LED Solar Simulator

Third Year Individual Project – Final Report

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Contents

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Abstract

In this project, the use of LEDs to create a simulator of the solar spectrum will be investigated. In the current market there have been solutions to LEDs being used as solar simulators, but it is not as popular as different alternatives such as Xenon arc lamps. The solar simulator will be powered and controlled by an Arduino and achieved to accomplish a classification of CAA with the spectral fitting encountering some problems which will be solved in the future work. In this report spectral fitting will be conducted in order to meet the official compliance standards of a solar simulator. Analysis and comparisons will be discussed between natural, and the LED solar spectrum and power and efficiency of the system will be calculated with the use of IV curves. Results prove that LEDs can be used to provide the same functions as other lamps while being cheaper and more efficient.

Declaration of originality

I hereby confirm that this dissertation is my own original work unless referenced clearly to the contrary, and that no portion of the work referred to in the dissertation has been submitted in support of an application for another degree or qualification of this or any other university or other institute of learning.

Intellectual property statement

Acknowledgements

I want to show appreciation towards the faculty within the Electrical and Electronic Engineering department and especially my supervisor, Professor. Matthew Halsall, for the guidance shown throughout this project. This was a very interesting project to participate in with all the necessary support and budget to successfully execute it. I would like to show gratitude towards Janet Jacobs for supervising and advising me during the lab sessions in the solar lab as well.

1 Introduction

1.1 Background and motivation

About 430 quintillion joules of solar energy reaches the surface of the Earth every hour, which is enough to power the whole world for a year [1]. There are technologies like Photovoltaic (PV) panels that can convert solar energy into electricity, and it is in fact one of the fastest growing renewable energy sources. However, commercial PVs need to be placed across large areas of land for it to be worth the investment. There are some other variations of PVs, floating solar photovoltaics (FPV), that are being implemented across the world to solve problems caused global warming. This new technology is predicted to increase in popularity by over 31% worldwide to reach a net-zero carbon emission target by 2050. Regions with high electricity costs and in need of land conservation can benefit from installing FPVs, which are photovoltaic solar panels that are installed anywhere that do not occupy land such as bodies of water and rooftops [2].

PV panels are one of the fastest growing products in the renewable energy industry and one of the most important changes in the future would improve efficiency. The panels are not exposed to the same amount of sunlight throughout the day due to various uncontrollable variables such as clouds, extreme weather, and the position of the sun etc. In order to test the PV panels for their efficiency in different environments, solar simulators are used.

A solar simulator is a system that can produce and mimic the solar spectrum by using a combination of light emitting components. It can be programmed to emit the required "sunlight" by adjusting the intensity of the emitter. There are many different options when choosing the light source of the simulator. Normally, filtered high-intensity xenon lamps are used to ensure a constant output is maintained. However, other options on the market such as Light emitting diodes (LED), are much cheaper and have a wide range of wavelengths from ultraviolet (UV) to infrared (IR). The light intensity of the LEDs can be easily adjusted through a programmed microcontroller [3,4].

Apart from testing PV panels it is also widely used in other industries such as automotive, medical environments, and cosmetics. In particular, the automotive industry uses it to observe the reaction of the vehicle when exposed to different environments by changing the temperature, humidity, and thermal load of the room [5].

1.2 Aims and objectives

To create a replica of the solar spectrum, there are a few compliance standards that could be used but for this project, the "Ideal Spectral Match Defined by IEC 60904-9" as shown in the figure below has been chosen; it specifies the spectral range and the equivalent percentage of irradiance per wavelength range [6]. Apart from meeting the requirements of the ideal spectral matching, a solar simulator also needs to be stable and have spatial uniformity. Due to the complicity and the short duration of the project, the spatial uniformity will not be calculated and assumed to be ideal.

IEC 60904-9 Compliance Standards

Class A, B and C Standards and Specifications Defined by IEC 60904-9

	Spectral Match*	Non-Uniformity of Irradiance	Temporal Instability, Short-term	Temporal Instability, Long-term
Class A	0.75-1.25	2%	0.5%	2%
Class B	0.6-1.4	5%	2%	5%
Class C	0.4-2.0	10%	10%	10%

* Acceptable range ratio of ideal % according to related table values for 'Ideal Spectral Match' standards for IEC 60904-9.

Ideal Spectral Match Defined by IEC 60904-9

Spectral Range (nm)	Total Irradiance Range	Ideal Percentage
400-500	13.8-23.0	18.4%
500-600	14.9-24.9	19.9%
600-700	13.8-23.0	18.4%
700-800	11.2-18.6	14.9%
800-900	9.4-15.6	12.5%
900-1100	11.9-19.9	15.9%

Figure 1.2: IEC 60904-9 Compliance standards[6]

The aim of this project is to build a solar simulator solely using LEDs. This will be achieved by adjusting the light intensity of 11 LEDs to cover an important section of the solar spectrum between 300 – 1000nm. An Arduino Mega 2560 will be used as the microcontroller to power and control the LEDs since it has 14 PWM output pins to control all 11 LEDs at the same time. Thorlabs will be used for the spectral fitting when choosing each LED while ensuring the classification standards are met. After spectral fitting has been completed, the simulator will be tested using a reference cell and spectrometer to obtain total power and efficiency.

2 Literature review

2.1 Introduction

In this section, existing solutions on the market will be introduced and discussed in detail how other researchers have achieved to solve the current issue within the solar simulator industry. One of the papers worth considering is, “A Low-Cost LED-Based Solar Simulator”, by Eduardo López-Fraguas, José M. Sánchez-Pena and Senior Member, IEEE, and Ricardo Vergaz [19]. Their concept is similar to the aims and objectives of this project. “Cost-effective and Smart AAA-Class RGB-LEDbased Sun Simulator for Real-Time Characterization of Solar Cells” by Saeed Nayeri, Ali Rostami and Javad Javadi Moghadam also have a very similar project working towards the same goal. All of them are trying to design and build an LED solar simulator and trying to classify it as AAA [18].

2.2 AM1.5G

AM stands for air mass, and it is an indication of the atmosphere thickness according to the position of the sun. AM1.5G represents the solar zenith angle which is 48.2^0. Depending on the angle of the sun facing towards Earth, the illuminance would differ. AM 1.5G is known to have $1000mW/m^2$, this is also known as 1 sun [17]. To create a solar simulator, AM1.5G is always used for the spectral fitting percentage as shown in the ideal percentage of the table on the right in figure 1.2.

2.3 Spectral matching

Both Eduardo Lopez-Fraguas and Saeed Naveri’s papers used a deviation equation to calculate whether their versions of an LED solar simulator qualify to be classified as class A[19].

$$Deviation = \left(\frac{\int_{\lambda 1}^{\lambda 2} I_{AM1.5G} - \int_{\lambda 1}^{\lambda 2} I_{Simulated}(\lambda)}{\int_{\lambda 1}^{\lambda 2} I_{AM1.5G}(\lambda)}\right) \times 100\% \qquad (2.3)$$

Equation 2.3 is the method that was taken to calculate the ratio of spectral fitting. The integration of irradiance within the ranges of wavelengths is basically calculating the respective area under the curve of the spectrum. By subtracting the simulated version from the ideal AM1.5G version, the percentage difference will show how much off the simulated is. Apart from using the irradiance to calculate the ratio, the values have to be turned from intensity to irradiance, which will be further discussed in the methodology section.

2.4 Spatial uniformity

This section describes the method on how the spatial uniformity or also known as the spatial homogeneity is calculated. The most common equation to obtain the value is given by equation 2.4, where I_{MAX} and I_{MIN} are the maximum and minimum irradiance [6]. This part of the project will not be obtained due to the shortness of time to complete but it will be further mentioned as part of the future works as mentioned above in section 1.2.

$$Spatial\ non-uniformity = \frac{I_{MAX}-I_{MIN}}{I_{MAX}+I_{MIN}} \times 100\% \qquad (2.4)$$

2.5 Temporal stability

The temporal stability of a solar simulator is important as it shows whether the system is stable enough to be continuously outputting the required illumination level. The LED power and current are both to be monitored for a short term and long term [6]. Equation 2.5 explains how the value is determined; it is similar to the spatial uniformity:

$$Temporal\ stability = \frac{I_{MAX}-I_{MIN}}{I_{MAX}+I_{MIN}} \times 100\% \qquad (2.5)$$

The system should be left untouched for a time period and record the power and current levels at a fixed time interval. The maximum and minimum irradiance will help determine the stability.

