JOURNAL OF
CHEMICAL EDUCATION
VOLUME 95, NUMBER 7 • JULY 2018
pubs.acs.org/jchemeduc

ACS Publications
Most Trusted. Most Cited. Most Read.

Division of Chemical Education, Inc.
American Chemical Society

JOURNAL OF CHEMICAL EDUCATION
Cite This: J. Chem. Educ. 2018, 95, 1161−1166
Demonstration
pubs.acs.org/jchemeduc

Luminescent Solar Concentrator Paintings: Connecting Art and Energy

Alexander Renny,[†] Chenchen Yang,[†] Rebecca Anthony,[‡] and Richard R. Lunt*,[†,§]

[†]Department of Chemical Engineering and Materials Science, Michigan State University, East Lansing, Michigan 48824, United States
[‡]Deparment of Mechanical Engineering, Michigan State University, East Lansing, Michigan 48824, United States
[§]Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824, United States

Supporting Information

ABSTRACT: The increased awareness of greenhouse gas emissions on long-term climate trends has put the spotlight back on the development of renewable energy technologies to mitigate these processes. Solar based electricity generation has gained widespread recognition as a viable source of renewable energy but has been slowed by a number of factors including cost and available application areas. Luminescent solar concentrators (LSC) are being investigated as a low-cost route to expand solar energy harvesting into new spaces. With this demonstration, we develop kits for educating students about renewable and solar energy while promoting a sense of creativity often lacking in STEM demonstrations. Students design LSC devices by painting newly developed luminescent dyes on plastic waveguides. Thin solar cell strips are mounted around the edges of the LSC paintings to generate power. Creativity in design, a central part of scientific discovery and advancement, is promoted throughout the painting and testing of LSC materials.

KEYWORDS: *Demonstrations, Dyes/Pigments, General Public, Elementary/Middle School Science, Public Understanding/Outreach, Hands-On Learning/Manipulatives*

With increasing greenhouse gas emissions,[1] electricity costs,[2] and international agreements on combatting climate change,[3] the need for access to inexpensive renewable energy is increasing every year. Globally, 21.6 trillion kWh of electricity was generated in 2012, and this value is projected to increase to 36.5 trillion kWh by 2040.[4] Increasing the fraction of this energy which comes from renewable sources is necessary for securing the energy future of the world and limiting the negative environmental impact in meeting that energy demand. The single largest source of renewable energy is our sun, which provides enough energy to power the planet for an entire year in a little over 1 h.[4,5] A key to effectively harnessing this energy lies in finding ways to creatively and synergistically deploy various solar technologies across a wide variety of spaces, and we aim to promote this kind of creative thinking.

While solar panels are becoming a more ubiquitous and publicly recognizable form of solar harvesting, current photovoltaic (PV) technologies are often prohibitively expensive in relation to savings available[6] and can be constrained in application areas due to bulkiness, flexibility, or aesthetics. Thin film silicon (Si) cells,[7] transparent organic PV,[8] and luminescent solar concentrators (LSC)[9,10] are all technologies which seek to address one or more of these issues. For this demonstration, we have developed a solar module design kit for making artistic and colorful LSC paintings. The principles of fluorescence[11−14] and solar energy harvesting,[15,16] as well as the production of photovoltaic devices[17−19] have all been previously examined in this *Journal*. With a combination of these topics in a single demonstration, students are engaged in the understanding of optics, waveguides, energy transport, solar energy, and the necessity of renewable energy generating devices while producing a device that can be kept as a reminder of these principles.

CONCEPTS OF MATERIALS

The fundamental goal of an LSC device as initially proposed[10] is to concentrate light gathered over a large area concentrator (waveguide) onto a small area of edge-mounted solar cells (Figure 1). Concentrators are doped with molecules which absorb certain fractions of the solar flux and re-emit this energy as luminescence at a longer wavelength (lower-energy photons,

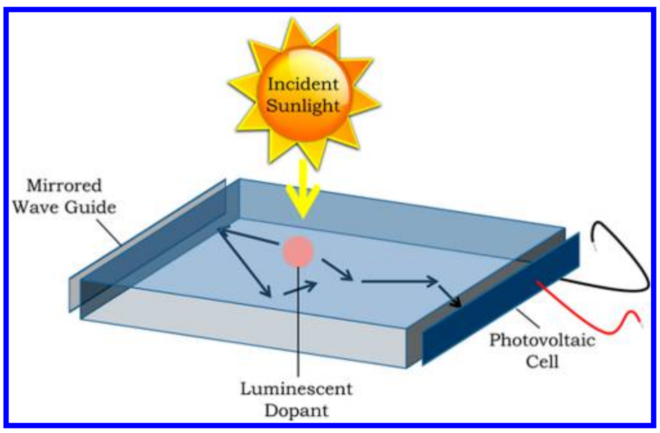

Figure 1. Luminescent solar concentrator schematic.

