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List of Acronyms

AM1.5 = Solar spectral irradiance on earth at an air mass of 1.5 (the standard solar irradiance conditions for terrestrial PV testing)

AVI = Add-vision Inc.

APV Research = Alers Photovoltaics Research

BIPV = Building integrated photovoltaics

DCM = [2-[2-[4-(dimethylamino)phenyl]ethenyl]-6-methyl-4H-pyran-4-ylidene]-propanedinitrile

EVA = ethylene-vinyl acetate

I_{sc} = Short-circuit current.

IV-curve = Current-voltage curve (a standard characterization tool for PV)

LBNL = Lawrence Berkeley National Laboratories

LR or LR305 = Lumogen Red 305 which is similar to perylene red.

LSC = Luminescent Solar Collector or Concentrator

NREL = National Renewable Energy Laboratory

OLED = Organic Light Emitting Diodes

PMMA = Poly methyl methacrylate

PL = Photoluminescence

PV = Photovoltaic

SVTC = SVTC Technologies, L.L.C.

UCSC = University of California, Santa Cruz

UV = Ultraviolet

UVA = Ultraviolet between 315 and 400 nm

UVB = Ultraviolet between 280 and 315 nm

V_{oc} = Open-circuit voltage

WSSC = Wavelength-selective Solar Concentrator

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Executive Summary

For the grand challenge of reducing our energy and carbon footprint, the development of renewable energy and energy efficient technologies offer a potential solution. Energy technologies can reduce our dependence on foreign oil as well as the energy consumed by the petroleum industry, the leading consumer of energy by a U.S. industry sector. Nonetheless, the manufacturing processes utilized to manufacture equipment for alternative energy technologies often involve energy-intensive processes. This undermines some of the advantages to moving to “green” technologies in the first place. Our answer to the Industrial Technology Program’s (ITP) Grand Challenge FOA was to develop a transformational low cost manufacturing process for plastic-based photovoltaics that will lower by over 50% both energy consumption and greenhouse emissions and offer a return-of-investment of over 20%. The project meet the objectives of Industrial Technology Program’s (ITP’s) Advanced Materials - Materials for Energy systems portfolio as it supports development of materials and technologies for emerging energy industries.

The specific goals for the one year project were to:

1. Determine the feasibility of the low-cost manufacturing process by developing and demonstrating a Luminescent Solar Concentrator (LSC), with face-mounted PV cells and fabricated using low-temperature processing on plastic substrates, that increases the power generated from the PV cell on average by a factor greater than 2.2x.
2. Obtain the data necessary to demonstrate a return-of-investment >20%, an energy-pay-back-time of less than 6 months and energy reduction >50% for printed LSCs, compared to photovoltaics manufactured with more conventional vacuum-based processes.

Both of these goals were met. We demonstrated an LSC fabricated on a plastic acrylic substrate (i.e. no glass) that increases the power output of the PV cell by 2.2x with a 2% power efficiency as well as an LSC with a 7% power efficiency that increased the power output from the PV cells by 35% (Figure 1). As shown in Figure 2, a large area 20” x 60” BIPV window was fabricated using contract manufacturing with a 4% power efficiency with improved the power output of the PV cell by over 50%. In addition, accelerated lifetimes of 20-years were demonstrated at APV’s research facilities, and testing at NREL’s PV reliability center has confirmed these results for greater than 10-years. Finally, we demonstrated efficient Forster Energy Transfer between two blended dyes which allows for color tuning from yellow to red and, when combined with an addition red-absorbing film, enables power generating windows with tints of blue and green.

A greenhouse was assembled that contained 20 of the BIPV modules (Figure 2) to understand the impact of the wavelength selectivity of the LSC windows on plant growth required for our initial commercial product, namely PV-integrated greenhouses. We are currently seeking \$2 million in funding to purchase select pieces of manufacturing equipment (i.e. cell dicer, pick and place tool, automatic soldering tool), and to place large purchase orders for the luminescent material, PV cells, and substrate materials. These purchases will allow us to lower our manufacturing costs (in collaboration with contract manufacturers) and offer a commercially viable LSC-window integrated product by late 2014.

Figure 1: Top: The 2.2x LSC module uses six 1cm x 12.5cm Si PV cells and the 7% module uses 2 cm x 12.5 cm SI PV cells. Bottom: An IV-curve for the 7% LSC demo module shown in bottom right under AM1.5 flash tester. The 7% demo generates an I_{sc} of 1.238 A, a V_{oc} of 8.18 V, and a fill factor of 75%, or 7.6 W.

Figure 2: Close up of a large area LSC module with a hatch design versus the linear design installed in the UCSC Arboretum greenhouse roof.

Introduction

The goal of this Concept Definition Stage ITP project was to determine and demonstrate the feasibility of a next generation print-based manufacturing technology capable of fabricating low cost building-integrated photovoltaic (BIPV) windows, while reducing energy and carbon intensity by >50% and enabling a return-on-investment of >20%.

Existing BIPV window technologies have been limited by their relatively high cost ($>\$200/\text{m}^2$) combined with relatively low power efficiencies ($<5\%$), which results in a cost of greater than $\$4/\text{W}$, well above standard PV technologies. Moreover, these technologies are energy intensive as they utilize two panels of glass and require materials that have to be deposited using a high temperature vacuum process. By replacing the glass and a large fraction of the silicon PV cell with plastics, both the energy and monetary costs can be significantly reduced.

A technology known as luminescent solar concentrators (LSC), which is largely based on luminescent plastic materials, has the potential to significantly reduce both the monetary and energy cost of renewable energy. In the 1980s, significant research on this technology was undertaken, including DOE-funded projects [1]; however, the technology was largely abandoned due to low power efficiencies and poor product lifetimes. In the mid-2000s, a brief reemergence in the LSC field was motivated by results from MIT and others [2]; however, the results were still not promising enough to result in a commercially viable product, despite commercial activities to do so.

To overcome these previous limitations, we proposed and demonstrated that the power efficiency can be significantly improved by modifying the geometry of the LSCs to a face-mounted, rather than edge-mounted design, as shown in Figure 3 so that the concentration factor is decreased and the PV cell itself is directly illuminated. In addition, through careful selection of existing dyes and additive materials, product lifetimes of 20 years are obtainable, even with no encapsulation. Furthermore, by using the wavelength selectivity of LSCs, the PV cell can coexist with agriculture, allowing simultaneous use of land for power and food production.

This technology can be directly integrated into existing U.S. window, plastic and PV manufacturing industries, circumventing the need to build new manufacturing lines customized for PV. The use of contract or existing manufacturing lines for fabrication of the LSCs will allow a rapid transition from the R&D stage to commercialization. Large area 20" x 60" modules have already been manufactured through Bay area PV contract manufacturing sources and integrated into a greenhouse roof to demonstrate our BIPV window technology. We are currently seeking either federal or industrial funding on the order of \$2 million to transition the technology to a full commercial BIPV window product.