2.6 Maximum power in IV curve

IV curves play a big role in the power calculations especially for PV cell testing. The equation 2.6 indicates the maximum power:

$$Output\ power = V_{maxpp} \times I_{sc} \qquad (2.6)$$

V_{MAXPP} represents the maximum voltage and I_{SC} represents the short circuit current. These two values are only available when the system is generating power and short circuit current is negative. When the simulator is in a dark room, no current would be going through the circuit therefore no power is generated [15]. This should be used to find the power of the LED simulator by using a reference cell.

3 Methods

3.1 Introduction

The methodology section will be answering three main questions about the project and explaining the methods and reasons behind each decision so that it can be recreated by another engineer.

1. What is a solar spectrum and how it will be simulated?
2. What and why components were used in this project?
3. How can the design be tested and whether it meets the standards?

In Figure 3.1.1, a theoretical solar spectrum is shown. The data was gathered from the National Renewable Energy Laboratory of the United States. This graph shows the distribution of spectral irradiance depending on the wavelength of light and will act as a reference when comparing with the spectrum of the LEDs captured by the spectrometer. Figure 3.1.1 shows the solar spectrum with a range of 250nm to 4000nm but for LEDs, the range was narrowed down to 300 – 1000nm, where the grand majority lies in. The black line indicates AM0 which is the extraterritorial spectrum so it can be ignored. Direct +circumsolar is the one that will be focused on, AM1.5G.

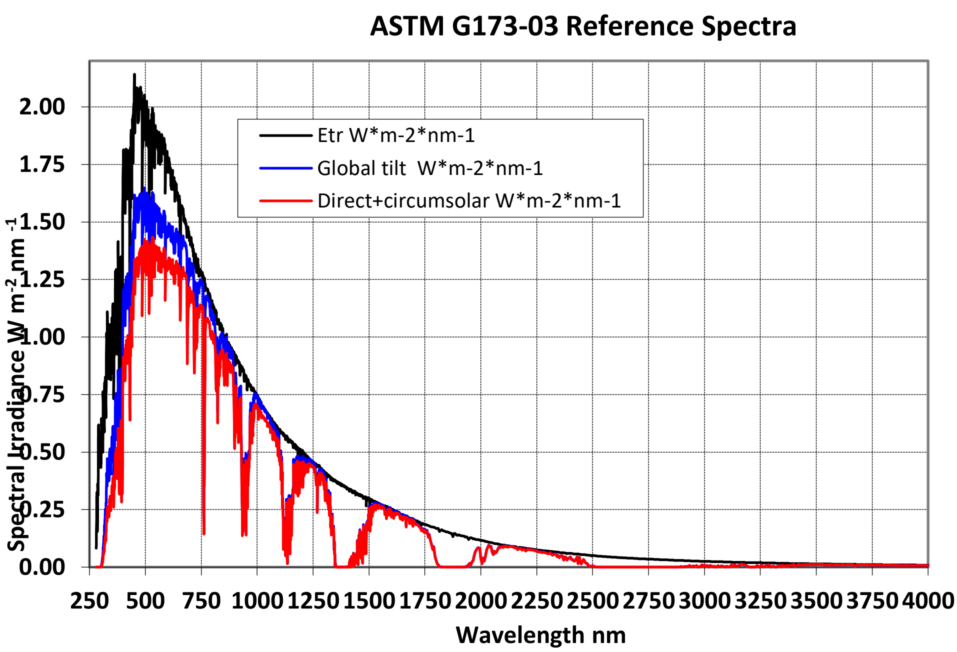


Figure 3.1.1: Reference Solar Spectrum [7]

Figure 3.1.2 shows a block diagram of the main components of the whole circulatory system, and they will be briefly discussed. The blue block is the microcontroller Arduino, which is mainly used to power the circuit and adjust the light intensity of each LED individually. This is connected to the circuit diagram which represents one of the 11 LED circuits that was built on a breadboard. All

LEDs have their own resistor to make sure the right amount of current is passed through the circuit. LEDs were fixed onto a shower head like component to focus all emitted light onto one point, which will be the input of the spectrometer. All components will be discussed in greater detail later on.

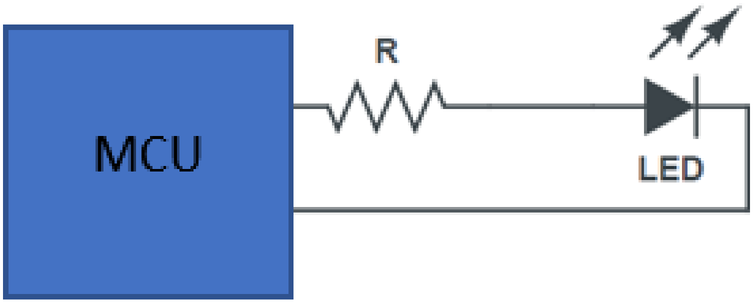


Figure 3.1.2: Block diagram showing the circuit diagram

3.2 Components:

Table 3.2: List of components

Name	Amount
LEDW7E	2
LED 405 nm	1
LED 465 nm	1
LED 680 nm	1
LED 760 nm	1
LED 800 nm	1
LED 840 nm	1
LED 870 nm	1
LED 910 nm	1
LED 940 nm	1
Arduino Mega 2560	1
220 Ω Resistors	10
270 Ω Resistors	1
Jump wires	24

Table 3.2 shows the overall required components that were used in this project to successfully create the solar simulator. In the following section the process of how each component was chosen will be explained in detail.

The one of the most important pieces of the puzzle is the Arduino because it is the component that controls the whole experiment. When choosing the right microcontroller to use, two options were taken into consideration, Arduino Mega 2560 or Arduino Uno + 16 channel PWM servo driver. The Arduino Mega 2560 stood out due to the 14 PWM output option that a normal Arduino Uno did not have. The Mega 2560 also allows a single output pin current of up to 40mA which is enough to power all 11 LEDs. However, the only downside is the total current it may provide is only 200mA. This means that having 11 LEDs will reduce the current to approximately 18.18mA per pin. [9] Considering the other option, if an Arduino uno was to be used, an extra PWM driver board would need to be purchased which may increase the chances of component failure and extra costs. Although the overall current provided by the PWM driver would be larger than the Mega 2560, the solar simulator is classified by spectral matching, not light intensity. The following figure is a picture of the chosen Arduino, where the pins are explained.

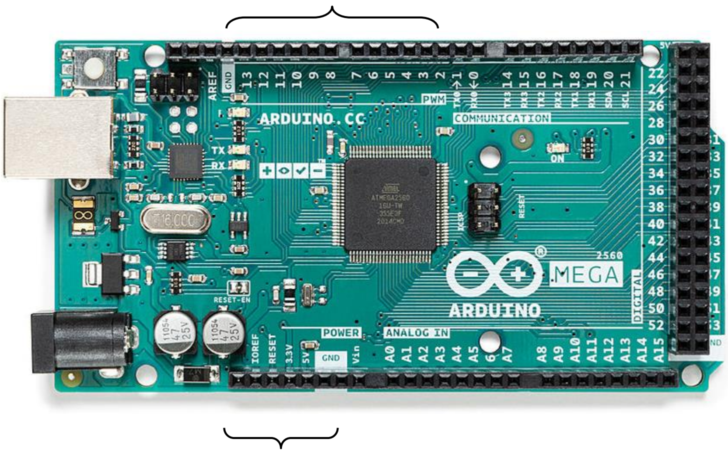


Figure 3.2: Arduino Mega 2560 [8]

3.3 PWM

PWM, Pulse width modulation, is a method commonly used when a user wants to control an analogue device with a digital output, for example controlling the brightness of LEDs when powered by a microcontroller. The theory behind it is that the microcontroller will send out waves of pulses with two possible states 1 or 0 which will turn on/off the LEDs[10]. Essentially, the microcontroller provides maximum voltage, and the user can choose to adjust it, or in simpler words, changing the duty cycle, the percentage on time of the pulse. The desirable average voltage supplied can be adjusted by altering the duty cycle which causes a change in brightness of the LED [10]. When the duty cycle is not at 100%, the LEDs will be constantly turning on and off so in order to make the flickering nonvisible, the frequency has to be increased. The figure below shows five different duty cycles and their average voltage (red line) to better illustrate the concept of PWM.