Received: September 23, 2017
Revised: April 10, 2018
Published: May 11, 2018

arrows in Figure 1). This photoluminescence is then guided by total internal reflection to edge-mounted solar cells for energy conversion[9] or lost from the front/back of the waveguide if emitted photons contact the waveguide surface at angles inside the escape cone. This principle is similar to that experienced at amusement parks in fiber-connected flashlights. The efficiency of light trapping in the waveguide (η_{Trap}, eq 1) is dictated by the contrast in the index of refraction of the waveguide (n) and the surrounding media (air):

$$\eta_{Trap} = \sqrt{\left(1 - \frac{1}{n^2}\right)} \quad (1)$$

For typical waveguides such as poly(methyl methacrylate) (PMMA) with an index of $n = 1.5$, this translates to a trapping efficiency of 75%. This means that up to 75% of the light which is captured within the waveguide can be directed to and emerge from the edges. Increasing the total LSC efficiency (η_{LSC}) is a primary goal of current research in the field and is defined by

$$\eta_{LSC} = (1 - R)\eta_{Abs}\eta_{PL}\eta_{RA}\eta_{PV}\eta_{Trap} \quad (2)$$

This equation includes the front face reflection (R), absorptive efficiency of the luminophore (η_{Abs}), photoluminescent efficiency (η_{PL}), reabsorption suppression efficiency (η_{RA}), and photovoltaic efficiency (η_{PV}).[20]

Ultimately, there are two goals for developing LSC technologies: (1) reduction in total PV surface area required for collecting light to reduce module costs and (2) the ability to deploy solar harvesting devices in new areas. Current LSC research goals focus on increasing the efficiencies in eq 2,[21,22] as well as increasing the scale of devices,[23,24] flexibility,[24] and concentrator transparency.[25−27] Additionally, the principles of LSCs can also be utilized to enhance traditional solar panels; for example, the low quantum efficiency of Si PV in UV/blue ranges can be avoided by down-converting blue photons to two photons of a lower energy/larger wavelength. This increases η_{PV} by emitting wavelengths which are more suited to energy conversion.

LSC devices were originally developed as a simpler solution to mirror based concentrators[10] which harvest direct-incidence sunlight with the aid of tracking equipment minimizing the use of silicon solar panels. LSCs can collect light across a wide range of incidence angles (including diffuse light), so complicated tracking equipment is not required, providing a low-cost alternative to mirror based concentrating systems.

Early concentrator designs generally absorbed and emitted light in the visible range. These devices have the ability to be highly efficient,[28,29] and their appearance makes them suitable colorful application areas.[30] Indeed, the maximum theoretical efficiency of a single junction solar cell (known as the Shockley−Queisser limit) is 33.7%.[31] Similarly, for a black LSC absorbing throughout the visible spectrum, the theoretical Shockley−Queisser limit is 33.7% assuming that the absorption (η_{Abs}), luminescence(η_{PL}), and collection (η_{Trap}, η_{RA}) efficiencies[10] are all 100%. More practically, there is an efficiency limit of 23.5%[32] for colorful designs, similar in appearance to colored panels installed at the Palais de Congrés in Montreal, Quebec.

While declining costs for traditional solar panels has limited the use of LSC technologies as an outright replacement for traditional panels, application of both transparent and colored LSC devices into architectural and other areas not suitable for traditional PV technologies has increasingly become a focus of research.[25−28] The light transmission characteristics of different devices provide architectural designers flexibility in implementation of solar harvesting technologies, from standard office windows to colored panels to enhance the aesthetic appeal of a structure. The Shockley−Queisser limit for visibly transparent devices that only absorb light outside of the visible spectrum is 21%;[20] however, these devices offer significant benefits in the opportunities for implementation into new areas. Integrating transparent LSCs into windows around buildings is especially advantageous, opening a large amount of surface area unsuitable for other device architectures. To increase efficiencies beyond the Shockley−Queisser limits for both visible and transparent LSC devices, the use of multijunction LSC devices which reduce thermalization losses is also possible.[20,33]

