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Bachelor of Science in
Electrical Services and Energy Management

The Enablement of a Comparative Performance Analysis of Cadmium Telluride Photovoltaic Cells

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DECLARATION

I hereby certify that the material, which is submitted in this assignment/project, is entirely my own work and has not been submitted for any academic assessment other than as part fulfilment of the assessment procedures for the program Bachelor of Science in Electrical Services Engineering and Energy Management (BSc) (DT 712/4).

Signature of student:………………………………

Date:………………..

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ABSTRACT

Solar energy is becoming increasingly important as alternative sources of electrical power. Photovoltaic Cells are electrical devices that convert light energy (solar energy) into electrical energy by the by means of the photovoltaic effect. Cadmium Telluride Photovoltaic cells are an integral part of solar energy. One of the fundamental factors affecting the highest achievable efficiency of PV technologies is the limited spectral response of Photovoltaic cells.

The potential exists to increase photovoltaic cells efficiency by making better use of short wavelength light by altering the makeup of the photovoltaic Cells. This alteration is achieved by means of Luminescent Down-Shifting (LDS), which can increase the efficiency of the photovoltaic cells. Luminescent Down-Shifting is an optical approach to increase photovoltaic cells ultra-violet response by shifting short wavelength light to longer wavelengths where the external quantum efficiency of photovoltaic cells are higher.

Cadmium Telluride Photovoltaic cells inefficiently absorb ultra/violet high energy light. Luminescent down shifting involves the absorption of ultra/violet energy light and reemitting it as low energy light (better matching the spectral response of the CdTe PV cell). This Low energy light is more efficiently absorbed by the Cadmium Telluride photovoltaic cells. This conversion of light changes the performance characteristics of the Photovoltaic cells and makes them more efficient.

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Glossary of Terms

A-Si	Utilizing Amorphous-Si
Cdte	Cadmium Telluride
Cm^2	Centimeter Squared
Co2	Carbon Dioxide
C-Si	Single Crystalline
EQE	External Quantum Efficiency
FF	Fill Factor
Imp	Maximum Power Current
Isc	Short-Circuit Current
Kg	Kilogram
Kwh	Kilo Watt Hour
Lds	Luminescent Down Shifting
M^2	Metre Squared
M3	Metre Cubed
Ma	Milliamps
Mc-Si	Multi-Crystalline Silicon
Mm	Millimeter
Mpp	Maximum Power Point
Mw	Milliwatt
Pmma	Dye-Poly Methyl Methacrylate
P-Si	Polycrystalline-Si
Pv	Photovoltaic
Std	Standard Test Conditions
V	Voltage
Vmp	Maximum Power Voltage
Voc	Open-Circuit Voltage
W/M^2	Watt Per Metre Squared
%	Percent

1 Introduction

1.1 Introduction

In this dissertation, the author Mark Gleeson and PhD student Hind Ahmed did a comparative performance analysis of Cadmium Telluride (CdTe) photovoltaic (PV) cells. The purpose of this project is to evaluate how different CdTe PV cells behave under certain test conditions. This involves the introduction of luminescent down shifting (LDS) to a number of CdTe PV cells and comparing them to a reference CdTe PV cell. The concept of this dissertation is to provide indoor test conditions and a real life analysis of the electrical behavior, performance and characterization of Cadmium Telluride photovoltaic Cells.

The prime focus of this dissertation is comparison of data taken with the same setup but under different experimental condition. This dissertation aimed to analyse the main issues raised by the measurement of CdTe PV cells and review the different variables affecting performance and measurements. This project is located on the roof of DIT Kevin St building in the South-East Inner City of Co Dublin. The location was evaluated to insure that the CdTe PV cells were installed at the correct orientation, azimuth angle and the inclination for this location.

Two advanced Solar Power S1 Series CdTe PV cells were installed on a south facing frame at a 53° angle. One of the CdTe PV cells is the reference CdTe PV cell and the other CdTe PV cell has a LDS layer applied to it. Five smaller advanced Solar Power S1 Series CdTe PV cells were installed horizontal to the roof facing up at a 0° angle. One of the smaller CdTe PV cells is the reference CdTe PV cell and the other four CdTe PV cells had LDS layers applied to them.

The luminescent down shifting layers were made using a host material (PMMA) and two different organic dyes Lumogen yellow 083 and Lumogen Violet 570. Three different organic dye LDS layers were made for this dissertation. The first LSD layer was made using Lumogen yellow 083, the second LSD layer was made using Lumogen Violet 570 and the third LSD layer was made using a mixture of Lumogen yellow 083 and Lumogen Violet 570.

All the CdTe PV cells were wired individually back to a data logger. This was done to give a better analysis of their individually performance and a better understanding of their electrical behaviour. The data logger recorded their respective characteristics every 15 seconds. The data logger was connected to a Labview useable interface, the program displayed the IV and PV curve for the cells, the Fill factor, open circuit voltage, short circuit current, maximum power point, maximum power current and maximum power voltage.

1.2 Aim

The fundamental aim of this dissertation is to achieve indoor test conditions and a real life test conditions to enable a comparative performance analysis of Cadmium Telluride photovoltaic cells with the introduction of luminescent downshifting.

1.3 Objectives

The main research questions and propositions that the author is putting forward in this dissertation are as follows:

- Does Luminescent Down-Shifting have the potential to increase the efficiency of Cadmium Telluride photovoltaic cells?
- Review the fundamental principles and operation of Cadmium Telluride Photovoltaic Cells.
- Review the fundamental principles and operation of luminescent downshifting.
- Test the absorption and emission of the luminescent downshifting layers.
- To determine how the photovoltaic cells have performed in terms of energy production and efficiency
- To determine the CdTe PV cells electrical behaviour, performance and characterization of CdTe PV cells in indoor test conditions.
- To determine the CdTe PV cells electrical behaviour, performance and characterization of CdTe PV cells on the Kevin St building.
- Compare the results of the indoor tests to the real life conditions.
- Determine if the introduction of luminescent downshifting can increase the efficiency of CdTe PV cells.
- Evaluate which Organic dyes luminescent downshifting layers perform best.

The fundamental objectives of this dissertation are to compare the electrical behaviour, performance, and provide a characterization of CdTe PV cells in five different physical states.

To compare the CdTe PV cells in their normal state to the CdTe PV cells with the addition of luminescent down shifting placed on top of the cells.

The potential remains to increase cell efficiency by making better use of short wavelength light. One way to do that is to improve the electric properties of the CdTe PV cells. One of the aims of this dissertation is to try improving the cell efficiency.

Various tests were carried out on the status of the CdTe PV cells in two separate operating conditions. These conditions will include various temperature and weather conditions. These tests are essential to provide information on the conditions where CdTe PV cells perform at their best efficiencies and worst efficiencies. This will provide information on what weather conditions the CdTe PV cells performed best.

2 Overview

2.1 Introduction

The introduction chapter provides some background information on the dissertation and on the aim of the dissertation.

2.2 Literature Review

This section lays out the information gathered on Cadmium Telluride photovoltaic cells and luminescent downshifting the research stage of this dissertation, which was carried out to meet the objective of this dissertation, ‘A Comparative Performance Analysis of Cadmium Telluride Photovoltaic Cells’

2.3 Method

This section describes the procedure used to meet the objectives of the dissertation.

2.4 Data Collection

This section describes the procedure of collecting and recording the data.

2.5 Results and Analysis

This section describes the results and analysis of the data that was collected during this dissertation.

2.6 Conclusion

This section is a summary of the dissertation.

2.7 Further Research

This section details the areas, which should be considered in future research by others researchers.

3 Literature Review

3.1 Introduction

In principle the PV cell converts incident sunlight directly into electricity by a process known as the photovoltaic effect (Nelson, 2003)

The sun provides the earth with enough energy in one hour to satisfy a year's worth of the world's energy needs. This energy is readily available and gives us a way to create electricity and heat without emitting carbon dioxide, which is one of the main causes of climate change. Depending on the time of day and the geographical location, on average every square meter of the earth's surface that is exposed to direct sunlight can receive about 1000 watts of energy from the sun's light.

(Center, 2014)

The technology is available to take advantage of the sun's energy. Unfortunately, this technology is expensive. Currently solar energy can be up to five times more expensive as energy we get from fossil fuels.

"To reduce that price we need to make good research and policy decisions for solar technology right now," (Center, 2014) These decisions will shape the future of solar power. To make intelligent choices, we need to understand present-day solar energy technology, estimate how it will advance, and then make the best judgment we can. (Center, 2014)

This section contains the relevant information found during the research stage of this dissertation. The purpose of this literature review is to examine literature related to Cadmium Telluride Photovoltaic Cells. However there are a number of different areas that need to be addressed and analyzed as separate topics.

These topics include

- A historic review of Cadmium Telluride Photovoltaic Cells.
- The fundamental principles and operation of Cadmium Telluride Photovoltaic Cells.
- The characteristics of Cadmium Telluride Photovoltaic Cells.
- A historic review of luminescent down-shifting
- The fundamental principles of luminescent down-shifting

For the most part, the information was gathered from textbooks, journals and websites which provide good, non-bias information which is peer-reviewed and well established, through peer-review.

3.1.1 First History Review

Adolf Goetzberger (2002) highlights that the history of CdTe-based cells is a story about an adventurous search for the appropriate structure on a track full of obstacles and traps. The first attempts at the RCA Labs, were made with CdTe single crystals. Indium was alloyed into n-type CdTe crystals resulting in an alloy-type pn-junction with 2.1% conversion efficiency.

Adolf Goetzberger (2002) Reports that at the same time, CdTe-cell efficiencies of 4% were published in the USSR.

Adolf Goetzberger (2002) Shows that Cusano reported on the first thin-film cell; he used a structure similar to the CdS cells, namely a p-Cu2Te/n-CdTe hetero junction, and succeeded in obtaining 6% efficiency, an excellent value for the first trial at that time. At this time they found problems with the CdTe-cells, they had difficulty with the doping p-type CdTe and difficulty in obtaining low-resistance contacts to p-type CdTe, and the recombination losses associated with the junction interface It wasn't till 1982 many years later till they reached 10% efficiency.

Adolf Goetzberger (2002) also reports that very thin CdS-layers, acting only as a buffer layer in the heterostructure with the transparent conductive oxide was the key to further improvements. The research groups at the National Renewable Laboratory and at the University of South Florida are those having pushed the efficiency to the range of 16%.

(Adolf Goetzbergera, 2002)

Adolf Goetzberger's research shows that the efficiency of the CdTe PV cells started out at extremely low efficiencies. Adolf Goetzberger explains that the CdTe PV cells were been tested in various parts of the world and in each location the results were different. Adolf Goetzberger states that the CdTe PV cells efficiencies didn't reach 10% until 1982 which was many years after the first tests began. He shows that vast improvements were made on the efficiencies after 1982.

3.1.2 Second History Review

Adolf Goetzberger and Christopher Hebling (2000) reports the first solar cell developed at Bell Laboratories in 1954 photovoltaic's was dominated by silicon.

Crystalline silicon today has a market share of 86%, which is almost equally distributed between single crystal and cast silicon. Amorphous silicon has another 13%. The main endeavour is to reduce cost. Other future possibilities include thin film crystalline silicon on deferent substrates. This is because of the low absorption coefficient of silicon light trapping is required. Amorphous silicon, copper indium diselenide (CIS) and CdTe cell are hopeful approaches for very cost-effective solar cells.

Adolf Goetzberger and Christopher Hebling (2000) highlights that CdTe is close to an ideal photovoltaic material with respect to its physical properties. It has a band gap close to the optimum and it is very easy to handle in thin deposition. Laboratory cells have already reached efficiencies over 16%. One major drawback is the high content of cadmium which gives rise to environmental concerns. It remains to be seen if the customers accept this product. Two companies are presently installing module production capacities of 10MW each.

(Adolf Goetzberger, 2000)

Adolf Goetzberger and Christopher Hebling research shows that PV cells have been in production since 1954 and they were dominated by silicon. Adolf Goetzberger and Christopher Hebling also state that there is a large market for CdTe cells. As the cells are more cost effect there market potential will Increase because they are an ideal material apart from the cadmium because it causes a risk for the environment.

3.1.3 Third History Review

Vasilis M. Fthenakis (2003) States that CdTe cells are manufactured from pure Cadmium and Tellurium. They are both by-products of smelting prime metals. Cadmium is generated as a byproduct of smelting zinc ores (80%), lead ores (20%), and to lesser degree of copper ores. Tellurium is a by-product of refining copper. Tellurium is a rare metal used in manufacturing photosensitive materials and catalysts.

Currently, high purity Cd and Te are used in synthesizing high purity (five 9s to six 9s) CdTe for PV cells. CdTe is produced from Cd and Te powder via proprietary methods. CdTe is produced in small amounts for detectors and photovoltaic's.

Reportedly, 100% of the feedstock is used and there are no quantifiable emissions during CdTe formation. The electrolytic purification does not produce any emissions and all waste is recycled. The melting and atomization steps necessary to form the

powder emit about 2% of the feedstock which are captured by HEPA filters. Milling produces some undesirably large particles, which are recycled into the process. (Fthenakis, 2003)

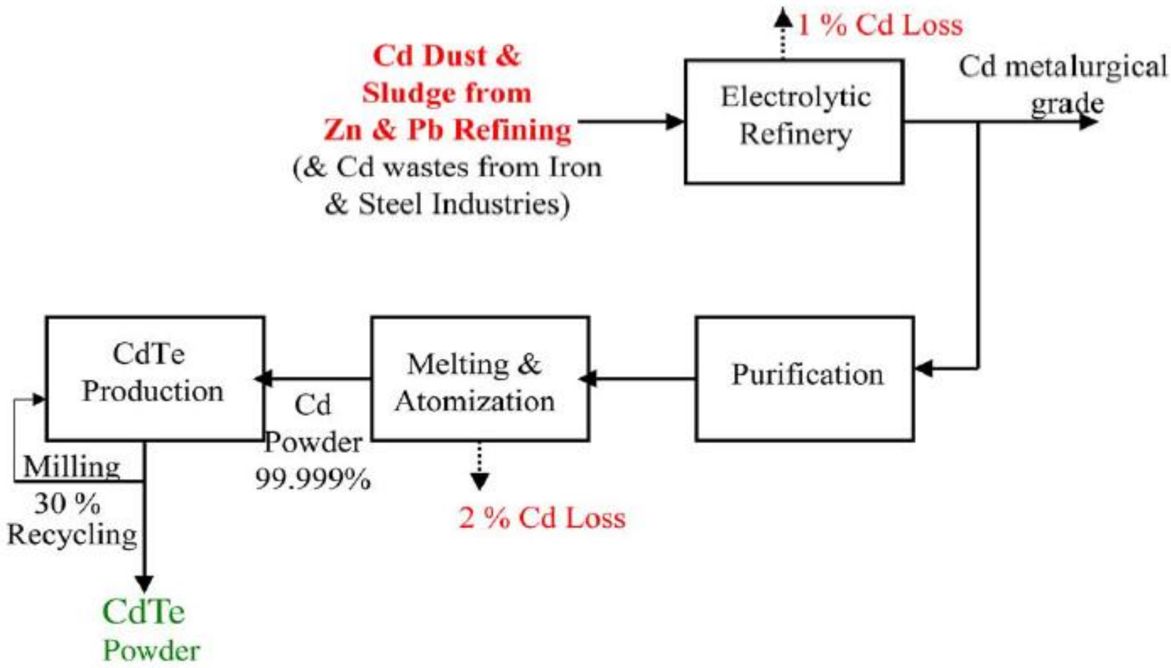

Figure 1 Production of CdTe from cadmium and tellurium

(Fthenakis, 2003)

Vasilis M. Fthenakis research shows the manufacturing process from pure Cd and Te to CdTe cells. How high purity Cd and Te are used in synthesizing high purity before it is produced from Cd and Te powder and that here are no quantifiable emissions and all waste is recycled.

3.1.4 Fourth History Review

Cadmium telluride (CdTe) photovoltaic's describes a photovoltaic (PV) technology that is based on the use of cadmium telluride thin film a semiconductor layer designed to absorb and convert sunlight into electricity. Thin-film cadmium telluride (CdTe) solar cells are the basis of a significant technology with major commercial impact on solar energy production. Large-area monolithic thin film modules demonstrate long-term stability, competitive performance, and the ability to attract production-scale capital investments. (R.Sites, 2003)

Brian E. McCandless and James R. Sites states that Cadmium telluride cell are thin film cells that absorb sunlight. This technology allows them to be commercial viable

and the technology pervades long-term stability which makes them good for investment.

3.1.5 Fifth History Review

All high-efficiency CdTe solar cells to date have essentially the same supersaturate structure as that successfully demonstrated by Bonnet and Rabenhorst in 1972. This structure is depicted in the Figure below. The alternative substrate configuration with the TCO/CdS/CdTe deposited onto an opaque substrate, has been much less successful, primarily because of poor CdS/CdTe junction quality and poor ohmic CdTe contact, resulting from chemical instability of the back contacts and from copper diffusion out of the back contact toward the CdTe surface during film growth.

The primary photodiode junction occurs between the p-type CdTe absorber and the n-CdS window layer. There are, however, a number of complicating factors, such as the need for a high-resistance oxide layer when the CdS is thin, the need for a thermal treatment with $CdCl_2$ and oxygen to improve the CdTe quality, the interdiffusion of CdS and CdTe and the barrier associated with the back contact. (R.Sites, 2003)

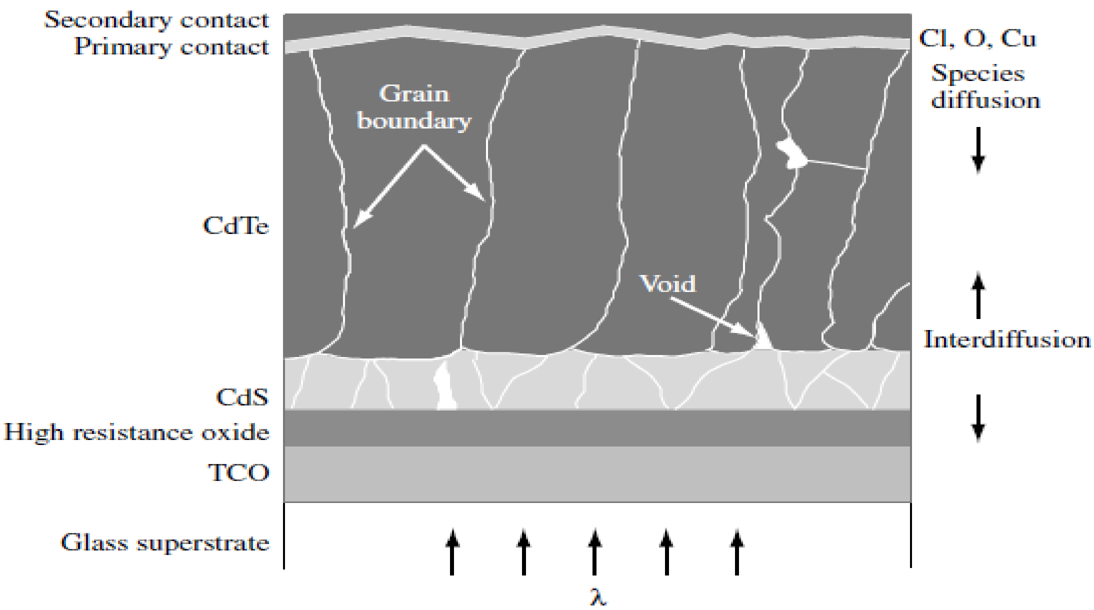

Figure 2 Basic CdTe solar cell structure

(R.Sites, 2003)

Brian E. McCandless and James R. Sites goes on to say that the CdTe solar cells have not changed since the same supersaturate structure as that successfully demonstrated by Bonnet and Rabenhorst in 1972. The figure above shows the basic CdTe solar cell structure which has been the same since 1972.

3.2 Efficiency Review

3.2.1 First Efficiency Review

The current PV market consists of a range of technologies which have been grouped from current first-generation, second-generation and third-generation technologies.

The first-generation PVs are crystalline silicon or wafer based single-junction solar cells, including single crystalline (c-Si) and multi-crystalline silicon (mc-Si). Crystalline silicon technologies constitute about 85% of the current PV market. The standard c-Si PV modules have efficiencies about 14%-16%. (SunShot, 2012) (Ahmed, 2013)

The second-generation PV was developed using thin film technologies to remove unnecessary materials cost while maintaining efficiencies of first-generation PV. The second-generation PVs are single junction devices utilizing amorphous-Si (a-Si), $Cu(In,Ga)Se_2$(CIGS), CdTe/CdS, or polycrystalline-Si (p-Si) deposited on low-cost substrates such as glass. Efficiencies of 16.5% for CdTe, and almost 20% for Cu(In,Ga) Se_2 have been reported by leading laboratories for these thin film solar cells When scaling up to larger module sizes, an efficiency of 6-9% for CdTe , 8% for a-Si and 8%-14% for CIGS modules have been reported Therefore, the expansion of second-generation PV has been lower than originally expected for the technologies. (Razykov, 2011) (SunShot, 2012) (Ahmed, 2013)

Third-generation PV devices which exceed the limitation of single junction devices and lead to ultra-high efficiency, potentially for the same production cost of first and second PV generations . The development of third-generation PV is showing rapid increase in cell efficiency. For example, an efficiency of 30.4% in double junction quantum well solar cell was demonstrated. Also a maximum of 32% efficiency for thin film GaInP/InGaAs/Ge triple-junction space PV and 41% for GaInP/InGaAs/Ge triple junction solar cell has been reported. A recent improvement to multi-junction PV cells efficiency of 43.5% has been demonstrated. (Razykov, 2011) (SunShot, 2012) (Ahmed, 2013) (Green M. , 2002) (Green M. , 2003) (Green M. , 2006) (Fraunhofer ISE, 2009)

The different authors above state that PV Cells have been grouped into a range of different technologies. These technologies have been classified as first-generation, second-generation and third-generation technologies. These classifications depend on PV cells make up and there efficiencies.

