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LUMINESCENT SOLAR CONCENTRATOR SETUPS FOR PHOTOVOLTAIC APPLICATIONS

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ABSTRACT

A Luminescent Solar Concentrator (LSC) is an optical waveguide of transparent host material doped with luminophores. LSC technology works by trapping incident solar radiation, converting the spectrum to the wavelength-band of interest and concentrating the light by total internal reflection (TIR) to the edge of the LSC where photovoltaic (PV) solar cell is attached. During the waveguiding process of solar radiation, a considerable proportion of photons are lost through mechanisms such as re-absorption, attenuation, scattering and escape cone losses which decrease the device optical efficiency (OE). In recent decades, various LSC generations with different configurations have been introduced and investigated to mitigate the inherent optical losses and enhance the device performance. Due to the achieved optical improvements, LSC has recently captured a significant growing interest implying its leading role as a low cost and passive technology for enhancing the power conversion efficiency (PCE) of PV systems. In this paper, large and small scale LSCs have been comprehensively reviewed to study the impact of device configuration (such as shape, geometric gain, host material, luminescent species, doping concentration and PV solar cell type) on the LSC loss mechanisms and optical performance. LSC generations are categorised and shortlisted based on their configurations; moreover, their limitations, best performance conditions, best achieved results, and their eligibility for large-scale building integrated PV (BIPV) applications are discussed.

INTRODUCTION: -

The goal 7.2 of the 2030 Sustainable Development Agenda testifies that now, more thanever, it is necessary to satisfy the growing need for energy using renewable sources. Inparticular, considering the amount of energy that strikes Earth's surface every day, Photo-Voltaic (PV) technology could be one of the most relevant energy sources. This is confirmedby the considerable size reached in these years by PV technologies market, which nowadaysamount to 7.6% of the energy produced by renewable non-combustible sources. Amongall PV technologies, Luminescent Solar Concentrators (LSCs) represent a promising way towiden the field of application of PV systems and increase the amount of energy producedby solar technologies. The performance of standard PV technologies is highly affectedby shading and, if bypass diodes or other bypass devices are not installed, the PV modulescan suffer of permanent damage when shaded. This is particularly true for high powermodules, employed in solar power plants, or for high performance solar cells employed inaerospace applications. LSC panels are instead extremely tolerant to shading, as theycan exploit both direct and diffuse radiation. Therefore, they are perfect candidates forBuilding Integrated Photovoltaic (BIPV) applications, especially in the countries with ahigh population density or in which diffuse solar radiation is dominant. LSC panelsare based on the coupling of a semi-transparent glass or plastic slab with PV cells. Theslab is functionalized with fluorophores able to absorb a portion of the impinging light and action, the remaining one is lost through the so-called escape-cone. Both the escapelosses and the amount of light entrapped in the LSC depend on the slab material andcan be expressed as a function of the slab refractive index. The self-absorption noumenon is due to the partial overlap between the luminophores absorption and emspectra, in fact if the Stokes shift is too small the luminophores inside the slab can an also fluorescence light, thus increasing the number of absorption events and the probity of escape-cone losses. The light that thanks to total internal reflection is trappedthe slab is waveguided to its edges where usually PV cells are mounted. This convention allows the conversion of light into electricity and minimize the area of the solneeded, thus leading to a potential reduction of the panel overall cost. The slab cmanufactured with various shapes and be functionalized by using different luminotypes like organic or inorganic dyes as well as quantum dots. Their optical propertfect the absorption and emission spectra of the LSC, changing its characteristic cool LSC panels show a high PV conversion efficiency, as fluorophores realize a down-shof wavelengths that cross the slab, which guarantees an efficient filter against theUV radiation, and ensures to expose silicon (Si) solar cells to a wavelength range in wtheir External Quantum Efficiency (EQE) is higher.

The semi-transparent slab is depicted in red, whereas the PV cells are schematized in blue. When a ray of light is absorbed by the dye of an LSC three phenomena can occur:

(1) the fluorescence radiation is trapped inside the slab until is absorbed by the cell,

(2) the re-emitted radiation is lost through the escape-cone and

(3) the fluorescence radiation is absorbed by another dye molecule (self-absorption). The intrinsic optical transparency of LSC panels opens the possibility to install themwhere traditional PV technologies would not be suitable, exploiting the solar radiationnot only for electrical energy production, but also to optimize the building thermal bud-get. Moreover, if installed on the roof of greenhouses, they can both contribute to supply the power needed by the greenhouse and increase the amount of light availablefor photosynthesis.Considering the aforementioned properties, LCS panels are ideal to be installed insemi-transparent façades of new type of buildings, which could take advantage of BIPVtechnologies and could autonomously produce all or part of the energy they need. Thiscould allow an increase of electricity generated from renewable sources, shifting the role ofbuildings form consumer to pro-summer (producer and consumer) of energy.

