# A New Design for Luminescent Solar Concentrating PV Roof Tiles

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***Abstract*—In our paper we explore the opportunity of combining luminescent solar concentrating (LSC) materials and crystalline PV solar cells in a new design for a roof tile by design-driven research on the energy performance of various configurations of the LSC PV device and on the aesthetic appeal in a roof construction. We present the roof tile in a system and executed optical modeling of the solar roof tile by Monte-Carlo/ray-tracing simulations by PVtrace. We determined the range of appropriate values for thickness and dye concentration for the conceptual design of roof tile LSCs. It can be concluded that thickness of PMMA sheet material could best be in the range of 4 to 6 mm and the concentration of BASF Lumogen Red dye in between 80 and 1000 ppm. Because of aesthetic considerations however various concentration values may be used. In follow-up activities include a.o. parameter studies for different BASF Lumogen dyes and a pilot setup for testing the prototypes outdoors in the Netherlands.**

***Index Terms*—design driven research, luminescent solar concentrators, building integrated photovoltaics, bipv, roof tiles, ray-tracing**

## I. Introduction

This paper addresses the integration of Luminescent solar concentrators (LSC) in PV powered roof tiles. The idea to combine LSCs with PV solar cells originates for the 70-ies [1], [2]. The LSC is a concept for harvesting solar energy that is comprised of a transparent shape acting as a lightguide with a large top surface. This lightguide consists of a material whose refractive index is higher than air and which contains luminescent material in it. Solar radiation enters the LSC through the large surface and is absorbed by the luminescent particles which re-emit the radiation at a longer wavelength. Subsequently, a large fraction thereof gets trapped by means of total internal reflection within the shape. The trapping is interrupted at the interface between the lightguide and an attached solar cell, where the radiation gets converted into electricity (Fig. 1) [3]. Hence, LSCs provide a large solar radiation surface while they employ less semiconducting material, whose purification requires significant amounts of resources due to the high temperature of the process [4].

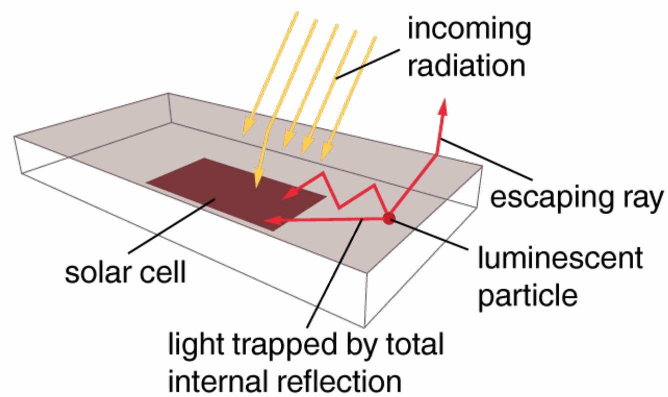


Fig. 1. Working principle of an LSC.

Other than the large top-surface there are no requirements on the shape of the LSC. Interestingly an LSC can therefore be either flat or curved while remaining a close to similar performance [5]. Similarly the colour can be determined by the choice of the species of the luminescent particles and their concentration. With these design features (formability and colour) and their eventual aesthetic appeal LSCs offer an excellent opportunity for design of building integrated photovoltaics (BIPV) [6].

Even though a variety of BIPV-solutions to roof-tiles exists [7]–[9] and some have already been commercialised [10], [11], these roof tile solutions remain identifiable as solar cells or at least as electronic components of a building.

The limited aesthetic appeal of conventional solar panels creates barriers to the implementation of some solar energy projects and has often been cited - though not supported by statistically relevant scientific evidence - as the source for the

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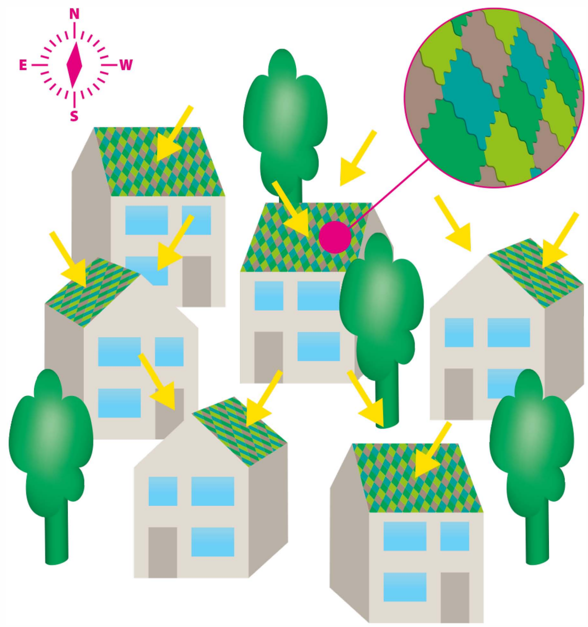


Fig. 2. Visualisation of the PV roof system

NIMBY ("Not in my backyard") - attitude of consumers [12], [13].

