

Photovoltaic Emulator

LabVIEW Based Modeling and Simulation

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Abstract:

The design goal for this project is to create a system capable of creating a consistent testing environment for photovoltaic inverters and charge controllers. The solution is to create a photovoltaic emulator which is a DC power supply that would have the same electrical output characteristics to a photovoltaic panel. In current systems, consistency problems arise when depending on nature to conduct tests on PV modules because it is impossible to properly replicate scenarios while testing specific conditions. This project will provide the user the ability to test their PV modules under various parameters which replicate real-world scenarios such as temperature and weather conditions. This paper will outline the design and simulation of a photovoltaic emulator.

Regarding the change in learning environment due to Covid-19, the original scope of the project had to be appropriately adjusted. All aspects of "Section 2: Project Planning" as well as the "Appendix A: Senior Project Design Analysis" will still account for the original design choices made during fall quarter preparation. "Section 3: System Design" will more accurately reflect the true scope of project. Please refer to "Appendix B: Alterations Due to Covid-19" for more details on changes made to better accommodate the situation.

Section 1: Introduction

Sustainable/renewable energy is becoming increasingly popular, with more and more companies dedicating money and resources into researching photovoltaic (PV) systems. In current solar technology, most solar cells are created using either polycrystalline or monocrystalline silicon which effectively determine the appearance and efficiency of a solar panel [1]. Polycrystalline panels are cheaper and less efficient when compared to monocrystalline panels, but both are still within industry standard. When looking at the top of the line solar panels available in today's market [2]-[3], monocrystalline solar cells are still widely more efficient.

With the many options of solar cells, more technologies are being developed with the intention of using solar energy to supply power such as PV inverters and power point tracking converters. Unfortunately, effective ways to test these devices are not widely available. Field testing cannot be relied upon due to the variations of conditions such as shade and temperature that can affect solar panel efficiency. Ultimately, increasing interests in PV devices lead to the logical conclusion of creating appropriate test equipment for these devices.

A photovoltaic emulator can be created through a variety of designs. One such method is to develop a PV emulator using a DC-DC converter such as a buck converter to study control and operating schemes [4]. Another method is to utilize a programmable DC power supply and implement the proper scripts to have the power supply output similar current and voltage characteristics to an array of PV cells [5]. The benefit of using an emulator vs a true PV panel is that the emulator allows for sustainable and repeatable test conditions on various equipment and systems.

In this paper, the process of testing and simulating a photovoltaic emulator will be discussed further. To test the emulator, the simulated results will be compared to actual results from a working PV device. Additionally, this project will consider a variety of solar cells with different cell current vs cell voltage curves. Finally, what this project will achieve is a small scale and cost-efficient method for testing PV modules.

Section 2: Project Planning

2.1 Customer Needs

The customer needs primarily center around the necessity for a stable and consistent testing environment for systems which take PV energy as an input. For modules which intake power sourced from solar cells, it is difficult to maintain testing conditions for extended periods of time due to variations in irradiance and temperature in nature. This problem was identified and brought to our attention by Dr. Dolan on the senior project listing and description. Upon further research, it was found that many pre-existing testing methods are large scale and costly in nature. There are not many solutions for smaller scale testing. Finally, the goals of this project should be easily tested by comparing the system outputs to the real-world data curves of existing solar cells. Tables 1 and 2 below summarize the different marketing and engineering specifications for the PV emulator. These specifications outline how a PV emulator should work and operate based on customer needs.

2.2 Requirements and Specifications

Table 1. PV Emulator Marketing Requirements

Marketing Requirements

1. Must be able to factor in a variety of different conditions which can affect solar cells such as cloud cover, temperature, front surface soiling, etc...
2. Simulated effects of the emulator should have high accuracy when compared to effects in real life.
3. Factors that contribute to change in PV characteristics just be controllable/ adjustable
4. Small Scale and Cost Effective
5. Easy to understand and use
6. Emulator considers more than one type of solar panel composition (Monocrystalline vs polycrystalline silicon vs thin film)

Table 2. PV Emulator Requirements and Specifications

Marketing Requirements	Engineering Specifications	Justification
1	Emulator must produce voltage/current characteristics and curves for each factor. The characteristics and curves should be able to combine different conditions as well	The main objective of testing is to monitor the performance of PV modules given various types of input from a solar cell
2	Voltage/Current curves from the emulator will be based on verified data obtained from pre-existing solar cells in conjunction with proven effects of various factors.	Emulator is supposed to simulate what happens in real life. So, results would have to be realistic. A realistic goal would be less than 5% error.
3	Variables must be adjustable in Labview	Allows us to see clearer how much each factor affects the characteristics of the PV device
4	Keep budget low and efficiently spend funds to properly complete project.	This is a student run project with no company funding other than from Cal Poly EE department
5	Labview interface will be intuitive and user friendly.	Makes the project more marketable and easier to explain to potential users.
6	Will aim to be able to select from many panels from existing databases.	Expands the potential of the project

Table 3. PV Device Emulator Senior Project Deliverables

Delivery Date	Deliverable Description
December 3, 2019	Design Review
March 15, 2020	EE 461 demo
March 20, 2020	EE 461 report
May 20, 2020	EE 462 demo
May 25, 2020	ABET Sr. Project Analysis
May 29, 2020	Sr. Project Expo Poster
June 5, 2020	Senior Project Final Demo
June 10th	Senior Project Final Report

2.3 Functional Decomposition

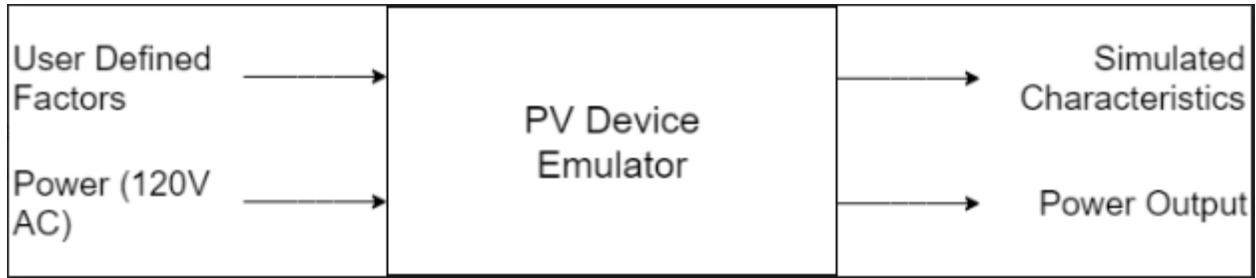


Figure 1. Level 0 Block Diagram for PV Device Emulator

Table 4. PV Device Emulator Senior Project Level 0 I/O and Functionality Descriptions

Module	PV device emulator
Inputs	DC power supply power (120V AC) User defined input factors: these change the characteristics of predetermined solar cell output. (ex: Irradiance, PV material/type, temperature, cloud cover, etc.)
Outputs	Simulated voltage/current curves of PV device Power Output based on current and voltage generated by simulated cells of the emulator (from DC power supply)
Functionality	Device will allow the reproduction of PV inputs into devices under test. Simulates the outputs of solar cells using LabView as the UI allowing for a wide range of user designed variables. The output of this device must be consistent under the defined conditions.

Taking a more system level approach, Figure 1. and Table 4. both provide a brief analysis of the inputs and outputs for the PV emulator. As mentioned earlier, the primary design goal is to output accurate electrical characteristics of existing solar cells based on user generated inputs. Looking at Figure 2, the level one block diagram splits the overall system into the various components needed to create the whole emulator. Tables 5, 6, and 7 then provide the detailed analysis for each components' inputs and outputs.