The efficiency of a solar cell is the percentage of the sun's energy striking the cell or module that is converted into electricity. Thin-film cells have lower DC efficiencies than c-Si modules, about 9%–12% for CdTe, 6%–9% for a-Si, and 8%–14% for CIGS. CdTe-based PV has experienced significantly higher market growth during the last decade than the other thin-film PV technologies primarily due to the success of First Solar, which utilizes CdTe technology. The performance of PV technologies has improved substantially, while PV manufacturing costs have declined during the past several decades due to a combination of technological innovation, improved manufacturing processes, and growing PV markets. (SunShot, 2012)

The figure below shows the increase in laboratory best-cell efficiencies by PV technology over the past few decades. These are laboratory prototype cells, developed through successful R&D. A number of challenges such as simplifying or modifying cell properties to improve manufacturability and economics must be overcome before laboratory cell innovations lead to improvements in commercial products. Some cell efficiency improvements are simply too expensive to implement at the commercial scale. Further challenges are encountered as small cells are linked together (e.g., c-Si or flexible thin film on metal substrate) or made in much larger areas (e.g., thin films) and then encapsulated to form commercial modules. Commercial module efficiencies typically track best-cell efficiency improvements, with a time and performance lag. (SunShot, 2012)

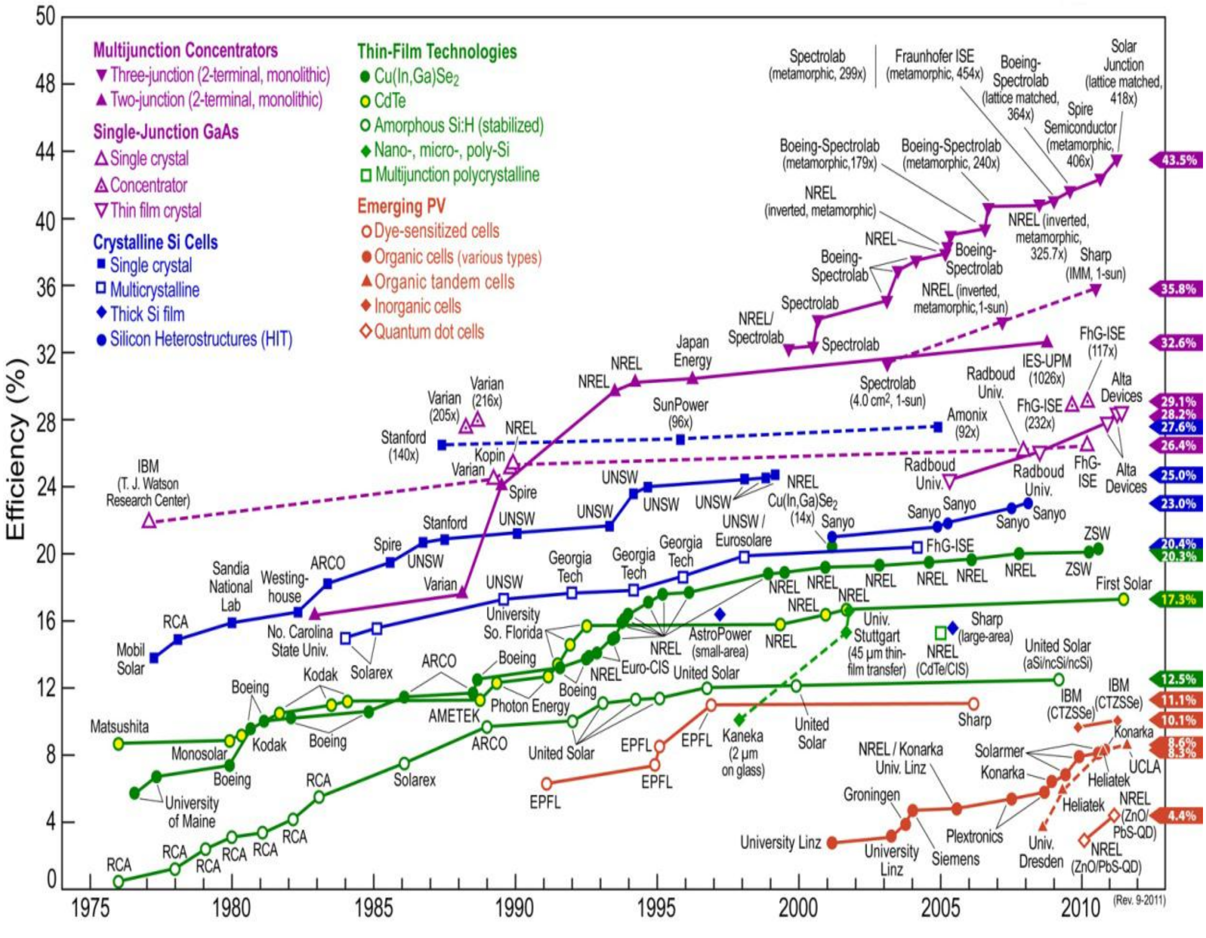

Figure 3 Laboratory Best-Cell Efficiencies for Various PV Technologies

(Razykov, 2011) (SunShot, 2012)

The different authors above explain efficiency of a solar cell is the percentage of the sun's energy striking the cell. They state that Thin-film cells such as CdTe cell have lower DC efficiencies than c-Si cells. CdTe cells are 6%–9% efficient compared to than c-Si cells which are 9%-12%. CdTe-based PV cells have experienced significantly market growth in recent years due to improvements in the production of CdTe PV cells. The figure above shows how the different PV cells on the market have improved their efficiencies over the past thirty years.

3.2.2 Second Efficiency Review

Currently the record value for CdTe solar cells is 19.6%. This rapid advancement was mainly achieved by minimizing optical losses in the window layers in order to improve the current density of the solar cells. The reported fast improvements in efficiency as well as the recently announced solar technology partnership between First Solar R&D and GE Global Research provide good reasons that efficiencies

above 20% might soon be possible. Besides the development of CdTe solar cells on rigid glass substrate scribed above, some deposition methods have been used to develop solar cells on flexible and light weight substrates. Replacement of the rigid glass by flexible materials requires the substrate to be resistant to processing temperature and to be sufficiently transparent for solar cells growing the conventional supersaturate configuration. Solar cells with efficiency up to 13.8% were achieved on flexible polyimide film and an 8.0% efficient mini-module was presented. For high temperature grown CdTe solar cells, flexible glass can be used and efficiencies up to 14.0% were achieved. An alternative approach is to reverse the layer order and to produce CdTe solar cells in substrate configuration, which allows the use of opaque substrates like flexible metal foil. Recent efficiency improvement in this configuration has resulted in 13.6% and 1.5% on glass and flexible metal foil, respectively, with large potential to further improve efficiency. (Lukas Kranz n, 2013)

Lukas Kranz n, Stephan Buecheler, AyodhyaN.Tiwari states that 19.6% is the highest recorded efficiency for a CdTe cell. This was achieved by minimizing optical losses in the window layers. The authors also state that efficiencies above 20% are possible. Different methods have been tried to improve the efficiency but no further improvement was made. This shows that there is potential for improvement and one way to improve the efficiency could be luminescent down-shifting which this project aims to do.

3.2.3 Third Efficiency Review

The efficiency is the most commonly used parameter to compare the performance of one solar cell to another. Efficiency is defined as the ratio of energy output from the solar cell to input energy from the sun. In addition to reflecting the performance of the solar cell itself, the efficiency depends on the spectrum and intensity of the incident sunlight and the temperature of the solar cell. Therefore, conditions under which efficiency is measured must be carefully controlled in order to compare the performance of one device to another. The efficiency of a solar cell is determined as the fraction of incident power which is converted to electricity and is defined as:

- Max Power = Voc x Isc x FF

- Efficiency = $\frac{\text{Voc x Isc x FF}}{Power\ in}$

1) Where Voc is the open-circuit voltage
2) Where Isc is the short-circuit current
3) Where FF is the fill factor

The IV curve of a solar cell is the superposition of the IV curve of the solar cell diode in the dark with the light-generated current. The light has the effect of shifting the IV curve down into the fourth quadrant where power can be extracted from the diode. (PVEducation, 2014)

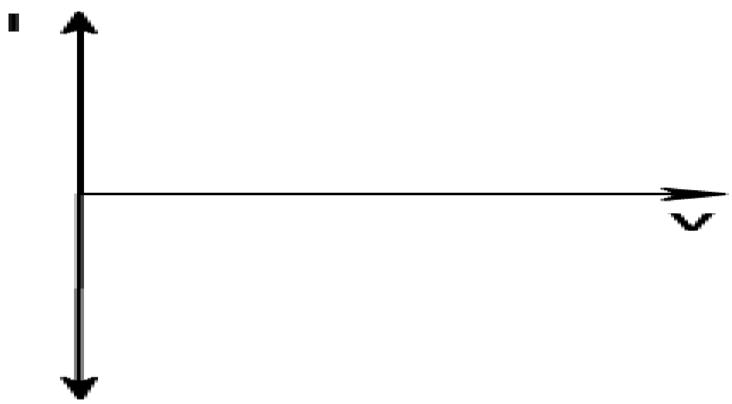

Figure 4 Current I - Voltage V

(PVEducation, 2014)

3.2.4 The short-circuit

The short-circuit current is the current through the solar cell when the voltage across the solar cell is zero (when the solar cell is short-circuited).
(PVEducation, 2014)

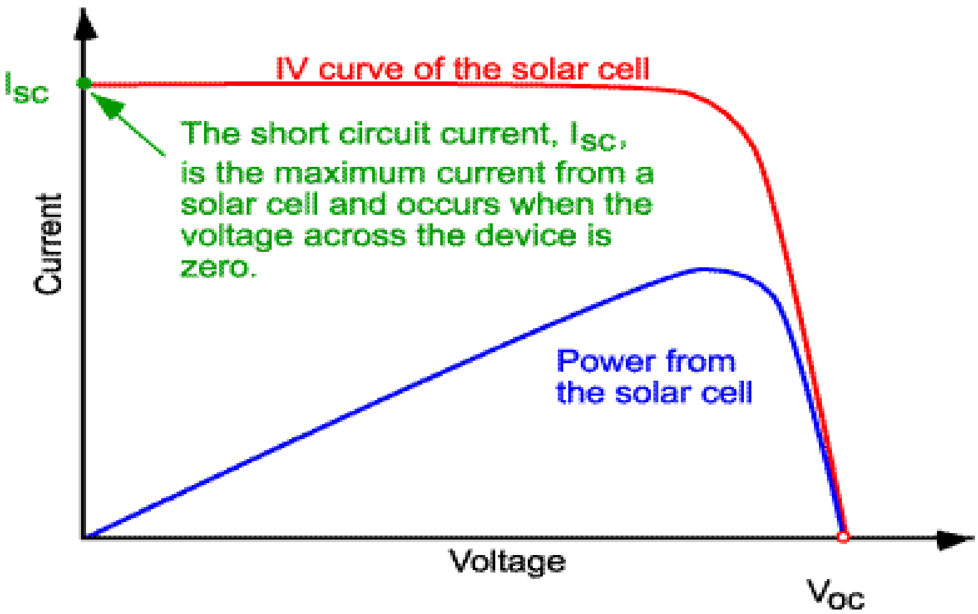

Figure 5 IV curve of a solar cell showing the short-circuit current

(PVEducation, 2014)

The short-circuit current is due to the generation and collection of light-generated carriers. For an ideal solar cell at most moderate resistive loss mechanisms, the short-circuit current and the light-generated current are identical. Therefore, the short-circuit current is the largest current which may be drawn from the solar cell.

3.2.5 The open-circuit voltage

The open-circuit voltage, VOC, is the maximum voltage available from a solar cell, and this occurs at zero current. The open-circuit voltage corresponds to the amount of forward bias on the solar cell due to the bias of the solar cell junction with the light-generated current. The open-circuit voltage is shown on the IV curve below.

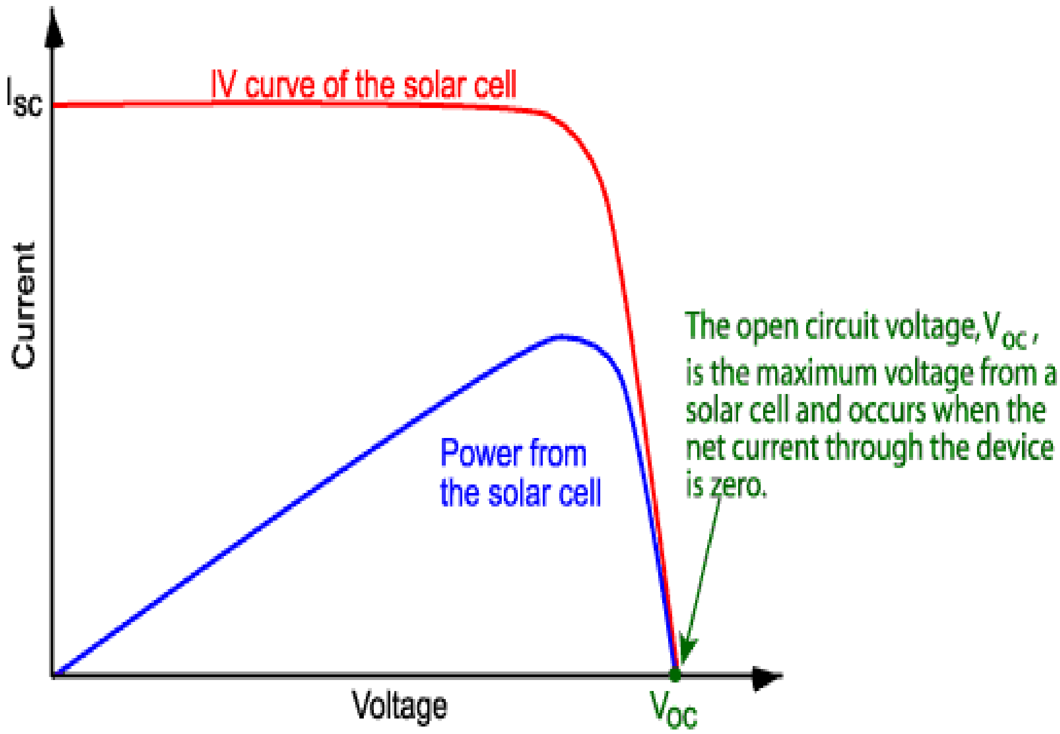

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Figure 6 I-V curve of a solar cell showing the open-circuit voltage

(PVEducation, 2014)

3.2.6 The Fill Factor

The short-circuit current and the open-circuit voltage are the maximum current and voltage respectively from a solar cell. However, at both of these operating points, the power from the solar cell is zero. The fill factor is a parameter, which in conjunction with Voc and Isc, determines the maximum power from a solar cell. The Fill Factor is defined as the ratio of the maximum power from the solar cell to the product of Voc and Isc. Graphically, the Fill Factor is a measure of the squareness of the solar cell and is the area of the largest rectangle, which will fit in the IV curve. The Fill Factor is illustrated below.

(PVEducation, 2014)

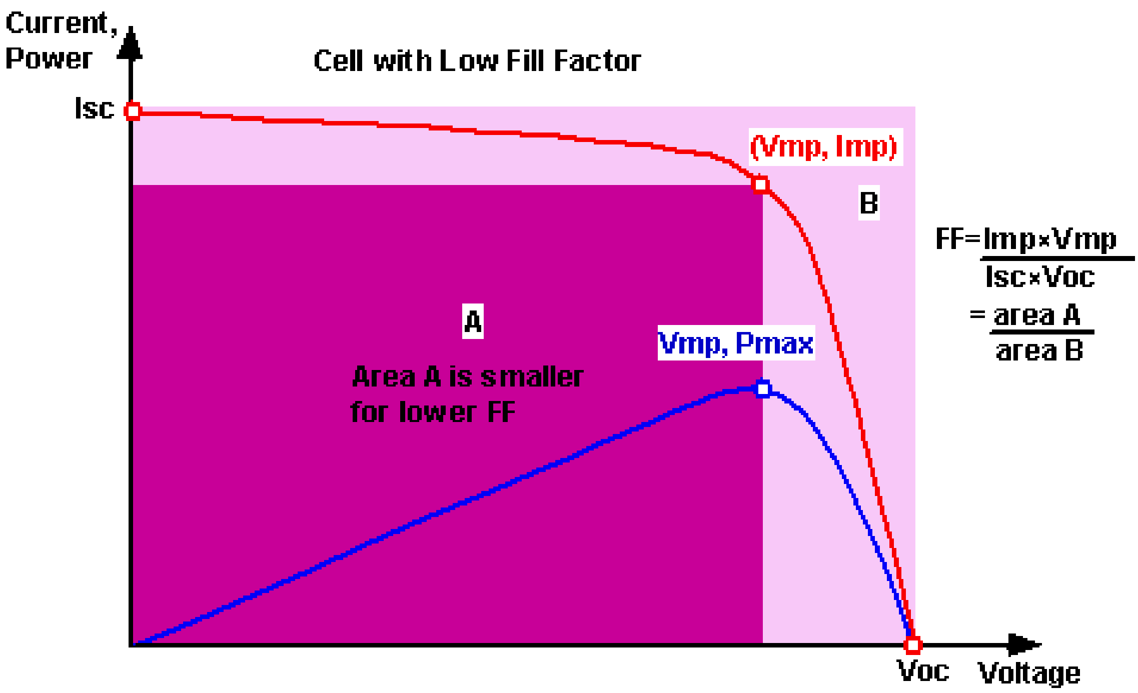

Figure 7 I-V curve of a solar cell showing Fill Factor

(PVEducation, 2014)

Graph of cell output current (red line) and power (blue line) as function of voltage. Also shown is the cell short-circuit current (Isc) and open-circuit voltage (Voc) points, as well as the maximum power point (Vmp, Imp).

The author states that efficiency is used to compare the performance of one solar cell to another. Efficiency is the ratio of energy output from the solar cell to input energy. The efficiency of a solar cell is determined as the fraction of incident power which is converted to electricity. The IV curve of solar cell is used to demonstrates the characteristics of the solar cell. The IV curve compares the short circuit and the

open circuit characteristics. The short-circuit current and the open-circuit voltage are the maximum current and voltage. The fill factor is a parameter, which determines the maximum power from a solar cell. The Fill Factor is the ratio of the maximum power from the solar cell to the product of Voc and Isc.

3.2.7 Significant characterisation issues of CdTe modules

In the year 2000 G. Agostinellia, D. Andersona, W. Zaaimana, T. Samplea, R. Wendtb, and E.D. Dunlopa carried out a study of the characterisation issues of CdTe modules. In the study of the actual outdoor performance of the CdTe module, a 40W CdTe module was monitored in the field for a Three-month period beginning in middle of February 2000. The two most interesting features of the CdTe module's operation were the significant decrease of module efficiency at low irradiances and the increase of fill factor with time as the module was monitored over the Three month period. The module efficiency was previously measured indoors using a solar simulator flash, and determined to be 5.3%. At irradiances above approximately 500W perimeter squared, the module is actually operating at a higher efficiency of approximately 5.9%. The increase of fill factor means that although Isc and Voc can be measured successfully using a flash simulator and the corresponding correction for spectral mismatch, the power output of the module may be underestimated. (Elsevier, 2001)

	I_{sc} [A]	V_{oc} [V]	P_{max} [W]	FF
Indoor	0.99	91.9	41.0	45.0
Outdoor	0.97	91.6	41.5	46.8
Difference (%)	2.0	0.3	−1.2	−4.0

Figure 8 Difference between indoor and outdoor calibration at STC

(Elsevier, 2001)

Hysteresis on Pmax and Fill Factor

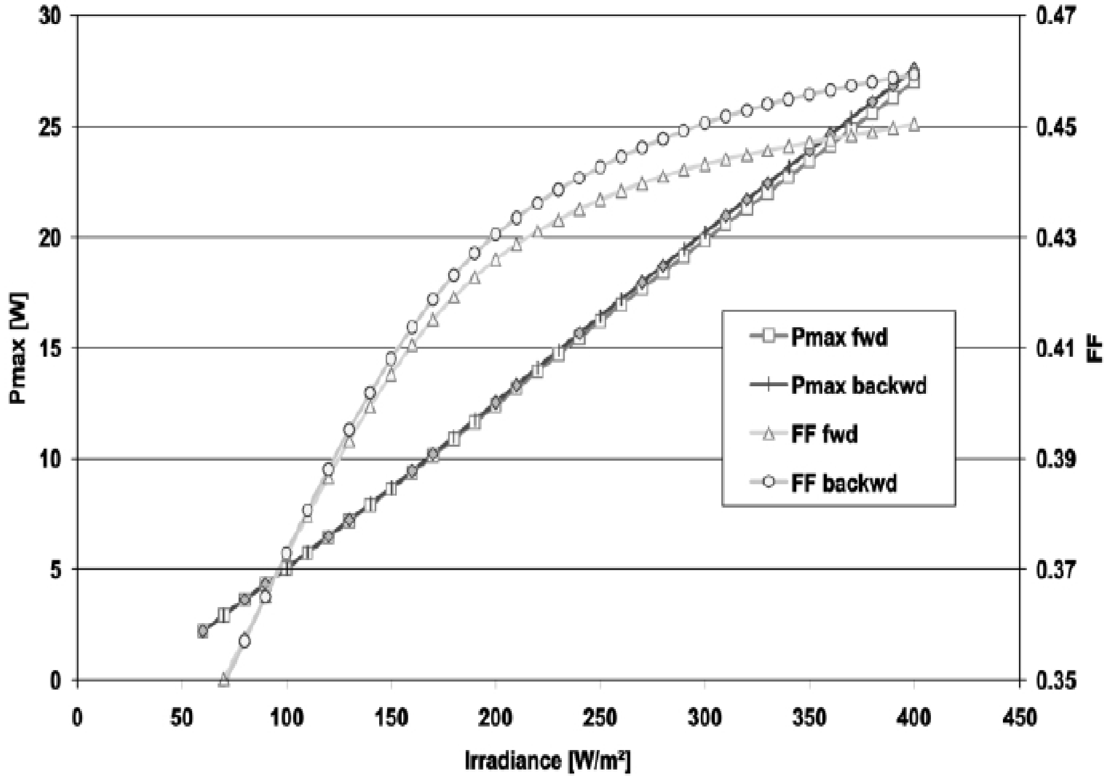

Figure 9 Sweep direction hysteresis at different irradiances

(Elsevier, 2001)

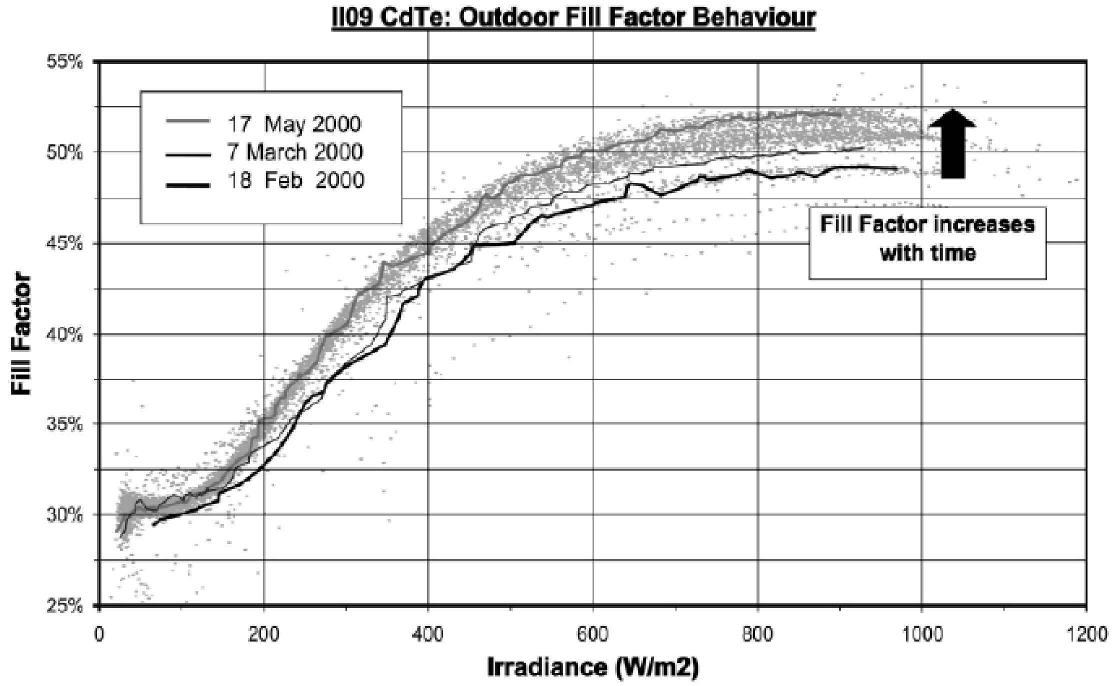

Figure 10 Fill factor of the CdTe module as a function of irradiance

(Elsevier, 2001)

The study of the characterisation of CdTe modules shows there are still issues. These translation equations, transient effects, and hysteresis require further investigation and measurement that is more detailed. Due to the time evolution of the module characteristic parameters the actual outdoor performance results were underestimated by the indoor performance measurements.