Figure 3: Top: Luminescent Solar Concentrator (LSC) with PV cell mounted on edge and concentration factors $\sim 100\times$. Bottom: Our wavelength selective solar concentrator using a luminescent sheet to enhance power efficiency. Sunlight is absorbed both by direct illumination of PV Cell and by luminescent sheet with concentration factors of $6\times$ to $9\times$.

Background

A Luminescent Solar Concentrator (LSC) uses a low cost, highly luminescent material to absorb the sun's photons which then emits these photons at longer wavelengths and then waveguides the emitted photons to a PV cell where the longer wavelength photons are converted to electricity using strips of active PV (see Figure 3). Significant previous research has been done on luminescent solar concentrators (LSC), and power efficiencies as high as 7.1% have been obtained for small area demos using small molecule organic dyes and GaAs PV cells (ref). Nonetheless, such demos are too small and too costly for commercial viability. Recent results have also suggested that the use of quantum dots, semiconducting polymers, and OLED materials would result in improved LSC efficiencies [1-2]; however, these materials are over an order of magnitude more expensive than small molecule dyes and have not resulted in higher efficiencies despite a significant investment in research effort.

All of these previous LSC studies are based on a design that involves mounting the PV cell to the edge of the luminescent sheet. While this design clearly results in higher concentration factors, it eliminates any benefit from direct solar illumination of the PV cell itself. As costs for PV cells have rapidly decreased over the last several years, lower concentration design become favored. Such designs favor the mounting of the PV cell to the face of the luminescent sheet, rather than the edge, to allow for power to be generated from direct solar illumination of the PV cell itself. This report represents, to our knowledge, the first complete study of face-mounted LSCs.

For face-mounted LSCs, the power efficiency (η_{LSC}) is given by:

$$\eta_{LSC} = (A_{PV}/A_{LSC})\eta_{PE} + (A_{LS}/A_{LSC})\eta_{PL}*\eta_{abs}*\eta_{WG}*\eta_{dc}*\eta_{MPE} \quad (\text{Equation 1})$$

where A_{PV} is the area of the PV cell, A_{LS} is the area of the luminescent sheet, A_{LSC} is the area of the LSC ($A_{LSC}=A_{PV}+A_{LS}$), η_{PE} is the power efficiency of the PV cell, η_{PL} is the photoluminescence efficiency of the luminescent sheet, η_{abs} is the fraction of the solar spectrum absorbed by luminescent sheet, η_{WG} is the fraction of light that is successfully waveguided to the PV cell (this term includes self-absorption), η_{dc} is the efficiency of the energy conversion

process from higher energy to lower energy photons, and η_{MPE} is the power efficiency of the PV at the wavelength of the emitted light (i.e. the “monochromatic” power efficiency). The first term represents the increase in power efficiency realized of the face-mounted versus edge mounted design arising from direct illumination of the PV cell. This is negligible at high concentration factors (i.e. when $A_{\text{PV}}/A_{\text{LSC}} < 1\%$ or concentration $> 100\times$); however, it becomes significant at lower concentration (i.e. when $A_{\text{PV}}/A_{\text{LSC}} > 10\%$ or at concentrations $< 10\times$). In the past, the 2nd term (i.e. the power efficiency of edge-mounted LSCs) has been too small for any LSC utilizing high concentration ($> 10\times$) or reasonable areas (i.e. more than 10 cm^2). No group has demonstrated a power efficiency greater than 1% for the concentration factors of $100\times$ that LSCs were originally designed for. Moreover, for these lower concentration designs, direct illumination of the PV cell used in the LSC design can actually result in more power output than using the LSC design, resulting in gains of less than 1. This effect defeats the purpose of using the LSC design in the first place and ultimately resulted in the technology largely being abandoned.

In contrast, for the face-mounted configuration, the gains have to be greater than 1 by design. The luminescent sheet therefore adds an additional gain in power above what the PV cell generates on its own. This enhancement factor, or gain, is given by the ratio of the total power generated by the LSC divided by the power generated by the PV cell alone, or $\eta_{\text{LSC}}/\eta_{\text{PV}}$. Because the luminescent sheet only adds about $\$10/\text{m}^2$ to the cost of the module, and the PV component costs greater than $\$200/\text{m}^2$ (for 20% cell this equates to $\$1/\text{W}$), significant cost savings can be realized even for small enhancement factors. For example, at 15% coverage by PV cell, the cost per m^2 for the PV would be $\$30/\text{m}^2$. If the LSC increases the power output by 50%, it is less expensive to use the luminescent sheet at $\$10/\text{m}^2$ than to add more PV cells. Moreover, the luminescent sheet is semitransparent which offers the additional advantage that it can be incorporated into windows, skylights, solariums, atriums and greenhouse roofs without blocking as much additional light as the PV cell itself blocks. Finally, it replaces an energy intensive material (i.e. Si PV cells) with a low energy intensity material (i.e. a thin plastic sheet) and thereby significantly reduces the overall energy intensity of the manufacturing process.

An optimum point occurs that depends on the percentage coverage of the PV cell, the price of the PV cell, the price of the luminescent sheet, and the additional enhancement that the luminescent sheet provides to the power generated by the PV cell. By decreasing the PV cell coverage, the additional enhancement provided by the luminescent sheet increases; however, the power efficiency decreases. It is possible to obtain very high enhancements ($> 400\%$) but this would result in power efficiencies well below 1%. It is also possible to obtain power efficiencies as high as 20% (if the 20% Si PV cell is at 100% coverage, for example); however, this would clearly result in no gain. An original milestone of our research was to demonstrate a power efficiency of xx%, but we quickly realized this was not a realistic goal. Ultimately, our goal was to minimize cost per watt of power produced while also minimizing energy consumed, but these quantities were not independently tunable. Our original results from over a year ago suggested that the optimal point would occur for an enhancement factor of 2.2x, assuming a cost for the 20% PV cell of $\$400/\text{m}^2$ or $\$2/\text{W}$ (the cost quoted by Sun Power), which we set our new milestone 1. However, by the time of the final report, the cost of Sun Power cells, as well as mot competing Si PV cells, has dropped by a factor of 2, which moves the optimal enhancement factor closer to 1.5x to 1.7x. It is this enhancement factor that we decided to scale up to large area prototypes to meet our ROI and energy targets for milestone 2.

The team we brought together to accomplish our goals includes Sue Carter, a Professor in the Physics department at UCSC, Glenn Alers, President of APV Research, and David Powell, a program manager at Abengoa Solar. Carter has over 15 years experience in PV technologies and luminescent materials and did some of the pioneering research on LSCs. Alers has over a decade of research experience in understanding reliability in semiconductor devices and his company (Alers Photovoltaics or APV Research) has focused on understanding the reliability of PV cells for the last 4 years. Abengoa Solar is one of the largest producers of concentrator-based solar farms in the world and brought significant expertise in terms of understanding manufacturing costs and negotiating prices with key suppliers, as well as providing the required cost share.