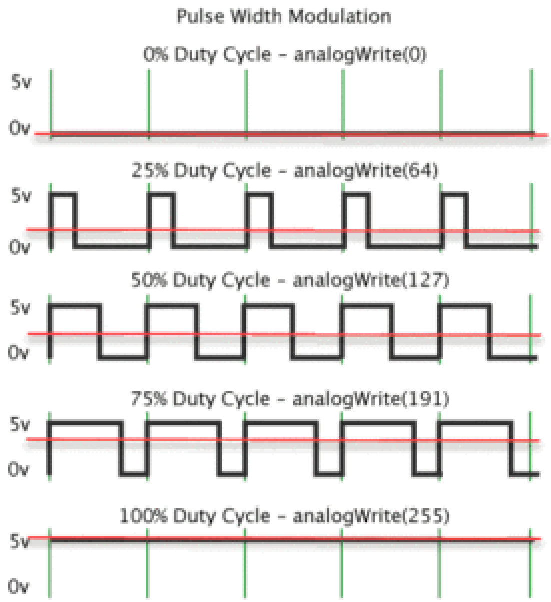


Figure 3.3: Pulse Width Modulation[10]

There are other alternatives to pulse width modulation to control the brightness of the LEDs. One of the more common choices includes implementing a potentiometer, where the user can manually change the resistance value connected to the LED, increasing/decreasing the potential drop on the resistor. One of the reasons why a potentiometer was not used was because the accuracy and precision required by the project may drop, as there will be human error when twisting the rotating shaft[11]. To purchase and implement 11 potentiometers would have caused extra costs onto the existing problem.

3.4 Light Emitting Diodes

After confirming the microcontroller, LEDs were next in line. Thorlabs was used to order the LEDs because it was one of the few electronic retailer websites that contained a wide variety of wavelengths in the unmounted LED sections ranging from 255nm to 4200nm. This range covers the 300 – 1000nm required LEDs for this project. Thorlabs was also used due to the fact that they sell spectrometers which can be used to capture the light spectrum it is being exposed to. This process will be discussed in more detail later on.

Firstly, to replicate the solar spectrum shown in Figure 3.1.1, the base needs to be populated by W7E white colored LEDs because it covers a wide range from 400nm to around 750nm. Once the base is settled, the other LEDs need to cover the gaps left between 300 – 1000nm. There are however some limitations when purchasing blue colored wavelengths between 400-500nm due to the complicated nature of production. This was not a major concern for my project because as long as the simulator lies within the ideal spectral matching standards, it could still be classified. Figure 3.5.1 shows the predicted spectrum after being fully populated by the list in Table 3.2:

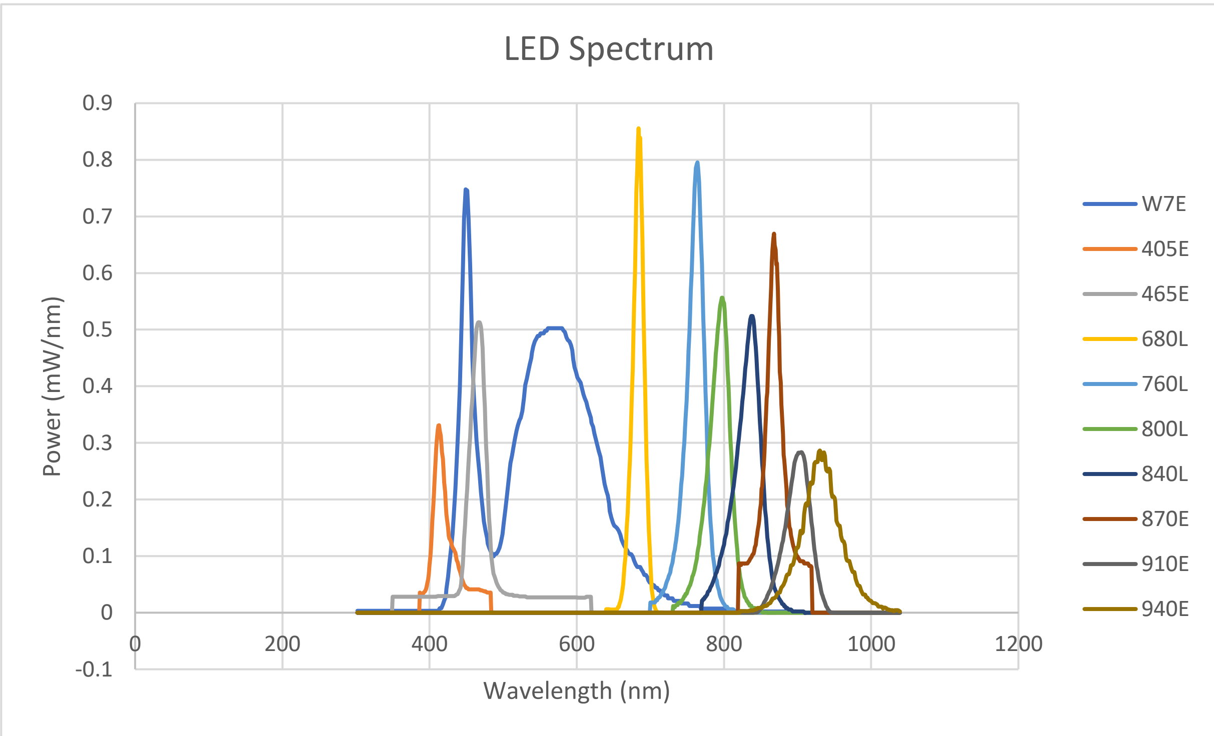


Figure 3.4.1: Calculated LED Spectrum

Figure 3.4.1 shows the bundle of graphs of all LED spectrums after using the method mentioned above. This is an indication of how the spectrum should look like. The graphs in Figure 3.4.1 show power against wavelength but in reality, the data sheets only show a normalized intensity. To calculate the relative power associated with each LED, the first step is to find the total output power of each LED. Each data sheet might be a bit different, but it should mention the output power at a certain value of current. From the total output power, the relationship between the percentage of the normalized intensity and power can be found. Let's say that f(λ) and g(λ) are the curves describing the spectrum of certain LEDs. The only difference between them is the representations of the y-axis. f(λ) and g(λ) have power and relative intensity as their y-axis respectively. From the datasheet, only g(λ) and the total output power are known. In order to find f(λ), the proportion between both functions needs to be found.

$$f(\lambda) = \frac{g(\lambda)}{\int g(\lambda)} \times output\ power \qquad (3.4.1)$$

Equation 3.4.1 describes the relationship between f(λ) and g(λ). $\frac{g(\lambda)}{\int g(\lambda)}$ is the proportion of the instantaneous and overall intensity of the LEDs. With this equation, the instantaneous power at any point on the plot can be determined.

As an example, LED 840L will be used to show the procedures taken to calculate the power from the intensity provided by the datasheets. In this case, the total output power was 22mW at 50mA. Figure 3.4.2 indicates the y-axis as intensity. This data was extracted from the data sheets by using a software called datathiefs that tracks the curve by the color and predicts the values for a given range of both axes.