OBJECTIVES OF THE STUDY: -

1. To evaluate how the concentrator geometry affects the power production.
2. To analysed effect of shading for photovoltaic applications.

REVIEW OF LITERATURE: -

An overview of various configurations of Luminescent Solar Concentrators for photovoltaic applications

MehranRafiee, Subhash ChandraHindAhmedSarah J. McCormack

A Luminescent Solar Concentrator (LSC) is an optical waveguide of transparent host material doped with luminophores. LSC technology works by trapping incident solar radiation, converting the spectrum to the wavelength-band of interest and concentrating the light by total internal reflection (TIR) to the edge of the LSC where photovoltaic (PV) solar cell is attached. During the waveguiding process of solar radiation, a considerable proportion of photons are lost through mechanisms such as re-absorption, attenuation, scattering and escape cone losses which decrease the device optical efficiency (OE). In recent decades, various LSC generations with different configurations have been introduced and investigated to mitigate the inherent optical losses and enhance the device performance. Due to the achieved optical improvements, LSC has recently captured a significant growing interest implying its leading role as a low cost and passive technology for enhancing the power conversion efficiency (PCE) of PV systems. In this paper, large and small scale LSCs have been comprehensively reviewed to study the impact of device configuration (such as shape, geometric gain, host material, luminescent species, doping concentration and PV solar cell type) on the LSC loss mechanisms and optical performance. LSC generations are categorised and shortlisted based on their configurations; moreover, their limitations, best performance conditions, best achieved results, and their eligibility for large-scale building integrated PV (BIPV) applications are discussed.

Luminescent solar concentrator photovoltaic designs

Angèle Reinders, Ravi Kishore, LennekeSlooff and WouterEggink

This paper discusses the opportunities and challenges of designing products using luminescent solar concentrator (LSC) photovoltaic (PV) technologies. The focus is on the integration of LSC PV technologies in PV modules, future products and buildings. It is shown that the typical material properties of LSCs — low cost, colorful, bendable, and transparency — offer a lot of design freedom. Two differently designed LSC PV modules with back contacted solar cells are presented including ray-tracing simulations and experimental results resulting from their prototypes. It is shown that the efficiency of a LSC PV module can be 5.8% with a maximum efficiency of 10%. Further the results of a design study which focused on product integration of LSC PV technologies are presented and discussed. In total 16 different and highly innovative conceptual designs resulted from this project, which were prototyped at scale to show their feasibility and integration features.

METHODS AND METHODOLOGY: -

1. Numerical Simulations

To evaluate how the concentrator geometry affects the power production, numerical simulations of light transport inside the 1. SC's were performed. The results presented in Appendix A guided us to simulate square-shaped 15C panels with an area of 25 x 25 cm² as smaller dimensions would still have spectral components of light affected by auto absorption, thus making obtained results difficult to project to larger size devices. In LSC panels with dimension of 25 x 25 cm or wider, the spectral components affected by auto absorption reaching the solar cells become negligible with respect to the longer wavelengths showing no auto absorption, and thus these components of the fluorescence light can be assumed to undergo free propagation within the LSC slab. Therefore, in the optical simulation, a ray of light was considered lost only when it was absorbed by an absorbing surface or when it escapes through the escape-cone.

The relative values of the irradiance on the ISC side were obtained with a Montecarlo raytracing technique, and the relative short circuit current produced by each cell was given by the integral of the irradiance distribution over the cell length, Rays of light were generated inside the ISC with a uniform spatial and angular distribution, therefore, the path of each ray of light was a straight line that ended on a surface of the ISC. The variance in panel performance due to the light incidence angle was neglected as incidence angle modifier was already studied by Kanellis et al. Three different configurations of LSC panels were simulated, with four, two, and one PV arrays, respectively. The PV arrays were simulated along the LSC edges and in the configurations with one or two PV arrays, the missing ones were replaced by reflective surfaces. The basic PV array was 25 cm long and was composed by 10 photovoltaic cells connected in series, however, in this study were evaluated also configurations in which the number of cells per PV array has been reduced.

Simulated Impact of Shading To evaluate LSC losses in efficiency because of the partial shading, irradiance profile on the IV cells array was simulated with the same parameters and methodology describedin the Section 212, but under relevant shading conditions. The reference design consists in the square LSC with PV arrays along the four sides, and without any reflective surface. This design has been taken as a reference because it represents the most common and spread LSC panel configuration used in transparent façades. As described in Section 21, the other simulated setups consist of 1.SC panels withcell arrays on one or two sides.