■ GOALS OF THE DEMONSTRATION

The creation of visually appealing designs which can harvest energy and demonstrate the working principles of LSC technology are the focus of this demonstration. This work specifically examines an approach to LSC technology implementation which is different than uniform LSC applications seen in previous studies. By incorporating absorptive and luminescent dopants into paint formulations, they can be applied onto an optically clear sheet which constitutes the waveguide of the LSC. We are focused on developing an activity combining a familiar creative exercise (painting) with solving an engineering problem (solar energy harvesting). Increasing student creativity in the approach of engineering problems helps to drive innovation which is essential for advances in science to occur.[34] The demonstration has four primary educational objectives:

(1) To engage students in discussion of renewable energy
(2) To highlight the energy potential from the sun
(3) To develop fun and instructive solar cell activities
(4) To associate creativity of design with STEM principles (e.g., linking art and energy)

■ DESIGN OF MATERIALS AND DEMONSTRATION

The key ingredients for building an LSC include a waveguide, PV cell(s), and luminescent materials. A 6 in. × 6 in. × 1/4 in. PMMA sheet was used as the waveguide for its suitable trapping (waveguide) efficiency as well the near complete transmission of light through the material before painting. The sheet dimensions allow for straightforward design and attachment of solar modules. While power can be generated with either flashlights or sunlight (indeed, both are encouraged), local illumination with the use of flashlights to control light penetration area and angle helps to visualize the principles of waveguiding and can make the glowing light more apparent. Different penetration angles can also be used to promote discussion on possible efficiency loss pathways.

Five different colored paints (red, orange, yellow, green, and blue) were designed. Paint color is determined by the absorptive, luminescent, and reflective properties of constituent dyes. Absorptive filtering allows for the transmission of certain wavelengths of light which results in visible paint coloring (the dominant mechanism in this exercise). Under normal lighting conditions, the paints produce luminescence from absorbed light which also contributes to the overall perceived color by producing a noticeable glow (the second dominant mechanism of coloring in this exercise). On application, a small amount of reflection from the surface of the waveguide[19] also produces

DOI: 10.1021/acs.jchemed.7b00742
J. Chem. Educ. 2018, 95, 1161−1166

some coloring but is less important here. Information on paints as well as other materials required for the demonstration is included in the Supporting Information.

The light absorbed by luminophore (dye) molecules is emitted at a longer wavelength (lower energy) than the absorptive color of the paint. This is caused by vibrational losses of the energy of electrons in the excited state before they return to the ground state. For example, a dye which has a yellow absorptive tint (from absorbing blue photons) when in solution emits green light under excitation by flashlight; a dye which has a red absorptive tint (absorbing green light) emits red light which reinforces the color. For this demonstration, matching paint absorption color with emission color was desired to amplify particular coloring. This was achieved by mixing luminescent dyes so the imparted colors from absorption and luminescence were similarly matched. The complementary blending of both the emission and absorption spectra of different dyes was performed to produce the five-color spectrum used in the demonstration (Figure 2). This

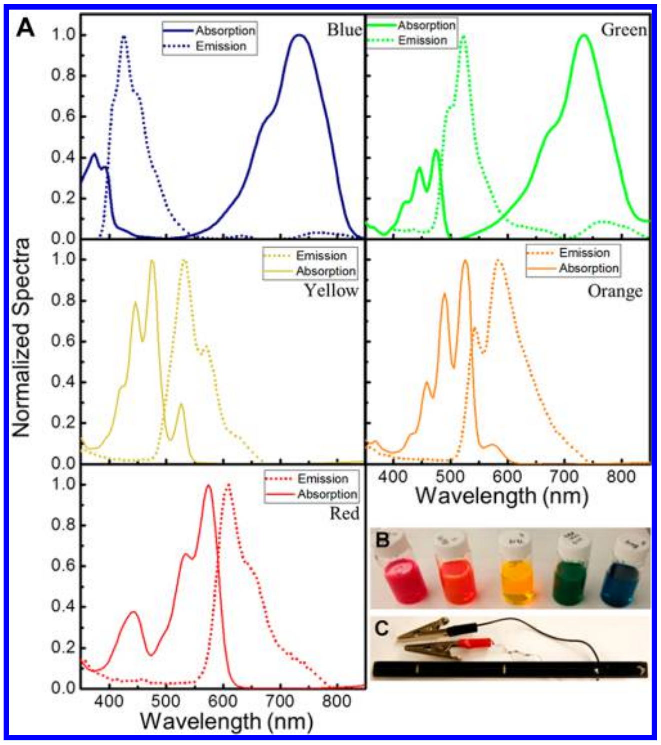

Figure 2. Normalized absorption (solid, A) and emission (dotted, A) spectra of paints used in the demonstration (B). Solar cell module (C). Note that the multiple absorption and emission peaks for blue and green paints stem from two distinct dyes with one dye emitting in the visible and one emitting in the infrared to reinforce absorptive coloring and provide greater power.

