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REGULAR PAPER

Luminescent solar concentrator photovoltaic designs

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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.

1. Introduction

The application of photovoltaic (PV) systems beyond primary energy production is still limited. Earlier work revealed that the design potential of PV solar cells and PV systems is often not fully used,[1] therefore in this paper the opportunities and challenges of designing with photovoltaics materials are explored in the context of five aspects that are relevant for successful product design. These five aspects[2] are (1) technologies and manufacturing, (2) financial aspects, (3) societal context, (4) human factors, and (5) design and styling. These five aspects connect to the slogan "High Tech Human Touch" of the University of Twente (UT) which stands for the strong focus of UT on research on new technologies that will be used in innovative applications and on related innovation processes with various stakeholders and end-users. These innovative applications are usually developed in house by a design-driven approach. In the following each of the five aspects will be shortly described.

The aspect "technologies and manufacturing" deals with photovoltaic materials that are used and the manufacturing techniques that are used to create PV cells and PV modules. Also the electric and electronic equipment that is applied to convert, distribute, monitor and store solar energy plays an important role. The "financial aspects" deal with investments in solar systems and related PV products and the economic value of the energy produced. The "societal context" plays an important role in the realization and acceptance of PV systems within society. Policy, regulations, laws, and standards are typically categorized as societal aspects. However the public opinion on sustainability and the willingness to use PV technologies play also important roles here. For instance from a prior study it was concluded that respondents were for instance quite positive about PV products that have an environmentally friendly or a social character.[3] The fourth aspect of "human factors" deals with the use aspects of PV systems. This is especially important in the case of PV systems in smart grid solutions, and product integrated PV. In the case of smart grids, for instance, the fact that energy should be used when it is available or on moments that the generation costs are low, could compromise the usability of appliances when user interfaces of home energy management systems are not well designed.[4] The last aspect, "design and styling" deals with the appearance of PV technologies, whether these are stand-alone or integrated in products. An interesting and contemporary appearance can have a major influence on the desirability of PV integrated products, but can also play a role in making PV systems more acceptable by its users or in its environment of use, for instance in the case of Building-Integrated PV systems. Well-designed objects tend to encounter less resistance and also have an increased functionality because of a positive and forgiving attitude of the user. As Donald Norman stated "attractive things really do work better".[5] Moreover, the communication function of design[6] can help to improve on the other four aspects, in particular the "human factors",[7] and, hence, also stimulate the acceptance of innovative technologies.[8]

Usually in the PV industry only two out of these five aspects, namely (1) "technologies and manufacturing" and (2) "financial aspects" are emphasized in product development of PV modules. Sometimes a third aspect, namely the "societal context", is taken along in the design process, however the two remaining aspects "human factors" and "design and styling", that are also required to create a successful product in the market, are usually neglected. This is a serious omission from the product development chain which potentially can negatively affect consumers' long-term interest in photovoltaic products and, as such, might limit the full exploitation of all PV markets. Therefore it makes sense to evaluate how we can design with photovoltaics instead of just technologically applying it.[1]

Given the context of product development, our paper will be focused on the specific case of luminescent solar concentrator photovoltaics. A luminescent solar concentrator (LSC) usually consist of a transparent, thin plate made of poly(methyl methacrylate) PMMA, polycarbonate, or an other transparent material, containing luminescent dyes enabling it to act as a spectrum-converting lightguide. If combined with photovoltaic cells at its edges and/or its backside, it is usually called an LSC PV application. The typical material properties of LSCs — low cost, colorful, bendable, and transparency — offer a lot of design freedom. This is acknowledged in practice where the matrix materials of LSCs, such as PMMA, polycarbonate or other plastics, are

Table I. In literature reported efficiencies of various LSC PV devices.

Author (date)	η_{STC} (%)	PV Cells	Location of cells	LSC size (cm)	Dye
Slooff (2008)[14]	7.1	GaAs	Edges (all 4)	$5 \times 5 \times 0.5$	Lumogen Red 305, CRS040
Witwer (1984)[16]	4	GaAs and Si	Edges	$40 \times 40 \times 0.3$	
Goldschmidt (2008)[17]	6.7	GaInP	Edges	$2 \times 2 \times 0.6$ (stack of two 0.3 cm thick plates)	BASF dyes, two colors. One in each plate
Atse (2015)	1.3	Si	Edges	$50 \times 50 \times 6$	DTB, DPA
Desmet (2012)[18]	4.2	Si	Edges	$5 \times 5 \times 0.5$	Lumogen Red 305, perylene, perinone
Sark (2016)[19]	0.2 to 2.0 (depending on size)	Si	Edges	Various	Lumogen various colors
Vishwanathan (2015)[20]	3.4	Si	Back	Curved LSC	Lumogen Red 305
Corrado (2016)[21]	3.4	Si	Back: straight lines	63×163	Lumogen Red 305
Corrado (2016)[21]	3.8	Si	Back: zig zag pattern	63×163	Lumogen Red 305
Reinders (2017)[13]	5.8	Si	Back	110×0.5	Lumogen Red 305 and other colors as well

commonly and reliably applied in outdoor applications. Knowing this, LSC PV technologies might be a good case to explore opportunities and challenges of designing new PV products that have not been considered in the past. In this paper this will be evaluated in the framework of PV modules, future products and buildings.