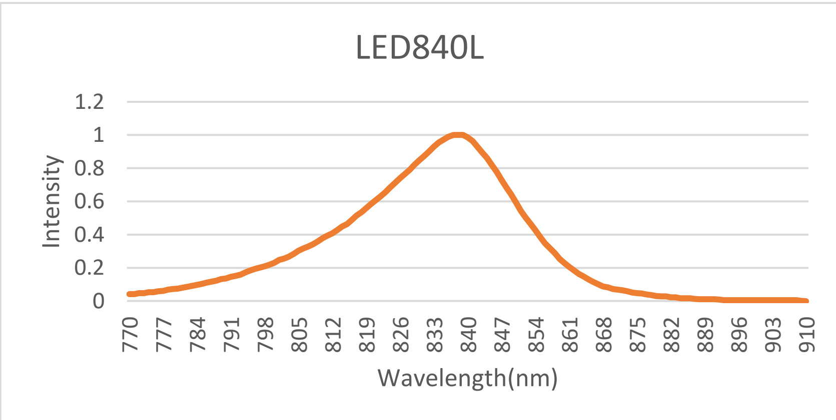


Figure 3.4.2: Spectrum of LED840L

The first step would be to obtain the summation of all intensities, $\int g(\lambda)$, which is also the area under the curve. Then, select a point on the graph as the instantaneous intensity $g(\lambda)$. Now with the use of equation 3.4.1:

$$f(\lambda) = \frac{0.041}{41.98} \times 22 = 0.02149\ mW/nm \qquad (3.4.2)$$

In excel, instead of integrating $g(\lambda)$, the summation of all instantaneous points was done to simplify the process when finding all values of the equivalent $f(\lambda)$. From this point onwards, all LED values are going to be discussed in terms of power because the intensity is not relevant to the aim of the project.

3.5 Circuit Board

With all the required components in hand, the circuit can be designed on the breadboard and programed by the Mega 2560 Arduino. This initial prototype was used to make sure all LEDs could be powered correctly, and brightness could be adjusted according to the needs and requirements of the project. A blink program was developed so that the light of all LEDs would slowly dim from maximum brightness and vice versa. This confirmed that the components were operating as expected and the faulty ones would be eliminated. For the LEDs with wavelengths larger than the visible range, which is larger than 300 – 700nm, an android phone was used. By shining the back camera of an android on the LED, it can pick up and make infrared rays visible [12]. The code for this test program can be found in the appendices.

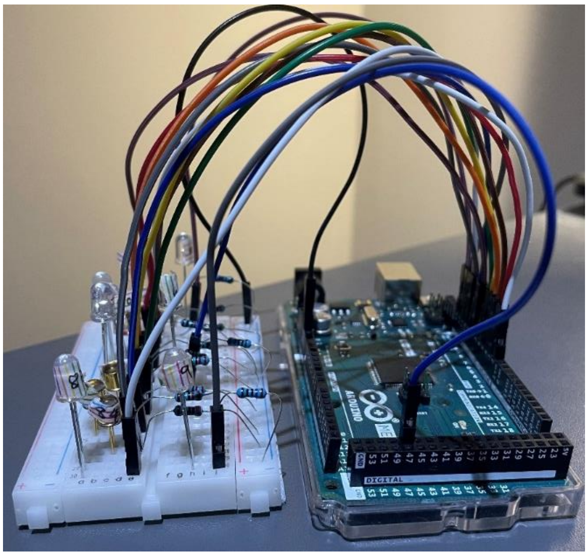


Figure 3.5.1: Testing of the circuit

Figure 3.5.1 shows the test board with all 11 LEDs and their resistors before it is mounted onto the 3D printed showerhead that directs all the light towards a center point. A header was designed and printed to fit up to 14 LEDs focused on the same point because during testing of the simulator, having a concentrated beam will make the results more accurate. Figure 3.5.2 below shows a picture of the LEDs mounted on the header. The showerhead was designed and provided by supervisor, Prof. Matthew Halsall, to simplify the project.

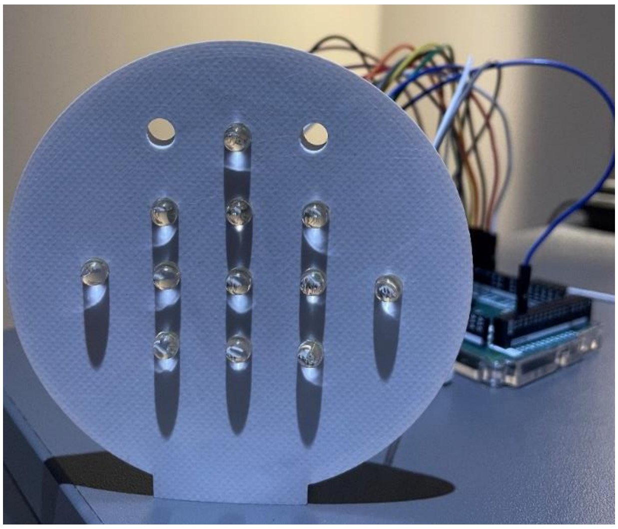


Figure 3.5.2: LEDs mounted on the showerhead

3.6 Spectrometer

To observe the results of the experiments, a Thorlabs compact CCD spectrometer with a range of 300 – 1000nm was used. Although the spectrum produced by the spectrometer does not provide any technical information about the results, it indicates the general trend which can be referred to when comparing the spectral fitting against the compliance standards. As a control, the spectrum of ambient light was first captured with the spectrometer and was compared with the commercial solar simulator provided by the NREL official website. Providing that the ambient light spectrum is the same or similar as the official version, the spectrometer can be verified that it is not faulty.

To obtain a spectrum for the results section, a software called ThorSpectra needs to be used in order to display the results. The experiment procedures only have a few steps:

1. Clip the LED solar simulator onto a stand
2. Place and aim the spectrometer input directly under the showerhead of the simulator
3. Measure exactly 10cm between the two devices

The reason for the distance of 10cm is to optimize the accuracy of the experiment and minimize indifferences between each setup. Since the showerhead corrects the direction of the LEDs, they should all be focused on the same point. On ThorSpectra, the “Auto setup” under the tab of instrument will automatically measure the time to capture a stable spectrum.

3.7 Test cell

As the last step of this project, the LED solar simulator was tested with a reference test cell in the solar lab. The purpose of this experiment was to identify the power and efficiency of the simulator. There are various ways to find power but the least complex one was to use the reference cell due to the ability to directly give a value in suns.

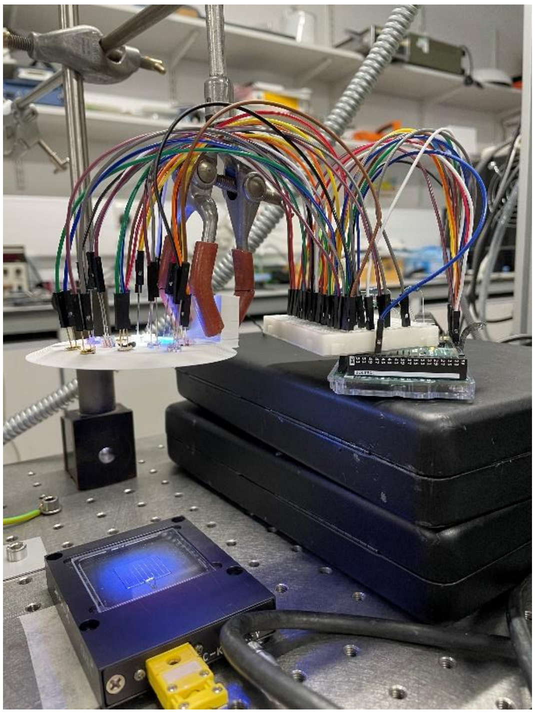


Figure 3.7.1: reference cell used to test the simulator

Figure 3.7.1 shows a picture of the reference cell being placed underneath the simulator with the lights shining on it. The same steps were utilized as the spectrometer experiment, having 10cm between the cell and the showerhead. The cell is connected to an LCD screen that displays the value of power in terms of suns, which is 100mW/cm^2[13]. The reference cell is able to not only measure the irradiance of the solar simulator but also the temperature. The test was conducted multiple times while changing different criteria such as with and without external light in the surrounding. This was completed because when the spectrum of the LEDs was taken, the surrounding light could not be eliminated which may have slightly affected the results. The cell was also connected to a computer to analyze the data including a plot of IV curve.