3.2.8 High efficiencies

In order for high efficiencies to be achieved in PV technologies energy loss mechanisms must be reduced. One principle energy loss in the conversion of solar energy to electricity is related to spectral losses, whereby low energy photons are not absorbed by the solar cell while high energy photons are not used efficiently. The major loss mechanisms at short wavelengths are summarised below for various PV technologies. (Ahmed, 2013) (Klampaftis E. R., 2009)

The losses associated with Cadmium Telluride photovoltaic cells are absorption in buffer, typically in CdS and TCO layers. These loss mechanisms represent a practical limit to the maximum efficiency that can be achieved by the cell. The potential remains to increase cell efficiency by making better use of short wavelength light. One way to do that is to improve the electric properties of the solar cell. (Ahmed, 2013)

One potential solution by using luminescent material to convert high energy photons into lower energy before the interaction with the solar cells occurs - a process referred to as luminescent down-shifting (LDS). This process involves a luminescent material, which is applied to the top of the PV cell.

(Ahmed, 2013) (Hovel, 1979) (Le Donne A. A., 2009) (Le Donne A. D., 2011) (Klampaftis E. R., 2009) (Klampaftis E. a., 2011) (Klampaftis E. R., 2012) (McIntosh, 2009) (Rothemund, 2001) (Strúmpel, 2007)

3.2.9 Luminescence Phenomena

Luminescence is the emission of light from any substrate and occurs from electronically excited states Depending on the nature of the excited state the luminescence can be either florescence or phosphorescence. In phosphorescence, the emission of light is from triplet excited states in which the electron in the excited orbital has the same spin orientation as the ground-state electron. In fluorescence, the electron is in the excited singlet state and it is paired in the excited orbital to a second electron in the ground-state orbital. Luminescent quantum yield is defined as

the ratio of photons emitted by the luminescent material relative to the number of photons absorbed. (Ahmed, 2013) (Lakowicz, 2006)

Luminescent Down-Shifting (LDS) is an optical approach to increase a CdTe PV cells ultra-violet/blue response by shifting short wavelength light to longer wavelengths where the external quantum efficiency (EQE) of solar cell is higher. Luminescent materials such as organic dyes can convert the high energy photons to lower energy, before the interaction with the solar cells occurs. As a result of the luminescent process more electron-hole pairs can be created in the solar cell for a given number of incident photons and higher short-circuit current (Isc) is generated. (Ahmed, 2013) (Hovel, 1979) (Klampaftis E. R., 2009) (Rothemund, 2001)

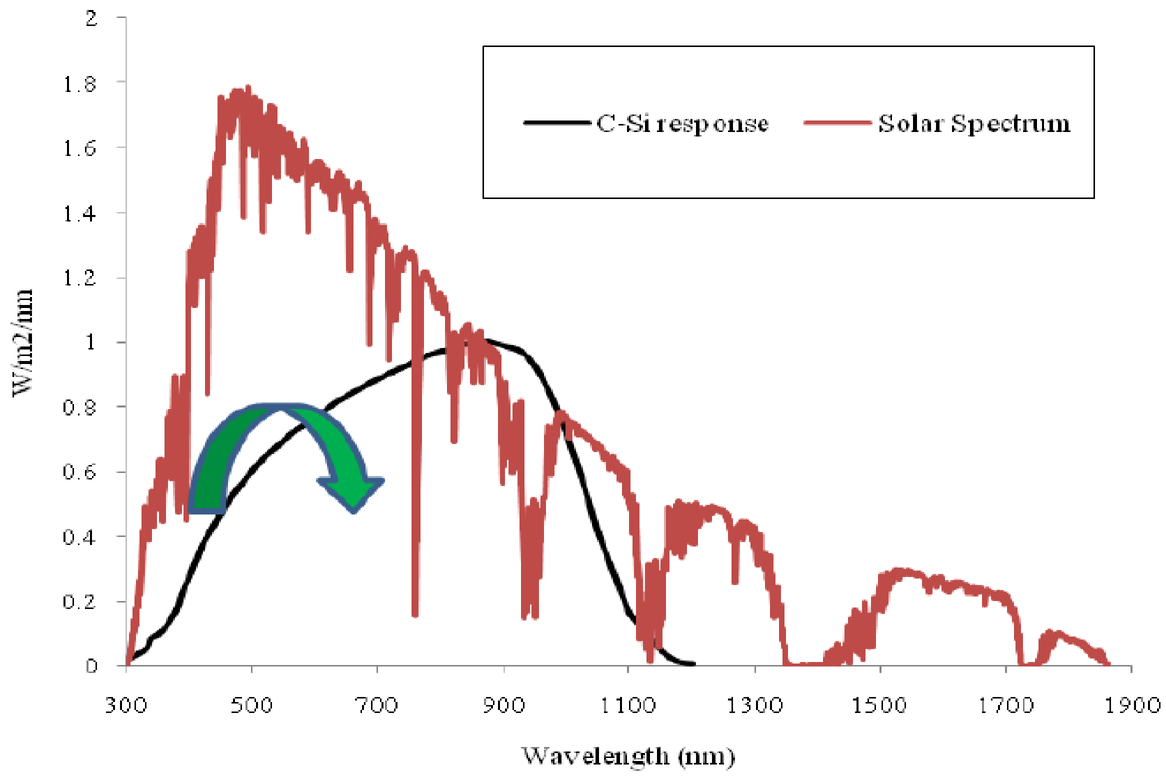

Figure 11 The Luminescent Down–Shifting process

Figure 11 above shows the luminescent downshifting process to increase solar cell active range and efficiency. High energy photons are reradiated at a longer wavelength, better matching the photosensitivity spectral response of the c-Si solar cell.
(Ahmed, 2013)

The typical LSD layer consists of a flat plate containing a luminescent dye. The CdTe PV cell is placed on one of the plate edges. This allows a certain wavelength to be absorbed by the luminescent dye and reemitted isotropically. The emitted photons are wave guided to a reduced area of the photovoltaic cell at the plate edges. the area of PV cell is not reduced by the LDS layer is used to modify the incident spectrum only.

(Ahmed, 2013)

The LDS optical process involved in an LDS layer placed on top of a CdTe PV cell. Incident solar radiation will be absorbed and reemitted at longer wavelength. The majority of the emitted radiation will be directly transmitted to the PV cell. Part of the luminescence will be emitted away from the PV cell through the top or the side of the LDS layer. Light could also be transmitted directly to the cell if is not absorbed by the luminescent species.

(Ahmed, 2013)

3.2.10 Literature Review Conclusion

The literature review is focused on the historic, efficiency and the potential for improving efficiency of CdTe Photovoltaic Cells. The reviews discussed the CdTe Photovoltaic Cells from different angles. The first review looks at the efficiencies of CdTe PV cells, how they started out with poor efficiencies. It also talks about how they performed in different locations and over time how they improved. The second review looked at the markets for PV cells and how the silicon dominates the market type cell and there is a market for the CdTe Photovoltaic Cells if they can improve their efficiencies. The third review showed the manufacturing process of CdTe Photovoltaic Cells. All three reviews relate to the history of the CdTe Photovoltaic Cells but from different points of view to show how we see them today.

When researching this topic, the researcher found there is very limited amount of information on this subject for Ireland. To the best of researcher knowledge there are no comparative studies done on this topic in the same location that the researcher is proposing to do the study for their dissertation. For this reason, the researcher feels there is scope for research in this field and that it would be a worthwhile dissertation as there is a need for an improvement into CdTe Photovoltaic Cells to make them more completive to the PV cells markets.

4 Method

4.1 Ethical Considerations

4.2 Introduction

Ethics are part of everyday life, there are a number of reasons why it is important to adhere to ethical norms to promote the aims of research, such as knowledge, truth, and avoidance of error. when undertaken this project a number of ethical standards were undertaken. When undertaken and writing this dissertation it was important to ensure that all DIT ethics, policies and requirements were adhered to, such as research ethics, safety ethics and health and safety standards.

4.3 Research Ethics

4.3.1 Carefulness

When performing research during this dissertation it was vital to avoid careless errors and negligence to ensure the quality of data. Great care was taken to ensure good records of research activities, such as data collection. It was vital to ensure that great care was also taken too adequately and clearly referenced information retrieved from other sources to avoid any unintentional plagiarism.

4.3.2 Honesty

When performing research during this dissertation it was vital to ensure that all data reports, results, methods and procedures, were carried out with complete honesty in mine and complied with all DIT standards. This ensured that no data was fabricated, falsify, or misrepresent.

4.3.3 Integrity

This dissertation was performed with the utmost integrity to act with sincerity, strive for consistency, and not deceive colleagues, classmates, or staff members.

4.3.4 Confidentiality

As this dissertation was performed alongside PhD student, Hind Ahmed it was important to protect confidential unpublished new data.

4.3.5 Social Responsibility

In everyday life as well as during this dissertation, it is important to strive to promote social ethics. Respect for colleagues, classmates, staff members and all people. (niehs, 2014)

4.3.6 Safety Ethics

Before starting work on the roof of DIT Kevin St building it was mandatory to take a safety course on roof safety. This course outlined all safety requirements and ethics. While undertaken this dissertation all DIT ethics, policies and requirements were adhered to with regard to safety ethics and health and safety standards.
(niehs, 2014)

4.4 Safety

The purpose of safety and risk assessment is to identify possible causes of harm and identify the measures needed to avoid these before an accident occurs. Safety is paramount to this project as there is a certain amount of general risk as this project was performed on the roof of the Kevin St building. There was also added risk due to working with electricity, working with construction tools and working in laboratory environments with chemicals. The complete process of this dissertation complied with DIT's policies and requirements concerning electrical safety, lab safety, manual handling, weather safety, and the buddy system. At all times when working on the roof the buddy system was fully complied with. To comply with safety in potential hazards areas a risk assessment was preformed to identify any potential hazards throughout the dissertation. A hazard is anything with the potential to cause harm. The risk is the likelihood that someone will be harmed by the hazard. By performing a risk assessment, this brought attention to any possible hazards to prevent injuries or ill health. When hazarders were identified safety measures were preformed to limit the risk.

- Five Steps to Carry Out A Risk Assessment
- Identify the hazards
- Identify who might be harmed and how
- Evaluate the risks and consider how the risk of harm can be reduced
- Record your findings
- Review and revise your assessment where necessary

4.5 Introduction/Experimentation /Objectives

The main objective of this dissertation was to demonstrate a comparative performance analysis of Cadmium Telluride (CdTe) Photovoltaic Cells with the introduction of luminescent downshifting layers. Various tests were carried out on the status of the Cadmium Telluride (CdTe) Photovoltaic Cells in two separate operating conditions. These conditions will include different systems and weather conditions.

4.5.1 Research Planning

In order to obtain a better understanding of this particular area of research this dissertation will start with a literature review of the Cadmium Telluride (CdTe) Photovoltaic Cells and luminescent downshifting. The literature review contains information on Cadmium Telluride (CdTe) Photovoltaic Cells and luminescent downshifting books, articles, websites and manuals. The aim of the literature review is to obtain vital current information surrounding this entire topic. The literature review will also provide knowledge about current standards and procedures to proceed with this dissertation.

4.5.2 Description

After reviewing literature about Cadmium Telluride (CdTe) Photovoltaic Cell and luminescent down shifting the author gained a better understanding of the subject, therefore the planning of constructing and process of making the (LDS) luminescent down shifting layers could begin.

4.5.2.1 Planning of Constructing

Two of the large PV cells were installed at an angle of 53° facing southeast. One as a reference CdTe PV cell and one CdTe PV cell with a LDS layer. Five of the smaller CdTe PV cells are installed horizontally to the ground at a 0° angle. The first is the reference CdTe PV cell, the second is a CdTe PV cell with a blank LDS layer (PMMA), the third is a CdTe PV cell with a Yellow LDS layer, the fourth is a CdTe PV cell with a Violet LDS layer and the fifth is a CdTe PV cell with a Yellow and Violet mixed LDS layer.

4.5.2.2 Making the (LDS) Luminescent Down Shifting Layers

The luminescent down shifting layers were made in the laboratory in the DIT focus building. The LDS layers were made using organic dyes Lumogen Yellow 083, Lumogen Violet 570. A mixed layer was made using a mixture of Lumogen Yellow 083 and Lumogen Violet 570. The host materiel for layers is (PMMA), one layer was made using only the host materiel for comparative porpoises only.

4.5.3 Justify/Methods/ Instruments Applied

It was essential to evaluate the area and location where the Cadmium Telluride (CdTe) Photovoltaic Cells are to be installed. The correct Orientation, Azimuth angle and the inclination for this location of the cells needed to be investigated to maximise the output of the cells. This project is on the roof of DIT Kevin St building in the South-East Inner City of Dublin 8, Co Dublin, Ireland. The area of the roof where the analysis was performed is south facing. This area is completely exposed to the elements and there is no significant element of shading CdTe PV cells.

An examination of the existing solar panels and weather instruments in this location provided an insight into the amount of electrical output, type of weather and the amount of sun light that could be expected in this location. The existing solar panels also give an insight into how to retrofit the CdTe Photovoltaic Cells to the existing framework. This provides information for a materials list and a design plan to install the CdTe Photovoltaic Cells.

4.5.4 Experiments

Once the (LDS) luminescent down shifting layers were made in the laboratory in the DIT focus building, their absorption and their emission properties were tested. Before the CdTe Photovoltaic Cells are installed on the roof, indoor test were performed on all the CdTe Photovoltaic Cells, the indoor test are the same as the outdoor tests. Once the indoor tests were completed, the CdTe Photovoltaic Cells were installed on the roof, testing could begin. The tests were carried out on each individual cell. The data logger measured the output voltage and output current. The user interface provided values for the output power, the Isc (short circuit current mA) values, the Voc (open circuit voltage V) values, the Pmax (max power W) and the FF (fill factor). This information gives the IV and the PV curves of the CdTe PV cells.

The weather is monitored via a weather station on the roof of the Kevin St building. The amount of sunlight, the temperature and all weather conditions as they will influence the PV cells outputs.

Variables

The Variables associated with this dissertation are sizes of the different Photovoltaic Cells, the location, Orientation, Azimuth angle, the inclination and the weather. The weather is the main variable, the amount of sun light and temperature as the higher the amount of sunlight the higher the output will be. The different LDS layers will also vary the output performance of the CdTe PV Cells

4.6 Design Stage

In the design stage of this dissertation the author was faced with a number of challenges. These challenges were in relation to the construction of the PV cells frame. The PV cells specifications did not include a frame for fixing the Cells; therefore, a frame would need to be designed to carry the PV cells. The frame specifications would have to insure that the PV cells had a secure fixing, as they would undergo adverse weather conditions on the roof of the Kevin St building. The frame needs to allow for cable entry on the bottom of the PV cells. The frame required at least ten to fifteen millimetres of movement between the frame and the main fixing to allow the LDS layers to be applied to the PV cells. The frame must not comprise the output of the PV cell. With these specifications taken into account, the following frame was designed. See figure below.

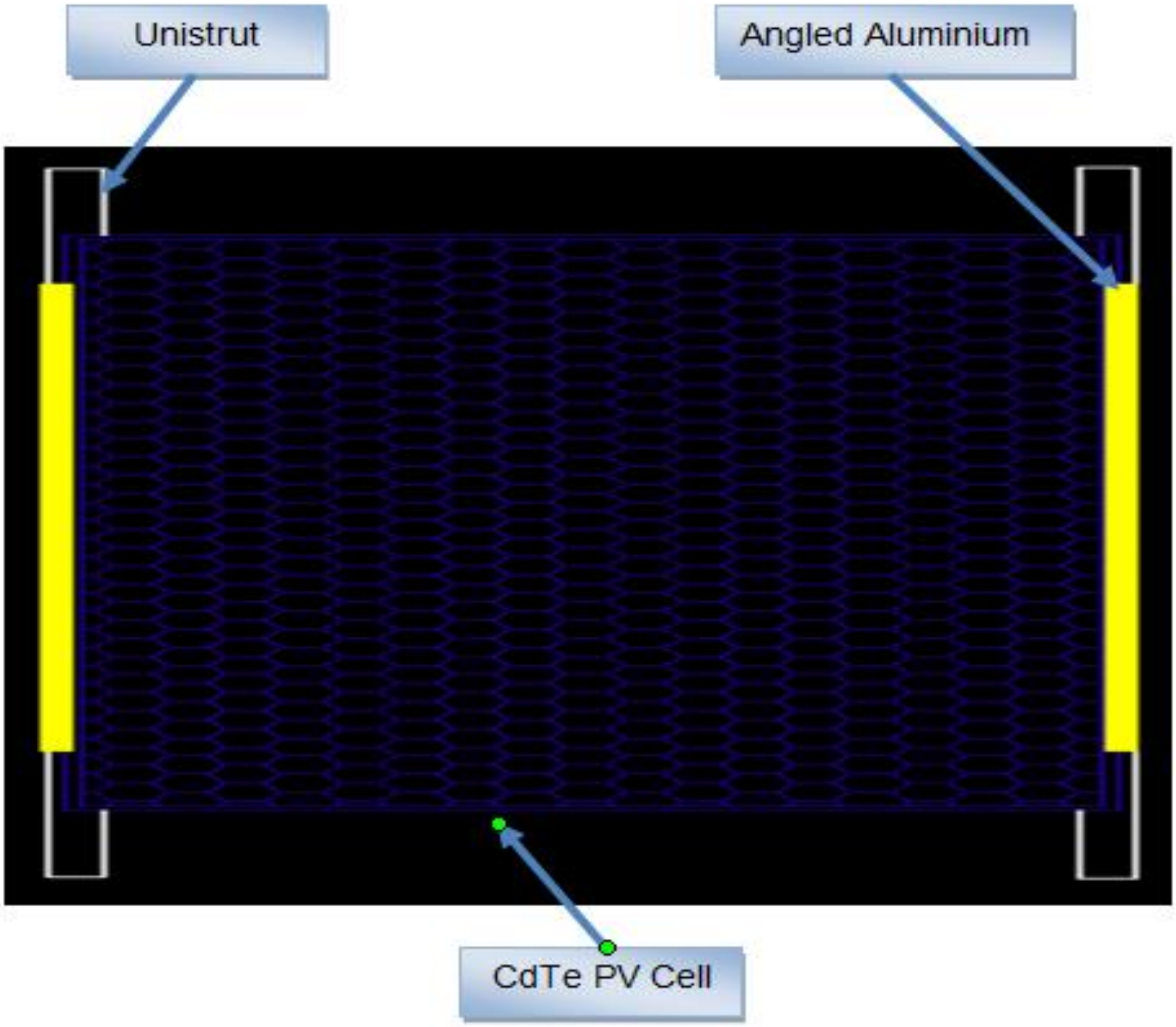

Figure 12 Auto Cad Drawing of the PV Cells Frame

The unistrut is designed to be the main structure of the frame, carry all the weight, and take any pressure from any adverse weather conditions. A rubber profile is attached to the outer ten millimetres of the PV cell this is to provide a cushion for the PV cell and prevent the cell from been damaged. The PV cell would simply sit on the unistrut and the light angled aluminium is fixed to the unistrut. The light angled aluminium is strategically fixed over outer ten millimetres of the PV cell thus applying downward pressure on the cell and holding the PV cell in place. The outer ten millimetres of the PV cell is not used to absorb light, therefore the frame will not comprise the output of the PV cell.

