The Electric Mondrian^{TM} Toolbox Concept - a Luminescent Solar Concentrator Design Study

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***Abstract* — Based on the performance characteristics of luminescent solar concentrator elements of different color and size, a toolbox is developed, which could assist product developers in their design of an Electric Mondrian: an LSC window design that can harvest solar energy to power and charge mobile devices. This paper demonstrates the steps needed and taken for such a toolbox.**

***Index Terms* — luminescent solar concentrator, product integrated photovoltaics, simulation study, design.**

I. Introduction

Luminescent Solar Concentrators (LSCs) have been developed since the 1970s as cost effective alternative to crystalline silicon photovoltaic (PV) technology [1]. With present record efficiency of 7.1% [2] and drastically lowered c-Si technology cost, LSCs are now being developed for building integrated PV (BIPV) applications [3], as the freeness in form and color are attractive to architects and building developers. A few examples exist of >1 m^2 scale LSCs [4,5], but they all suffer from low efficiencies, albeit that this is not considered important due to the aesthetical value of the applications.

Inspired by the works of the Dutch artist Piet Mondriaan (1872-1944, who changed his name to Mondrian during his Paris period), especially his colorful abstract works such as the famous Broadway and Victory Boogie Woogie (Fig. 1), we have developed an Electric Mondrian^{TM} based on LSCs [6].

It is based on square and rectangular elements of standard sizes based on multiples of 15 cm, as this the standard size of the c-Si cells that are used at the sides of the elements. The elements are commercially available luminescent concentrator Perspex plates of 5 mm thickness that were purchased from PlasticSheets [7]. Cells were obtained cut to size from Solar Capture Technologies [8].

Figure 2 shows the final device of 1 m^2 in size. The sides of the plastic elements are covered with c-Si cells. All cells are connected in series. As the elements differ in color and size, the design is not optimized for efficiency. Nevertheless, preliminary measurements showed that the efficiency is about 1% [6]. The cells connect to a maximum power point tracker. A small Lithium-ion battery is included and the user can either directly charge a mobile phone via a USB connector, or the Li-ion battery.

The Electric Mondrian presently is a registered trademark, and public interest for such a decorative element as a potential replacement for stained leaded-glass warrants further development.

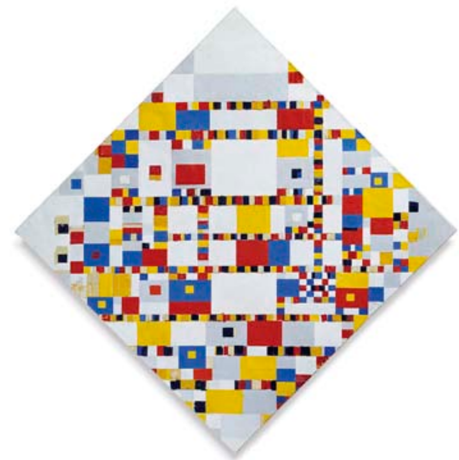

Fig. 1. Piet Mondrian, Victory Boogiewoogie (1942-1944), Gemeentemuseum Den Haag, the Netherlands.

Fig. 2. Photograph of the 1-m^2 Electric Mondrian^{TM}, with the Utrecht Dom tower in the back.

II. APPROACH

The design as shown in Fig. 2 prompts the development of a toolbox consisting of several standard sized and colored elements. Color (and transparency) depends on the type and concentration of the specific luminophore embedded in the Perspex plate. We propose to use 5 different colors (blue, green, yellow, orange, red) in 4 different shades (transparency 20, 40, 60, 80%). Sizes come in 3 squares (15x15, 30x30, and 45x45 cm^2) and 3 rectangles (15x30, 15x45, and 30x45 cm^2). Plate thickness can be varied between 3 and 8 mm with 1 mm step size. This totals 720 possible elements for design use. The flexibility added by cutting c-Si cells to 5, 10 and 15 cm length (by 3-8 mm width, being the thickness of the plates), gives additional options for designing smaller sized devices, with squares and rectangles with sides of multiples of 5 cm. A similar approach was recently reported by Kerrouche et al. [12].