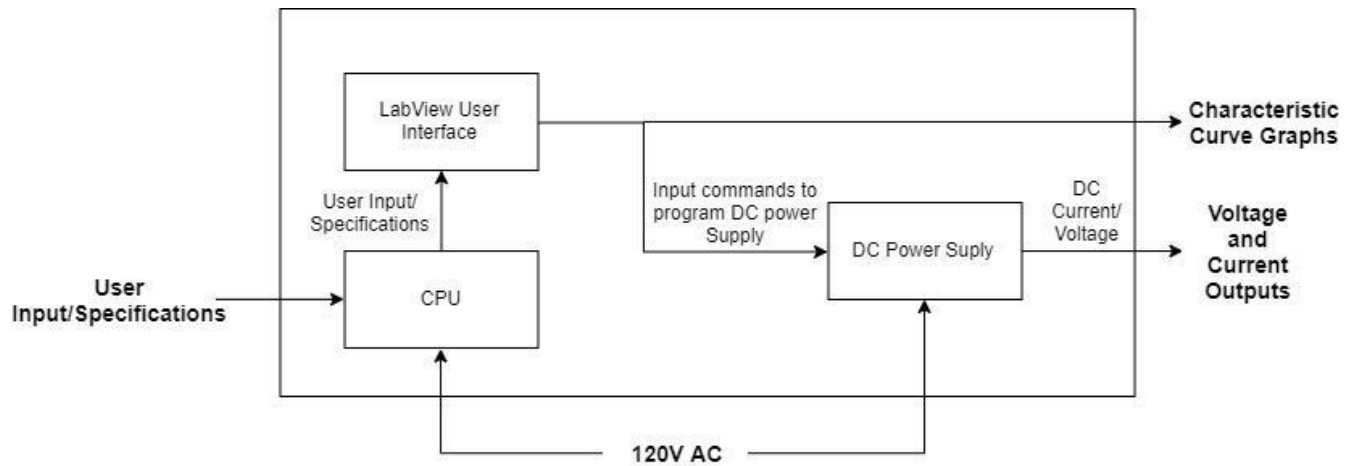


Figure 2. Level 1 Block Diagram for PV Device Emulator

Table 5. CPU Level 1 Functionality Description

Module	CPU
Inputs	<ul style="list-style-type: none"> - 120V AC from wall - User Input/Specifications
Outputs	<ul style="list-style-type: none"> - Translated User Input/Specifications to Labview
Functionality	<ul style="list-style-type: none"> - The CPU serves as the primary hardware responsible for connecting to the PV emulator. It allows users to communicate desired inputs and specification to LabView.

Table 6. LabView Level 1 Functionality Description

Module	LabView User Interface
Inputs	<ul style="list-style-type: none"> - Translated User Input/Specifications
Outputs	<ul style="list-style-type: none"> - Simulated Curves and Graphs representing PV cell outputs - Input Commands to DC Power Supply - User Interface
Functionality	<ul style="list-style-type: none"> - LabView will be the software in charge of programming the DC Power Supply as well as providing the user an easy to operate interface

Table 7. Programmable DC Power Supply Level 1 Functionality Description

Module	Programmable DC Power Supply
Inputs	<ul style="list-style-type: none"> - 120V AC from wall - Input commands from LabView
Outputs	<ul style="list-style-type: none"> - DC Voltage/Current
Functionality	<ul style="list-style-type: none"> - The DC power supply will take in instructions from LabView and output the specified voltage/current.

2.4 Project Planning (Gantt Chart and Cost Estimates)

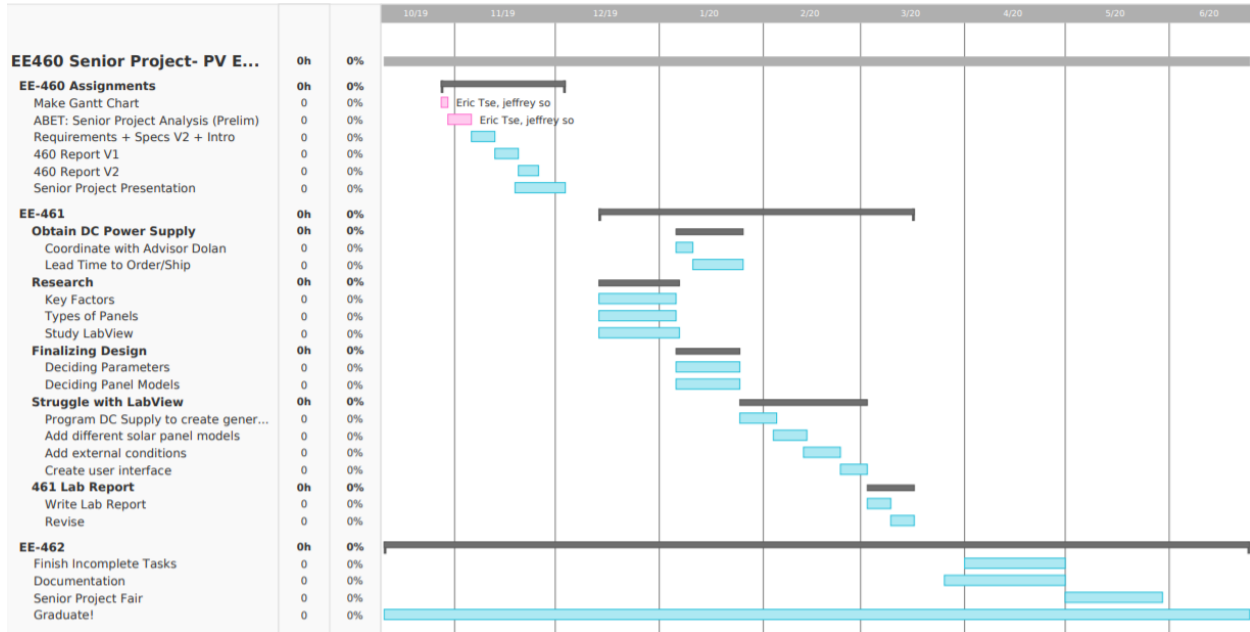


Figure 3. Gantt Chart Full

Figure 3 above shows the estimated time scale for this project. All of the key deliverable days noted in Table 3 are included within the Gantt chart along with various deadlines set to ensure a timely completion of this project. Figures 4, 5, and 6, provide a more easily viewed breakdown of the three quarters of senior year and the scope for finishing the project. Table 8, on the other hand, breaks down the estimated costs of this project.

▼ EE-460 Assignments	0%	Start	Due
Make Gantt Chart	0%	Oct 28, 2019	Oct 29, 2019
ABET: Senior Project Analysis (Prelim)	0%	Oct 30, 2019	Nov 5, 2019
Requirements + Specs V2 + Intro	0%	Nov 6, 2019	Nov 12, 2019
460 Report V1	0%	Nov 13, 2019	Nov 19, 2019
460 Report V2	0%	Nov 20, 2019	Nov 25, 2019
Senior Project Presentation	0%	Nov 19, 2019	Dec 3, 2019

Figure 4. Fall Quarter Break Down














▼ EE-461	0%		Start	Due
▼ Obtain DC Power Supply	0%			
Coordinate with Advisor Dolan	0%		Jan 6, 2020	Jan 10, 2020
Lead Time to Order/Ship	0%		Jan 11, 2020	Jan 25, 2020
▼ Research	0%			
Key Factors	0%		Tomorrow	Jan 5, 2020
Types of Panels	0%		Tomorrow	Jan 5, 2020
Study LabView	0%		Tomorrow	Jan 6, 2020
▼ Finalizing Design	0%			
Deciding Parameters	0%		Jan 6, 2020	Jan 24, 2020
Deciding Panel Models	0%		Jan 6, 2020	Jan 24, 2020
▼ Struggle with LabView	0%			
Program DC Supply to create generic IV curve	0%		Jan 25, 2020	Feb 4, 2020
Add different solar panel models	0%		Feb 4, 2020	Feb 13, 2020
Add external conditions	0%		Feb 13, 2020	Feb 23, 2020
Create user interface	0%		Feb 24, 2020	Mar 2, 2020
▼ 461 Lab Report	0%			
Write Lab Report	0%		Mar 3, 2020	Mar 9, 2020
Revise	0%		Mar 10, 2020	Mar 16, 2020

Figure 5. Winter Quarter Break Down





▼ EE-462	0%		Start	Due
Finish Incomplete Tasks	0%		Apr 1, 2020	Apr 30, 2020
Documentation	0%		Mar 26, 2020	Apr 30, 2020
Senior Project Fair	0%		May 1, 2020	May 29, 2020
Graduate!	0%		Oct 11, 2019	Jun 24, 2020