The setup of this paper is therefore as following. In Sect. 2 existing LSC PV applications will be presented and discussed to provide a context for the results that will be presented in this paper. Next in Sect. 3 two different experiments on the design of LSC PV modules will be presented, namely regarding the LSC PV modules that were developed in the Leaf Roof project (Sect. 3.1) and a more recent project on the design of LSC PV metal wrap through (MWT) modules (Sect. 3.2). Subsequently in Sect. 4 the results of a design project that took place in 2016 at the School of Design of University of Twente, using LSC PV elements will be presented and shortly discussed. This paper will be completed with an overall discussion and conclusions in Sect. 5.

2. Existing LSC PV applications

For an excellent overview of existing lightguide materials and luminescent dyes we like to refer to Debije.[9] In this paper it is shown how flexible an LSC device is in its design, with a variety of possible shapes and colors. The primary challenge faced by LSC devices is increasing their photon-to-electron conversion efficiencies to improve the efficiency and lifetime of the LSC device. A significant amount of research is put into the development of novel luminophores, including organic fluorescent dyes, inorganic phosphors,[10] and quantum dots.[11,12] At present two types of characteristic LSC PV device configurations can be distinguished; to start with LSC PV devices with cells attached to the back of the LSC and secondly those with cells attached to the edges of the LSC. At present the highest efficiency achieved for prototypes of the first type of LSC PV modules is 5.8%[13] and for the LSC PV's with cells attached to the edges 7.1%,[14] see also Table I. These values remain substantially below the 10% limit[15] that is sometimes mentioned for LSC devices, which is based on LSC devices with perfect side mirrors and a very low absorbing polymer material with a high refractive index of 1.7. In the examples mentioned above PMMA is used with a refractive index of about 1.49, resulting in less trapping of the light and thus lower efficiencies.

Fig. 1. (Color online) Various differently colored prototypes of Leaf Roof LSC PV modules.[13]

3. LSC PV module experiments

In this section two types of LSC PV modules will be presented from a design perspective and their experimental performance. Both types of LSC PV modules contain back contacted PV cells to create a better optical coupling at the interfaces between the lightguide and the cells. In the following two sections the designs, prototypes and the experimentally determined performance of these LSC PV modules of the respective type "Leaf Roof" and "MWT" will be presented and shortly discussed.

3.1 Leaf Roof LSC PV modules

There has been extensively reported about the design, simulation and prototyping of a LSC PV module, called Leaf Roof[13,22,23] (see Fig. 1). This project aimed at demonstrating the design features of LSC PV technologies such as coloring, transparency, and flexibility in a physical shape. With an eye on performance, various cell configurations have been evaluated with regard to their efficiency

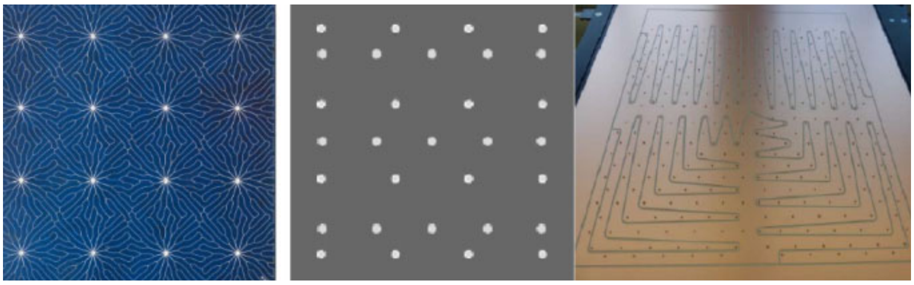

Fig. 2. (Color online) Front side (left figure) and rear side (middle figure) of a MWT cells and its back contact sheet (right figure).

by numerical simulations[22,23] using various concentrations of dyes from the Lumogen series by BASF and different contours and thicknesses for the PMMA lightguide. These results will enable the application of LSC PV modules in a number of shapes and colors and therefore provide design freedom to architects. The final design consists of a rhombic tile configuration (see Fig. 1), comprised of six PV cells with a customized size of 52 cm^2 resulting from cutting complete C60 PV cells (GEN C BIN J) from Sunpower with a 22.5% efficiency under STC in three slices. The total area covered by PV cells is, therefore, 0.0304 m^2. The prototype of this module has been presented in Journal of Photovoltaics.[13] In this publication, the first measurements of its performance were shown. The geometrical gain of this new type of PV module is 3.6. For two types of Leaf Roof modules, current–voltage (I–V) curves have been measured resulting in efficiencies of 5.8% for a red-colored PV module, and 5.5% for a green-colored PV module under standard test conditions. These results demonstrate colorful, robust solar energy collectors which can be produced in a wide variety of shapes are viable, attractive devices for use in building integrated systems. Additionally, thanks to the use of PMMA as a cell encapsulant, it was found by outdoor measurements that the Leaf Roof modules are less susceptible to energy losses at elevated temperatures due to high irradiance and high ambient temperature conditions.

