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Using Berries to turn Sunlight into Electricity: Taking advice from Mother Nature because she has already mastered the art of using solar energy

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Using Berries to turn Sunlight into Electricity:
Taking advice from mother nature because she has already mastered the art of using solar energy

Senior Project Submitted to
The Division of Science, Math, and Computing
of Bard College

by
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Annandale-on-Hudson, New York
May 2023

USING BERRIES TO TURN SUNLIGHT INTO ELECTRICITY

Taking advice from mother nature because she has already mastered the art of using solar energy

QUINCY ROSS

ADVISED BY BEATE LIEPERT

Spring 2022

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Dedication

I would like to dedicate this paper to the incredible beauty of the Hudson Valley and the world. From the smallest detail to the largest ecosystems the biosphere is a magnificent and complex harmony. It is a constant source of joy and inspiration for me.

Acknowledgements

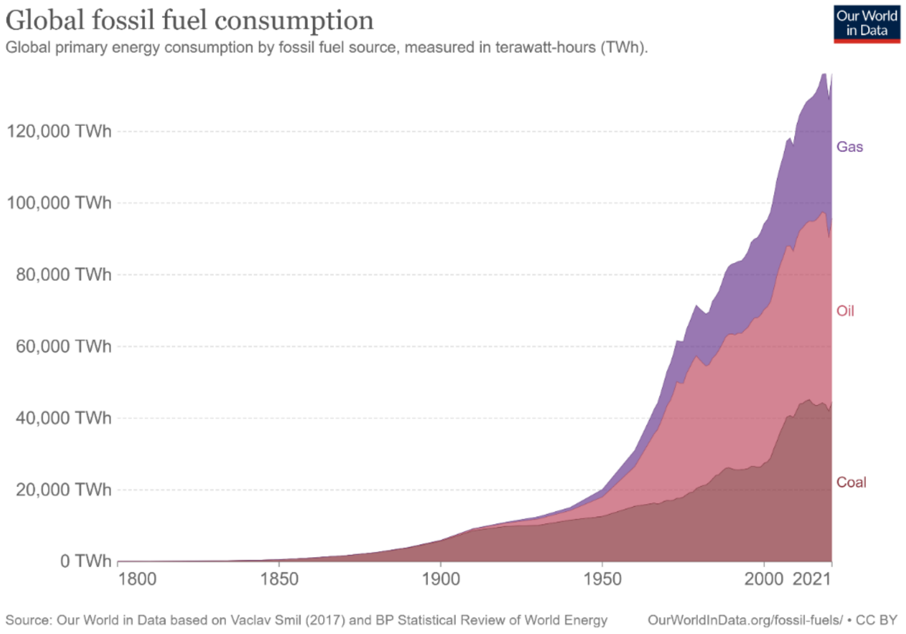
There are many people I need to sincerely thank for helping me get to where I am now and achieve what I have. I want to thank my parents for raising me to be curious, creative, and kind. I want to thank the Bard physics department for giving me a comprehensive and thorough education while maintaining an empathetic environment. I want to thank professor Christopher Lafratta for providing constant support throughout my project. A special thanks to my advisor, professor Beate Liepert, for encouraging me to think wildly and helping me overcome the challenges of physical injury. Your enthusiasm is infectious. My final thanks goes to my friends and community, every day I am reminded that the world is a good place and is worth trying to make better. You make the world kinder by being kind.

Abstract

As we try to stop anthropogenic climate change, we need to find energy sources that don’t involve burning fossil fuels. The Earth is constantly being hit with energy in the form of sunlight, we just need to figure out how to use it, thankfully plants have already gotten very good at photosynthesis. Solar energy is being improved at an exciting rate but has some material downsides when it comes to raw material mining. Dye sensitized solar cells, though having a lower efficiency than traditional photovoltaics open up opportunities for improving solar energy in many other aspects, such as reducing material ecological impacts, reducing production cost, increasing recyclability, mitigating weather related losses in power by better utilizing diffuse light, reducing land space needed through vertical arrangements, and by potentially being beautiful works of art. In this study I consider the geometric aspects of placing solar cells and deliberate tree foliage. I studied the absorption spectra of the pigment from blueberries and compared it to the emission spectra of the sun to see if it is an appropriate dye to use for dye sensitized solar cells. I also created dye sensitized solar cells from scratch and summarize the process and challenges faced, as well as calculated their efficiency at turning light into electrical power.

Introduction

In our current era we rely on electricity in our day to day lives. Electric potential is a very high form of energy that most often is unnaturally manufactured. Electricity often comes from turning chemical or atomic energy into heat, then using that heat to turn a turbine, and turning that mechanical energy into electrical. Each of these transitions between types of energy causes an increase in entropy, reducing efficiency, and losing energy to unusable forms. Wind and Hydro energy involve directly converting the mechanical energy in nature into electrical with a turbine. Our reliance on fossil fuels has involved unearthing vast amounts of sequestered carbon and burning them releasing CO_2 into the atmosphere. The following figure shows the increasing global consumption of fossil fuels since 1800 broken down by type of fossil fuel:



Global fossil fuel consumption

Global primary energy consumption by fossil fuel source, measured in terawatt-hours (TWh).

Source: Our World in Data based on Vaclav Smil (2017) and BP Statistical Review of World Energy OurWorldInData.org/fossil-fuels/ • CC BY

FIGURE 1

This figure shows the increasing amount of fossil fuel use over time since 1800 by type of fuel. Coal, oil, and gas are shown. The global energy consumption by fossil fuel source has skyrocketed since 1950 to a total of over 120,000 TWh in 2021. Reprinted from *Fossil Fuels*, Ritche et all.

These greenhouse gas emissions have already had negative global consequences on climate through the greenhouse effect. The greenhouse effect is when gasses in the atmosphere allow short wavelength light from the sun reach Earth's surface warming it up, then absorb longer wavelength infrared light radiated back from the earth trapping the energy as heat. "Human-caused climate change is already affecting many weather and climate extremes in every region across the globe. Evidence of observed changes in extremes such as heatwaves, heavy precipitation, droughts, and tropical cyclones, and, in particular, their attribution to human influence, has strengthened since AR5" (Lee et al., 2023 p.12). AR5 was the previous Intergovernmental Panel on Climate Change's synthesis report released in 2014. Continued use of fossil fuels and accumulation of greenhouse gasses in the atmosphere will be even more devastating if we cannot limit global warming to 1.5 degrees Celsius compared to the preindustrial era (Lee et al., 2023).

To avoid this climate disaster while not giving up modern conveniences we need to find better ways to make electricity. Electrical power generation is the cause of 25% of the global greenhouse gas emissions. The following figure from the Environmental Protection Agency shows the breakdown of United States greenhouse gas emissions by sector. Transportation is the leading contributor at 28% and electrical power is a close second at 25%:

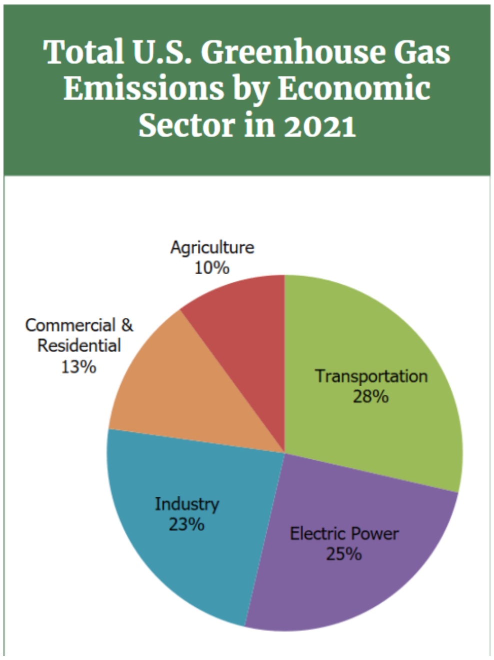


FIGURE 2

This figure is a pie chart showing the breakdown of the sources of greenhouse gasses from the U.S. The leading contributor is transportation at 28%. In second is electric power at 25%, followed by industry at 23%, commercial & residential at 13% and agriculture at 10%. Reprinted from *Sources of Greenhouse Gas Emissions*, EPA.

If the emissions made when producing electric power could be reduced that would be a big improvement seeing as it is the second highest contributor to greenhouse gas emission. This could also help to reduce emissions in the transportation sector too when transportation is electrified. Figure 3 shows that in the last ten years there has been a significant increase in market uptake for electric vehicles.

All of the energy we use on earth either came from gravitational potential, is stored in its matter as nuclear energy, or most significantly, came from the sun in the form of radiation. Even wind energy originally comes from the sun. The equator to pole distribution of incoming sunlight drives the general circulation of the atmosphere. Even fossil fuels are sunlight stored in a chemical form of energy in coal, gas and oil deposits or the biosphere (i.e., wood). The gravitational energy from the moon has something to offer with ideas about harvesting tidal energy being worked on (Pacific Northwest National Laboratory, n.d.). Nuclear energy is a highly debated source of energy, offering lots of energy but also posing dangers and hazardous waste. Solar energy is so abundant and available that the earth is constantly bombarded by over 1000 watts per square meter from the sun. "A large amount of solar energy – 3.9x10^24 J = 1.08x10^18 kWh – reaches the earth's surface from the sun each year. This amount is nearly 10,000 times greater than the global primary energy demand." (Quaschning, 2016, p. 23)

Solar energy is a very promising energy solution, and it has already had significant research done to improve it. It is already showing to be a more financially feasible energy source than fossil fuels on top of the reduced CO_2 emissions (Lee et al., 2023). The following figure is from the Synthesis Report of the IPCC Sixth Assessment Report (AR6) Longer Report and shows the price of energy from solar, onshore wind, and offshore wind. It compares it with the price of fossil fuels. It shows that since 2000 the price of solar energy has dropped significantly to the point where it is competitive with the price of fossil fuels. It also shows the market uptake increasing significantly since 2010.:

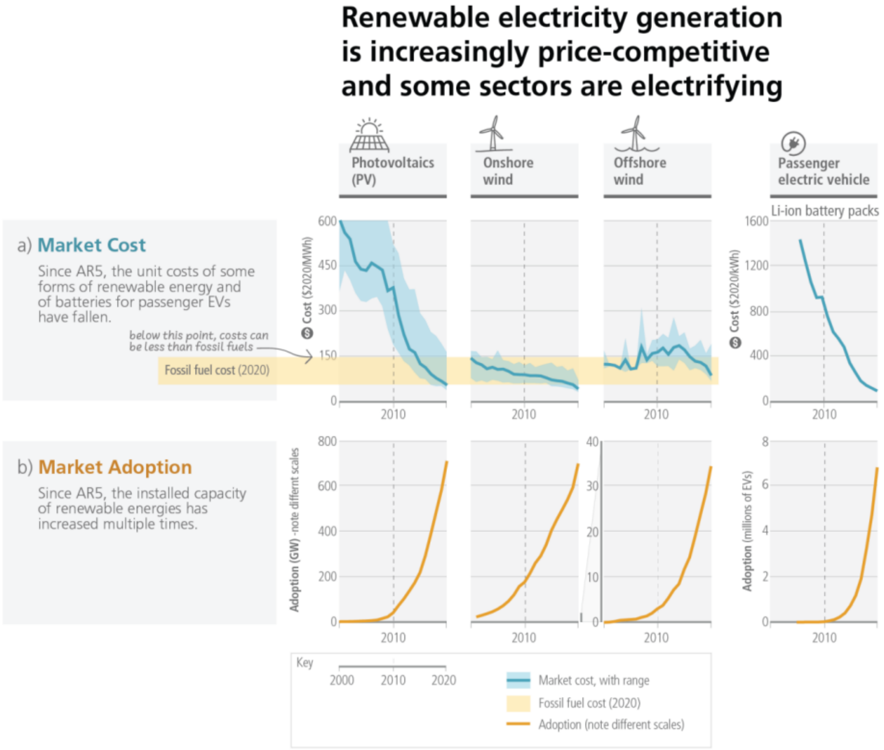


FIGURE 3

This figure shows that the prices of photovoltaics has dropped dramatically in the last 20 years, to the point where it is in competition with the cost of fossil fuels (coal and gas). The shaded areas around the center line represents the range between the 5th and 95th percentile. It also shows that since 2010 the market has shown a large increase in adoption of photovoltaics and wind energy. Reprinted from *Synthesis Report of the IPCC Sixth Assessment Report (AR6) Longer Report*. Lee et all., 2023, p. 20.

Solar energy converts radiation to electric potential in only one step (this is basically the photoelectric effect). Each time you convert energy from one form to another, inefficiencies are introduced, entropy increases, and you lose some of your energy to lower forms like heat. If you can minimize energy conversions, you use more and lose less of your initial energy. Solar energy directly converts solar energy into electrical with no extra steps to lose energy at. Current concerns about creating solar panels involve production costs and raw materials. Currently, solar panels require the mining of raw materials such as silicon, aluminum, silver, and copper, which has its own environmental downsides. A possible solution to this is more responsible recycling of these materials rather than mining them raw. Another possible solution is to rethink how we design them.