Depending on the arrangement of the cells in the 1SC panels, it is possible to identify different shading situations. In the reference system equipped with four PV cell arrays, being symmetrical on two axes, any shading mode is equivalent. In the system with two PV arrays on opposing sides, two shading options are possible: across the arrays, and parallel to the arrays, because, due to system symmetry, it is not important which array is being shaded. In the system with only one I'V array, three options are possible the first one involves the shading across the array, whereas in the second one the shading is parallel to the PV array on the half of the slab opposite to the PV cells. The third shading mode involves the shading of the half surface that includes the IV array.

1.2 Prototype Assembly Process

The modules consist of square slabs of PMMA (PolyMethylMethAcrylate) dopedwith a concentration of 300 ppm organic dye developed by BASF Corporation, and thus belonging to the commercial Lumogen F family: Violet 570, Green 850, Yellow 083, Orange 240, and Red 305. The latter four dyes are perylene-based, while Violet 570 is a naphtalimide-based one. The slabs (5 mm thick) were laser-cut with a size of 25 x 25 cm². The ISC slabs were coupled with monocrystalline Passivated Emitter Rear Contact (PFRC) silicon solar cells (SunPower C50) with dimensions of 23 x 8 mm², which were obtained by the mechanical cutting of 156 x 156 mm² area walers [13]. The cells were arranged in arrays of 10 cells, connected in series, and soldered onto a Printed Circuit Board (PCB) 244 mm long

The assembly of the cells soldered on the PCB represents the modular PV array. Further information about the electrical characterization of both the bare solar cells and the PV arrays can be found in the Supplementary Material (Figure S1). The modules were assembled mounting the IV arrays along the edges of the slabs, by using an optical UV glue (Dela Photobond GB368) and placing a high efficiency dielectric mirror film (DF2000MA, manufactured by 3M) along the sides without cells. The film consists in a dielectric mirror deposited on plastic layer with an overall thickness of 104 um and a contact adhesive applied on it. The main feature of the mirror film is the high specular reflectivity. It shows a reflectivity higher than 90% in the 400-775 nm range, at an angle of incidence between 0 and 80 that helps to minimize the absorption losses even in case of multiple reflections [32]. The glue is a one-component UV-curing adhesive, specifically formulated to bond optical devices made of glass, plastic, or metal. This glue has a refractive index of 1.506 in the visible range, slightly higher than PMMA, but close enough to achieve a good optical coupling between the slab and the cells [33]. Figure 4 displays the pictures of the assembled prototypes in the different configurations.

2. Prototype Electrical Performance

The prototypes were placed on a dual-axis sun tracking system equipped with a pyranometer Delta Ohm LP Pyra 03 AV. The pyranometer was used to measure the inci dent global irradiance on the plane of the module. The 1-V and P-V characteristic curves were measured by mean of a Keithley 2000 SourceMeter controlled by a custom Virtual Instrument written in LabView. The software automatically calculates all the parameters of the curve, such as the short circuit current, the open circuit voltage, the maximum power point, the voltage and current at maximum power point, and the Fill Factor (FF). The software saves automatically the I-V curve data and performs batch and periodic 4 wires measurements. The efficiency of the prototypes was obtained analyzing both the I-V curves and the irradiance data, which was measured by the pyranometer.