3.2 LSC PV MWT modules

LSC PV modules can also be made by using back contacted MWT silicon solar cells, also called MWT cells, which have been developed at ECN in the Netherlands[24–26] (see Fig. 2). In this case a PMMA sheet of 3 mm thickness and an aperture area of $250 \times 250\,mm^2$ was doped with Lumogen Red 305 dye at 100 ppm. The MWT cells were laser cut in 16 smaller cells each measuring $39 \times 39\,mm^2$. For three different configurations containing respective 4, 6, and 8 small cells the optimal positioning and distance between cells was simulated using ray-tracing software called LightTools. To fix the location of the cells for the four cell layout, the distance of the centre of the cell to the corner of the tiles was varied in the LightTools model and LSC concentration was calculated each time. The results are plotted in Fig. 3. The LSC concentration was found to be maximum when solar cells were placed exactly at the midpoint of the line joining the corners and the centre of the tile. Using a similar method, optimum cell placement was calculated for the 6 and the 8 cell layouts and the same is shown in Fig. 4 and the obtained performance parameters are listed in Table II.

Finally the prototypes that were developed using the configurations shown in Table II were experimentally

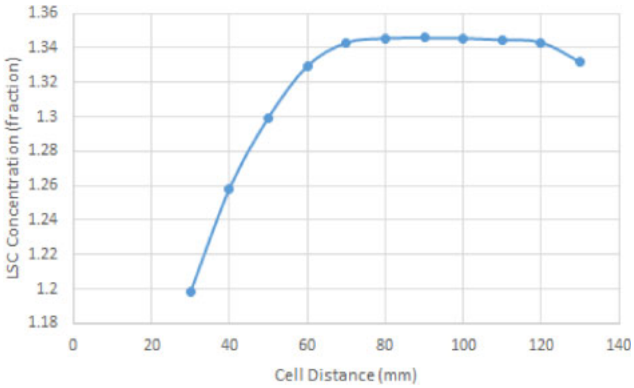

Fig. 3. (Color online) LSC concentration as a function of cells' intermediate distance at PMMA thickness of 3 mm and a Lumogen Red dye concentration of 100 ppm.

evaluated at ECN by flash tests in an PASAN flash tester and at UT by outdoor monitoring in the PV module test bench. Each LSC was prepared in two configurations: in the first one, an airgap was introduced between the cells and the lightguide, while in the second one there is no airgap. It was hypothesized that introducing an airgap ensures that there is no contact between the PMMA sheet and the cells which may reduce thermal stresses on the cell in outdoor conditions. First half laminates were made, consisting of a glass back support for preventing curving of the Cu backsheet after lamination. Then the Cu backsheet with EVA and solar cells was added and this stack was laminated at 150 °C and a pressure of 900 mbar for 15 min. Then the PMMA was glued to the half laminate using Acryfix 1R0192. It was observed that three of the modules with no airgap between the cells and the PMMA sheet curled due to thermal stresses between the PMMA sheet and the glass which also led to cracks in the glass sheet. The results of the flash tests are plotted in Fig. 5. It may be noted that "laminate" refers to the half device where the cells are connected to the back contact sheet and there is no lightguide attached. It can be seen from Fig. 5, that affixing the lightguide to the laminates improved the performance in case of devices without airgap. The reason behind the low performance of the modules with an airgap between the cells and the PMMA sheet may be explained by the fact that the thickness of the airgap could not be tightly controlled during fabrication due to manufacturing constraints while as per ray tracing simulations this thickness should be within the thickness of solar cells for improved performance. Another loss could be higher reflection off the silicon surface as silicon under air has higher reflection than silicon under glass.

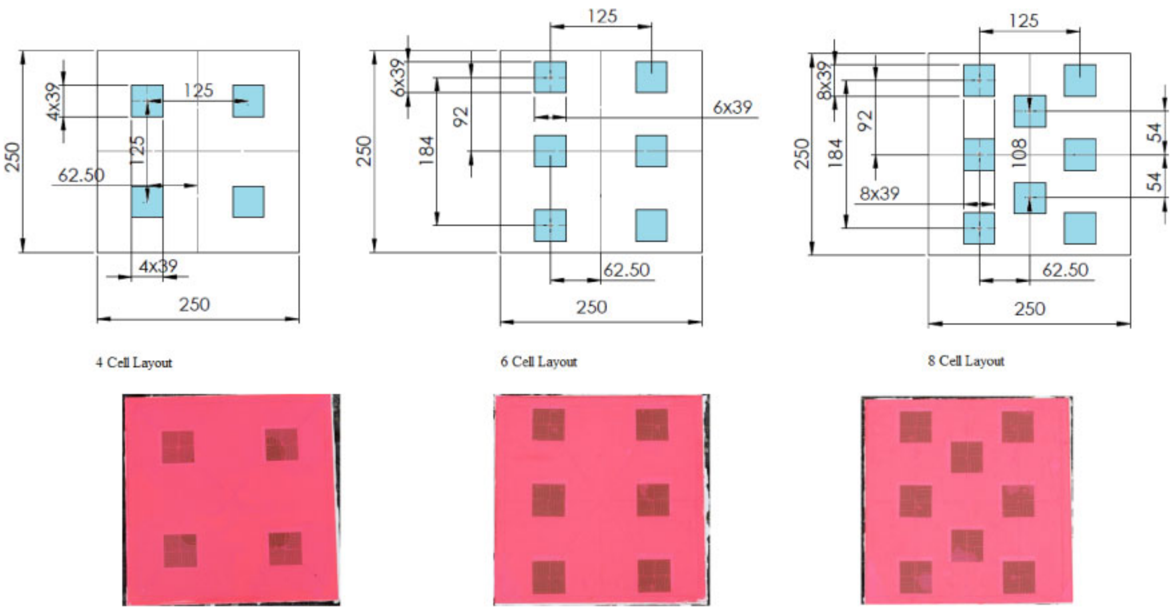

Fig. 4. (Color online) Scheme showing typical distances between small MWT cells in a mini-module; the in the project realized prototypes of these mini-modules are shown below the schemes.