Apart from the use of the computer to achieve the power, a different approach was taken to understand the power within each range of wavelengths. LEDs representing different wavelengths were turned off to read corresponding values for a specific range which should represent the percentage in the spectral fitting. However, there were some difficulties encountered which will be discussed in further detail in the results section.

3.8 Summary

As a summary for the Methodology, the individual components were explained in detail and shown how the LED Solar Simulator was created. Each approach that was taken has been mentioned without concrete results as that will be part of the results and discussion section.

4 Results and discussion

4.1 Introduction

In the results section, waveforms captured by the spectrometer will be discussed and compared. IV curves were plotted with the results output from the reference cell. For this experiment, LEDs from different ranges were measured separately in a light and dark room environment.

After comparing the LED solar spectrum with the official NREL version, the intensity of the LED spectrum will be converted to power and discussed as how accurate it fits within the official standards.

To show the inaccuracies of the spectrometers, two different versions are going to be discussed, a spectrum captured by a spectrometer with a range of 350 – 750nm and the same spectrum captured using a spectrometer with a range of 200 – 1000nm.

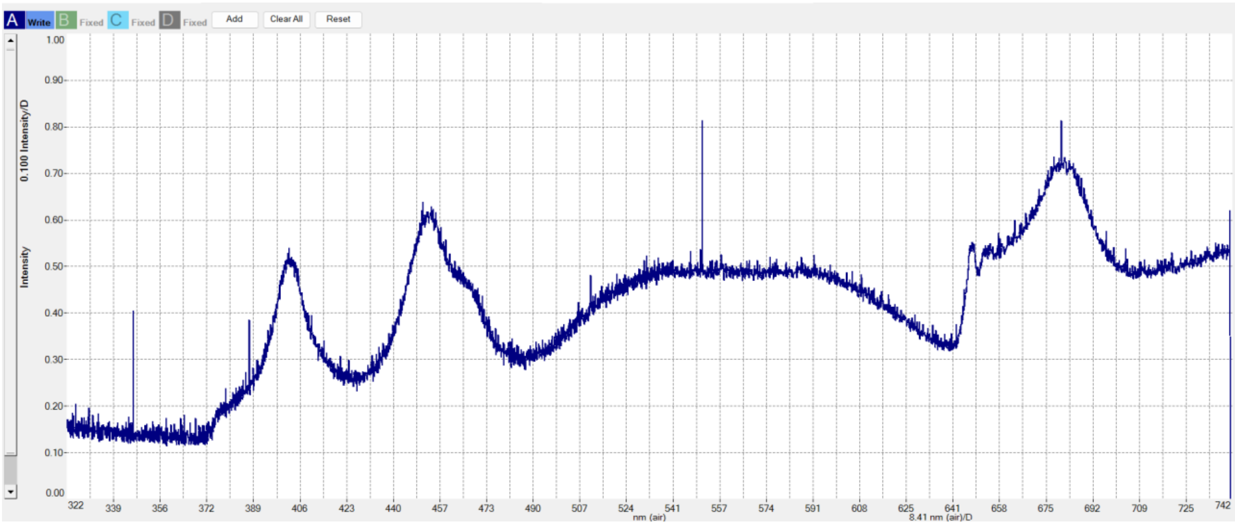


Figure 4.1.1: LED spectrum with range 350 – 750nm range

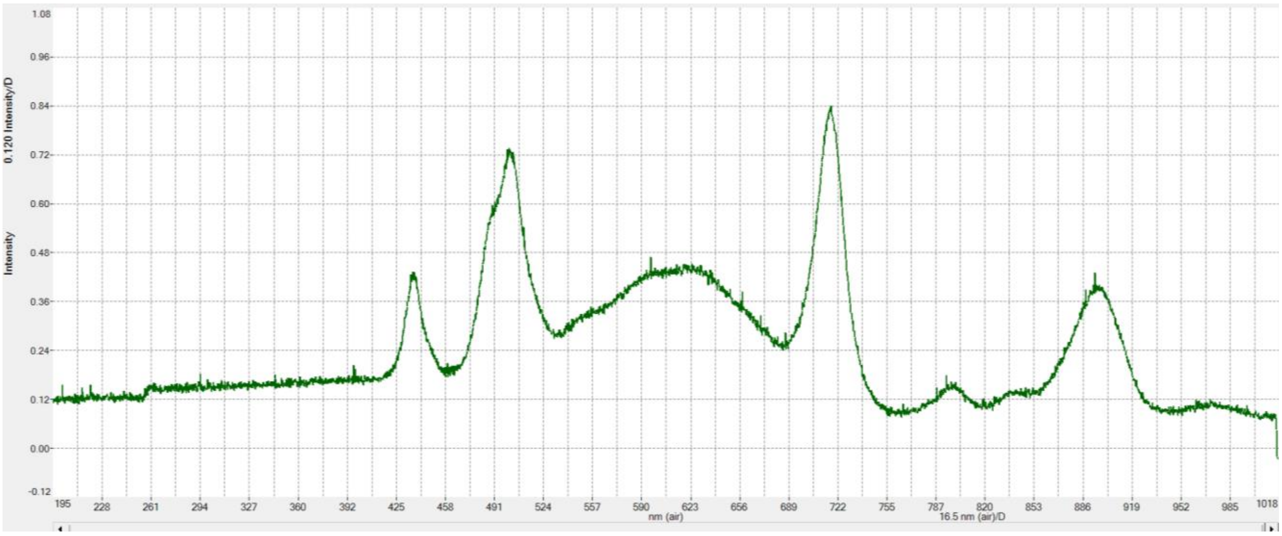


Figure 4.1.2: LED spectrum with 200 – 1000nm range

Figure 4.1.1 shows the captured spectrum using the 350 – 750nm spectrometer. For this procedure, not all LEDs were used as it would be reductant if it cannot be observed. There were in total of 6 LEDs used for this experiment including two white LEDs, 405nm, 465nm, and two 680nm. Figure 4.1.2 shows the full spectrum with all LEDs turned on. There were a few reasons why the spectrum could be different between the two figures. An obvious difference is the spike around 700nm which both have but the intensity is marginally different. These indifferences could be the cause of the spectrums' position where the focus of the LEDs is slightly different. This problem was tried to be solved by placing a piece of blank A4 paper on top of the input sensor of the spectrometer to spread out the focus of the LEDs. The results were still similar with changes in the spectrum every time the program was run.

This could become a problem when calculating the area under the graph in each wavelength range according to the spectral fitting compliance standards. Should there be a change in percentage, that could mean the spectral fitting could be wrongly classified. To solve this issue, a fiberoptic cable was used to capture a more realistic version where it is not as sensitive to ambient white light. One important variable that needs to be reiterated is to capture the spectrums in the dark because at the time of the experiment, the lab lights and curtains could not be turned off and closed, affecting the accuracy of the results. This will be mentioned in the future works section further on.

4.2 Spectral Fitting

IEC 60904-9 Compliance standards states a range of percentage for every wavelength in order to classify a solar simulator. The following table shows the results of the project, and the classification of the simulator will be explained.

