Improving the Efficiency of Natural Dye Sensitized Solar Cells

By

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An Honors Project submitted to the University of Indianapolis Strain Honors College in partial fulfillment of the requirements for a Baccalaureate degree "with distinction." Written under the direction of Dr. Brad M. Neal

April 10, 2017

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First Reader

Second Reader

Abstract

Solar energy has the potential to be a major source of energy for the world if an effective means can be produced to harness it. Various methods of converting solar energy into electrical energy have been explored, including photovoltaic devices. In order for these devices to be viable for large scale production, it is important to improve the efficiency of the devices in terms of both effectiveness and cost. The construction of these devices will be discussed, as well as the trials performed in order to evaluate the performance of the devices. The construction of an instrument built in-house to analyze these solar cells will also be discussed. Dye-sensitized solar cells are an alternative to traditional silicon-based photovoltaic cells and if their efficiencies can be improved, they have the potential to be another viable option for solar energy utilization. Focus will be given to the impact of the different components used to construct the solar cells, the decision to build an instrument to better analyze these cells, and the differences in the observed properties when different sensitizing dyes and electrolyte solutions are used. The products of this project include an instrument to be utilized by future solar cell research students, a better methodology for fabricating the solar cells, and a better methodology for testing the solar cells; as well as preliminary conclusions of the best electrolyte and dye combinations based on completed trials.

Acknowledgement

I would like to thank my main honors project advisor, Dr. Brad M. Neal, and my secondary research advisor, Dr. David Styers-Barnett, for their dedication to helping me with this project. They were both instrumental in my completion of this project as well as helping me grow academically and personally throughout my career at the University of Indianapolis. I would also like to acknowledge Dr. Stephen Spicklemire, from the physics department, for his support and instruction throughout the process of building my new instrument. I extend gratitude to James Hall and the Sigma Zeta Research Grant Fund for financial support of this project. Finally, I would like to thank family and friends for their support throughout the course of this project as well as my academic career. Without the support of these people, and others not listed, I would not have been able to produce a project of this caliber, so again I offer my gratitude to them.

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Statement of Purpose

Alternative and renewable forms of energy (known as "green" energy) are currently being explored by scientists around the world as a way to reduce dependence on oil and coal as a source for energy. Solar energy is a forerunner in potential, sustainable energy. Before solar energy can be used, though, it must be captured, which is where photovoltaic devices (PV devices), also known as called solar cells, come into play. There are many kinds of PV devices which are commercially available and have been used in practice for years, however, their use is not wide spread due to some key issues. One of the problems with traditional solar energy capture is that it is usually done using silicon-based cells. The best silicon solar cells are expensive to fabricate and are susceptible to damage by the elements, such as hail, if used outdoors. The cost of these cells and their durability limit their deployment on large scales without significant financial investment. An alternative to silicon cells are dye-sensitized solar cells (DSSCs). A major issue with DSSCs is that they are not yet efficient enough to be considered as a viable option. There is work being done to address this though, as will be discussed herein. Ultimately, these DSSCs may prove to be more effective than their silicon counterparts if the proper effectiveness to cost ratio can be produced, i.e. one higher than silicon cells have.

Many dye-sensitized solar cells are made with a potassium iodide/tri-iodide electrolyte and stained with a dye made from the juice of crushed blackberries. This combination is currently seen as the gold standard for natural dye-sensitized solar cells but has not proven to be as efficient as scientists had hoped. To be able to evaluate solar cells, a variety of parameters must be evaluated. While measuring the technical definition of efficiency for solar cells was deemed to be out of the scope of this honors project, the maximum power and current driven by the cell were decided to fall within the scope of being able to record and evaluate. The main focus of this project is to look at different electrolyte and berry dye combinations to determine the best combination to produce the maximum amount of power. An additional benefit of this project was the creation of a new instrument for testing solar cells fabricated by future undergraduate students in their own research projects.

Introduction

Scientists around the globe have reached a consensus that humans are consuming oil and coal to produce energy faster than the Earth can reproduce these resources.[1] The Environmental Protection agency finds coal fired power plants excessively harmful to the environment and is working to reduce the dependence on energy gotten from coal and it has been determined that between 2008 and 2035 the global electricity generation is expected to increase 2.2% per year to sustain energy demands by the growing populations.[1] One form of renewable energy that scientists are focusing their research on is solar energy.[2, 3, 4, 5] The sun provides an abundant supply of solar energy to the Earth at a rate of 3.0×10^{24} joules per year, which is more energy than the population of the earth currently consumes per year.[1] If this energy can be harnessed, particularly with the use of low cost solar cells using renewable components such as organic dyes, the world's energy demands can be met at a lower price with less potential environmental repercussions, including exhausting the supply of natural resources.

Scientists are working hard to improve the efficiency of all kinds of solar cells to maximize the energy converted while reducing the cost to fabricate these cells. Michael Grätzel, known widely as the father of dye-sensitized solar cells (DSSCs), was one of the first scientists to begin working with DSSCs in an attempt to improve their energy conversion efficiencies to the point where they could be substituted for silicon solar cells. These cells are assembled with nano-crystalline inorganic oxides, ionic liquids (electrolytes), and an organic dye with a hole conductor.[6] Although Grätzel has managed to make great improvements in the DSSCs he fabricates; they still are not viable when compared to silicon cells in terms of energy conversion efficiency. Also, Grätzel is one of few scientists who have managed to reach the higher end of DSSC efficiency, near 11%[2] compared to 40%[7] for a typical silicon solar cell.

There are many different and important measurements and calculations that must be made when testing and analyzing the results of the solar cell experiments.[7] Open-circuit voltage, short-circuit current, and maximum power of the cells are important measurements and calculations to make during the test cycle. Energy conversion efficiency, fill factor, incident photon to current efficiency, diffusion coefficient and the nanoparticle layer thickness are a few of these measurements and calculations made during analysis. These factors are used to "grade" solar cells as good or bad and comparable to accepted literature values or not comparable. At the beginning of this honors project it was hoped that all or most of these measurements could be recorded or calculated in order to compare the results of the experiments to published results. It was quickly realized that not all were possible with available equipment, so decisions were made of what measurements were most important and how they could be obtained on a low-cost budget. For this reason, a new instrument was built to record some of these more important measurements and calculations, including open-circuit voltage, short-circuit current, and maximum power, which will be described below.

Types of Solar Cell Measurements

The basic idea of solar cell efficiency is that it is a ratio of energy output from the solar cell to energy input from the sunlight.[7] This means that the number of photons from the sun directly influences the ability of the solar cell to convert energy. Cloud cover, temperature, and angle of light can also greatly affect the power outcome, or energy produced, of the solar cell. For this reason, although efficiency is an important calculation, it is not the sole measurement that should be taken. Also, testing conditions must be carefully noted so that proper comparison can be made when referencing published results from other experiments. Efficiency is calculated using the open-circuit voltage, short-circuit current, fill factor and the power input from the sun, which can be seen below in Equation 1. Power input can be directly calculated using available instrumentation, the other factors can be more difficult to obtain. Due to the complexity of calculating efficiency, it was decided this would not be a measurement focused on in the course of this honors research project.

Equation 1: Efficiency Calculation

$$\eta = \frac{V(OC)I(SC)FF}{P(IN)}$$

Equation 1: This equation shows how the calculation for efficiency is performed, where n is the efficiency, V(OC) is the open circuit voltage, I(SC) is the short circuit current, FF is the fill factor, and P(IN) is the power output of the light source.

Three measurements of the solar cell can be found using IV (current-voltage) and Power Curves, as shown in Figure 1 below for an example of an IV curve. The first measurement, the short-circuit current, is the maximum current produced from a solar cell, it can be found where the IV curve crosses the y-axis.[7] The second measurement is the open-circuit voltage, which is where the solar cell produces maximum voltage. This can be found where the IV curve crosses the x-axis.[7] The problem with both the open-circuit current and open-circuit voltage is that at these points the power produced by the solar cell is zero. The reason the power is zero is that where the maximum current (open-circuit current) is found is that the voltage is zero and the opposite is true for the open-circuit voltage.[7] Power is the product of the current and voltage multiplied, so when one is zero the power is zero. The third measurement is found on the Power Curve portion of the graph; it is the data point where the y-value (power) is at its highest (also known as y-max).[7]

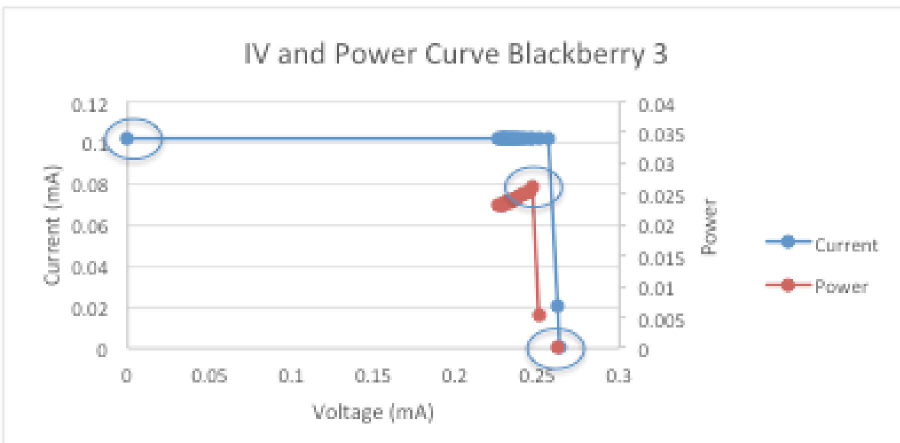


Figure 1: IV and Power Curve where short-circuit current is shown crossing the y-axis, open-circuit current crossing the x-axis, and maximum power being y-max.

To find where the maximum power output of the solar cell occurs the fill factor (FF) is determined, and a larger fill factor can mean a higher maximum voltage produced by the solar cell.[7] Fill factor is a derivative of the maximum power taken with respect to voltage and setting it equal to zero. An easier way to determine fill factor is to take the ratio of two areas of the IV curve, this can be seen below in Figure 2.[7] It is also further discussed below in the section titled *How to Read IV and Power Curves*. For this research project, fill factor was not a calculated measurement due to limited resources and being unable to accurately determine some of the measurements.

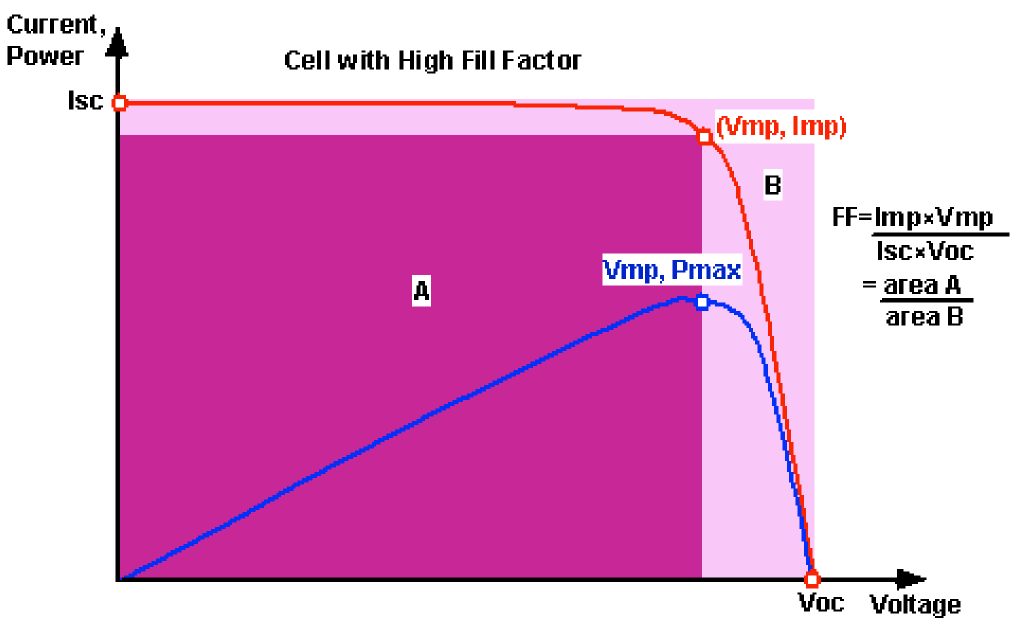


Figure 2: Graph showing how to calculate fill factor. Area A is determined by multiplying the current and voltage at the maximum power point and Area B is determined by multiplying the open circuit current and voltage. Fill Factor is the ration between the two.[7]

Incident Photon to Current Efficiency (IPCE) is another way to measure the efficiency of the solar cell at converting solar radiation into electrical energy. IPCE is a way to relate the ratio of measured electrons as current in the test circuit to the photon flux at one wavelength that reaches the cell.[8] It includes measurements of the efficiency of the solar cell at harvesting light at a specific wavelength, the number of electrons that leave the sensitizer and reach the conduction band of the semiconductor oxide, and the efficiency of collecting electrons. IPCE is an important measurement, but it is another difficult measurement to make with limited resources and a complex equation so it was decided to forgo attempting to calculate IPCE.[8]

The above-mentioned measurements are not the only types of measurements discussed in literature. However, other measurements, such as diffusion coefficients and nanoparticle layer thickness, were deemed out of the scope of this research project from the beginning and thus were never studied in depth. Although these types of measurements may be important depending on the variables being tested, they are not considered the most important measurements and it was determined that not pursuing them would not diminish the results of this honors project.

Types of Solar Energy Available

There are two main types of solar cells currently on the market or being tested by researchers. The first is the type of solar cell that typically comes to mind when people talk about solar energy, silicon cells.[7] They are made using special doped silicon and must be made in a clean lab for this reason, as shown in Figure 3 below. Thus far, they have reached the highest energy conversion efficiencies of any solar cell, around 40% efficient.[7] However, these cells are expensive to fabricate due to the cost of material and the clean lab is needed for manufacturing. Another type of solar cells, the ones many researchers are currently focusing their efforts on, are natural dye-sensitized solar cells, as shown in Figure 4 below. These solar cells are much cheaper to fabricate, as the materials needed are abundant and no clean lab is needed for most of their fabrication and manufacturing. The main problem with these solar cells is that the maximum-recorded efficiency is just over 11% and most efficiencies hover between 1-7%.[1] This is not high enough for this type of cell to be considered a viable option for consumers to rely on. Scientists are working hard to rapidly improve this energy conversion efficiency in the hopes that solar energy will be a more attainable option for more consumers in the near future.

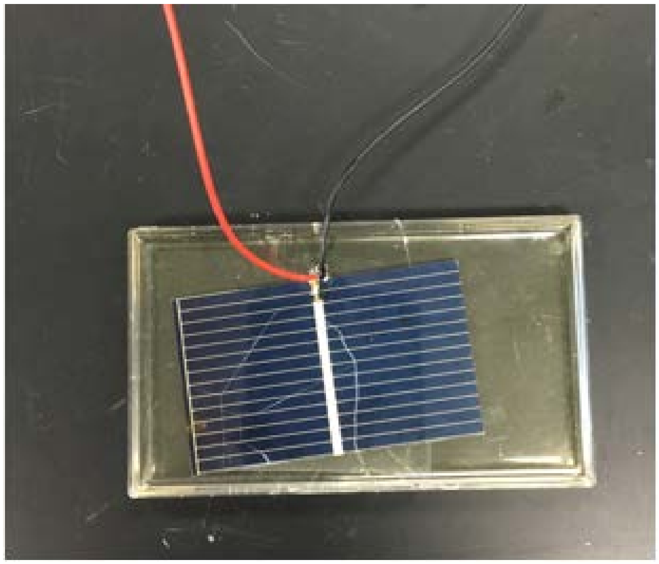


Figure 3: Silicon prefabricated solar cell used as the control for testing the instrument and as a comparison to DSSCs prepared in-house.

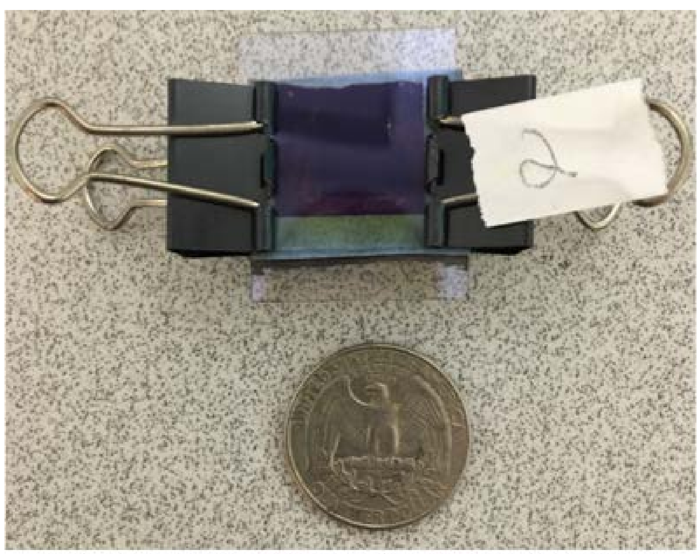


Figure 4: Natural Dye Sensitized (DSSC) solar cell fabricated in lab with a quarter to show size

How DSSC's Work

Dye-sensitized solar cells have several important parts that come together to form a working solar cell, as seen in Figure 5 below. Briefly, a sensitizer (the berry dye) is attached to the titanium dioxide (oxide) layer so that when photo-excitation of an electron due to a photon (from the sun) occurs the electron can be transferred to the conduction band of the oxide.[6] This electron transference can only occur when the energy of the photon striking the berry dye closely matches the energy gap of the dye molecules. This energy gap, also called a band gap, is the energy difference between the highest occupied molecular orbital (HOMO) and the lowest unoccupied molecular orbital (LUMO).[9] What this means is that energy transferred from the photon must be enough for the electron sitting in the HOMO to be excited and "jump" levels to the LUMO.[9] The dye is then regenerated with an electron from the electrolyte/ionic liquid which contains a reduction-oxidation system.[10] Regenerating the dye prevents it from recapturing the excited electron, it also allows the reduced electrolyte to oxidize itself at the counter electrode. This step completes the circuit and allows electron migration through the system. This process produces a voltage and a current that can be measured with a multimeter when wired between the cathode and counter electrode.[6]

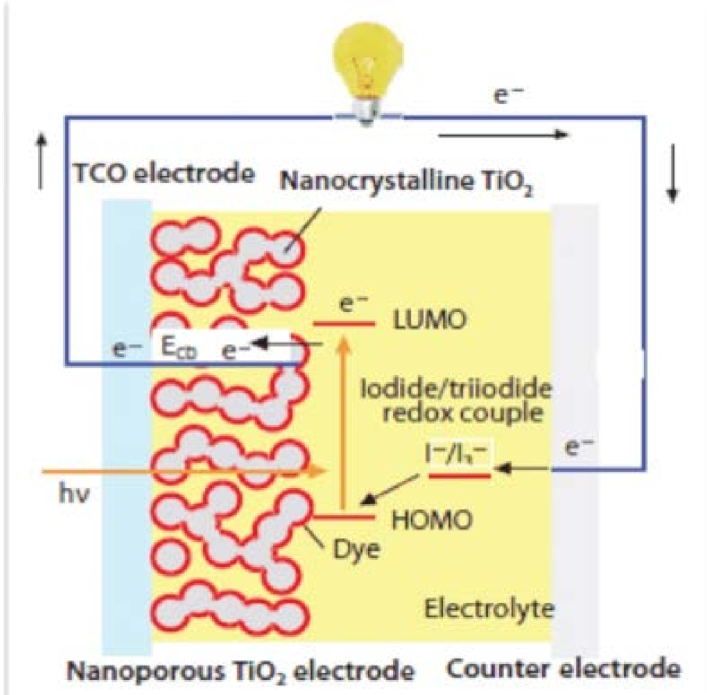


Figure 5: Solar Cell Electron Diagram: An electron from the dye is promoted and flows through the nanoparticle layer, through the conductive glass and through a wire before returning to the counter electrode and entering an oxidation-reduction reaction in the electrolyte.[11]

How to Read IV and Power Curves

IV and Power curves contain the necessary components to determine important information about the solar cells. Although they contain several parts, these curves are not difficult to interpret, as shown in Figure 1 above for a representative IV and Power curve from this project and Figure 2 for an IV and power curve from the literature. The first measurement that can be determined is from the IV curve and is the short circuit current produced by the solar cell.[7] This can be found by looking at the flat portion of the curve. This flat portion extends to the left until it crosses the y-axis; the point at which it crosses is the short circuit current, seen on Figure 1 above. This is also the maximum y-value in the data set; it is marked on the figure with a circle around the data point.[7]

The second measurement that can be determined from the IV curve is the open circuit voltage produced by the solar cell. This voltage can be found by determining where the sloped portion of the curve crosses the x-axis, which is to the right on the curve in Figure 1.[7] This is the maximum x-value in the data set. The third measurement is one that can be determined from the Power curve, it is the maximum power produced by the solar cell. This is the data point with the largest y-value in this data set.[7] It is found where the Power curve slope changes from positive to negative and it is also typically a harsh turn, not a slow change. Both of these measurements are also marked on the IV and Power curves shown on Figure 1, with a circle around the data points.[7]

The information gained from these curves can then be used to determine the fill factor and eventually the efficiency of the solar cell. Determining two areas under the curve can do this, as seen above in Figure 2. The first area is the square area of the IV curve, it will be larger than the actual area under the curve, but multiplying the short circuit current and open circuit voltage together will determine this area.[7] The second area is the square area based on the maximum power of the solar cell. This area can be calculated by multiplying the voltage and current at the maximum power point of the IV curve. This area will be slightly less than the actual area of the curve. Fill factor is a ratio of the second area divided by the first area.[7] This fill factor can then be used in the equation to find the efficiency. The equation involves multiplying the short circuit current, open circuit voltage, and fill factor then dividing by the total power input into the solar cell.[7]

Without the IV and Power curves, these measurements would be difficult or not possible to obtain. These measurements are important if the solar cells fabricated in the honors research project are to be compared to those found in literature so to that end, a new instrument was designed and constructed as part of this project. Due to an improvement that needs to be made to the new instrument, which is explained below, these measurements will need further investigation. However, because this instrument has been built, research students at the University of Indianapolis are several steps closer to being able to make all the above-mentioned measurements, instead of just being able to measure the short circuit current, open circuit voltage and the maximum power.

Methods

Overview of Approach

A method for building and testing the solar cells was modified from a University of Kansas inorganic chemistry laboratory experiment.[12] Table 1, below, lists the different variables tested, and where the variables came from, meaning whether they were bought or synthesized. Before the chemicals were used in any trials, they were stored in the chemical preparation room under proper storage conditions. Proper storage was critical to ensure no chemical contamination occurred, as well as reducing the potential for harm caused by the potent chemicals. Chemicals that were synthesized in the lab were stored in glass volumetric flasks and disposed of according to material safety standards after their use. Excess electrolytes, berry dyes, and titanium dioxide nanoparticle suspensions prepared were disposed of immediately and properly after each trial instead of being reused in later trials. This was to ensure a known concentration of each solution was used as well as reduce the potential for contamination between trials. In addition, experiments showed degradation of the electrolytes and titanium dioxide nanoparticle suspension over time, which reduces the efficiency of the solar cells at converting energy. Software built during the latter portion of this project was ultimately used to collect the data from each trial and quantitatively determine the IV curve and maximum power output of each cell.

Table 1: DSSC variable combinations tested

ELECTROLYTE	Iodine	Iodine	Ferrocene	Ferrocene
BERRY DYE	Blackberry	Blueberry	Blackberry	Blueberry

Table 1: Chart of electrolyte and berry dye combinations used during the trials

Preparation of Solar cells[12]

There are three important and distinct parts to fabricating and assembling the natural dye-sensitized solar cells. The first part is preparing the titanium dioxide nanoparticle layer and sensitizing it with the dye created from crushed berries. The second part is preparing the counter electrode and the final part is assembling the solar cell using the first two parts and an electrolyte. Care must be taken when preparing solar cells, if not assembled correctly the solar cells will be useless and the chemicals used can be dangerous if not handled properly.