mixing is described in greater detail in the Discussion section. The dyes are dissolved into an acetone solution and then combined with a poly(butyl methacrylate-*co*-methyl methacrylate) resin based polymer matrix solution (n = 1.51) to create the final paint which can adhere to the PMMA waveguide and dry within 15 min of application.

Disposable pipettes were used in place of traditional paintbrushes to increase the thickness (and associated color density) of applied paints. The technique used is similar to drop-casting, a common method[18] used in prototyping new dye formulations. Paint brushes can also be utilized but often require multiple coats due to the limited dye solubility. We note that, even if higher solubilities were possible, concentrations above those utilized in this work often lead to "concentration quenching" of the luminophore resulting in a reduction in luminescence efficiency[35] and less glowing. Pipettes are initially less intuitive for participants to use but provide more control than brushes. It is helpful to have participants practice controlling them with scrap pieces of acrylic before attempting more complicated patterns and paintings.

Clips were designed and 3D printed to allow easy mounting and dismounting of fragile PV cell around the edge of the waveguide. A laser-cut 6 in. × 1/4 in. silicon solar cell was inserted into the printed clip with holes for soldered electrical leads (Figure 2B). The cell was then encapsulated in a clear epoxy for durability. Producing solar modules which were durable and easy to attach was a necessity for hands-on demonstration, especially for younger participants.

The demonstration is composed of four segments: (1) initial introduction to solar energy and LSCs, (2) painting of devices, (3) paint drying time, and (4) device testing. The painting is preceded by an introduction which briefly describes the principles of LSC technology and a demonstration with a previously painted LSC device (Figure 3). Students were then

Figure 3. Sample painted device under direct illumination using a UV flashlight (left, spectrum included in Figure 5, UV) and ambient conditions (right). Note luminescence along waveguide edge where solar modules are attached during demonstration.

allowed 5−10 min to paint their own LSC devices. During the following drying time (∼15 min), a variety of topics were covered, depending on the age/educational level of participating students. A discussion on the difficulties facing the implementation of solar harvesting technologies, including cost, application areas, and integration into the electrical grid, was presented to students at all educational levels. For more advanced students, additional topics can include the following: factors which impact LSC efficiency, efficiency records, use of blocking diodes to prevent battery discharge, maximum power point tracking, and battery recharging time from instantaneous or average solar flux.[36]

Upon completion of drying, solar modules were attached to one edge of each student's device and returned to students. Fans were then connected to the LSC to first get a qualitative idea of power generation by the devices before moving on to multimeters where current and voltage could be measured. Students were encouraged to collaborate and experiment with linking devices together in parallel and/or series to determine changes to device output in current, voltage, and fan speed.

IV curves are shown in Figure 4 from solar cell modules attached to a painted LSC in either parallel or series. The short circuit current, I_{SC} (current at zero voltage), and the open

DOI: 10.1021/acs.jchemed.7b00742
J. Chem. Educ. 2018, 95, 1161−1166

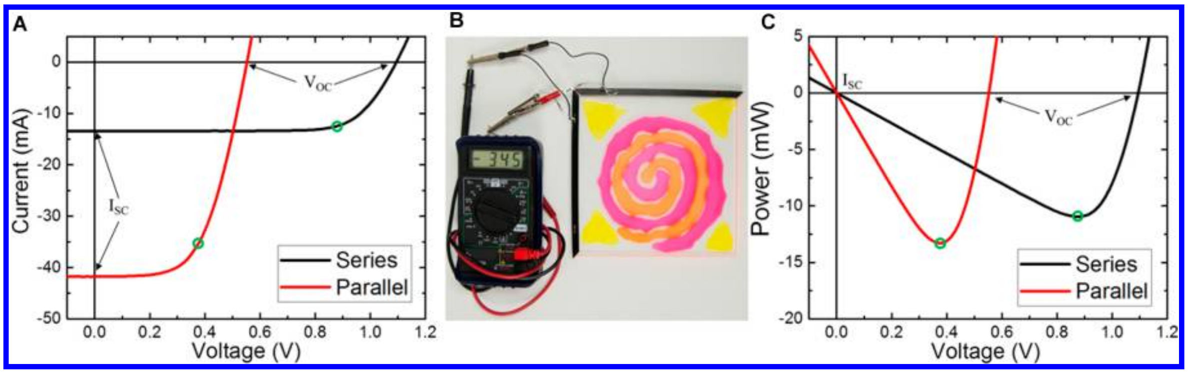

Figure 4. Current−voltage (*IV*, A) and power−voltage (C) of a painted LSC device (B) with two edge-mounted solar modules connected in parallel or in series. The multimeter in part B is shown displaying the voltage (mV) of the parallel-connected solar cells. Green circles indicate MPP of device.