Table 4.2: Spectral fitting results

Wavelength	Intensity	% of spectrum	Ideal Percentage (%)	Ratio between ideal and simulated
400 - 500nm	271.3765717	31.27808409	18.4	1.699895875
500 - 600nm	172.7555475	19.91130814	19.9	1.000568248
600 - 700nm	157.6362563	18.16870207	18.4	0.98742946
700 - 800nm	118.2215983	13.62588181	14.9	0.914488712
800 - 900nm	78.66874497	9.067133559	12.5	0.725370685
900 - 1100nm	62.89950136	7.249615839	15.9	0.455950682

From the spectrum produced by the spectrometer, the intensity of each wavelength was able to be calculated. Since the summation of all intensity was around 867.6, the percentage of the spectrum it covers can be calculated. From table 4.2, it can be analysed that the ranges of 400 – 500nm and 900 – 1100nm are not nearly as close as it should be compared to the fourth column, Ideal Percentage, which will affect the classification. According to the standards, there is an acceptable range ratio, which is what the last column is going to be compared against. The last column indicates the ratio between the percentage of the spectrum and the ideal percentage. The two ranges mentioned before are considered to be classified in Class C whereas the rest are in Class A. Overall, the spectral fitting will need some extra work to balance out the intensity or change number of LEDs used in the ranges.

One solution to this misclassification is to remove an LED within the 400 – 500nm range and buy an extra one for the 900 – 1100nm which should improve the results. The multiple white LEDs implemented in this design may also affect the results because of the spike around 500nm.

4.3 Temporal stability

As mentioned before, there are three major sections within the compliance standards to classify a solar simulator [14]. Temporal stability is given by the following equation:

$$Temporal\ Stability = \frac{Max\ Irridiance - Min\ Irridiance}{Max\ Irridiance + Min\ Irridiance} \times 100\% \qquad (4.3)$$

As the stability cannot be simulated using any equipment, for this to be achieved, two tests were required, one for short term stability and the other for long term stability. The first experiment was executed by leaving the LEDs on for 5 minutes with results taken every minute. The results for short term temporal stability were 0.337838% meaning that it is within the 0.5% requirement to be classified as Class A. For the second experiment, the LED solar simulator was left on for 2 hours and the power value was noted down every 30 minutes to see whether there would be any changes. The results showed promising with only a slight change of 0.509338% which is also within the 2% allowed range classifying it as a class A.

4.4 Spatial uniformity

The spatial uniformity could not be achieved due to the length of the project. Spatial uniformity being the hardest standard to achieve, requires the measurements of irradiance from each wavelength range of LEDs. A spectroradiometer could be used to measure the distribution of irradiance more efficiently. For this project, the uniformity will be assumed to be ideal to classify it as class A. The actual equation that needs to be used has been mentioned be fore in the literature review in equation 2.4

4.5 IV curves

IV curves were obtained as part of the testing procedure to identify the output power of the LED solar simulator. Due to different variables that may affect the results, four experiments were conducted to compare all cases, including IV curves of an ideal commercial solar simulator in the solar lab, LED solar simulator in a room with ambient light, LED solar simulator in a dark room, and a darkroom with nothing turned on.

As mentioned in the literature review, power is calculated as the product of V_{max} and the short circuit current. The equation 2.6 is reintroduced below:

$$Output\ power = V_{maxpp} \times I_{sc} \tag{2.6}$$

Firstly, the commercial solar simulator results will be discussed.

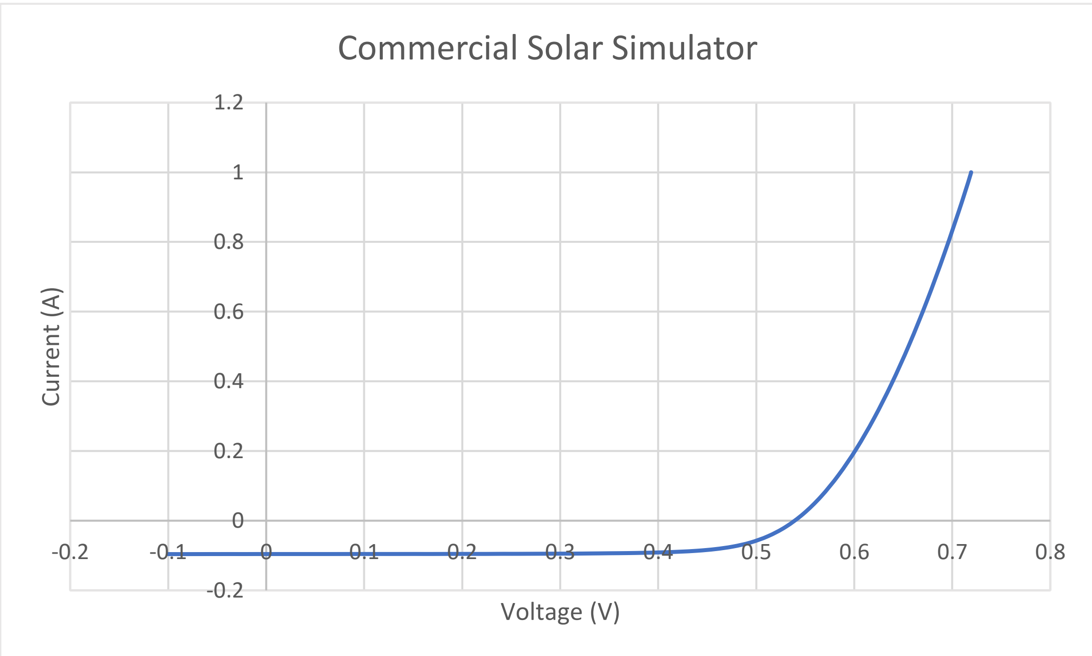


Figure 4.5.1: Commercial Solar Simulator IV curve

From the graph in Figure 4.5.1, the power can be calculated by using the equation 2.6 where the short circuit current is 0.09574 A, and the maximum voltage is 440 mV. Therefore, the output power can be calculated to be:

$$Power = 0.44 \times 0.09574 = 0.042126\ W \tag{4.5.2}$$

This cell also had an efficiency of 9.49% which can be justified because the reference cell is made from monocrystalline Silicon, which was purchased for its stability and not efficiency [15].

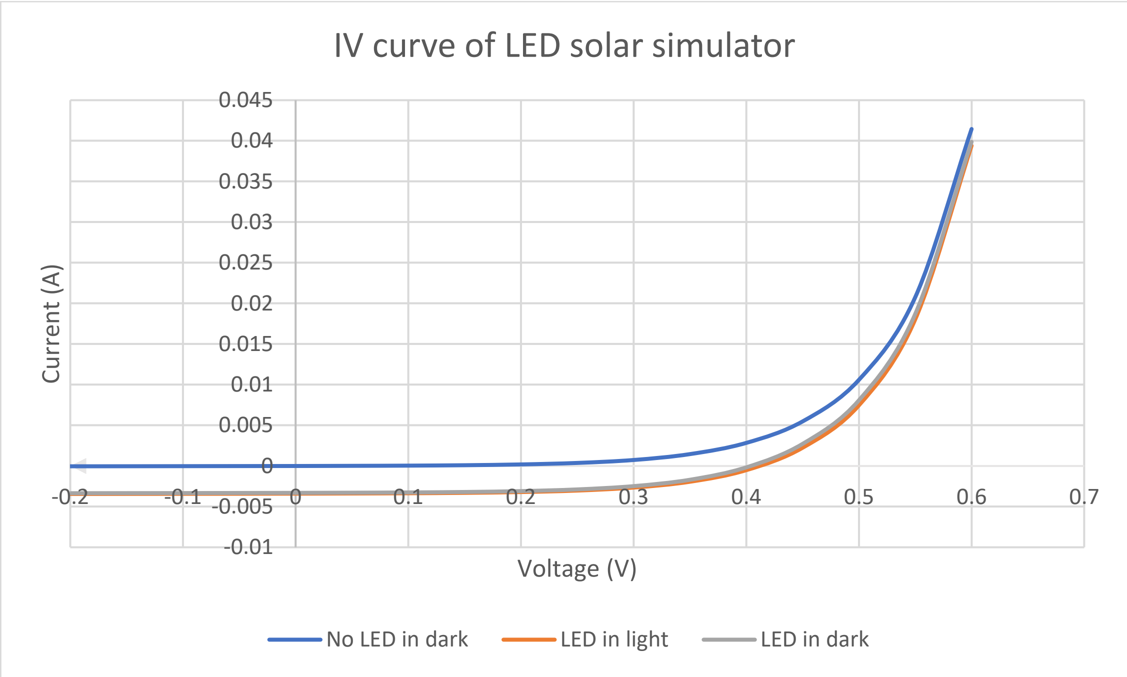


Figure 4.5.2: IV curve of LED solar simulator

In Figure 4.5.2, there are three lines shown, the LED solar simulator under room light, in a dark room, and when all LEDs were completely turned off. It can be observed when the LEDs were all turned off in a dark room, the curve behaved exactly like a silicon diode[16] with no short circuit. When there is a short circuit current going into the negative direction, it indicates that there is power generation within the diode. That is why to calculate the max power, the area under the x-axis is calculated. The difference between the LED in a room with and without light are barely visible because of the sensitivity of the reference cell. When measuring the power of the simulator, there was a small change of 0.0007 suns, which is also around a 2% difference. The Maximum power of the LED solar simulator was calculated to be 0.001021W and 0.000991W, in a room with and without light respectively.