This work is a design-driven study that investigates the optimal parameters for integration of LSCs into roof tiles. Its focus is not mainly on achieving high photovoltaic conversion efficiencies, but rather the production of a functional and aesthetically pleasing rooftop system that includes the additional feature of solar energy conversion. Fig. 2 shows an artist's impression of the final system integrated in a roof top. As the reader may notice the colours of the roof tiles may very, providing interesting options for pattterning to be explored in more detail in our future work.

To evaluate the performance of various designs of these roof tiles, ray tracing simulations have been executed using the following variables as input: the thickness of the LSC-lightguide and the concentration of the luminescent material. The information gained is used to define the best approach to the conceptual design of the LSC roof tiles made from PMMA and BASF Lumogen Red 305.

## II. Methods

In this work we used PVtrace, a ray-tracing software developed by Daniel J. Farrell specifically for the design of LSCs [14]. As runtime environment we used Python 2.7 to run the simulation from within a RAM-disk.

PVtrace computes the paths of photons through a given geometry. Further input parameters for the simulation are the wavelength dependent spectrum of the illumination source, the refractive index of the LSC-plate and the absorption/emission spectra of the luminescent particles. The software uses the law of Beer-Lambert for extinction of radiation in a medium

$$\frac{I}{I_0} = \mathrm{e}^{-\alpha(\lambda)lc}, \quad (1)$$

with $I/I_0$ being the ratio of the transmitted radiant flux and the initially incident radiant flux; $\alpha(\lambda)$ the natural molar absorption coefficient of the absorbing component of medium in which the radiation propagates in litres per mole and per metre depending on the wavelength of radiation $\lambda$; $l$ the propagation length of the radiation in this medium in metres and $c$ the concentration of the absorbing component in the medium in moles per litre.

The radiant flux ratio $I/I_0$ is a number between 0 and 1 and is replaced by the pseudo random number $\xi$ . Now the "solving for $l$" for every number $\xi$ results in a distribution of lengths for the propagation path for the photons [15]. Subsequently, the programme computes the directions of the photon through the modeled object taking into account changes in directions due to refraction and Fresnel reflection at the interface of two media, which includes the total internal reflection. The coordinates at which a change in propagation direction occurs are recorded in a data base. This database also contains information about the direction, wavelength and the surface which interacted with the photon.

Every simulation was run with 50,000 photons that were sampled randomly from an at 1100 nm truncated AM1.5g spectrum. Beyond this region neither the PV cell nor the fluorescent materials can absorb the light. Therefore, computation power was only used for the photons that are active within the system. This amount of photons corresponds to $10^{-23}$ W. The photons are generated randomly 50 cm above the LSC-plate, encountering the LSC normal to the lightguide surface.

Due to the limitation of the geometry functionality in PVtrace the actual quasi-rhombic design of the roof tile had to be approximated with a square-like design preserving the surface area. This resulted in a square with the side length of 32 cm. During the first series of simulations plate thickness of the square were varied from 2 mm to 12 mm. The dimensions of the solar cell were 6.4 x 25.6 cm$^2$ and it was positioned 3.2 cm from each of the nearest edges on the bottom surface of the lightguide (Fig. 3). The luminescent species was BASF Lumogen Red 305 [16], whose concentration was chosen such that the product of the decadic molar absorption coefficient and the concentration was $\varepsilon(\lambda = 520\text{nm}) = 4.96\ \text{cm}^{-1}$. This corresponds with the data of Wilson and Richards to 230 ppm [17]. For second and third simulation runs the concentration was chosen to be one fifth and four times that of the first simulation, and the thickness was varied between 2 mm and 15 mm. The final simulation series the thickness was kept constant at 4 mm during the change of the concentration between the eightfold and one eighth of the original concentration.

An analysis script went through the generated photon database and counted only the photons located in the solar cell with no propagation direction i.e. are absorbed by the solar cell. This number is called the number of harvested photons,

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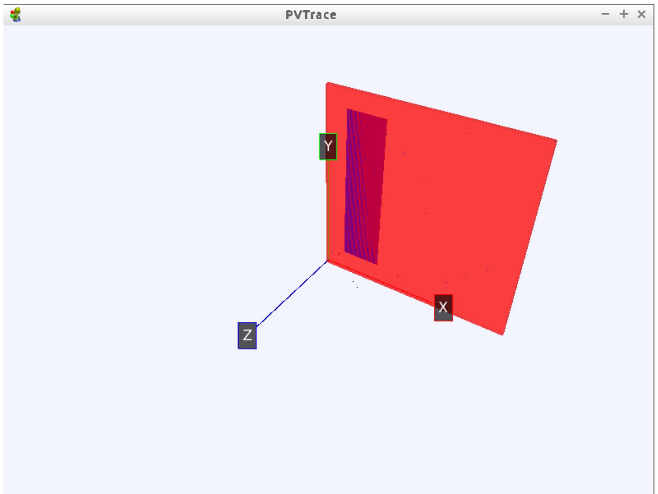


Fig. 3. Visualisation of the simulation with PVtrace. The red-embedded lightguide has a rear mounted silicon-based photovoltaic cell, which is indicated as the shaded rectangle. Incident light enounters the surface parallel to the z-axis (blue line) from the top surface.