For fabrication of the first part in making the solar cells a piece of conductive glass is coated with a titanium dioxide (TiO_2) nanoparticle layer, which is doped with benzene-1,3,5-tricarboxylic acid, also known as trimesic acid, to help it create a stronger adhesion between the TiO_2 with the glass. The titanium dioxide used is a fine, low-density white powder and 0.75 grams was weighed into a weigh boat using an analytical balance before being placed into a mortar. Trimesic acid is a bulky, clear crystalline solid and 0.0075 grams was weighed into a new weigh boat, using an analytical balance, before being placed into the mortar with the titanium dioxide. 4.25 Milliliters of deionized water was poured into the mortar. This mixture was then ground together for 15-20 minutes, creating a uniform consistency and viscosity within the mixture, as shown in Figure 6 below. The glass slide to be coated with titanium dioxide was connected to a digital multimeter using alligator clips touching one surface of the glass. The ground clip and the positive clip must both be touching the same side of one piece of glass to complete the circuit and obtain measurable reading. The Ohms setting is used, this is a measure of resistance through the circuit across the glass slide. The side of the glass that has a finite resistance is the conductive side; the nonconductive side will return an overload value to the multimeter.

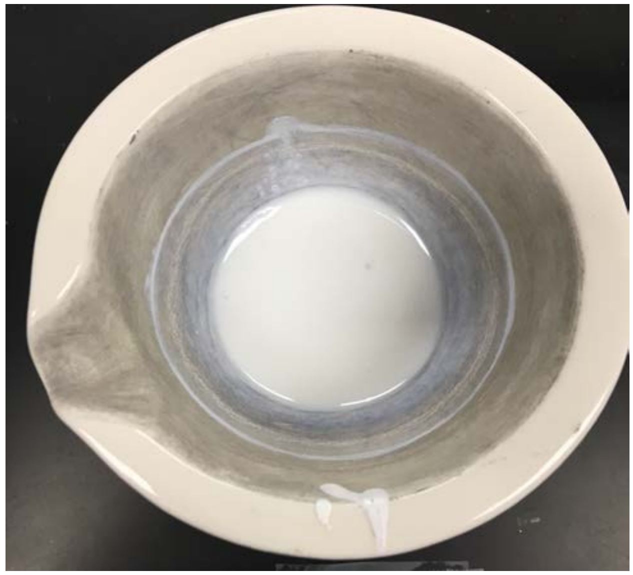


Figure 6: Titanium Dioxide, trimesic acid, and water that has been ground together with a mortar and pestle.

Once the conductive side is determined the glass must be cleaned before proceeding. Acetone was poured over the glass and the glass was allowed to dry completely. Once dried, the glass must be prepared for the titanium dioxide nanoparticle layer. Four pieces of tape were used to create a well for the titanium dioxide solution to sit in while drying. Three pieces of the tape were placed along the edge of the glass slide, covering about 2-3 millimeters of the edges. The fourth piece of tape was placed long the last edge, covering about 5 millimeters of the edge. This fourth edge is important for offsetting the assembled solar cell to allow alligator clips to be attached for testing. The tape must be pressed firmly to the glass to create a tight seal, with special care taken at the corners where the tape meets. Using a glass stir rod, 5 drops of the titanium dioxide suspension were placed on the glass inside the well of tape. One drop was placed near each corner of the well and one drop was placed near the center. A razor blade was then dragged across the titanium dioxide suspension to create a more even coating and the suspension was allowed to dry for 30 minutes. Dragging the suspension is important to create a dried nanoparticle layer with a smoother, rather than ridged, surface as the smooth surface allows for easier electron flow. The nanoparticle suspension on the conductive glass can be seen below in Figure 7. After the suspension dries enough to pull the tape off, it was carefully removed and the slides were placed in an oven for at least 6 hours. The dried titanium nanoparticle layer can be seen in Figure 8 below.

Figure 7: Glass slides with tape creating the well for the TiO_2 nanoparticle layer.

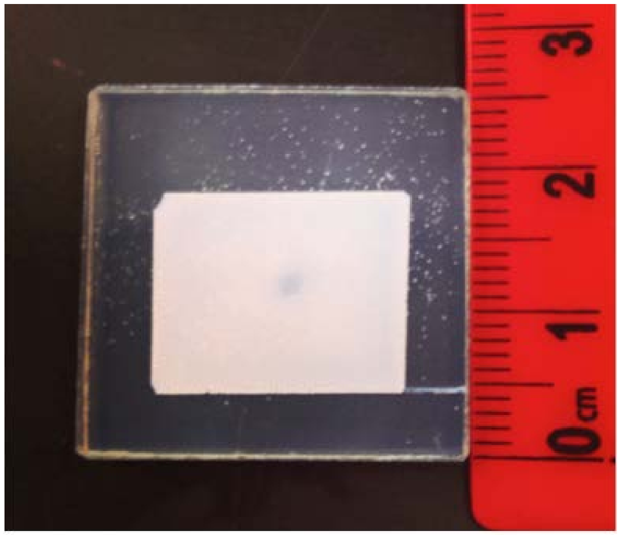


Figure 8: Titanium Dioxide Cathode: Titanium dioxide nanoparticle coated conductive glass slides ready to be stained and assembled into a functioning solar cell.

The second part of fabricating solar cells is preparing the counter electrode. To do this, the conductive side must be determined using the same manner as previously described. Once found, the conductive glass must be cleaned and prepared for its carbon coating. To clean the glass, it was rinsed with acetone and allowed to dry. To prepare it for the carbon coating it was then rinsed with reagent alcohol, which is a solution of 95% ethanol and 5% methanol. A tea candle was lit and the glass slide was held conductive side down over the candle using a pair of tongs. The glass slide should be slowly moved back and forth across the flame from the candle to evenly coat the conductive slide with a layer of soot. This carbon soot forms the counter electrode for the solar cell and is shown in Figure 9 below.

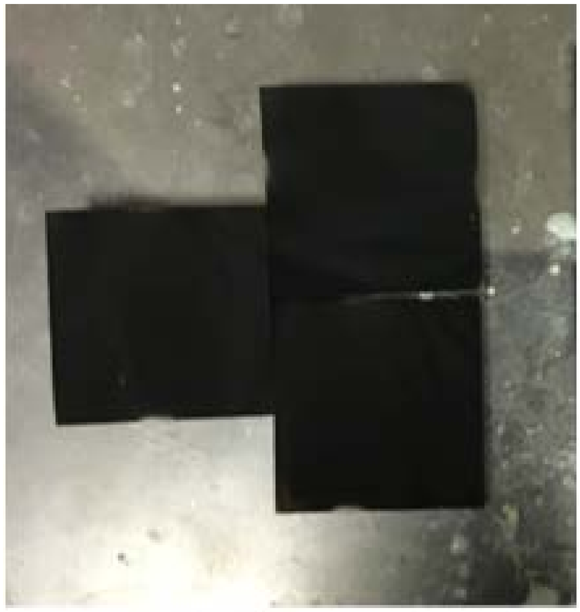


Figure 9: Solar Cell Anode: Carbon coated conductive glass slides ready to be assembled into a functioning solar cell to act as the counter electrode in the circuit.

While the glass slides were cooling after being removed from the oven, another mortar and pestle were obtained and 4 berries (blackberries or blueberries, depending on the trial) were crushed to release the juice. It is important to crush the berries well to release as much juice as possible while also breaking up large berry chunks. Large chunks tend to stick to the titanium dioxide nanoparticle layer and when removed can often pull some of the nanoparticle layer with them, which reduces the surface area viable for electron excitation to occur. Once cooled, the slides were rinsed with deionized water then acetone, lightly to ensure the titanium dioxide coating was not removed. The slide was then placed titanium dioxide nanoparticle layer side down in the berry dye for 15 minutes to sensitize the oxide layer, as shown below in Figure 10. After removing the glass slides from the stain, they are rinsed with acetone again and lightly blotted dry with a kimwipe, as shown below in Figure 10b. It is important to dry the glass after each step to ensure no water or other chemicals get sealed into the cell, as this could affect the productivity of the cell.

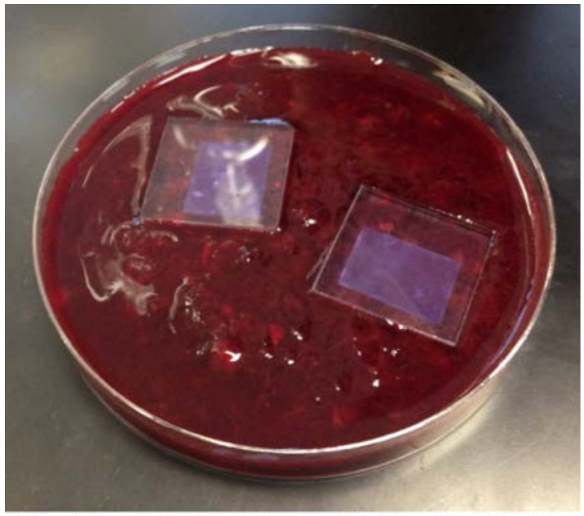


Figure 10: Titanium dioxide glass slides being stained with crushed blackberry juice.

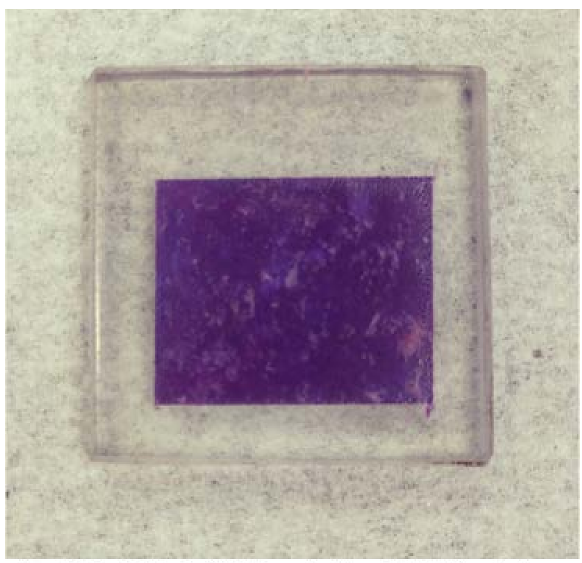


Figure 10b: Stained Titanium Dioxide Layer: The left row is the blackberry dyed titanium dioxide nanoparticle layer of glass slides, the middle row is the strawberry dyed slides, and the right row in the blueberry dyed slides.

Once dry, the first and second parts of the solar cell are ready to be assembled together in the third part of the fabrication process. A piece of Garlock Gylon PTFE gasket was used to form a seal between the two pieces of conductive glass. The gasket is cut to match the size of the conductive glass, however on one edge it is cut about 2 millimeters short to allow for the offset glass and alligator clip connection. Once this rectangle is cut out, a rectangular hole is cut out of the middle. This rectangular hole leaves an opening where the titanium dioxide nanoparticle layer on the one piece of conductive glass is located. The gasket is then placed on the titanium dioxide coated glass slide and pressed down, as shown below in Figure 11. Three drops of the chosen electrolyte solution (in this project either the iodide/tri-iodide electrolyte or the ferrocene/ferrocenium electrolyte) are dropped into the newly formed well, covering the titanium dioxide nanoparticle layer.

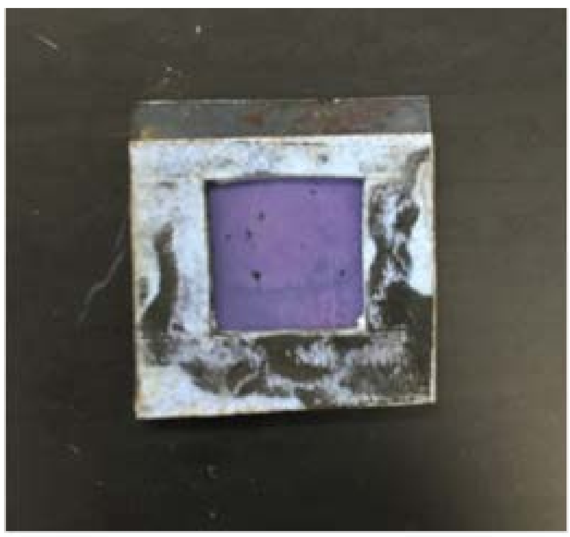


Figure 11: Garlock gasket lying on stained titanium dioxide nanoparticle layer

Next, the carbon coated counter electrode was placed on top of the gasket to complete the solar cell. It is placed slightly offset from the other conductive glass to leave an overhang on either side of the cell, as shown in Figure 12 below. This is to allow for the alligator clips to attach to the cell during testing. Two binder clips are attached to the solar cell to compress the gasket and make a tight seal, which can be seen in Figure 13 below.

These binder clips are placed on the two flush edges, but they must not cover the titanium dioxide nanoparticle layer, or else productivity of the cell will be reduced. When the binder clips are attached, some electrolyte will leak from the edges. A kimwipe is used to remove the excess electrolyte as well as clear the carbon coating off the overhang from the counter electrode. Here, it is important to dry the two electrodes well so that when the alligator clips are attached the liquid does not short the circuit out.

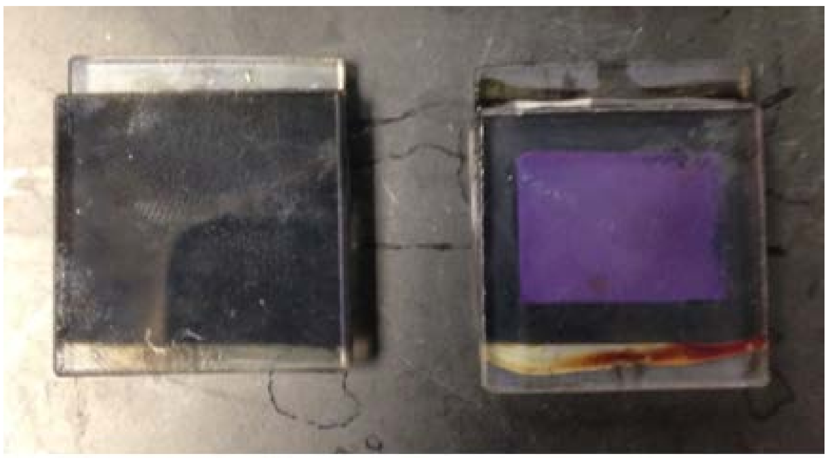


Figure 12: Fully Assembled Solar Cell: On the left is the anode, the carbon coated slide. On the right is the cathode, the dye stained titanium dioxide coated slide. When put together with the electrolyte these two slides form a fully functioning solar cell.

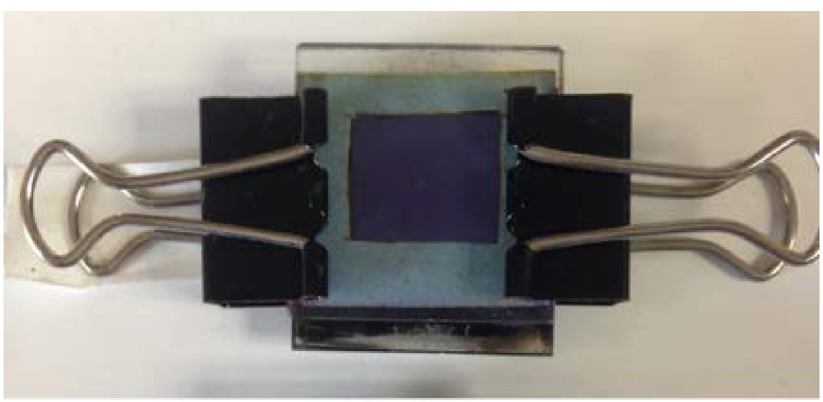


Figure 13: Fully assembled DSSC held together with binder clips to create a tight seal around the gasket to hold the electrolyte in the well.

Preparation of the Ferrocene/Ferrocenium Electrolyte

The ferrocene/ferrocenium electrolyte was synthesized with the help of the honors research advisor. If not handled with caution, this synthesis can be dangerous. Ferrocene can cause eye, skin, intestinal, and respiratory irritation with prolonged exposure.[13] If exposure occurs the area should be flushed and a physician contacted. Ferrocenium hexafluorophosphate can cause eye, oral, intestinal, skin, and respiratory irritation with prolonged exposure.[14] If exposure occurs the area should be flushed and a physician contacted. 3-methoxypropionitrile can cause eye, skin, respiratory, and intestinal irritation with prolonged exposure.[15] If exposure occurs the area should be flushed and a physician contacted.

Ferrocene is a rust colored crystal that provides the reduced state of the electrolyte; its crystals can be seen below in Figure 14. A 0.10 molar ferrocene solution was prepared from 0.1863 grams of ferrocene and 10.00 mL of deionized water.[16] Ferrocenium hexafluorophosphate is a dark blue crystal that provides the oxidized state of the electrolyte; its crystals can be seen below in Figure 15. A 0.10 molar ferrocenium hexafluorophosphate solution was prepared from 0.3309 grams of the ferrocenium hexafluorophosphate and 10.00 mL of deionized water. [16] 3-methoxypropionitrile was bought as a solution and was not diluted in any way, as shown below in Figure 16.[16]

Figure 14: Ferrocene crystals used in the ferrocene electrolyte. They are rust colored and somewhat fine.

Figure 15: Ferrocenium hexafluorophosphate crystals used in the ferrocene synthesis. They are dark blue (somewhat purple) and very fine.

Figure 16: 3-Methoxyproprionitrile used in the ferrocene electrolyte. It is a colorless liquid.

To prepare the electrolyte, 10 milliliters of the ferrocene solution, measured out with a volumetric flask, and 10 milliliters of the ferrocenium hexafluorophosphate solution, measured out with a volumetric flask, were mixed in an Erlenmeyer flask with excess 3-methoxypropionitrile, then mixed with a stir bar on a stir plate until a consistent solution is formed, which took approximately 10 minutes.[16] When the ferrocenium hexafluorophosphate and ferrocene were combined with the 3-methoxypropionitrile the solution turned a dark green/blue color. After mixing, the solution was bubbled with nitrogen to remove oxygen molecules from it. Putting a rubber tube on a nitrogen tank and affixing a capillary tube to the end did this. This capillary tube was then placed into the volumetric flask with the solution and allowed to bubble the nitrogen through the solution for 10 minutes. The Schlenk line can be seen below in Figure 17.[16]

Figure 17: Schlenk line used to bubble Nitrogen through the ferrocene electrolyte after synthesis

The electrolyte was used immediately in the solar cells and tested. Excess electrolyte was kept isolated in a gas hood, originally to be used in later experimental trials. It was determined through trial and error that if any flasks containing the solution are agitated the solution crashes, which means the ferrocene and ferrocenium hexafluorophosphate solutions precipitate and a color change of the remaining solution occurs. It was hoped that excess electrolyte could be used in future experimental trials, but after several days isolated in a gas hood the solution was also susceptible to crashing and precipitating. Therefore, it was determined that the ferrocene/ferrocenium electrolyte must be freshly synthesized every time it is to be used in the fabrication process.

Making the Instrument

A new instrument was built and a computer program was created to make a solar cell current-voltage (IV) curve based on a paper written by a Bowling Green State University research student.[17] The first part of the experiment was to build a circuit, illustrated below in Figure 18, that the solar cell could be hooked into for testing. The circuit was designed to send a voltage into the positive terminal of the operational amplifier using a data acquisition (DAQ) board to do so. The operational amplifier then demands the negative terminal of the circuit to match the current produced by the voltage going into the positive terminal. The solar cell is attached to the negative side of the operational amplifier in the circuit. This means that the voltage producing the current from the conversion of sunlight into electrical energy from the solar cell must match the current from the DAQ board. A transistor is contained within the circuit to ensure the current flows the correct way through the circuit into the operational amplifier. Resistors are used in the circuit to scale the current and voltages to those that match the current and voltage going into the operational amplifier. The computer program that was built to control the circuit takes into account the resistors and scale factors when calculating and measuring the current and voltage.

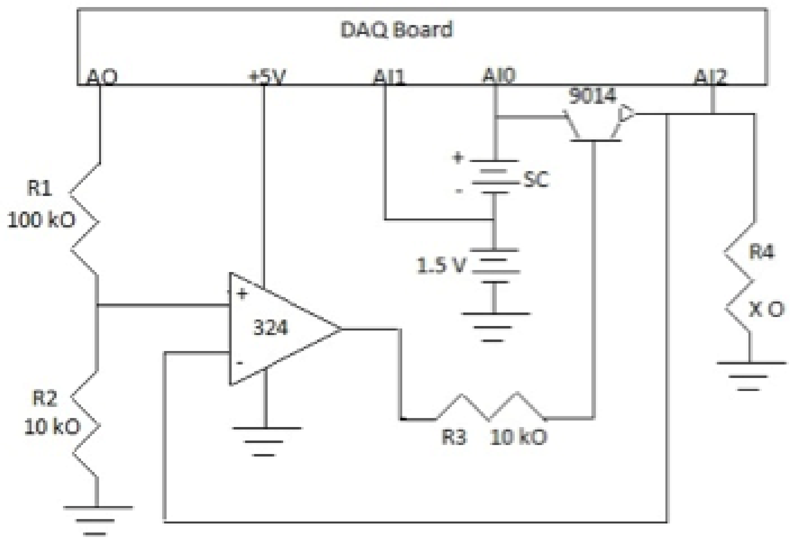


Figure 18: Circuit diagram showing the electrical components and their relationship to each other in the instrument.

A LabView computer program was written to control this new instrument; the block diagrams and front panel can be seen in Figures 19, 20 and 21, below. The purpose of the computer program is to drive the circuit by controlling a DAQ board as well as create the graphical representation of the recorded data. The program is split into three parts; the first one that sets the voltage of the positive of the operational amplifier, the second one that measures the voltage and current produced by the solar cell to match, and the third one that writes the IV and Power curves after the trial is completed. This instrument is important in reducing measurement error and increasing comparability of results, which moved this honors project forward.

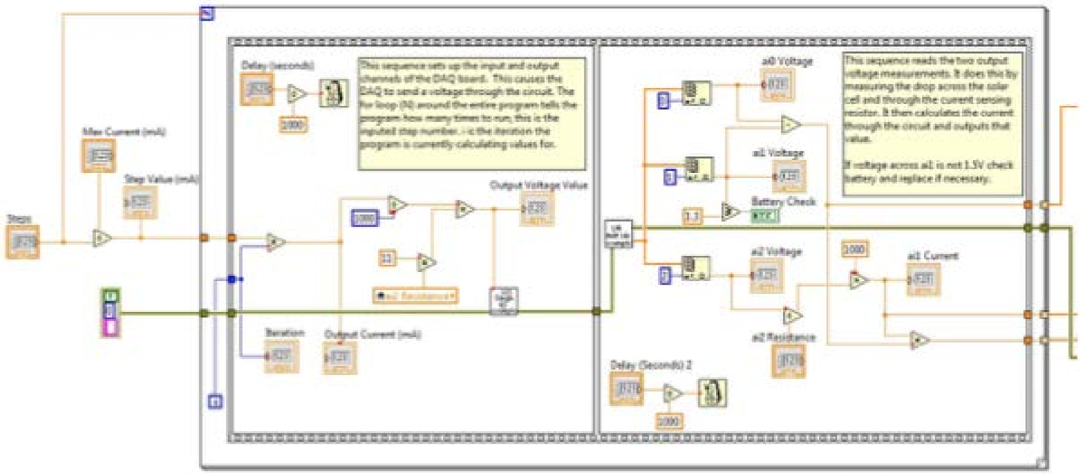


Figure 19: Block Diagram 1 showing the first part of the computer program designed for the instrument.