Table II. Simulated parameters for 4, 6, and 8 cell LSC PV design referring to designs of LSC PV mini-modules shown in Fig. 4.

Parameter	4 cell design	6 cell design	8 cell design
Geometric gain	10.27	6.85	5.14
LSC output (W)	1.64	2.24	2.78
LSC efficiency (%)	2.62	3.58	4.45
LSC concentration	1.35	1.22	1.14

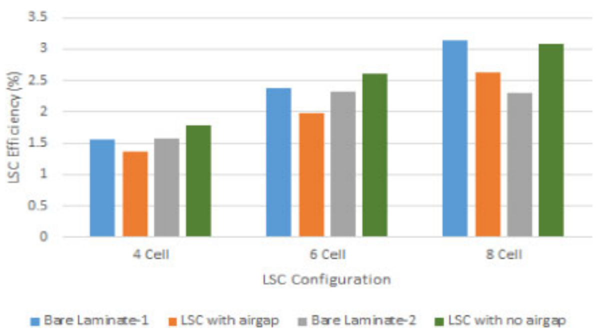

Fig. 5. (Color online) Efficiency of prototyped LSCs as measured from flash tests.

The three higher performing modules were mounted on the PV test bench at UT for outdoor testing and 1-min based performance parameters were recorded for a period of 8 days from 22nd August 2017 to 29th August 2017. The PV monitoring setup at UT is located on the roof of the Citadel building at latitude 52°14′19.7″N and longitude 6°51′18.6″E. It has a facility to mount six PV modules facing South, inclined at an angle of 30° with the horizontal. The meteorological measuring equipment consists of a pyranometer by Kipp&Zonen which measures the global irradiance, while another pyranometer of the same specification measuring in-plane irradiance (30°). A monocrystalline silicon reference cell by Mencke and Tegtmeyer is also calibrated to measure the in-plane irradiance in the same plane. A spectroradiometer from Eko is also placed to measure the in-plane spectral irradiance. An anemometer is placed to measure the wind speed. There is an ambient temperature sensor along with 12 thermocouples to measure module temperature. The signals from all these devices except the spectroradiometer are fed into a datalogger, which converts them to physical values, gives them a time stamp and stores them for 24 h, after which the data is transferred to a central server. The spectroradiometer has a separate control system and operates in the same way though with different software.

The results from the outdoor tests confirmed the results from flash tests, i.e., the module efficiency of a device with higher solar cell area was higher but the optical concentration was lower. The error in concentration with respect to the flash test results was found to be less than 5% for outdoor monitoring however it was up to 25% for the simulated data. This mismatch could be explained as the simulations were carried out using 20% efficient cells while the actual cells had 17.03% efficiency only. The simulations did not take into account the dependence of external quantum efficiency of the solar cells on wavelength. The value of photoluminescent quantum yield for the final PMMA sheets was assumed to be 95% in simulations but this could not be measured for the fabricated sheet and is very likely to be lower resulting in the lower measured performance of the modules. The presence of air bubbles in the transparent adhesive between PMMA and solar cells also affected the performance adversely which could not be predicted through simulations.

An encouraging aspect of these modules is their lower module temperature as compared to front glass covered modules, as is shown in Figs. 6 and 7. It can be seen that the temperature difference of the LSC modules with respect to the ambient at peak irradiance is 10 °C while the temperature difference for the normal multi-crystalline silicon (mc-Si) module is 30 °C. This allows les influence of temperature over module performance and could be an interesting topic for further research. The reason behind the lower module

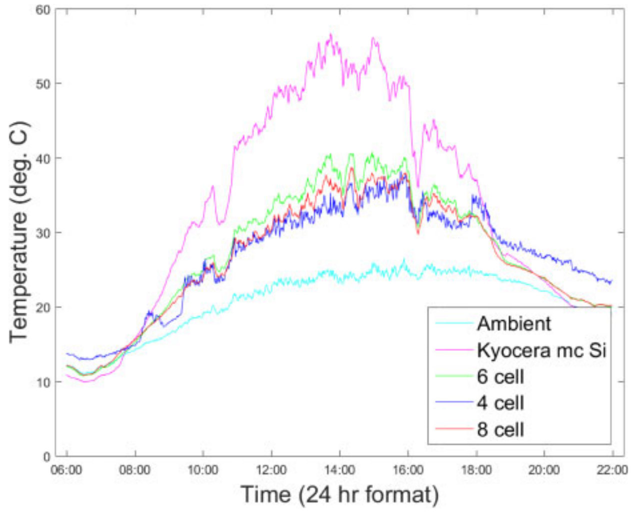

Fig. 6. (Color online) Module temperatures of normal and LSC PV modules as measured on 28 August 2017.