History of Solar Cells

Humans have been harvesting sunlight since before the ancient Greeks. They would use it for heating or magnify it to start fires. In 1887 the photoelectric effect was discovered by Heinrich Hertz. The photoelectric effect is when electrons are emitted from a material when hit with light that surpasses a certain threshold frequency depending on the material. The photoelectric effect is what led Einstein to consider light as quantized and coined the term photon in 1905. The first time that solar panels that looked like the ones we have today were made was in 1954 at Bell Laboratories in the United States. These solar panels were mostly motivated by powering space expeditions rather than terrestrial uses. Since then, climate and energy concerns have encouraged solar power to be used on earth rather than just in space. The efficiency of solar cells has also been greatly improved over time. Just recently in an article released in 2022, "researchers at the U.S. Department of Energy's National Renewable Energy Laboratory (NREL) created a solar cell with a record 39.5% efficiency under 1-sun global illumination. This is the highest efficiency solar cell of any type, measured using standard 1-sun conditions" (NREL Creates Highest Efficiency 1-Sun Solar Cell, 2022). As figure three showed there has been a significant increase in market adoption of solar energy since 2010. Homeowners have the chance to install solar. "Though most commercial panels have efficiencies from 15% to 20%, researchers have developed PV cells with efficiencies approaching 50%" (Photovoltaic Energy Factsheet, n.d.). Solar cells are being created with high efficiencies in lab environments but when in practical use they have lower efficiency.

There are many different types of solar cells, but the current most popular kind are crystalline silicon solar cells. There is a different kind of solar cell called dye sensitized solar cells. "The dye sensitized solar cell is a kind of photo electrochemical system, in which a semi-conductor material based on molecular sensitizers is placed between a photoanode and an electrolyte" (Smets et al., 2016, p 151). Though they typically have lower efficiencies they also have a cheaper production cost and a less environmentally damaging material cost. The first dye sensitized solar cells with high efficiency were made in 1991 by Michael Gretel in Switzerland at the Ecole Polytechnique federale de Lausanne (EFPL). In 2022 scientists at EFPL "fabricated dye-sensitized solar cells with greater than 15% efficiency under direct sunlight, and achieved efficiencies of up to 30% under varying ambient light condition (Enkhardt, 2022)" which is an appreciable efficiency considering most commercial solar panels are 15%-20% efficient.

Although they are less efficient at capturing the sun, it is worth exploring to see if the benefits outweigh the downsides when compared to the status quo of solar panels. These solar cells are created with two pieces of glass with a conductive coating, which is already a cheap and recyclable material. One piece of conductive glass is coated with a thin layer of titanium dioxide, an ingredient found in paint and sunscreen. The titanium is immersed in a pigment to darken it so that it absorbs the sun better. The pigment can be chemically engineered to have favorable energy levels and absorption spectra, but excitingly, I found success using pigment found within blueberries. Another piece of glass is coated with a layer of soot which can be created by simply holding it over a candle. You then make a sandwich with these glass pieces and put an iodide electrolyte between them and it is already turning light into electrical potential.

Theory

Electricity is about the motion of electrons. We create it by forcing them to move. There are different strategies to do this, like moving a magnet with mechanical energy in a generator, or creating a chemical reaction in a battery using chemical potential energy. Dye sensitized solar cells make electrons move by using the energy from sunlight through the photoelectric or photo electrochemical effect. Electrons are negatively charged and surround the positive nucleus of an atom. The positive nucleus attracts the negative electron. Like a rock on top of a building would have more gravitational potential energy than a rock on the ground, an electron can carry more potential energy by being pushed away from the nucleus. Because the electron would rather be closer to the nucleus it carries more potential energy when it is further away. An electron having this potential energy by being pushed somewhere it wouldn't want to go is in an "excited state". An electron sitting comfortably with no potential energy is in its "ground state". Electrons are only allowed to have very specific amounts of potential energy depending on the atom they are surrounding [electron cloud model]. In the gravitational potential analogy imagine a set of stairs rather than a continuous ramp. Because the electrons orbiting a nucleus can only carry specific amounts of energy, this means that they can only absorb or emit light (photons) as radiative energy that has a wavelength carrying the amount of energy corresponding to a difference between two of these levels.

The wavelength of light corresponds to the amount of energy carried in the photon. The equation to calculate this energy is:

Equation 1: $$E = \frac{hc}{\lambda}$$

Where h is Plank's constant, c is the speed of light, λ is the wavelength of the photon, and E is the energy (in joules).

Electrons are used to hold atoms together and create molecules. "Electron affinity" is a term used to describe and rank how much a molecule wants to hold onto electrons. In more technical terms, it is the change in energy when a neutral molecule gets an extra electron and becomes negatively charged. Molecules can have a more complicated structure than single atoms and, because of this, they have a much more complicated set of energy levels that the electrons are allowed to be at. Rather than having really specific energy levels that the electrons are allowed to be at, molecules have more degrees of freedom to hold or not hold energy in. Because of this, molecules can absorb wider wavelength ranges of light (wavelength bands) rather than the sharp exact lines of an atomic absorption spectrum. The places electrons are allowed to be are called orbitals. Orbitals can only hold two electrons before being full. Orbitals hold different amounts of potential energy, electrons in lower orbitals have lower energies and electrons in higher orbitals have higher energy. Electrons would rather be in lower energy orbitals so all of the lowest energy ones fill in first. Once all the electrons fall into their lowest energy orbitals and make the molecule neutral, one of the electrons will be in an orbital with the highest energy. This electron is in the "highest occupied molecular orbital", called HOMO for short. The first orbital that is empty after the HOMO is called the "lowest unoccupied molecular orbital" or LUMO for short.

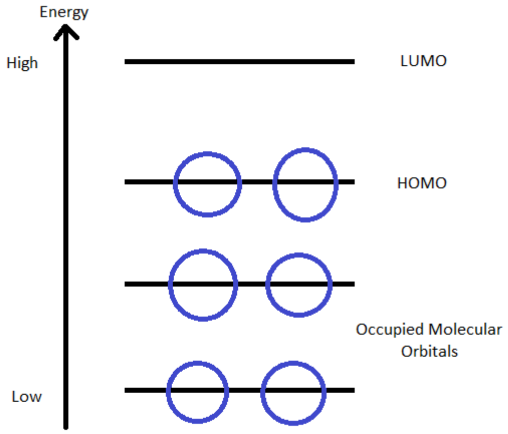


FIGURE 4

Visual representation of molecular orbitals. In this example the orbitals can only contain two electrons and fill up low energy to high. The HOMO and LUMO are labeled.

As previously stated, electrons cannot carry any amount of energy, instead are only allowed to occupy orbitals with discrete amounts of potential energy. Molecules can only absorb photons that carry energy in an amount that brings an electron from one orbital to another. The energy in the photon needs to be the same as the potential energy difference of an electron moving from one allowed state to another for absorption to have a chance of happening. This is why carbon dioxide is good at absorbing infrared light but doesn't absorb visible light. It doesn't have orbital transitions that have the amount of energy of visible light. More complicated molecules can have structures that make them better at absorbing certain types of light, because the orbitals are arranged such that the energy gaps between them correspond to a certain regime of the electromagnetic spectrum. Dyes are molecules that are good at absorbing light in the visible spectrum while leaving out some specific colors to create a visible color to our eyes. This happens because of a combination of reflection, absorption, and transmission of light.

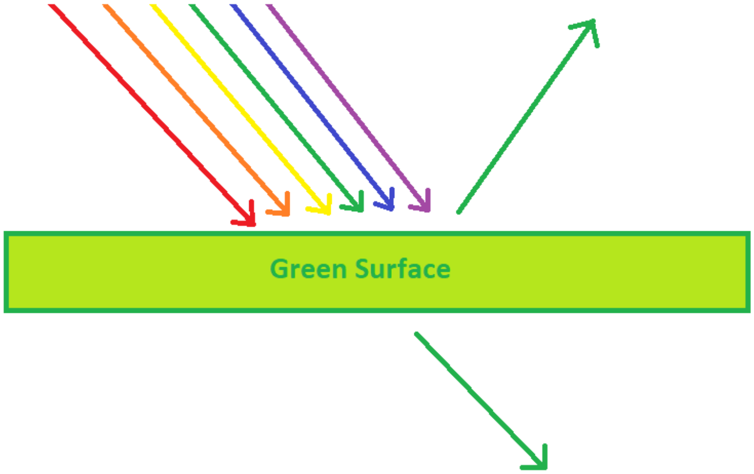


FIGURE 5

When in an environment with white light, a material that appears green to an observer is reflecting green light, while absorbing everything else.

When a molecule absorbs a photon in a wavelength it can absorb, usually what happens is an electron jumps from the HOMO to the LUMO. When an electron is brought to the LUMO, we imagine that it leaves behind a hole where it used to be. The excited electron and the electron hole together are called an "exciton".

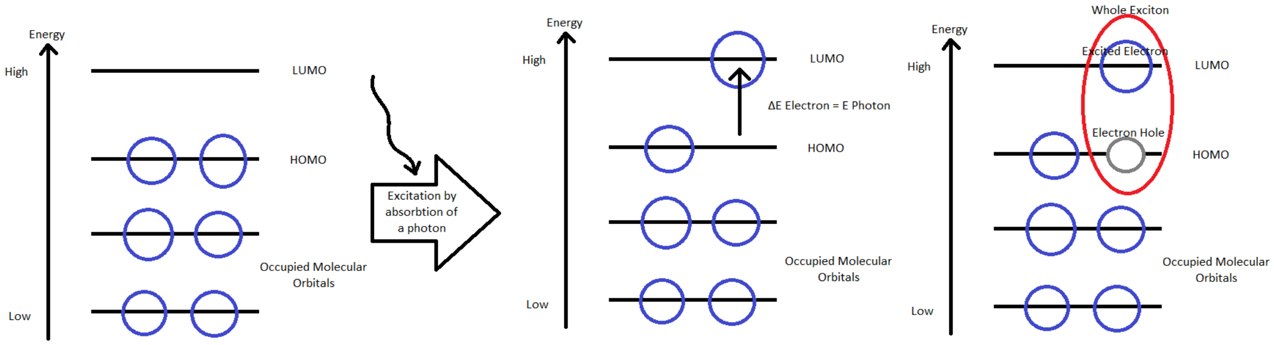


FIGURE 6

Diagram showing the absorption of a photon causing an electron to rise up an energy level, leaving behind an electron hole creating an exciton.

The formation of an exciton is the first step of how dye sensitized solar cells capture sunlight. What the electron would usually want to do is then relax back to its ground state in the HOMO, dissipating the energy. Instead, we can put it into a material with a higher electron affinity that has an orbital with a potential energy between the HOMO and LUMO of the original material.

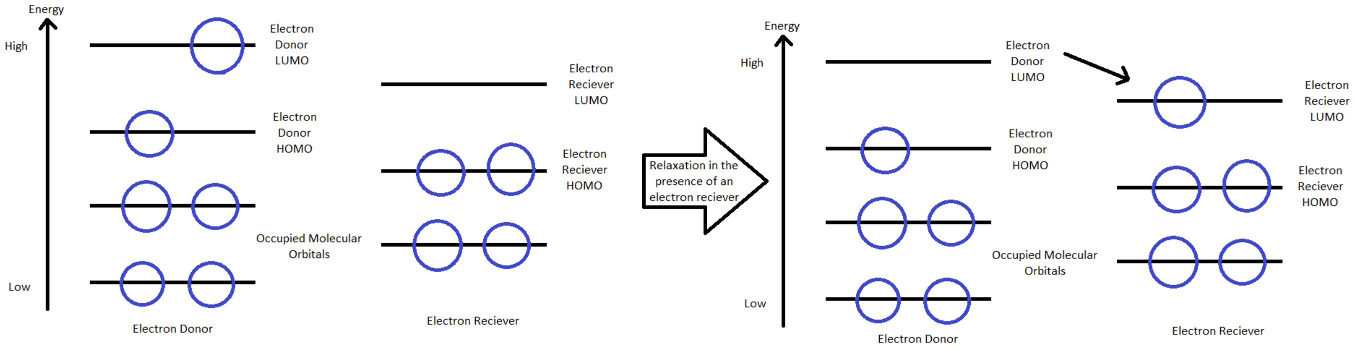


FIGURE 7

Diagram showing the process of an excited electron leaving the original material to the receiving material taking a smaller potential energy drop.

In this case, the electron instead will jump to the new material taking a smaller potential energy drop.