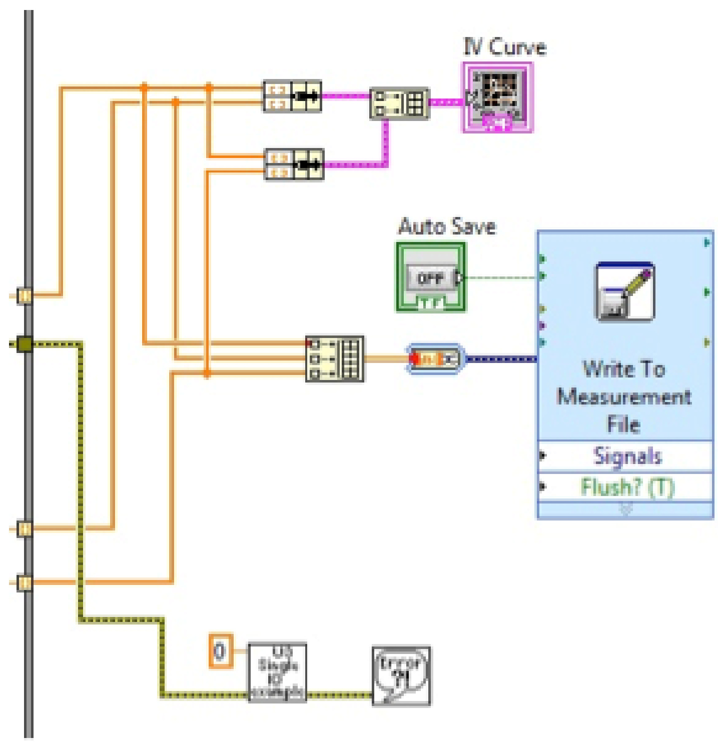


Figure 20: Block Diagram 2 showing the second part of the computer program designed for the instrument, this part writes the graph files.

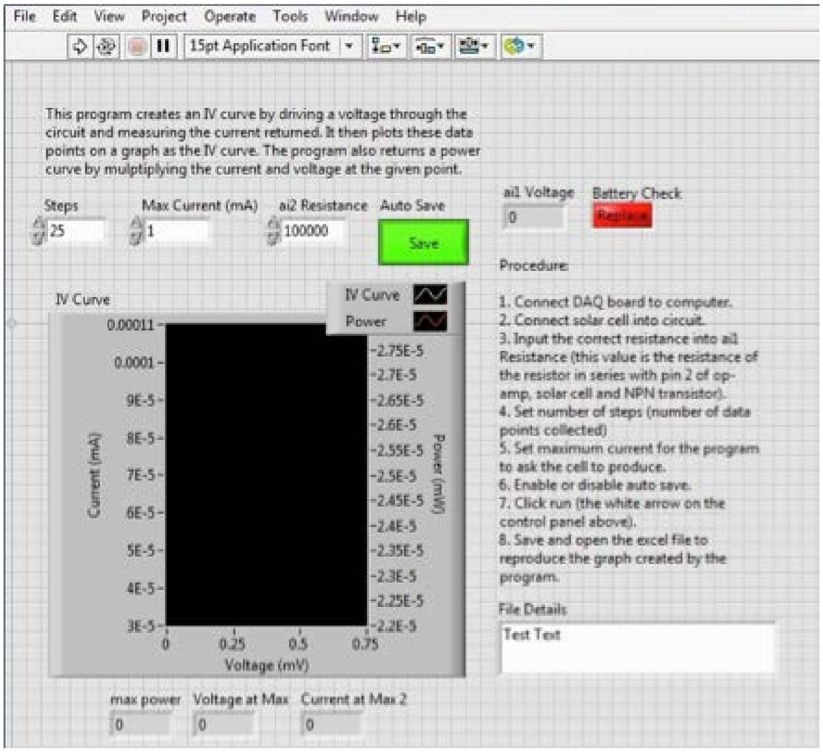


Figure 21: Front Panel of the instrument, where the original IV and Power curves appear.

The first part of the program uses the computer to send a message to the DAQ board. This message tells the DAQ board to send a voltage to the positive terminal of the operational amplifier. The purpose of the operational amplifier is to match the current coming into the positive and negative terminals. The program is designed to run in iterations, starting at zero volts and increasing stepwise. It tells the DAQ board to send the proper voltage to reach the current needed for that iteration of the program. The maximum voltage the DAQ board can provide is a +5 volt but the program will rarely, if ever, send that high of a voltage to the circuit. The researcher sets the maximum current the circuit receives from the DAQ board as well as the number of steps the program will run to reach the maximum current.

The second part of the program tells the DAQ board to read the digital input channel for the voltage and current coming into the negative terminal of the operational amplifier. This terminal is connected to the solar cell, so the voltage and current readout are those being produced by the solar cell. After each step the program pauses to allow the solar cell to react to the increase in current to the operational amplifier. After this pause, the DAQ board reads the new voltage and current, this cycle continues until the maximum current set by the researcher is reached.

The third part of the program was designed to write the two graphs, the IV and Power curves. The computer records each data point collected from the second part of the program and compiles them together on a single graph with two y-axes. These curves can be seen below in Figure 22. The IV curve is built from the current and voltage collected from the digital input. The voltage is graphed on the x-axis and the current on the y-axis. The data points are connected by a smooth marked line. The power curve is built from the current times the voltage and the voltage. The voltage is graphed on the x-axis and the current•voltage, also called the power, is graphed on the y-axis and the data points are connected by a smooth marked line. This graph will show up automatically on the front panel of the program but will not be exported with the .lvm file that the program saves the experimental trial as. These graphs must be recreated when analyzing the results using Excel.

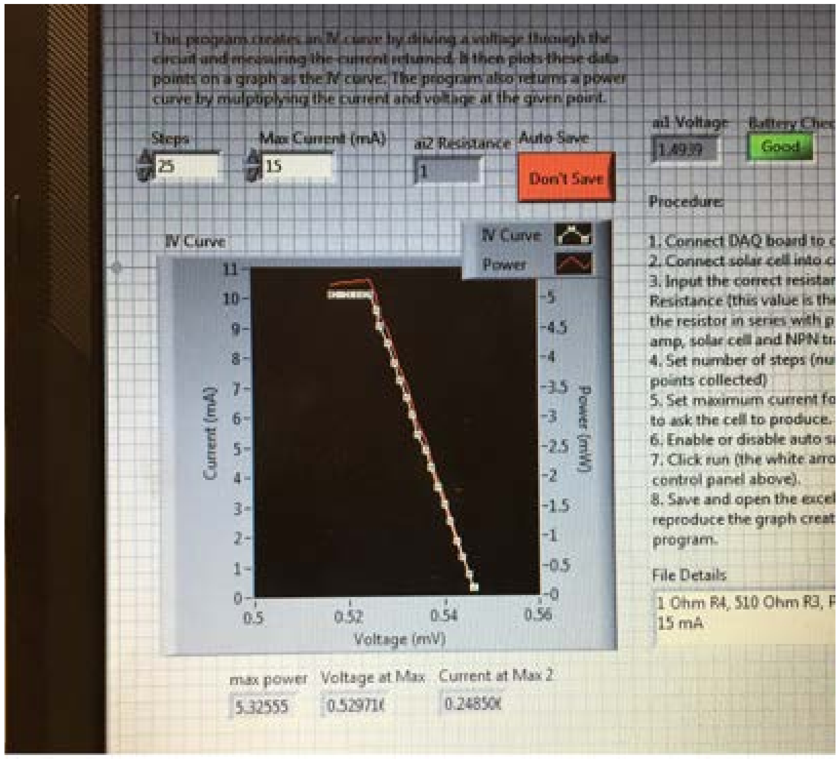


Figure 22: IV and Power curve returned by the instrument on the front panel of the LabView program

The instrument is contained in a small plastic box of dimensions 3.5 inches wide by 7.0 inches long, with a metal plate at the front and back ends of the box. Only the necessary cables come out of the front and back of the instrument, all wiring and electronics are otherwise housed within the box for safety and protection from damage. A LabJack U6 DAQ board was chosen and wired into the instrument. A hole was drilled into the back plate for the USB cable from the DAQ board to connect the instrument to the computer; this can be seen in Figure 23 below. The computer is connected to a power source and must be powered on for the instrument to work. Two holes were drilled into the front plate and two Bayonet Neill-Concelman (BNC) connectors were attached, as shown in Figure 24 below. The circuit is connected to the BNC connectors and the DAQ board, which can be seen in Figure 25 below. One wire is attached to each BNC connector and at the end of each wire is an alligator clip. One wire gets connected to the positive terminal of the solar cell and one wire gets connected to the negative of the solar cell, these wires are properly labeled for ease of use and are shown in Figure 26 below. After the instrument was assembled and tested, the top plate of the box was screwed into the bottom to complete the instrument.

Figure 23: Back Panel of the Instrument: The USB cord from the DAQ Board comes out of the back panel of the instrument and inserts into the computer to power and drive the DAQ board.

Figure 24: Front Panel of the Instrument: Two alligator clips soldered to wires attach to the BNC connectors on this front panel and go to the solar cell.

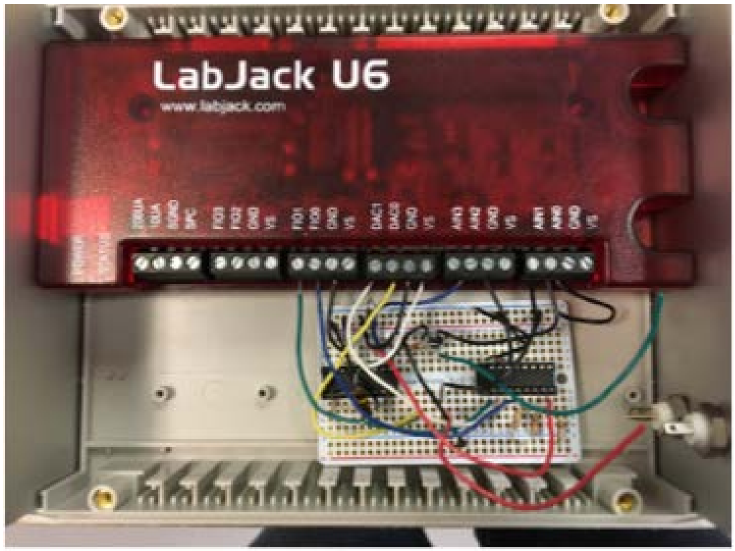


Figure 25: DAQ Board and Circuit: The circuit connects to the DAQ board and to the solar cell by way of alligator clips. These are the main electrical components of the new instrument and allow the IV curve to be created.

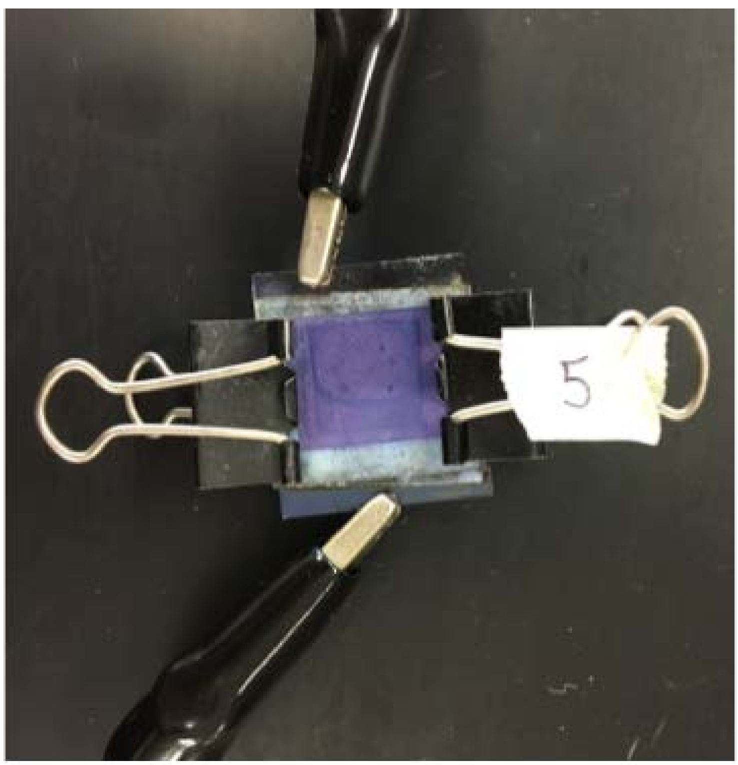


Figure 26: Instrument wires connected to solar cell to complete the circuit and allow the instrument to collect data

Testing the Solar Cells

Before the instrument can be used to test the solar cells fabricated in the experimental trial the computer must be plugged into its power source and powered on. Before opening LabView, the USB cable from the instrument should be plugged into the proper channel on the computer. LabView will open with a menu of program files, select the Solar Cell Curve Generator file and wait for the front panel to open. The block diagram of the LabView program should never be opened during normal solar cell testing. The only time it should be opened is if an instrument malfunction occurs and it must be determined if the problem is contained within the circuit or the computer program. Ensure the program recognizes the DAQ board is connected. If LabView does not acknowledge the DAQ board refer to the instrument manual, which is attached in Appendix B, for troubleshooting. If everything is in order, connect the solar cell to the instrument using the labeled alligator clips coming from the front of the instrument.

The red alligator clip gets connected to the positive of the solar cell, or the titanium dioxide coated piece of glass. The black alligator clip gets connected to the negative of the solar cell, or the carbon coated counter electrode. Ensure both alligator clips are tightly connected so that if the table or solar cell is bumped the connection will not be lost. Turn the overhead projector on, but use caution, as this light is bright and can harm the eyes if care is not taken to avoid looking directly at the source. Place the solar cell under this light with the titanium dioxide coated glass piece facing the light. Care should be taken to ensure that the solar cell is always placed in the same distance and angle from the light source to decrease variability between trials. Figure 27, below, shows how the instrument looks when set up for testing DSSCs in the laboratory.

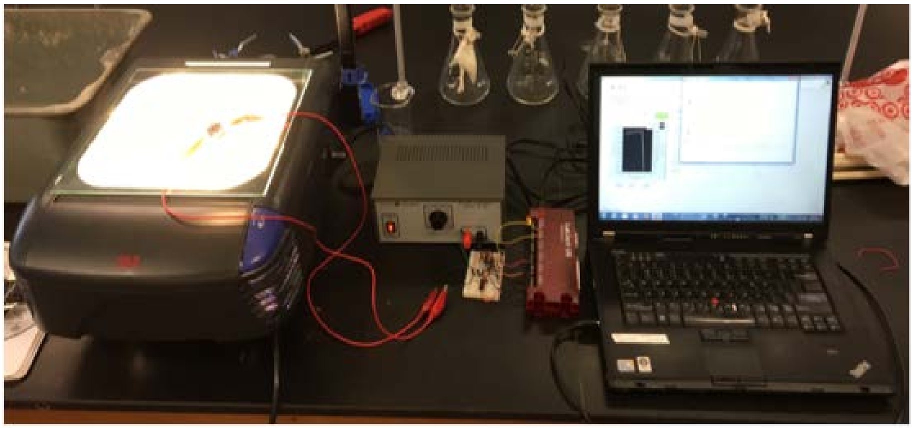
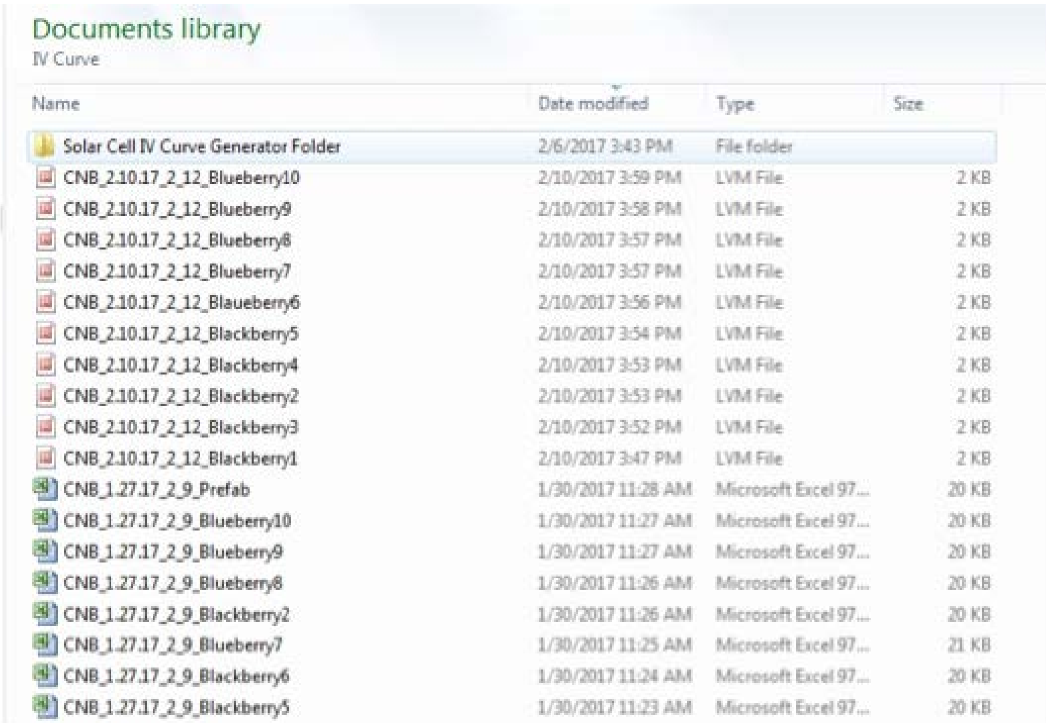


Figure 27: Instrument set up for testing DSSCs using the computer program, circuit and overhead projector

On the front panel of the instrument important information about the trial should be noted in the text box; including the solar cell identifier, the resistor used for the curve generation, what experiment the cell belongs to, and any other pertinent information that will help the researcher when analyzing the results. After this step has been completed the auto save button can be turned on, which can be verified if the auto save button is green. The button to run the program can now be pressed so that the curves will be generated. This button is a white arrow with a black outline and can be found towards the top control panel of the front diagram. After the program finishes running the instrument, it will automatically save the file and ask the researcher to name it. The trial should be saved to the researcher's personal folder inside the solar cell research folder under this title format: Researcher Initials_Date of Experiment_Lab Notebook Page Number_Cell Identifier (note that no spaces should be used in the title between words and the underscore should be used between sections), and example can be seen in Figure 28 below. This file should be saved as an .lvm file so that it can later be exported to an excel file for analysis.


Documents library
IV Curve

Name	Date modified	Type	Size
Solar Cell IV Curve Generator Folder	2/6/2017 3:43 PM	File folder	
CNB_2.10.17_2_12_Blueberry10	2/10/2017 3:59 PM	LVM File	2 KB
CNB_2.10.17_2_12_Blueberry9	2/10/2017 3:58 PM	LVM File	2 KB
CNB_2.10.17_2_12_Blueberry8	2/10/2017 3:57 PM	LVM File	2 KB
CNB_2.10.17_2_12_Blueberry7	2/10/2017 3:57 PM	LVM File	2 KB
CNB_2.10.17_2_12_Blaueberry6	2/10/2017 3:56 PM	LVM File	2 KB
CNB_2.10.17_2_12_Blackberry5	2/10/2017 3:54 PM	LVM File	2 KB
CNB_2.10.17_2_12_Blackberry4	2/10/2017 3:53 PM	LVM File	2 KB
CNB_2.10.17_2_12_Blackberry2	2/10/2017 3:53 PM	LVM File	2 KB
CNB_2.10.17_2_12_Blackberry3	2/10/2017 3:52 PM	LVM File	2 KB
CNB_2.10.17_2_12_Blackberry1	2/10/2017 3:47 PM	LVM File	2 KB
CNB_1.27.17_2_9_Prefab	1/30/2017 11:28 AM	Microsoft Excel 97...	20 KB
CNB_1.27.17_2_9_Blueberry10	1/30/2017 11:27 AM	Microsoft Excel 97...	20 KB
CNB_1.27.17_2_9_Blueberry9	1/30/2017 11:27 AM	Microsoft Excel 97...	20 KB
CNB_1.27.17_2_9_Blueberry8	1/30/2017 11:26 AM	Microsoft Excel 97...	20 KB
CNB_1.27.17_2_9_Blackberry2	1/30/2017 11:26 AM	Microsoft Excel 97...	20 KB
CNB_1.27.17_2_9_Blueberry7	1/30/2017 11:25 AM	Microsoft Excel 97...	21 KB
CNB_1.27.17_2_9_Blackberry6	1/30/2017 11:24 AM	Microsoft Excel 97...	20 KB
CNB_1.27.17_2_9_Blackberry5	1/30/2017 11:23 AM	Microsoft Excel 97...	20 KB

Figure 28: Example of the proper way to name files collected by the instrument, including researcher's initials, date, lab notebook information and cell identifier

Creating the IV and Power Curves

After all of the solar cells have been tested LabView can be shut down and the overhead projector light turned off. The files can now be opened in Excel and the IV and Power curves can be generated. The IV curve is a current versus voltage graph where the data points come directly from the results at the end of each iteration of the program. The Power curve is a voltage versus voltage•current (voltage•current is equivalent to power) graph where the data points came from the product of the current and voltages from each iteration of the program graphed versus the current at which the resulting power occurred at. Both of these curves should be generated using a smooth marked scatter plot with no trend line, slope equation, or R^2 value added. Both generated curves should be plotted on the same graph with the same x-axis, however they should be plotted on separate y-axes. The same x-axis is used because both curves are graphed against voltage, and the voltage values for each data point will be the same. The separate y-axes are used to allow for proper scaling of each curve to ensure ease of readability. The graphs should have major and minor tick lines on each axis but it is up to the researcher to decide if background lines should show up on the graph or if they should be left out. For this honors project the tick lines were used on the axes but not behind the curves. Once the curves have been generated the Excel file can be re-saved under the same file name.

The IV curve allows the researcher to easily find the open-circuit voltage and short-circuit current values produced by the solar cell during energy conversion. The Power curve allows the maximum power output of the solar cell to be determined, as well as the voltage at which this power occurs. These two curves are easy to read and understand and the information they provide is important in the analysis of the productivity of the experimental solar cells. This instrument is also important in allowing the solar cells built at the University of Indianapolis to be compared to those built by other researchers who have published their findings. This is an important step forward if this research is to be continued by other research students.

Progression of the Project

The original goal of this honors project was to test three different dyes obtained from crushed berries and three different electrolytes for a total of 9 different combinations to determine which combination of electrolyte and dye would produce the highest energy conversion efficiency. The berries were chosen based on local availability and the relative "darkness" of dye produced, which was determined visually. The idea is that dyes from a darker berry, such as a blackberry, absorb more wavelengths of visible light and therefore allow more solar energy conversion due to more electrons being promoted to their LUMO and falling into the channel created by the titanium dioxide nanoparticle layer. Blackberries, blueberries, and strawberries were chosen, this gave a dye with a darker color, one with a medium color, and one with a lighter color. The dyes produced by the crushed berries can be seen below in Figure 28. By using a berry that provides a dye in each of the relative darkness categories, it can be determined if the original ideas about wavelength absorption had an effect.

The electrolytes chosen were a two-step oxidation-reduction iodide/tri-iodide electrolyte, a one step oxidation-reduction reaction ferrocene/ferrocenium electrolyte, and a one step oxidation-reduction reaction cobalt electrolyte. The iodide electrolyte is commonly used in literature, so it was chosen as the "gold standard" electrolyte to compare the results of the ferrocene and cobalt electrolytes to. The ferrocene and cobalt electrolytes were chosen for their one step oxidation-reduction reaction in the hopes that a higher energy conversion efficiency will occur because of a lower amount of energy needed to drive the crucial oxidation-reduction cycle of the electrolyte. Premade iodide electrolyte was used in the cells but it was decided that the ferrocene and cobalt electrolytes would be synthesized in-house alongside the project research advisor.

While working on the honors project proposal, a semester was spent on preliminary research to prepare for completing the honors project, if accepted. This preliminary research was necessary to prepare for the research to be done for the honors project. This semester was spent mastering the solar cell fabrication process to ensure reproducibility from trial to trial. During this time, it was realized that even the best solar cells produced by the methods described previously lasted only a few hours before their gasket failed and the majority of the electrolyte leaked from the cell. Once the electrolyte leaks out the solar cell is rendered useless, which is a problem that needed to be fixed before any work on the honors project could begin. At the time, a parafilm gasket was previously used in the solar cell fabrication process; an example can be seen in Figure 29 below. Parafilm is a type of pliable plastic often used to cover beakers and Erlenmeyer flasks. This parafilm gasket did not create a tight seal and even with the pressure applied from the binder clips could not keep the electrolyte in the well.