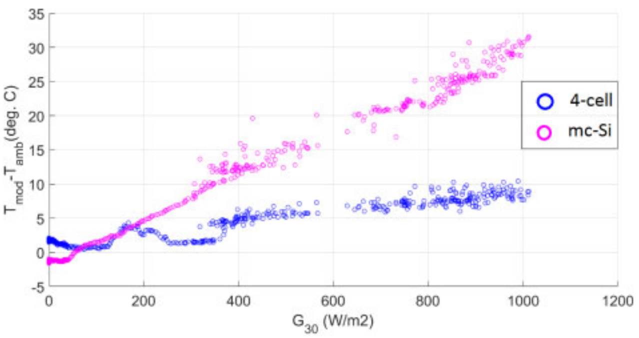

Fig. 7. (Color online) Difference between module temperature of a LSC PV MWT module containing 4 cells and the ambient temperature as a function of the in plane irradiance at 30° tilt angle and South orientation, measured on 28 August 2017.

temperatures for the LSC modules as compared to the mc-Si modules could be the difference in thermal conductivity of their front surfaces, i.e., PMMA and glass.[13]

4. Designing products with LSC PV technologies

A design study on possible applications for LSC PV technologies was executed within the scope of the master course "Sources of Innovation". This course is part of the Master in Industrial Design Engineering of the University of Twente. The course is especially targeted at developing novel designs for innovative technologies.[27] In previous years this approach was also applied to Concentrating PV and other PV technologies.[28–32] A series of theories about innovation processes from the book *The Power of Design*[2] is applied in an accompanied design project. In the academic year 2016–2017 about 40 students executed this design project in groups of two or three. The end results that they had to attain were a feasible concept design worked out to the level of a scaled prototype and a report that describes the design process and the application of the innovation methods.

The project resulted in a total of 16 prototyped conceptual designs. Due to the course's emphasis on innovation and creativity,[33–35] the student design projects were very diverse. In random order, the designed objects consisted of; a tourist shelter, a garden fence, greenhouse panels, safety staircases, parking assistance in the form of trees, outdoor tables, a casing to charge cell phones, a labyrinth for parks, an illuminated bicycle frame, an LSC powered boat, outdoor furniture, a sundial, a festival tent, and a colorful bike parking with integrated LSC PV technologies.

In the following subsections we will highlight a subset of all the results which represent the broad application possibilities of the LSC technology on different dimensions. These dimensions are scale (from big to small), application purpose (for professional use or for leisure and entertainment), and user experience (either active or more passive). The presented designs are also illustrative examples of the use of the design features of the LSC material: colorful, transparent, relatively cheap and bendable.

Fig. 8. (Color online) "Allisee" transparent boat concept by Jullian Claus, Rosan Harmens, and Hieu Nguyen.

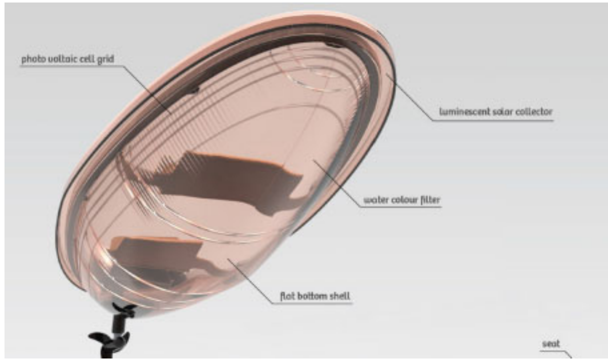

Fig. 9. (Color online) LSC transparent sculpted hull design with PV cell grid by Jullian Claus, Rosan Harmens, and Hieu Nguyen.

4.1 *AlliSee* LSC-boat

This project presents a product design for leisure activities. The design consisted of a modular platform for a small electrically powered boat for outdoor activities like snorkeling and fishing (Fig. 8).

The design makes use of one of the discerning design features of LSCs, which is the possibility to realize three-dimensional shapes. The curved form of the hull would be molded from one large sheet of LSC material. The transparency of the material adds to the user experience because the underwater world will be visible through the hull. In the design concept, the solar cells that are needed to harvest the light that is collected in the LSC hull are located in the reinforced gangway of the dinghy. Because the total LSC surface area is rather big, segmentation with an additional PV cell grid would be applied to minimize the self-absorption of the photons by the material (Fig. 9).

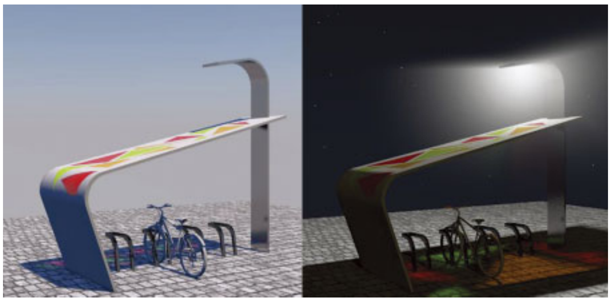

Fig. 10. (Color online) Bicycle parking concept with integrated LSC material and lantern by Ruben de Noord, Eduard Tudor, and Sem Vossebeld. During daytime (left) and during the night (right).

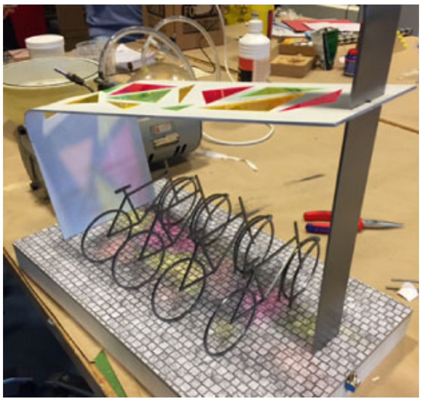

Fig. 11. (Color online) Colorful effect of the LSC material in the Bike parking concept demonstrated in the prototype.