With commercial fluorescent acrylic, size limits the efficiency due to self-absorption. New nanocrystal-based luminophores are under development that allow for larger sizes at high device efficiencies [9-11].

We model the elements by Monte Carlo ray-tracing using the code pvtrace [13,14]. The simulations have been validated with the samples used in the Electric Mondrian design [6]. In this way, we develop a look-up table with efficiency, maximum power point voltage and current, per element. Custom designs are now possible, while attention must be paid to series and/or parallel connections of these elements to ensure optimum power of the whole device.

III. RESULTS

The look-up table presently is being constructed, and a first design is being made. Simulations for full LSC devices including 18% c-Si solar cells and the luminophore Red305 are presented in Figs. 3 and 4, for 3 sizes (15x30, 15x45, and 30x45 cm^2) and three thicknesses (5, 6, and 7 mm). Important observations are that the LSC efficiency increases with increased dye concentration as well as with thickness of the LSC plate. Clearly, the amount of luminophores is responsible for this. Note, however, that a saturation effect is observed, which is well known [3, 9, 12]. Increasing the area does lower the LSC efficiency, but not by a large amount.

On the basis of the simulations, a start has been made to fill the look-up table, see Table I. This shows color, size and maximum power (P_{max}) for the LSC device. Work is going on presently to complete the table.

For the design shown in Fig. 2, the total power is calculated, as shown in Table II. Assuming that all power of the separate components can be added a total power of 13 W can be generated at standard test conditions (1000 W/m^2, 25 °C, AM1.5 spectrum). This would constitute a full LSC efficiency of 1.6% for the aperture area of 0.81 m^2. Simply connecting the plates in series does not allow full power to be generated, as the lowest current will limit the full LSC device current. This would be the blue plate, as is clear from Table II. To tackle this, a series-parallel construction must be designed such that plates of the same color (and size) are connected in series, which are then connected in parallel to other colors. Alternatively, power classes can be defined that should be connected, while DC-DC upconverters may be installed as well.

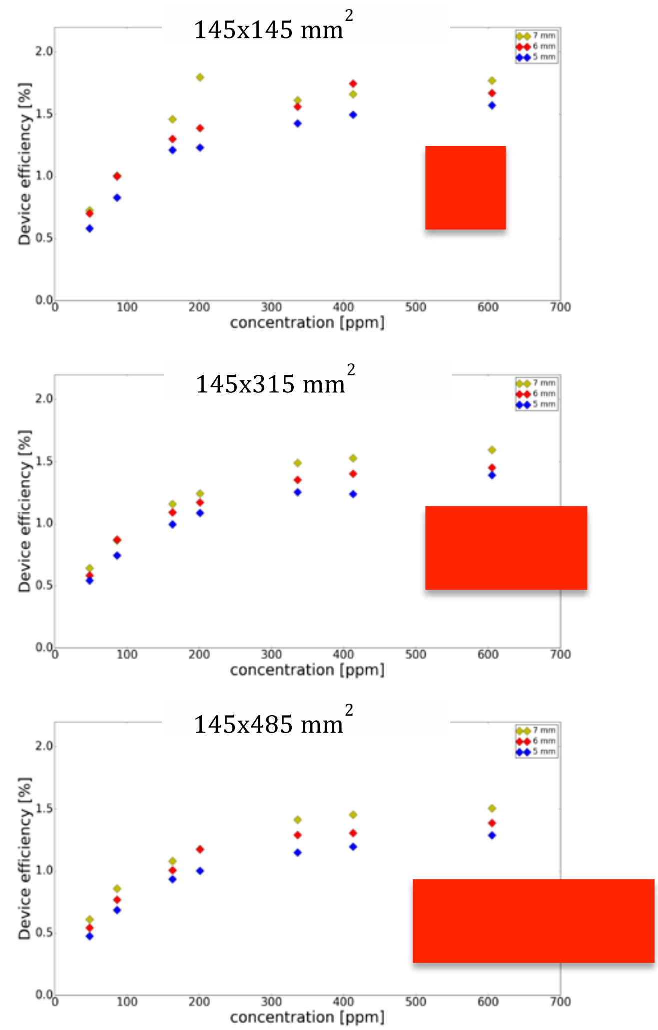

Fig. 3. Simulated efficiency as a function of size, luminophore concentration and thickness of the LSC plate.