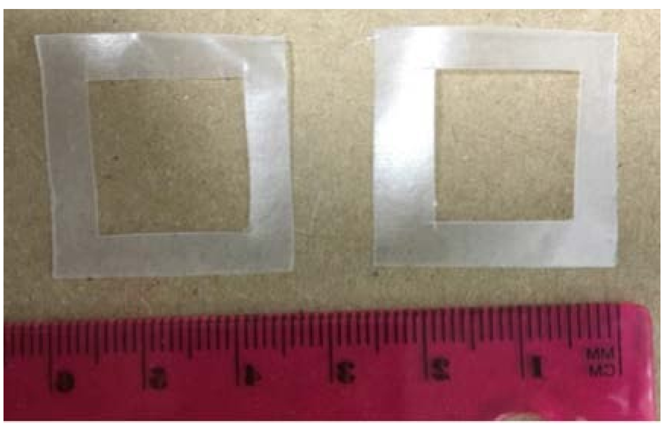


Figure 29: Parafilm Gasket: Two pieces of parafilm gasket cut to fit the solar cell and create the well for the electrolyte.

After researching many other types of gasket, it was decided to test a type of gasket called Blue Gylon Style 3504, which is a polytetrafluoroethylene (PTFE) material with aluminosilicate microspheres contained within it. An example of this gasket can be seen below in Figure 30. This gasket is a product of Garlock, a major gasket producing company located in New York. This Gylon gasket is made from thicker and sturdier material, which makes it easier to work with than the previous parafilm gasket. This gasket allows more of the electrolyte to sit in the well it creates as well as creates a tighter seal between the two pieces of conductive glass. Using this gasket increased the longevity of the solar cells from only a few hours to several weeks. Most cells created using the new gasket material were still viable after 7 weeks and several lasted as long as 9 weeks. This new gasket also streamlined the fabrication process, as it decreased the time it took to assemble the solar cells, and increased ease of assembly, as the Gylon gasket is much easier to place into between the conductive glass slides than the flimsy parafilm gasket. Increasing the longevity and ease of assembly of these solar cells was an important step forward during the preliminary research period and would prove vital to the honors project research. If the solar cells last less than one day, few results can be obtained and they will never be viable as a potential source of renewable energy for consumers.

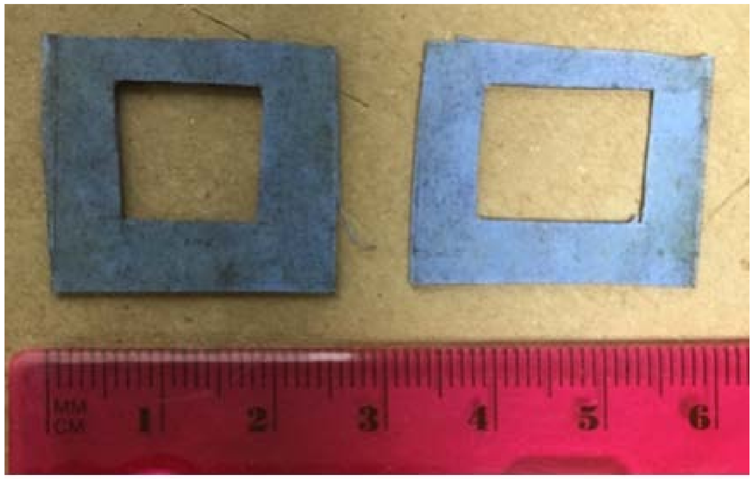


Figure 30: Garlock Gasket: Two pieces of PTFE Blue Gylon 3504 gasket cut to the same dimension as the area of the titanium dioxide layer on the inner side and slightly smaller than the dimensions of the glass slide on the outer side.

In addition to finding a new gasket to use in fabrication of the solar cells, the preliminary research period was also spent creating a more standardized method to testing the solar cells after fabrication. The original method used a digital multimeter was attached to the solar cells using alligator clips, one on the anode and one on the cathode. Other than those instructions, no official procedure was in place to ensure consistency between trials. This would reduce the validity of any results obtained during the honors project research. To collect meaningful data, a method of irradiating the solar cells with a consistent light source needed to be developed. To this end, a variety of options were evaluated. Previous work by other students had focused on using a plant grow lamp as a light source. It was chosen as it was supposed to mimic the spectral output of light produced by the sun. As such, this lamp was incorporated into this work toward a new standardized test procedure. A box, made of foam core poster board and metal sewing pins, was built to house the new lamp and solar cells during testing. The box was made to fully enclose the lamp and block ambient light from the overhead lamps and sunlight through the windows. By blocking ambient light, it can be ensured that the only source of light causing energy conversion in the solar cells was the light coming from the plant grow lamp. This new box allows more consistent testing and results from each trial of fabricated solar cells, which is vital to the honors project research if accurate analysis is to be performed. This test set-up can be seen below in Figure 31.

Figure 31: Test Method 1: The grow lamp and light containment box previously used to test the solar cells.

The new standardized procedure included putting the plant grow lamp into the new box and plugging it into a power source. The solar cell was placed on the taped x on the lamp's holder. The solar cell was placed with the titanium dioxide coated side upwards facing the lamp. The red alligator clip was attached to the cathode and the black alligator clip attached to the anode. The front door of the box was shut with the solar cell inside while measurements are being recorded. The lamp was left off and the digital multimeter is used to measure the voltage and current produced by the internal chemistry of the solar cell. The lamp was then switched on and the current and voltage were again measured with the digital multimeter. These measurements were recorded and later compared between cells.

At the end of the semester, the honors proposal was accepted and the preliminary research was incorporated into the start of the honors project research. It was determined that the current and voltage produced by the solar cells was still lower than expected. It was hypothesized that the glass used in the cells had worn out after being reused multiple times. Supporting evidence for this came in the form of the internal resistance increasing over time presumably because the glass sides were becoming more difficult to clean properly due to TiO_2 and carbon soot being stuck to the glass. New glass was ordered, and after a trial to compare the results with the old glass it was determined that some diminished energy conversion was resulting in the old glass. A DSSC assembled with the old glass can be found below in Figure 32, a DSSC assembled with the new glass can be found below in Figure 33, and a side-by-side comparison of the glass can be found in Figure 34, seen below.

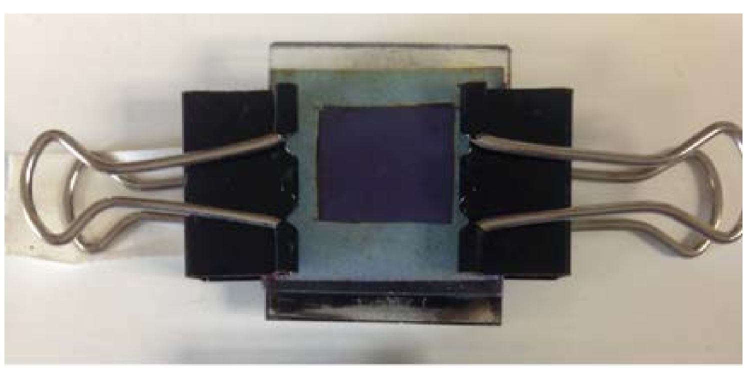


Figure 32: Fully assembled DSSC made with the old glass slides. The glass is cloudy, dirty, and difficult to clean after trials and to make good connections with the alligator clips.

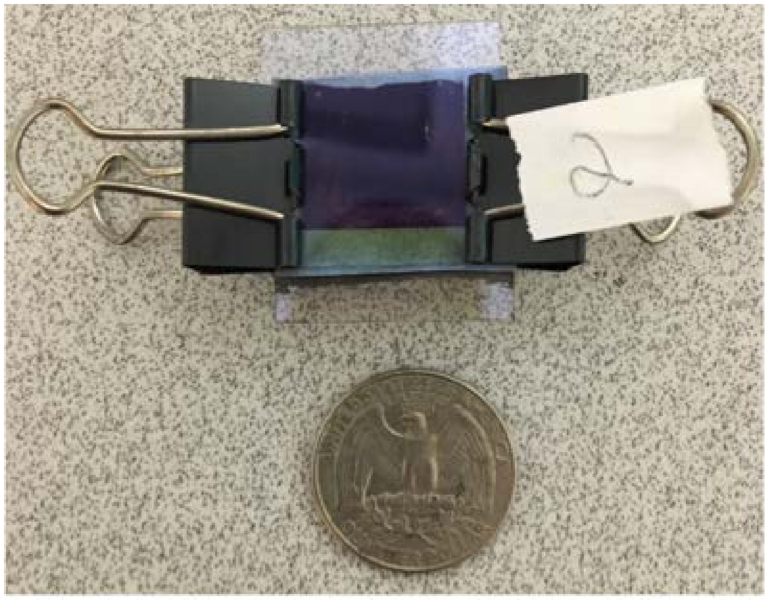


Figure 33: Fully assembled DSSC made with the new glass slides. The glass is clear, clean and easy to wipe clean to make a good connection with the alligator clips.

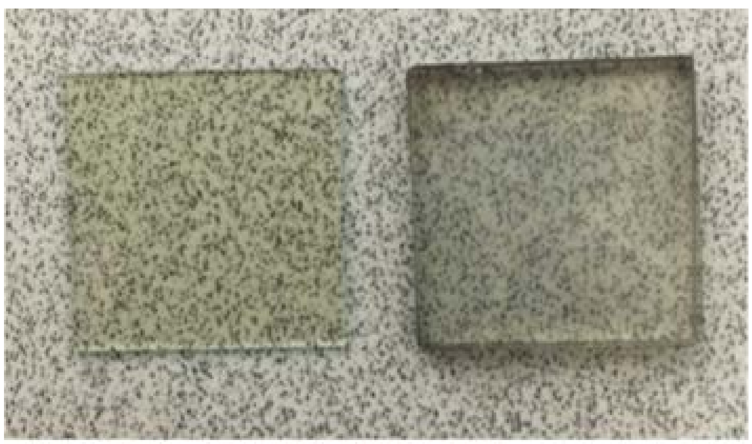


Figure 34: Glass Slides: On the right is the old glass used in cell fabrication. It became stained and difficult to clean so new glass was bought for future trials (glass slide on the left).

Although the results were slightly better, after several trials with the new glassware the results were still not as high as previously expected. It was then hypothesized that the light source being used was not putting off the expected wavelength spectrum. To test this theory a red tide emission spectrometer was borrowed from the physics department to determine the wavelengths of light produced by the plant grow lamp.

The red tide emission spectrometer measures the intensity of light from all wavelengths in the visible and ultraviolet light spectra. If the grow lamp produced a wavelength spectrum similar to that of the sun, it would show up as a fairly smooth curve with intensities for every wavelength of light in these two regions, there would be no large, distinct peaks. However, the spectrum from the grow lamp had distinct peaks at the red, blue, and yellow wavelengths, which can be seen below in Figure 35. These wavelengths match those put off from individual light emission diodes better than those of the sun, which can be seen in Figure 36. Although these wavelengths can be considered some of the more important ones, they are not the only ones that the berry dyes absorb at and therefore only using those wavelengths diminished the solar cell's ability to convert light into electrical energy and its maximum capacity. Additionally, this does not mimic the emission spectrum of the sun seen in Figure 35.

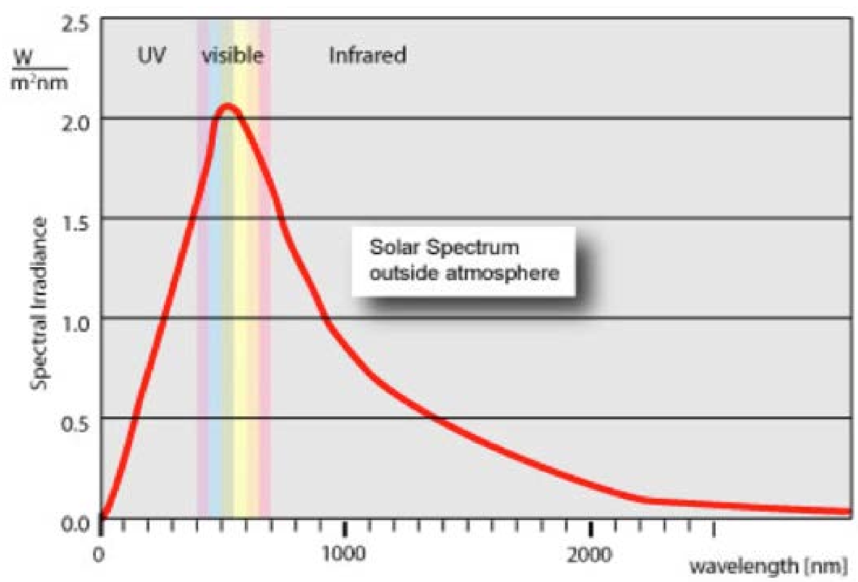


Figure 35: Emission Spectrum of the sun with its smooth curve. Note, the scale of this graph is much larger than the other two emission spectrums shown.

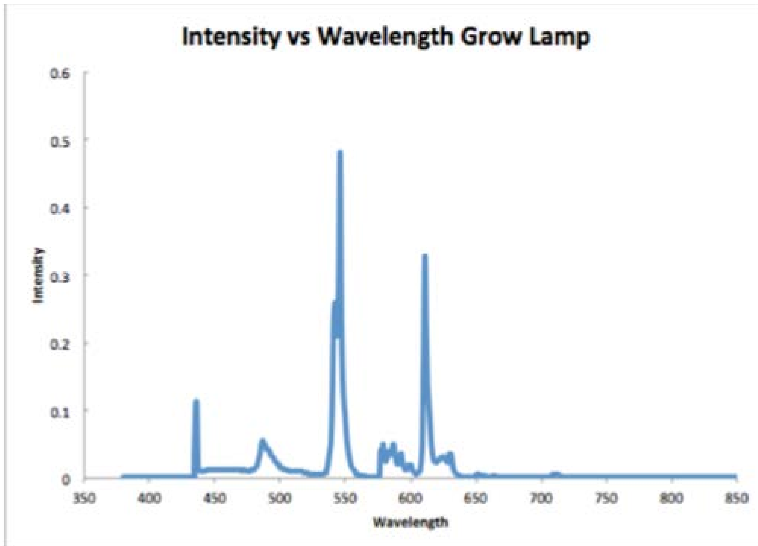


Figure 36: Emission Spectrum of the plant grow lamp with three distinct peaks.

The red tide emission spectrophotometer was used to look at other available light sources to determine if any of them had an emission spectrum more similar to that of the sun than the grow lamp. When an overhead projector lamp was tested, it had a smooth emission spectrum, with no distinct peaks having higher emission intensity than others. This smooth curve can be seen below in Figure 37. It was decided that moving forward, the overhead projector would be used when testing solar cells instead of the plant grow lamp and the test box. It was hoped that this change would help greatly increase the voltage and current produced by the solar cells when converting energy during trials and better mimic true working conditions for a solar cell being outdoors.

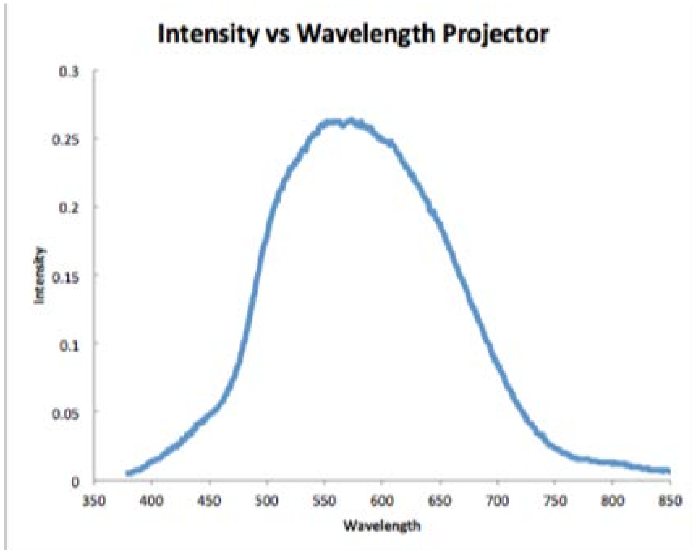


Figure 37: Emission Spectrum of the overhead projector lamp, with a smooth curve.

The next task was to focus on synthesizing the two new electrolytes and comparing them to the iodide electrolyte. Due to unforeseen circumstances, only one electrolyte was synthesized. These syntheses are time intensive and require direct supervisor supervision due to potentially dangerous chemicals that need proper handling and it was difficult to find the sufficient blocks of time to complete these syntheses. It was decided to synthesize the ferrocene/ferrocenium electrolyte first. After completion of this electrolyte synthesis was complete, testing under normal conditions was performed. After testing, it was realized that proper measurements to calculate efficiencies could not be recorded due to the instrument capabilities at the time. Work toward finding a better method to collect voltage and current data from the solar cells was then prioritized to help move the honors project forward.

Eventually, a paper was found where the researchers built an instrument and a computer program to run the instrument which could collect the necessary data from the cells. It was decided to properly understand the results from the cells being created, a detour from the original proposal of the honors project would be necessary. This detour would be to build an instrument that records better measurements for better analysis of the fabricated solar cells. If the instrument could be built and properly tested, the original goal of the honors project would be resumed and enhanced. The prototype for this instrument was built during a three-week summer research internship under the direction of Dr. David Styers-Barnett and with the help of Dr. Stephen Spicklemire. This instrument contains a circuit and a computer program that work in conjunction to produce a current-voltage curve and a power curve. The graph the instrument produces provides data for the open-circuit maximum, the open-voltage maximum, and the maximum power obtained, as well as shows at what voltages the solar cell produces the highest current flow. A full description of the instrument and how it works and it's capabilities can be found above in the methodology section.

After testing the prototype instrument to determine if it worked as expected, a semester was spent building the standalone instrument and making improvements to both the circuit and computer program. Problems were encountered at this point and most of the semester was spent troubleshooting a new piece of the circuit and the part of the computer program that controls it. This piece would allow for a digital switch (created using a multiplexor) to choose the proper resistance to be used in the circuit depending on which solar cells were being tested. After spending a majority of the semester working on this piece, it was the determined that the digital switch method would not work as according to plan, so an analog switch method was considered for use. In the end, it was decided that adding the switch was not as high a priority as testing the variables, so the switch was left out and the resistors were changed by hand depending on the solar cell being tested by the instrument.

These improvements to how the fabrication and testing of solar cells allow for maximum efficiency of the instrument and ease of use for future undergraduate research students working with solar cells. An instrument manual was prepared to store with the instrument in case questions arise of how to use it in the future. After the instrument was finished, the original goals of the project were resumed and testing the different berry dye and electrolyte combinations began. Due to time before graduation being a factor, it was decided to test only one new electrolyte, the ferrocene/ferrocenium electrolyte. It was also decided to test only two of the berry dyes, as the berry dyes are a simple variable to exchange because they require no synthesis and little preparation.

Results and Analysis

The prefabricated solar cell was tested at the beginning of each experimental trial to ensure the instrument was working properly. The IV and Power curves for this cell can be found below in Figure 38. The open circuit voltage for the first trial was found to be 0.5598 V, the short circuit current was found to be 10.1511 mA and the maximum power was calculated to be 5.4758 mW. Based on tests using a digital multimeter on the prefabricated cell that returned a voltage of 0.55 V it can be concluded that the instrument is working, with only the minor tweaks explained above needing to be made. This solar cell IV curve cannot be compared to the DSSCs prepared in lab because they are not made of the same materials, however, as it is a prefabricated and sealed cell it acts as a good control test cell to ensure the instrument is working properly. It is important to note that the instrument measures the prefabricated solar cell current in milliamps and power in milliwatts, whereas it measures the fabricated DSSC current in microamps and power in microwatts. When the IV and Power curves are created, Excel is used to convert the current into milliamps and the power into milliwatts.

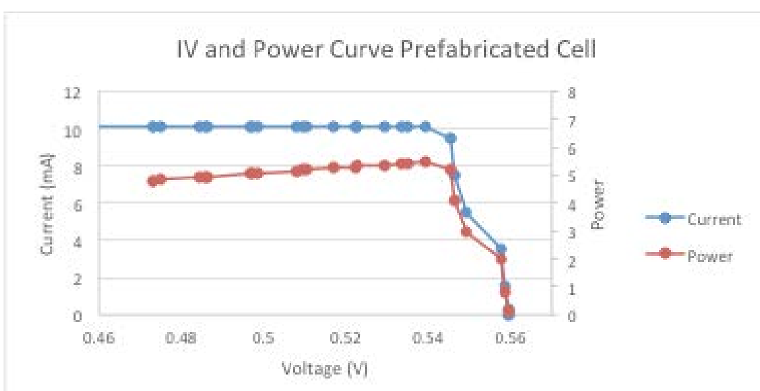


Figure 38: Prefabricated silicon solar cell tested with a 1.0 Ohm resistor and a maximum current draw of 10.0 mA.

Table 2, shown below, represents the results obtained for the prefabricated solar cell from the Solar Cell IV Curve Generator without manipulation, other than exporting the file into a readable format. These data files contain information pertinent to the solar cell identifier and the conditions under which the trial was run. The first column of data is the measured voltage, the second is the measured current, and the third is the calculated power. These headings do not appear when exported from the instrument file so they are added to the columns before graphing the results.

Table 2: Prefabricated Cell Data

Voltage	Current	Power	Comment	
0.559769	0		50 mA; 1 Ohm ai2 resistance; Prefab Solar Cell	
0.559571	0.265688	0.148671		
0.558623	1.488868	0.831716	Area B	
0.557675	3.533203	1.97038		5.682296286
0.549303	5.457111	2.99761		
0.546223	7.479694	4.085583		
0.545433	9.520955	5.193047		
0.539431	10.151145	5.475842		
0.534929	10.151145	5.430143		
0.533508	10.151145	5.415712		
0.529164	10.151145	5.371617		
0.522766	10.151145	5.306676		
0.522055	10.151145	5.299461		
0.516843	10.151145	5.246546		
0.510209	10.151145	5.179201		
0.509419	10.151145	5.171183		
0.507839	10.151145	5.155149		
0.498441	10.151145	5.059742		
0.497098	10.151145	5.046113		
0.496624	10.151145	5.041302		
0.486199	10.151145	4.935474		
0.485725	10.151145	4.930663		
0.48454	10.151145	4.918637		
0.474747	10.151145	4.819222		
0.472851	10.151145	4.799981		
0.472851	10.151145	4.799981		
0	10.151145			

Table 2: Data collected from the instrument for the prefabricated solar cell and exported into Excel without manipulation.

The graph shown below in Figure 39 shows a representative IV and Power curve of a DSSC fabricated with the factory synthesized iodine electrolyte and blackberry dye. In this specific curve, the short circuit current was measured to be 0.0102 mA and the open circuit voltage was measured to be 0.173066 mV. The maximum power of this specific DSSC was calculated to be 0.00404 mW. For the entire data set, the short circuit current was the same and the open circuit voltage range was 0.1128 mV and 0.2633 mV. The maximum power ranged from 0.0140 mW to 0.0963 mW. These IV and Power curve graphs can be found in Appendix A.

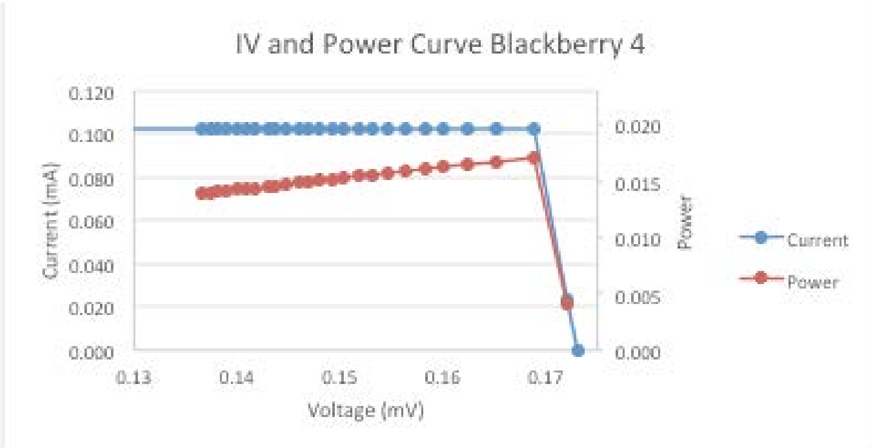


Figure 39: DSSC Blackberry #4 fabricated with the iodine electrolyte and blackberry dye. The 100,000 Ohm resistor was used and 0.5 mA was set as the maximum current draw.