The original material is called the electron donor and the one that receives the electron is the electron receiver. In the case of the dye sensitized solar cell, the electron donor is the blueberry pigment and the electron receiver is the titanium dioxide. The titanium dioxide is conductive and then conducts the electron into the circuit. This then leaves an electron hole behind which needs to be filled. To solve this there is an electrolyte of negatively charged iodide that gives electrons to the dye. Three negatively charged iodide ions ($3I^-$) give two electrons to two positively charged dye molecules, creating one negatively charged triiodide (I_3^-) and two neutral dye molecules:

Equation 2: $$2Dye^+ + 3I^- \rightarrow 2Dye + I_3^-$$

The triiodide then goes to the end of the cell opposite where the titanium conducts the electrons to, picks up 2 electrons from the circuit, and converts back to 3 negative iodides. In Arno Smets' description of dye sensitized solar cells in the book *Solar Energy*, he describes a platinum to facilitate this reaction. In the protocol I followed which was Smestad's *Titanium Dioxide Raspberry Solar Cell*, candle soot is used in the place of platinum:

Equation 3: $$I_3^- + 2e^- \rightarrow 3I^-$$

This completes the cycle, moving an electron excited by the absorption of a photon from the dye molecule through the titanium dioxide to a contact of a circuit, and replacing the electron hole with an electron received from the other end of the circuit.

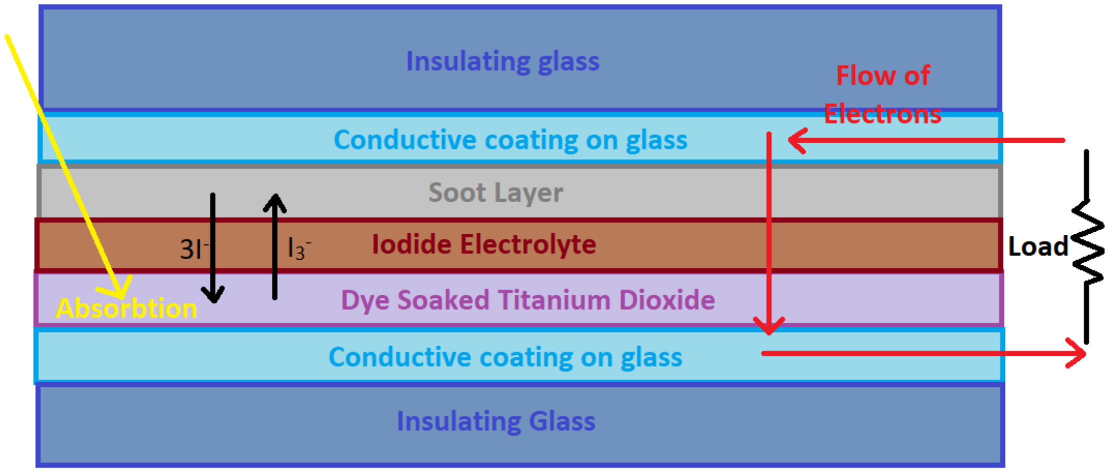


FIGURE 8

Visual representation of the layers in the constructed solar cell. The direction of electron flow is also shown. In reality, the soot layer is pressed against the dye-soaked titanium dioxide layer and the iodide electrolyte is saturated through the soot and dye-soaked titanium dioxide layer. The titanium dioxide layer is where the photons are getting absorbed. It also shows the path of the negative iodide giving electrons to the titanium and becoming one negative triiodide, then returning to the soot layer and becoming three negative iodides again.

Application: Geometric Considerations

Locating the Sun

The path the sun takes is not as simple as one would think, and is very important when considering the geometry of how to arrange solar panels. The sun goes from 0 to maximum elevation at solar noon every day depending on the day of the year and latitude. The azimuthal angle changes based on latitude, time, and day of the year. 12 pm solar time is different from 12 pm of the time zone. Solar time is specific to the exact location.

There are equations that can be used to calculate the solar altitude a_s and the solar azimuth A_s with great accuracy. These equations are from the book *Solar Energy* written by Arno Smets et al. in the chapter *Some aspects on location issues.* This equation takes into account earths elliptic orbit and rotating tilted axis:

Equation 4:
$$tan\ A_s = \frac{-\sin\theta_L \cos\lambda_S + \cos\theta_L \cos\epsilon \sin\lambda_S}{-\sin\varphi_0\ \cos\theta_L \cos\lambda_S - (\sin\varphi_0 \sin\theta_L \cos\epsilon - \cos\varphi_0 \sin\epsilon)\sin\lambda_S}$$

Equation 5:
$$\sin a_S = \cos\varphi_0\ \cos\theta_L \cos\lambda_S + (\cos\varphi_0 \sin\theta_L \cos\epsilon - \sin\varphi_0 \sin\epsilon)\sin\lambda_S$$

Where φ_0 is the latitude of the observer. θ_L , λ_S and ϵ all have their own multi step calculations. First, we need to calculate the time passed since Greenwich noon on January first 2000, D:

Equation 6:
$$D = JD - 2451545.0$$

Where JD is the Julian date. "The Julian date is defined as the number of days since 1 January 4713 BC in a proleptic Julian calendar or since 24 November 4717 BC in a proleptic Gregorian calendar (Smets et al., 2016, p 419)." ϵ is the angle of the tilted ecliptic and is calculated as follows:

Equation 7:
$$\epsilon = 23.429° - 0.00000036°\, D$$

λ_S is the ecliptic longitude of the sun which you can calculate with:

Equation 8:
$$\lambda_S = 280.459° + 0.98564736°\, D + 1.915° \sin(357.529° + 0.98560028°\, D) - 0.02° \sin 2(357.529° + 0.98560028°\, D)$$

θ_L is the local mean sidereal time and is calculated with the following equation (h stands for the unit hour. The word hour is where you put time of day in hours from 0 to 24):

Equation 9:

$$\theta_L = \left(18.697374558h + 24.06570982441908h \times D + 0.000026h \times \frac{D}{36525}^{2}\right)\frac{15°}{hour} + \lambda_0$$

Where λ_0 is the longitude of the observer. Now all of the pieces are there to solve for tan A_s and sin a_s. To solve for the actual values of A_s and a_s you can apply the inverse functions of arcsine and arctan. Arcsine is a well-defined function in this case and will give you a value for a_s between -90° and 90° degrees which is an appropriate range for this situation. If a_s has a value below 0° this means the sun is below the horizon. Arctan is less well behaving for this case however. We want to get a value within the range of 0° to 360° but that is not in the range for arctan so we add some conditions. Different cases call for different treatments. It is helpful to define two terms:

Equation 10: $$A = -\sin\varphi_0 \cos\theta_L \cos\lambda_S$$

Equation 11: $$B = -\sin\theta_L \cos\lambda_S + \cos\theta_L \cos\epsilon \sin\lambda_S$$

In the case that A is more than zero and B is less than zero you would add 360° to arctan (tan A_s). In the case that A is more than zero and B is more than zero you would add nothing. In the case that A is less than zero (regardless of B being greater than or less than zero) you would add 180° to arctan (tan A_s). Following these guidelines, the values received for A_s will make sense translating to the way the earth rotates in a circle.

These equations find exact angles of sunlight but become very difficult to visualize very quickly. There are plots that show A_s and a_s in a much easier to visualize way. They show the path of the sun through a day as a line and have lines for different times of year. One of these kinds of plots evaluated for the latitude and longitude of Bard College is included:

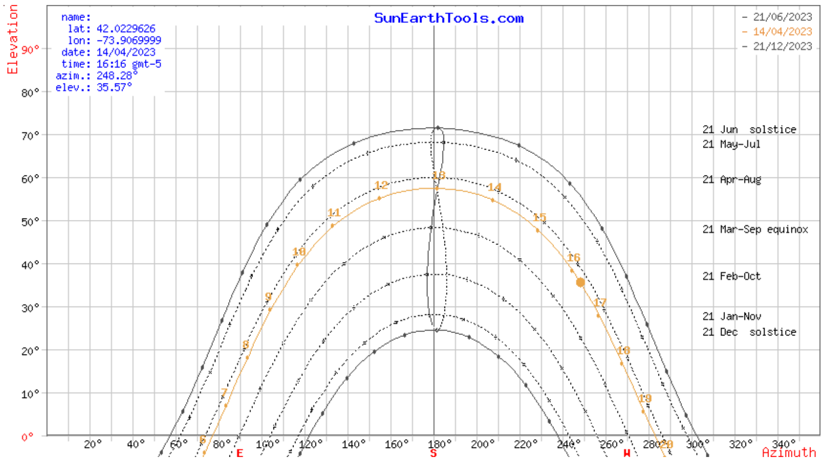


FIGURE 9

This figure was generated using SunEarthTools.com's sun position calculator. Each continuous line represents the path of the sun through a day, the azimuthal angle changes from sunrise to sunset, and the elevation changes. The separate lines represent days at different times of year showing that the elevation of the sun changes over the course of a year.

When thinking about how light reflects off the surface of solar panels ray tracing is a helpful tool to follow the path of the light as it hits an interface. The angle of light leaving the interface (reflected light) of the solar panel can be calculated with the following equation (note that the use of φ and θ here are distinct from the previous set of equations):

Equation 12: $$\varphi = \pi - \tau - 2\theta$$

Where the angle is measured from horizontal to the left and sweeping 2π radians clockwise about the point of contact. φ is the angle of the reflected light from the left horizontal. τ is the angle of the incoming light's direction. θ is the angle the surface makes to the closest horizontal. In the case where the light is transmitted through the surface rather than reflected the angle wouldn't change. The following figure visualizes these angles and where they are in reference to.

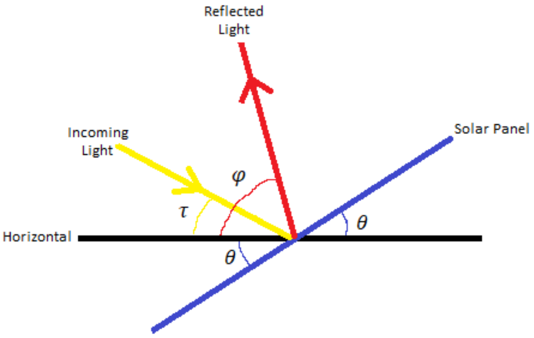


FIGURE 10

Diagram showing the path of light being reflected off the surface of a solar panel. Each angle is shown with a letter and an arc showing where the angle is measured from.

You can repeatedly apply this equation in an iterative method. After solving for the angle of the light after hitting the surface, you can use that angle solved for as the new angle of incoming light for the second time using the equation. If you say that the light was transmitted the angle of incoming light would remain the same. This example is only in two dimensions. A 2D case doesn't capture all of the complexity of living on a planet with a tilted plane, however.

A natural next question to ask would be how much light gets absorbed compared to how much gets reflected to decide which to prioritize engineering to capture. If more light is reflected than transmitted, one would want to create arrangements that would capture the light. If more light is transmitted one would want to prioritize layering them in the same path as the original light. In traditional solar farms, you usually see large fields filled with solar panels. If you think about stacking solar cells vertically this frees up land space to be used for other purposes or wildlife habitat. Vertical stacking of solar cells also allows them to be installed in cities that don't have access to open fields but flat roof tops and vertical walls.

Absorption, Reflection, and Transmission

One could answer this question of the ratio between absorption, transmission, and reflection experimentally, however a challenge to this experiment would be measuring the transmitted light because the solar cell diffuses the light. If you were doing an experiment with a collimated beam of light the input, and reflection would be easily measured, but the transmission would be challenging to accurately measure. Without the transmission it would be challenging to calculate how much got absorbed. To calculate how much got absorbed you would want to know the input, then subtract the transmitted and reflected, but without the transmitted you couldn't know exactly how much was absorbed. Reflection of light is also very dependent on angle. When hitting an interface between two materials with different refractive indices, some light will get reflected and some will get transmitted. How much that gets reflected depends on angle and polarization. Polarization, put in simple terms is like the direction that light is facing. Sunlight is unpolarized meaning that it is facing all random directions. Unpolarized light can be roughly be approximated to being a 50/50 combination of perpendicular and parallel (vertically and horizontally) polarized light. The equations to determine how much light gets reflected and transmitted are called the Fresnel equations. The Fresnel equations for perpendicularly polarized light are:

Equation 13:
$$t_{\perp} = \frac{2\, n_1 \cos\theta_i}{n_1 \cos\theta_i + \ n_2 \cos\theta_t}$$

Equation 14:
$$r_{\perp} = \frac{n_1 \cos\theta_i - n_2 \cos\theta_t}{n_1 \cos\theta_i + \ n_2 \cos\theta_t}$$

Where $r_{\perp}$ represents how much of the perpendicularly polarized light gets reflected and $t_{\perp}$ transmitted. There are similar equations for the parallel light:

Equation 15:
$$t_{\parallel} = \frac{2\, n_1 \cos\theta_i}{n_1 \cos\theta_t + \ n_2 \cos\theta_i}$$

Equation 16:
$$r_{\parallel} = \frac{n_1 \cos\theta_t - n_2 \cos\theta_i}{n_1 \cos\theta_t + \ n_2 \cos\theta_i}$$

Where n_1 is the refractive index of the first material and n_2 is the refractive index of the material being hit. An index of refraction is a value that depends on how quickly light can move through a material. The slower light moves through a material the higher its index of refraction. Vacuum has in index of refraction of 1. Air has an index of refraction of very nearly 1 and glass has an index of refraction of usually around 1.5. θ_i is the angle the light makes to the normal (normal means perpendicular to the surface) when hitting the surface. θ_t is the angle the transmitted light makes to the normal.