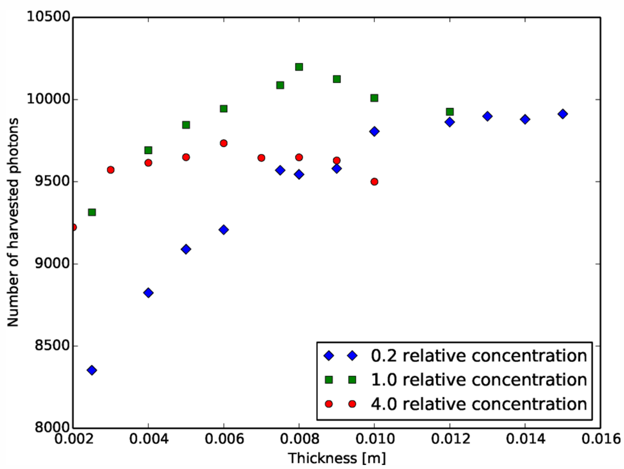


Fig. 4. Number of photons reaching the solar cell at different thicknesses of the LSC plates at a concentrations corresponding to the product of the molar absorption coefficient and the concentration 4.96 $cm^{-1}$ for 1.0, 0.99 $cm^{-1}$ for 0.2 and 19.8 $cm^{-1}$ for 4.0.

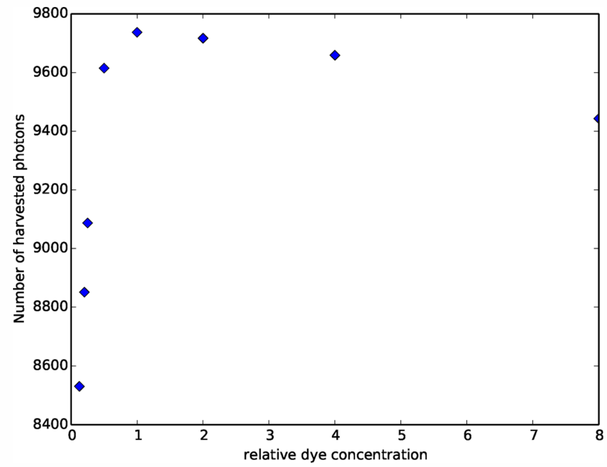


Fig. 5. Dependence of LSC performance on dye concentration. Where one is the concentration at which the product of the molar extinction coefficient and the concentration is 4.96 per cm, which corresponds to 230 ppm.

Fig. 6. Different colours result from different dye concentration using Lumogen Red 305. The concentrations are from top left to bottom right: 500, 184, 127, 97, 35.5, 15.5 and 4 ppm.

which is the quantifier of LSC-performance for the purpose of this study.

## III. Results and Discussion

The amount of harvested photons at different plate thicknesses is displayed in Fig. 4. The behaviour is in accordance with the law of Beer-Lambert and its implication on LSCs: as the thickness of the LSC increases, the LSC plate absorbs more photons. Hence, the performance of the LSC increases. Since in this model we use solar cells facing the photon source, some of the photons that are not absorbed by the LSC plate still end up converted in the solar cell. This contribution decreases with increasing absorption of the LSC plate as it effectively shades the front facing solar cell from the incoming radiation. The competing effect is the feeding of the solar cells from the trapped photons in the LSC. It balances the shading effect to some degree as the concentration of the dye increases at low level. However, it cannot compensate for the shading at higher concentrations. It can be concluded from Fig. 4 that increasing the plate thickness beyond a certain point does not increase the efficiency but increases the demand on material curing time and therefore the costs. For this reason it is more effective to use LSC-plates of thickness between 4 and 6 mm.

The dependence of LSC performance on dye concentration is indicated in Fig. 5. It shows that it is advantageous to take a rather higher concentration.