Table 3, shown below, represents the results obtained for DSSC Blackberry #4 from the Solar Cell IV Curve Generator. These data files contain information pertinent to the solar cell identifier and the conditions under which the trial was run. The first column of data is the measured voltages, the second and third are the measured currents, and the fourth and fifth are the calculated powers. These headings do not appear when exported from the instrument file so they are added to the columns before graphing the results.

Table 3: Blackberry #4 Data

Voltage	Current	Current (m)	Power	Power (mW)	Comment	
0.173066		0			0.5 mA; 100000 Ohm ai2 resistance; Blackberry #4	
0.172097	2.34E-05	2.34E-02	4.04E-06	4.04E-03		
0.168858	0.000102	1.02E-01	1.71E-05	1.71E-02	Area B	
0.165146	0.000102	1.02E-01	1.68E-05	1.68E-02		1.77E-02
0.162303	0.000102	1.02E-01	1.65E-05	1.65E-02		
0.159934	0.000102	1.02E-01	1.62E-05	1.62E-02		
0.158275	0.000102	1.02E-01	1.61E-05	1.61E-02		
0.156301	0.000102	1.02E-01	1.59E-05	1.59E-02		
0.154642	0.000102	1.02E-01	1.57E-05	1.57E-02		
0.153221	0.000102	1.02E-01	1.56E-05	1.56E-02		
0.151799	0.000102	1.02E-01	1.54E-05	1.54E-02		
0.150377	0.000102	1.02E-01	1.53E-05	1.53E-02		
0.149351	0.000102	1.02E-01	1.52E-05	1.52E-02		
0.148008	0.000102	1.02E-01	1.50E-05	1.50E-02		
0.146823	0.000102	1.02E-01	1.49E-05	1.49E-02		
0.146033	0.000102	1.02E-01	1.48E-05	1.48E-02		
0.14477	0.000102	1.02E-01	1.47E-05	1.47E-02		
0.143664	0.000102	1.02E-01	1.46E-05	1.46E-02		
0.143032	0.000102	1.02E-01	1.45E-05	1.45E-02		
0.141768	0.000102	1.02E-01	1.44E-05	1.44E-02		
0.1409	0.000102	1.02E-01	1.43E-05	1.43E-02		
0.14011	0.000102	1.02E-01	1.42E-05	1.42E-02		
0.139004	0.000102	1.02E-01	1.41E-05	1.41E-02		
0.138135	0.000102	1.02E-01	1.40E-05	1.40E-02		
0.137504	0.000102	1.02E-01	1.40E-05	1.40E-02		
0.136556	0.000102	1.02E-01	1.39E-05	1.39E-02		
0		1.02E-01				

Table 3: Data collected from the instrument for the Blackberry #4 solar cell and exported into Excel without manipulation.

The graph shown below in Figure 40 shows a representative IV and Power curves of a DSSC fabricated with the factory synthesized iodine electrolyte and blueberry dye. In this specific curve, the short circuit current was measured to be 0.0102 mA and the open circuit voltage was measured to be 0.1624 mV. The maximum power of this specific DSSC was calculated to be 0.0159 mW. For the entire data set, the short circuit current was the same and the open circuit voltage range was 0.0967 mV and 0.2510 mV. The maximum power ranged from 0.0090 mW to 0.0250 mW. These IV and Power curve graphs can be found in Appendix A.

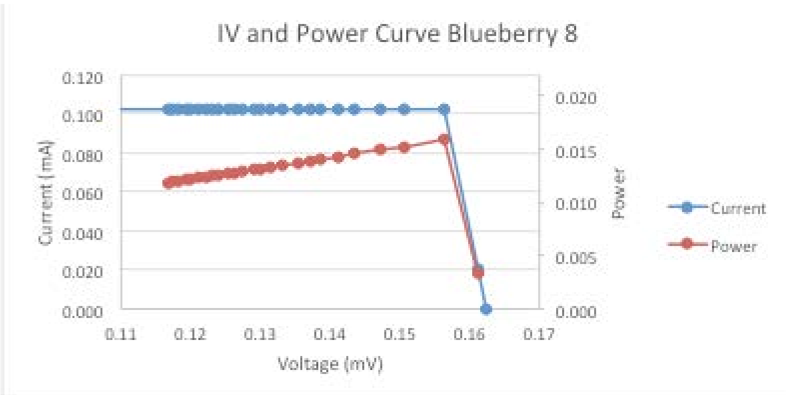


Figure 40: DSSC Blueberry #8 fabricated with the iodine electrolyte and blueberry dye. The 100,000 Ohm resistor was used and 0.5 mA was set as the maximum current draw.

Table 4, shown below, represents the results obtained for DSSC Blueberry #8 from the Solar Cell IV Curve Generator. These data files contain information pertinent to the solar cell identifier and the conditions under which the trial was run. The first column of data is the measured voltages, the second and third are the measured currents, and the fourth and fifth are the calculated powers. These headings do not appear when exported from the instrument file so they are added to the columns before graphing the results.

Table 4: Blueberry #8 Data

Voltage	Current	Current (mA)	Power	Power (mW)	Comment	
0.162356		0			0.5 mA; 100,000 Ohm ai2 resistance; Blueberry #8	
0.161118	2.06E-05	2.06E-02	3.32E-06	3.32E-03		
0.156222	0.000102	1.02E-01	1.59E-05	1.59E-02	Area B	
0.150535	0.000102	1.02E-01	1.53E-05	1.53E-02		1.66E-02
0.14706	0.000102	1.02E-01	1.49E-05	1.49E-02		
0.143506	0.000102	1.02E-01	1.46E-05	1.46E-02		
0.141058	0.000102	1.02E-01	1.43E-05	1.43E-02		
0.138609	0.000102	1.02E-01	1.41E-05	1.41E-02		
0.137109	0.000102	1.02E-01	1.39E-05	1.39E-02		
0.135292	0.000102	1.02E-01	1.37E-05	1.37E-02		
0.133081	0.000102	1.02E-01	1.35E-05	1.35E-02		
0.131343	0.000102	1.02E-01	1.33E-05	1.33E-02		
0.130079	0.000102	1.02E-01	1.32E-05	1.32E-02		
0.129053	0.000102	1.02E-01	1.31E-05	1.31E-02		
0.127394	0.000102	1.02E-01	1.29E-05	1.29E-02		
0.126209	0.000102	1.02E-01	1.28E-05	1.28E-02		
0.125499	0.000102	1.02E-01	1.27E-05	1.27E-02		
0.124077	0.000102	1.02E-01	1.26E-05	1.26E-02		
0.12305	0.000102	1.02E-01	1.25E-05	1.25E-02		
0.12226	0.000102	1.02E-01	1.24E-05	1.24E-02		
0.121076	0.000102	1.02E-01	1.23E-05	1.23E-02		
0.120049	0.000102	1.02E-01	1.22E-05	1.22E-02		
0.119417	0.000102	1.02E-01	1.21E-05	1.21E-02		
0.118233	0.000102	1.02E-01	1.20E-05	1.20E-02		
0.117364	0.000102	1.02E-01	1.19E-05	1.19E-02		
0.116811	0.000102	1.02E-01	1.19E-05	1.19E-02		
0		1.02E-01				

Table 4: Data collected from the instrument for the Blueberry #8 solar cell and exported into Excel without manipulation.

The graph shown below in Figure 41 shows a representative IV and Power curve of a DSSC fabricated with the laboratory synthesized ferrocene/ferrocenium electrolyte and blackberry dye. In this specific curve, the short circuit current was measured to be 0.0102 mA and the open circuit voltage was measured to be 0.0103 mV. The maximum power of this specific DSSC was calculated to be 0.00572 mW. For the entire data set, the short circuit current was the same and the open circuit voltage range was -0.0015 mV and 0.0982 mV. The maximum power ranged from -0.00572 mW to 0.00455 mW. These IV and Power curve graphs can be found in Appendix A. An anomaly occurred during this trial, many of the voltages measured by the instrument were negative, which is indicative of an error. Possible errors here could include a defective cell, possibly from a short within the cell or possibly the electrolyte solution not working correctly. Future studies should work to clarify this.

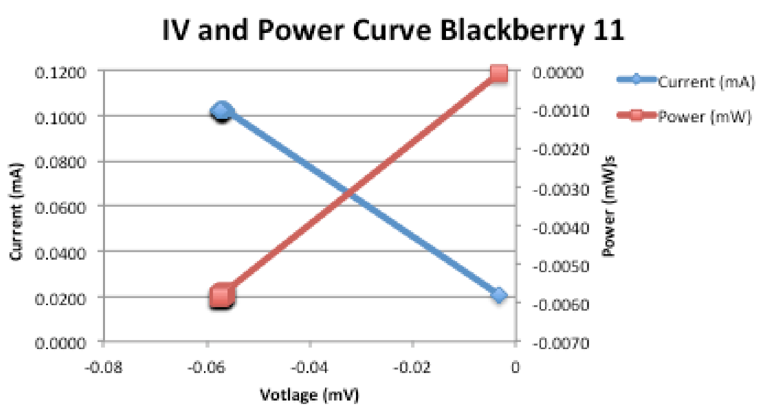


Figure 41: DSSC Blackberry#11 fabricated with the ferrocene electrolyte and blackberry dye. The 100,000 Ohm resistor was used and 0.5 mA was set as the maximum current draw.

Table 5, shown below, represents the results obtained for DSSC Blackberry #11 from the Solar Cell IV Curve Generator. These data files contain information pertinent to the solar cell identifier and the conditions under which the trial was run. The first column of data is the measured voltages, the second and third are the measured currents, and the fourth and fifth are the calculated powers. These headings do not appear when exported from the instrument file so they are added to the columns before graphing the results.

Table 5: Blackberry #11 Data

Voltage	Current	Current (mA)	Power	Power (mW)
0.0103		0		
-0.003238	2.07E-05	2.07E-02	-6.70E-08	-6.70E-05
-0.056391	0.000102	1.02E-01	-5.72E-06	-5.72E-03
-0.056707	0.000102	1.02E-01	-5.76E-06	-5.76E-03
-0.057023	0.000102	1.02E-01	-5.79E-06	-5.79E-03
-0.057023	0.000102	1.02E-01	-5.79E-06	-5.79E-03
-0.05647	0.000102	1.02E-01	-5.73E-06	-5.73E-03
-0.057181	0.000102	1.02E-01	-5.80E-06	-5.80E-03
-0.056865	0.000102	1.02E-01	-5.77E-06	-5.77E-03
-0.056786	0.000102	1.02E-01	-5.76E-06	-5.76E-03
-0.057418	0.000102	1.02E-01	-5.83E-06	-5.83E-03
-0.057023	0.000102	1.02E-01	-5.79E-06	-5.79E-03
-0.05647	0.000102	1.02E-01	-5.73E-06	-5.73E-03
-0.057418	0.000102	1.02E-01	-5.83E-06	-5.83E-03
-0.056944	0.000102	1.02E-01	-5.78E-06	-5.78E-03
-0.056786	0.000102	1.02E-01	-5.76E-06	-5.76E-03
-0.057418	0.000102	1.02E-01	-5.83E-06	-5.83E-03
-0.056707	0.000102	1.02E-01	-5.76E-06	-5.76E-03
-0.056786	0.000102	1.02E-01	-5.76E-06	-5.76E-03
-0.057576	0.000102	1.02E-01	-5.84E-06	-5.84E-03
-0.057734	0.000102	1.02E-01	-5.86E-06	-5.86E-03
-0.056944	0.000102	1.02E-01	-5.78E-06	-5.78E-03
-0.05726	0.000102	1.02E-01	-5.81E-06	-5.81E-03
-0.057497	0.000102	1.02E-01	-5.84E-06	-5.84E-03
-0.057181	0.000102	1.02E-01	-5.80E-06	-5.80E-03
-0.057497	0.000102	1.02E-01	-5.84E-06	-5.84E-03

Table 5: Data collected from the instrument for the Blackberry #11 solar cell and exported into Excel without manipulation.

The graph shown below in Figure 42 shows a representative IV and Power curve of a DSSC fabricated with the laboratory synthesized ferrocene/ferrocenium electrolyte and blueberry dye. In this specific curve, the short circuit current was measured to be 0.0102 mA and the open circuit voltage was measured to be 0.0029 mV. The maximum power of this specific DSSC was calculated to be 0.00125 mW. For the entire data set, the short circuit current was the same and the open circuit voltage range was -0.0093 mV and 0.0658 mV. The maximum power ranged from -0.000249 mW to 0.00116 mW. These IV and Power curve graphs can be found in Appendix A. An anomaly occurred during this trial, many of the voltages measured by the instrument were negative, again indicating some kind of error. Please see the previous example for possible reasons.

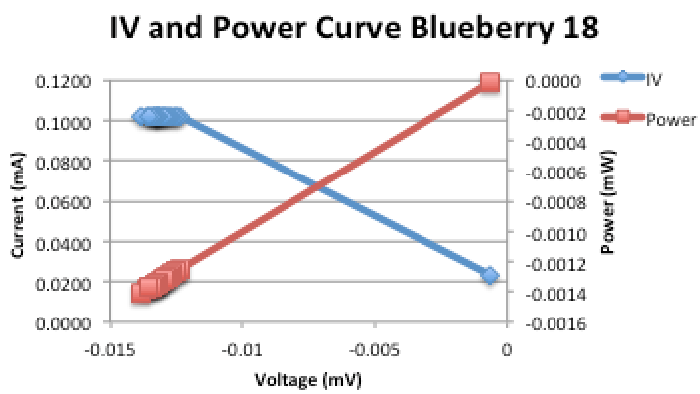


Figure 42: DSSC Blueberry #18 fabricated with the ferrocene electrolyte and blueberry dye. The 100,000 Ohm resistor was used and 0.5 mA was set as the maximum current draw.

Table 6, shown below, represents the results obtained for DSSC Blueberry #18 from the Solar Cell IV Curve Generator. These data files contain information pertinent to the solar cell identifier and the conditions under which the trial was run. The first column of data is the measured voltages, the second and third are the measured currents, and the fourth and fifth are the calculated powers. These headings do not appear when exported from the instrument file so they are added to the columns before graphing the results.

Table 6: Blackberry #18 Data

Voltage	Current	Current (mA)	Power	Power (mW)	Comment
0.002874		0			Blueberry #8, 100,000 Ohm
-0.000632	2.35E-05	2.35E-02	-1.49E-08	-1.49E-05	resistor AI2
-0.012321	0.000102	1.02E-01	-1.25E-06	-1.25E-03	, max current 0.5 mA
-0.012479	0.000102	1.02E-01	-1.27E-06	-1.27E-03	
-0.012479	0.000102	1.02E-01	-1.27E-06	-1.27E-03	
-0.012637	0.000102	1.02E-01	-1.28E-06	-1.28E-03	
-0.012716	0.000102	1.02E-01	-1.29E-06	-1.29E-03	
-0.012795	0.000102	1.02E-01	-1.30E-06	-1.30E-03	
-0.012953	0.000102	1.02E-01	-1.31E-06	-1.31E-03	
-0.012874	0.000102	1.02E-01	-1.31E-06	-1.31E-03	
-0.013032	0.000102	1.02E-01	-1.32E-06	-1.32E-03	
-0.01319	0.000102	1.02E-01	-1.34E-06	-1.34E-03	
-0.013111	0.000102	1.02E-01	-1.33E-06	-1.33E-03	
-0.01319	0.000102	1.02E-01	-1.34E-06	-1.34E-03	
-0.013348	0.000102	1.02E-01	-1.35E-06	-1.35E-03	
-0.012953	0.000102	1.02E-01	-1.31E-06	-1.31E-03	
-0.01319	0.000102	1.02E-01	-1.34E-06	-1.34E-03	
-0.013506	0.000102	1.02E-01	-1.37E-06	-1.37E-03	
-0.01319	0.000102	1.02E-01	-1.34E-06	-1.34E-03	
-0.013269	0.000102	1.02E-01	-1.35E-06	-1.35E-03	
-0.013584	0.000102	1.02E-01	-1.38E-06	-1.38E-03	
-0.013348	0.000102	1.02E-01	-1.35E-06	-1.35E-03	
-0.013427	0.000102	1.02E-01	-1.36E-06	-1.36E-03	
-0.013821	0.000102	1.02E-01	-1.40E-06	-1.40E-03	
-0.013427	0.000102	1.02E-01	-1.36E-06	-1.36E-03	
-0.013506	0.000102	1.02E-01	-1.37E-06	-1.37E-03	

Table 6: Data collected from the instrument for the Blackberry #18 solar cell and exported into Excel without manipulation.

In table 7, shown below, the open current voltage, open circuit current, and maximum power for all fabricated DSSCs are shown. This table was compiled to more easily compare the results of the two trials to determine which electrolyte and dye combination produced the best results. In this table, Blackberry cells 1-5 and Blueberry cells 6-10 were fabricated with the iodine electrolyte and Blackberry cells 11-15 and Blueberry cells 16-20 were fabricated with the ferrocene electrolyte. From this table, several things can be determined. As far as the iodine electrolyte is concerned, neither berry dye appears to be better than the other. As far as the ferrocene electrolyte is concerned, it failed so no conclusion can be drawn. Overall, the iodine electrolyte performed better because it did not fail during trials. In order to draw further conclusions, trials should be replicated and statistical analysis should be performed on the resulting data.

Table 7: Open Circuit Voltage, Short Circuit Current, and Max Power for All Trials

	Open Voltage	Open Current	Max Power
Prefabricated	0.5598	10.1511	5.4758
Blackberry 1	0.1960	0.1020	0.0194
Blackberry 2	0.1128	0.1020	0.0963
Blackberry 3	0.2633	0.1020	0.0260
Blackberry 4	0.1731	0.1020	0.0171
Blackberry 5	0.1424	0.1020	0.0140
Blueberry 6	0.1721	0.1020	0.0170
Blueberry 7	0.2510	0.1020	0.0250
Blueberry 8	0.1624	0.1020	0.0159
Blueberry 9	0.1705	0.1020	0.0149
Blueberry 10	0.0967	0.1020	0.0090
Blackberry 11	0.0103	0.1020	-0.0057
Blackberry 12	0.0002	0.1020	-0.0002
Blackberry 13	-0.0015	0.1020	-0.0001
Blackberry 14	0.0982	0.1020	0.0045
Blackberry 15	-0.0004	0.1020	-0.0001
Blueberry 16	0.0002	0.1020	0.0000
Blueberry 17	-0.0009	0.1020	-0.0002
Blueberry 18	0.0029	0.1020	-0.0013
Blueberry 19	0.0658	0.1020	0.0012
Blueberry 20	0.0239	0.1020	0.0005

Table 7: Table with the open circuit voltage, short circuit current, and maximum power for all trials to consolidate the most important information into one data table.

Due to the fact that the short circuit current for almost every trial run was 0.0102 mA, this suggests that there is potentially a minor issue with the instrument that was built for this project. Although the instrument is fully functional, the results returned are hovering around the detection limits of the instrument. This means that the measured current output of the solar cell under load potentially does not cover the full range of currents produced by the solar cell. A 1.5 V battery was added to the original instrument design to help avoid this limit of detection issue, but it appears that it was still not enough to boost the performance of the DSSCs enough to exceed the limit of current detection of the instrument. For this reason, although the results obtained from this project are acceptable, they cannot be used to determine the fill factor or the efficiency of the solar cell. Only the open circuit voltage and maximum power output can reliably be analyzed with confidence. The short circuit current measured can be reported, but not with confidence that the value is as accurate as had previously hoped it would be. This problem is discussed further in the conclusion with respect to the future direction of this research project with new research students.

Conclusion

This honors project made an important step forward for undergraduate solar cell research at the University of Indianapolis. This new instrument will make testing the solar cells easier as well as streamline the process. It will also greatly improve the readability and reproducibility of the results by creating the IV and Power curves. Never before has a solar cell research student at the University of Indianapolis been able to measure current and voltage produced by the solar cell concurrently to produce these graphs. In the past, only open circuit voltage and short circuit current could be measured. Therefore, great improvement for the future direction of this project has been made as a result of this project. It will allow students to gain results that are more easily comparable to published values, rather than having to do complicated mathematical manipulation or being unable to analyze collected data. This instrument will allow future student researchers to focus on testing other variables rather than constantly needing to improve the testing conditions of the solar cells.

Although great advances were made to this solar cell research project with the creation of Solar Cell IV Curve Generator, future students should continue improving this instrument. One adjustment that needs to be made is improving the sensitivity of the instrument. Trouble-shooting has revealed that this problem is most likely with the circuit design, not a problem with the design or fabrication of the solar cells. Future research students should work with Dr. Styers-Barnett and Dr. Stephen Spicklemire to determine if an improvement can be made to the circuit to increase the limit of detection and obtain results over the full range of currents under differing amounts of load on the solar cell. This will lead to the ability to confidently determine the short circuit current, fill factor, and efficiency of DSSCs fabricated in the laboratory.

The results of the electrolyte and dye experiments also made an important step forward, for this honors project and for the future directions of this research project. Although the results are promising, more trials should be done in the future using electrolytes synthesized on campus. Until then, the data must be considered inconclusive. The synthesis method should be improved to increase the stability of the electrolyte after synthesis, including both the shelf life and the electrolyte in the solar cell. The ferrocene electrolyte seems to be problematic, possibly due to exposure to oxygen, which can disrupt the redox cycle of this electrolyte.[16] While care was taken for reduce exposure to air, future work can utilize air-free techniques to possibly provide better, more meaningful data. Other electrolytes should also be synthesized in the laboratory. Each synthesized electrolyte should be tested with a variety of berry dyes, both on their own and co-sensitized (mixed) with each other to determine. The dye and electrolyte combination can greatly affect the energy conversion of the solar cell and to find the highest efficiency many combinations should be tried. Another research student should continue this research, as the results could be important to society's future in using solar energy to replace that of fossil fuels.

Reflection

Throughout my academic career I have gained extensive theoretical knowledge about chemical reactions and chemistry concepts. Through the completion of this honors project I have learned how to apply this theoretical chemistry knowledge to real world applications that could potentially benefit consumers. The oxidation-reduction chemistry learned in general and inorganic chemistry courses proved important in understanding the mechanism of the electrolyte replacing the lost electron form the berry dye. Knowledge of organic chemistry and the absorption spectra of organic molecules were important for understanding how the different berry dyes would absorb photons. Knowledge gained in inorganic chemistry on molecular orbitals and band gaps proved useful in understanding how electrons become promoted in their orbitals and how they flow through the circuit when they fall back to their ground state. These chemistry courses were vital to my ability to complete this honors project and provide accurate results and analysis.

Throughout this honors project I encountered roadblocks and setbacks. I learned how to overcome these roadblocks by looking at my research from different perspectives, talking to my advisor as well as other professors, and doing more research on the different topics relating to solar cells and the chemistry that runs them. Overcoming the roadblocks were important to the success of the honors project, but more importantly learning to overcome roadblocks was vital to my growth as a student and a person. Throughout the rest of my academic career and my future career, there will be times when I will have to overcome struggles and setbacks to succeed, and participating in this honors project showed me that I have the ability to do so.

During the preliminary literature review and throughout the course of the project I improved my skills in reading primary literature for understanding. I also learned how to apply previous research done with a different set of variables to the research I was interested in completing. This research project also helped me hone my problem-solving skills. These skills will transfer well to my future studies and career as a doctor.