circuit voltage, V_{OC} (voltage at zero current), are used to characterize solar harvesting devices, but operation at either of these points will not provide usable power since $P = IV$. Power output is maximized at the MPP (maximum power point), which for the painting in Figure 4 was 11.0 mW (0.87 V, 12.6 mA) or 13.3 mW (0.38 V, 35.0 mA) for series and parallel, respectively.

■ HAZARDS

The primary solvent used in this demonstration is acetone (the active ingredient in nail polish remover), which has a high vapor pressure and produces a noticeable smell. The paint also contains <42 wt % of toluene, another component of some nail polishes (classified as having a Degree of Hazard level of 2 in the NFPA 704 standard), indicating that intense or long-term continued exposure could cause possible injury. The demonstration should be performed in a well-ventilated space. Acetone as well as the adhesive used in the paints are flammable and should be kept away from spark or open flame. Participants are advised to wear gloves and smocks to prevent the direct contact with paints and to reduce the likelihood of staining skin or clothing.

■ DISCUSSION

Two questions were most frequently brought up by participants in the demonstration: (1) which color is the best and (2) how can a device which powers a fan or other device be produced? These questions provide an opportunity to discuss the mechanics behind electricity generation using LSC devices in more detail and are outlined below.

What is the Best Color?

The question first raised by most students is which paint will produce the most power. While the most efficient device is not the goal of this activity, in real world applications the highest device efficiency is desired, so it is a worthwhile question to address. Photon energy (E, eV) is inversely proportional to the wavelength (λ, μm) by eq 3:

$$E = \frac{1.240 \text{ eV } \mu\text{m}}{\lambda} \tag{3}$$

As a result of this equation, many students' initial (and intuitive) conclusion is that lower-wavelength (higher-energy) fluorescence/solar absorption would yield higher current generation. However, the energy of the photon does not directly impact the efficiency of current generation because each absorbed solar photon produces, at most, one luminescence photon. This re-emitted photon can be reabsorbed, be lost through the escape cone, or produce a maximum of one electron in the solar cell (in the absence of charge carrier multiplication). Also, the excess energy of all the absorbed photons in the edge-mounted PV are thermalized to the bandgap of the PV so that the amount of energy produced by each absorbed photon is determined by the bandgap of the semiconductor material instead of the energy of the photons being absorbed. That is, the energy of the photon is not informative about the power generation in single junction LSCs. Again, the amount of power generated depends on the overall amount of absorption within a particular wavelength range, the amount of photons in the light source at those wavelengths, the luminescence efficiency, reabsorption losses from the dyes, and the efficiency of converting particular wavelength photons into electrons in the solar cell (eq 2). The wavelength efficiency (or quantum efficiency) for Si PVs is relatively flat across the spectrum (500−1000 nm) except at UV and blue wavelengths where the efficiency drops off by about half and the solar photon spectrum is also relatively flat in the range 500−1000 nm (visible and infrared) (Figure 5, Sun AM1.5G).

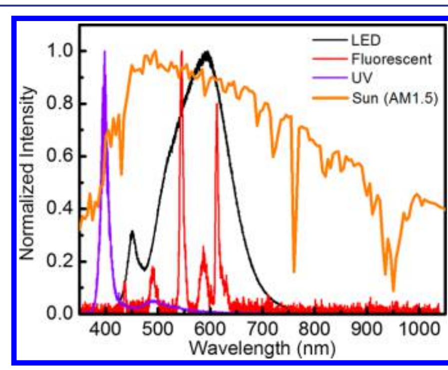

Figure 5. Spectra for sunlight, and a common LED lamp, UV lamp (sometimes referred to as "black lights"), and fluorescent lamp.