4.2 Bike parking shed with integrated LSCs

The second example is a somewhat larger object for professional use. In this concept, LSC material is integrated in the roof of a bicycle parking (Fig. 10).

The LSCs generate electrical energy that can be used to illuminate the stand-alone unit during the night. An integrated lantern will shed a colorful shadow pattern on the floor. This type of use of the color of the LSC material again adds to the consumers' experience in two ways. During the day it draws attention to the sunlight as an energy source and during the night it is supposed to support the feeling of safety (Fig. 11).

Apart from the safety-enhancing lighting during the night, the LSC PV panels could also be used to generate power for charging e-bikes. However, the charging station should be connected to the grid then as well, to ensure enough power supply during all seasons.

4.3 LSC table for outdoor charging of devices

This concept, on a smaller scale, uses the LSC material to harvest energy in an outdoor table for use at festival sites. The energy is then used to charge cellphones of the visitors of the festivals. The cables that are provided to connect the cellphones with the table are deliberately kept short, so the visitors are unable to use their phones during the charging. This should trigger them to have real-life conversations with other visitors of the festival instead of keeping them busy with their phone (Fig. 12).

The table design consists of a LSC material tabletop and four legs with a cellphone charger integrated in each of them. The PV cells that harvest the energy are located in the edges

Fig. 12. (Color online) LSC PV Charging table concept by Niek Eggink, Gydo Nijensteen, and Mark Zwart in a typical festival environment. The charging functionality should stimulate personal contact among the visitors.

Fig. 13. (Color online) Table with LSC PV tabletop for charging cellphones. The tabletop can be lit-up by leds during the night (inset right).

Fig. 14. (Color online) Application example of LSC illuminating safety strips concept by Ashley Hogt.

that surround the table surface. During the evenings, the transparent tabletop can also be lit by integrated led strips (Fig. 13). The distinct color of the LSC material and the design of the table should attract people and tickle their curiosity, in order to enhance the social function.

4.4 Illuminating safety strips

This concept consists of a modular system for illuminating outdoor surface edges, in particular stairs and steps (Fig. 14).

The design is self-sufficient. With the use of LSC material in combination with solar cell strips, energy will be converted during daytime and stored by the power controller. In the evening, the energy will be used to activate the LED module inside the casing (Fig. 15).

Because one of the proposed design methods of the course is platform driven product development,[2] a lot of projects

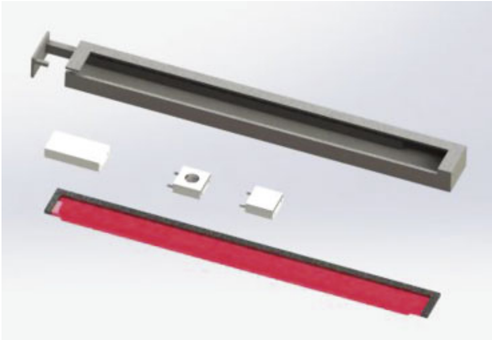

Fig. 15. (Color online) Impression of the construction of the modular LSC safety strips with the LSC material (magenta) surrounded by solar cells.

Fig. 16. (Color online) Active engagement of the user by responding to the movements of people ascending and descending the staircases.

pay attention to a modular design. Also in the case of the LED strips, several platform possibilities were explored. Apart from the more obvious options of altering the size and color of the strips, the incorporation of additional sensors to provide more functionalities was discussed. The safety strips can provide safety in a passive manner, as delineators of a "dangerous" edge, warning people to step back. However, they could also function in a more active way to create a feeling of safety by illuminating places in a playful manner, for instance while walking public stairs when it is dark. To increase the engagement of the user, sensors will be used to make the experience interactive by responding to the users' movements (Fig. 16).

4.5 LSC PV garden fence

This design uses the LSC material to create a multifunctional garden fence with a modular set-up. The system consists of hexagonal panels with integrated light strips that can be put together to create a fence with the desired dimensions (Fig. 17).

The students report that from the application of the innovation journey (one of the innovation methods provided in the course), it was shown that in previous time the LSC technology was mostly used in the public environment or applied for public utilities, so their design is an attempt to expand the use of the LSC material towards private architecture. Unlike conventional PV modules, the LSC panels can easily be cut into different shapes. The students therefore explored various possibilities with different building blocks to give the consumer the opportunity to build their own appearance (Fig. 18).

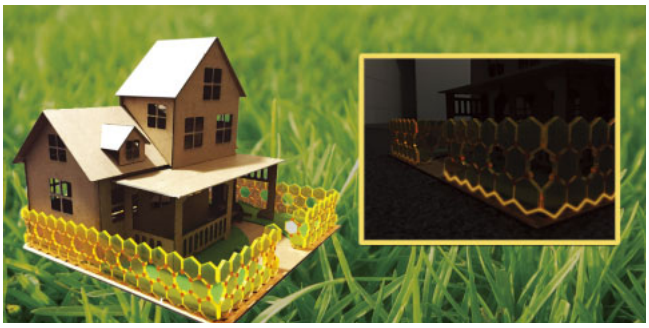

Fig. 17. (Color online) Modular garden fencing system by Yanxin Wang and Biying Zhang. Scale prototype (left) and nighttime effect (right).

Fig. 18. Exploration of basic shapes for the garden fence module: square, rhombus, pentagon, and hexagon. In the prototype, the hexagon was used.