Figure 6. Spring Quarter Break Down

2.5 Cost Estimates

Table 8: Cost Estimate Breakdowns

Item	Amount (\$)	Source/Justification
LabView Software	\$0	Cal Poly Library Software provides a free download of LabView Designer Suite
Programmable DC Power Supply	TBD	Will be working with Senior Project Advisor to obtain this unit.... Price remains unknown
Labor	1800	Approximately 60 hours at \$30/hr
Wire-Wound Power Resistor and Cables	~\$70	<p>To properly simulate PV source, we need a massive power resistor capable of handling power in the Kilowatt range</p> <p>Source: https://americas.rsdelivers.com/product/te-connectivity/te1000b10rj/te-connectivity-te-series-solder-lug-wire-wound/7015793?cm_mmc=US-PLA-DS3A--google--PLA_US_EN_CatchAll_New--Catch+All--PRODUCT_GROUP&matchtype=&pla-673097410467&gclid=CjwKCAiA5o3vBRBUeIwA9PVzagthtx5J4_vc4qdxp39y7tL4nU_2ksNMOC2JafRsgC3fu_WpSWDhLBoC0dcQAvD_BwE&gclid=aw.ds</p>
LabView Text	~\$12	<p>This text is intended to assist team members in learning how to properly use LabView and its many functions. Price may vary depending on the decision to rent or purchase.</p> <p>Source: https://www.amazon.com/John-Essick-Dr/dp/0190853069/ref=pd_lpo_14_t_1/136-4202417-0655623?encoding=UTF8&pd_rd_i=0190853069&pd_rd_r=f24e0cda-3b0e-4958-8181-13569fb66067&pd_rd_w=MCz1G&pd_rd_wg=cY1f4&pf_rd_p=7b36d496-f366-4631-94d3-61b87b52511b&pf_rd_r=5K3BDV27R84R04DR3A4W&pssc=1&refRID=5K3BDV27R84R04DR3A4W</p>

Section 3: System Design

The overall scope of the project has been defined through sections one and two. To continue the design process, the purpose of this section will be to introduce a more technical background in properly modeling a photovoltaic module using LabVIEW. Key parameters and the formula which integrate them will be highlighted below [4].

3.1 Electrical Equivalent of Solar Cell

Typically, solar panels can be represented by a diode-based circuit which can then be mathematically modeled to demonstrate the electrical functioning of the cell.

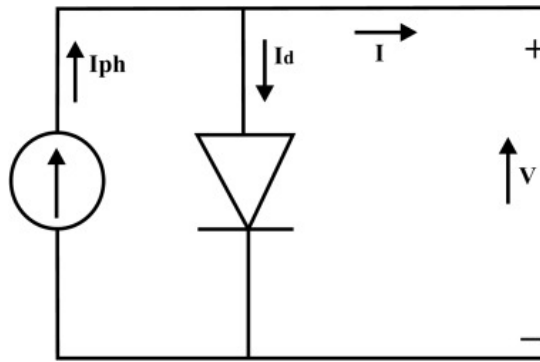


Figure 7. Ideal Model of PV Cell

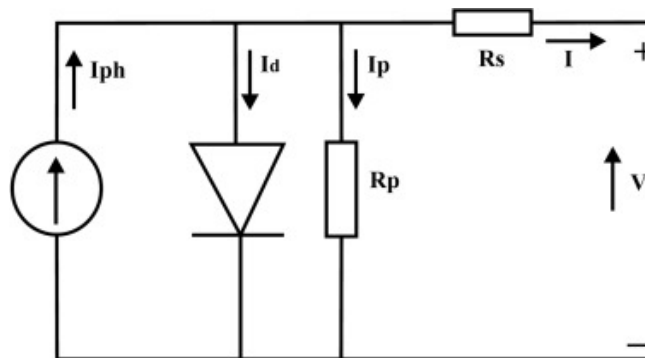


Figure 8. Realistic Model of PV Cell

As seen in Figure 7, an ideal PV cell can be modeled simply by using a current source in parallel with a diode. The diode is necessary to model the I-V curve produced by solar cells [6]. When sunlight strikes the solar cell, photocurrent, I_{PH} is generated. In the ideal model, 100% efficiency can be assumed with zero loss, and in doing so, the output current would be equivalent to $I_{PH} - I_D$. Keep in mind that while both solar cells and photodiodes are considered photovoltaic devices,

the diode model above is not a photodiode. Solar cells are optimized for converting light energy to electricity while photodiodes are optimized for detecting light energy.

Figure 8 represents a more realistic model of a solar cell in which series and parallel resistances for a cell are accounted for. The software program being developed for this senior project will accommodate both singular PV cells as well as PV modules, which are the same cells connected in some combination of series or parallel. It should be noted that all typical PV generation systems will be built using PV modules rather than single cells. Figure 9 above is a representation of the same PV cell used in Figure 8 but configured as a module with N number of parallel and series components [7].

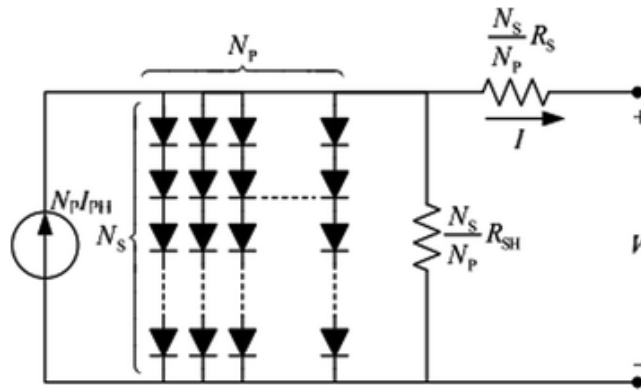


Figure 9. Realistic Model of PV Module

3.2 Physical Model of a Solar Cell

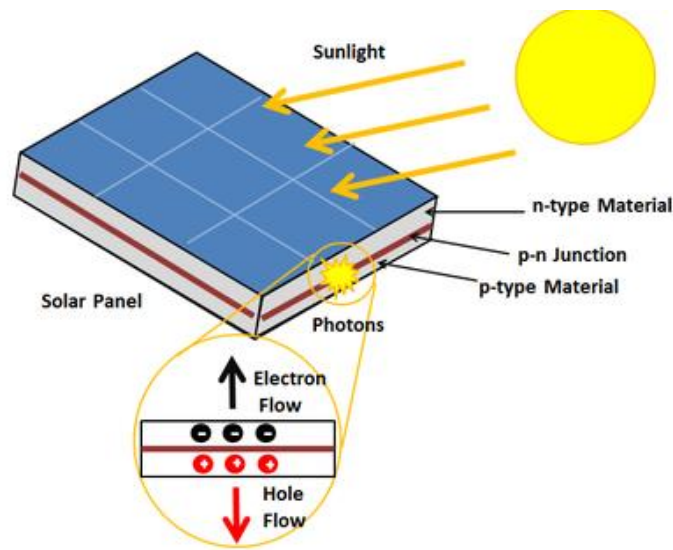


Figure 10. Solar Cell as Semiconductors

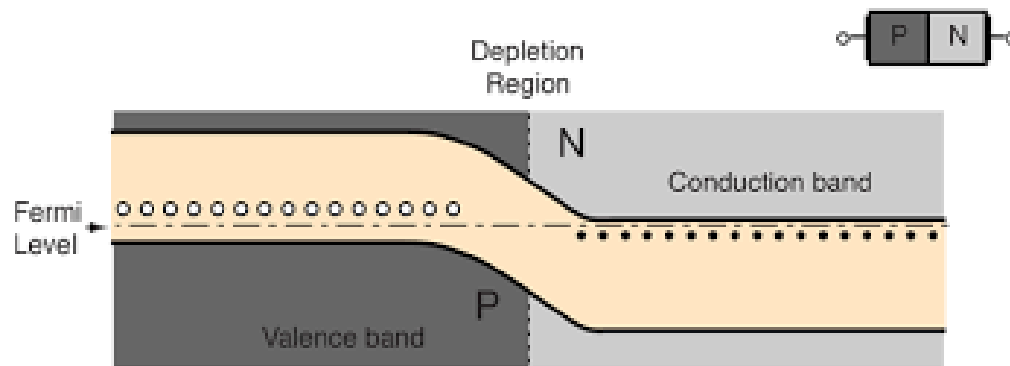


Figure 11. Solar Cell PN Junction

Moving away from the electrical model of the solar cell, it is also important to understand the physical model of a solar cell. Shown in Figure 10, a solar cell can be best represented as two semiconductors sandwiched together which absorb light energy and convert it into electricity. The semiconductors are able to perform this conversion due to the underlying physics behind having two distinct electron energy levels, the valence band and the conduction band which are created by the joining of a P-type and N-type semiconductor [8].

The N-type semiconductor will have an excess of negatively charged electrons and the P-type semiconductor will have an excess of positively charged holes. In the solar cell's initial state, the PN junction observed in Figure 11 will be subjected to the creation of a depletion region in

which electrons transition from the N-type region to concentrate in the P-type region leaving behind positive vacancies in the originally negative N-type. Inside the depletion region, the presence of oppositely charged ions will induce an internal electric field that prevents any further movement of electrons. This state of equilibrium will be maintained until the solar cell is subjected to light energy in the form of photons as seen in Figure 12.