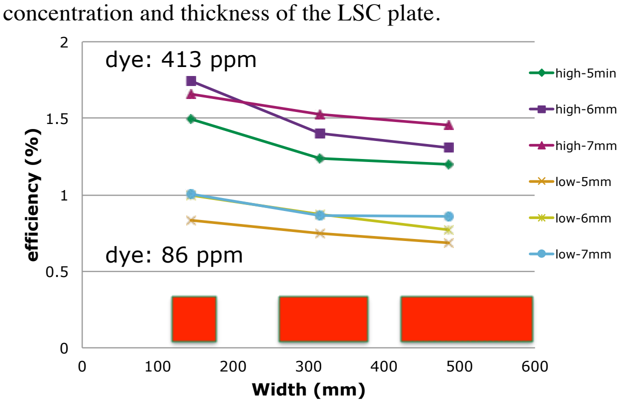

Fig. 4. Simulated efficiency as a function of size and thickness of the LSC plate for two dye concentrations.

TABLE I

FIRST PART OF THE LOOK-UP TABLE

Color	**Concentration** (ppm)	**Size** (cm^2)	P_{max} (mW)
Red	100	15x15	122
		15x30	248
		15x45	335
	200	15x15	259
		15x30	496
		15x45	704
	…		
Orange	…		
Green	…		
Yellow	…		
Blue	…		

IV. OUTLOOK

The toolbox combined with proper interconnection schemes would allow designing custom-made stained leaded-glass window look-a-like designs, e.g., like the one shown in Fig. 5, which presently is being used as a decorative element in a restaurant in the Netherlands. Such elements were used in the past (early twentieth century) in mansion houses as windows, but are increasingly being found in many buildings as decorative elements for use at the inside of double-glazed windows to prevent passers-by from looking directly into living rooms thus providing privacy to inhabitants. In addition, designs are commissioned for office buildings with glass entrances.

The Electric Mondrian has received quite some attention in the national newspapers and requests have been received for purchase. However, the cost of the prototype is too high for market success, mainly due to the cost of the solar cells. Presently, stained leaded-glass of a design such as in Fig. 5 would cost 300-500 €/m^2. The fact that an Electric Mondrian has a stained leaded-glass look with an additional benefit of charging mobile phones makes it attractive and a little higher cost compared to stained leaded-glass may very well be marketable. As such, the Electric Mondrian rather is a product integrated PV (PIPV) application [15] than a BIPV one.

Fig. 5. Photograph of stained leaded glass decorative element

V. CONCLUSION

A set-up of a toolbox for designing Electric Mondrian stained leaded-glass look-a-likes has been presented. Simulations will be further extended, and connection design of LSC components must be optimized based on the design (such as in Fig. 5). Presently, the look-up table is being completed, and new designs will be made, with focus on manufacturability and cost.

TABLE II

CALCULATION OF COMPONENT EFFICIENCY AND TOTAL POWER FOR THE DESIGN IN FIGURE 2.

Color	**Number**	**Size** (cm^2)	**Efficiency** (%)	P_{max} (mW)	**Total** P_{max} (mW)
Red	1	15x15	2	900	900
	2	15x30	1.6	1440	2880
Orange	1	15x15	1.7	765	765
	1	15x30	1.3	1170	1170
	1	15x45	1	1350	1350
Green	3	15x30	1.1	990	2970
	1	30x45	0.1	270	270
Yellow	1	15x15	1.4	630	630
	2	15x30	0.8	720	1440
Blue	2	15x15	0.3	135	270
	1	15x30	0.2	180	180
	1	30x30	0.1	180	180
Total	**17**				**13005**

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