They both had an efficiency of around 6% to 7%. The value is 3% lower than the commercial simulator because the spectrum of the LEDs does not fully represent a solar spectrum therefore the results will be affected. In order to obtain more accurate results, the spectral fitting needs to be improved as mentioned in the subsection 4.2.

The only difference when compared against the commercial solar simulator is the instantaneous power at any point. When the voltage is at 0.6V, the power for the LED version is 0.024W whereas the commercial one gives a larger value of 0.12W. A direct relationship cannot be determined as the change in gradients are different.

5 Conclusions and future work

5.1 Conclusions

An LED solar simulator was researched, designed, and developed while keeping in mind the classification requirements. A prototype was developed on a breadboard as a proof of concept which can be improved in the future. The achievement of successfully classifying the solar simulator with a class of CAA was completed through the use of a spectrometer and a 2x2cm silicon reference cell. It was identified that the spectral fitting needs slight modifications to the first and last ranges of the standards to upgrade it into a class A. The spatial uniformity has been assumed to be Class A as that would be part of the future works needed to be achieved. For the temporal stability of the solar simulator, it was classified to be class A for both short and long term stability.

After the spectrum captured by the spectrometer were shown and the indifferences were explained with some circumstances that could be improved in the future, IV curves of the commercial and LED solar simulator were then compared and analysed in different situations and the maximum power and efficiency were measured in the process.

5.2 Future work

There are many areas to further improve on this short term project. The problems encountered will be discussed first and how it could be executed in the future of this project. Firstly, the LED solar simulator was difficult to hold all connections in place during the testing process due to it having three pieces, the Arduino, breadboard, and the showerhead. Therefore, the first thing that needs to be accomplished is the creation of a PCB to avoid loose ends and maximize accuracy in the results. Secondly, a new showerhead should be design and printed because the one that was provided by Prof. Matthew Halsall was a general design meaning some smaller sized LEDs would slip out. A customized showerhead would be ideal for a project that requires all LEDs to be in place during the experiments. Thirdly, if time constrain was not an issue, a black box could be created to contain the solar simulator and the testing devices to maintain a dark room environment at all times. This was an issue that was unavoidable during the lab sessions in the Dry labs as there were more people in the room.

In terms of the physical design of the simulator, a more powerful microcontroller that allows higher current in each output PWM port would be ideal. The Arduino Mega 2560 has a limit of 200mA in total which restricts the current to as low as around 18mA per port for 11 LEDs. A PWM servo board could be considered for the future. To further improve the spectral fitting process, an interface could be designed and created to automize the adjustment of brightness. Once the interface has been created, it would make the reclassification process more efficient. The spatial uniformity is also a very important section to focus on in the future as it is a crucial box to tick.

References

[1] M. B. Gallagher, "The race to develop Renewable Energy Technologies," MIT News | Massachusetts Institute of Technology, (2019).

[2] L. Beshilas, "Floating solar photovoltaics could make a big splash in the USA," NREL.gov, (2019).

[3] M. Tawfik, X. Tonnellier, and C. Sansom, "LIGHT SOURCE SELECTION FOR A SOLAR SIMULATOR FOR THERMAL APPLICATIONS: A REVIEW," Cranfield University, (2018).

[4] A. Chapman, "LED solar simulators: Benefits vs. traditional technologies," Prophotonix, (2015).

[5] I. Electric, "Central Automotive Products Ltd. Solar simulator," IWASAKI ELECTRIC CO., LTD., (2017).

[6] N. Corporation, "Solar simulator standards – definitions & comparisons," Newport, (2022).

[7] NREL, "Reference Air Mass 1.5 Spectra," www.nrel.gov, (2022)

[8] Arduino, Arduino Mega 2560 rev3. Available: https://store.arduino.cc/collections/boards/products/arduino-mega-2560-rev3, (2023)

[9] Atmel, "Atmel ATmega640/V-1280/V-1281/V-2560/V-2561/V-Datasheet_02/2014", Atmel, (2014).

[10] J. Heath, "PWM: Pulse Width Modulation: What is it and how does it work?", Analog IC Tips, (2017).

[11] Digikey, "The Fundamentals of Digital Potentiometers and How to Use Them," www.digikey.com.

[12] Carolinastaff, “Detecting IR Light with a Smart Phone,” Carolina Knowledge Center, (Dec. 10, 2020).

[13] G. Optics, “What is the Calibrated Output Spectral Irradiance for a Solar Simulator?”, G2V Optics Inc., (Mar. 03, 2022).

[14] “Technical Note: Solar Simulator Standards – Definitions and Comparisons,” www.newport.com.

[15] R. H. Plante, “Chapter five - Solar Photovoltaic Systems,” ScienceDirect, (Jan. 01, 2014).

[16] Prof M.P.Halsall, “Laboratory 2 –Solar Cells”, University of Manchester, (Nov, 2022)

[17] enlijoseph, “Solar Simulator- Basic Knowledge and Working Principles Solar Simulator- Basic Knowledge and Working Principles» We Enlighten Your Ideas!”, enlitechnology.com, (Mar. 02, 2022).

[18] “Cost-effective and Smart AAA-Class RGB-LED-based Sun Simulator for Real-Time Characterization of Solar Cells,” www.researchsquare.com, (Sep. 01, 2022).

[19] E. López-Fraguas, J. M. Sánchez-Pena and R. Vergaz, "A Low-Cost LED-Based Solar Simulator," in IEEE Transactions on Instrumentation and Measurement, vol. 68, no. 12, pp. 4913-4923, (Dec. 2019), doi: 10.1109/TIM.2019.2899513