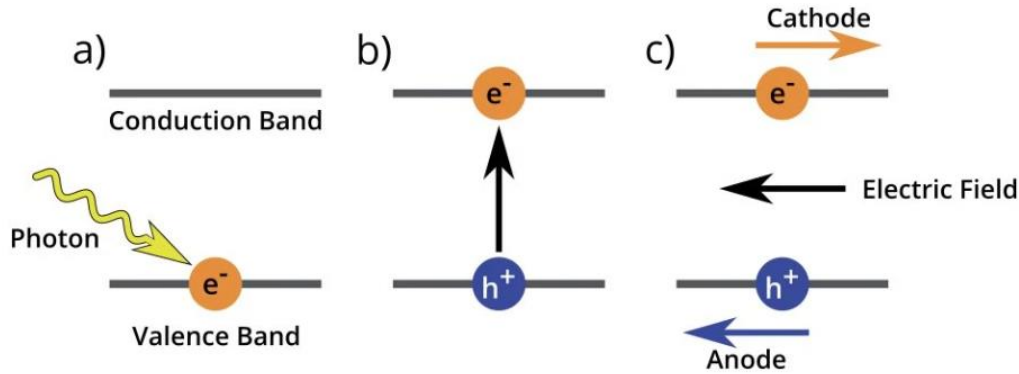


Figure 12. Operational Process of a Solar Semiconductor

Following the process of Figure 12, the valence band is where low level electrons lay. Once sunlight strikes the cell, photons with more energy than the band gap will excite the low level electrons to jump into the conduction band leaving behind a positive hole in the valence band. Once the electrons are ejected, the previously induced electric field will facilitate the movement of electrons, effectively creating the photocurrent of the cell [9].

3.3 Key Variables

With some understanding of the electrical circuit model of a solar cell and the physics behind solar cell functionality, it is important to introduce the variables which can affect the output of a solar cell from its ideal state. These variables include environmental factors as well as intrinsic features of the solar cell due to the materials chosen to create it.

3.3.1 Irradiance

Irradiance is a measurement of solar power defined by units of watt per meter squared (W/m^2). Best understood as the intensity of light, irradiance is shown to have a directly linear affect on the IV output curve of a solar cell. Figure 13 is taken from the datasheet of the JA Solar Jap6 solar panel module. In color, it clearly shows how a stronger light intensity or higher irradiance value will result in a higher short circuit current while slightly increasing open circuit voltage [4].

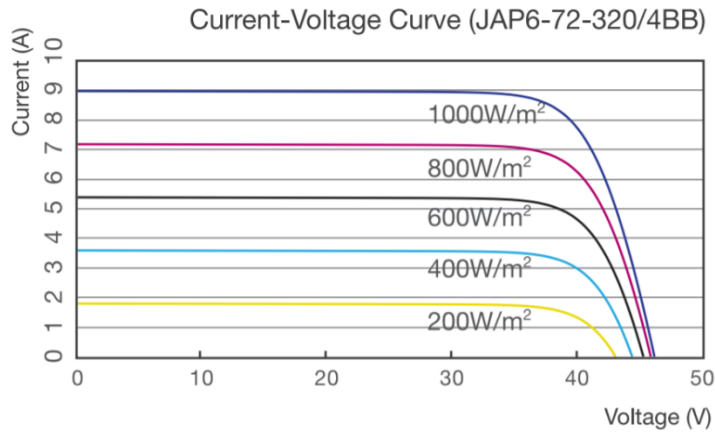


Figure 13. Effects of Irradiance on Solar Panel Performance

3.3.2 Temperature

Temperature also plays a pivotal role in the output characteristics of a solar cell due to the electron bandgap energy having a significant dependence on temperature. The bandgap energy of a semiconductor is the amount of energy needed to excite an electron from the valence band to the conduction band. This also directly relates to the open circuit voltage of the solar cell as the maximum allowable voltage across a cell is equal to the bandgap energy. A key behavior followed by all semiconductors is that an increase in temperature results in a decrease in bandgap energy. Effectively, less voltage is needed to excite an electron and the maximum voltage seen across the cell will decrease. Figure 14 below references the same JA solar panel from Figure 13. It can be observed that increasing temperature will decrease the allowable open circuit voltage while slightly increasing short circuit current [10].

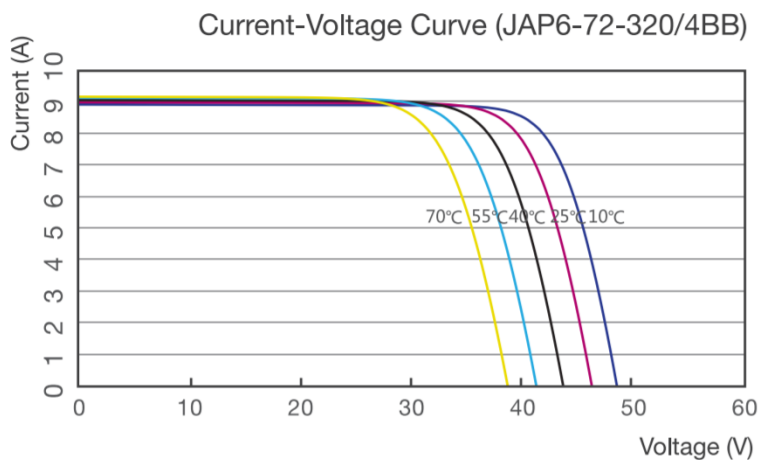


Figure 14. Effects of Temperature on Solar Panel Performance

3.3.3 Bandgap Energy and Diode Ideality Factor

The two factors of bandgap energy and diode ideality factor are intrinsic to the material sourced in building the solar cell. As described in both sections 3.2 and 3.3.2, bandgap energy is a parameter derived from the semiconductor material used to generate the PN junction. Diode ideality on the other hand refers to how closely the diode used in the electrical model of a solar cell follows the mathematical performance of an ideal diode. Typically the ideality factor will be between values of 1 and 2 where 1 represents an absolutely ideal diode. The values of band gap energy and diode ideality will ultimately vary depending different solar cell materials[10].

3.3.4 Series and Parallel Resistances

As first shown in Figure 8, the realistic model of a solar cell includes both a series resistance and a parallel shunt resistance. Series resistances are primarily induced by the delivery of current through the solar cell, contact resistance between semiconductor material, and further series connections between cells. The parallel or shunt resistance are often associated with current leakage due to cell thickness and surface effects. Many models of solar cells choose to ignore the shunt resistance because it is often an extremely large value. Should there be power loss due to low shunt resistance, this can be attributed to manufacturing defects rather than poor solar cell design [10].

3.4 Nomenclature

Table 9. Nomenclature

I_{PH}	Photocurrent
I_{RS}	Reverse Saturation Current
I_0	Saturation Current
I	Output Current
V_{OC}	Open Circuit Voltage
I_{SC}	Short Circuit Current
V_{OCR}	Temp Rated V_{OC}
I_{SCR}	Temp Rated I_{SC}
G	Irradiance
G_{Nom}	Nominally Rated Irradiance
T_C	Cell Temp
T_R	Rated Cell Temp
K_{ISC}	Short Circuit Temp Coeff.
A	Diode Ideality Factor
E_G	Bandgap Energy
N_S	Number of Cells in Series
N_P	Number of Cells in Parallel
R_S	Series Resistance
R_{Sh}	Shunt/Parallel Resistance
K	Boltzmann Constant = $1.6 \cdot 10^{-19}$
q	Charge of Electron = $1.3805 \cdot 10^{-23}$

3.5 Key Formulae

Keeping in mind the circuit diagram in Figure 8, the mathematical formulation can be used to better understand the workings of a solar cell.

$$I_{PH} = \frac{G}{G_{Nom}} * [I_{SC} + K_i * (T_C - T_r)] \quad (1)$$

$$I_{RS} = I_{SCR} \div [\exp \left(\frac{q * V_{OCR}}{N_S * K * A * T_C} \right) - 1] \quad (2)$$

$$I_O = I_{RS} * \left(\frac{T_C}{T_R} \right)^3 * [\exp \left(\frac{q * E_G}{A * K} \right) * \left(\frac{1}{T_C} - \frac{1}{T_R} \right)] \quad (3)$$

$$I = (N_P * I_{PH}) - N_P * I_O * [\exp \left(\frac{q * (V + I * R_S)}{N_S * K * A * T_C} \right)] \quad (4)$$

$$I_{SH} = \frac{\left(V * \frac{N_P}{N_S} \right) + (I * R_S)}{R_{SH}} \quad (5)$$

Equations 1 – 4 are the core equations used to accurately model solar panels for this project. These 4 equations are standardized throughout the solar industry and can be cross referenced across varying articles apart from varying variable nomenclature [6].