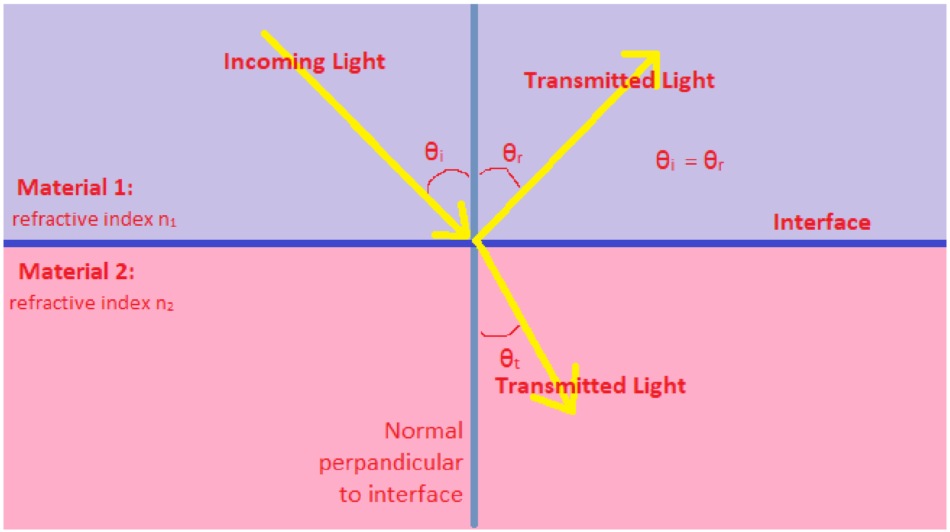


FIGURE 11

This figure helps to visualize light hitting an interface and the different angles it makes with different surfaces.

θ_t can be calculated using the relationship known as Snell's Law:

Equation 17: $$n_1 \sin\theta_i = n_2 \sin\theta_t$$

These solar panels absorb, reflect, and transmit any light that hits them. Our goal is to maximize how much energy gets absorbed which could mean sending the reflected and transmitted light into more solar panels. Rather than experimentally solving for the ratio transmission, reflection, and absorption you can use these equations to solve for the relationship between angle of incidence and these ratios. The cheaper and more recyclable nature of the dye sensitized solar cells allow us to consider creating more and placing them in an advantageous arrangement. You could lay them all flat and cover a larger area or you could get creative and place them in a way that makes better use of the light that is transmitted and reflected, trees are already experts at doing this.

Biomimicry

Trees use leaves arranged in a pattern such that any one of them isn't absorbing 100% of the light, but letting some through and scattering onto all the other ones. Nature has spent millions of years refining how to turn sunlight into other forms of energy, so we don't need to reinvent the wheel when it's already been perfected. For photosynthesis "The theoretical maximum efficiency of solar energy conversion is approximately 11%. In practice, however, the magnitude of photosynthetic efficiency observed in the field, is further decreased by factors such as poor absorption of sunlight due to its reflection, respiration requirements of photosynthesis and the need for optimal solar radiation levels. The net result being an overall photosynthetic efficiency of between 3 and 6% of total solar radiation" (Miyamoto et al., 1997). Though 3-6% efficiency sounds low it is obvious that plant life is thriving. So much so that it allows other life forms like humans to thrive off them too. Low efficiency is balanced by quantity and clever arrangements. Current solar panels leverage the high intensity direct sunlight, but plants are good at capturing diffuse light. Maybe we can learn from nature better ways to use the sun.

There is a beautiful paper by Alexander Knohl and Dennis D. Baldocchi titled *Effects of diffuse radiation on canopy gas exchange processes in a forest ecosystem*, that discusses the effect of leaf arrangements on their rate of gas exchange. Gas exchange is measured as the flux of CO_2 and water vapor. This measurement can be used as an analogue for the rate of photosynthesis. Trees are able to make use of light better the more diffuse it is. This is because the leaves on the top are usually radiation saturated in usual sunlight conditions, so brighter light does not mean they are able to photosynthesize any better. The shaded leaves layers under the top are usually not radiation saturated, so if the light is more diffused it goes more evenly through to leaves under the surface ones, overall increasing the radiation use efficiency. (Knohl & Baldocchi, 2008). The following plot shows normalized net ecosystem exchange (NEE) for two different forest sites plotted over different ratios of diffuse to direct sunlight (R_d/R_s). Normalized data means they took the average of all the data points and made set the average to one. Then the data is centered on one, it is a good strategy to be able to see change. R_d/R_s is the ratio of diffuse light to total light, 0 would be no diffuse light, .5 would mean half of the light is diffuse, 1 would mean all of the light is diffuse.

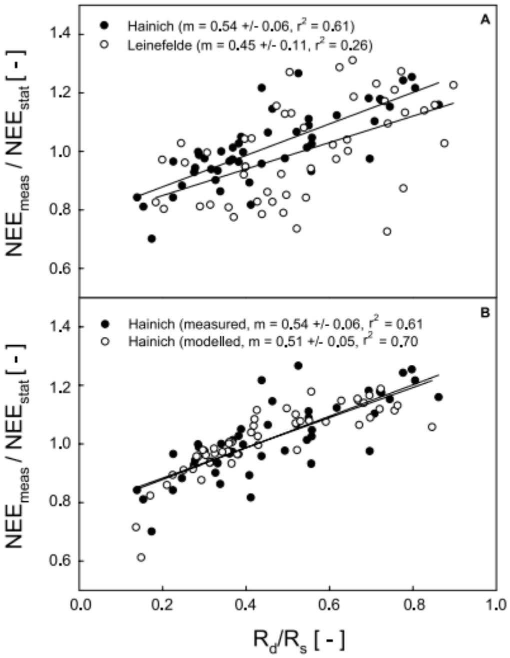


FIGURE 12

This plot shows the relationship between the net ecosystem exchange at different ratios of diffuse light. Panel A on top shows this relationship at two different forest sites. Panel B shows this relationship from measured data and modeled data. The model very closely resembles the measured data. The trend linear growth, showing that NEE is higher at higher ratios of diffuse light. Reprinted from *Effects of diffuse radiation on canopy gas exchange process in a forest ecosystem.* Knohl, A., & Baldocchi, D. D. 2008. P. 5.

This plot shows that light being diffused is advantageous to a forest ecosystem's rate of net ecosystem exchange (or photosynthesis). Knowing that the diffusion of light has a positive impact on the rate of photosynthesis, the higher the diffuse light effect the higher the rate of photosynthesis. Figure 13 shows the diffuse light effect plotted over leaf area index. Diffuse light effect (slope) means how steep a slope would be on a plot like figure 12. A higher diffuse light effect means higher increase in photosynthesis as light goes from direct to more diffuse. It is how sensitive the system would be to the diffusion of light. Leaf area index is in m^2/m^2 and is a value representing how many leaves there are per unit of space. A leaf area index of 6 would mean there are six leaves total in the area of a single leaf.

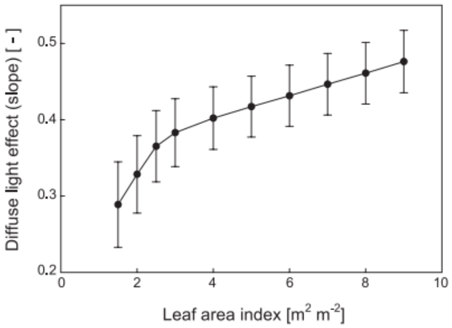


FIGURE 13

This figure shows and increasing diffuse light effect at higher leaf area indexes. The slope gets less steep at a leaf area index of 3 but remains positive. Reprinted from *Effects of diffuse radiation on canopy gas exchange process in a forest ecosystem.* Knohl, A., & Baldocchi, D. D. 2008. P. 6.

The data shows that the higher the leaf area index the more strongly the system benefits from the diffusion of light. There is also data on the arrangement structure on leaves. The following two plots show the relationship of the diffuse light effect to leaf clumping factor and to leaf inclination angle. A leaf clumping factor close to one means randomly distributed leaves, and a leaf clumping factor that is low means leaves are clumped together.

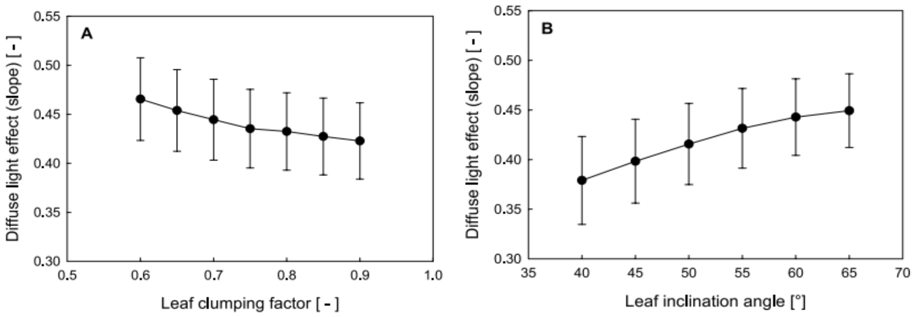


FIGURE 14

Panel A shows the diffuse light effect's relationship with leaf clumping factor. The higher the leaf clumping factor the lower the diffuse light effect is. Panel B shows the diffuse light effect's relationship with leaf angle of inclination. The higher the leaf angle of inclination the higher the diffuse light effect. Reprinted from *Effects of diffuse radiation on canopy gas exchange process in a forest ecosystem.* Knohl, A., & Baldocchi, D. D. 2008. P. 6.

The figure shows that trees with high leaf clumping factor (randomly distributed leaves) have a smaller diffuse light effect than trees with lower leaf clumping factor (clumped leaves). It also shows that trees that have leaves at a higher angle of inclination have a higher diffuse light effect. These effects are because they allow for light to penetrate deeper into the canopy without needing diffusion to reach lower leaves. Clumped leaves leave gaps for light to reach deeper leaves, and leaves angled up allow similarly allow light to deeper canopy layers without requiring external diffusion of the light. Knohl and Baldocchi also plotted the relationship between diffuse light effect and reflectance and transmittance.

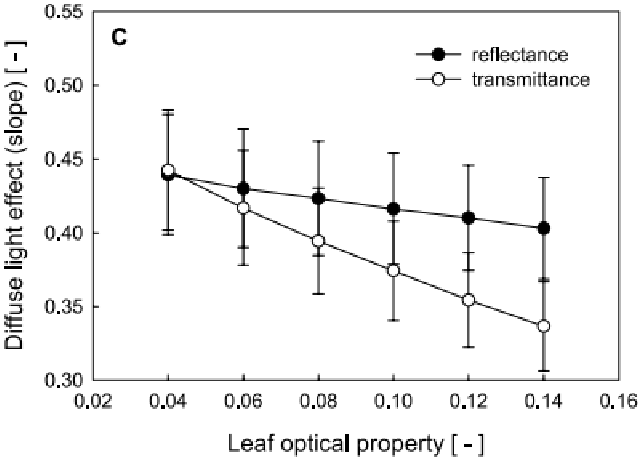


FIGURE 15

Diffuse light effect plotted over the reflectance and transmittance of leaves. Reprinted from *Effects of diffuse radiation on canopy gas exchange process in a forest ecosystem.* Knohl, A., & Baldocchi, D. D. 2008. P. 6.

This figure shows that the higher the reflectance of the leaves the smaller the diffuse light effect is. It also shows that the higher the transmittance of the leaves the weaker the diffuse light effect is with an even steeper slope than the reflectance relationship. This is because highly transmittive and reflective leaves diffuse the light on their own. Leaves that don’t reflect or transmit as much diffuse the light less themselves and therefore are more sensitive to external diffusion of light.

Dye sensitized solar cells can be treated similarly to tree leaves. They have reflection and transmission and diffuse light that passes through them. The amount of light that gets transmitted could potentially be designed to be in different amounts using different thicknesses of layers of titanium. Knowing everything we know now about clumping, angle, and leaf area index, maybe the forest can give us inspiration for how to arrange our solar panels.