The "best" paint, which has the highest current generation potential, can then be attributed to the tuning of absorption widths (total light source absorption) and luminescence efficiency, combined with a particular pairing of light source. Under sunlight, the red, yellow, and orange paints (all of which have similarly high η_{PL} of close to 1) typically have the highest power generation. When testing the current generation

DOI: 10.1021/acs.jchemed.7b00742
J. Chem. Educ. 2018, 95, 1161−1166

potential with the blue and green paints under different light sources, a luminophore which emits in the near-infrared is used with a visibly luminescent dye to reinforce the blue or green color by absorbing the red part of the spectrum. This causes blue and green paints to absorb light at ∼650−800 nm (red/infrared) and 300−400 nm (UV), both of which are present in the Air Mass 1.5 Global (AM1.5G) spectrum, a standard reference spectrum for terrestrial irradiance (Figure 5). While the blue and green paints have good absorption in the infrared, the lower η_{PL} value of the NIR emitting constituents and the lower absorption efficiency of the UV absorbing constituents results in a noticeably lower power generation potential under sunlight (roughly a factor of 2−3 times less). If NIR emitters with η_{PL} values closer to 1 were found and utilized for the blue and green paints, the power generation potentials of all the paints would be similar.

However, sunlight is not always available due to weather conditions or the time of day the activity is carried out. The use of flashlights allows students to test devices inside or at times when the sun may not be shining and to target only a single paint/area. The red paint has an absorption peak of ∼570 nm, a wavelength which is emitted at a much higher intensity by flashlights used in the demonstration (Figure 5, LED). This leads to high power generation potential with these flashlights. Most commercial fluorescent and LED flashlights and lamps emit very little in the UV or infrared, and the combination of absorption characteristics and η_{PL} values results in an even lower current generation potential by blue and green paints under artificial illumination. Consideration of the wavelength dependence of the LSC paintings can help students to understand the ability (or the lack thereof) of solar PVs to operate under different lighting conditions (indoor, outdoor, fluorescent vs LED, etc.).

How To Produce a Usable Device

Generation of the most power from a device is important but is often secondary to producing the correct voltage and current for a particular application. Fortunately, this can be achieved primarily through a different PV cell arrangement. Connection of multiple devices into an array as seen in large scale solar installations is carefully considered to satisfy voltage/current requirements. Similarly, connection of PV cells used in the demonstration in series and/or parallel circuits allows for tuning of voltage or current, respectively, to meet application requirements. An application requiring higher current levels than that provided by a single device could utilize several devices with solar cell modules connected in parallel to increase output current; an application requiring higher voltage than produced by a single PV module (∼0.4 V for Si based LSCs) could be configured with several modules wired together in series to build voltage like batteries in series.

In this demonstration, the dc fan required 0.3 V to begin spinning. Because the operating point in both series and parallel exceeds the 0.3 V threshold, the fan speed is limited only by the current provided. The combination which produces the most current will then yield the fastest fan speed. Wiring the edge-mounted solar cells in parallel will produce the best device in this case. However, many applications (e.g., recharging batteries) require at least 1.8 V, significantly more than can be generated by two cells connected in series. Connection of several devices (e.g., 4 cells from the four edges) in series is then required to produce a device suitable for these applications if they are to be powered directly.

CONCLUSION

The goals of this demonstration are to engage students in discussion of renewable energy, highlight the potential from the sun, develop a fun and instructive activity, and associate creativity of design with STEM principles. Throughout the activity, students are engaged in the discussion of renewable energy, from initial concepts of total available potential through to devices used in harvesting solar energy. With the use of different measuring devices, the energy potential available from the sun can be demonstrated both quantitatively and qualitatively. Parallels can be drawn between the activity provided and current research in the energy harvesting field. Materials (dyes used in paints) and techniques (drop-casting) used in the activity are the same as those used in current LSC research. While the competitive nature of students will often drive them to want to find the "best" design, discussion of the efficiency factors which determine overall dye effectiveness does not require indication of the highest efficiency paint. This allows students the freedom to produce devices which generate energy while they can express themselves through artistic paintings.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available on the ACS Publications website at DOI: 10.1021/acs.jchemed.7b00742.

Further explanation of luminescence with use of a Jablonski diagram, details regarding paint production (dye, quantities, solvents, mounting media), and information for procurement of other materials (PDF, DOCX)

AUTHOR INFORMATION

Corresponding Author

*E-mail: rlunt@msu.edu.