Another important criterion for the selection of dye concentration is the aesthetic appearance of the resulting colour. The concentration at which the maximum efficiency is achieved may result in a too bright colour, so that it might be necessary to strike a concentration balance between appearance and performance (Fig. 6). Based on the obtained information

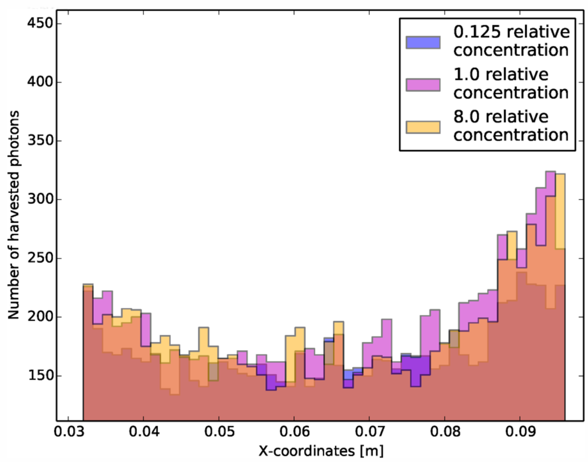


Fig. 7. Histogram of X-coordinates of the photons arriving at the rear side mounted solar cell .

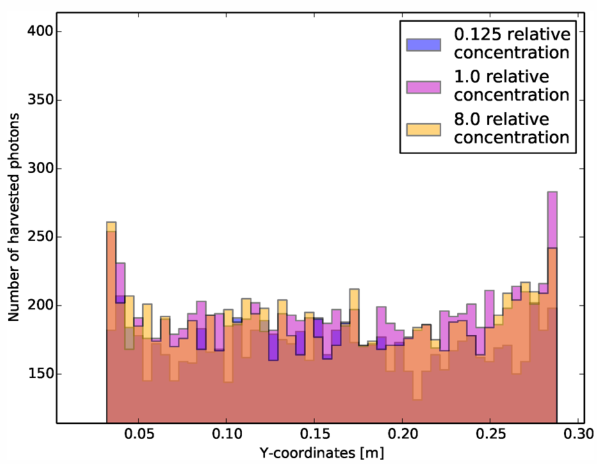


Fig. 8. Histogram of Y-coordinates of the photons arriving at the rear side mounted solar cell .

we estimate for a 5 mm thick lightguide and 80 ppm dye concentration a yield of $\Phi_{\text{out}} = 9400$ photons. Since we truncated the illumination spectrum at 1150 nm, the total number of incident photons $\Phi_{\text{in}}$ is not 50,000 but rather 78,000. Thus the optical quantum efficiency (ratio of the outgoing and incoming photon flux) of the roof tile is estimated to be

$$\eta_{\text{opt}} = \frac{\Phi_{\text{out}}}{\Phi_{\text{in}}} \approx 12\%. \tag{2}$$

The data generated by the simulation can also be used as indication for the alignment of solar cells in the LSC system. For every photon that enters the solar cell its coordinates of entry are recorded. A histogram of X/Y-coordinates is given in Fig. 7, Fig. 8 respectively. None of the photons arrives with a smaller coordinate than 0.032 m. The X-coordinates do not exceed 0.096 m and the Y-coordinates do not have any higher value than 0.288 m. All three limits represent the edges of the solar cell. However, closer to the cell edges there are up to twice as many as photons as in a region of the same size around the centre of the solar cell. If this is a physical effect and not an artifact of the simulation, it will mean that application of multiple small solar cells is more advantageous than the deployment of few large ones.

The assumptions under which this model operates limit the accuracy of the results. E. g. the lightguide is assumed not to absorb or scatter any radiation other than through the luminescent species. In reality PMMA absorbs a finite amount of radiation and also scattering cannot be neglected. The optical coupling of the lightguide and the solar cell is assumed to be perfect. However, some of the radiation might escape. Luminescence is modeled statistically, where the probability data is taken from the spectra of the luminescent material. This means that the wavelength of a photon after re-emission is sampled randomly from the emission spectrum taking its previous wavelength as a lowest limit, but no intrinsic molecular properties as the Stokes-shift are considered. With sufficient number of photons this effect can be neglected. Furthermore emission is assumed to occur isotropic, this is however not necessarily the case.

## IV. Conclusions

By means of ray-tracing simulation we determined the range of appropriate values for thickness and dye concentration for the conceptual design of roof tile LSCs.From these ray-tracing simulations it can be concluded that thickness could best be in the range of 4 to 6 mm and the concentration of BASF Lumogen Red dye in between 80 and 1000 ppm. Aesthetic considerations, however indicate that the lowest concentration from this range should be used.

In follow-up activities results will be obtained for more accurate approximations of a rhombic roof tile shape. Also parameter studies for different BASF Lumogen dyes will be undertaken. More realistic illumination conditions will be taken into account such as angular incidence and diffuse radiation in further ray-tracing simulations. With the information gained prototypes will be manufactured. A pilot setup for testsing the prototypes a roof in the vicinity of Eindhoven, The Netherlands is planned.

## Acknowledgement

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