Fabrication

This chapter describes the process required to create dye sensitized solar cells. The process starts with an attempt at making glass with a surface conductive coating but I was unsuccessful in completing this. The glass was ordered but the process of creating surface conductive glass is described. Then using this glass, it is explained how to create a functional solar cell.

Creating conductive glass

The method followed to create surface conducting glass was *Preparation of Surface Conductive Glass* retrieved from MRSEC Education Group. The materials required to create surface conducting glass are:

- Propper PPE (goggles, heat resistant gloves, protective clothing i.e., lab coat)
- Tongs
- Fume hood
- Scale
- Furnace able to reach 600c
- 5g of $SnCl_4 5H_2O$
- 0.10g of Sb_2O_3
- 5mL of methanol
- 1 mL of concentrated HCl
- Compressed air source
- Capillary tubes
- Glass microscope slide
- Heat resistant ceramic tile
- Syringe
- Glass to be coated

A main requirement for this sort of solar cell to be created is to have a solid surface that allows light to pass through and has one surface that is conductive. Some pieces of glass with these properties were kindly lent by Christopher Lafratta but the surface area was very small. A search online showed that ordering conductive coated glass would be rather expensive.

Step 1: Preparing the solutions and applicator

Create a solution of 5g of $SnCl_4 5H_2O$ dissolved into 5mL of methanol. Create another solution dissolving 0.10g of Sb_2O_3 into 1 mL of concentrated HCl. Mix the two solutions. An atomizer is made using two capillary tubes taped to the same side of a glass microscope slide such that the ends of one side of each tube is secured near the edge of the slide pointing at each other at an angle. The other ends of the capillary tubes are left free to dangle at this point. Pump pressurized air through one of the capillary tubes and with a syringe inject the prepared solution into the other capillary tube. With enough air pressure through the air tube the solution should be propelled into the air. See Figure one for example of atomizer setup.

FIGURE 16

Constructed Atomizer with capillary tubes fixed to a glass microscope slide meeting at an angle. One tube is for a gas propellant and the other tube is for the liquid.

Step 2: Baking Process:

For this step, to observe proper safety, work in a fume hood with eye protection and heat protective gloves and tongs. Preheat a furnace to 600c with a large ceramic tile inside. Place the glass microscope slides onto another ceramic tile and insert them in the oven to preheat for ten minutes. The atomizer and solution are on hand ready for use. After the preheating, remove the top tile with the glass on it from the oven and spray with the solution using the atomizer then return to the oven for two minutes. After two minutes of reheating repeat the spraying procedure. Repeat for several coats. Allow to cool.

I found the ambiguity of “several coats” to be annoying but after I did four, any usable size piece of glass had been shattered by temperature shock so I couldn’t persist on to see what a good number of coats would be.

Creating the solar cell

The procedure followed to create the solar cells were following Smestad’s *Titanium Dioxide Raspberry Solar Cell* retrieved from MRSEC Education Group. Modifications were made to this procedure. The materials required to create the dye sensitized solar cells are:

- Gloves
- Mortar and pestle
- Hot plate
- Scale
- Deionized water

- Ethanol squirt bottle
- Scoopula
- Glass microscope slide or flat edge
- Scotch tape
- Kimwipes
- 1M Acetic acid
- Nanocrystalline Titanium Dioxide
- Candle
- Matches
- 10 ml Graduated Cylinder
- Transfer Pipette
- Litmus paper (appropriate for a 3-7 range)
- Multimeter and banana cables with alligator clips
- Tongs or Tweezers
- Chemical waste container, labeled with titanium dioxide, acetic acid, and ethanol
- Beaker in the size range of 200-600ml

Step 1: Preparing the Glass

On each piece of glass double check which side is conductive coated and which side isn't. Wear gloves and use ethanol to wipe clean any dust or fingerprints off of each piece of glass. On the conductive side of one of the pieces of glass, place one layer of scotch tape along three of the edges covering about 2mm of the edges of the glass. (See Figure 1)

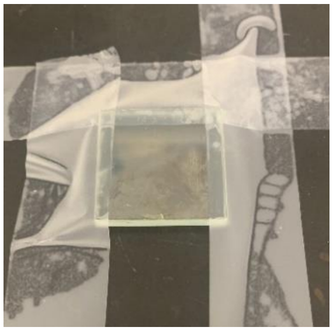


FIGURE 17

Visual of how to arrange the tape edges

Step 2: Applying the titanium paste

Create a solution of acetic acid diluted with deionized water until it is a pH of about 3.5. An appropriate amount to create would use 10mL of deionized water and 1 mL of 1M acetic acid. This ratio should get you a proper dilution but it is good to check with litmus paper. In a mortar and pestle combine 0.35g of titanium dioxide with 1mL of the diluted acetic acid solution. These numbers are appropriate for coating the surface of one 2.5cmx2.5cm piece of glass. Scale this ratio up as needed. Do not mix the titanium dioxide and acetic acid until you are ready to apply it immediately after mixing it because it dries and thickens quickly. Spread out the titanium dioxide paste across the surface of the glass and scrape it flat using a flat surface. I used a microscope slide for this. This process will make the titanium paste the thickness of the tape

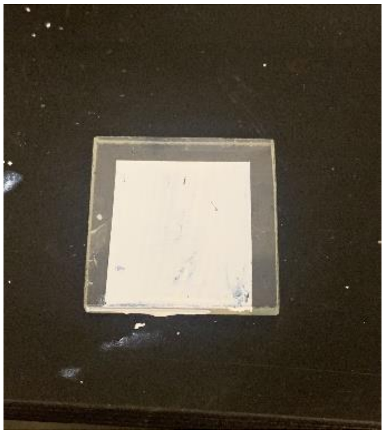


FIGURE 18

Proper titanium application

border at the edges all the way across the surface. Allow the paste to dry then remove the tape without disturbing the paste in the center. Then put the coated glass on a hot plate and bake at 260C for 20 minutes. The white surface must darken to a brown color then return to white. Only once it has returned to white after a darkening is it ready.

Step 3: Coating with soot

For the other piece of glass, pass it over a lit candle using tongs or tweezers to coat it in soot. Don't let the glass linger of the fire, pass it over in consistent paced one second passes until an even dark coating is achieved. Then, using a wipe, clean off three edges in a similar way to the other piece of glass not having titanium at the edges. The soot wipes off very easily so b careful not to touch the other parts of the glass to not remove it where you don't want to remove it.

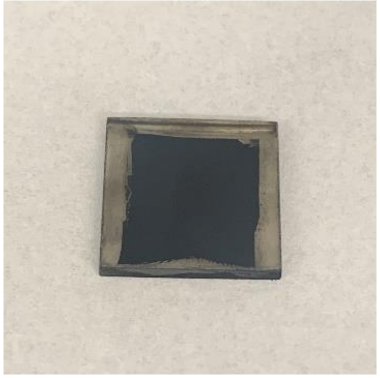


FIGURE 19

Soot with wiped edges

Step 4: Preparing and applying the dye

Place a handful of berries into a pan or beaker with a small amount of water. Crush the berries with a spatula and heat over medium high heat stirring constantly and mixing. Do this until the mixture has thickened substantially but not dried out. Pour the contents of the pan into a cheese cloth over a container. Allow it to cool enough to grab then squeeze the remaining liquid from the berry solids. You should be left with a dark purple somewhat viscous liquid with no solid in it in the container. If there are solids run the liquid through a cloth with smaller holes. Then using a transfer pipette suck up a small amount of this dye liquid and place drops on the titanium coated glass to coat the surface of the titanium. You don't need so much that it overflows over the edges. Let sit like this for 15 minutes. After the 15 minutes use the ethanol squirt bottle to spray the surface and remove the excess liquid. You should be left with only the titanium that now has a purple hue. Leave them titanium side up until they evaporate completely and are dry.

Step 5: Final assembly

Once the piece of glass with the titanium is cooled down place it in a dish submerged in the berry juice pigment. Let sit for 15 minutes. After the 15 minutes, rinse the surface gently with ethanol to remove any debris. Do this over your beaker to catch all of the ethanol and runoff. Once both pieces of glass are cooled and dried create a sandwich with them, placing the sides with the coatings facing each other. Each piece of glass should have three exposed clean edges and one where the substrate is all the way to the edge. The pieces should be placed such that they overlap completely on the soot and titanium sides but not where the glass edges show.

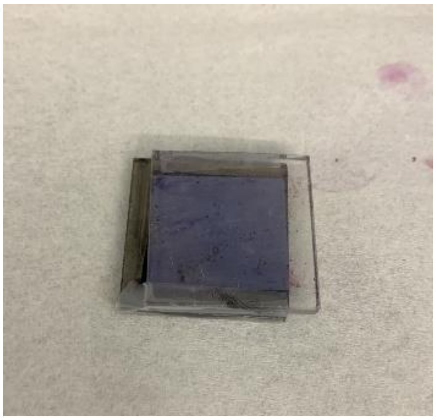


FIGURE 20

How the two pieces should be stacked

Rotate one 180 degrees and offset by the distance between the cleaned edge and soot and titanium coating so each side has the middle exposed glass edge sticking out enough to be clamped to with an alligator clip. On the edges that don't have overhang you can clip together using binder clips or tape with scotch tape. Now put a few drops of the iodide solution into the exposed overlaps. Let it seep in until it reaches the center and that is enough of the iodide. Now clamp one of each of the exposed pieces of glass to a volt meter or a resistor with an ammeter and you should have your functioning solar cell!

Step 5: Cleanup

To clean up rinse your mortar with deionized water and wearing gloves rub the surfaces to clean them. Pour the contents into the chemical waste container. Repeat as necessary with the mortar and pestle until it is clean enough that you are confident washing it in the sink won't put anything more than trace amounts of titanium down the drain. Titanium should not go into the wastewater system and should instead be disposed of in a chemical waste container for proper responsible disposal. Repeat this with the scoopula and all other dirtied materials. The only thing you can pour down the drain is clean water. Leftover diluted acetic acid can be saved for a future solar cell or poured into the waste container.

Obstacles in Fabrication

Going through all of the steps of creating the solar cell there are a lot of places things can go wrong. The following section describes all of the places things went wrong, and possible solutions to each obstacle. It is not an extensive list of everything that can go wrong just the ones encountered.

Conductive Glass:

The process of attempting to put a conductive coating on glass myself posed its own problems. I was following a procedure that involved spraying a solution onto the surface with an atomizer and baking at 600C then repeating with several coats. The temperature shock of coming out of a 600-degree oven then getting sprayed with compressed air and methanol then being put back into the oven would cause all of my glass to shatter. Even the ceramic plates used to transport the glass would crack. More temperature resistant glass could be used. The solution was at room temperature and the compressed air to propel the solution with the atomizer came out rather cold. The cold air from the atomizer will be hard to get around because the rapid expansion of compressed air it will always cool down significantly. Potential solutions to this are slower cool down and ramp up times, using hot air and solution to spray onto the glass so there is less temperature shock. I could also use a less aggressive misting spray bottle to apply the solution. The other option is to fully find a different way to apply a conductive coating. The procedure followed only said to apply "several" coats, which was not very descriptive. After four applications any appreciable size piece of glass was broken by temperature shock, so I will not attempt this again unless a solution to this issue is created. After doing five coats a small shard of glass read to have a resistance of 132 ohms across about a half centimeter length. Many regimes of the glass surface were also not at all conductive, I suspect due to uneven application with the atomizer. Doing the procedure alone was challenging to transfer the hot materials and quickly use an unwieldly atomizer and return to the oven. To those attempting to reproduce I recommend having a partner to operate the tongs or the atomizer so you don't have to place the glass on the countertop. Ultimately, 10 2.5cmx2.5cm pieces of conductive coated glass were ordered ready-made.

In theory the material used to make a solar cell of this type just needs to let light pass through and have a conductive surface. If one wanted to follow up with the fabrication of coating a transparent surface there are several leads they could follow. There are companies that work with 3D printing ceramic material. Ceramics can have many different properties when chemical engineered with purpose, like being transparent, conductive, or temperature shock resistant. The 3D printed aspect also allows freedom of shape that can create interesting geometries. One of these ceramic 3D printing companies is Lithoz America. Another possible solution to creating a conductive coating could be evaporating a thin layer of material onto the surface. Bard has several pieces of equipment capable of depositing a thin layer of gold or chrome onto surfaces. I am unsure of how thickness of a metal coating relates to the opacity or conductivity.

We already have in the lab a piece of flexible plastic that is conductive on one side, but the downsides to using this are that it is tinted blue and would absorb some of the light before it is able to be converted to electricity. Also, the surface being used needs to be able to withstand a high temperature for the step when the titanium dioxide acetic acid mixture gets baked on. Part of what is going to be explored is the advantages of cheaper semi-transparent solar cells' ability to better absorb diffuse light rather than largely direct light, and coming from the sky a lot of the diffuse light is blue. Regarding the plastic, however, the flexibility does present exciting versatility to its potential applications.