ORCID

Rebecca Anthony: 0000-0003-3391-4442
Richard R. Lunt: 0000-0003-4248-6312

Notes

The authors declare the following competing financial interest(s): A. Renny and R. Lunt are cofounders and majority owners of a start-up science education company, GlowShop, LLC, incorporated in the state of Michigan. The company has begun to manufacture and is preparing to sell a luminescent solar concentrator painting kit containing materials described in this paper as the first product. No promotion of this product to the exclusion of other potentially similar products should be construed, and an alternative recipe for paint production is included in the Supporting Information along with instructions for acquiring other materials required for the activity.

ACKNOWLEDGMENTS

Financial support for this work was provided by the National Science Foundation (CAREER award, CBET-1254662 and CBET-1702591) and the MSU Sustainability Office. The authors would like to thank MSU Sustainability for hosting the outreach events where this demonstration was performed.

REFERENCES

(1) Intergovernmental Panel on Climate Change. *Climate Change 2014: Mitigation of Climate Change*. 2014. https://www.ipcc.ch/pdf/assessment-report/ar5/wg3/WGIIIAR5_SPM_TS_Volume.pdf (accessed Mar 2018).

(2) US Energy Information Administration. Short-Term Energy Outlook. 2016. https://www.eia.gov/outlooks/steo/report/ (accessed Mar 2018).

(3) Savaresi, A. The Paris Agreement: A New Beginning? *J. Energy Nat. Resour. Law* **2016**, *34*, 16−26.

(4) Energy Information Administration. *International Energy Outlook 2016: With Projections to 2040*. 2016. https://www.eia.gov/outlooks/ieo/pdf/0484(2016).pdf (accessed Mar 2018).

(5) Lewis, N. S.; Nocera, D. G. Powering the Planet: Chemical Challenges in Solar Energy Utilization. *Proc. Natl. Acad. Sci. U. S. A.* **2006**, *103*, 15729−15735.

(6) Breyer, C.; Gerlach, A. Global Overview on Grid-Parity. *Prog. Photovoltaics* **2013**, *21*, 121−136.

(7) Chen, Y.-H.; Chen, C.-H.; Wu, C.-L.; Huang, C.-F.; Lai, W.-C.; Yang, H.-J.; Hwang, J.-C. Adjusted Colorful Amorphous Slicon Thin Film Solar Cells by a Multilayer Film Design. *J. Electrochem. Soc.* **2011**, *158*, H851−H853.

(8) Lunt, R. R.; Bulovic, V. Transparent, near-Infrared Organic Photovoltaic Solar Cells for Window and Energy-Scavenging Applications. *Appl. Phys. Lett.* **2011**, *98*, 113305.

(9) Batchelder, J. S.; Zewai, A. H.; Cole, T. Luminescent Solar Concentrators. 1: Theory of Operation and Techniques for Performance Evaluation. *Appl. Opt.* **1979**, *18*, 3090−3110.

(10) Weber, W. H.; Lambe, J. Luminescent Greenhouse Collector for Solar Radiation. *Appl. Opt.* **1976**, *15*, 2299−2300.

(11) Powell, A. The Fundamentals of Fluorescence. *J. Chem. Educ.* **1947**, *24*, 423−428.

(12) Goodall, D.; Roberts, D. Energy Transfer Between Dyes. *J. Chem. Educ.* **1985**, *62*, 711−714.

(13) Salter, C.; Range, K.; Salter, G. Laser-Induced Fluorescence of Lightsticks. *J. Chem. Educ.* **1999**, *76*, 84−85.

(14) Blitz, J.; Sheeran, D.; Becker, T. Classroom Demonstrations of Concepts in Molecular Fluorescence. *J. Chem. Educ.* **2006**, *83*, 758−760.

(15) Mickey, C. Solar Photovoltaic Cells. *J. Chem. Educ.* **1981**, *58*, 418−423.

(16) Cady, S. Music Generated by a Zn/Cu Electrochemical Cell, a Lemon Cell, and a Solar Cell: A Demonstration for General Chemistry. *J. Chem. Educ.* **2014**, *91*, 1675−1678.

(17) Boudreau, S.; Rauh, R.; Boudreau, R. A Photoelectrochemical Solar Cell: An Undergraduate Experiment. *J. Chem. Educ.* **1983**, *60*, 498−499.

(18) Smith, Y. R.; Crone, E.; Subramanian, V. A Simple Photocell To Demonstrate Solar Energy Using Benign Household Ingredients. *J. Chem. Educ.* **2013**, *90*, 1358−1361.

(19) Jin, Z.; Li, Y.; Yu, J. C. Gaining Hands-On Experience with Solid-State Photovoltaics through Constructing a Novel n-Si/CuS Solar Cell. *J. Chem. Educ.* **2017**, *94*, 476−479.