If I were to complete this project again there are several things I would do differently. First, I would have begun the instrument build as the first mini-project. This would have given me more time to test a greater number of the variables I was most interested in researching. I also would have obtained new glassware and electrolytes earlier in the project. The final major thing I would have done differently is doing the red tide emission spectrometer tests as soon as we procured the plant grow lamp so that we could have replaced it with the overhead projector sooner.

Overall, I am extremely proud of the results and products of this honors project. I gained invaluable experience in learning to apply theoretical knowledge to real world applications, problem solving effectively when setbacks arise, and working alongside local experts in other departments to create a multidisciplinary product. I have grown tremendously as a student, researcher, and person throughout the course of this honors project and feel that it will play a role in my future successes. I am grateful for the opportunities partaking in this project has brought me and the dedication I had to creating a finished product that will continue benefitting the university after I have graduated.

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15 Material Safety Data Sheet 3-Methoxypropionitrile sc-226123. Santa Cruz Biotechnology, Inc.

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Appendices

Appendix A: IV and Power Curves

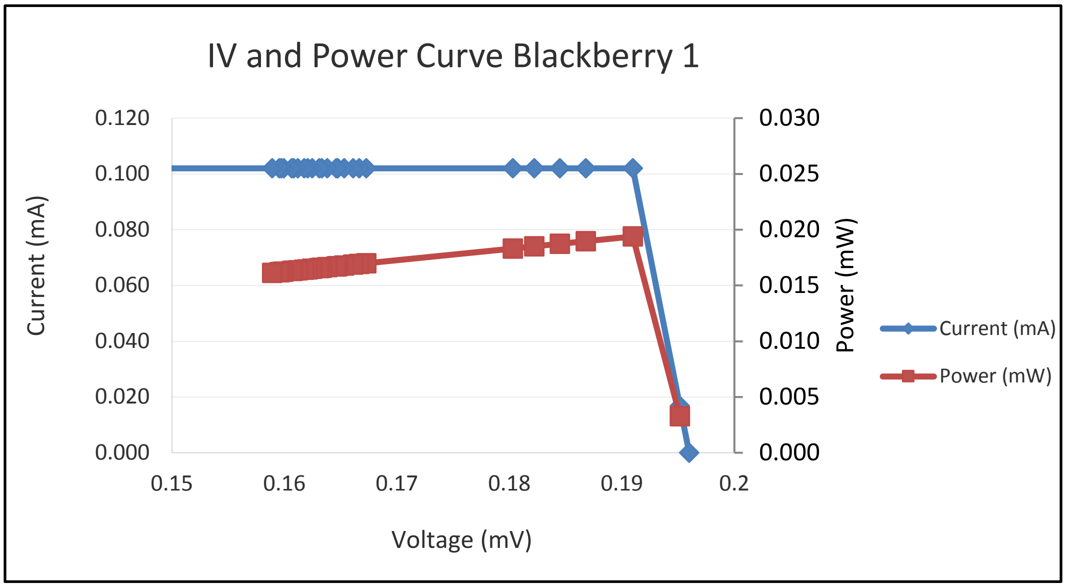


Figure 43: DSSC Blackberry #1 fabricated with the iodine electrolyte and blackberry dye. The 100,000 Ohm resistor was used and 0.5 mA was set as the maximum current draw.

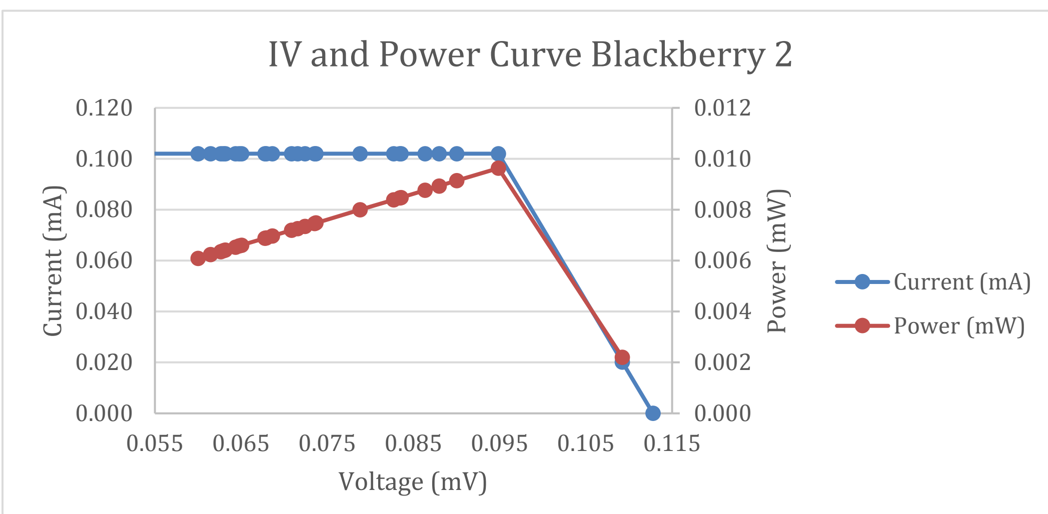


Figure 44: DSSC Blackberry #2 fabricated with the iodine electrolyte and blackberry dye. The 100,000 Ohm resistor was used and 0.5 mA was set as the maximum current draw.

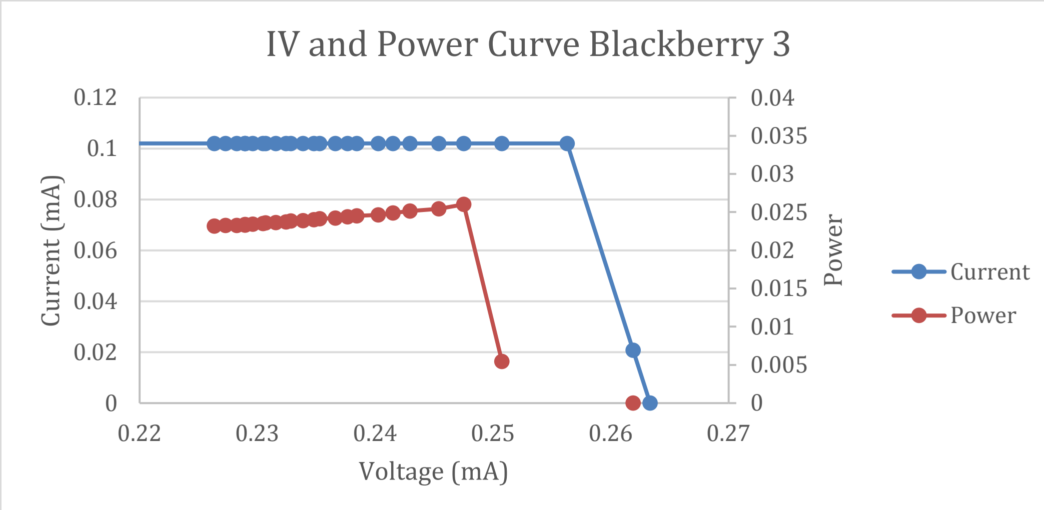


Figure 45: DSSC Blackberry #3 fabricated with the iodine electrolyte and blackberry dye. The 100,000 Ohm resistor was used and 0.5 mA was set as the maximum current draw.

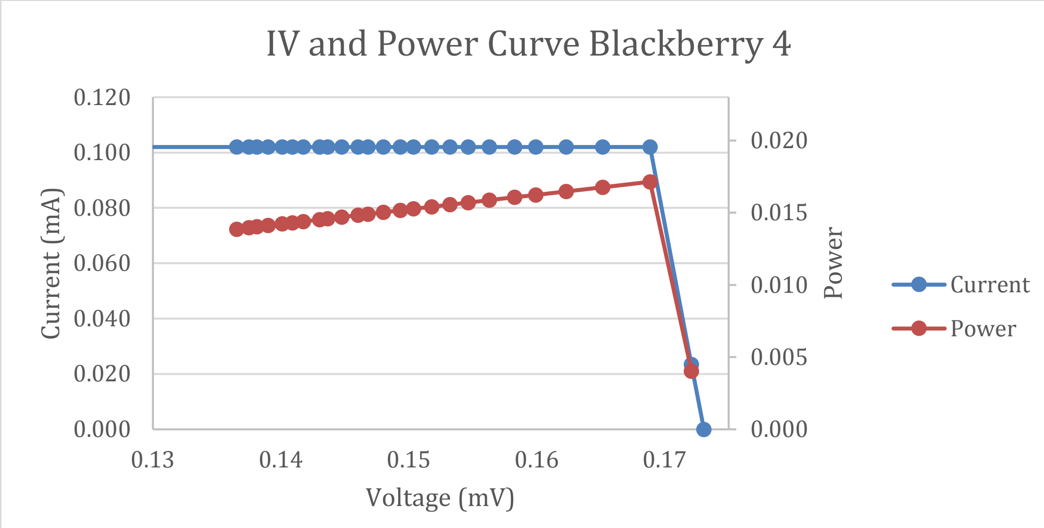


Figure 46: DSSC Blackberry #4 fabricated with the iodine electrolyte and blackberry dye. The 100,000 Ohm resistor was used and 0.5 mA was set as the maximum current draw.

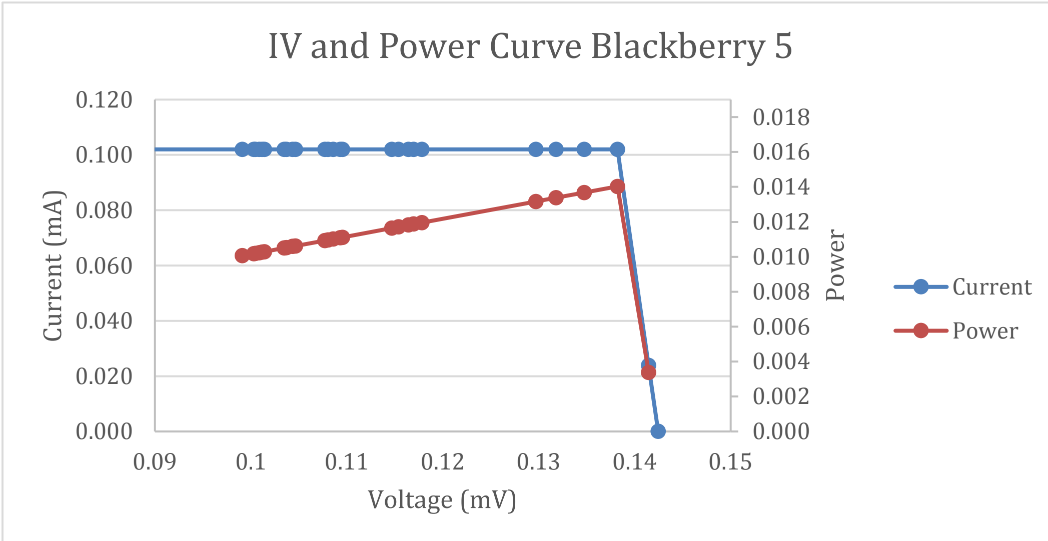


Figure 47: DSSC Blackberry #5 fabricated with the iodine electrolyte and blackberry dye. The 100,000 Ohm resistor was used and 0.5 mA was set as the maximum current draw.

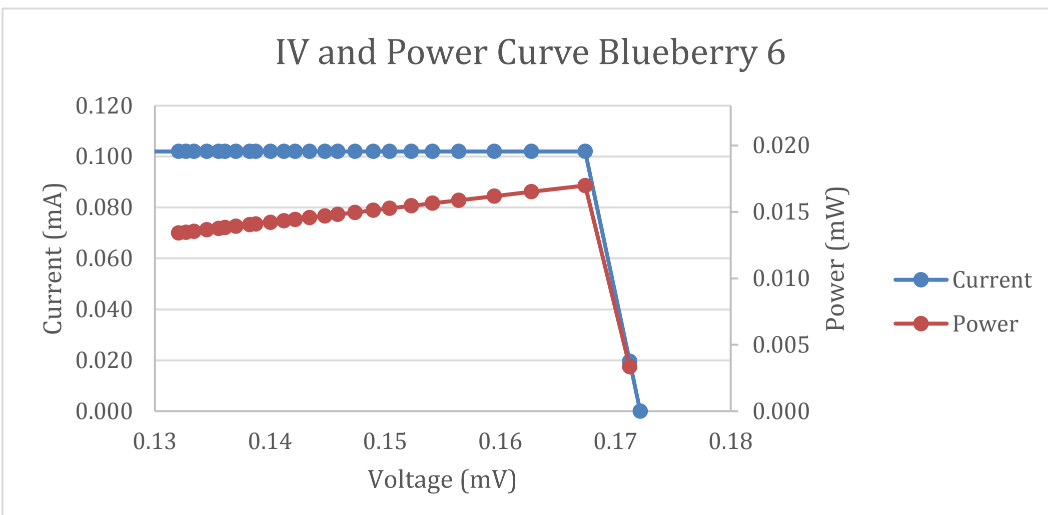


Figure 48: DSSC Blueberry #6 fabricated with the iodine electrolyte and blueberry dye. The 100,000 Ohm resistor was used and 0.5 mA was set as the maximum current draw.

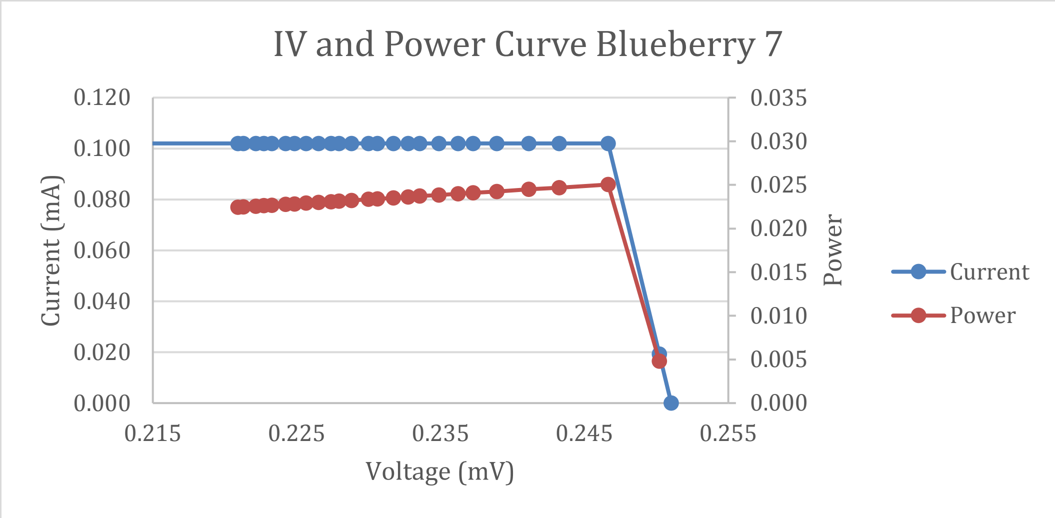


Figure 49: DSSC Blueberry #7 fabricated with the iodine electrolyte and blueberry dye. The 100,000 Ohm resistor was used and 0.5 mA was set as the maximum current draw.

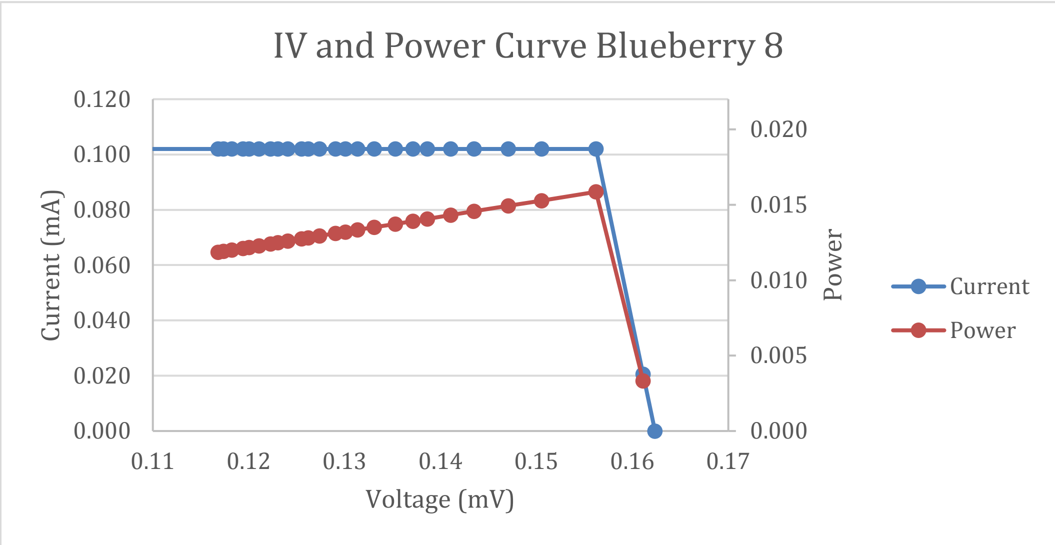


Figure 50: DSSC Blueberry #8 fabricated with the iodine electrolyte and blueberry dye. The 100,000 Ohm resistor was used and 0.5 mA was set as the maximum current draw.

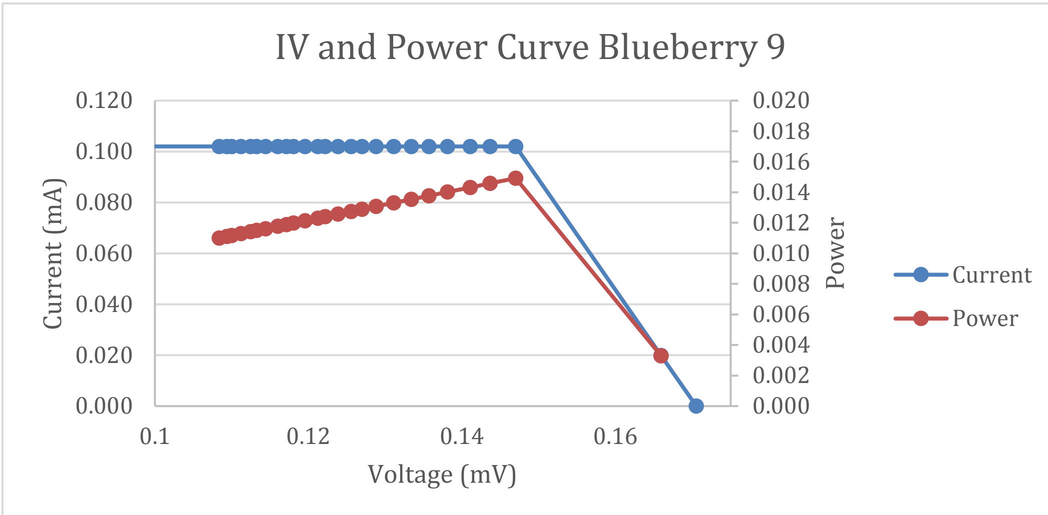


Figure 51: DSSC Blueberry #9 fabricated with the iodine electrolyte and blueberry dye. The 100,000 Ohm resistor was used and 0.5 mA was set as the maximum current draw.

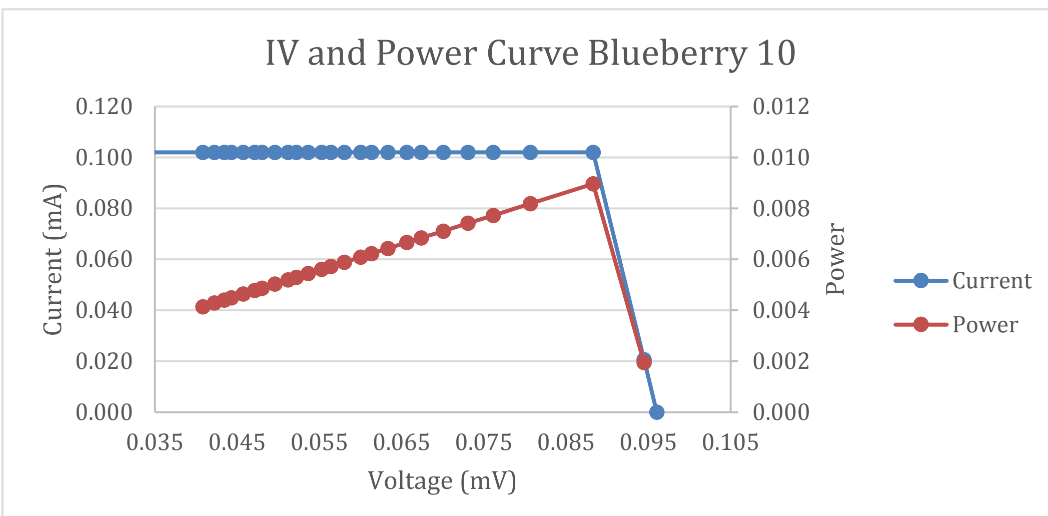


Figure 52: DSSC Blueberry #10 fabricated with the iodine electrolyte and blueberry dye. The 100,000 Ohm resistor was used and 0.5 mA was set as the maximum current draw.

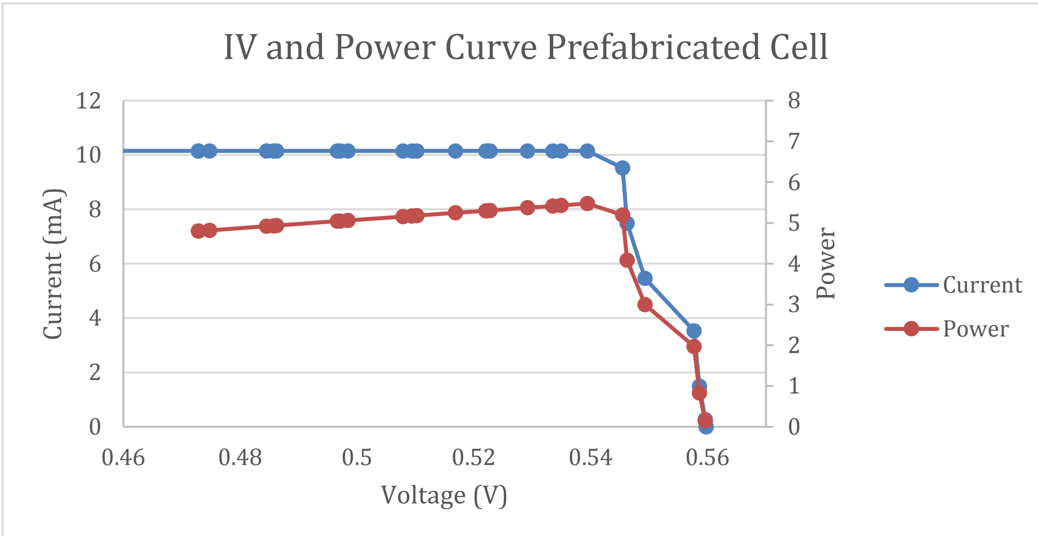


Figure 53: Prefabricated silicon solar cell tested with a 1.0 Ohm resistor and a maximum current draw of 10.0 mA.