4.7 Making the LDS layers

All stages of making the LDS layers were carried with safety in mind and adhering to all safety regulations and requirements of DIT. Protective clothing such as a lab coat, powder free gloves and safety eyewear was worn at all times.

Three different organic dye LDS layers were constructed, one LSD layer using Lumogen yellow 083, one LSD layer using Lumogen Violet 570 and one LSD layer using a mixture of Lumogen yellow 083 and Lumogen Violet 570.

4.7.1 Materials list

- Lumogen Yellow 083
- Lumogen Violet 570
- PMMA
- Dimethylformamide (DMF)

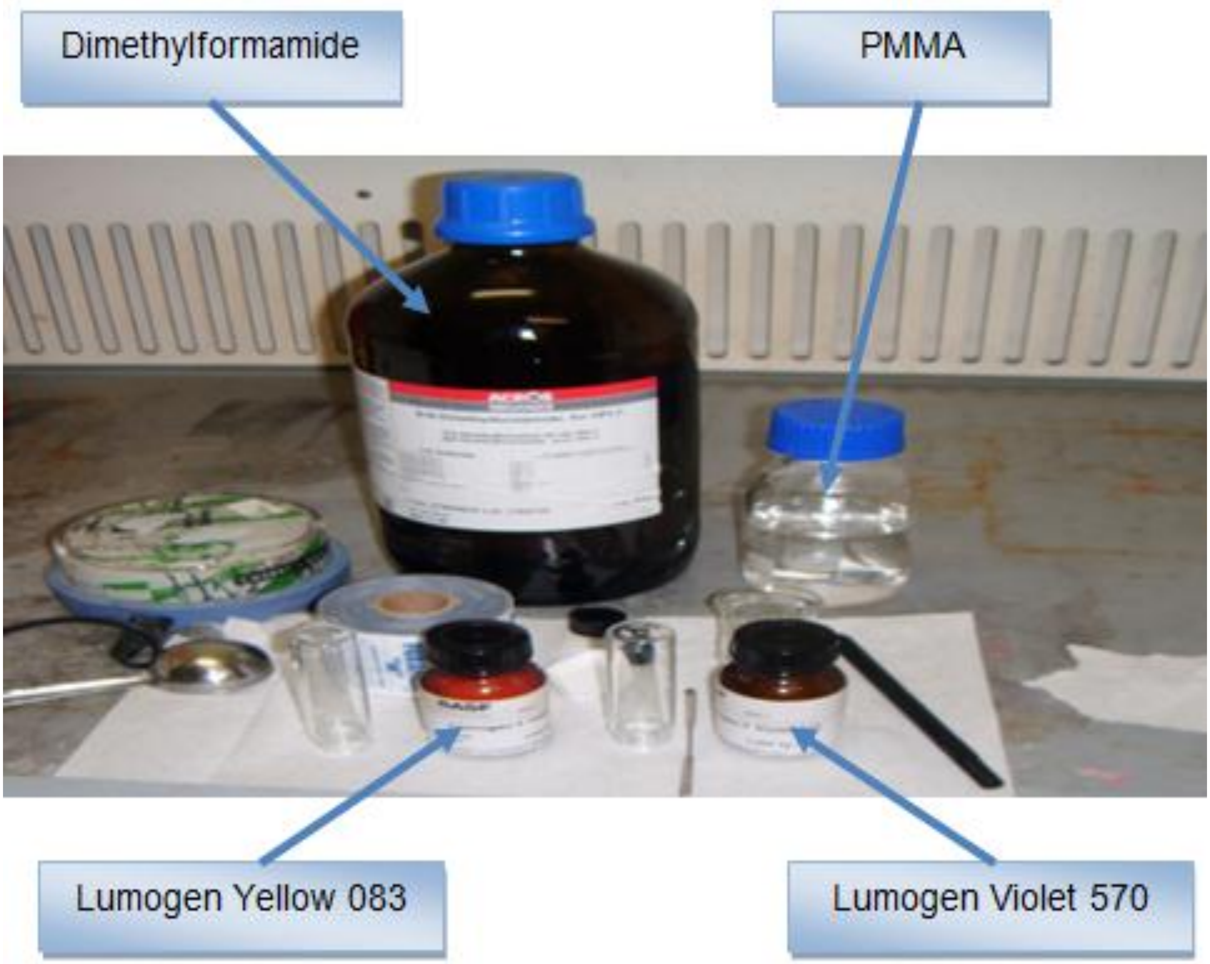

Figure 13 Materials for Making the LDS Layers

4.7.1.1 Step 1

For the first layer using a weighing scales and a spatula weigh out 2mg of Lumogen Yellow 083 dye and dissolve it in 100ml of Dimethylformamide (DMF). For the second layer repeat the same process for Lumogen Violet 570 dye. For the third layer repeat the same process using 2mg of Lumogen Yellow 083 dye using 2mg of Lumogen Violet 570 dye. Separate containers were used for each dye solution to prevent contamination from occurring and each container was labeled.

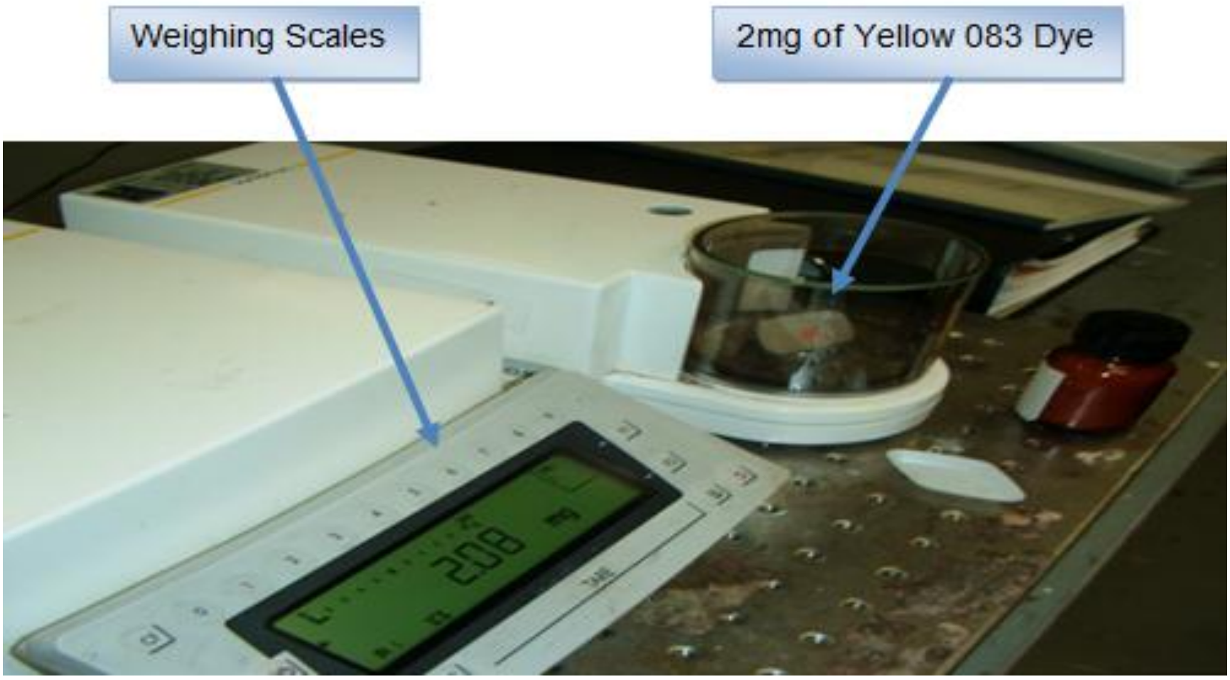

Figure 14 Weighing Scales

Figure 15 Micropipettes

Micropipettes are used to accurately measure and dispense small volumes of liquid.

4.7.1.2 Step 2

Place the labeled containers into an ultrasonic bath for approximately 20 minutes to allow the different solution to mix using ultrasonic waves. Once the solution has finished mixing in the ultrasonic bath. Then move the containers to the fume hood to continue the mixing process.

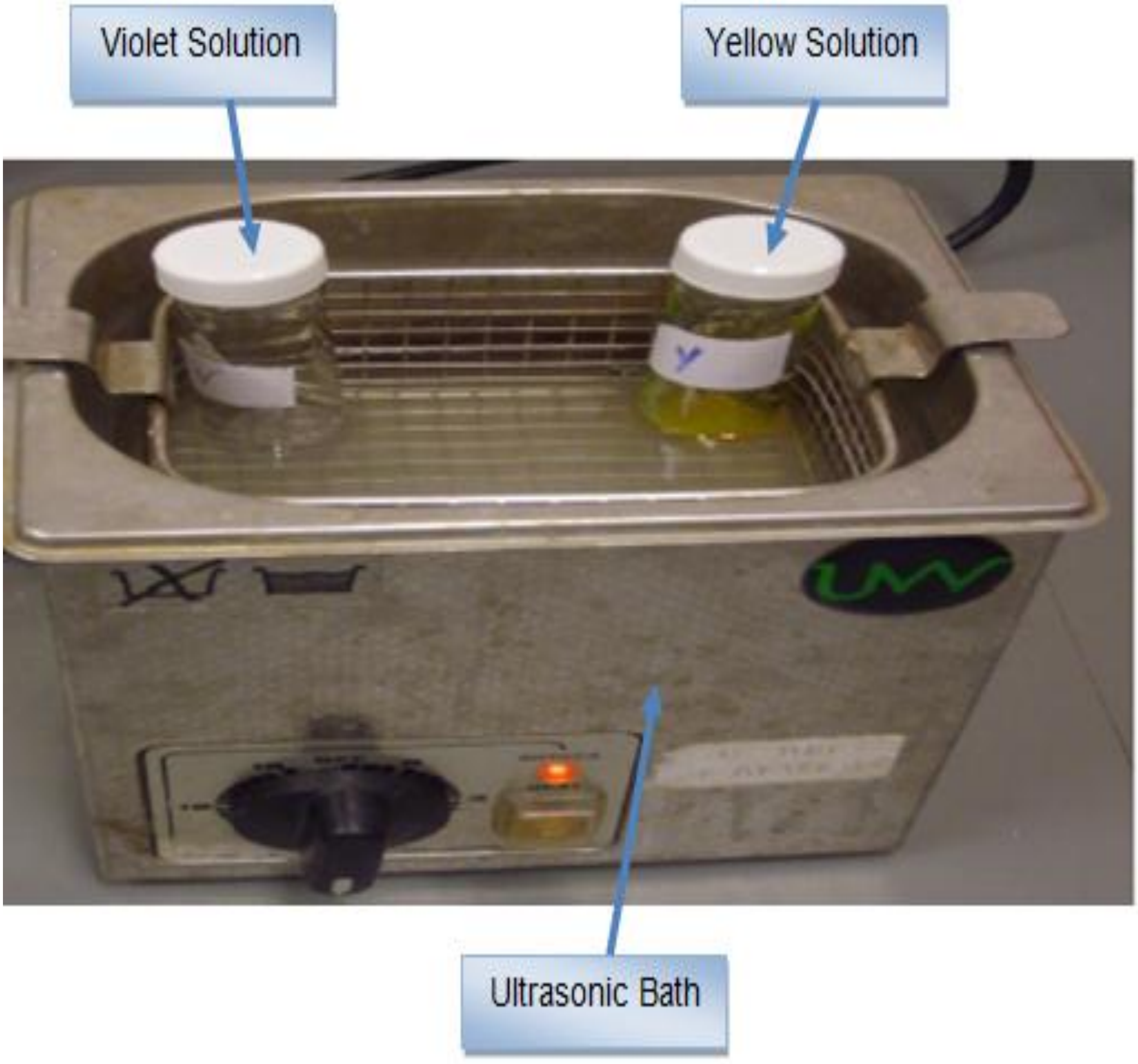

Figure 16 Solution Mixing In the Ultrasonic Bath

4.7.1.3 Step 3

Using a scales and a container add 25ml of PMMA into each of the three different solutions. Put a 3mg magnet bar into each of the containers. Place the three containers on electro magnets for 45 minutes. The magnetic bar will spin in the containers and stirrer the solution evenly to give a consistent mixture.

Figure 17 The magnetic bars

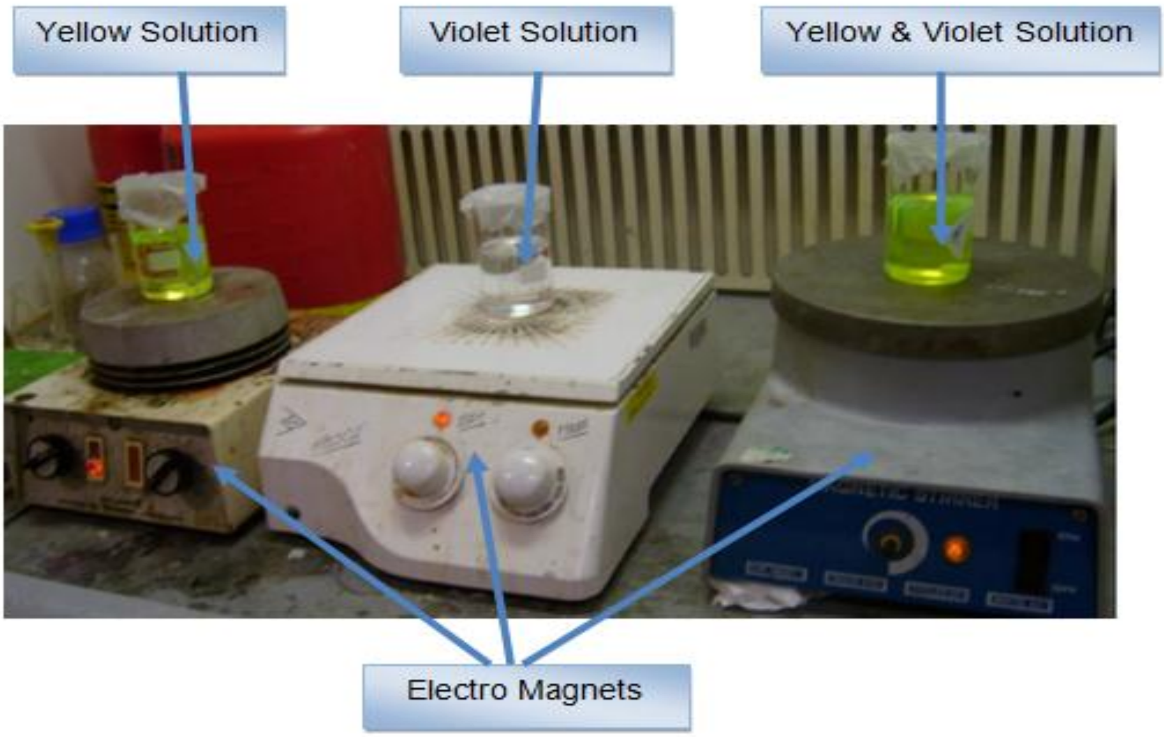

Figure 18 The Mixing Process

4.7.1.4 Step 4

Place sheets of glass into the oven, pour the contents of the containers onto the glass sheets. Use a circular motion to spread the solution evenly. Place another sheet of glass on top of the solution and glass. This will form a glass sandwich, and then bake the layers for three days at 30°C.

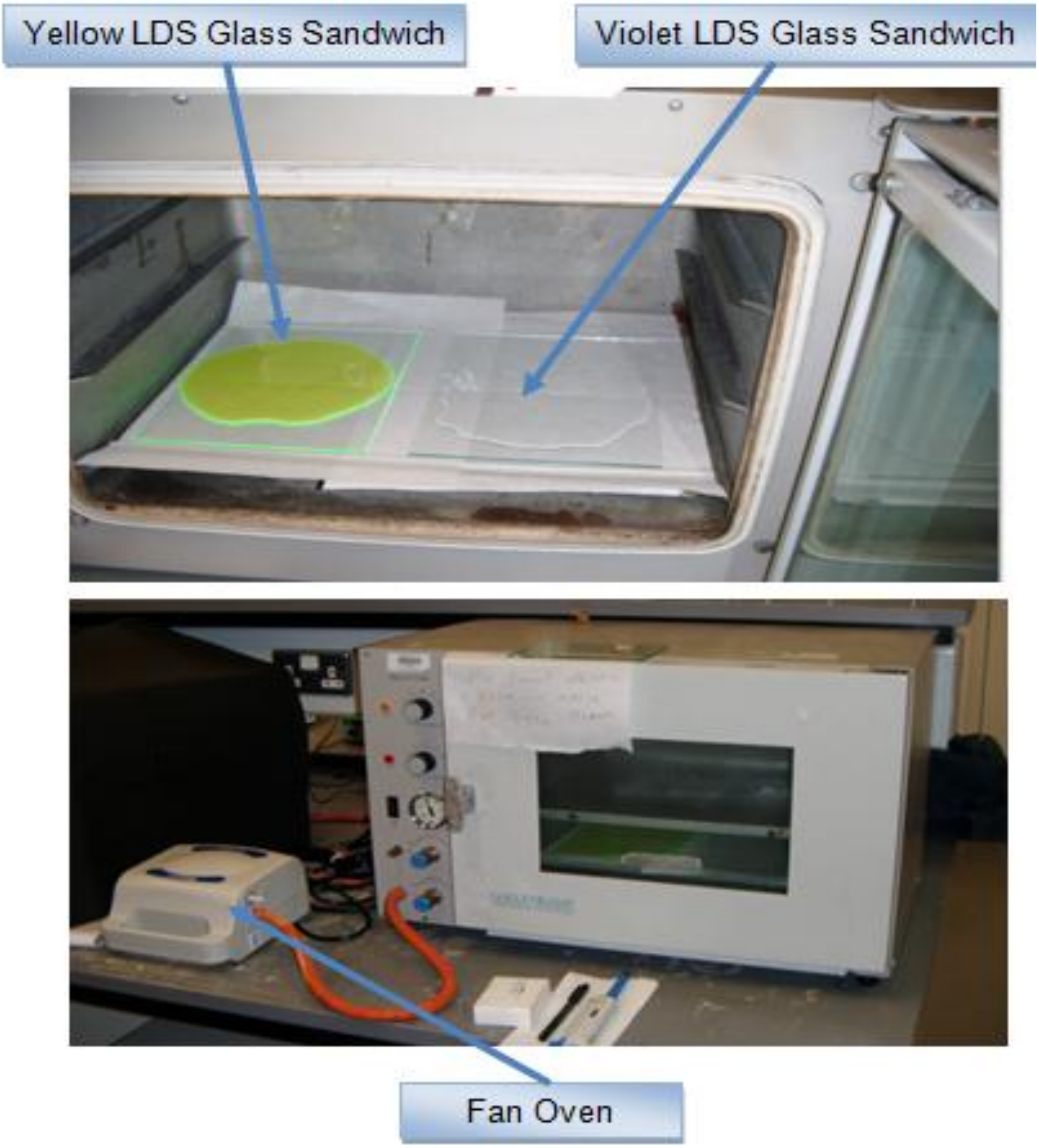

Figure 19 The Baking Process

4.7.1.5 Step 5

Once the layers were finish in the oven they needed to be separated from the glass sandwich. This left a tin LDS layer that was then applied to the PV cell. Excess LDS material was used for testing the quality of the LDS layers.

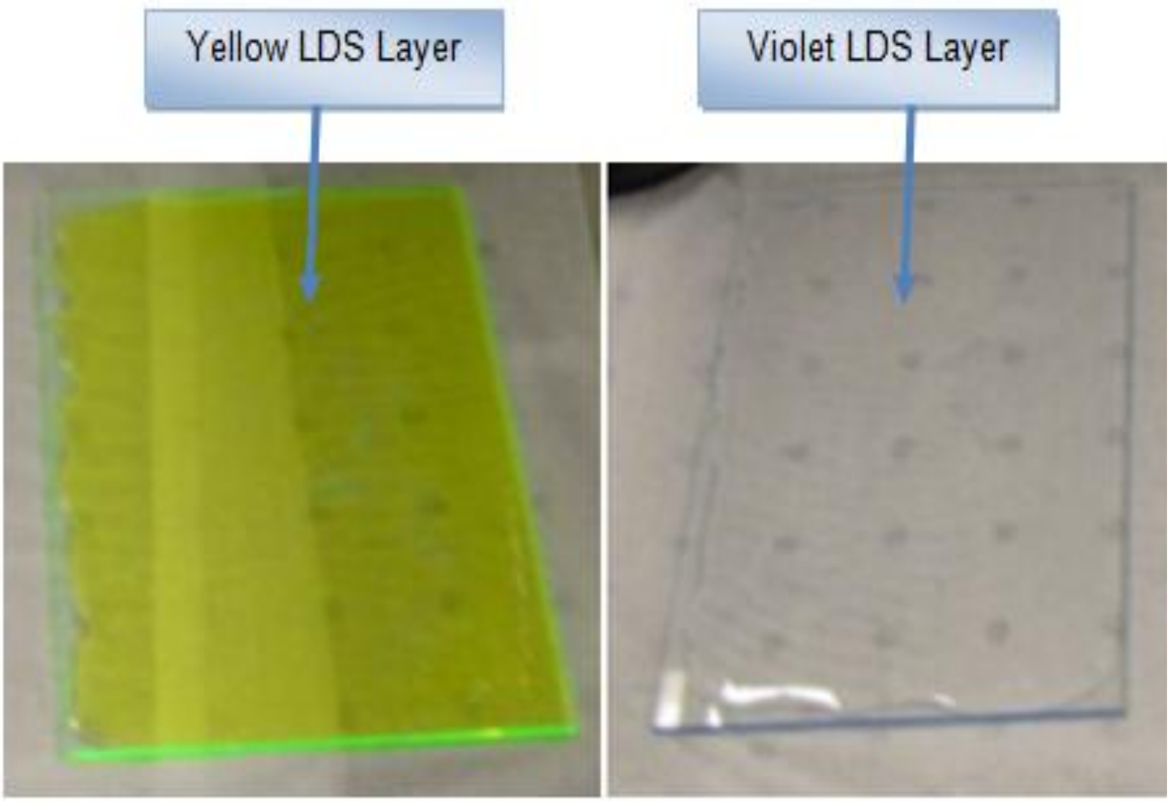

Figure 20 Finished Yellow LDS layer and Violet LDS Layers

This method used is known as drop casting the layers, this involves the LDS solution being sandwiched between two glass plates. Once the LDS layers are baked for three days at 30°c the LDS solution becomes a solid tin layer. The glass plates can then be separated from the LDS layer. The separation of the glass plates from leaves a tin LDS layer as shown in the figure above, the LDS layer is then applied to the CdTe PV cells. This method would allow the LDS layers on a solar cell to be changeable, without having to apply the LDS layer permanently onto the solar cell.