(20) Yang, C.; Lunt, R. R. Limits of Visibly Transparent Luminescent Solar Concentrators. *Adv. Opt. Mater.* **2017**, *5*, 1600851.

(21) Gamelin, D. R.; Knowles, K. E.; McDowall, S.; Bradshaw, L. R. Nanocrystals for Luminescent Solar Concentrators. *Nano Lett.* **2015**, *15*, 1315−1323.

(22) Coropceanu, I.; Bawendi, M. G. Core/Shell Quantum Dot Based Luminescent Solar Concentrators with Reduced Reabsorption and Enhanced Efficiency. *Nano Lett.* **2014**, *14*, 4097−4101.

(23) Kanellis, M.; de Jong, M. M.; Slooff, L.; Debije, M. G. The Solar Noise Barrier Project: 1. Effect of Incident Light Orientation on the Performance of a Large-Scale Luminescent Solar Concentrator Noise Barrier. *Renewable Energy* **2017**, *103*, 647−652.

(24) Correia, S. F. H.; Lima, P. P.; Pecoraro, E.; Ribeiro, S. J. L.; André, P. S.; Ferreira, R. A. S.; Carlos, L. D. Scale up the Collection Area of Luminescent Solar Concentrators towards Metre-Length Flexible Waveguiding Photovoltaics. *Prog. Photovoltaics* **2016**, *24*, 1178−1193.

(25) Zhao, Y.; Lunt, R. R. Transparent Luminescent Solar Concentrators for Large-Area Solar Windows Enabled by Massive Stokes-Shift Nanocluster Phosphors. *Adv. Energy Mater.* **2013**, *3*, 1143−1148.

(26) Meinardi, F.; McDaniel, H.; Carulli, F.; Colombo, A.; Velizhanin, K. A.; Makarov, N. S.; Simonutti, R.; Klimov, V. I.; Brovelli, S. Highly Efficient Large-Area Colourless Luminescent Solar Concentrators Using Heavy-Metal-Free Colloidal Quantum Dots. *Nat. Nanotechnol.* **2015**, *10*, 878−885.

(27) Zhao, Y.; Meek, G. A.; Levine, B. G.; Lunt, R. R. Near-Infrared Harvesting Transparent Luminescent Solar Concentrators. *Adv. Opt. Mater.* **2014**, *2*, 606−611.

(28) Debije, M. G.; Verbunt, P. P. C. Thirty Years of Luminescent Solar Concentrator Research: Solar Energy for the Built Environment. *Adv. Energy Mater.* **2012**, *2*, 12−35.

(29) Slooff, L. H.; Bende, E. E.; Burgers, A. R.; Budel, T.; Pravettoni, M.; Kenny, R. P.; Dunlop, E. D.; Büchtemann, A. A Luminescent Solar Concentrator with 7.1% Power Conversion Efficiency. *Phys. Status Solidi RRL* **2008**, *2*, 257−259.

(30) Vossen, F. M.; Aarts, M. P. J.; Debije, M. G. Visual Performance of Red Luminescent Solar Concentrating Windows in an Office Environment. *Energy Buildings* **2016**, *113*, 123−132.

(31) Rühle, S. Tabulated Values of the Shockley-Queisser Limit For Single Junction Solar Cells. *Sol. Energy* **2016**, *130*, 139−147.

(32) Li, Y.; Dong, W. J. Estimating the Theoretical Limit of the Power Conversion Efficiency of a Luminescent Solar Concentrator Device from the Perspective of Shockley-Queisser Limit. *IEEE 42nd PVSC* **2015**, 1−3.

(33) Currie, M.; Mapel, J.; Heidel, T.; Goffri, S.; Baldo, M. High-Efficiency Organic Solar Concentrators for Photovoltaics. *Science* **2008**, *321*, 226−228.

(34) Thompson, G.; Lordan, M. A Review of Creativity Principles Applied to Engineering Design. *Proc. Inst. Mech. Eng., Part E* **1999**, *213*, 17−31.

(35) Lakowicz, J. R. Quenching of Fluorescence. *Principles of Fluorescence Spectroscopy*; Springer US: Boston, MA, 1983; pp 257−301.

(36) Lunt, R. R. Solar Charging Calculator. http://www.egr.msu.edu/~rlunt/Solar_Charging_Worksheet_Calculator.xlsx.

DOI: 10.1021/acs.jchemed.7b00742
J. Chem. Educ. 2018, 95, 1161−1166