Flaking Titanium:

Regarding the process of baking the titanium dioxide acetic acid mixture, flakes of titanium peeled off the glass while soaking in the pigment the first time I made a solar cell. I suspect two reasons for this. One could be because it didn't bake for long enough. The second reason could be because I applied too thick of a layer of titanium paste. To apply the titanium dioxide acetic acid paste with a consistent thickness, you put scotch tape around the edges of the glass, then scrape a flat surface across the glass so the paste is at a consistent thickness across the whole surface, as thick as the tape at the edges. I elected to put two layers of tape on the edges, which may have been too thick and caused the flaking. In subsequent attempts a single layer of tape was used, baking was longer and hotter. Another potential cause for the flaking titanium could be a sub optimal ratio of mixture of titanium and acetic acid in the mortar and pestle, the directions I followed weren't super precise, they described a desired texture rather than giving measurements of each.

After following up, utilizing a single layer of tape, with a standardized ratio of titanium dioxide to acetic acid solution, and measured baking time, the titanium did not flake off the surface of the glass. The standardized ratios and measured baking times are the ones used in the procedure described above. These corrections creating a more successful product validate my hypotheses about what went wrong in the earlier trial.

Baking the Titanium dioxide paste:

The baking process is an important step of the procedure. In earlier versions of creating them I would only bake at 150C and not observe the darkening and return to white. Solar cells that were created without baking to a high enough temperature would behave almost like capacitors. They would take 15 or so minutes to charge to a voltage of about 150mV, then when exposed to light would return to nearly zero volts. They would also return to zero volts if a circuit was completed and only produce a very small current in darkness and produce less current when exposed to light. At higher baking temperatures this was no longer an issue.

Optical Experiments

Three experiments were attempted to better understand the properties of the fabricated solar cells. The first experiment was about the type of light the blueberry dye that was used absorbed so it can be compared to the light of the sun to see if it is an effective match. The second experiment utilizes a white light source shined on the solar panel to see the effective power produced by the solar cell. If you measure the total energy of the light hitting the surface of the solar cell and compare it to the total energy produced by the solar cell you can calculate the efficiency. The final attempted experiment was to see the lifetime of the solar cells.

Experiment 1: Absorption Spectrum of Blueberry Dye

Background Theory

In choosing the pigment that will be used you need to consider if it will be effective at absorbing the light that is being radiated from the sun. To do this one can compare the absorbance spectrum of the pigment to the emission spectrum of the sun. In this case this would be the absorbance spectrum of the blueberry pigment used to create the solar cells. An absorbance spectrum can be measured using a spectrophotometer.

The spectrophotometer can only measure the absorbance of something accurately within a range, so if the material measured is too dark the reading will be inaccurate. The ideal range to measure absorbance using a spectrophotometer accurately is between 0 and 1. Absorbance is a unitless quantity. To measure darker materials, you can dilute the substance with a transparent solvent to put it in the measurable range. Diluted materials should follow the Beer-Lambert Law:

Equation 18: $$A = \varepsilon bC = \ln\frac{I_0}{I}$$

Where A is the absorbance, ε is the molar absorbtivity, b is the path length, and C is the concentration. Because this is a linear relationship, if you hold ε and b constant and reduce C by one half, then A should go down by one half. So, if A is too high to be in a measurable range, you can dilute by a known amount reducing C until A falls within a measurable range. If you keep track of how much you changed C by you can calculate the effect it caused on A. The spectrophotometer measures absorbance through taking the logarithm of the ratio of incident light (I_0) over transmitted light (I). The logarithmic component of this equation is why the spectrophotometer is only sensitive in the regime where A is at low values (0-1 range). The more the material absorbs the closer I gets to zero making the ratio $\frac{I_0}{I}$ approach infinity which is difficult to measure with accuracy, so calculations made have little credibility. When I and I_0 are the same value that means the material absorbed none of the light, and $\frac{I_0}{I}$ is equal to 1. The logarithm of one is 0 which makes sense because that means the absorbance is 0 for a material that doesn't absorb light.

Procedure

Start with preparing the pigment as you would to create the solar cell by cooking down blueberries into a liquid and straining out the solids. Then prepare the materials needed to do a serial dilution:

-Five 10mL volumetric flasks with caps

-Blueberry pigment

-Pipette and tips

-Clean Cuvette

-Spectrophotometer

-Deionized water

The spectrophotometer requires selecting a range and calibration. Select the range of wavelengths of interest. The wavelength range selected is 300nm to 700nm because this is where the sun radiates the most intensely and is the visible range, so it is the range we are interested in capturing. Then run the sample with the path of the light fully blocked as a full absorption control. Then run the sample with the cuvette filled with only deionized water to serve as the zero-absorption blank. Deionized water is the solvent being used to dilute the pigment so running Deionized water will serve as the background to subtract out.

To start the serial dilution, pipette 1 mL of the original berry product into one of the volumetric flasks, then pipette 9mL of deionized water into the flask. Cap the flask and mix thoroughly. This is a 1:9 dilution. Then take 5ml of the 1:9 dilution and mix it thoroughly with 5ml of deionized water in the next flask. This is now twice as diluted, or half as concentrated as the previous one, so this is a 1:18 dilution. Repeat this process using 5ml of the 1:18 dilution and 5mL deionized water to get a 1:36 dilution. Repeat this process two more times using the previous dilution to get a 1:72 and a 1:144 dilutions. It should look something like this

FIGURE 21

The concentrations from left to right go 1:9, 1:18, 1:36, 1:72, 1:144.

With each dilution made just measure their absorbance spectra in the spectrophotometer. If the 1:144 dilution doesn't fall withing the 0-1 absorbance range you may need to dilute further.

Results

The results of the absorption spectra of the blueberry pigment are measured and plotted as follows. The chart next to it is the solar radiation from the sun.

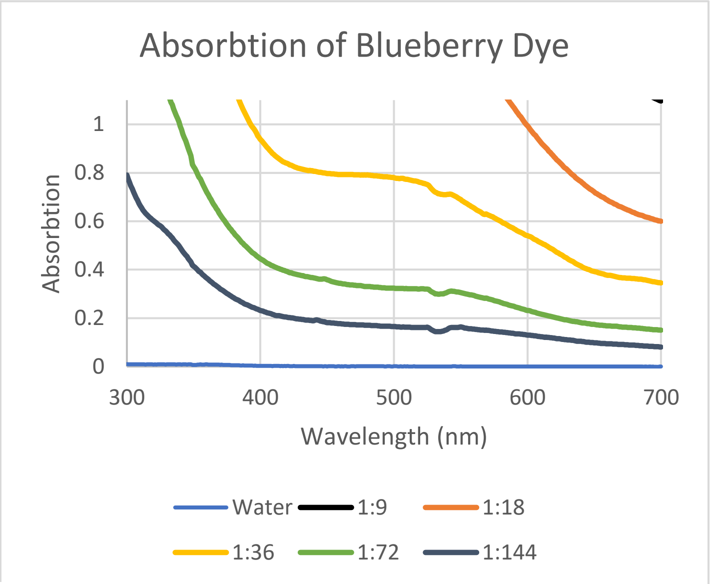


FIGURE 23

This figure shows the absorption spectra of blueberry pigment of different dilutions at wavelengths from 300nm to 700nm. The 1:9 dilution was measured too high to be pictured.

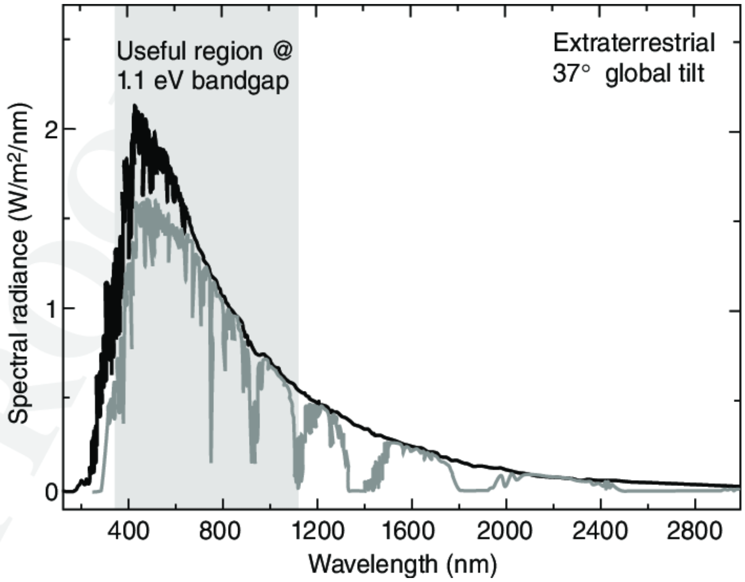


FIGURE 22

This chart shows in black the solar radiation hitting earth at the top of the atmosphere, and in gray the solar radiation hitting Earth's surface. Reprinted from "Polycrystalline Silicon for Thin Film Solar Cells," Budini N. et al., 2016, p. 229.

Putting these two charts in comparison we can see that the sun emits most strongly in the 400nm to 800nm range. This is approximately the visible spectrum. It is also worth noting that the higher the wavelength the lower the energy each photon carries. Because of this it seems most appropriate to have a dye that would absorb in this range. Looking at the absorption of blueberry dye we can see that it does in fact absorb well in this range.

The following plot is of absorption over dilution ratio at a selection of wavelengths.

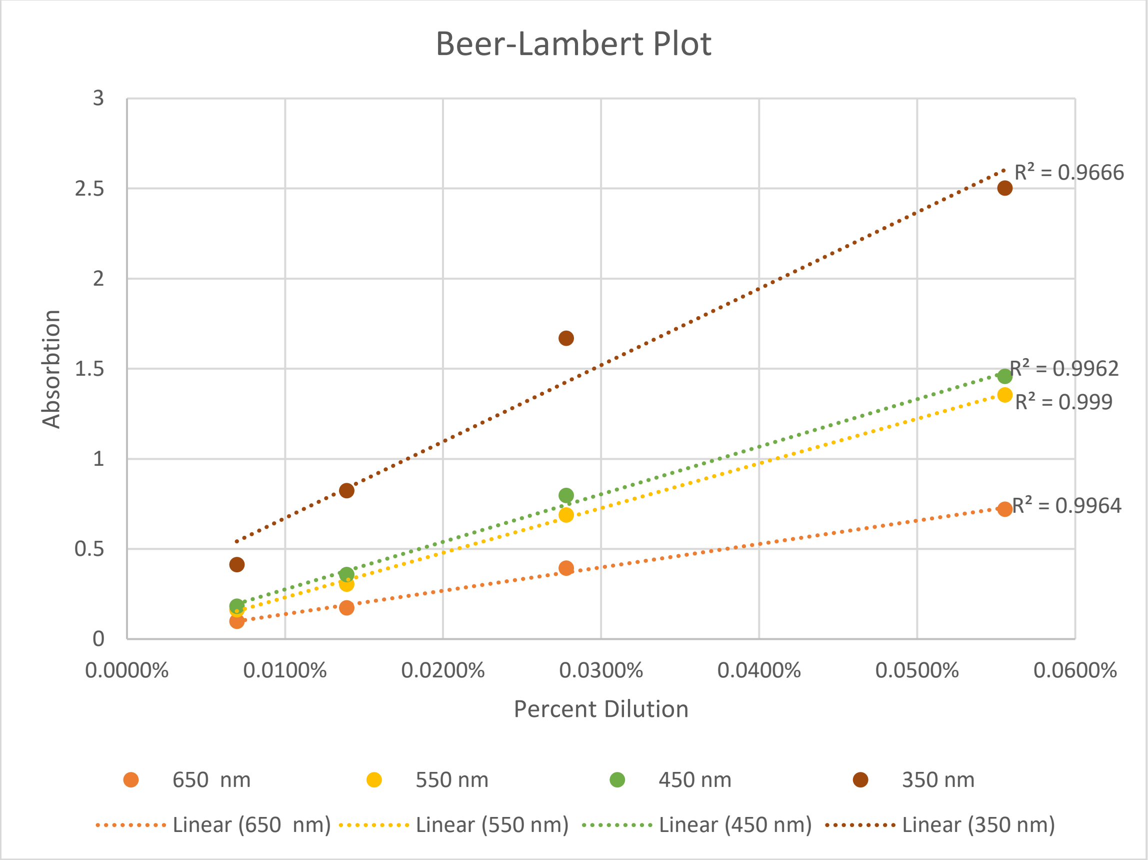


FIGURE 24

Absorbance at different dilution percentages at 650nm, 550nm, 450nm, and 350nm light. The data is plotted with linear fits for each wavelength. R^2 values are displayed for each linear fit.