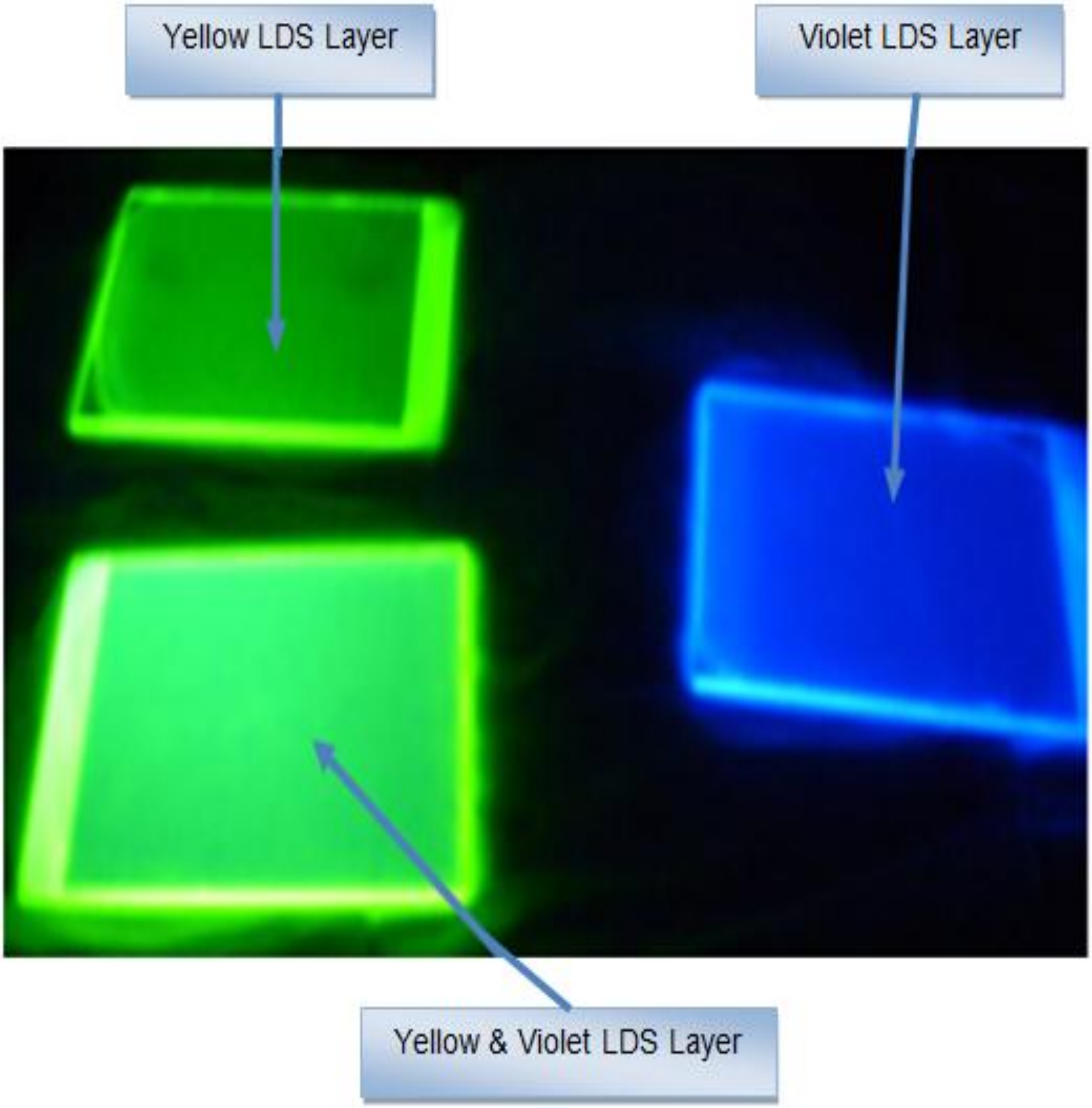

Figure 21 The Three LDS Layers under an Ultraviolet light

Figure 20 above is a picture of the three different LDS layers under an Ultraviolet light to give a perspective on how they perform in the Ultraviolet conditions. It can clearly be seen the layers containing Lumogen Violet 570 make the best use of the light.

4.8 Construction Stage

All stages of construction were carried with safety in mind and adhering to all safety regulations and requirements of DIT.

4.8.1 Materials list

- 32mm unistrut, Total 12m of 32mm unistrut
- Unistrut right angles
- Unistrut tee angles
- Spring loaded nuts
- A box of 10mm gutter bolts and nuts for the fixings.
- Total 6m of 10mm x 20mm x 1m Angle Aluminium Unequal Sides
- Rubber profile 6m
- 0.75mm^2 cable
- Cable ties
- Connecter blocks
- Insulation tape

4.8.2 Hand Tools

- Cordless drill
- Drill bits 6mm and 10mm
- Cone drill bit
- Screwdrivers Flat head and Phillips head
- Measuring tape
- Hacksaws Junior and Senior
- Snips
- Pliers
- Long nose pliers
- Stanley knife
- Pipe grips (Slip grips)
- Spanners 6mm and 10mm
- Set square
- Fluke Multi meter

4.9 Building the Frames

There are two different size frames one for the large PV cells and one for the smaller PV cells. The large frame is fixed to the existing unistrut structure on the roof at an angle of 53° facing south. The smaller PV cells are fixed to a frame mounted on existing cable tray. The existing cable tray is horizontal to the ground therefore the frame for the small PV cells is at a 0° angle.

4.9.1 Building the Frame for the Large PV Cells

- The large PV cells
- Length = 1200mm
- Width = 600mm
- Thickness = 6.8mm
- Area = 0.72m²
- Weight = 11.8kg

4.9.2 Step 1

Measure the distance between the top and bottom of the existing unistrut structure on the roof. Than measure and mark the same distance on a lengths of unistrut. Use the set square and Pencil to draw square lines around the unistrut and cut the unistrut using a senior hacksaw. Repeat the process again to have two lengths of unistrut the same size.

4.9.3 Step 2

Attach unistrut right angles to bottom of the two lengths of unistrut. Using the existing holes in the unistrut and unistrut right angles pieces, fix them together using spring-loaded nuts and 10mm bolts. Attach the unistrut tee angles to top of the two lengths of unistrut. Than fix the lengths of unistrut to the existing structure using the unistrut right angles and unistrut tee angles, hold them in place with spring-loaded nuts and 10mm bolts. The unistrut right angles at the bottom of the two lengths of unistrut will hold the weight of the PV cells and stop the PC cell from sliding down the frame.

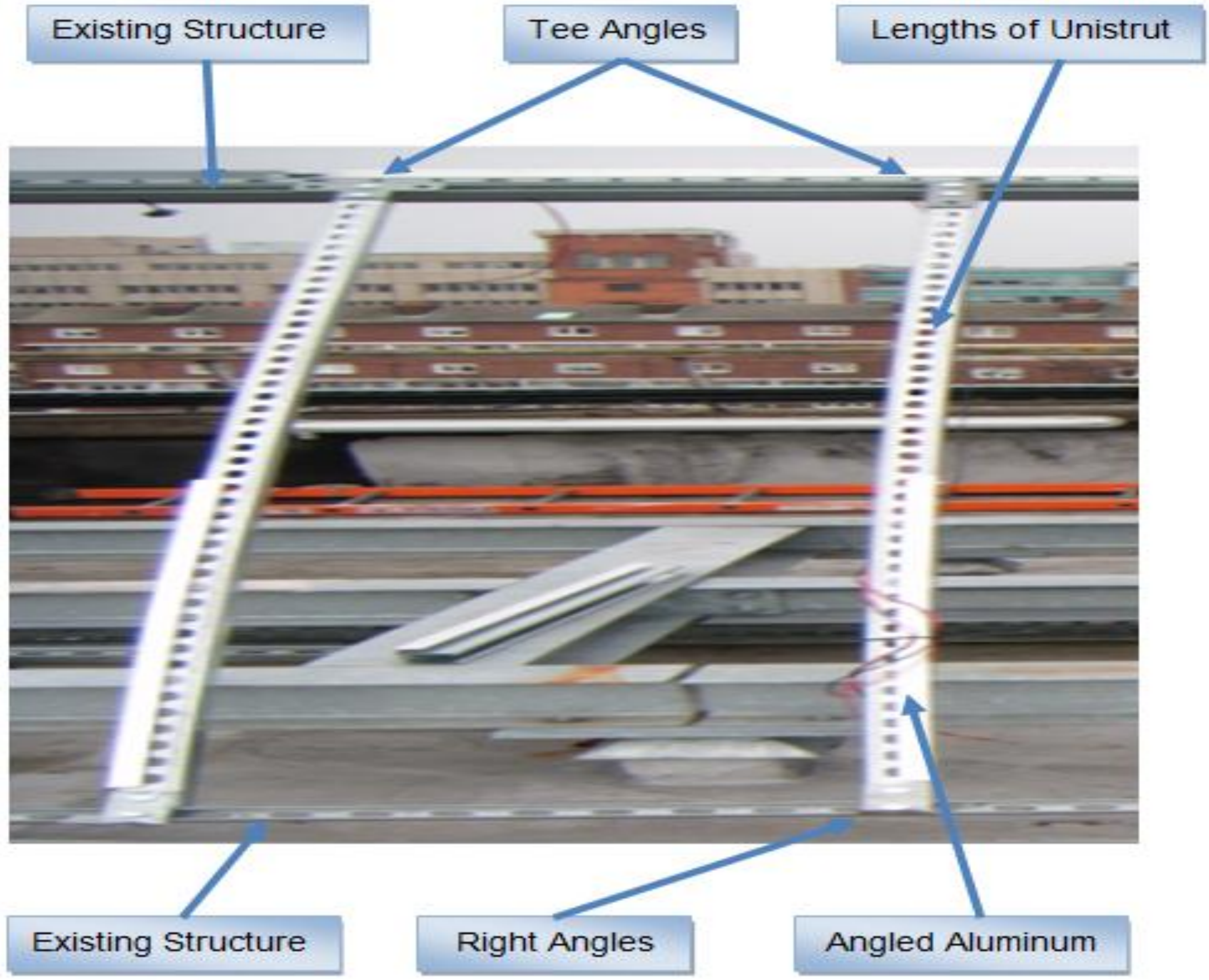

Figure 22 The PV Cell Frame at a 53° Angle

4.9.4 Step 3

Attach rubber profile to the outer ten millimetres of the PV cell, hold it in place with black insulting tape. Repeat this for all sides, top, and bottom of the PV cell. Seat the PV cell on top of the lengths of unistrut and place the angle aluminium on top of the PV cell. Mark three points on the side of the angle aluminium for holes. Take the angle aluminium off the PV cell and drill the holes. Place the angle aluminium back on top of the PV cell and using the drilled holes mark the side of the unistrut. Take the angle aluminium and the PV cell off the unistrut and drill the marks in the unistrut. Put the PV cell and the angle aluminium back on top of the lengths of unistrut and bolt the angle aluminium to the unistrut using 6mm nuts and bolts.

4.10 Building the Frame for the Smaller PV Cells

The Smaller CdTe PV cells

- Length = 150mm
- Width = 150mm
- Thickness = 6.8mm
- Area = 0.225m²

The smaller frame is fixed to the existing cable tray on the roof. The cable tray is fixed to the existing unistrut structure on the roof. The cable tray is horizontal to the ground therefore the small PV cells will be will at a 0° angle.

4.10.1 Step 1

Measure the length unistrut and mark the centre point. Use the set square and pensile to draw square lines around the unistrut and cut the unistrut using a senior hacksaw to have two lengths of unistrut the same size. Attach rubber profile to the outer ten millimetres of the PV cell, hold it in place with black insulting tape. Repeat this for all sides, top, and bottom of the PV cell. Seat the PV cell on top of the lengths of unistrut and place the angle aluminium on top of the PV cell.

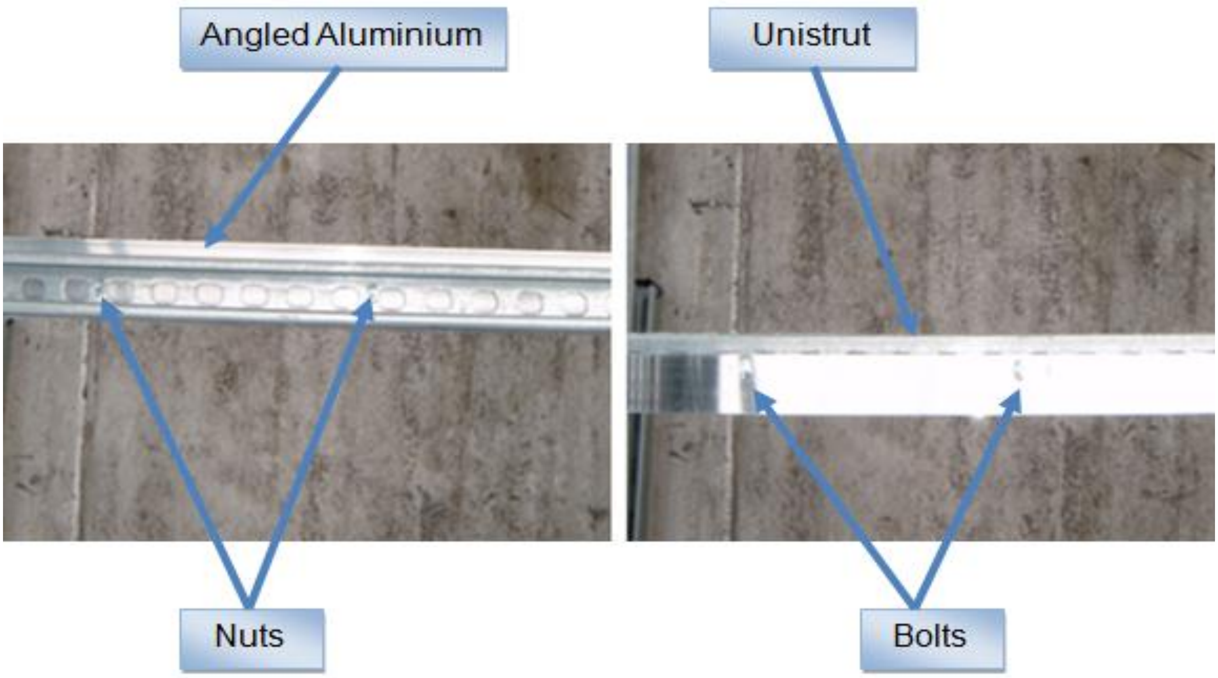

Figure 23 The Angled Aluminium & Unistrut Fixed Together

Mark three points on the side of the angle aluminium for holes. Take the angle aluminium off the PV cell and drill the holes. Place the angle aluminium back on top of the PV cell and using the drilled holes mark the side of the unistrut. Take the angle aluminium and the PV cell off the unistrut and drill the marks in the unistrut.

Put the PV cell and the angle aluminium back on top of the lengths of unistrut and bolt the angle aluminium to the unistrut using 6mm details.

4.10.2 Step 2

Take the unistrut and angle aluminium pieces and place them on the cable tray. Mark holes from the underside of the cable tray into the unistrut.

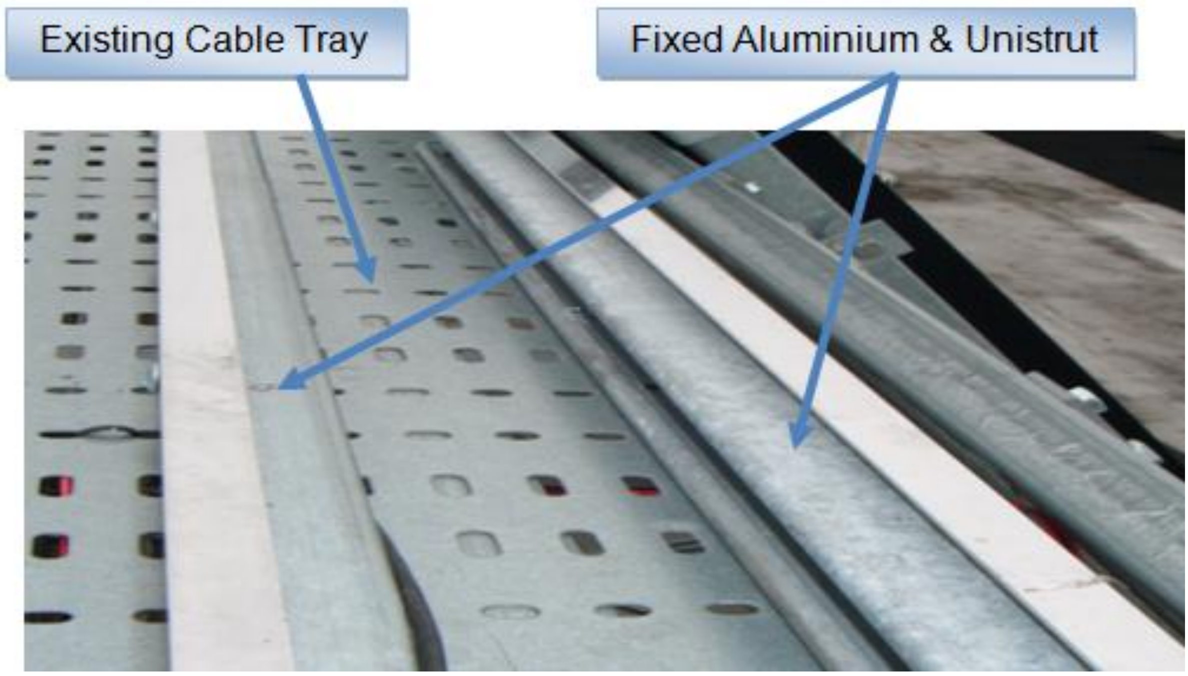

Figure 24 Unistrut & Angle Aluminium Pieces

Drill 6mm holes in the unistrut and fix the unistrut and angle aluminium pieces to the cable tray using 6mm nuts and bolts. Measure the width of the PV cells and place the second unistrut and angle aluminium piece the same distance apart from the last unistrut and angle aluminium piece. Repeat marking and drilling the holes and fix the piece to the cable tray.

4.10.3 Step 3

Release the nuts and bolts between the unistrut and angle aluminium pieces. Place the PV cells with the rubber profile on the frame and tighten the nuts and bolts to secure the PV cell in place.