Results and Discussions

When we originally set out to do this research, we were focused on working with Add-vision to develop a printing method for the luminescent sheet. Add-vision's bankruptcy prompted us to pursue alternative manufacturing methods. We ended up working with two companies, namely Evonik and Spartech, who developed a process for injection molded luminescent plastic sheets, based solely on the LR305 chromophore, that were both high efficiency and long lifetimes. While the overall cost was somewhat higher (\$10/m² compared to \$3/m²) than what can be achieved with printing, the substantially longer lifetimes result in a more viable commercial product. While our intention is to still pursue printing in the future to further reduce costs, it will not be the focus of our initial commercial product. We note that for all experiments involving different concentrations of LR305, dyes other than LR305, or a blend of LR305 with another dye, we still used printing methods (doctor blading) for film deposition due to the smaller scale of the experiments for which injection molding is too costly.

Our results section is focused on 5 areas, namely the optimization of the LSC on acrylic, optimization of blended dye LSCs for color tuning, development of the manufacturing process, reliability studies, and the cost and energy analysis.

Optimization of Luminescent Solar Concentrator (LSC) on Acrylic

We have prepared two publications detailing our work on optimization of the LSC:

1. "Optimization of concentration factor and power efficiency using front-facing PV cell LSC Design," by C. Corrado, S.W. Leow, M. Osborn, E. Chan, B. Balaban, and S. A Carter, for publication in Solar Energy Materials & Solar Cells.
2. "Nonradiative Energy Transfer In Blended-Dyes for Luminescence Solar Concentrators," by B. Balaban, S. Doshay, M. Osborn, Y. Rodriguez and S. A. Carter for publication in Optics Materials Express.

The results presented here are a summary of these two papers. We first present our experimental methods and then our results.

Experimental Methods: Construction of LSC Window

Photovoltaic cells (Sun Power, unless otherwise noted), 1 cm x 12.5 cm and 2 cm x 12.5 cm in dimension, were optically attached to clear acrylic panels (Sylgard 184 silicone elastomer, unless otherwise noted). Flexible acrylic sheets, 500 μ m thick embedded with Lumogen Red 305 (LR305) dye manufactured by Evonik, were fused to clear spaces on the acrylic panels (Weld-On 4SC solvent) surrounding the PV cells. The thicker clear acrylic serves as a waveguide for concentrating photons and the thin LR305 embedded sheets acts as the absorbing layer. PV cells and luminescent material were arranged in various configurations to study how cell placement affects power output and enhancement factor.

Experimental Methods: Optical Measurements

The main optical data needed to characterize the performance of the LSC films was the absorption spectra and the photoluminescence spectra and quantum yields. Steady-state absorption spectra were taken using an N&K UV-vis spectrometer. Steady-state photoluminescence (PL) spectra were measured with an LS-45 Perkin Elmer spectrometer. PL Quantum yields of solid films were measured using an integrating sphere (Horiba Jobin Yvon) attached to a Fluorolog-3 spectrometer (Horiba). Films were mounted in a solid sample holder at 22.5 degrees incidence to the incoming 573-nm excitation. Excitation and luminescence

measurements were collected at a 90° angle from incidence through a 1 nm slit. Dark spectra were subtracted from sample spectra, and then intensity values at each wavelength were corrected based on prior measurements of a calibrated light source. The integrated areas of the excitation peaks (568-580 nm) relative to those of the corresponding blank samples were used to determine absorbed photon counts. The emission photon counts, i.e. the integrated areas of the emission peaks (578-780 nm) were divided by the absorbed photon counts to arrive at the quantum yield.

Experimental Methods: LSC Power Efficiency Measurements

Current-voltage (IV) curves were taken on the Si PV cells with a Keithley 2400 source-measure meter, a Fluke, or a flash testing system, in order to determine power efficiency. To obtain a correlation between the area of luminescent material surrounding the PV cell and the enhancement factor, masking experiments were performed. By placing a PV cell in the middle of an acrylic panel (45.7 cm × 45.7 cm) and covering the LSC panel with a mask template, we sequentially exposed increasing amounts of surrounding luminescent area, recording the current and voltage values. The resulting power was compared against a reference and radiometer readings to obtain the enhancement factor and efficiency respectively. The reference reading used was obtained by masking off all luminescent material leaving only the PV cell under clear acrylic exposed. Both 1 cm wide and 2 cm wide cells were tested using the same set up.

Results: Optical Properties of the Luminescent Absorber

Lumogen Red 305 (LR305) was chosen as the LSC luminescent material due to its high quantum yield and stability in air. Its absorption and PL emission are shown in Figure 4. It absorbs strongly below 400 nm and in the 500-600 nm range. Between 400-500 nm, absorption drops to 50% with a peak at 573 nm. The PL emission spectrum peaks at 611 nm and has a shoulder around 650 nm. Photon reabsorption in the LSC shifts the emission peak toward the 650 nm shoulder gradually reducing the overlap between absorption and emission spectra, as shown in Fig. 4B. The LR305 was embedded into a flexible acrylic sheet of 500 μm thickness in which it has a quantum yield of 85% (+/- 3%).

Results: Optimization of LSC window parameters

Several waveguide parameters can be adjusted to increase the amount of light collected by an attached PV cell, two of which are the waveguide thickness and its edge surface properties. Thicker waveguides reduce reabsorption losses but increase the likelihood of photons passing over the PV cell uncollected. The effect is reversed for thinner waveguides. In addition, a waveguide that is too thin will cause the majority of trapped photons to be directed to the edges of the PV cell, leaving the middle unenhanced by the LSC. Hence waveguide thickness and PV cell size must be properly matched. Acrylic sheet waveguides of 4 different thicknesses, 1/16", 1/8", 3/16", and 1/4", were used to construct LSC panels and the power output of a 1 cm wide PV cell on each window was tested. For this cell dimension, the 3/16" (0.476 cm) thick acrylic was found to provide the highest power output, and all designs thereafter were based on this thickness.

Fig. 4. Steady state absorption and photoluminescence emission spectra for LR305 (top). PL emission spectra of LR305 embedded in an acrylic sheet for increasing distances between excitation and detection (bottom). Inset: Molecular structure of LR305.

Next the effect of the waveguide edge on performance was investigated. With rough untreated edges, the probability of trapped light refracting out of the waveguide at the edge is high. Treating the edge to increase reflectivity so that trapped light will not escape at the edges of the panel was used to increase the amount of light collected by the PV cell. Ideally, a surface that is 100% reflective would be engineered to completely remove this mode of loss.

To test the impact of the edge treatment, two LSC windows were constructed. One had the edges fire-polished to create a smooth vertical wall and the other was left untreated. The surface was further modified in each experiment by coating the edges black, reflective or left unmodified. The power output was measured for each case and is shown in Table 1. With black coating, both panels had the same power, as expected since all waveguided light reaching the edge would be absorbed. This was used as a check to ensure that both panels had the same starting conditions. The fire-polished panel showed an increase in power of 4% over the rough edge panel, both with and without reflective coating. Fire-polish treatment was again applied to a more complex Tic-Tac-Toe window (described below) but showed no significant improvement. This treatment being both time consuming and costly was discontinued. The addition of a reflective coating increased power output by 11% compared to uncoated edges in both the rough and fire-polished panels. On the masking panel (described below), the addition of a reflective

coating resulted in a 12% increase in power. All subsequent demos had the edge treated with reflective coating.