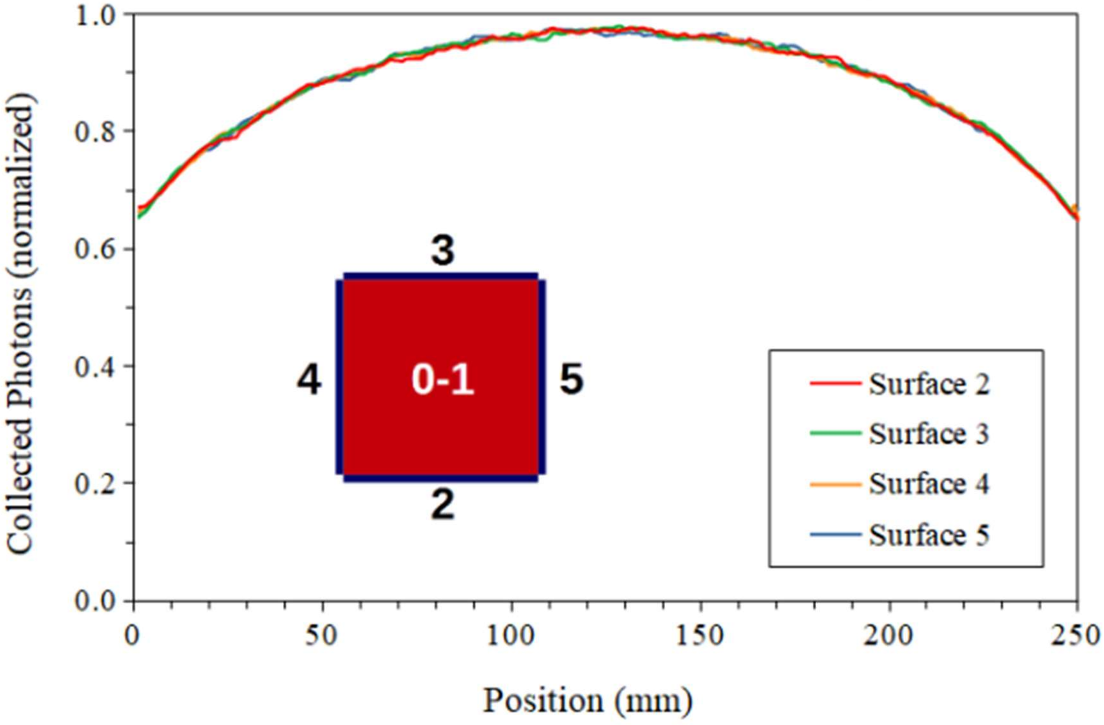
Impact of Shading on the Prototypes

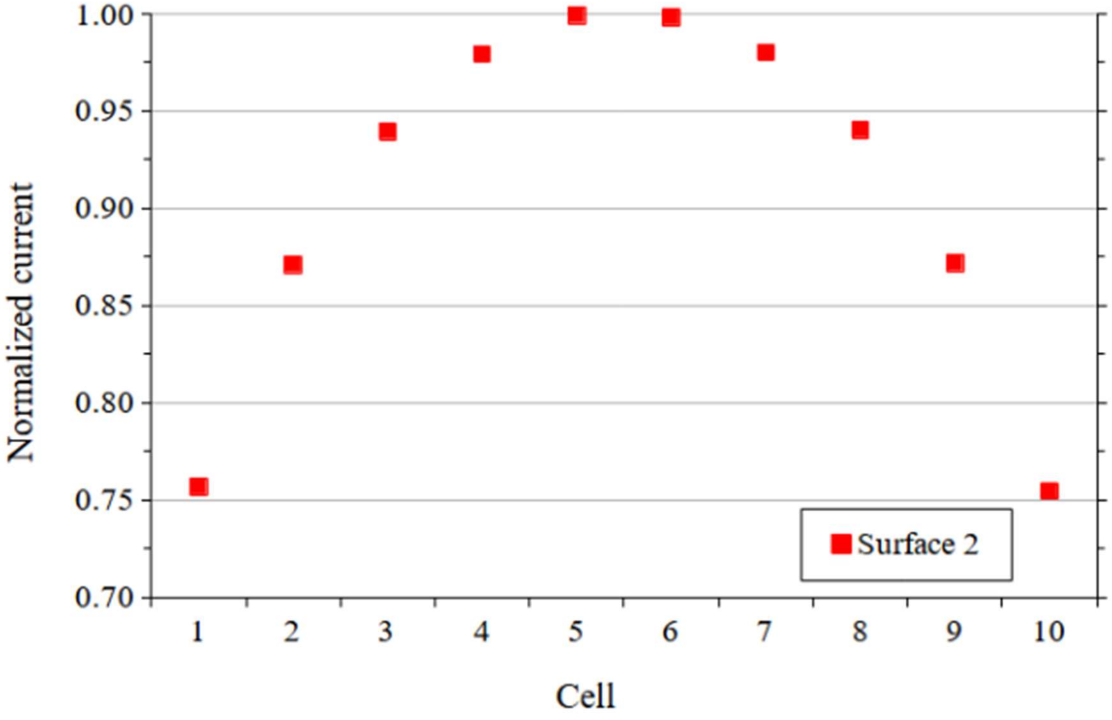
In order to study a maximized effect of shading, the tests were performed by covering half of the concentrator with black absorber. This precaution is needed to avoid that the light emitted by self-absorption and lost from the escape-cone could be reflected by the shading surface. The covering of the half of the system is obviously a situation of extreme shading, which should be avoided by a proper installation of the modules. Nevertheless, modules working fairly in this situation could be used on purpose when partial shading is unavoidable, and when the installation of other systems is economically infeasible. The symmetry conditions, which led to different shading configuration, are the same presented in Section 2.1.2.