The plot shows that the absorbance has a very linear relationship with dilution. The linear fits to the data have consistently very high R^2 values which means that the linear fit represent the data extremely well. These high R^2 values are consistently high across a sampling of wavelengths over the range of wavelengths tested. Because the data shows a linear relationship with dilution this means that it appropriately follows the Beer-Lambert law across the tested range of wavelengths. Because it follows the Beer-Lambert law, that means that the data is trustworthy, and that dilution doesn't change the way that the spectrum would look. This absorption spectrum is an appropriate representation of the dye at full concentration just less absorptive. Knowing the absorption spectrum measured is an accurate representation we can also see that it is effective at absorbing in the desired range of 300nm to 800nm that the sun is most strongly providing. The pigment found in blueberries is in fact a good pigment to use for capturing sunlight.

Experiment 2: Efficiency

Background Theory

The goal of this experiment is to measure the total efficiency of the solar cells. To test this, we need to hit the solar cells with a measured power of light and measure the power generated by the solar cells. To create consistent and measurable source of light measurements were taken in a windowless basement with a white light source. This light source is the Thorlabs SLS201L Broadband 360-2600 nm Source. Its spectrum looks like:

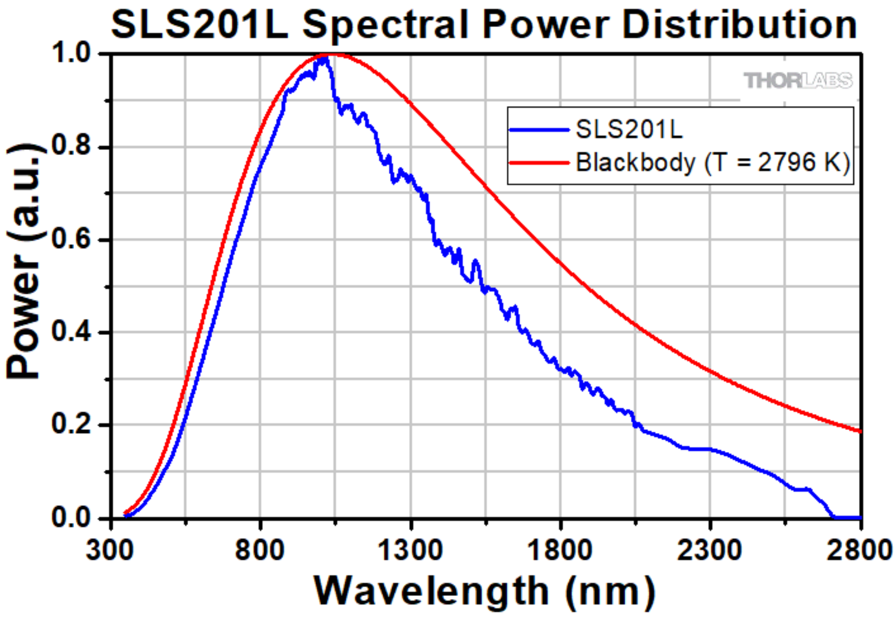


FIGURE 25

This chart shows the light being emitted from the light source that is used. It is worth comparing to figure 22 which is of the spectrum of sunlight. This white light source roughly mimics the spectrum of sunlight in its gaussian shape but peaks at 1,050nm rather than 500 nm which is a much lower peak. It also trails off much longer into the higher wavelengths than sunlight. Reprinted from Thorlabs' Compact Stabilized Broadband Light Sources web page.

Although this white light source is not an ideal replica of the spectrum of sunlight, it does provide a consistent power output and a wide range of wavelengths. It is worth comparing the figure 25 to figure 22 which is the spectrum of sunlight to notice similarities and differences between the two.

Light carries energy, but power is energy as a rate. The sunlight generates about 1000 watts of energy, or 1000 joules of energy every second. Because things (like the sun) are sometimes continuous sources of energy it is easier to measure things in terms of power than it is energy. In this experiment I use a tool that can measure the power of light. Knowing the power of light that hits the surface of the solar cell we can compare that to the power being generated by the solar cell to calculate its efficiency. There are multiple ways to calculate power in a circuit:

Equation 19: $$P = VI = \frac{V^2}{R} = I^2R$$

Where P is power, V is the voltage, I is the current, and R is the resistance. We can set up a circuit that has only one resistor and it would be the entire load on the solar cell making this calculation a simple one. This is the way we will get at measuring the power generated by the solar cell, and by extension its efficiency.

Procedure

Materials needed to carry out this experiment are:

- Thorlabs SLS201L Broadband 360-2600 nm Source
- Thermal light power meter
- Mount for light source
- Lenses to focus the light into a circle with a diameter small enough to fully fit on the solar cell (I used a series of three lenses)
- Neutral Density filters to adjust light strength
- Created solar cells to measure
- Two multimeters
- 1000 Ohm resistor
- Banana cables and alligator clips
- Method for mounting the solar cells in the path of the light. (I used a rubber band and a lens mount)

Mount the light source on an optical table. To get the light to be directed rather than just in an outward propagating cone like a flashlight I used three lenses in a tube mounted to the front of the light source. The order of the lenses went two with a 25nm focal length and a final one with a 50 nm focal length. The light will still expand as it propagates but much more gradually. Place the power meter and the solar cell in the path such that the entirety of the beam will be on the surfaces. Once the light source is set up place your mount that will be used to hold the solar cells and clamp it in place to keep the distance and placement consistent. Place the mount for the power meter in the path of the light too, clamped for consistency. Measure the power of the light beam and record it. Place the solar cell in the mount and using banana cables with alligator clips connect one side of the solar cell to a 1000Ω resistor. Connect the other side of the resistor to an ammeter, then connect the other side of the ammeter to the other side of the solar cell. In parallel connect a volt meter to either side of the resistor:

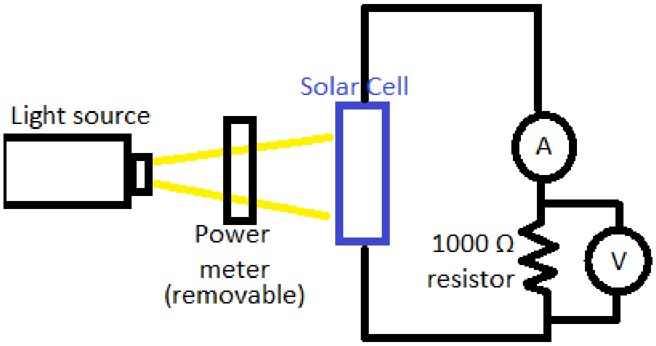


FIGURE 26

Circuit diagram showing the setup used to measure power of the solar cell.

With this setup you should be able to measure the volage drop across the circuit and the current through the circuit. Because there is only one resistor in the circuit the voltage drop across the resistor is the voltage of the entire circuit.

For a set power of light hitting the surface of the solar cell write down the current and voltage. Repeat this for each of the solar cells you want to test. To measure different strengths of power it is only possible to go as bright as the light source can go. It is possible however to dim the light source using neutral density filters. Neutral density filters dim the light everywhere in the spectrum by a set ratio. Place a neutral density filter on the front end of the light source and measure the power of the light now. Using different neutral density filters to achieve different powers of light you can repeat the voltage and current measurements for each solar cell at different powers of light.

Results

I carried this experiment out with four different solar cells made using a blueberry pigment. Out of curiosity I also created one solar cell using raspberry pigment to compare its effectiveness. Power was calculated utilizing $P = VI$. I calculated using all three formulas and $P = \frac{V^2}{R}$ was consistently the lowest value by a small amount, $P = I^2R$ was consistently higher by a small amount. $P = VI$ was in between the two and was very close to the average of the previous two. I decided to use the one that fell in the middle. The following plot is of power generated by the solar cell over power of light hitting the surface of the solar cell:

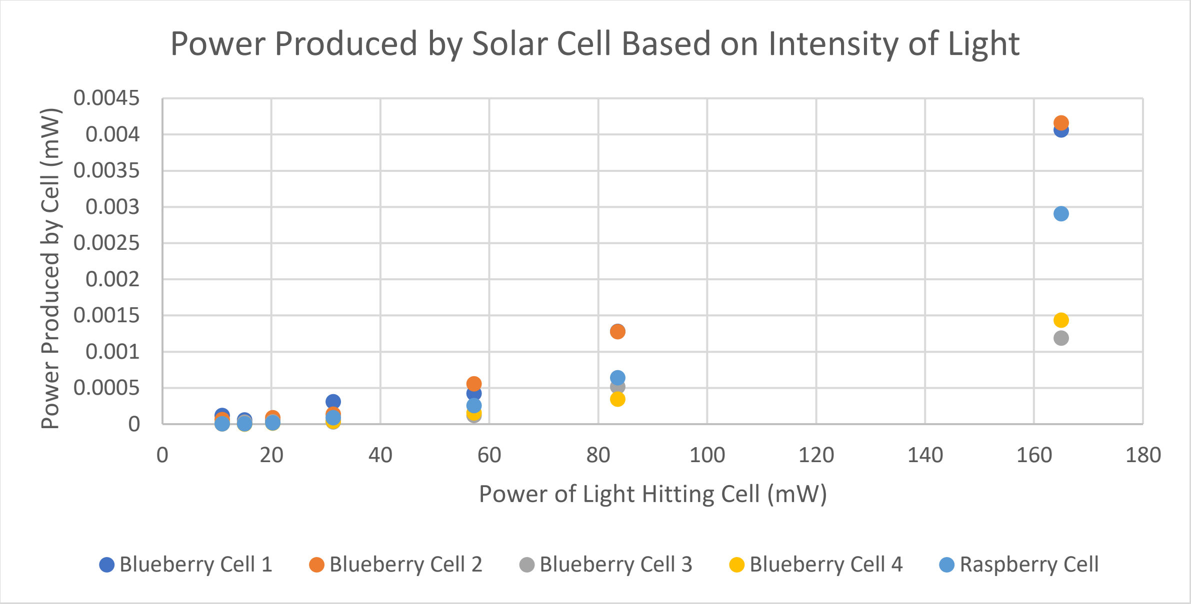


FIGURE 27

A plot of power generated by the solar cell in mW over power hitting the surface of the solar cell in mW for each solar cell tested.

The relationship between power hitting the surface of the solar cell and power produced by the solar cell appears to be exponential in this range. If we divide power produced by power hitting the surface, we can calculate the efficiency of the solar panels. The following plot show the most efficient solar panel I created using blueberry and using raspberry pigments.

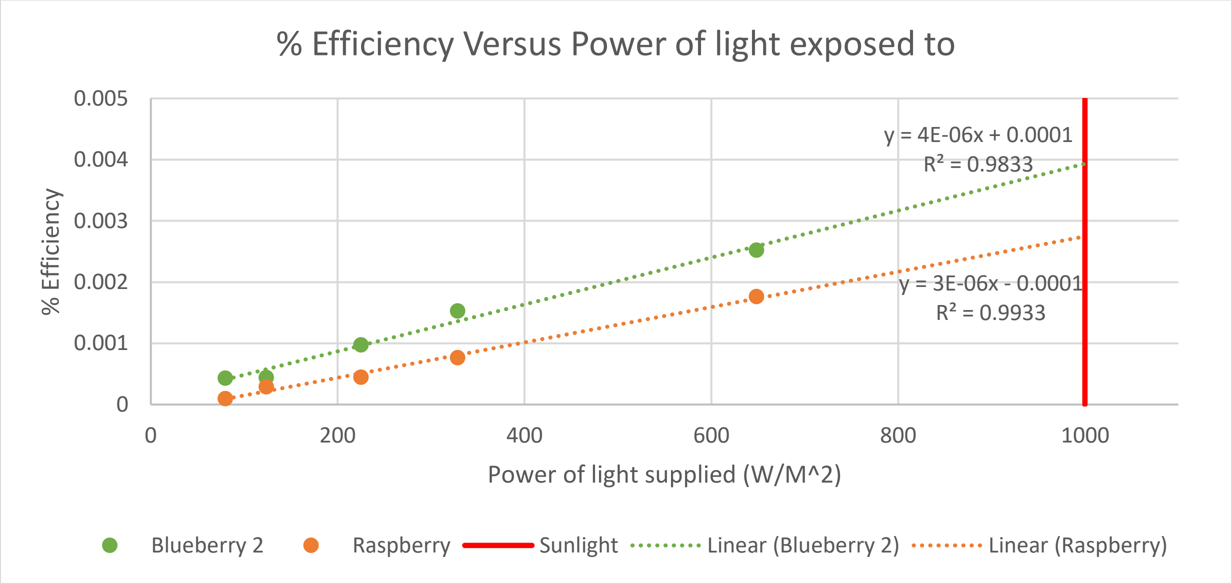


FIGURE 28

This graph shows the efficiency of the most efficient created blueberry solar cell and the raspberry solar cell over watts per square meter. Linear fits are plotted on the data along with R^2 values and linear fit equations. The red vertical line represents the approximate watts per square meter of sunlight on Earth's surface.