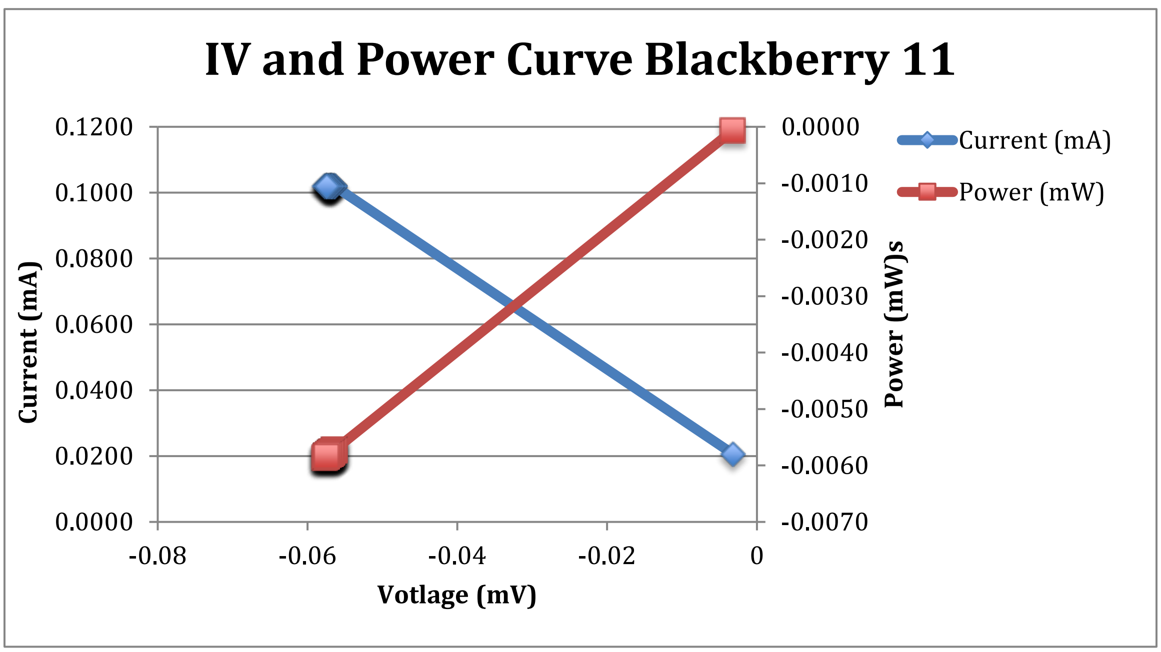


Figure 54: DSSC Blackberry#11 fabricated with the ferrocene electrolyte and blackberry dye. The 100,000 Ohm resistor was used and 0.5 mA was set as the maximum current draw.

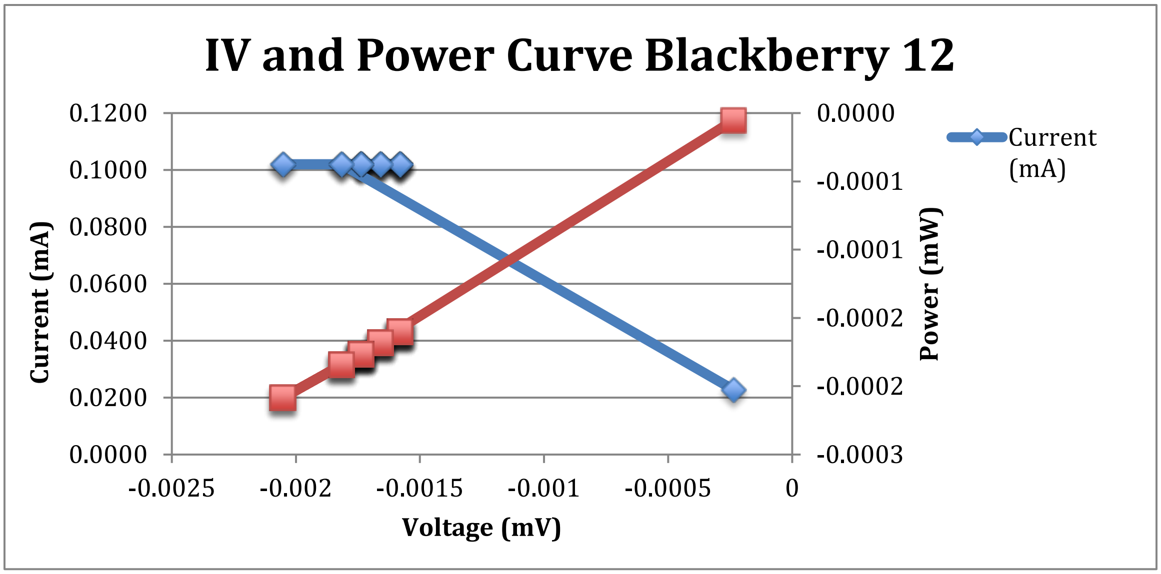


Figure 55: DSSC Blackberry #12 fabricated with the ferrocene electrolyte and blackberry dye. The 100,000 Ohm resistor was used and 0.5 mA was set as the maximum current draw.

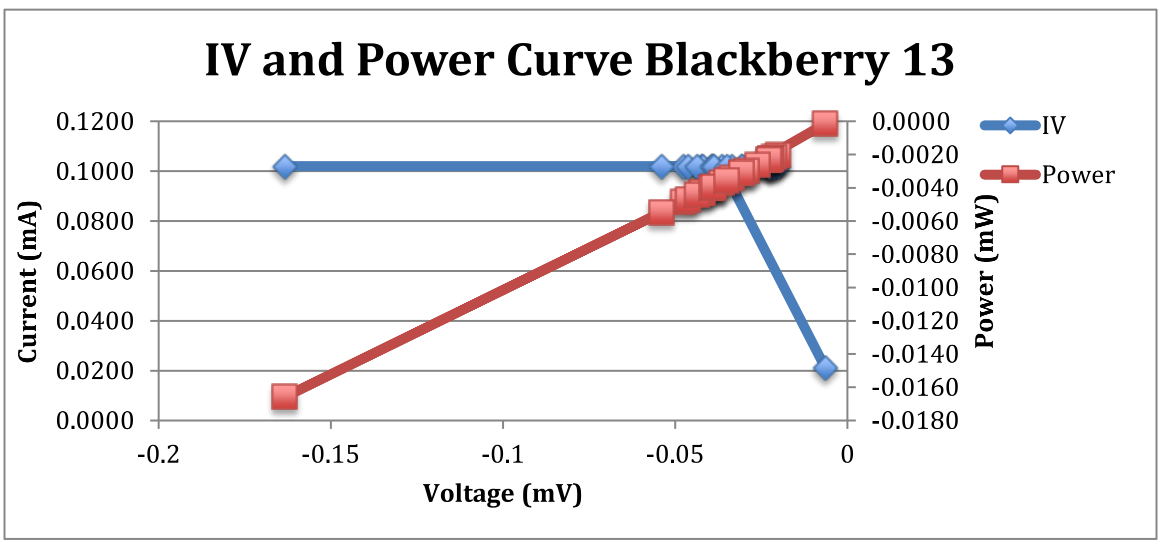


Figure 56: DSSC Blackberry #13 fabricated with the ferrocene electrolyte and blackberry dye. The 100,000 Ohm resistor was used and 0.5 mA was set as the maximum current draw.

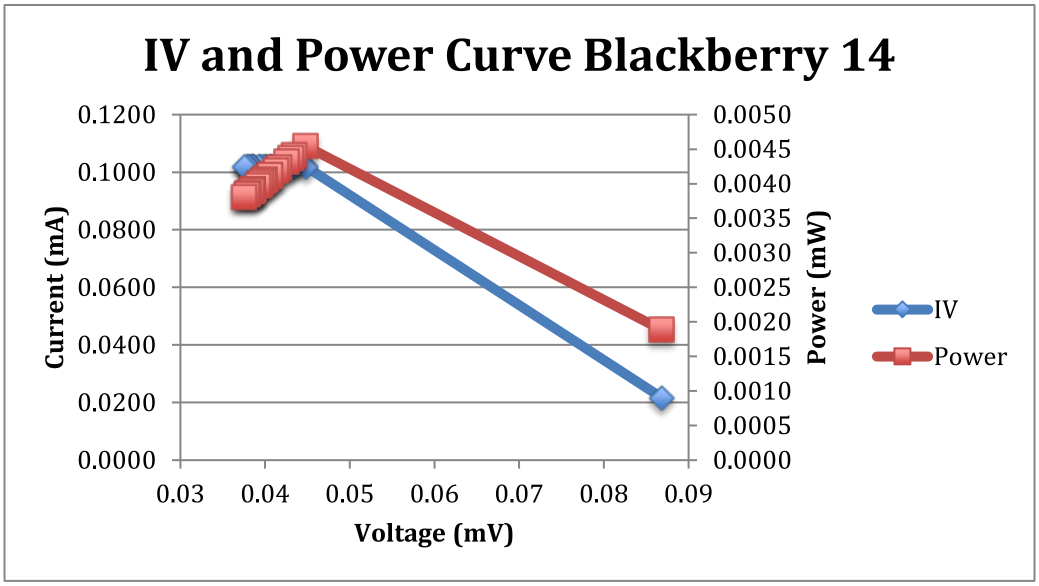


Figure 57: DSSC Blackberry #14 fabricated with the ferrocene electrolyte and blackberry dye. The 100,000 Ohm resistor was used and 0.5 mA was set as the maximum current draw.

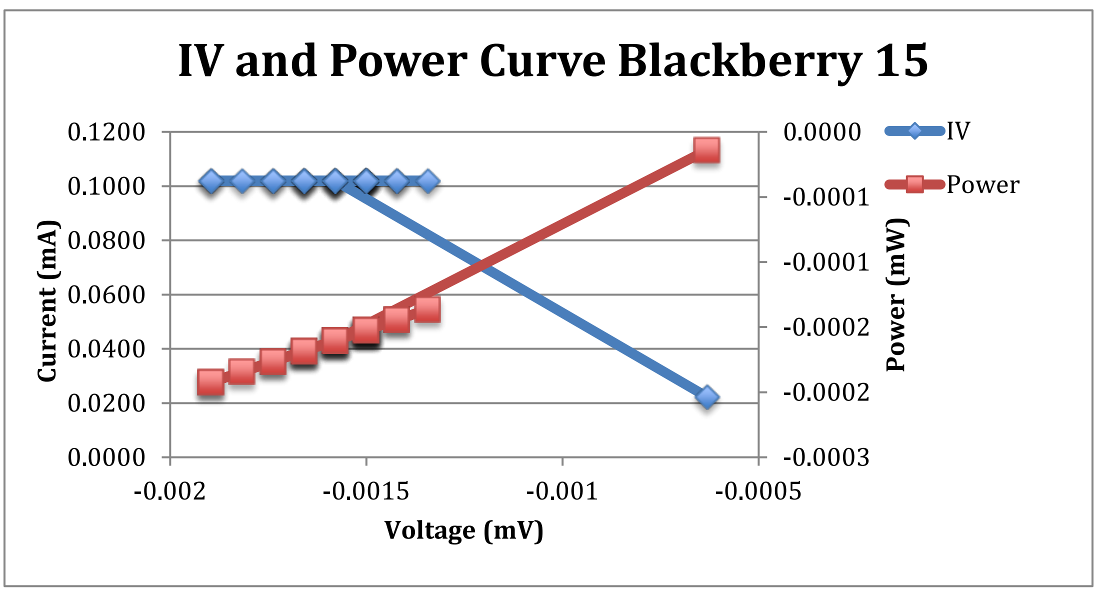


Figure 58 : DSSC Blackberry #15 fabricated with the ferrocene electrolyte and blackberry dye. The 100,000 Ohm resistor was used and 0.5 mA was set as the maximum current draw.

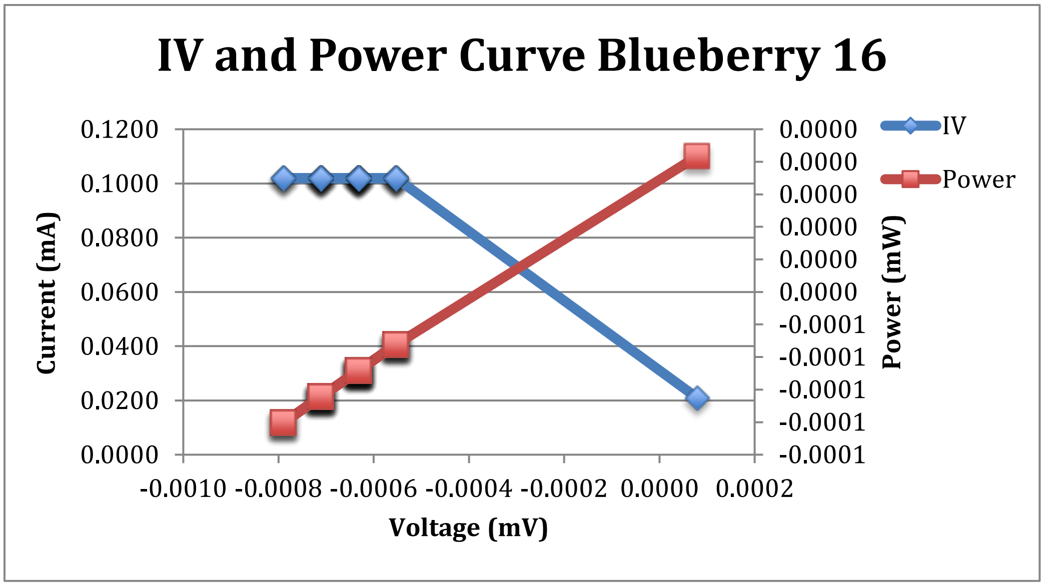


Figure 59: DSSC Blueberry #16 fabricated with the ferrocene electrolyte and blueberry dye. The 100,000 Ohm resistor was used and 0.5 mA was set as the maximum current draw.

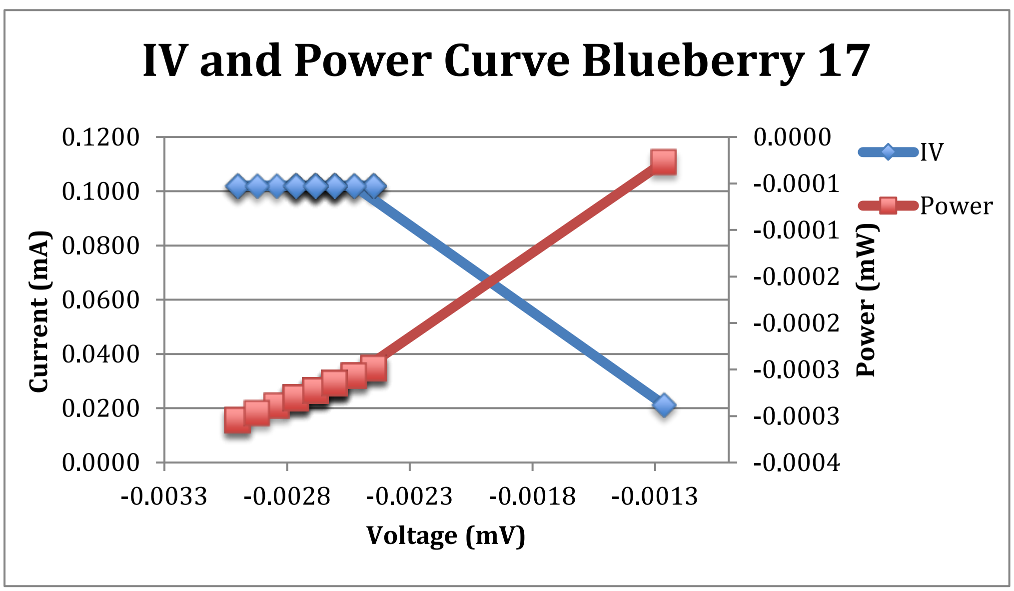


Figure 60: DSSC Blueberry #17 fabricated with the ferrocene electrolyte and blueberry dye. The 100,000 Ohm resistor was used and 0.5 mA was set as the maximum current draw.

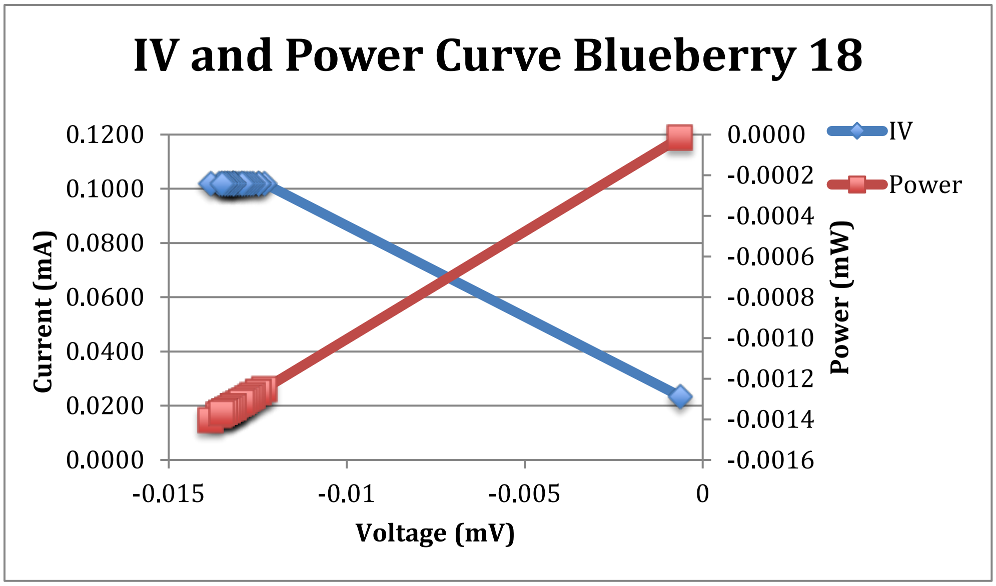


Figure 61: DSSC Blueberry #18 fabricated with the ferrocene electrolyte and blueberry dye. The 100,000 Ohm resistor was used and 0.5 mA was set as the maximum current draw.

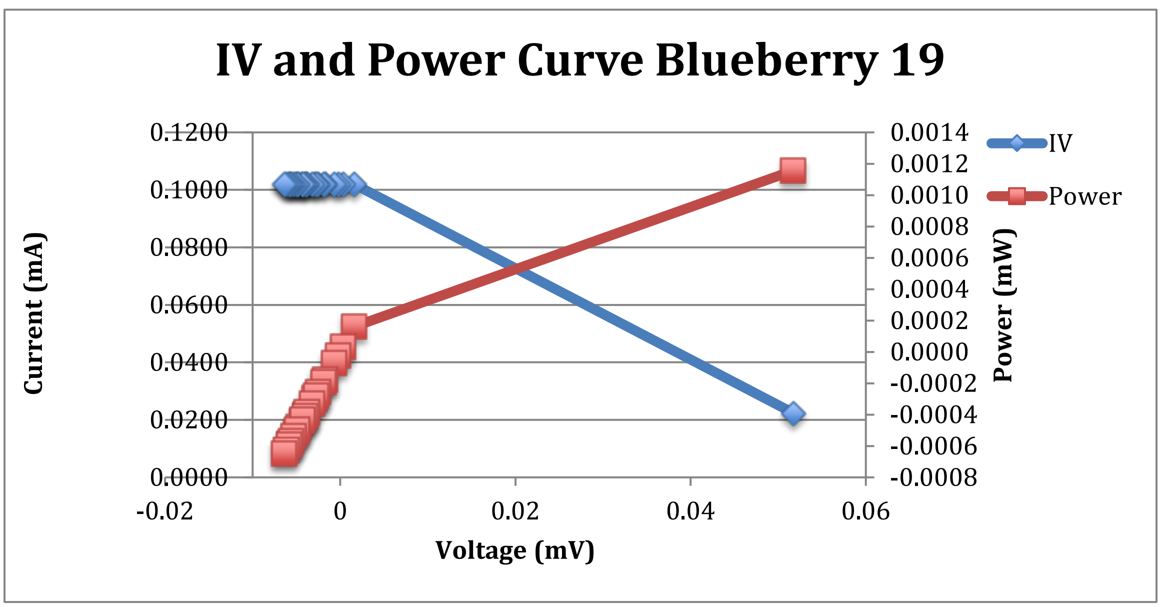


Figure 62: DSSC Blueberry #16 fabricated with the ferrocene electrolyte and blueberry dye. The 100,000 Ohm resistor was used and 0.5 mA was set as the maximum current draw.

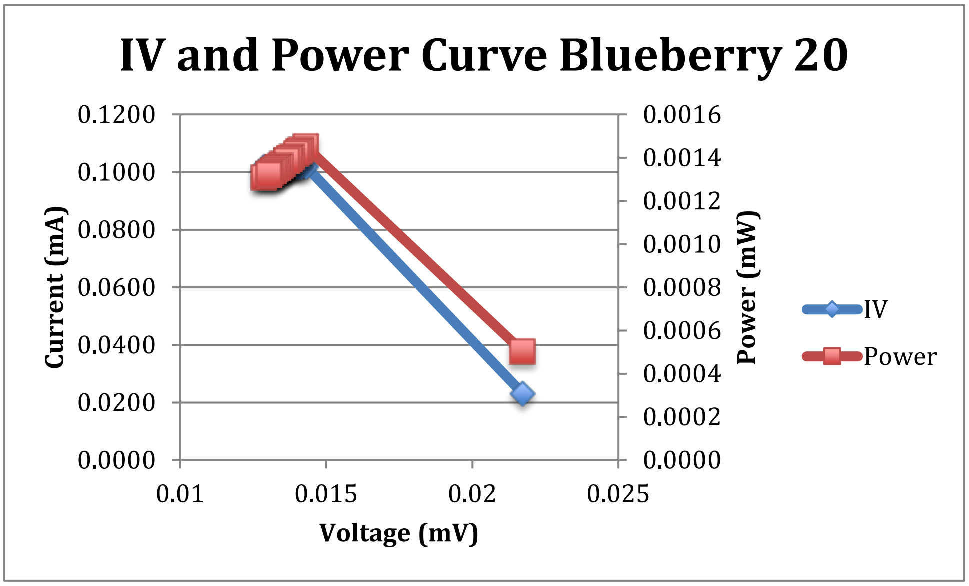


Figure 63: DSSC Blueberry #16 fabricated with the ferrocene electrolyte and blueberry dye. The 100,000 Ohm resistor was used and 0.5 mA was set as the maximum current draw.

Appendix B: Instrument Manual

SOLAR CELL IV CURVE GENERATOR

Instruction Manual

Caitlin Behme

University of Indianapolis

2017

Table of Contents

1. Introduction

The Solar Cell IV Curve Generator is the latest solar cell curve generator designed by Caitlin Behme to enable scientists to conduct cutting edge solar cell research experiments in the laboratory. It has updated hardware, updated software, a greater range of measurable currents and voltages, and an improved user interface from prototype models. This manual is intended to aid the scientist in utilizing the Solar Cell IV Curve Generator to its greatest potential.

Additional accessories are not currently available.

Specifications:

Current Sink:

Data Acquisition Board:

LabJack U6 Data Acquisition Board

Minimum PC Requirements:

Windows 7 or higher

Installed LabView Program

512 MB RAM

50MB available hard drive space

USB port

Power Requirements:

120V Power Outlet

2. Safety Precautions

The following safety precautions must be observed during all phases of operation, service, and repair of this instrument. Failure to follow these instructions, warnings, or cautions provided in this manual could impair the protection provided by the equipment. Warnings and cautions will be made clear. Noncompliance could also violate safety standards and intended use if this instrument.

Caitlin Behme and the University of Indianapolis do not assume liability for scientist's failure to comply with instructions, warnings, and cautions.

- Ground the instrument to avoid shock.
- For outdoor use: ensure dry conditions.
- DO NOT exceed the input voltage and current levels appropriate for the computer, instrument, or solar cell.
- Electrostatic discharge can damage the circuit in the instrument. This is most likely to occur when connecting or disconnecting the instrument. Ground yourself to discharge static buildup by touching the grounded chassis before connecting or disconnecting.
- DO NOT place the solar cell, instrument box, or computer in fluid or expose internal circuit elements to fluid.
- DO NOT operate in an explosive atmosphere.
- Keep away from live circuits, DO NOT replace components with the power cable connected to the computer. Internal adjustments must be made by qualified personnel. The USB (power) cord should be disconnected and circuits discharged before the instrument circuit can be touched.
- Do not substitute parts or modify the instrument. Modifications could alter the instrument and pose new safety concerns.

If any of the following abnormal conditions are noticed, terminate operation of the instrument and disconnect the power cable. Contact a professor for repair of the instrument. There is potential danger to the instrument or user if precautions are not taken.

- Instrument operates in unusual manner
- Instrument emits noise, smoke, smell, or spark

- ❖ Instrument generates high temperatures or electrical shock during use
- ❖ Battery begins to charge (battery will get hot to touch)
- ❖ USB (power) cord or wires and cables on instrument are damaged
- ❖ Foreign Substance/liquid has penetrated the instrument cover

Throughout this manual, the following symbols will be used to note important function:

WARNING- This signifies extreme hazard. Not following instructions could cause serious injury.