Figure 25 PV Cell Fixed in Position

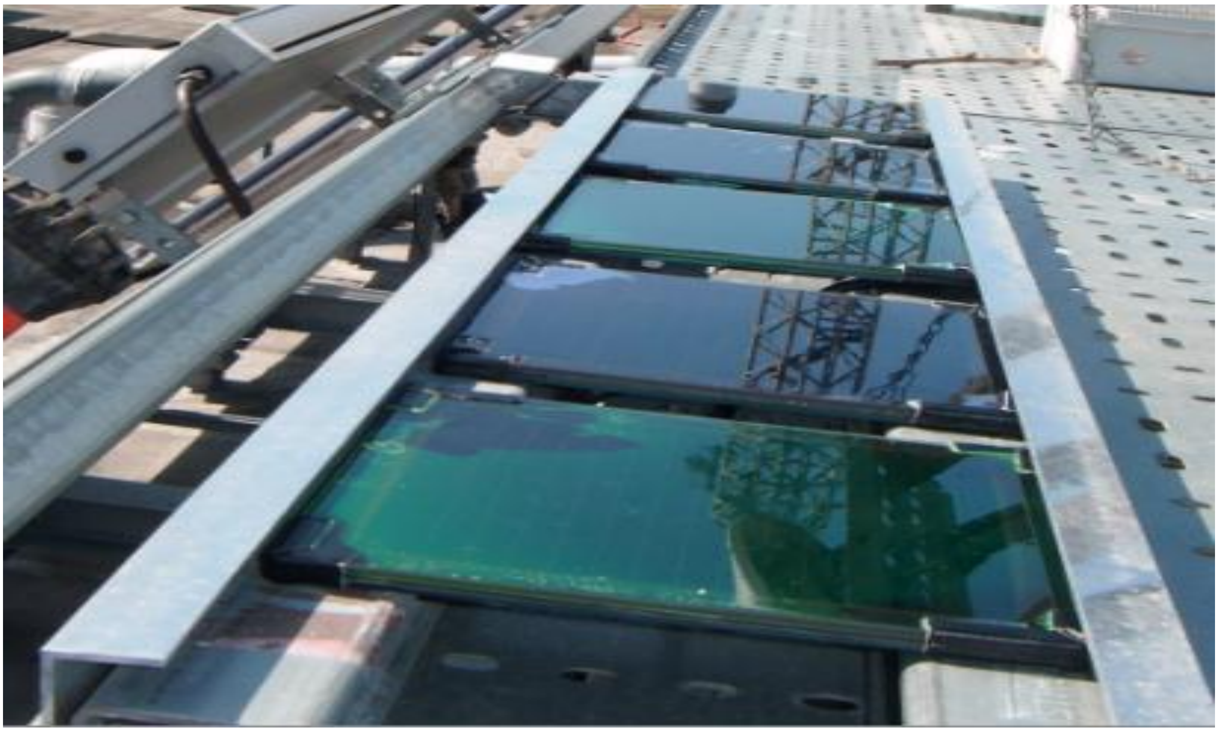

Figure 26 All the Smaller PV Cells Fixed in Position

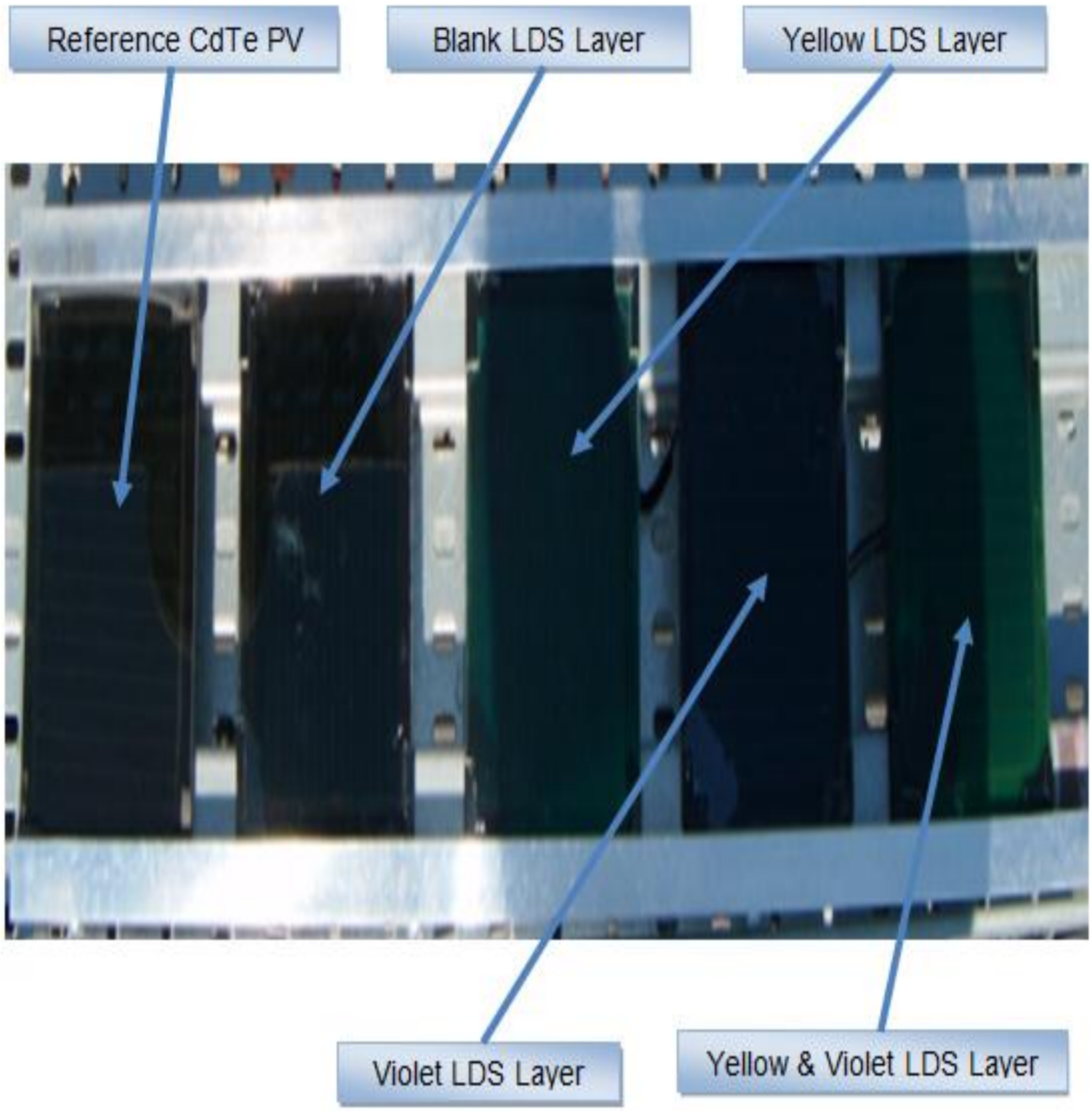

Figure 27 All the Smaller PV Cells Fixed in Position

4.10.4 Step 5

Using 0.75mm² red and black cables, red for positive and black for negative. Each individual PV cell is wired back to the communications box. A number of strategically placed cable ties were wrapped around the underside of the cable tray. The cables are wired from the PV cells to the communications box via the cable ties. This protects the cables and keeps them neat.

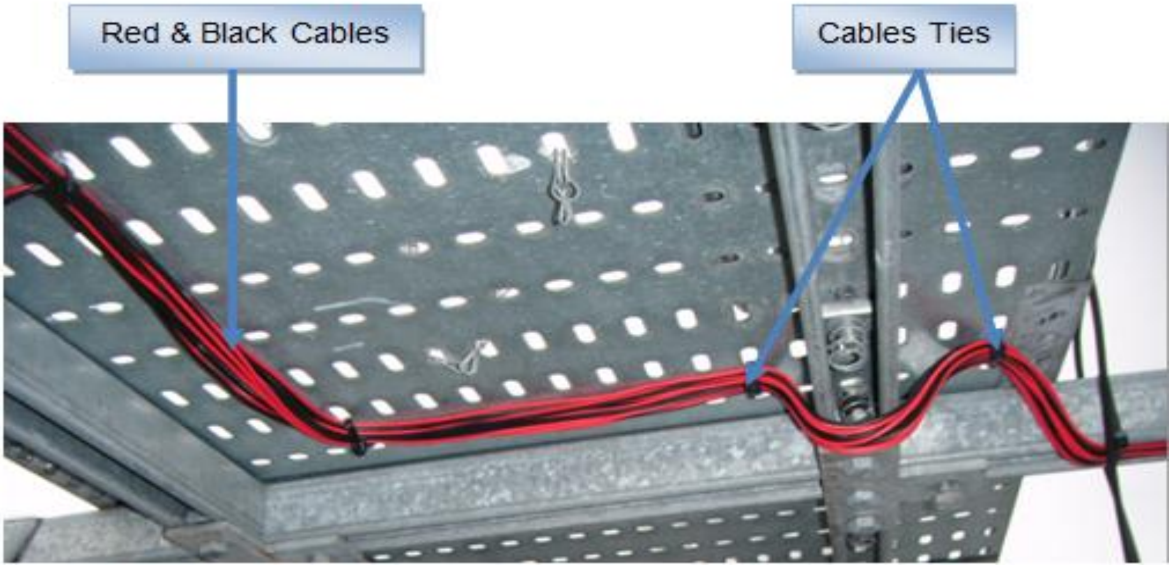

Figure 28 Cables & Strategically Placed Cable Ties

4.10.5 Step 6

A continuity test was performed to ensure the cables are connected to the correct channel of the data logger. One end of each cable is connected to the appropriate channel positive and negative and the opposite ended is connected to the PV cell via a connecter block. Each channel and PV cell has positive and negative connection, red for positive and black for negative the connecter blocks are wrapped in black insulation tape to protect the connection.

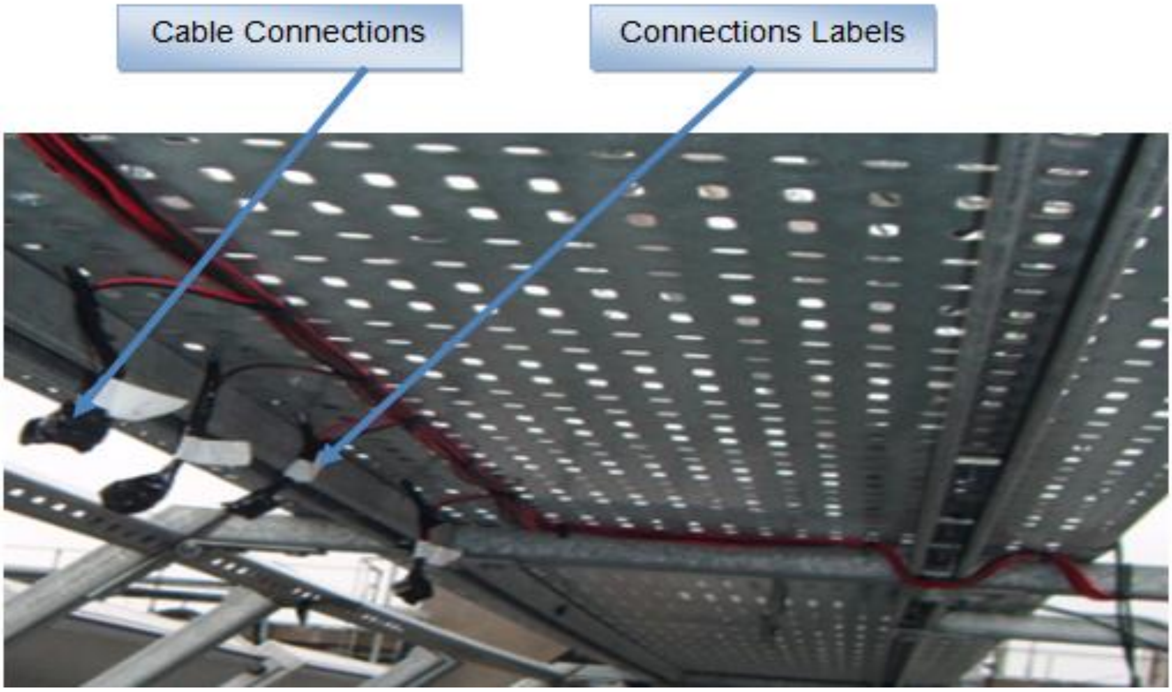

Figure 29 Cable Connections

Test were performed on the connector blocks regulary to see if damp is seeping in. The resistance of the connections and the circuits were measured before and after the project and there was no change in the resistance of any of the circuits.

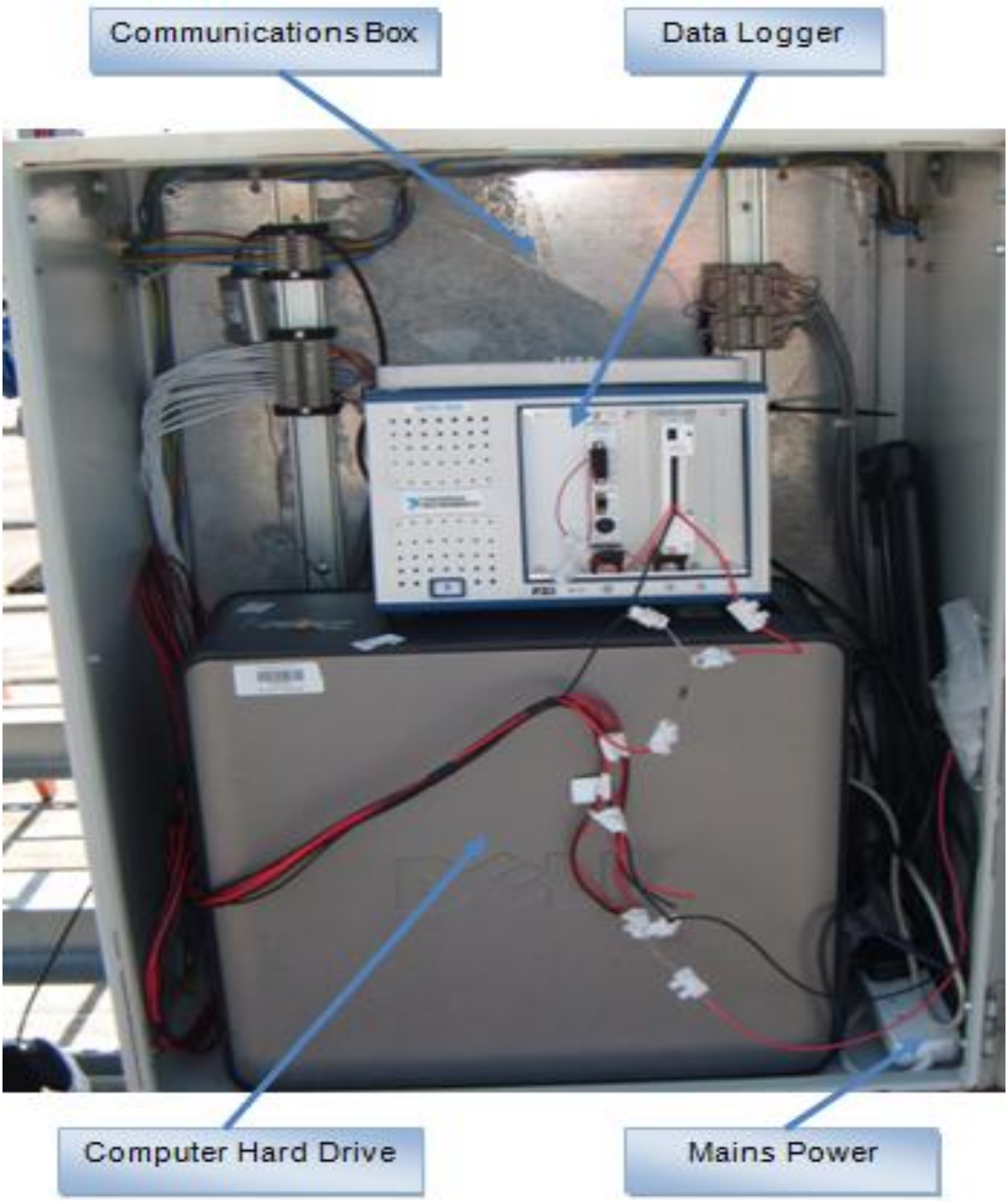

Figure 30 Data Logging Equipment

4.11 Problems Encountered with the Method

4.11.1 First Problem

The first problem was with making the luminescent down shifting layers for the large CdTe PV cells. The large cells are 1200mm long and 600mm wide with a total area of 0.72m². The process of making the LDS layer requires, LDS liquid solution sandwiched in between two sheets of glass and baked for three days at 30°C. This meant that oven for the baking process was too small for the glass sandwich to fit into the oven. The total area of the LDS layers must be equal to or greater than the area of the PV cell.

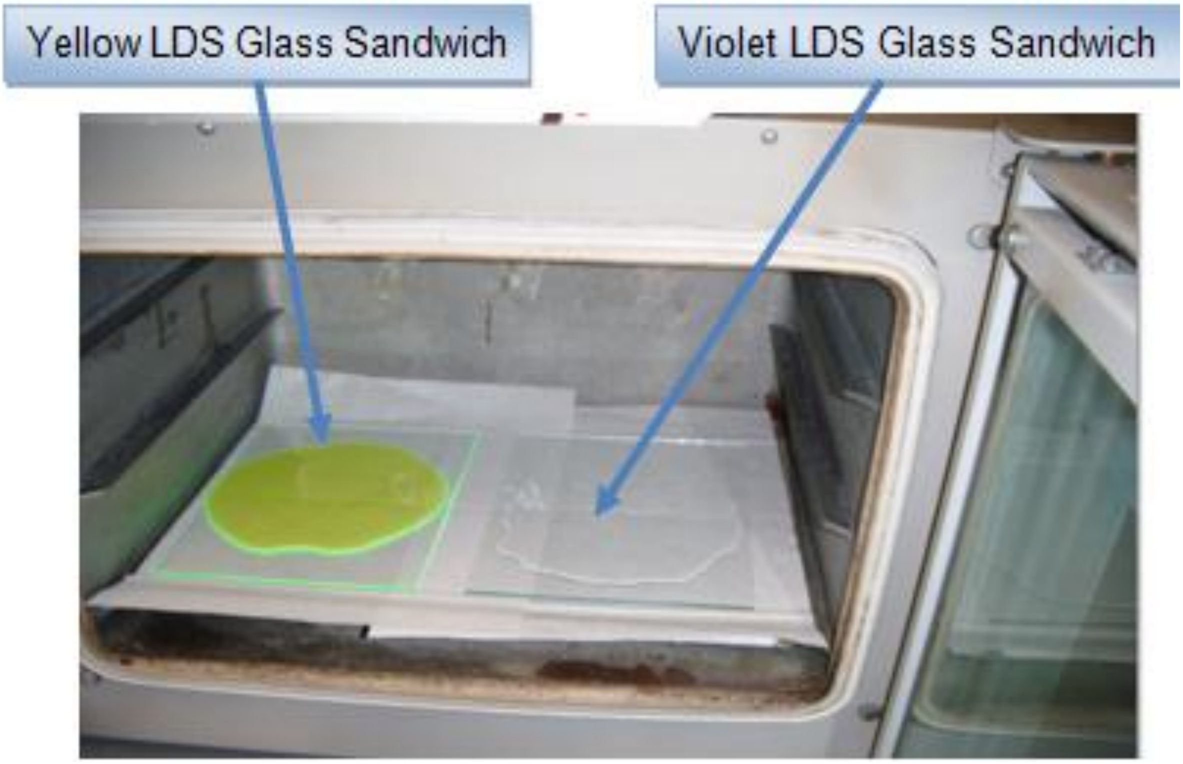

Figure 31 Glass sandwich LDS layers in the Oven

The figure above shows the Lumogen yellow 083 layer and the Lumogen Violet 570 layer in preparation for the baking process. These LDS layers are for the smaller CdTe PV cells. The smaller CdTe PV cells are 150mm long and 150mm wide with a total area of 0.225m². The figure above clearly shows there is only enough square area for two of the smaller CdTe PV cells, therefore there it is clear there would not be enough square area for the large CdTe PV cells glass sandwich to fit into the oven.

4.11.2 Solution to the First Problem

The only solution to this problem is to use an oven with enough square area for the large CdTe PV cells glass sandwich to fit in. At present the DIT do not have a oven large enough to accommodate this process.

This problem was related to the PhD student's scope of the project, therefore it was outside the author's scope of the project and there was nothing the author could do about this problem.

4.11.3 Second Problem

The second problem was with the method of applying the LDS layers to the CdTe PV cells. The method used is known as drop casting the layers, this involves the LDS solution being sandwiched between two glass plates. Once the LDS layers are baked for three days at 30°c the LDS solution becomes a solid thin layer. The glass plates can then be separated from the LDS layer. The separation of the glass from leaves a thin LDS layer as shown in the figure below the LDS layer is then applied to the CdTe PV cells.

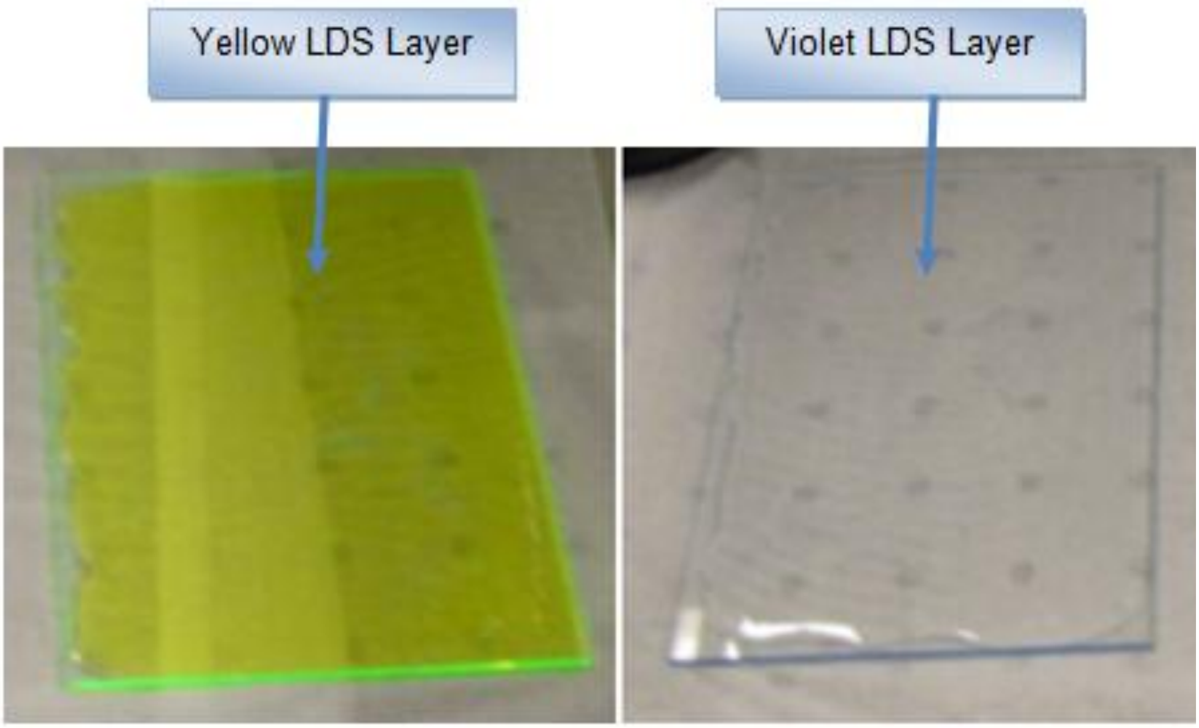

Figure 32 Finished Yellow LDS layer and Violet LDS layer

This method would allow the LDS layers on a solar cell to be changeable, without having to apply the LDS layer permanently onto the solar cell. The problem with this

was the LDS layer would not apply directly to the CdTe PV cell. There was a air gap between the LDS layer and the CdTe PV cell. These air gaps could corrupted the data and reduce the efficiencies in the PV cells.

4.11.4 Solution to the Second Problem

The solution to this problem was to repeat the process of making the LSD layers. This time the LDS layers were directly applied to the CdTe PV cells to prevent any chance of an air gap. The process was the same but instead pouring the LDS solution between two glass plates to form a glass sandwich when baking the layers, The LDS solution was poured directly into the CdTe PV cell and one glass plate was placed on top of the solution and the cell. This was then baked for three days at 30°c the LDS solution becomes a solid thin layer permanently attached to the CdTe PV cell. The integrity of the CdTe PV cell was not affected during the backing process as the max temperature was 30°c.