Equation 1 demonstrates how the photocurrent of the cell is seen to be primarily influenced by the intensity of light and temperature of the cell. It represents the main current generated by the solar cell. Equations 2 and 3 represent the reverse saturation and saturation currents of the cell, respectively. The intrinsic variables of a solar cell such as ideality factor and band gap energy play a key role in determining the values of these two currents. Equation 4, the final output current, finally combines equations 1-3. The variables V and I in the equation represent the real time voltage and current produced by the solar cell. It should be noted that other models of a solar cell factor in I_{SH} which can be interpreted as the current lost to shunt resistance. In most modules however, R_{SH} is such a large value, that the shunt current can be ignored to reduce model complexity [7].

Section 4: System Implementation

As stated in the original project specifications, the model of the solar cell will be built using LabVIEW 2019. LabVIEW is a well-established software with plenty of available online resources and support. Another reason for originally choosing LabVIEW was the proven power supply drivers which would have been used to interface with the BK Precision 9153 Power Supply. Unfortunately, due to limitations imposed by Covid-19, the power supply interfacing was removed from the system implementation.

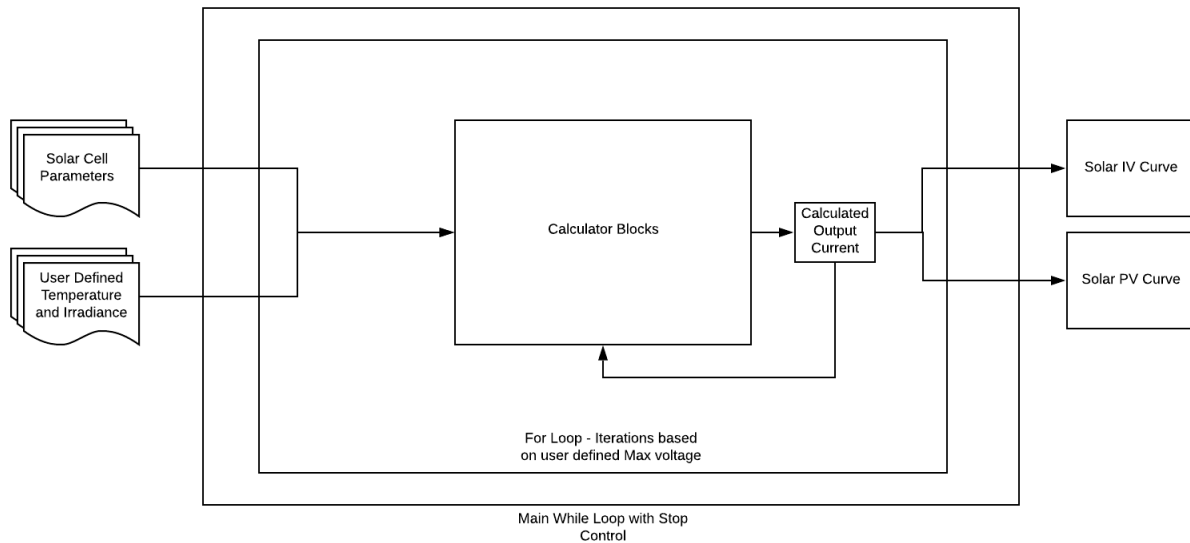


Figure 15. Main System Algorithm

The main system algorithm used to model a solar cell was derived through the cross-referencing of multiple studies of varying methodologies. The final product can be visualized through Figure 15 where solar cell parameters and user defined temperature and irradiance are the inputs while Solar IV and PV curves are the output.

The system functions first as a top level While Loop controlled by a single start/stop operator. This While Loop allows the system to run in real-time and produce dynamic data given by user command [11].

A middle level For Loop is defined by a maximum voltage level determined by the user. By manipulating LabVIEW's pre-existing iteration counter and loopers, the algorithm runs through voltages with a resolution of 0.01V and produces a corresponding output current.

Figure 16 provides a detailed look at the manipulations used to successfully calculate and graph more voltage points. The control input named "voltage points" represents an integer value defined by the user. By multiplying the value by 100, the total number of iterations is directly increased by a factor of 100. Adding one to that value brings the final iteration number to the set max voltage rather than "max voltage - 1 ". Then, for each iteration, the system divides the current counter by 100 to achieve the mV resolution discussed earlier.

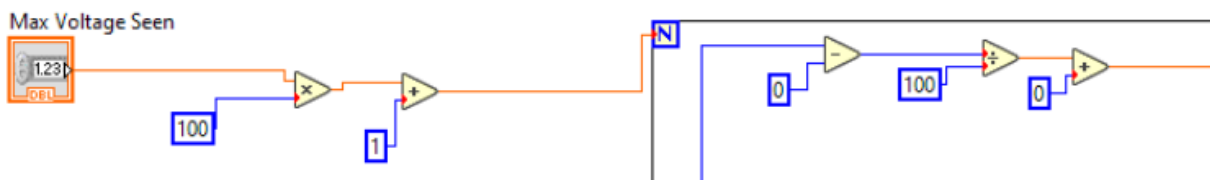


Figure 16. Iteration Count and Looper Count Modifiers

Within each For Loop, the input parameters from the solar panel as well as the user are sent into calculator blocks represents equations 1-4 from Section 3.5. The calculators were developed using the LabVIEW Mathscript Module which is an external download from the main LabVIEW package. This addition module allows for mathematical equations to be represented by singular blocks rather than individual numeric components [12].

Figure 17. shown below demonstrates how the Mathscript Modules are used to determine various constants such as I_{PH} , and I_0 by taking inputs such as Cell Temperature or Irradiance. These calculated values link to other calculator blocks result in the values used to generate the solar panels' I-V characteristics curve as well as the P-V characteristic curve.

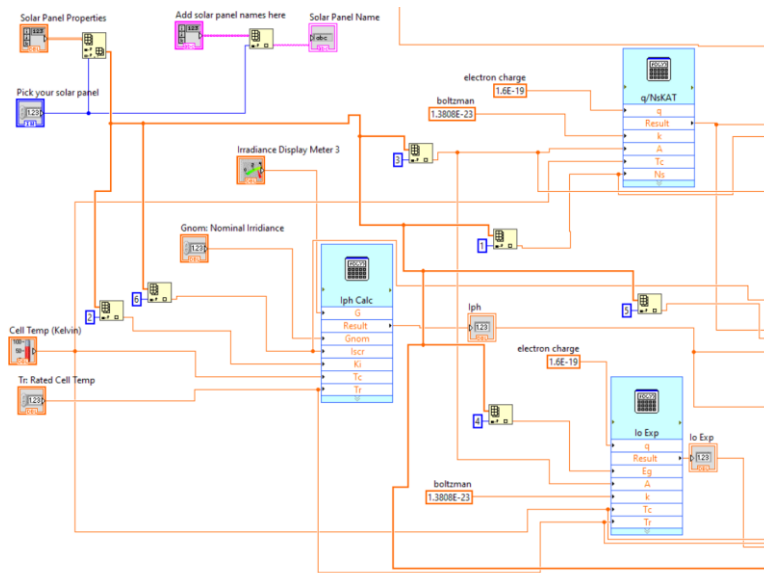


Figure 17. Calculator Blocks

Figure 18. shows the final calculator block for the output current. The system takes in the calculated current and plots it against the voltages defined by Figure 16. Original implementation produced grossly negative current values for voltages past the open circuit voltage caused by LabVIEW's usage of feedback loops. An If Statement is implemented to remove unwanted negative Voltages from the I-V curve. Doing so flattened out the curve of the I-V graph and allows the data to be exported from the graph accurately. Figure 19. Represents the True vs False algorithm used to negate the issues mentioned above.