	Power (W)	
	Rough	Fire polished
Reflective coating	0.470	0.489
No coating	0.423	0.441
Black coating	0.378	0.378

Table 1. Power output for various acrylic edge treatments.

The next parameter investigated was the LSC enhancement as a function of the LSC area exposed around the PV cell. A larger LSC area collects more light and concentrates it onto the PV cell thus increasing its enhancement factor. At the same time, a larger proportion of that waveguided light travels a longer distance before reaching the PV cell, incurring losses along the way and dropping the enhancement gained per area. As seen in Figure 5, the gain per area LSC decreases significantly up to 6 cm of LSC exposed around the cell and flattens out as photon re-absorption decreases resulting from the increased redshift of emission that occurs with distance in the waveguide (Figure 4). It was also observed that LSC material placed along the long edge of the PV cell contributes a greater enhancement per area than LSC along the narrow edge of the PV cell. This can be seen in Fig. 6, which shows the LSC enhancement per area with two different shaped masks. The first mask is rectangular, the same shape as the cell, as to expose area equally around the cell. The second mask is square, the same shape as the panel so that the dimension of the mask would stay constant until the whole of the panel was exposed. As seen in Figure 4, a dye molecule emitting photons isotropically located at the long-edge of the PV cell will emit photons to be absorbed by the cell over a larger angle than one located the same distance from the short edge of the cell. Therefore, LSC adjacent to the long-edge emits light that has a higher probability of being wave guided to the PV cell than LSC along the short-edge, thus provides a greater contribution to the LSC enhancement factor.

Fig. 5. Enhancement factor per area for increasing distances of exposed LSC material to PV cell.

Fig. 6. LSC enhancement as a function of LSC area surrounding a PV cell in masking experiments and “cut-to-size” windows. Inset: Schematic illustrating that LSC exposed on the long-edge of the PV cell contributes greater LSC enhancement than the LSC on the short-edge of the cell.

From Fig. 6, a discernible difference in the enhancement factors is observed from masking and from LSC panels cut to the same dimension as the mask (labeled as “cut to size”). The masking experiments consistently underestimate the level of actual enhancement. This is due to additional losses experienced by waveguided light traveling underneath the mask to the panel edges before being reflected back, instead of doing so at the mask edge as a “cut to size” panel would. As mentioned throughout this section, longer distances spent in the panel increase the probability of photon re-absorption or scattering. This discrepancy between masked and “cut-to-size” is factored into our measured masking data accordingly for our design projections in Fig. 7, labeled as “corrected”.

Fig. 7. Projected LSC enhancement and window efficiency as a function of % LSC area. Projections calculated for 18% efficient PV cells.

Plotting the LSC enhancement against the percentage area of LSC coverage, we were able to make projections of the area ratio needed to produce panels of a desired efficiency or enhancement factor. Projections were calculated assuming the PV cells had 18% efficiency. For high LSC enhancement, we estimated from Fig. 7 that a 98-98.5% LSC coverage would yield an enhancement factor of 2. Similarly for high power efficiency, approximately 72-77% LSC coverage would produce a window power conversion efficiency of 6%. Based on these projections, demos were constructed to attain each individual goal. There exists a tradeoff between efficiency and enhancement factor. To achieve high enhancement factors requires a much higher ratio of LSC, which lowers the power conversion efficiency of the LSC window. The converse is also true for the high efficiency panel. To attain both targets simultaneously necessitates improving the enhancement beyond ratio adjustments. This led us to explore further the effect of cell placement on the enhancement factor and power output.

In the masking experiments, the 2 cm PV cell had much lower enhancement factors per LSC area exposed compared to the 1 cm PV cell on the same setup, as seen in Fig. 8. One possible reason is that the ratio of LSC area to PV cell area is halved for the 2 cm cell. Normalizing the plot in Fig. 6 to percentage LSC area, Fig. 7, yielded a much better correlation between the two curves, but the question still arises, which width of cell, 1 cm or 2 cm, would lead to the most optimized design? Two 1 cm cells would compose a design with a greater amount of LSC directly adjacent to the cells, allowing photons to be collected after traveling a shorter distance in the LSC. One 2 cm cell though yields a more compact design allowing more

energy conversion. To satisfy this query, three new panels were constructed for 1 cm and 2 cm cells keeping the PV to LSC ratio the same as shown in Fig. 8.

Panel	Cell area (cm ²)	Power (W)*	Norm. power (W)**	Enh. factor
One <u>1cm</u> cell	12	0.360	0.674	1.86
Two <u>1cm</u> cells	24	0.777	0.728	2.01
One <u>2cm</u> cell	22.5	0.699	0.699	1.79

* 1cm fill factor is 0.679, 2cm fill factor is 0.723

** Normalized by cell area

Figure 8 and Table 2: Power output and LSC enhancement for cell width demos. **A:** panel with one 1 cm wide PV cell; **B:** panel with two 1 cm wide PV cells; **C:** panel with one 2 cm wide PV cell. Table 2 provides a summary of 1 cm versus 2 cm cell results.

The output power shown in Table 2 was normalized between the cells since the width of the 1 cm cell (0.96 cm) was not in fact half that of the 2cm cell (1.8 cm), and both dimension of cells had different fill factors. After normalizing, the power output and enhancement factor of the single 1 cm and 2 cm panels (Figure 8) were found to be similar, indicating little difference in performance. Of greater interest is the better enhancement factor and normalized power seen in the two 1 cm panel compared to the 2 cm panel, as a result of a change in cell placement. Redistributing the PV area permits wave-guided photons a shorter traveling distance before being collected by the cell. However, cutting the PV cells to size introduces defects into the crystal structure, which act as current shunting pathways that lower the fill factor and output current of the cell. Hence, cutting the cells into smaller pieces is only justified if this loss is more than compensated by an increase in the enhancement factor through optimized cell layout and panel dimensions. The comparison of 1 cm and 2 cm cells was further explored by constructing more complex windows of identical design using both types of cells, as explained in the following section.

Results: LSC acrylic window demos

In analyzing the efficiency and LSC enhancement factor in the different designs, measurements were taken under three conditions, which yielded varied results. Fig. 9B depicts the three ways measurements were taken: outside with the window lying flat; outside with the window tilted normal to the sunrays; and with a flash tester (Sinton Instruments). The case study in Figure 9 exemplifies the differences in measurements for a 6% efficiency window.

Light incident on the LSC at an angle greater than 90° increases the path length of light in the LSC thereby increasing the absorption by the dye and hence the enhancement factor. Additionally, the PV cell's efficiency is dependent on the angle of incidence. Best efficiencies are obtained with light at normal incidence and deteriorate with increasing angles. Taken together, angled light on the LSC window (resulting from taking measurements with the panel laying flat) favors higher enhancement due to a slightly greater contribution from the LSC and significantly poorer power contribution from the PV cell.