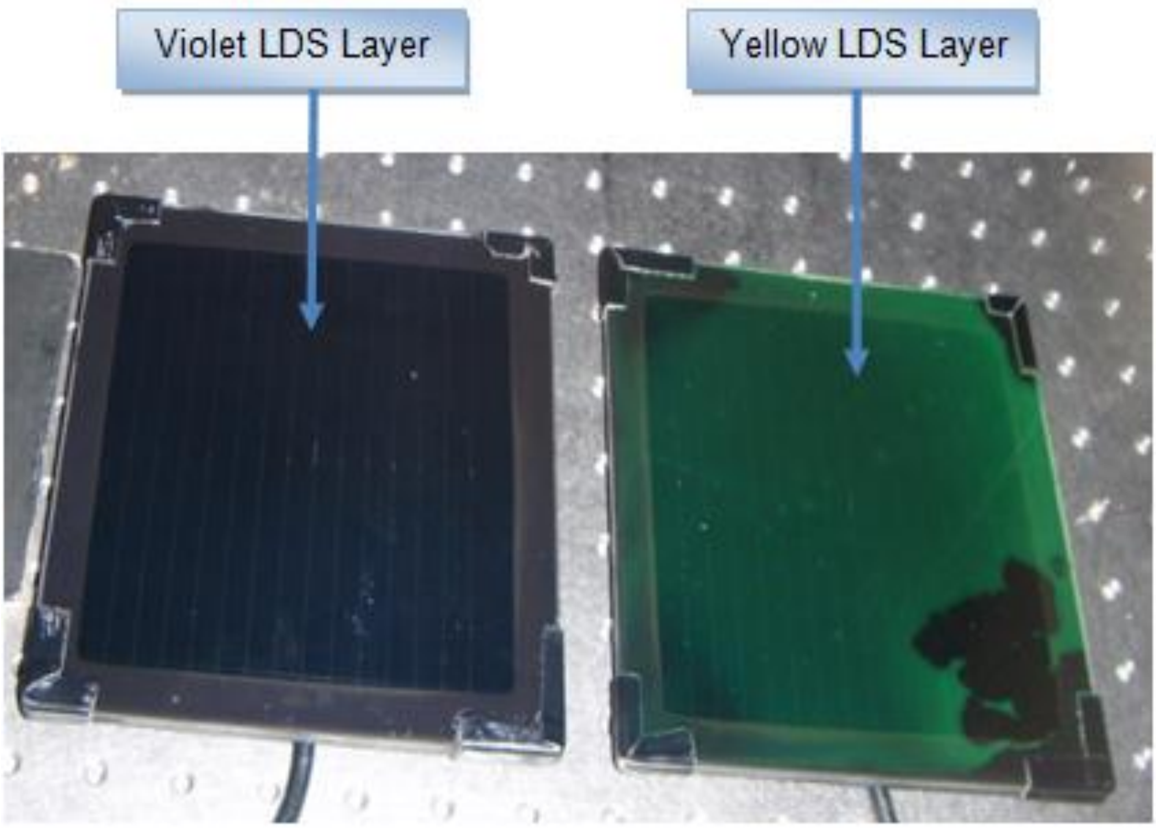

Figure 33 Layers permanently attached to the CdTe PV

4.11.5 Third Problem

The third problem was the buildup of dirt on the PV cells. As the PV cells were fixed horizontally to ground at a 0° angle it was easy for dust and dirt to buildup on the PV cells. Rainwater would not clean the PV cells because there was no angle for the water to run off.

Figure 34 The Difference between the PV Cell When It Dirty & Clean

The figure above shows a PV cell with dirt on the left side of the cell and the right side of the PV cell has been cleaned this picture is just to indicate and give an idea of the problem associated with dirt buildup.

4.11.6 Solution to the Third Problem

The only solution to this problem was to clean the PV cells by hand before recording data. The build-up of dirt on the PV cells would affect the amount of sun light reaching the cells. Therefore, this would affect the output of the cells. This dirt would corrupted data and reduce the efficiencies in the PV cells.

5 Data Collection

5.1 Characterization of LDS layers

The luminescent down shifting layers are characterized in terms of their absorption and emission. The luminescent down shifting layers in question are lumogen yellow 083, lumogen violet 570 and LSD layer using a mixture of lumogen yellow 083 and lumogen violet 570. The reference layer is a blank layer; this is a layer with just the host material PMMA. The absorption and emission of the LDS layers were tested using a PerkinElmer Lambda 900 UV/VIS/NIR spectrometer and a Perkin Elmer Lambda LS55B luminescent spectrometer scanning over of wavelength range of 300nm to 550nm.

5.2 Testing the Absorption of the LDS Layer

Where the electrons of the LDS layers absorb light or radiation energy this is known as absorption. Absorption is the ability of the LDS to absorb light or radiation that makes them transition into a higher energy state. Absorption is used to determine the absorption level of layers and their ability to retain heat. Absorption spectrum is the plotting of the energy that is absorbed by layers. The absorption of the LDS layers are plotted against wavelength.
(info, 2014)

Figure 35 Perkin Elmer Lambda 900 UV/VIS/NIR Spectrometer

A Perkin Elmer Lambda 900 UV/VIS/NIR Spectrometer was used to test the absorption of LDS layers. The Spectrometer has a double beam. The double monochromator ratio recording system has pre-aligned tungsten-halogen and deuterium lamps as sources. The range of wavelengths over which the device operates is 175nm to 3300nm with an accuracy of 0.08nm.

This Perkin Elmer Lambda uses light in the visible and adjacent (near ultraviolet and near infrared) ranges. The absorption in the visible ranges directly affects the colour of the Layers. In this region of the electromagnetic spectrum, molecules undergo electronic transitions. A broadband light source is passed through a grating monochromator. This has a narrow band of radiation, which is divided by the beam splitter. The beams travel through the reference and sample channels. Any absorption of the reference layer is subtracted from the absorption of the sample LDS layer. This will give the adsorption of the sample LDS layer.

(Ahmed, 2013) (focas, 2014) (Walshe, 2013)

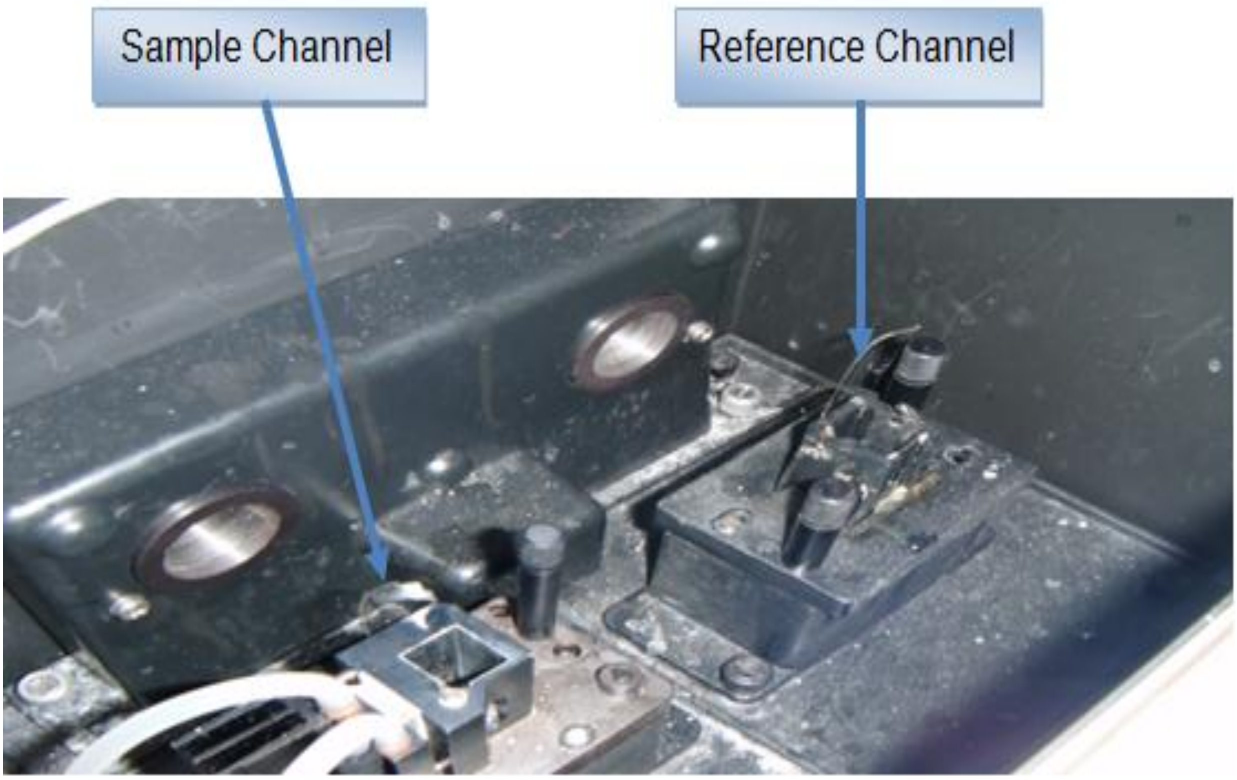

Figure 36 Blank layer (PMMA) in the sample and reference channel

To begin testing, the spectrometer needed to be switch on 15 minutes prior to the experiment to allow spectrometer to warm up. Using the preinstalled spectrometer software, open the software and adjust the scanning wavelength range to be 200nm to 900nm as the absorption range. Enter the number of samples required and label them appropriately i.e. blank layer (PMMA), yellow, violet and mixed yellow and violet.

First, a reference spectrum must be taken to ensure that any absorption is due to the Organic dyes incorporated into the LDS layers. For this reason two blank layer (PMMA) are fixed into the sample and reference channel of the spectrometer.
The spectrometer will then scan the range of wavelengths selected and store the reference spectrum data. After this, the rest of the layers containing organic layers will have the reference spectra subtracted from them. The subtraction of the reference layer will give the true absorption spectra of the organic layers.

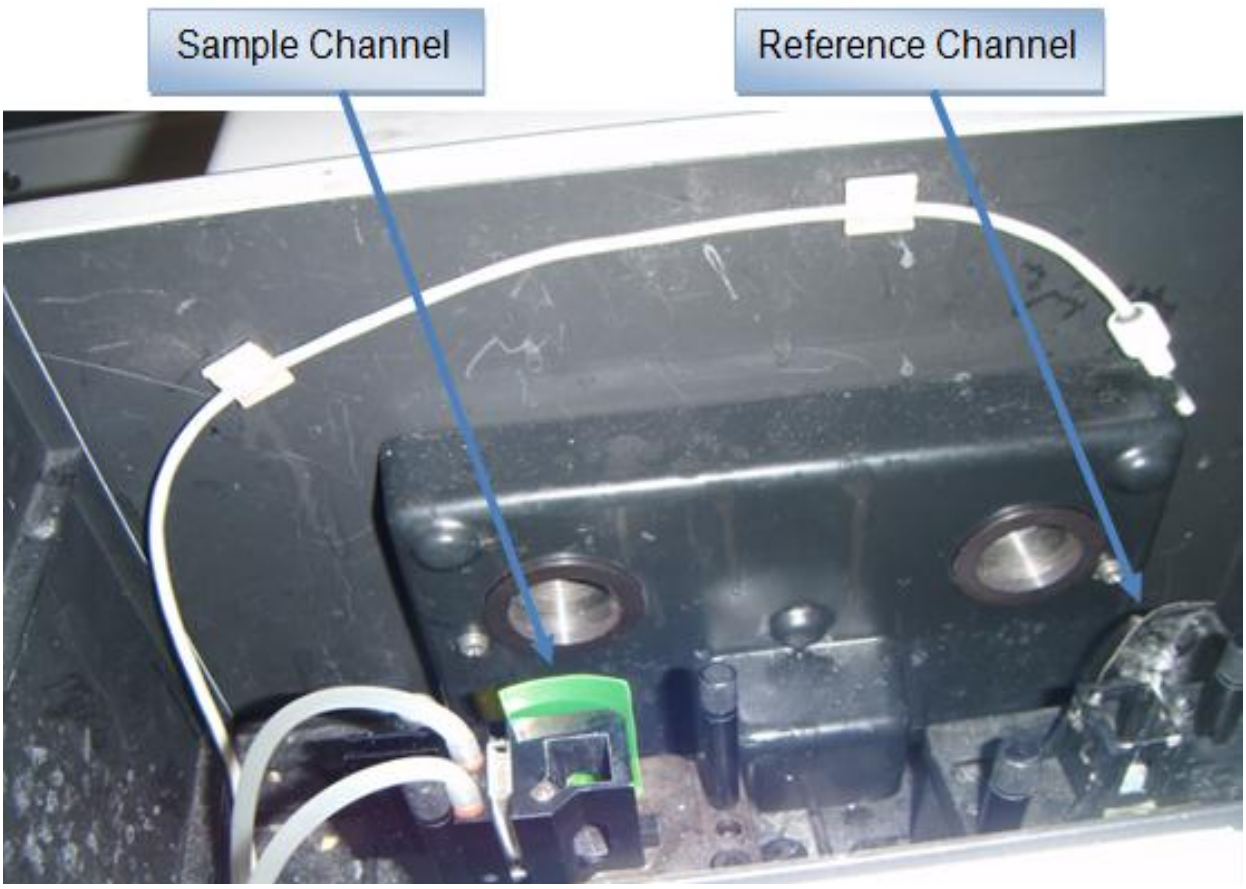

Figure 37 Yellow layer in the sample channel & PMMA layer in the reference channel

Ensuring the blank layer is in the reference channel, load the organic layer in the sample channel. It is vital that the layers are in the same passion for each test to reduce the possibility of corrupting the data. To reduce the chances of corruption happening 3 absorption spectra were taken and the average spectra was used. This process is repeated for all the LDS layers. The data was saved to a Microsoft Excel sheet where it could be analyzed and the data could then be plotted in graphs. The peak absorption wavelength for each organic layer (yellow, violet and a mixture of the 2) was required for measuring the emission spectra therefore a note was taken.
(Ahmed, 2013) (focas, 2014) (info, 2014) (Walshe, 2013)

5.2.1.1 Testing the Emission of the LDS Layer

Emission is the opposite of absorption, emission is the ability of a substance to give off light, when it interacts with heat. Every substances reacts differently when it interacts with light. When heat, energy or light is applied to a substance, some of the molecules transition into a higher energy state or an excited state. During this state the molecules are unstable and try to emit the energy in order to reach the state of equilibrium. The molecules emit energy in the form of photons or light. The difference between the substance in ground state and excited state is then used to determine the emission level of the substance.
(info, 2014)

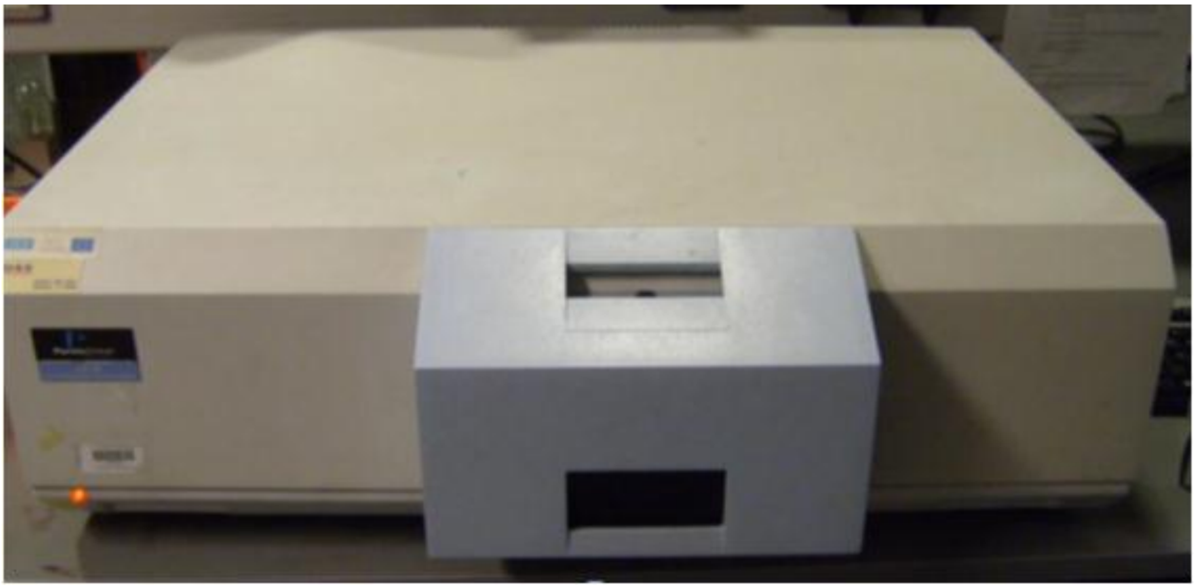

Figure 38 Perkin Elmer Lambda LS55B Luminescent Spectrometer

The Perkin Elmer Lambda LS55B Luminescent Spectrometer was used to test the emission of the LDS layers. Excitation is provided with a pulsed Xenon discharge lamp. This passes light through a Monk-Gilleson type monochromator. The Monk-Gilleson monochromator is scanned over a range of 200nm to 800nm. The light emitted by the sample is passed through a similar monochromator with a range of 200nm to 900nm. The Luminescence spectrometer can provide two types of Fluorescence measurements. The excitation wavelength can be constant and the emission monitored over a range of wavelengths. The detector can be constant emission wavelength and the excitation is monitored over a range of wavelengths.

(Ahmed, 2013) (focas, 2014) (Walshe, 2013)

To begin testing, the Luminescence spectrometer needed to be switch on 15 minutes prior to the experiment to allow Luminescence spectrometer to warm up. Load the LDS layer onto the sensor holder, making sure the LDS layer is in place close the cover on the Luminescence spectrometer. Using the preinstalled Luminescence spectrometer software, open the software and adjust the operating range of the wavelengths to 300nm to 550nm. The peak absorption wavelength for each organic layer is now required as the excitation wavelength chosen must be close to the wavelength of peak absorption for optimal results. This is vital, as corrupted data can be a result of the wrong excitation wavelength chosen. The data was saved to a Microsoft Excel sheet where it could be analyzed and the data could then be plotted in graphs.

(Ahmed, 2013) (focas, 2014)

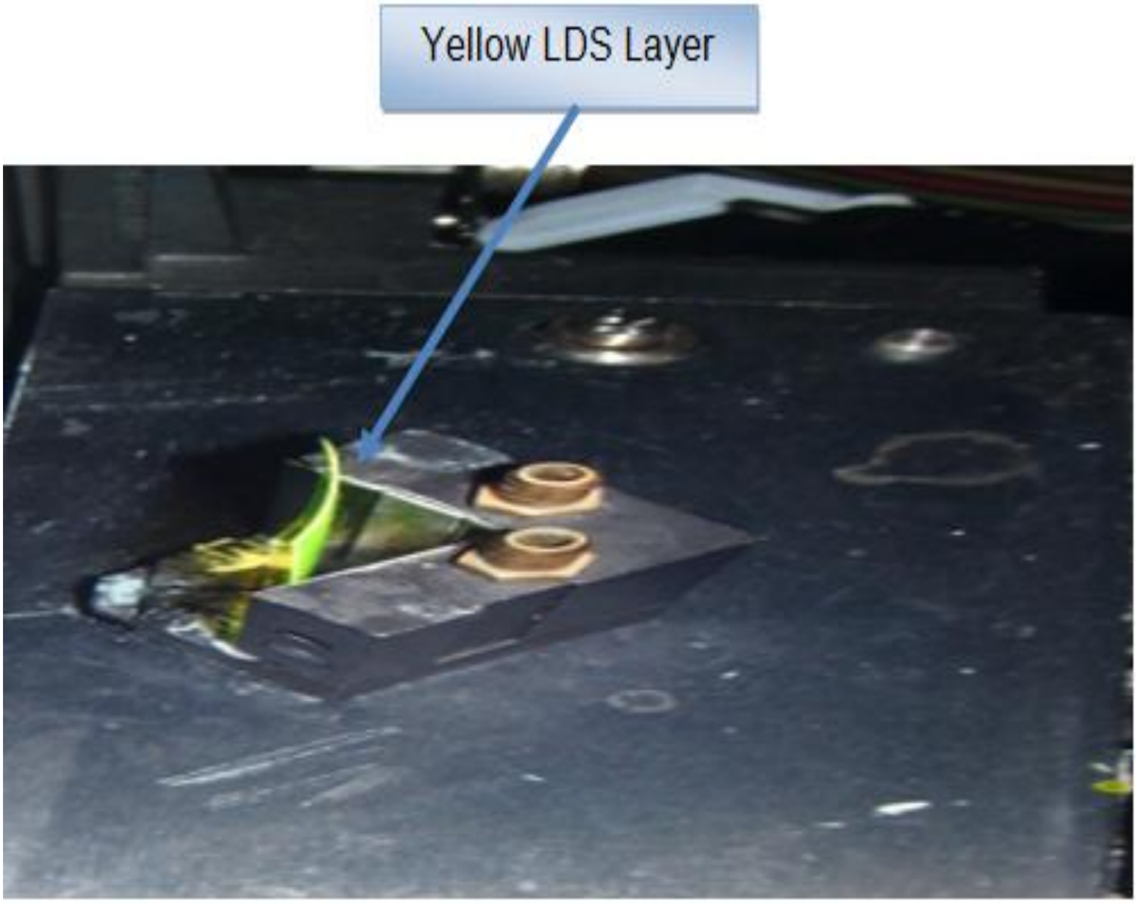

Figure 39 The Layer inside the Luminescent Spectrometer

The figure above shows a sample piece of the LDS layer in the Luminescent Spectrometer chamber. This was done for all the LDS layers, it was vital to make sure the LDS layer was fixed correctly to prevent it from falling over and to insure the quality of the data.

5.3 Indoor characterization

The indoor tests were performed in the laboratory in the DIT focus building. The PV cells were characterized in terms of their electrical properties. The test conditions for the indoor test was set up manually using a solar simulator (Griven lighting) to try recreate sun light conditions. A Keithley 2400 source meter was used to record the outputs of the PV cells. The Keithley 2400 source meter was connected to a desktop computer via a USB cable / connection. The connection provided a user Labview interface (Labview 2010), to adjust setting, monitor and record the output readings.

A pyranometer was used to accurately measure broadband solar irradiance of the solar simulator. To get a light Intensity / Irradiance of 1000 W/m² the distance of the solar cell would need to be in the correctly possession. By adjusting the distance of the pyranometer away from the solar simulator and recording the reading, it was possible to establish the distance between the solar cell and the solar simulator to give a light Intensity / Irradiance of 1000 W/m². The solar simulator and the PV cell platform were than fixed in position and they remained in the same position throughout the testing process.