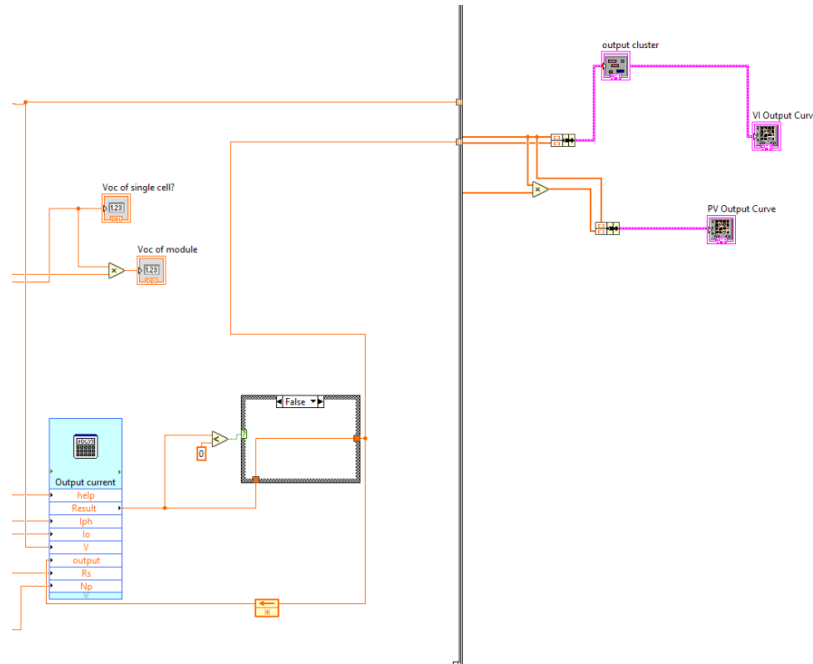


Figure 18. Output Current to IV and PV Curves

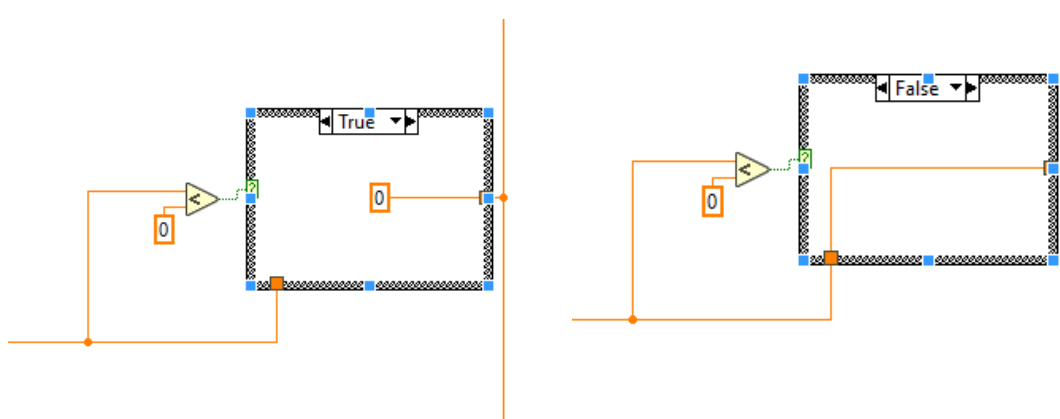


Figure 19. True/False Statement

Section 5: System Operation

The final deliverable is best depicted by Figure 20 below. To operate the emulator, the user must first define the parameters for a specific solar panel and input them into the array labeled "solar panel properties". These values can easily be found in any datasheet for the solar module. The area labeled as "constant inputs" are also variable should the user desire but should remain the same for typical usage. Once the parameters are decided upon, the two sliders representing Irradiance and Cell Temperature allow for dynamic data input which will be reflected in the output curves on the bottom left of the GUI.

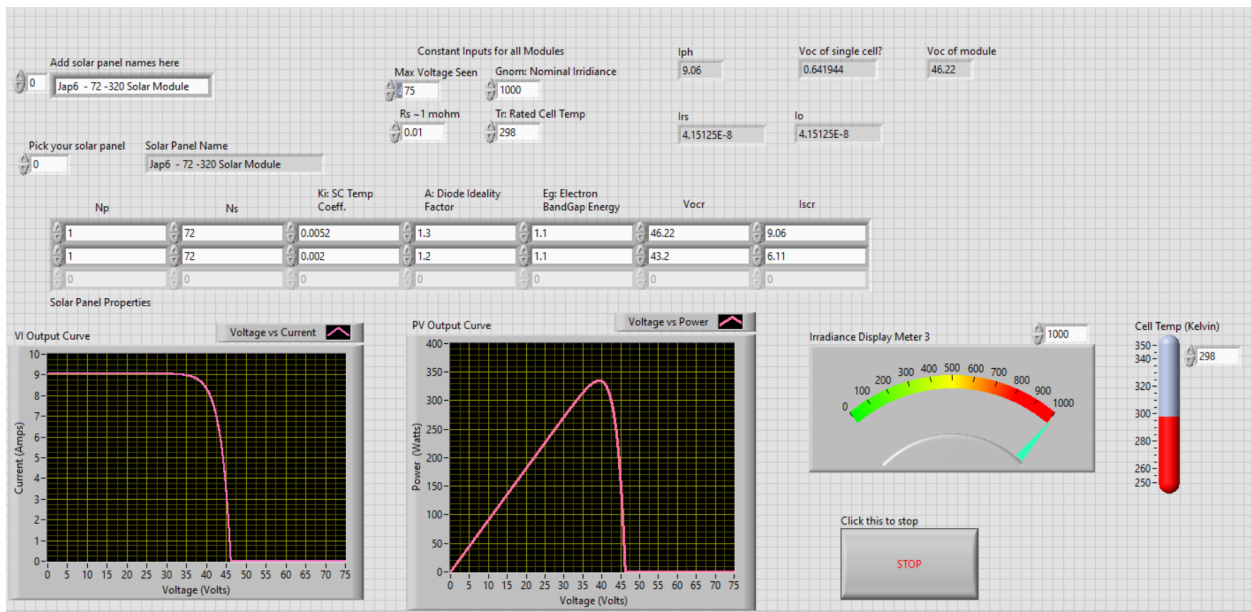


Figure 20. System Front Panel

5.2 IV and PV Curves

To verify emulator accuracy, the results of the system were cross referenced with solar module data sheets as well as with similar emulator models described in reference articles. Figures 21 – 24 show the system performance of two different solar panels with varying input conditions. In comparing the system output to datasheet values and other simulators, it can be observed that the system produces highly accurate results. The outputs for the Jap6-2-305 can be compared to the data sheet curves used earlier in this paper in Figures 13 and 14 [3].