Flash testing involves illuminating the panel with a short burst of simulated sunlight. This prevents the PV cells from heating up and thus yields a higher measured V_{oc} compared to outdoor measurements, and hence a higher cell efficiency. The enhancement factor of the panel when flash tested was approximately the same as the tilted measurements but with higher efficiencies recorded.

Fig. 9. Case study: testing methods on 6% Efficiency window. **A:** 6% Efficiency window; **B:** Different testing methods: (1) flash tester; (2) outside with demo lying flat; (3) outside with demo tilted towards the sun; **C:** Summary of variations in measurements for different testing methods.

Enhancement factor for the panels measured outdoors were somewhat variable and depended on the month and time of the day measurements were taken. This was largely due to the changes in the angle of the sun. To the best of our abilities, we took outdoor measurements within the same 2-3 hour time slot each day but could not correct for monthly variations in the sun's angle or variation of the sun's intensity. As such, an objective comparison between panels can only be carried with the flash test data. Since angled light produces a greater contribution from the luminescent dye, panels with high LSC coverage exhibited significantly smaller enhancement factors with the flash tester compared to outdoors.

A window was built targeted to have an enhancement factor of 2 with 95.4% LSC coverage on a 45.7 cm x 45.7 cm panel. Six PV cells (Evergreen Solar) were arranged in three rows of two, equidistant from each other and the panel edges, as shown in Figure 10. Less LSC coverage was used than projected due to expected improvements in performance from cell placement and additional reflected light from the closer proximity of the window edges to the cells. The window was tested outdoors lying flat and attained an enhancement factor of 2.2. Adding a white reflective background returned a portion of the transmitted and escaped light to the window and raised enhancement factor further to 2.4. Flash testing with light entering normal to the panel surface gave a lower enhancement factor of 1.8. Power efficiency cannot be accurately compared to other window designs because a different PV cell type was used.

A 6% efficiency demo was built with 69% LSC coverage on a 31.8 cm x 31.8 cm panel. Twelve PV cells were arranged in six rows of two, equidistant from each other and the edges, as shown in Figure 10. Data taken with the panel lying flat attained a power conversion efficiency of 6.2%, with an enhancement factor approaching 1.4. A maximum panel efficiency of 6.8% was obtained with flash testing.

In the above two designs, we see many large zones that light can potentially travel and reflect multiple times without ever hitting a PV cell as illustrated in Figure 10. While photons may eventually scatter in a favorable direction, the likelihood of the photon being lost increases with distance travelled after the initial absorption event. A better design reduces these escape zones and increases the amount of light collected as show in Figure 10. To find a balance between LSC enhancement and panel efficiency, two demos with a "Tic-Tac-Toe" pattern were built with 90.4% LSC coverage on 45.7 cm x 45.7 cm panels. Twelve PV cells (Evergreen Solar) were arranged in a Tic-Tac-Toe formation as shown in Figure 10. One Tic-Tac-Toe window was created on an acrylic panel with fire-polished edges and one Tic-Tac-Toe window was created on an acrylic panel with rough (untreated) edges. Reflective coating was applied to the edges of both demos. This design was projected to have an enhancement factor of 1.6 based on the masking experiments but attained a factor of 1.8 outdoors. The design was chosen to better capture light radiating isotropically in the LSC material. The panel power efficiency cannot be compared to the other demos due to a difference in PV cell type used. No difference was observed between the panel with fire-polished edges versus the one with rough edges. Fire-polishing acrylic edges appear to have no effect on power output and LSC enhancement in this design.

To further improve light trapping, a Zig-Zag pattern was constructed next. Two Zig-Zag demos with different cell widths where built on 50.8 cm x 50.8 cm acrylic panels, as shown in Figure 10, and were designed to have the same LSC coverage. One panel was built with 15 – 2 cm PV cells and the other was built with 30 – 1 cm PV cells. Inaccuracy in dicing resulted in actual cell widths of 1.8 cm and 0.96 cm respectively, giving both panels slightly different cell coverage than intended.

The 1 cm and 2 cm Zig-Zag demos had a LSC coverage of 84.9% and 86.1% respectively. The demos attained LSC enhancement factors of 1.4 and 1.5 when tested outdoors, against a projected enhancement of 1.5. Construction of the Zig-Zag design was much more complicated than any of the previous panels resulting in many defects, especially in the seams where LSC pieces were joined. The additional scattering could have adversely affected the panel performance. This draw back might be overcome by laminating the LSC directly over the cells in future iterations. Panel conversion efficiency was calculated using power output measurements taken with a flash tester. The 1 cm Zig-Zag demo reached a panel conversion efficiency of 3.7% and the 2 cm Zig-Zag demo reached 3.8% efficiency. Table 3 provides a summary of the dimensions and performance of all windows/panels constructed.

Fig. 10. Design of LSC windows. **A:** 2x enhancement; **B:** 6% panel efficiency; **C:** Tic-Tac-Toe; **D:** 1 cm Zig-Zag; **E:** 2 cm Zig-Zag. Sample layouts showing potential escape zones (F) and superior light trapping (G)

Demo	Panel area (cm ²)	Cell coverage	Panel efficiency	LSC enh.
High Power Eff.	1011	31%	6.8%	1.2
Zig Zag 1cm	2581	15%	3.7%	1.6
Zig Zag 2cm	2581	14%	3.8%	1.6
Tic Tac Toe*	2088	10%	---	1.6
High LSC Enh.*	2088	5%	---	1.8

*Efficiencies are not comparable to other demos because of difference in cell type

Table 3: LSC window performance summary. LSC enhancement and panel efficiency measured with flash tester. Enhancements are higher under standard operating conditions.

Optimization of LSCs based on a Blended Dye Systems

In order to further improve performance and to tune the color for different window applications, we also studied blended dye systems. Single films, stacked films, and blended films comprised of two air-stable, wide Stokes-Shift materials, namely LR305 and DCM were

compared. This combination of the two dyes results in significant increases in photoluminescence due to Forster (nonradiative) energy transfer, accompanied by up to a 50% increase in power conversion efficiency in a single layer film when incorporated into an LSC device. Moreover, the color can be tuned across the blue/green absorption spectrum by controlling the blend ratio, which enables most colors of the visible spectrum to be achieved when combined with a red absorber and/or bragg reflector composed of layered dielectric films.

Experimental Methods

DCM ([2-[2-[4-(dimethylamino)phenyl]ethenyl]-6-methyl-4Hpyran-4-ylidene]-propanedinitrile) (Exciton) and Lumogen Red 305 (BASF) were used as obtained. Luminescent inks were prepared from a mixture of the as-received powdered dyes, polymethylmethacrylate, and toluene. To achieve global film uniformity across a range of dye to host polymer concentrations, a standard 13.3% PMMA:Toluene weight ratio was established for all inks. The film deposition was performed using an Industry Tech Auto Draw III automatic drawdown machine. The machine draws a rod across a slide at constant pressure and velocity to produce a film. Film thickness was set using a single layer of Scotch 810 magic tape. The films were deposited on 3"x1" quartz glass microscope slides. The films themselves were determined to be approximately 20 microns in thickness.

