004.

Zarcone et al., 2016 "Building Integrated Photovoltaic System for a Solar Infrastructure: Liv-lib' Project," in Energy Procedia, 2016, vol. 91, pp. 887–896. doi: 10.1016/j.egypro.2016.06.255. 21

Reinders et al., "Leaf roof - Designing LSC PV roof tiles," in Conference IEEE Photovoltaic Specialists Conference, 2016, vol. 2016-Novem, pp. 3447–3451. doi: 10.1109/PVSC.2016.7750307.

Moraitis et al., 2018. Nanoparticles for Luminescent Solar Concentrators - A review, Optical Materials, Volume 84, 636-645, ISSN 0925-3467, https://doi.org/10.1016/j.optmat.2018.07.034.

Sethi et al., 2021. Outdoor Characterization of a Plasmonic Luminescent Solar Concentrator, Plasmonics, https://doi.org/10.1007/s11468-021-01562-y

Aste et al, 2019. Triggering a large scale luminescent solar concentrators market: The smart window project, Journal of Cleaner Production, Volume 219, 2019, 35-45, ISSN 0959-6526, https://doi.org/10.1016/j.jclepro.2019.02.089.

Mateen et al., "Large-area luminescent solar concentrator utilizing donor-acceptor luminophore with nearly zero reabsorption: Indoor/outdoor performance evaluation," Journal of Luminescence, vol. 231, 2021, doi: 10.1016/j.jlumin.2020.117837.

Á. Bognár et al., "The solar noise barrier project 4: Modeling of full-scale luminescent solar concentrator noise barrier panels," Renewable Energy, vol. 151, pp. 1141–1149, 2020, doi: 10.1016/j.renene.2019.11.102

Trinity College Dublin
Coláiste na Tríonóide, Baile Átha Cliath
The University of Dublin

PEARL PV

Thank You