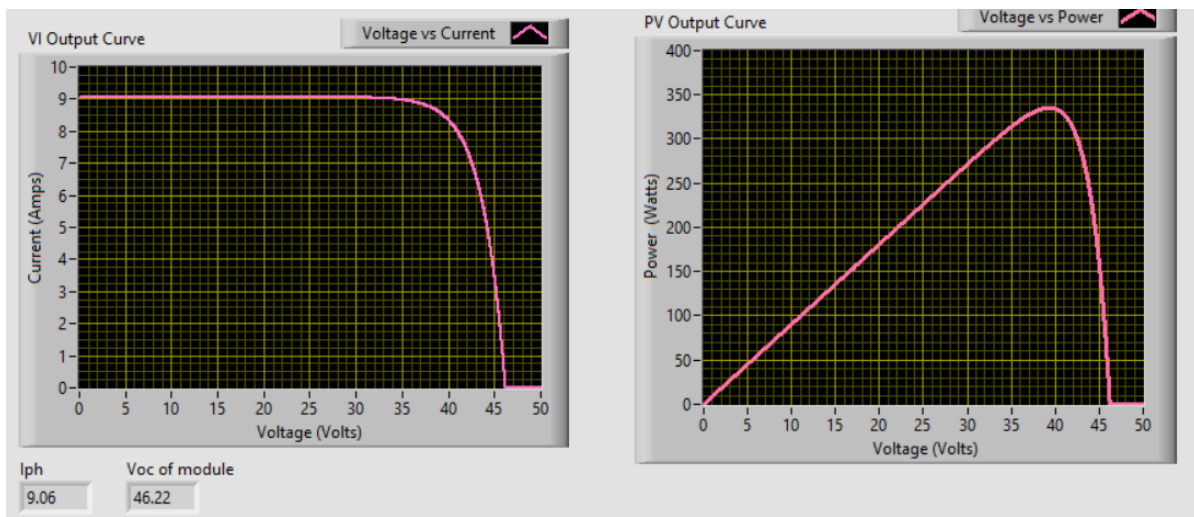


Figure 21. PV Emulator: Jap6-2-305 Operating at Gnom and Tr

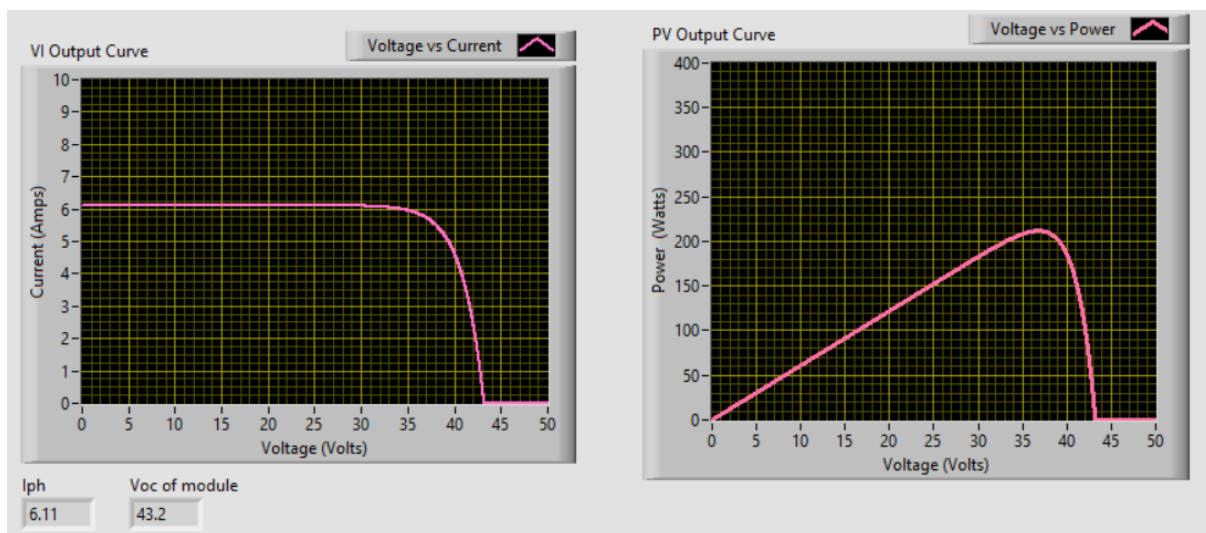


Figure 22. PV Emulator: Tapan Ds-100 Operating at Gnom and Tr

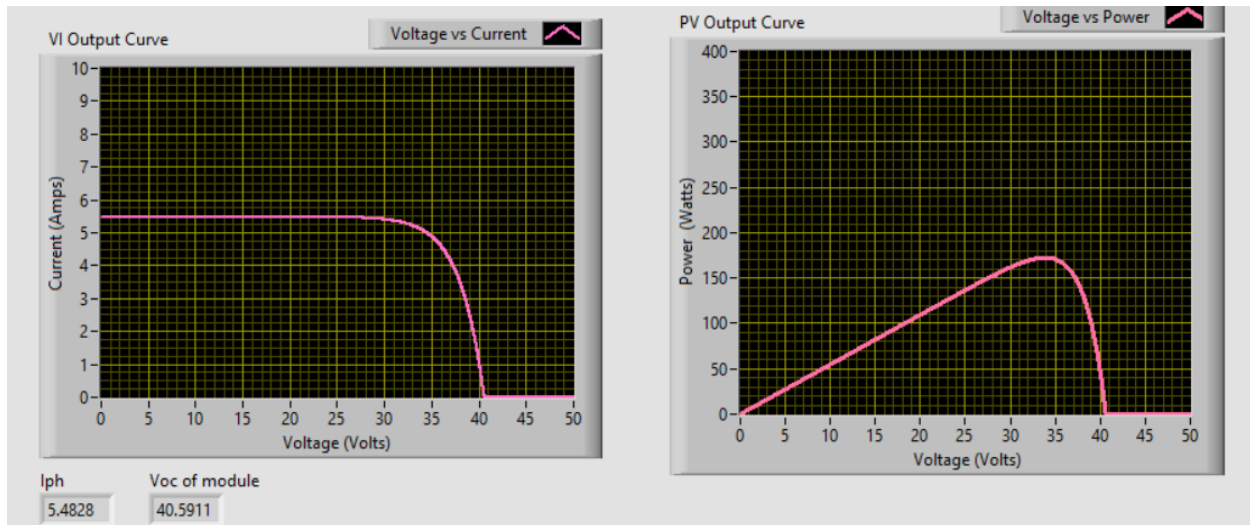


Figure 23. Emulator: Jap6-72 $G = 600$, $T_c = 313K$

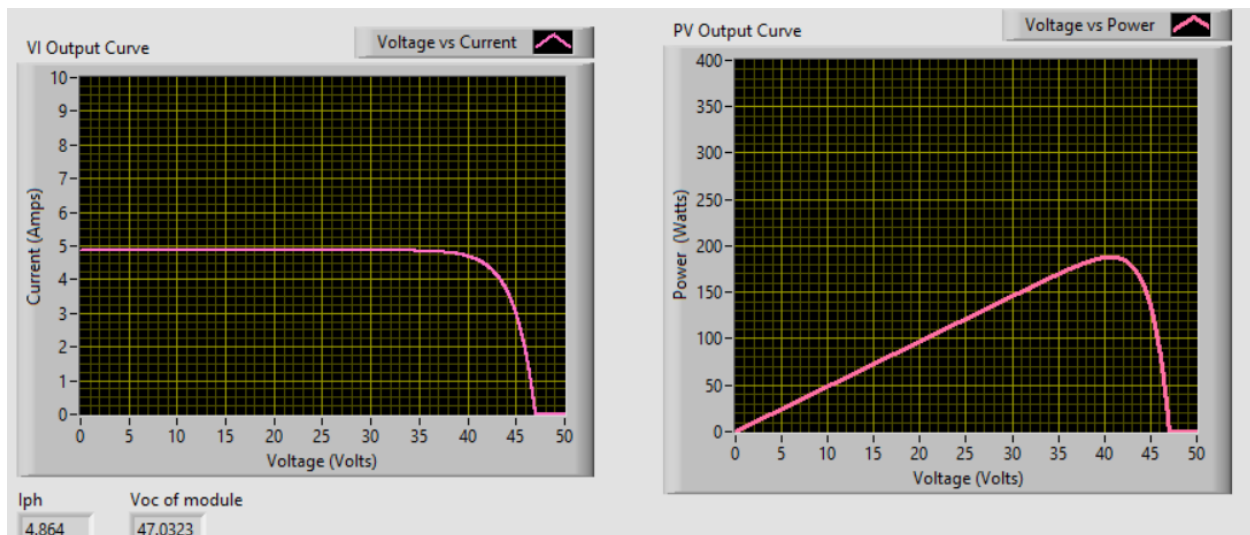


Figure 24. Emulator: Tapan Ds-100M $G = 800$, $T_c = 283K$

Figures 21 and 22 represent the emulator operating under the same standard rated conditions of the datasheet information. The resulting output currents, along with short circuit current and open circuit voltage, show a 0% error in results. When comparing Figure 23 and 24 to datasheet results, the output curves again show high accuracy [2]. Figure 23 demonstrates how a reduced irradiance and increased temperature result in a decrease in both open circuit voltage and short circuit current. Figure 24 demonstrates that a decreased irradiance will decrease the short circuit current, but a decrease in temperature will increase the open circuit voltage.

5.3 Specification Verification

The table below compares our final project with the original engineering specifications from Fall 2019.

Table 10. Engineering Specifications Verification

Engineering Specifications	Final Results
Emulator must produce voltage/current characteristics and curves for each factor. The characteristics and curves should be able to combine different conditions as well	Emulator can produce I-V and P-V curves while factoring in temperature and irradiance
Voltage/Current curves from the emulator will be based on verified data obtained from pre-existing solar cells in conjunction with proven effects of various factors.	By referring to section 5.2, provided output curves match existing datasheet curves.
Variables must be adjustable in LabView	Temperature and irradiance can be dynamically adjusted in LabView
Keep budget low and efficiently spend funds to properly complete project.	Able to cut costs due to Cal Poly offering LabVIEW licenses, and no longer needing to factor in power supply with test equipment
LabView interface will be intuitive and user friendly.	LabView interface is clearly labeled, with slots, sliders, and knobs where the user can easily find and adjust the solar panel properties, the temperature, as well as the irradiance
Will aim to be able to select from many panels from existing databases.	Unable to link to pre-existing database, user must manually input solar cell parameters.

Section 6: Conclusion

Using the single diode model of a solar cell, this paper describes the physics and formulae used to construct an accurate photovoltaic emulator. This paper also describes the algorithms used to implement the emulator in LabView 2019. By describing and developing this emulator, this paper aims to assist future students and researchers alike in developing a stronger understanding of photovoltaic cells and their operation.