A Stellar Net Thin Film Measurement System, including an SL-1 Filter, a CXR-SR-25 BW-16 Spectrometer, and a Wave NIR-25 InGaAs BW Spectrometer, was used to estimate film thickness and measure absorption spectra. A Perkin Elmer Instruments LS45 Luminescence Spectrometer was used to measure the surface emission of the films. Photovoltaic performance was measured by optically coupling 1 cm Sunpower cells to 5"x5" quartz glass with LSC film doctor bladed on either side according to the standard deposition method previously described. Power output of the cells was calculated by from V_{oc} and J_{sc} measurements using a hand-held multimeter.

Results and discussion

BASF Lumogen Red 305 and DCM dyes fluoresce in the yellow-red visible range, with emission peaks around 610nm and 550 nm, respectively, when embedded in a PMMA polymer matrix. Both have been considered for use in LSC applications because of their broad Stokes Shifts and high quantum yields. In addition to its promising spectroscopic properties, DCM was investigated as a companion dye to Lumogen Red 305 because its absorption peak compliments a dip in the absorption spectrum of LR305 (Figure 11).

Figure 11: Absorption and Photoluminescence for DCM and LR305. Structure for DCM is shown in inset.

We compared the surface emission and absorption spectra of single dye LSC films, blended LSC films, and stacked single dye films (Figure 12). The data shown in Figure 12 are taken from films of like composition: 20 micron thick doctor bladed films on silicate glass, with PMMA as a host polymer. The single dye DCM and LR305 films have dye:polymer ratios of 0.5% and 0.75% by weight respectively. The blended dye film has the same amounts of dye as in the single films, that is: 0.5% DCM:PMMA and 0.75% LR305:PMMA by weight, for a total dye concentration of 1.25% dye:polymer. Stacked film emission data were taken by placing the two single dye films on top of one another. While the stacked films clearly show the superposition of both the DCM and LR305 emission and absorption spectra, the blended dye films superpose just the dyes' absorption spectra; only surface emission from the LR305 dye is seen. We note that the emission of DCM shifts from orange to red depending on its cis/trans state established by the polarity of its surrounding matrix. The orange emission observed here is characteristic of the trans state which has been shown to have a quantum yield of 80% in DMSO [3]. LR305 has been shown to be capable of near unity quantum yield in PMMA [4].

Figure 12: Photoluminescence for DCM and LR305 stacked films versus blended films.

Several mechanisms can result in energy transfer between fluorescent dye molecules. Radiative energy transfer, or emission of a photon by a donor chromophore and its subsequent reabsorption by the acceptor, can occur over macroscopic distances. The large spectral overlap between the absorption spectrum of LR305 and DCM's emission suggests that radiative energy transfer will occur to some extent if the dyes are placed in close proximity. However, when the relative intensities of the DCM and LR305 fluorescence peaks are compared between the blended dye film and the stacked films, the radiative process are shown not to be the dominant energy transfer mechanism. The spectral overlap of the normalized emission spectra in Figure 12 neatly matches the additive superposition of the two single dye spectra, with virtually no change in the ratios of the DCM and LR305 fluorescence peaks. This result demonstrates the emission for the blended samples must be due to a nonradiative process.

Two well known mechanisms responsible for nonradiative energy transfer in fluorescent molecules are Dexter Electron Transfer and Foerster Resonant Energy Transfer. Both operate in

distinct distance regimes. Dexter Electron Transfer (also referred to as exciton diffusion) stems from a physical overlap of donor and acceptor electron wavefunctions and operates over distances of less than 20 angstroms. Forster Resonant Energy Transfer, in contrast, comes from interactions between transition dipoles as fluorophores decay from excited states. Foerster Resonance Energy Transfer (FRET) theory treats the fluorophores as oscillating dipoles with like resonance frequencies; FRET is best understood in systems dealing with a single species of donor and acceptor molecules. As a general rule, nonradiative energy transfer mechanisms are not sensitive to the host environment of the fluorophores in the same manner as radiative transfer mechanisms, though both are highly distance dependent. Unlike exciton diffusion, FRET does not require the physical overlap of electron wavefunctions, and works on distance scales generally up to an order of magnitude larger. Both mechanisms are dependent on the spectral overlap of the donor fluorescence and acceptor absorption spectra (Figure 13), which is observed to be large in the 525-575 nm range.

A useful figure of merit in Foerster theory is the critical distance R_0 , at which the rate of energy transfer from the donor to the acceptor fluorophore is equal to the rate at which the donor will decay from its excited state in the absence of the acceptor. This can also be described as the donor-acceptor pair distance at which energy transfer is 50% efficient, and is given as described by equation 2:

$$R_0^6 = \frac{9000 \ln(10) \kappa^2 \phi_d}{128 \pi^5 N n^4} \int_0^\infty F_d(\lambda) \epsilon_a(\lambda) \lambda^4 d\lambda \quad (\text{Eq. 2})$$

where $F_d(\lambda)$ is the normalized donor fluorescence per unit wavelength, $\epsilon_a(\lambda)$ is the molar extinction coefficient of the acceptor between λ and $\lambda + d\lambda$, n is the refractive index of the host medium, and N is Avogadro's number. κ^2 is the dipole orientation factor, here taken to be .476, which has been shown to be the value of the orientation factor for randomly distributed donor and acceptor molecules in a rigid polymer matrix [5]. Taking a donor quantum yield of 80% for DCM (ϕ_d), and using an overlap integral numerically determined to be $6.15 \times 10^{-14} \text{ cm}^3 \text{ M}^{-1}$ from Figure 11, we obtain a critical FRET distance of 40.1 Å.

This relatively well sized FRET distance is especially useful for allowing DCM to enhance LR305 fluorescence in lightly doped PMMA LSC films. Even at an 8:1 donor:acceptor molecular ratio (1:2 LR305:DCM weight ratio), the fluorescence of the donor is rapidly quenched (Figure 13). The resulting enhancement of the LR305 emission is also notable across a broad range of dye:polymer concentrations. For the purposes of enhancing the fluorescence intensity of the acceptor fluorophore, FRET likely plays a much more useful role, as the critical FRET distance is twice the distance maximum intermolecular distance at which Dexter Electron Transfer (DET) would take place. Since molecular spacing goes like the cube root of dye concentration within the host polymer, FRET should occur at dye concentrations nearly an order of magnitude less than the regime at which DET, and the associated nonradiative collisional quenching processes, would take place.