Appendices

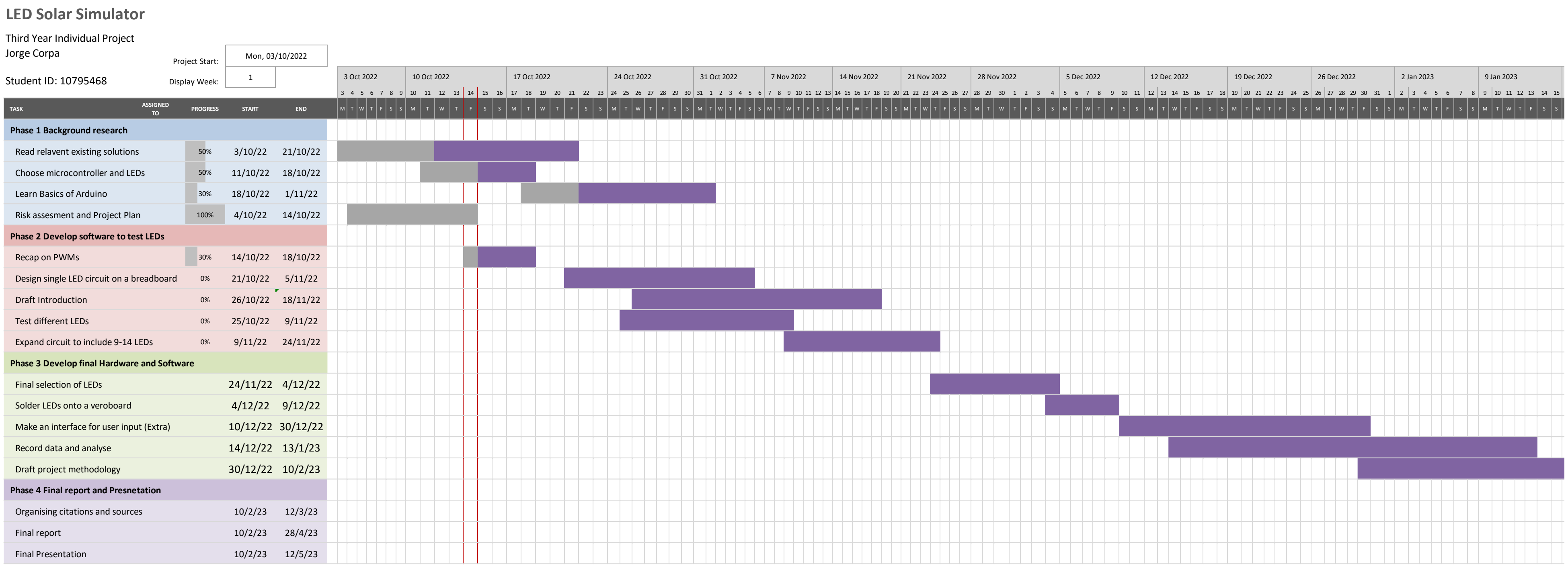
A Project outline

According to the European space agency, Solar PV and wind energy are going to be one of the largest sources of energy to power the earth. To test the PV panels, they need to be illuminated by a specific areal power density of sunlight. A solar simulator would accommodate the fact that the sun cannot constantly provide the same amount of power density. LEDs can be used to create a relatively accurate solar simulator while keeping the costs low. The spectrum that can be simulated is roughly between 380 – 780nm with a variety of coloured LEDs lined up. The project will require the use of a microcontroller to control the light intensity of each individual LED by changing the duty cycle of the on/off time (PWM). The first step is to understand existing solutions on the market and choose a microcontroller that can power 9-15 LEDs at once. After that, a circuit should be built to test individual LEDs before running them all together. This will also require the making of a Veroboard and application shield if needed.

Currently, I have chosen to use the Arduino Mega 2560 since it has 14 PWM output pins instead of using a 16 channel PWM servo/driver board. On Thorlabs, there are large amounts of LEDs, and the next step is to select the potential ones and go through the data sheet to understand the characteristics and constraints of each LED before deciding which ones to buy.

Through this project I wish to familiarise myself with Arduino and the control of LEDs though PWM. Hopefully by the end of the project I would have finished the tests and made improvements such as 3D printing a case for the LEDs and an application shield for the Veroboard or PCB that will be made.

Below is a screenshot of the GANNT chart which includes all dates and objectives of the projects.



The GANTT chart is split into 4 big sections including background research, Development of software to test LEDS, Development of final hardware and software, and the Final report and presentation. Under each section there are three to four sub sections to break the task down. It has a timeline for all subtasks to make sure I have enough time to finish the project in time. Phase 1 and Phase 2 are to research and test that the system I am creating works then in phase 3 and 4, the actual model will be built, and results can be analysed. The final part consists of the final report writing and final presentation.

B Risk assessment

Date: (1) 14/10/2022	Assessed by: (2) Prof Matthew Halsall	Checked / Validated* by: (3)	Location: (4) Alan Turing Building	Assessment ref no (5)	Review date: (6) 18/10/2022
Task / premises: (7) Building an LED solar simulator which will consist of hardware and software development.					

Activity (8)	**Hazard** (9)	**Who might be harmed and how** (10)	**Existing measures to control risk** (11)	**Risk rating** (12)	**Result** (13)
Soldering	Burning the person using the soldering iron. Excessive smoke coming out of the soldering iron.	The person using the soldering iron. The lab supervisor.	There is an extraction fan to eliminate the excessive smoke. There are courses and lab rules on how to use the soldering iron which were taught in year one.	Low	
Electricity Plug voltage	There might be the chance of getting electrocuted when touching the components being powered.	The person conducting the experiments with the PCB.	Make sure to turn off the power supply before touching any component.	Low	

Activity (8)	**Hazard** (9)	**Who might be harmed and how** (10)	**Existing measures to control risk** (11)	**Risk rating** (12)	**Result** (13)
Using UV and IR LEDs	Excessive exposure to UV and NIR	The person conducting the experiments with the LEDs. Supervisor that is checking the function of LEDs. Anyone directly looking into the LEDs might be exposed to UV.	Wear anti UV glasses to keep eyes protected from the harmful UV light.	Medium	
Laptop breaking	Software is developed on the laptop and there might be a risk of the laptop breaking	The laptop owner risking losing all data that has been recorded.	Always remember to have backups on another laptop or saved on a cloud drive.	Low	

Activity (8)	Hazard (9)	Who might be harmed and how (10)	Existing measures to control risk (11)	Risk rating (12)	Result (13)
Burning components on the Veroboard	When testing, power supply might be used therefore any excessive power being supplied might burn the components.	The person conducting the experiment with the Veroboard. The lab supervisor when trying to help.	Double check the components are placed right if they are polarized before turning on the power supply.	Low	

Action plan (14)				
Ref No	**Further action required**	**Action by whom**	**Action by when**	**Done**
	Backup stored data onto cloud drive every week	Jorge Corpa	Every week, 21/10/2022	

C. Arduino code

Blink Test:

```
int pwmPinW7E = 2;
int pwmPin680 = 3;
int pwmPin940 = 4;
int pwmPin405 = 5;
int pwmPin465 = 6;
int pwmPin680_2 = 7;
int pwmPin760 = 8;
int pwmPin800 = 9;
int pwmPin840 = 10;
int pwmPin870 = 11;
int pwmPin910 = 12;
int pwmPinW7E_2 = 13;


void setup() {
 pinMode(pwmPinW7E, OUTPUT);
 pinMode(pwmPin680, OUTPUT);
 pinMode(pwmPin940, OUTPUT);
 pinMode(pwmPin405, OUTPUT);
 pinMode(pwmPin465, OUTPUT);
 pinMode(pwmPin680_2, OUTPUT);
 pinMode(pwmPin760, OUTPUT);
 pinMode(pwmPin800, OUTPUT);
 pinMode(pwmPin840, OUTPUT);
 pinMode(pwmPin870, OUTPUT);
 pinMode(pwmPin910, OUTPUT);
 pinMode(pwmPinW7E_2, OUTPUT);
}
void loop() {
  for(int value = 0; value<=255; value++){
    analogWrite(pwmPinW7E, value);
    analogWrite(pwmPin680, value);
    analogWrite(pwmPin940, value);
    analogWrite(pwmPin405, value);
    analogWrite(pwmPin465, value);
    analogWrite(pwmPin680_2, value);
    analogWrite(pwmPin760, value);
    analogWrite(pwmPin800, value);
    analogWrite(pwmPin840, value);
    analogWrite(pwmPin870, value);
    analogWrite(pwmPin910, value);
    analogWrite(pwmPinW7E_2, value);
    delay(10);
    }
  delay(10);

for(int value = 255; value>=0; value--){
    analogWrite(pwmPinW7E, value);
    analogWrite(pwmPin680, value);
    analogWrite(pwmPin940, value);
    analogWrite(pwmPin405, value);
    analogWrite(pwmPin465, value);
    analogWrite(pwmPin680_2, value);
    analogWrite(pwmPin760, value);
    analogWrite(pwmPin800, value);
    analogWrite(pwmPin840, value);
    analogWrite(pwmPin870, value);
    analogWrite(pwmPin910, value);
    analogWrite(pwmPinW7E_2, value);
    delay(10);
    }
  delay(50);
}
```