The overall design of the emulator is intuitive and operates fluently with the user interface. Output curves adjust instantaneously to real time inputs with accuracy up to 100% given standard testing data. The user defined "solar cell parameters" array allows for the potential of having an infinite number of solar cells in the emulator.

However, the PV Solar Cell is far from perfect and has room for many improvements. In the future, the program should be integrated with a separate algorithm to interface with a variable power supply. The emulator should then be able to adjust the current/voltage according to the load connected while staying true to the expected outputs defined by the IV and PV curves. Furthermore, rather than having user inputs for the solar cell parameters, it would be ideal to access a pre-existing database with necessary information already available. Doing so would allow the user to more easily choose from a greater number of solar cells to test and emulate.

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Appendix A. Senior Project Analysis

Table 11. ABET Senior Project Analysis

Project Title: PhotoVoltaic Emulator	
Student's Name: Eric Tse , Jeffrey So	Student's Signature: <i>Eric Tse , Jeffrey So</i>
Advisor's Name: Dale Dolan Advisor's Initials: Date:	
• 1. Summary of Functional Requirements	
<p>The main feature of the system should emulate the voltage and current characteristics of existing PV modules with a percent error of less than 10%. Secondary features of the system include providing the user a variety of input options to emulate a wide range of conditions. Furthermore, the system should be designed to accommodate any user, and so must be intuitive with a clean graphical user interface.</p>	
• 2. Primary Constraints	
<p>The primary limiting factor of concern will be the amount of work hours capable of being invested towards this project. The design group consists of only two senior standing members, each with at least an addition 12-14 units of classes on top of the designated senior project class. Another limiting factor that directly relates to the amount of time being invested, is the level of prior experience towards the subject matter. Both members of this group have zero experience working with PV modules, solar energy, and LabView. With the limited starting baseline, a significant portion of the invested time will be allocated towards research along with trial and error.</p>	
• 3. Economic	
<p>The largest economic impact will be towards human capital. As this project consists primary of a software design in LabView, as well as the necessary research to properly emulate solar cells, the majority of costs will be shouldered by work hours put in by team members. Outside of human labor wages, the monetary costs should not be too significant. The LabView text and large power resistor costs will not exceed \$150 and most likely be brought down after further shopping and research. As seen in table 7, they are currently estimated to cost ~\$120 this represents the original estimated cost of component parts.. An area of concern, however, is the course of obtaining the programmable DC power supply. This</p>	

component should not incur any costs as it is currently under the assumption of being obtained via the project advisor.

In terms of environmental costs, nothing significant is at stake. The power supply itself will draw a large amount of current to produce results, but there are no concerns of any bio/chemical waste and costs.

During the course of this project, no monetary benefits are expected to arise. The goal is to create a PV emulator to test devices which require photo-voltaic energy as an input. Once finished, the software should be sold for about \$59 per license. Under current assumptions, all costs will currently be covered by the team members, but will eventually be reimbursed by the Electrical Engineering department so long as costs remain with \$200 which is what the budget allows for. The timeline to manufacture is to hopefully have a working product by the beginning of June, and once created, there should be little upkeep as it is a software file at the core.

- 4. If manufactured on a commercial basis:

The software can be sold in mass amounts, and since each company will need one license per person, it is estimated that upwards to a hundred thousand licenses will be sold per year. License holders will be required to pay once a year to access our software to ensure that our company is sustainable. The manufacturing cost for the PV emulator will be fairly low, with only the need to maintain the software to be bug free. Adding more features will require a small team of one or two, and at a cost of \$30 an hour, it is estimated that maintaining the emulator will cost 10 hours of labor, or \$300, per month and \$3600 yearly. Charging \$59 yearly would yield \$590 thousand, and \$586,400 after software maintenance costs. With a small server to keep the emulator updated, it would cost an extra thousand dollars yearly, which brings our profits to \$585,400.

- 5. Environmental:

This project should have the potential to positively influence the environment. By supporting the design and validation of devices requiring PV inputs, the project promotes the usage of the renewable resource of sunlight. So while not directly using sunlight itself, the project helps facilitate the improvement of other devices that do directly use the natural resource. The limited physical materials being used to create the emulator also means less overall waste and emission. The primary benefits will be the overall ecosystems in the world as an increased usage of solar energy means less usage of energies that are known to create many carbon emissions. A cleaner air and less waste also benefits all species that call the natural environment a home.

Physical components will be used to initially validate the functionality of this project, but upon completion, the product itself is primary code outside of the user provided DC power supply. Therefore, it is safe to say there is little to no environmental impact associated with any large scale distribution of the product.

- 6. Manufacturability:

Manufacturing the PV emulator requires a lot of research. If the research is off, the PV emulator may not be accurate, which could discredit the entire software. With that being said, the research done on the emulator must be precise. If the emulator doesn't give accurate information, then no one would want to use the software. With that being said, while research will be the most critical part of accurately designing the emulator, properly writing the software will be the most challenging aspect of this project. A higher proficiency in LabView will ultimately equate to a more accurate emulator.

- 7. Sustainability:

Maintaining the emulator will not be too challenging as it is not an intricate software. Once all the research has been done and the emulator created, the only maintenance done on the software would be updating information and increasing the PV device database. In other words, maintaining the device just means adding more support to other PV devices and updating the outputs if new research about solar panels come out. Since the maintenance required is all software based, it will be sustainable, with no physical materials needed to upgrade services.

Adding more PV devices to the emulator's database makes it so that companies will be able to sort through and compare different types/brands of solar panels so that the company will be able to decide which brand/types will be best for their needs. This increases the list of potential customers that can use the emulator. Unfortunately, increasing the amount of available models to emulate equates to having to obtain the consent from the original manufacturers. This could prove to be an issue from a legal standpoint.

- 8. Ethical:

To ensure that the PV device is ethical, the software will be completely unbiased and outputs will solely be based on thoroughly tested results. Each solar panel will be tested in controlled environments and will undergo the same tests as every other panel to ensure that no panel

will have an unfair advantage. Information from other companies will not be accepted to prevent incorporating biased data into the emulator. Criticism will be taken though, and if a company believes that their product is being inaccurately simulated, the emulator's database will be updated with accurate outputs based on retests.

This project strives to meet all 10 listed points in the IEEE Code of Ethics. In particular:

"to be honest and realistic in stating claims or estimates based on available data";

"to seek, accept, and offer honest criticism of technical work, to acknowledge and correct errors, and to credit properly the contributions of others",

"to assist colleagues and co-workers in their professional development and to support them in following this code of ethics.",

"These specific three statements of ethics will be covered in depth over the course of this project as specified above."

- 9. Health and Safety:

The nature of this project requires an output of high voltage and high current. Working with high power designs always requires proper safety procedures and careful actions around the test environment. Other than the safety concerns with testing the functionality of the product, any future users must also be cautious when operating the device at high voltage and current.

- 10. Social and Political:

This project is clearly politically and socially inclined to supporting more progressive views towards renewable energy. The aim of this project is to help better test devices that traditionally utilized PV energy inputs, which ultimately supports the notion of using solar power on a larger scale. This type of project is certainly more well received in the state of California, where renewable energy is well accepted. While not exactly affecting any direct stakeholders, this does impact those indirect stakeholders with a large investment in traditional power sources such as natural gas and coal companies. It harms them in the sense that as more and more people turn to solar energy as the primary source, the value in natural gasses and coal could drop. On the other hand, this project could directly benefit companies who manufacture solar panels and other PV devices as this emulator helps to validate their products in a more controlled environment which also could increase potential customer's

trust in the product. Unfortunately, this project still does not help those with lower incomes, as solar energy is still a relatively expensive investment to begin with.

- 11. Development:

For this project, LabView is primary tool/software that must be learned in order to properly create a functional design. LabView is not taught through any academic curriculum and must be learned separately. Secondly, a new tool that members must learn to operate is the programmable DC power supply as it directly ties in with the LabView software. Furthermore, team members must learn new techniques in the design and emulation of PV devices.

Appendix B: Alterations and Changes

Appendix B describes the alterations and changes of the project since Fall 2019 planning

- No in-person access to lab
 - Power Supply no longer used
 - Wire-Wound Power Resistor and Cables no longer used
- Not able to implement the variable voltage/current supply based on load
- No longer accessing solar panel data from external databases
- No longer using cloud cover and humidity as a user defined input
 - Only user input is temperature and irradiance