Figure 13 also shows the peak LR305 fluorescence intensity (~610 nm) versus the total dye:PMMA ratio by weight. The overall fluorescence intensity begins to be quenched at lower total dye concentrations in the blended films than it does in the single-dye LR305 film. In addition, the enhancement factor (that is, the ratio of the peak fluorescence intensity of LR305 with and without DCM added at the same total dye: polymer ratio) is shown to decrease as the dye:polymer ratio increases. This shows that blended dye films will give the largest benefit to diffuse dyes. Foerster theory predicts an r^6 dependence on FRET efficiency; by relating the

energy transfer rate to the donor fluorescence lifetime, it is possible to show that the efficiency of the nonradiative energy transfer (calculated from the ratio of the donor fluorescence intensity in the presence of the acceptor to its intensity in the acceptor's absence) has the following relation [6]:

$$E = \frac{R_0^6}{R_0^6 + r^6} \quad (\text{Eq. 3})$$

This dependence has also been experimentally confirmed [14,15]. From this relation, and from our calculated R_0 in the DCM-LR305 system, we obtain an approximate fit for the relation between the dye:polymer weight ratio and the average donor-acceptor pair distance (Figure 13). Dimensional analysis suggests a power relationship between dye concentration and molecular spacing, a fit roughly seen in the data. Such a fit is useful for investigating the spacing regime in which FRET will most greatly benefit the fluorescence intensity without the associated quenching effects. At the right intermolecular distances, surface fluorescence enhances of more than threefold have been achieved from the addition of DCM to LR305 doped PMMA films.

Figure 13: Top: Changes in the Photoluminescence with the addition of DCM to LR305. Bottom Right: The peak emission with increasing dye percentage. Bottom Right: Fit to the calculated D-A pair distance.

Incorporating the blended dyes into an LSC structure results in power efficiencies that varied between no enhancement to up to 50% depending on the dye concentration. An additional benefit to varying the blend concentrations and adding absorbers is color tunability across the visible spectrum. Figure 14 shows various chromaticity possibilities for the blended dye films, both by themselves and with the addition of a red absorber, and a dielectric Bragg reflector. A large portion of the visible spectrum can be covered, all while maintaining the fluorescence peak of LR305 dye alone.

Figure 14: Example of colors obtainable using a DCM/LR305 blend, LR305, or DCM. The addition of a bragg reflector or red absorber enables green and blue windows to be obtained.

Development of Low Cost Manufacturing process for LSC

We worked with APV Research and D2 Solar to transition our lab-based prototypes into manufacturable modules. While the laboratory demos were made of acrylic, we were not able to fully solve the delamination issue resulting from differential thermal contraction between the Si PV cell and the epoxy used to attach it the acrylic. Attempts to use EVA to laminate the cells to the acrylic results in issues with the deformation of the acrylic substrate. Because of these difficulties, we decided to make our first set of modules using a single glass substrate and the plastic luminescent sheet as the back encapsulation layer. While this increased the energy cost some, it decreased the \$/W and also improved our product reliability. Our future research will focus on using a lower temperature EVA's to see if we can successfully laminate without deformation of the acrylic substrate

The Si PV cells were diced by a 3rd party and than soldered together by APV Research in series. We soldered 48 12.5 cm x 2 cm PV cells per 22" x 66" module, resulting in approximately 15% PV coverage which was our optimal coverage base on the studies above. The assembled string of PV cells were then made into a module using D2 Solar's lamination equipment. This involved putting down a glass sheet, a layer of EVA, laying the PV string onto the EVA, placing another sheet of EVA over the PV cells, and finally laying the luminescent sheet onto the 2nd layer of EVA. The modules were than placed in the D2 Solar large area laminator, heated to 120 C for the 10 minute lamination step, and then slowly cooled to avoid issues with deformation of the plastic luminescent sheet. An example of the modules produced using this method is shown in Figure 2.

To scale up to manufacturing, we will need to purchase our own PV cell dicing tool as this is currently a significant cost per wafer. SVTC has already indicated that they can make us a custom tool that will cost about \$100K per tool and meet the volumes/cost targets we need. A pick and place tool is required to rapidly place the cells onto EVA where they can be soldered together using an automatic soldering tool (we note that the order of this process may be reversed). Having a cooling oven separate from the lamination tool will also greatly speed up the manufacturing speed. We estimate that this extra equipment will cost ~\$1,200,000 to purchase. While we can continue contracting out our manufacturing in the prototype stage, we will need to make this investment in order to decrease our manufacturing costs sufficiently to achieve the cost of \$1/W discussed below.

Reliability studies of LSC

Besides self-absorption, one of the criticisms of LSCs is the poor stability under solar irradiation as luminescent dyes are known to be unstable in the presence of oxygen/water and light; however, over the last 25 years significant research has gone into what causes the degradation of dye chromophores and the *degradation issue has now been largely solved for some materials*.

Figure 15: Accelerated light soaking results for PMMA/perylene with 4 UV stabilizers at 60°C and >85% relative humidity.

For example, BASF's Lumogen series is highly stable when embedded into PMMA with UV stabilizers, with lifetimes exceeding 20 years under solar intensities even with no encapsulation. In Figure 15, sufficient UV stabilizer is shown to result in lifetime equivalent of 20 years under accelerated UV aging conditions and over 3-years (1-year 24/7) under no acceleration. Additional environmental reliability tests were performed on small 8" x 8" test samples of the complete package including luminescent sheet laminated to glass with PV cells. These tests are based on IEC 61215 qualification tests for PV panels (Table 4).

Table 4: IEC 61215 Environmental Qualification Tests

Test	Condition	IEC Requirement	WSSC window (pass-0 fails)
Damp Heat	85°C / 85% RH	1000 hours	>3000 hours
Humidity-Freeze	-40 to 85°C / 85% RH	10 cycles	200 cycles
Thermal Cycle	-40 to 85°C	200 cycles	200 cycles
UV soaking	UVA + UVB / 60°C	15 kW-hr/m ²	2000 kW-hr/m ²

We have since sent our panels to NREL which placed them into their light soaking environmental chambers for 4 months (24/7) at 2 suns and 65 C. This is NREL's equivalent to 10-years of aging. As shown in Figure 16, no significant degradation was observed for the module with the greatest quantity of UV stabilizers. We are currently arranging to get more time on NREL light soaking chambers so that this test can be extended to 20 years.

Figure 16: PL data on the LSC modules that were placed in NREL's environmental chambers for 4 months (24/7) at 2 suns and 65 C. The inset shows the UV absorption for the 3 modules.

Benefit Analysis: Reduced Cost, Energy Savings and Return-on-Investment

Product Cost

An outline of our projected product costs for different markets are provided in Table 5. All numbers are based on known costs from our suppliers and our contract manufacturers. The manufacturing line would consist of a cell dicer, and pick and place tool, an automatic solderer, and a lamination machine with cool down oven. These tools are low cost non-vacuum equipment that is readily available from contract manufacturers. Manufacturing costs in Table 5 are based on building our own manufacturing line which greatly reduces our current expense.