Figure 27 is in total power hitting the surface of the solar cell compared to total power produced by the solar cell because the units are easier to compare that way and visualize the efficiency. In figure 28 the power produced by the light source was converted to watts per square meter by dividing the total power of the light hitting the surface of the solar cell by the area of the beam of light. It is a more meaningful comparison to make to compare the efficiency of the solar panel to watts per square meter because sunlight is often reported in watts per square meter and not watts. The data is fit with a linear regression that has a high R^2 value indicating a strong fit. This may be due to the small sample size of the raspberry solar cell tests, but the best of the blueberry solar cells outperformed the raspberry solar cells in power output and efficiency. Visibly the blueberry cell was darker than the raspberry one so it makes sense for it to be better at absorbing light. There were blueberry solar cells that were made that did however preform worse than the raspberry one likely due to inconsistencies in fabrication. The vertical red line is to represent the power of sunlight so you can visualize the efficiency of the solar panels as they would be outside. Though the data looks linear in this regime it is hard to say if it behaves linearly far outside this range. Because of this it would be inappropriate to use the linear regression to make approximations of efficiencies at values that are much higher without collecting more data. That being said, 1000 watts per square meter might not be too much higher than the 650 watts per square meter of my highest measurement. I am going to approximate the efficiency of the blueberry solar cell using the linear regression at the brightness of sunlight but keep in mind that it might fall outside of the range that this relationship behaves linearly.

Equation 20: $$\%\, efficiency = 4E-06x + 0.0001$$

Evaluated at x = 1000

$$\%\, efficiency = 0.0041\%$$

A projected efficiency of 0.0041% is a little disappointingly low, but this could have to do with the use of soot instead of platinum. High efficiencies aren't the only way to measure the overall effectiveness of a solar harvesting system, you could evaluate cost to watt ratio. Remember photosynthesis shakes out to only being about three percent efficient after all and I think it's clear that that works well enough.

Experiment 3: Lifetime

Background Theory

This type of solar cell relies on a liquid electrolyte. Though you can make efforts to seal them there will likely be a slow evaporation process that eventually means the iodide solution will dry out making the solar cell unable to operate. This however would be a simple solution to fix by rehydrating the electrolyte, but it is still a downside worth studying. There is also the fact that over time through exposure to the sun the blueberry pigment will eventually become bleached and lighten, becoming less effective at absorbing sunlight. I can think of a relatively easy solution to this problem too. If you open the solar cell up rather than going through the whole process again you can simply resoak the titanium with the pigment if it is still intact.

Procedure

This procedure aims to measure the effectiveness of the solar cell at periodic time intervals over a long time span. The materials you will need to conduct the experiment are:

- A windowless room
- A consistent light source (I used a phone flashlight)
- A multimeter and banana cables with alligator clips
- Something to put the light source on
- Solar cells to be tested.

The method used to test the effectiveness of the solar cells was to put a voltmeter connected to each end of the solar cell and then turn all of the lights out and measure the voltage that the solar cell equilibrates to. Then turn a light source on and measure the new voltage that it equilibrates to and take the difference between the light conditions and the dark conditions. It is important to make sure that the flashlight is the same distance from the solar cell for each measurement, I placed my flashlight on top of a stack of books to do this. Take these measurements periodically for each solar cell over a long span of time to measure the effective lifetime and see how their performance changes with time since fabrication.

Results

The initial run of this experiment was flawed. The procedure used was to measure the voltage difference across the two ends of the solar cell under dark and illuminated conditions and take the difference. The circuit was not completed and would take long amounts of time to reach a consistent number. This yielded inconsistent results. If this experiment would be carried out again, I recommend using power as done in the efficiency experiment. Complete a circuit with a resistor and measure the current through and voltage drop across the resistor to calculate power using a consistent light source. Do this experiment periodically over a long period of time. By the time I realized the flaws of the initial lifetime experiment and thought of a better way to carry it out there was not enough time left to test a meaningful “lifetime”.

Conclusion

In response to the climate crisis people have done lots of research into solar energy as an alternative energy source to help transition from fossil fuels. It is optimistic that efficiencies have been improved so much lately, but just brute force increasing efficiency can only get us so far. While it is absolutely helpful, it isn't the only factory to consider. There are other aspects to making solar energy viable. There is the financial viability, resource availability, and spatial concerns.

Compared to traditional solar cells these dye sensitized ones have more readily available construction materials making them cheaper and requiring less mining having a smaller environmental price. They likely have a shorter lifespan due to the bleaching of they dye sensitizer and the drying of the liquid electrolyte. Though they are less efficient, their cheaper cost allows you to make more and arrange many in an overlapping pattern. They also reflect and transmit light and diffuse the light that they transmit. Cheaper production and lower efficiency but transmitting some amount of light lets you consider placing more solar cells stacked over each other so that the light that reflects or transmits can hit another solar panel. These differences make the dye sensitized solar cells sound very similar to how trees operate with leaves. Trees create many short-lived solar harvesters and arrange them in a strategic pattern. Trees have the advantage of hundreds of millions of years of evolution to master this, so maybe there is some wisdom they could impart to us with how to arrange this sort of solar cell. Trees are good at capturing diffuse light, so maybe these dye sensitized solar cells will be better at finding ways to capture diffuse light, even if they are less efficient at direct light than their traditional counterparts.

Popular solar panels are designed to be efficient at capturing direct sunlight, which on sunny days is the highest intensity of light by far, but on cloudy days there is much less direct sunlight and more diffused sunlight. Trees benefit from the diffusion of sunlight, so maybe dye sensitized solar cells can be used in a similar way. A big downside to solar energy is being unreliable by depending on weather conditions. Cloudy days are a downside for solar panels that rely on direct sunlight, but if they can be designed to actually benefit from the diffusion of light this downside could be mitigated. There are certain parts of the world where most of the days are cloudy or have weather conditions that lead to very diffused light. This would usually strongly disincentivize the use of solar energy, but again solar, panels that benefit from the diffusion of light would give these locations access to an effective choice of solar panel.

Another advantage of the materials used to make dye sensitized solar cells if they are much more easily recyclable, they also can be more easily made from recycled materials. The glass can be wiped and re-used easily. Glass is also a relatively easy material to source from recycled material, you just need to go through the process of giving it a conductive coating. The thin titanium coating might need replacing but titanium dioxide seems to be very commonly used in a disposable way in other uses like sunscreen, for example. It is possible that if the titanium isn't damaged but the dye is simply bleached out from sunlight you can repeat the process of soaking it in the dye. This would be a very easy and low resource cost method of reusing these solar cells. The electrolyte drying is something that is very easy to remedy by occasionally adding more. It is also possible to seal it off very well to prevent any evaporation. The soot layer is something that is easily recreated in a very cheap way. If the solar panels were made with platinum instead of soot, the platinum would remain intact even if the titanium needed replacing.

There is a school of thought that part of counteracting anthropogenic climate change is to "re-wild" much of the land that humans have claimed. While this is subject to debate, I don't think it is up for debate that land is a limited and valuable resource. Current solar farms look like large fields filled with solar panels, but that land could be used for agriculture, housing, or wildlife habitat. Additionally, cities don't have access to large flat areas of unused space. Solar energy that can take a more vertical profile rather than a large horizontal profile has the advantage of taking up less space. It can be implemented on the roofs and walls of city buildings.

Solar energy has another advantage that it gives the freedom to take things off of the grid. Gadgets for example can be independently charged through solar energy. Any amount of removing load from the grid is a reduction to consumption which is an improvement. If you get creative there are many places solar panels can be integrated in small ways, window blinds for example. When thinking about implementing solar energy as a solution to the climate crisis, improved efficiency is an important aspect but there are many other aspects to consider and improve on. The greatest innovation comes from open minds.

Solar energy doesn't need to be created for strictly functional reasons to an optimized set of parameters. Humans are a species that makes art for art's sake. Inspiration is an important part of motivating people to change their behavior. If you can make solar energy beautiful that can give an extra reason to make people to want to install it. People already buy sculptures just for the sake of being beautiful. The fact that dye sensitized solar cells require two parallel pieces of glass lend them selves to flat surfaces, but if you were a skilled glassblower, you could probably make more shapes. Here is a shape I made from origami that could lend itself to being made from solar cells:

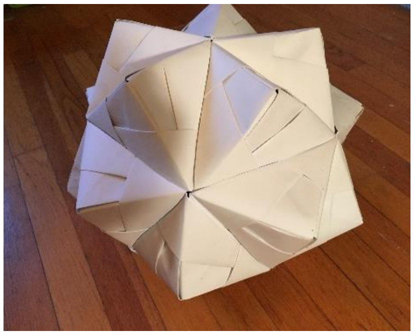


FIGURE 29

In an artistic sense dye sensitized solar cells have the dye element that you use opening up options for artistic avenues. The pigment from the blueberry I used on my solar cells created a really lovely color.

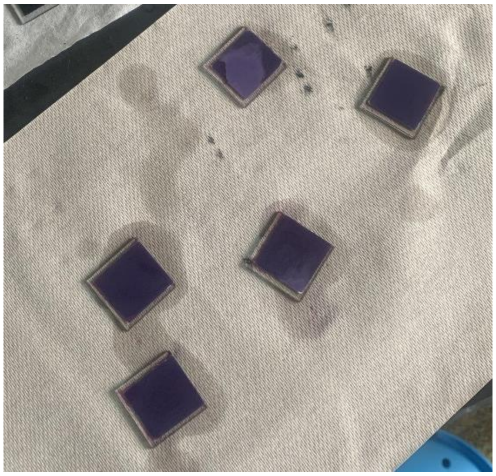


FIGURE 30

Because you have a freedom of choice with what dye to use for the solar cell it is easy to imagine putting the dye on the titanium dioxide in a strategic way to "print" patterns or images you want which could be very interesting.

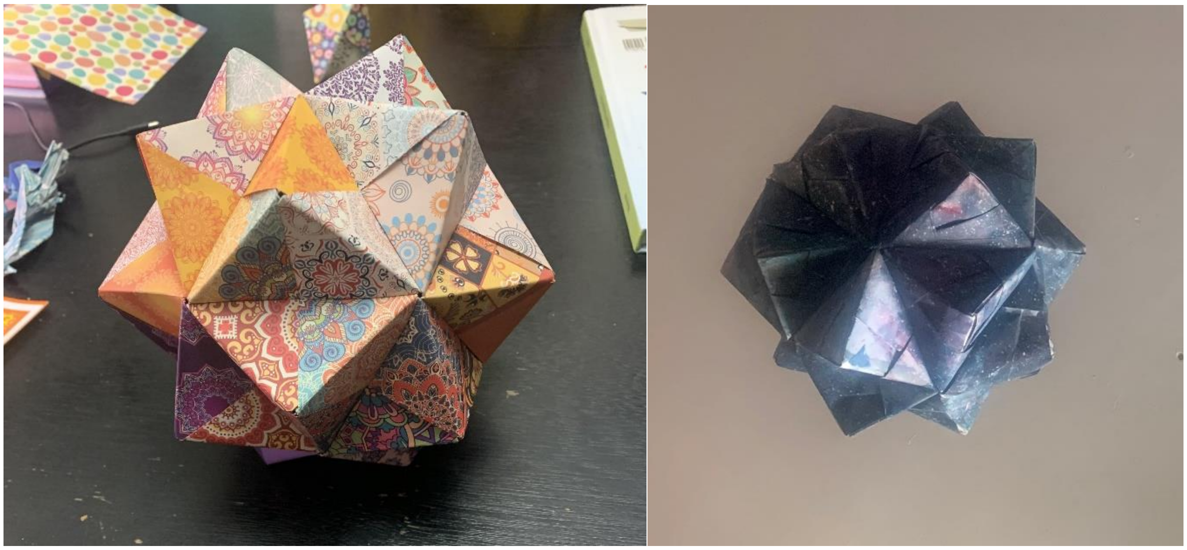


FIGURE 31

Moving away from geometric shapes to a little more abstract here is a sculpture I made and am proud of that I think I interesting to look at. I think you could make something inspired by this that out of solar cells utilizing this shape and placing solar panels on the outward facing circles.

Figure 32

You could simply replicate nature in sculpture. I find trees and flowers to be very beautiful and they clearly are already capable at capturing sunlight.

Figure 33

Dye sensitized solar cells, though having a lower efficiency than traditional photovoltaics open up opportunities for improving solar energy in many other aspects, such as reducing material ecological impacts, reducing production cost, increasing recyclability, mitigating weather related losses in power by better utilizing diffuse light, reducing land space needed through vertical arrangements, and by potentially being beautiful works of art.

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