CAUTION- Following information relates to a hazard. If instructions are not followed the instrument may be damaged.

3. Installation

Connections to the cell are made on the front panel of the instrument using the wires connected to the BNC. The USB (power) cord is on the rear panel.

3.1 Power

The computer requires a grounded power supply of 120VAC provided by its power cord. The DAQ board requires a power supply from the computer provided by the USB cord. The circuit requires a +5V power supply from the DAQ board. There is no power button, if the instrument is plugged into the computer and the computer is plugged into its power supply the instrument is powered on.

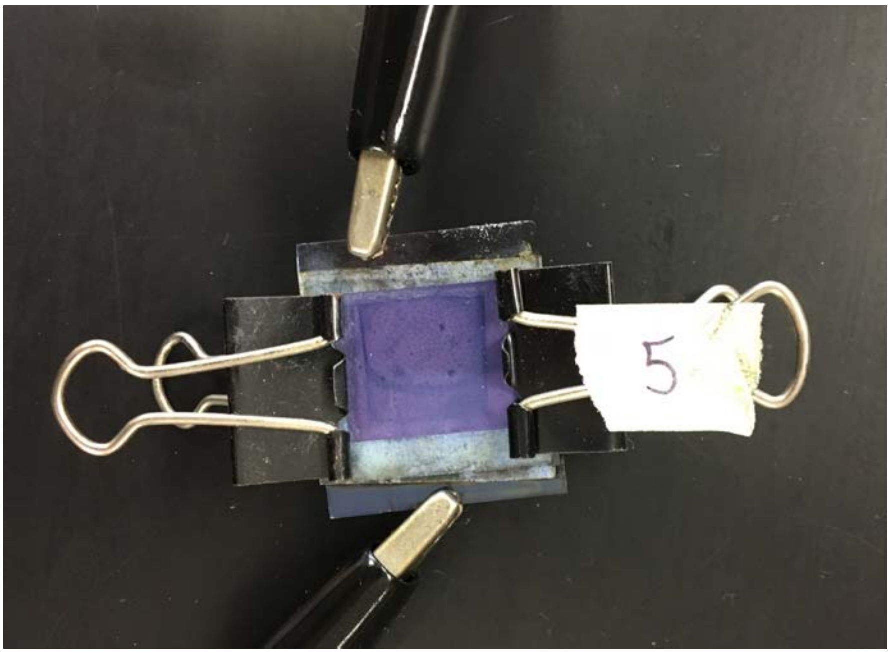
3.2 Computer

The instrument requires a laptop computer running Windows 7 or later with available hard drive space. Connect the standard USB cord from the back of the instrument to any USB port on the laptop. The instrument is run by a LabView program, which was written specifically for the instrument and includes necessary codes to run each component of the instrument and create the Excel file needed to reproduce the Current-Voltage (IV) Curve. The name of this program is Solar Cell Curve Generator and the most updated program version has been downloaded. The program is preloaded on the designated computer but can be transferred to any computer installed with LabView.

3.3 Solar Cell Connection

The solar cell connection can be found on the left hand side of the front panel of the instrument. Two alligator clips have been wired to two BNC cables that connect to the instrument. The alligator clips will be connected to the solar cell to connect the cell into the circuit. The RED lead goes to the cathode of the solar cell (the glass side coated with titanium dioxide) and the BLACK lead goes to the anode of the solar cell (the glass slide coated with carbon). If the clips are connected to the wrong side of the solar cell the graph will be incorrect.

WARNING: Do not adjust the cell leads during an experiment as this will break the circuit and invalidate results and could results in harm to the instrument or operator.



3.4 Starting the Instrument

Turn the computer on using the power button; ensuring the computer is attached to its power supply. Plug the NAME into the USB port on the computer and open the Solar Cell Curve Generator LabView software. The software automatically connects to the instrument. If the following error message is displayed when the software is opened, check the power supply and USB connections (this requires opening the instrument box).

If the connection is broken after it has been established the program will need to be closed and reopened after reconnecting the instrument.

4. Instrument Test Procedure

4.1 Purpose

The purpose of this test procedure is to ensure the instrument is functioning properly. This test will provide the user with an IV Curve calculated for a reference solar cell and is to be used to ensure the user can properly operate the instrument. The test procedure with the reference cell is to provide the user with an IV Curve that will look similar to the shape of their solar cells, but is not to provide an exact replicate, as each solar cell will have different current and voltage outputs. This test procedure will help the user verify the instrument is working correctly as well as gain operation experience.

4.2 Instrument Installation

Please follow the installation instructions from the beginning of the manual. This instrument should not be moved to avoid disconnecting internal parts.

4.3 Reference Cell

A sealed silicon solar cell is provided as a test cell for this procedure.

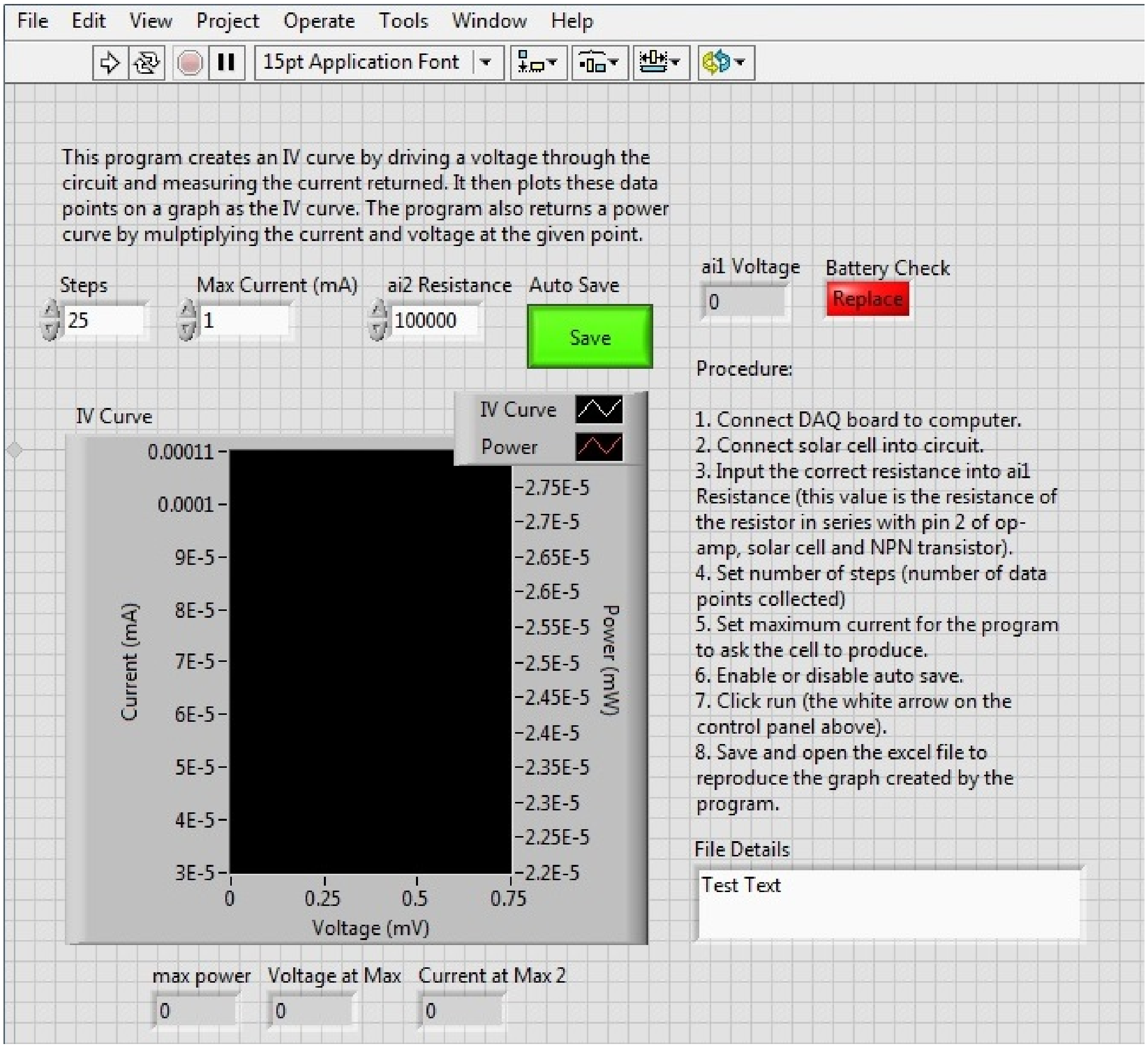
4.4 Preparation of Test Cell

1. Ensure the seal is not broken on the cell
2. Ensure the wires or insulation of the cell are not broken
3. Connect to instrument before running the program

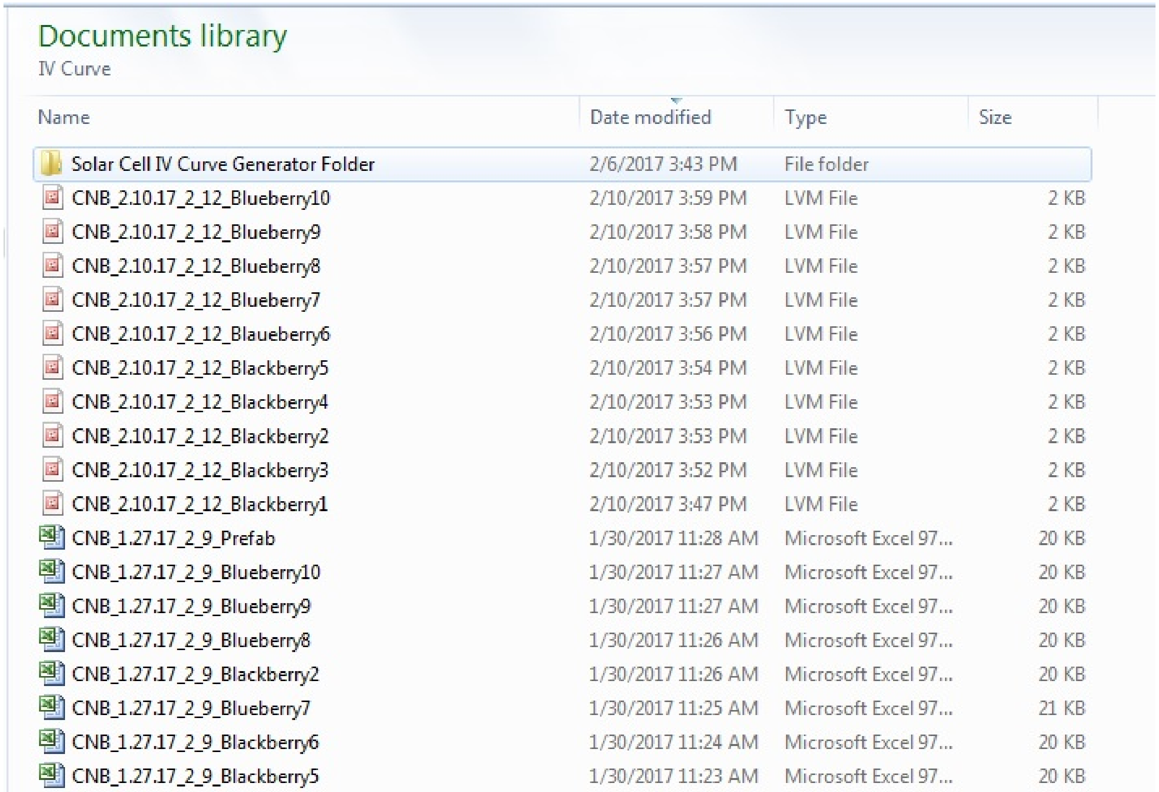
4.5 Procedure

1. Connect the power cord to the computer and the USB from the instrument to the computer.

2. Open the LabView software by clicking the LabView icon. Open the Solar Cell Curve Generator. The software will automatically connect to the instrument.
3. Connect the alligator clip leads to the reference solar cell. Red goes to the cathode and black to the anode.
4. Set the desired number of steps (25 is standard).
5. Set the desired maximum current (1 mA is standard).
6. Set the AI2 resistance by choosing the desired current range of the data (<10 mA is standard for the reference cell).
7. Ensure Auto Save is enabled (button will be green).
8. Record file details in the text box, including the solar cell identifiers and what experiment it came from, the steps, max current, and AI2 resistance as well as any other information deemed important.
9. Click the Run button (white arrow at the top of the screen).



10. Wait for instrument to complete all cycles.
11. Save file as an Excel file with file name: Initials_Date_Lab Notebook #_Page #_Cell Identifier. If this is not done the program will save it as a LabView (.lvm) file and it will be unable to be reopened and analyzed at a later time.



Documents library
IV Curve

Name	Date modified	Type	Size
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CNB_2.10.17_2_12_Blueberry9	2/10/2017 3:58 PM	LVM File	2 KB
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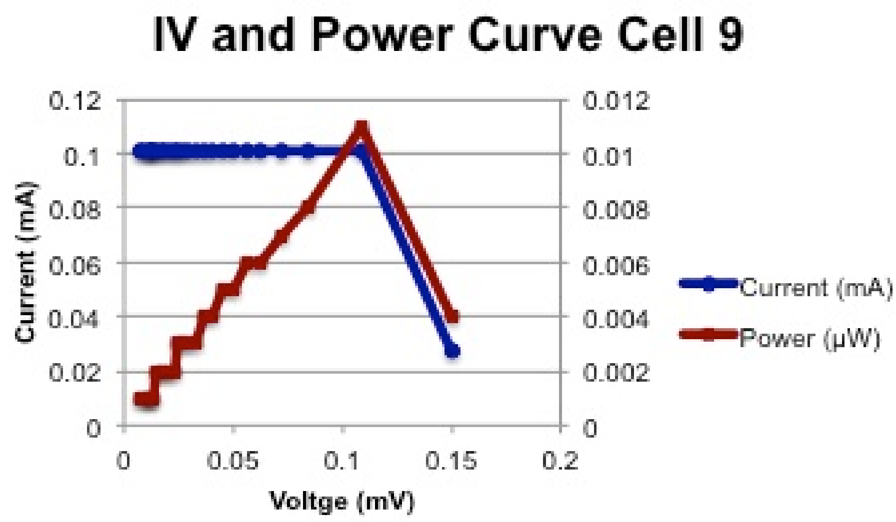
CNB_1.27.17_2_9_Blueberry8	1/30/2017 11:26 AM	Microsoft Excel 97...	20 KB
CNB_1.27.17_2_9_Blackberry2	1/30/2017 11:26 AM	Microsoft Excel 97...	20 KB
CNB_1.27.17_2_9_Blueberry7	1/30/2017 11:25 AM	Microsoft Excel 97...	21 KB
CNB_1.27.17_2_9_Blackberry6	1/30/2017 11:24 AM	Microsoft Excel 97...	20 KB
CNB_1.27.17_2_9_Blackberry5	1/30/2017 11:23 AM	Microsoft Excel 97...	20 KB

12. Open the Excel file.
13. Create column headings with proper units for the data (first column is the Current, second is Voltage, and third is Power)
14. Use the data to create a scatter plot with lines connecting the data points (ensure the line is a straight line not a curved line or this will alter the graph and render it unusable). Graph Current vs. Voltage on one Y-axis and Power vs. Voltage on a second Y-axis.



15. Save changes to the document.

This completes the procedure test.

5. Interfacing Accessories

Accessories are not available for this instrument. Such use of any third party accessories could damage the delicate electronics of the instrument and render it useless. Use of these accessories could also result in injury to the user of the instrument. The creator of the instrument assumes no liability for any injury or damage resulting from the use of third party accessories.

6. Upgrading

Upgrades are not available from the creator of this instrument, either for the instrument software or for the instrument design. Any upgrades wished to be made to either the instrument software or instrument design must be approved by the research advisor or creator of this instrument before implementation.

7. Instrument Software

7.1 Introduction

A detailed description of the experimental techniques and how to perform them using the included software is provided below. The functions of this instrument are available from the front panel of the instrument software. If you are new to the instrument it is suggested you perform the test procedure using the step-by-step guide to an example experiment and after installation familiarize yourself with the basic functions of the software. The step-by-step guide can be found above.

7.2 General Overview

The NAME software runs on the Windows operating system. It is compatible with Microsoft Windows 7 and above. It is important to note there is only one version of the software available and the only configuration differences are based on the specifications of the solar cell being tested.

7.3 Starting the Software

After installing the software for LabView (which should already be pre-loaded onto the designated solar cell research computer) it can be opened by clicking the icon on the desktop or found in the applications list. The specific VI for this instrument can be downloaded after LabView has been properly installed on the laptop (again, it should already be preloaded and named Solar Cell Curve Generator). The software should automatically connect with the instrument once it is powered on. If it fails to connect or is disrupted, close the VI program and reconnect the USB cord before re-opening the program. If this does not work, disconnect the instrument from its power source and open the instrument panel to ensure there are no broken connections.

7.4 Instrument Menu

The instrument menu is the front panel of the computer program. This panel allows various instrument settings to be altered for a specific experiment. Some settings available to be set by the user are (but not solely limited to) number of steps, desired max current, and the current range of the data output.

CAUTION: some settings are hard wired into the program to avoid changes that will cause the program or instrument to malfunction. Some settings are not hard-wired in, but if set incorrectly can also cause the program or instrument to malfunction.

7.5 Measuring Short Circuit Current

The computer program automatically measures the short circuit current of the instrument while it runs. This data point is displayed as the y-intercept of the IV curve.

7.6 Measuring Open Circuit Voltage

The computer program automatically measures the open circuit voltage of the instrument while it runs. This data point is displayed as the x-intercept of the IV curve.

7.7 Power Calculation

The instrument automatically calculates the power for each data point by multiplying the current by the voltage for each step of the circuit. The maximum power output can be found at the maximum of the power curve (graphed on a second y-axis).

7.8 Available Techniques

The only available techniques are the ones described in above sections. The computer program automatically measures and records each of the three data points for each step and records them on a graph with two plots (and therefore two y-axes), one is current vs. voltage (the IV curve) and one is power vs. voltage (which is used to find efficiency).

Appendix C: Grant Proposal

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Development of Instrumentation and Software to Economically Measure Solar Cell Properties

Dye sensitized solar cells are an attractive option for viable renewable energy production.[1,2] The proposed project is to increase the testing capacity of the University of Indianapolis Department of Chemistry's dye-sensitized solar cell project. The previous method of testing proved to be inaccurate, difficult, and incomparable to literature standards.[3] The project will build an instrument allowing for measurement of standard current-voltage (I-V) curves, resulting for better analysis of the solar cells.[4] Without the proposed instrumentation, only individual measurements of voltage and current produced by the cell in dark and light conditions could be collected, but no measurements of the cells under various loads could be performed. The results were incapable of being compared to literature values, and actual efficiencies could not be determined.[3,4] The new test method will improve the ease of testing solar cells, as well as provide the opportunity to perform statistical analysis and create graphical representations of the data. These results can then be compared to the literature values to determine if improved efficiency has occurred.[3,4]

This project contains two parts: a computer program was written over the summer using LabView to interface with a data acquisition board and generate I-V curves.[5] These curves allow for calculating various important data including (but not limited to) the maximum power point, the open circuit current values and the open circuit voltage values. This computer program is a modified version of one found in the literature and has been shown effective in initial testing.[5]

The second part of this project is physical construction the new instrument.[5] A working prototype including an electron sink circuit has been constructed using borrowed parts. A data acquisition board that interfaces the computer program to the circuit is essential for successful operation. The data acquisition board is involved with both sending and receiving information to the circuit in order to produce the data described above. These curves are what can be compared between cells to determine what set of variables produced the most efficient solar cell.[5]

The money from this grant, if received, will go towards buying the major components needed to build the finished, stand-alone model which will be used for years to come in the chemistry department both in research and laboratory coursework. The crucial pieces needed for completion of the instrument are a dedicated data acquisition board and a variable power supply for testing the circuit and solar cells, along with various electrical components. If these can be purchased, a final, working model will be constructed in such a way that it will create a lasting, functional instrument that can be run with minimal training by any person who needs it. As such, I am requesting funds to aid in completion of my project.

Works Cited

[1]Green, M. A., Emery, K., Hishikawa, Y., Warta, W., Dunlop, E. D., Progress in Photovoltaics. 2015, 23, 1-9.

[2]Boschloo, G.; Hagfeldt, A.; Accounts of Chemical Research. 2009, 42, 1819-1826.

[3]Ze Yu (2012). Liquid Redox Electrolytes for Dye-Sensitized Solar Cells, ISBN: 978-91- 7501-231-5, KTH Chemical Science and Engineering.

[4]Grätzel, M.; Solar Energy Conversion by Dye-Sensitized Photovoltaic Cells. Inorg. Chem. 2005, 44, 6841-6851.

[5]Mayer, E. A.; Powell, A. L., A low-cost laboratory experiment to generate the I-V characteristic curves of a solar cell, presented at ASEE Vancouver, BC, 2011, 1842.

Expected Timeline of Project:

October: Collect parts that are currently available from the chemistry department

November: Order parts needed to complete the project, Improve computer program interface

December: Build permanent circuit and DAQ board inside of box, update computer program to work with electronics from the box

January: Test solar cell variables from honors project with new instrument

Budget of Expenses:

Item, Unit Cost, Quantity

LabJack U6 DAQ Board, $299.00, 1

Tekpower TP3005T Variable Linear, $79.95, 1

Miscellaneous Electronic Components, $50.00, 1

Total Cost: $428.95

Appendix D: CITI Training

COLLABORATIVE INSTITUTIONAL TRAINING INITIATIVE (CITI PROGRAM) COURSEWORK REQUIREMENTS REPORT*

* NOTE: Scores on this Requirements Report reflect quiz completions at the time all requirements for the course were met. See list below for details. See separate Transcript Report for more recent quiz scores, including those on optional (supplemental) course elements.

• Name: Caitlin Behme (ID: 4703198)

• Email: behmec@uindy.edu

• Institution Affiliation: • Institution Unit: University of Indianapolis (ID: 473) Chemistry

• Phone: 812-746-8015

• Curriculum Group: Human Research

• Course Learner Group: • Stage: Group 1.Biomedical Research Investigators and Key Personnel.

• Description: Stage 1 - Basic Course The biomedical track is applicable when the majority of your human research studies involve therapeutic or diagnostic agents.

• Report ID:

• Completion Date: • Expiration Date:

• Minimum Passing: • Reported Score*:

15375342 03/10/2015 03/09/2017 75

76

REQUIRED AND ELECTIVE MODULES ONLY

Belmont Report and CITI Course Introduction

Students in Research

History and Ethics of Human Subjects Research

Basic Institutional Review Board (IRB) Regulations and Review Process Informed Consent

Social and Behavioral Research (SBR) for Biomedical Researchers Records-Based Research

Populations in Research Requiring Additional Considerations and/or Protections Research and HIPAA Privacy Protections

Conflicts of Interest in Research Involving Human Subjects

DATE COMPLETED

02/21/15 02/21/15 03/10/15 03/10/15 03/10/15 03/10/15 03/10/15 03/10/15 03/10/15 03/10/15

For this Report to be valid, the learner identified above must have had a valid affiliation with the CITI Program subscribing institution identified above or have been a paid Independent Learner. CITI Program

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Web: https://www.citiprogram.org

COLLABORATIVE INSTITUTIONAL TRAINING INITIATIVE (CITI PROGRAM) COURSEWORK TRANSCRIPT REPORT**

** NOTE: Scores on this Transcript Report reflect the most current quiz completions, including quizzes on optional (supplemental) elements of the course. See list below for details. See separate Requirements Report for the reported scores at the time all requirements for the course were met.

• Name:

• Email:

• Institution Affiliation: • Institution Unit:

• Phone:

• Curriculum Group:

• Course Learner Group: • Stage:

• Description:

• Report ID:

• Report Date:

• Current Score**:

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Human Research

Group 1.Biomedical Research Investigators and Key Personnel.

Stage 1 - Basic Course

The biomedical track is applicable when the majority of your human research studies involve therapeutic or diagnostic agents.