Product Type	PV-integrated into glass windows (50W)	PV-integrated into crop covers (40W)
Si PV cell 20% \$1/W	\$25 (12.5% coverage)	\$20 (10% coverage)
Luminescent Sheet	\$10 (20-year)	\$7 (10-year)
Glass substrates (low-iron)	\$10	NA
Wiring + adhesives	\$3	\$2
Inverter \$0.15/W	\$7	\$6
Added Installation cost	\$2	\$2
Manufacturing + depreciation	\$3	\$2
Labor, overhead (20%)	\$12	\$6
Our Costs (direct sale)	\$72	\$45
Selling Price U.S.	\$95	\$65
Profit Margin U.S.	\$23	\$20

Energy-pay-back-time and GHG emission

Silicon PV cells have an energy-pay-back-time of 2 years while vacuum-based thin film technologies have an energy-pay-back-time of 1 year. Our LSC technology is compared to thin film technologies. Our product eliminates the need of extra glass since we can just use the glass that is already installed in a greenhouse roof. Therefore, the added energy cost is approximately 12.5% of the 2-year pay-back-time for Silicon (at 12.5% PV coverage and 87.5% luminescent material coverage) plus the energy cost need to make the luminescent sheet and do the lamination process. The pay-back time for the silicon PV cells used in our product is 0.125×2 years = 0.25 years or 90 days. Efficient plastic extruders consume 0.24 kWh per kilogram of material produced. The weight of 1 meter square of the 0.5 mm thick Evonik luminescent sheets is approximately $0.05 \text{ cm (thickness)} \times 10000 \text{ cm}^2 \text{ (area)} \times 1.18 \text{ g/cm}^3 \text{ (the density of acrylic)} = 590 \text{ grams or } 0.6 \text{ kg}$. Therefore, we consume ~0.15 kWh per m², an energy that the 50W panel

could produce over $150 \text{ Wh}/50\text{W} = 3$ hours or less than 1 day. EVA laminating tunnels are known to consume less energy than other processes. They typically consume about 10 kW, producing 5 m^2 panels per hour or 2 kWh/panel. It would take a 50W panel approximately $2000/50 = 40$ hours to generate this amount of electricity. At 5 hours/day, this would add 8 days to the pay back time. Taken together, we obtain approximately 100 days for the energy pay-back time. Using similar analysis, we overestimate the energy cost of the cutting tool, automatic solderer at 10 days/each and typically costs for transportation at 20 days to arrive an overall energy cost of 150 days, or less than 5 months, similar to our initial estimates.

LSC PV modules at the 5% power efficiency will enter the commercial market by 2014 and modules at 10% will be available by 2017 (the 10% modules depend on the development of lower cost GaAs cells by others). If we assume our technology scales up to 1 GW/year in manufacturing volume by 2018, as is obtainable with existing US manufacturing lines and PV production volumes, we would be producing $10 \times 10^6 \text{ m}^2$ of PV at 10% efficiency, resulting in a saving of $4 \times 10^{-7} \text{ Tbtu/m}^2 * 10 \times 10^6 \text{ m}^2 \text{ of PV} = 4 \text{ Tbtu/year}$. Based on the 1 GW/year volume mentioned above, sales would be on the order of 50 billion dollars/year (at 0.5 per Watt). These products would largely take advantage of existing US manufacturing lines so it should directly inject these funds into the US economy.

Greenhouse gas emissions for photovoltaics strongly depend on the energy pay back time, varying from 21 g CO₂-eq/kWh for thin films like CdTe and 43 g CO₂-eq/kWh for monocrystalline Si. Therefore, our LSC technology should reduce GHG by a minimum of 33% and up to 66%, saving on average 10 g CO₂-eq/kWh compared to conventional PV technology. At $10 \times 10^6 \text{ m}^2$ per year and 180 kW-hr per m^2 per year, our PV panels would produce approximately $1 \times 10^9 \text{ kW-hr/year}$ for a savings of $1 \times 10^{10} \text{ g CO}_2\text{-eq/year}$ or 1×10^6 metric tons CO₂-eq/year.

Return-of-investment on production line

A laminator that can laminate 10 m^2 panels/hour costs ~\$400,000. An automatic cell dicer tool costs \$150,000 and cell tabbing tool costs \$100K at similar volumes, for a total manufacturing line cost of \$650,000 per 200 m^2 panels per day operating 20 hours/day. Over 1 year, this tool would produce $300 \text{ days} * 200 \text{ m}^2/\text{day} = 60,000 \text{ m}^2/\text{year}$. At a 5-year depreciation schedule, that would result in a cost of $650,000/5 = \$130,000/\text{year}$ or $\sim \$2/\text{m}^2$, consistent with the manufacturing costs estimates in Table 2. These manufacturing costs, combined with 10% in overhead, administrative, and other costs, result in a \$23 profit margin on a product that sells for \$95, or a 24% return-on-investment.

Commercialization

We are currently working with Abengoa Solar to evaluate the commercial potential of this technology. A market analysis has been done, and an initial target market of greenhouses has been identified as a relatively low barrier of entry (compared to windows in commercial buildings). A breakdown of the market for PV-integrated greenhouses is provided in Figure 17.

In order to commercialize this technology, greenhouse growers (i.e. farmers) require a 5-year pay-back time. This pay-back time is available in states such as California and Hawaii, who have favorable solar irradiation, electric rates, and net-metering laws. It is also possible in Japan and Europe due to their higher electric rates and therefore feed-in tariffs. Several countries (Canada, Italy) have particularly favorable feed-in tariffs particular to PV-integrated greenhouses.

Figure 17: Projected PV-integrated Agricultural Market for our LSC Modules

To service these initial markets, we need to demonstrate that our modules do not impact plant growth. Our initial data suggests that plant growth is actually enhanced by our LSC modules since our luminescent materials absorb the light that plants don't use and convert it to the red light that plants use for flower and fruit production (Figure 18). We are currently leasing 6000 sq ft of greenhouse space in Watsonville as a demonstration site where greenhouse growers and farmers can test the impact of our modules on their crops.

Figure 18: Left: Yield of strawberries under a luminescent sheet (LSC) at high (90%), medium (60%) and low concentration (30%) compared to control (0%). Right: Our greenhouse test facility at KB Farms at Watsonville.

Accomplishments

We successfully met our objectives of developing a new PV technology and manufacturing process that decreases energy used in manufacturing by 50% while still enabling a ROI greater than 20%. Moreover, we demonstrated that our technology can positively impact plant growth, opening up new markets for PV-installation directly over agriculture. Our technology will therefore allow us to use the U.S. vast agricultural lands to produce low cost electricity ($< \$1/W$) while using simultaneously the same land to grow crops with improved yields. Furthermore, our technology will mitigate environmental and infrastructure concerns of PV installation given the large availability of agriculture lands near established electrical grids.

Conclusions

Given the favorable results from this research, our LSC technology should be able to move to the commercialization stage pending results from plant studies that are currently underway. Currently existing US contract manufacturing facilities can be used for much of the manufacturing process; however, an investment of \$2 to \$3 million dollars will be required to purchase equipment needed to reduce manufacturing costs to deliver a product that can meet the 5-year payback periods required of the Agricultural industry. This funding is not available from VC's due to their reluctance to fund solar projects; however, modest funding from strategic investors and government grants should provide sufficient funding to reach the commercialization stage. We have been awarded a Phase I SBIR grant that we hope to convert to a Phase II, and we are also receiving continued funding from our industrial partner, Abengoa Solar, to help transition the technology.

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