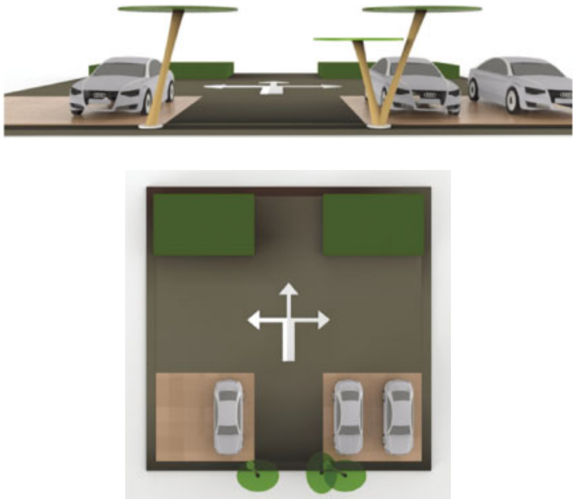

Fig. 19. (Color online) LSC PV "trees" concept for an interactive parking lot, by Samantha IJkhout and Jennifer van Zeil.

4.6 Parking lot with LSC PV "trees"

The parking lot design with solar powered artificial trees is intended to support drivers with finding an empty parking spot. The tree-like structures incorporate a large LSC panel on top in the shape of a leaf that harvests the energy from the sun. The energy is used to power a system of sensors and arrows that can direct the drivers to the proper place. The trees can also be used to light the parking lot in the dark. The arrows are inserted in the tarmac and light up to show the correct direction (Fig. 19).

The interactive prototype showed the functionality of the system (Fig. 20). The shapes of the LSC PV energy sources are resembling a tree to add to the idea of sustainability of solar power.

4.7 LSC PV labyrinth

The labyrinth that is built from large LSC PV panels is one of the more explicit examples of the benefits of the relative

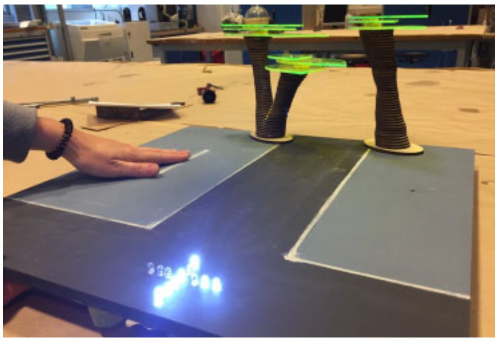

Fig. 20. (Color online) Prototype of the interactive parking lot. If a parking spot is occupied (mimicked by the hand on the left), drivers are directed to the other spots by the lighted arrows.

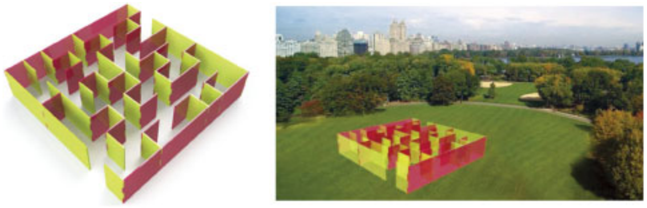

Fig. 21. (Color online) LSC PV labyrinth by Natasha Tanushevska, Renée Schrauwen, and Eline de Wall.

Fig. 22. (Color online) Impression of the sustainable festival tent by Rolf van der Toom, Steven Oonk, and Kasper Schriek.

cheapness of the material. The labyrinth is meant for public parks and can easily be modified, enlarged or altered to stay interesting for the public (Fig. 21).

The design concept uses the energy that is produced by the solar panels to make the labyrinth interactive. A number of rotating panels will dynamically change the route through the labyrinth in reaction to the people inside. The changes can either direct the user to the exit or conversely make the route more difficult.

4.8 LSC PV sustainable festival tent

The largest concept in terms of scale is the sustainable festival tent. This concept uses LSC PV modules to generate a part of its own electricity consumption. In terms of design features of the LSC material, the color of the luminescent dyes in the LSC panels is used to create a special atmosphere inside the tent. Because most festivals are held both during day and night, the lighting effect is both special when the sunlight comes through the surface and when the tent is lit with artificial lighting (Fig. 22). The students made a working prototype at scale to demonstrate the lighting effect (Fig. 23).

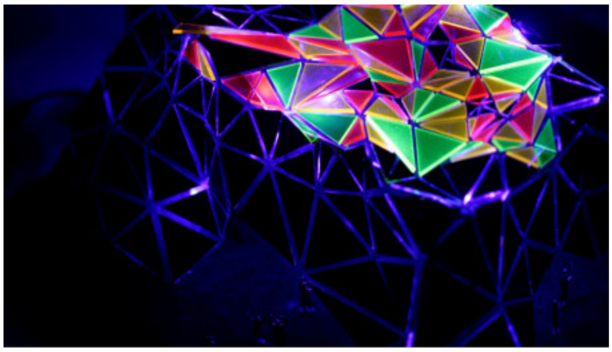

Fig. 23. (Color online) Scale model of the sustainable festival tent, demonstrating the lighting effect.

Fig. 24. (Color online) Impression of the construction of the modular LSC tent segments, with both LSC and conventional PV panels. Bottom-right the setup of an LSC PV panel with solar cells and a LED strip around the edges.

Fig. 25. (Color online) Street furniture concept by Canxuan Li, Théo Sauzon, and Jules Troia.