3. Prototype Electrical Performance

The prototypes were placed on a dual-axis sun tracking system equipped with a pyranometer DeltaOhm LP Pyra 03 AV. The pyranometer was used to measure the inci dent global irradiance on the plane of the module. The I-V and PV characteristic curves were measured by mean of a Keithley 2400 SourceMeter controlled by a custom Virtual Instrument written in LabView. The software automatically calculates all the parameters of the curve, such as the short circuit current, the open circuit voltage, the maximum power point, the voltage and current at maximum power point, and the Fill Factor (FF). The software saves automatically the I-V curve data and performs batch and periodic 4-wines measurements. The efficiency of the prototypes was obtained analysing both the 1-V curves and the irradiance data, which was measured by the pyranometer.

RESULTS: -


Collected Photons (normalized)
1.0
0.8
0.6
0.4
0.2
0.0
0
50
100
150
200
250
Position (mm)
3
4
0-1
5
2
Surface 2
Surface 3
Surface 4
Surface 5


Normalized current
1.00
0.95
0.90
0.85
0.80
0.75
0.70
1
2
3
4
5
6
7
8
9
10
Cell
Surface 2

Unshaded LSC panel with four 10-cells PV arrays: (a) Normalized number of rays of light collected by the PVcells as a function of the position along the LSC side, which ranges from 0 mm to 250 mm. (b) Normalized current produced by each PV cell

DISCUSSION: -

Simulated Electrical Performance

The first simulated LSC had four arrays, one for each side, with 10 cells per array. As mentioned above, such a configuration represents a reference to evaluate the effectiveness of the others. The arrays on each side allow the maximum absorption but as shown in Figure Sa, the irradiance profile is uneven, and seems to follow a cosine-like function. This irregularity led to a mismatch in current production, approximately equal to 33%, between the central cells and the ones at the ends of the same array.Therefore, if the cells are connected in series, this configuration turns to be unprofitable unless bigger cells are employed at the array ends. Differently, cells of equal size could be used if connected in parallel, since their operating voltage is barely affected by such mismatch.

Unfortunately, the use of cells of various sizes would make impractical the scaling up of the concentrator to larger areas. In fact, to correctly fit the different irradiance levels across the same side, the larger cells should be 50% longer than the smallest ones, making them extremely fragile. Moreover, the maximum size that can be handled by the assembling machines is limited. Thus, if the largest cell size is limited, an approach with cells of different sizes requires the use of more cells to cover the same length Using a large number of cells, also the option to connect all the cells in parallel would be equally not convenient. It would result in an output with a high current and low voltage, which requires the use of conductors with large cross section and leads to significant losses in de-de or de-ac conversion. Removing one cell per array and replacing them with reflective films have a dramatic effect on the irradiance profile.

CONCLUSION: -

The results presented in this work highlight that Luminescent Solar Concentrators area promising technology well suited for building integration. Most of the research aboutLSCs is currently focused on the development of dyes with low self-absorption or dyealignment, whose purpose is the reduction of the self-absorption losses, and the consequentincrease in the system efficiency. Presently, the main drawback of LSCs is their highprice-per-watt ratio. In order to improve their appealing to the market, it is mandatoryto reduce as much as possible the price difference between a normal transparent and aLSC façade.

The difference between the simulations and the real performance of the modules canbe attributed to several factors. Among them, the most significant are a mirror reflectivitylower than the expected and minor assembly errors. These are caused by the bending ofthe arrays, which resulted in a non-optimal optical coupling between the LSC and thecells at the far ends of the arrays. The increase in concentration factor, which is shownby the systems employing mirrors, is close to the expected value: 1.97× and 3.5× for theconfigurations with two and one array, respectively. The irradiance along the cells side ofthe LSC with three reflective sides have been estimated to be 4.2 times greater than thesolar irradiance on the LSC surface. Tests performed in case of shadowing provided two remarkable results. The first oneis that in this case the differences between the simulation and the measurements are highlyreduced, thus leading to a good accordance between the simulations and the measurementsperformed on the prototypes. The second result concerns the systems assembled with thereflective films, which perform very well when shaded. In particular, the configurationwith the cells on one side have shown the highest efficiency in all shading configurations.

The demonstration that, despite the illumination conditions, the systems that employ asmall number of cells can yield to a higher efficiency than a traditional system represents a significant result. In fact, any reduction in the number of cells implies not only a lower costof the components, but also a faster, and hence cheaper, assembly process.

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