The tent surface consists of triangular modules. When the night falls in the LSC panels are lit with the use of led strips that are placed at one edge of the triangles. At the other two edges solar cells are attached to catch the energy of the light that is trapped (Fig. 24).

The students calculated that the tent could not provide enough energy when powered by LSC PV panels only and therefore suggested to incorporate both LSC PV modules and conventional PV modules in a complete festival set-up.

4.9 LSC PV urban street furniture

In this project the students designed multifunctional street furniture (Fig. 25). The playful modules of the furniture contain LSC panels that provide energy for integrated cell phone chargers, similar to the festival table described earlier. The colorful units represent the different block shapes of the popular Tetris game and can be combined in several ways.

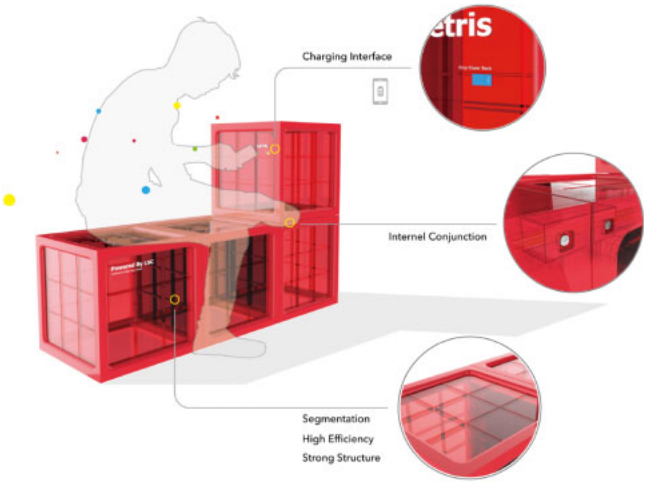

Fig. 26. (Color online) Details of the Letris urban furniture concept with charging interface, connections and LSC grid surfaces by Li Canxuan, Théo Sauzon, and Jules Troia.

This invites the users to build their own "urban landscape". To enhance the association with the game the students named their system "Letris". Because the blocks are meant to be positioned to the users wish, they contain LSC panels at each side of the cubes. The panels also incorporate a grid to minimize the internal loss through self-absorption of the photons by the material (Fig. 26).

5. Discussion and conclusions

From this paper it can be concluded that LSC PV technologies offer plenty of opportunities for integration in various designs of products and building components at a reasonable efficiency which at present is in the order of 5.5% to 7%. However supposedly large area LSC PV technology can reach an efficiency of 10% provided that the right design combinations of LSCs and PV cells will be found and that the optical coupling between LSC lightguides and PV cells will be excellent. To our opinion, based on the experiences with two types of LSC PV module designs prototyping and testing is key to the future success of LSC PV modules. It seems promising that at first sight, LSC PV modules thermal behavior might lead to less temperature losses during outdoor operation of these modules under high irradiance conditions.

Apart from the use of organic dyes in LSC's, recent developments with applications of quantum dots (QDs)[36,37] in LSC PV devices show a far greater potential for concentration of incoming irradiance and the efficiency of these devices. Namely Bronstein et al.[36] showed that LSC's doped with CdSe/CdS QDs can exhibit 30-fold concentration of irradiance and a geometric gain of 61. This is achieved by coupling of a wavelength-selective photonic mirror to an LSC to form an optical cavity where emitted luminescence is trapped. This sort of LSC PV devices contain a micro silicon solar cell. However Li et al.[37] show that also for large area device good results can be obtained. They have demonstrated a low-loss, large-area (up to about $90 \times 30\,\mathrm{cm}^2$) LSCs fabricated from colloidal core/shell QDs whose optical spectra are tailored so as to minimize self-absorption of waveguided radiation. For improved compatibility with a polymer matrix and enhanced stability, these QDs are encapsulated into silica shells, which allows for maintaining high emission efficiencies (~70% quantum yields) resulting in semi-transparent devices on glass demonstrating internal quantum efficiencies of more than 10% for dimensions of tens of centimetres. As such this sort of breakthroughs in LSC PV research are expected to result in future high efficiency applications of LSC PV technologies.

In general LSC's properties (low cost, colorful, bendable, and transparent) offer a lot of design freedom and therefor incorporation of LSC PV technology into the overall functions and experience of applications seems a feasible option.

For all the presented product concepts, the design features of the LSC material play a major role in the appearance of the designs. That the transparency and color were important in the shape of the concepts was to a certain extent as expected. However besides that, the colorfulness and transparency of the material often also play a major role in the user experience of the designs. The transparency affords the users of the boat to experience the underwater world, the colors add to the nighttime feeling of safety in the bicycle shed, attracts the attention in the festival table, and ensures a permanent disco atmosphere in the festival tent. The third design feature that we discerned in the setup of the project, the bendability, played a less decisive role. Only in two of the projects, this form freedom was used, though bending is a relatively easy production step for plastics which would slightly increase the efficiency of an LSC.[20]

A more important factor is that the relatively limited energy yield of LSC PV elements sometimes constrained the functionality of the designs. In several cases, for instance the one of the festival tent, this was compensated by the use of additional conventional PV modules. In other cases, like the safety strips, the energy demand of the chosen applications was kept low to maintain the stand-alone functionality of the LSC PV technology.

In general we therefore may conclude that with LSC PV technologies it will be possible to design with PV instead of simply applying PV technology on existing products and buildings.

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