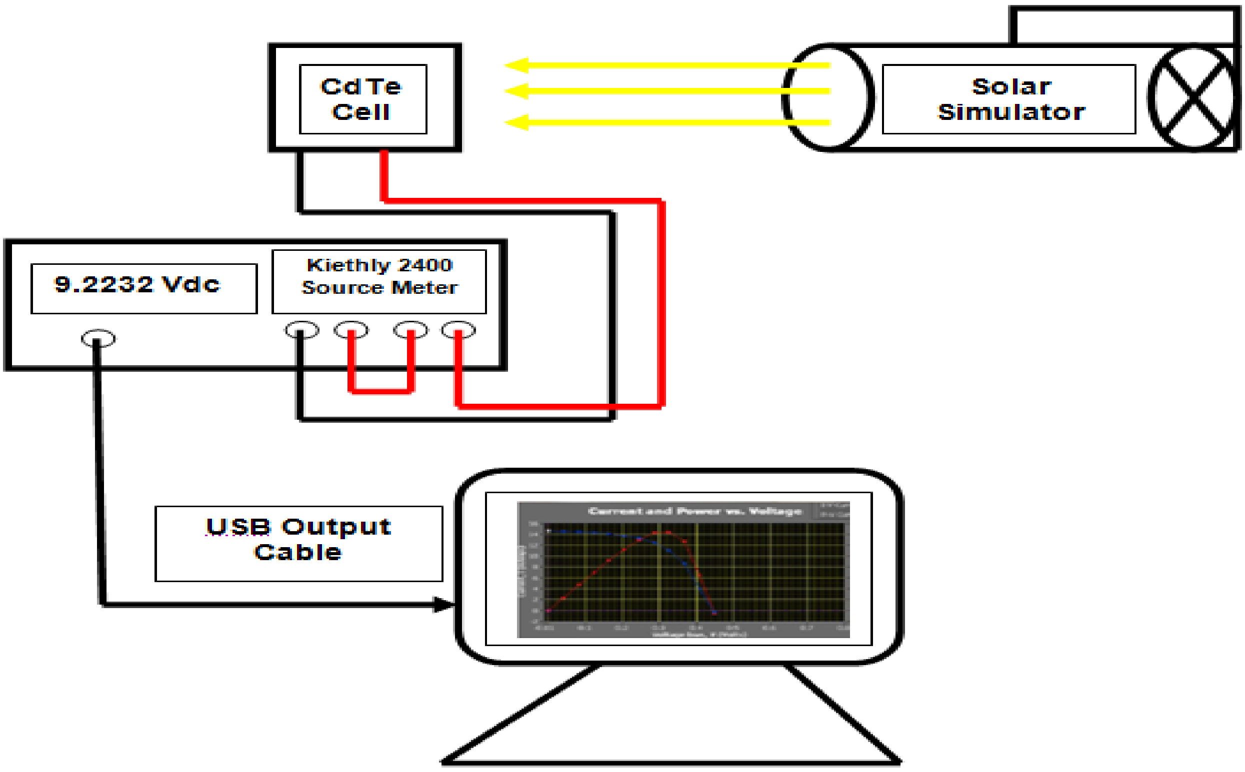

Figure 40 Schematic Diagram of the Indoor Test Setup

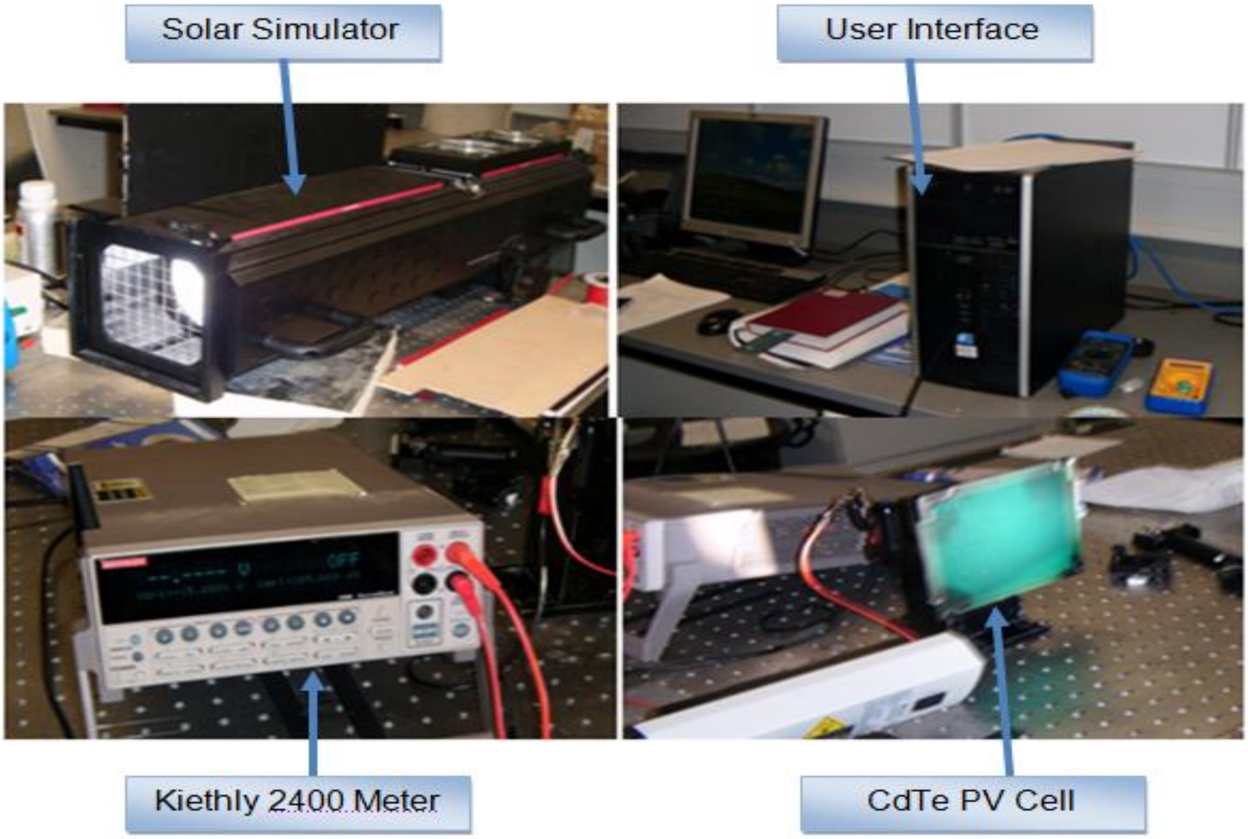

Figure 41 The Equipment Required for the Indoor Testing

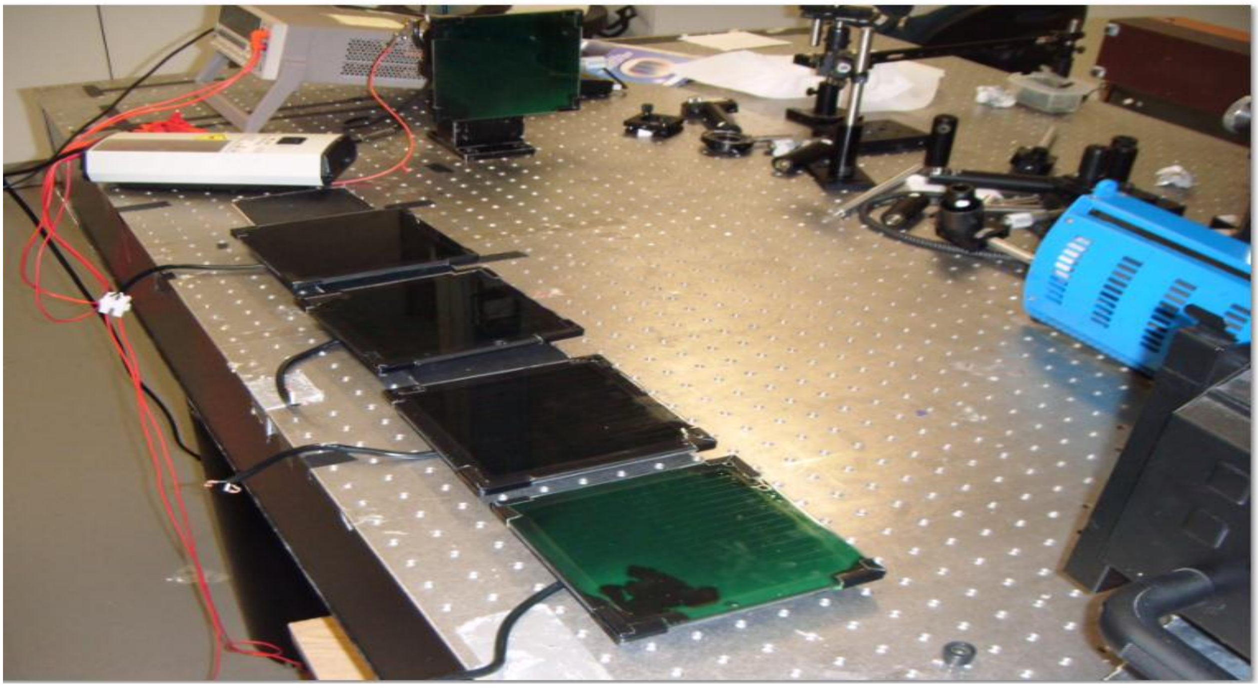

Figure 42 Indoor Testing Setup

Once the indoor setup was fixed and in position, the testing could begin. The CdTe PV cell was the reference cell for these tests. The same tests were performed on the all the different cells, the reference CdTe PV cell, the blank layer (PMMA), yellow layer, violet layer and mixed yellow and violet layer. The electrical properties of the cell are monitored by the Labview interface (Labview 2010), using the 'Solar cell IV sweep modified NI-DC power' software. The figure below shows the output of the reference CdTe PV cell on the user Labview interface.

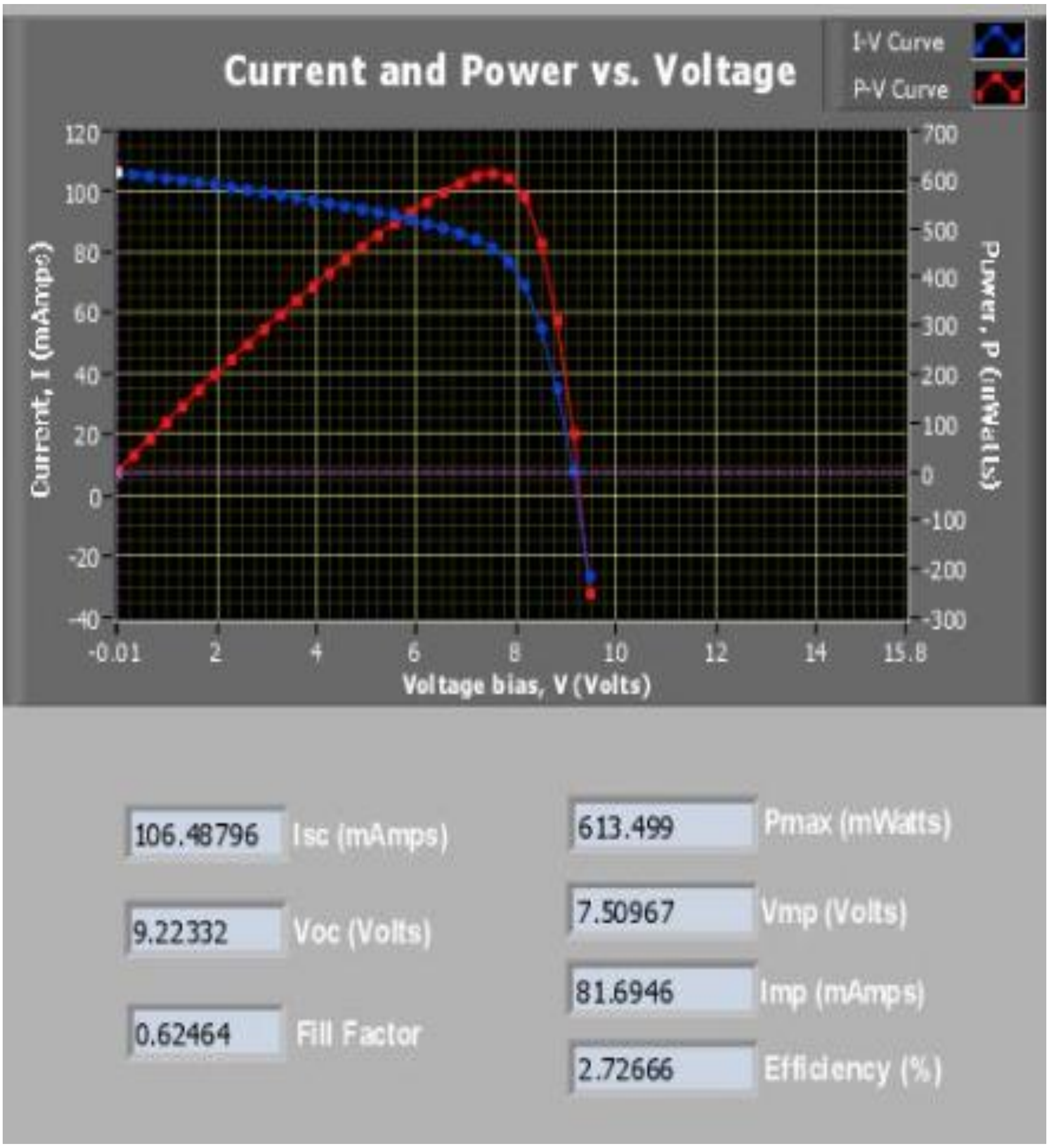

Figure 43 Output of CdTe PV cell on Labview interface

5.3.1 Test settings for the PV CdTe Cells

- Source Mode = Voltage
- Minimum Voltage = 0 Vdc
- Maximum Voltage = 16 Vdc
- Number of points = 50
- Measurement speed = 1 (PLC)
- Light Intensity/ Irradiance = 1000 W/m²
- Area of Solar Cell = 225 cm²
- Delay before measurement = 3 seconds
- Delay between each point = 0.04 seconds

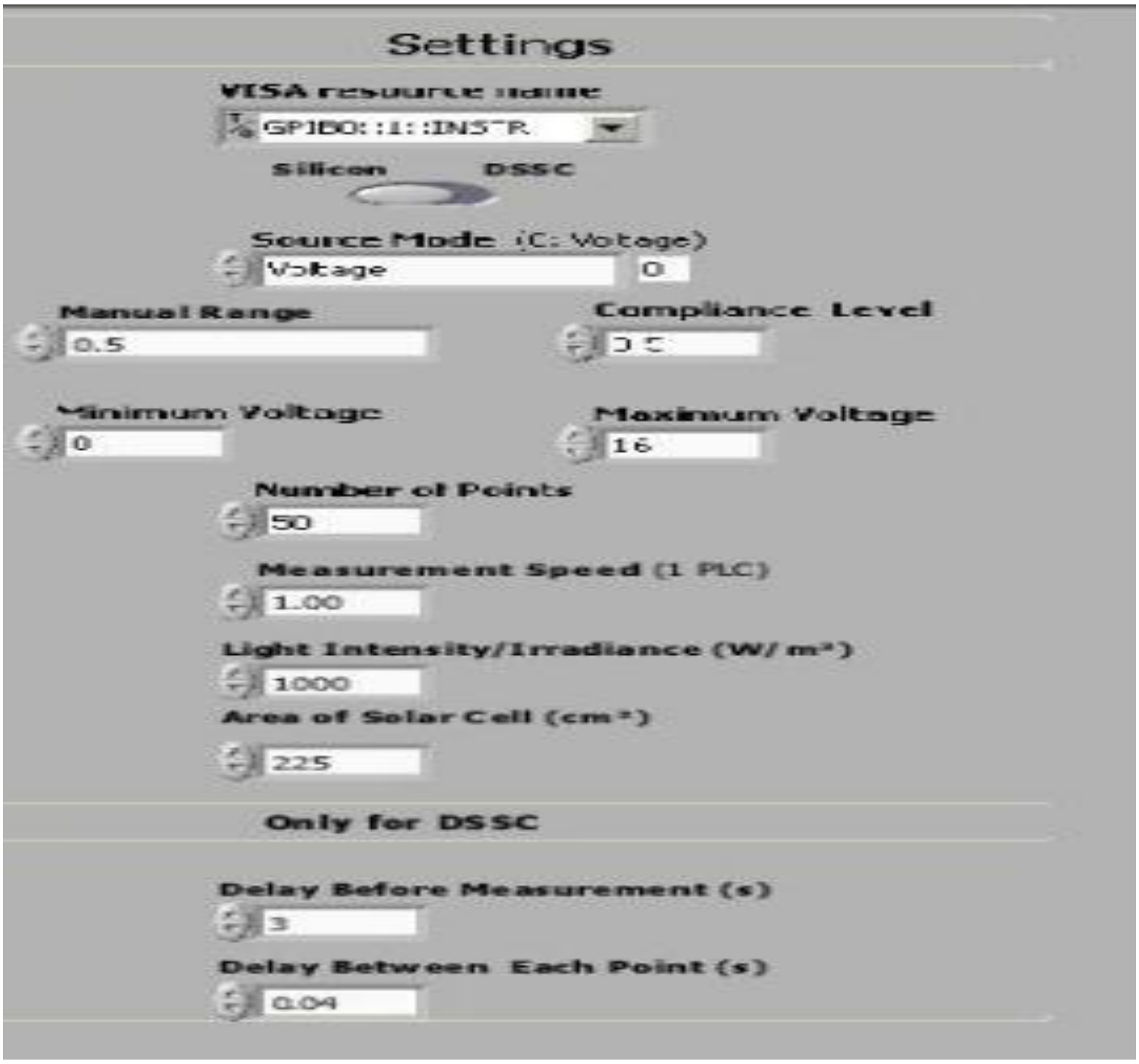

Figure 44 Test sittings for the solar sweep software

Once Labview interface settings were set to the test conditions, the program displayed the IV and PV curve for the cell tested and a table containing the Fill factor, open circuit voltage, short circuit current, and point of maximum power. These process the same for each PV cell. To ensure that the tests were accurate the readings were taken three times for each cell. The data was saved to a Microsoft Excel sheet where it could be analyzed and the data could then be plotted in graphs.

- The reference CdTe PV cell
- The blank (PMMA) layer CdTe PV cell
- The Yellow LDS layer CdTe PV cell
- The Violet LDS layer CdTe PV cell
- The mixed Yellow & Violet LDS layer CdTe PV cell

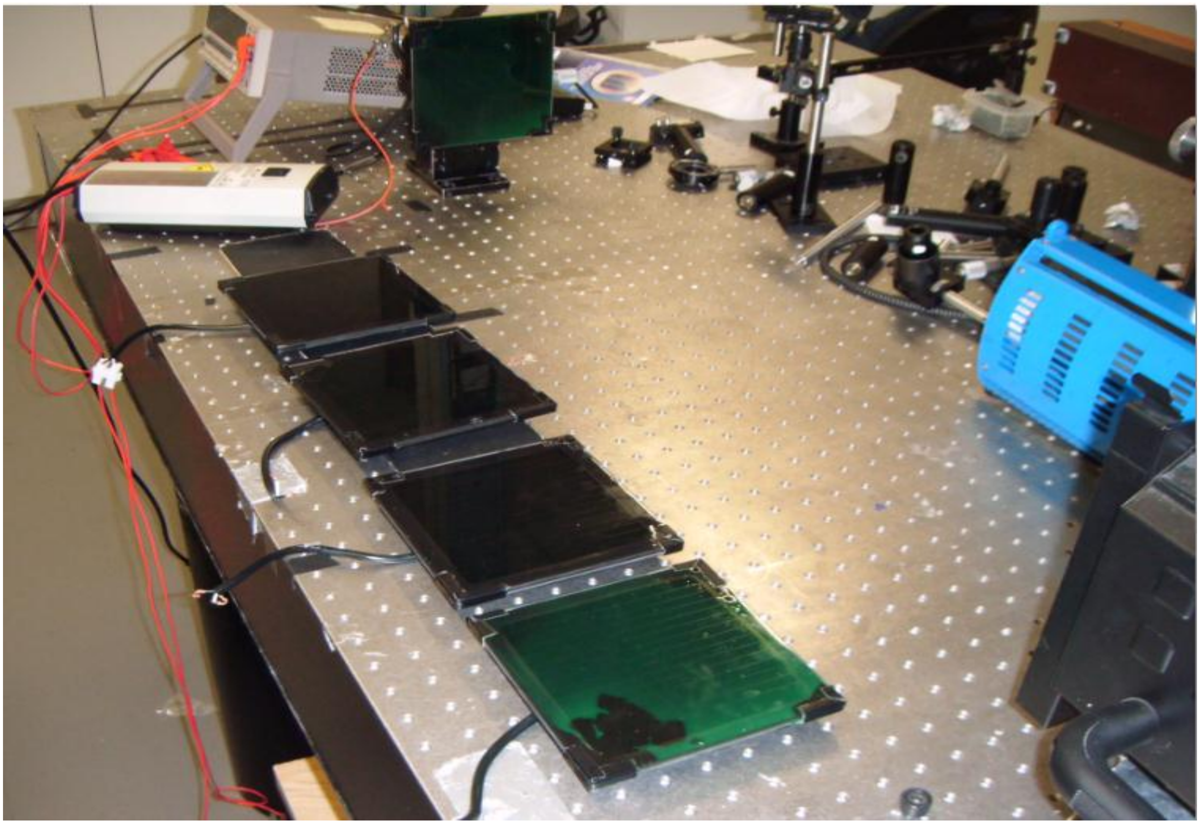

Figure 45 Indoor Testing Setup

5.4 Outdoor characterization

Once all the reference CdTe PV cell, blank (PMMA) layer CdTe PV cell, yellow LDS layer CdTe PV cell, violet LDS layer CdTe PV cell and the mixed yellow & violet LDS layer CdTe PV cell were in place on the roof of the DIT Kevin St building the testing could begin. The PV cells are characterized in terms of their electrical properties. The test conditions for the outdoor tests were set up manually with the PV cells are installed on the horizontal platform using natural sun light conditions to energize the PV cells.

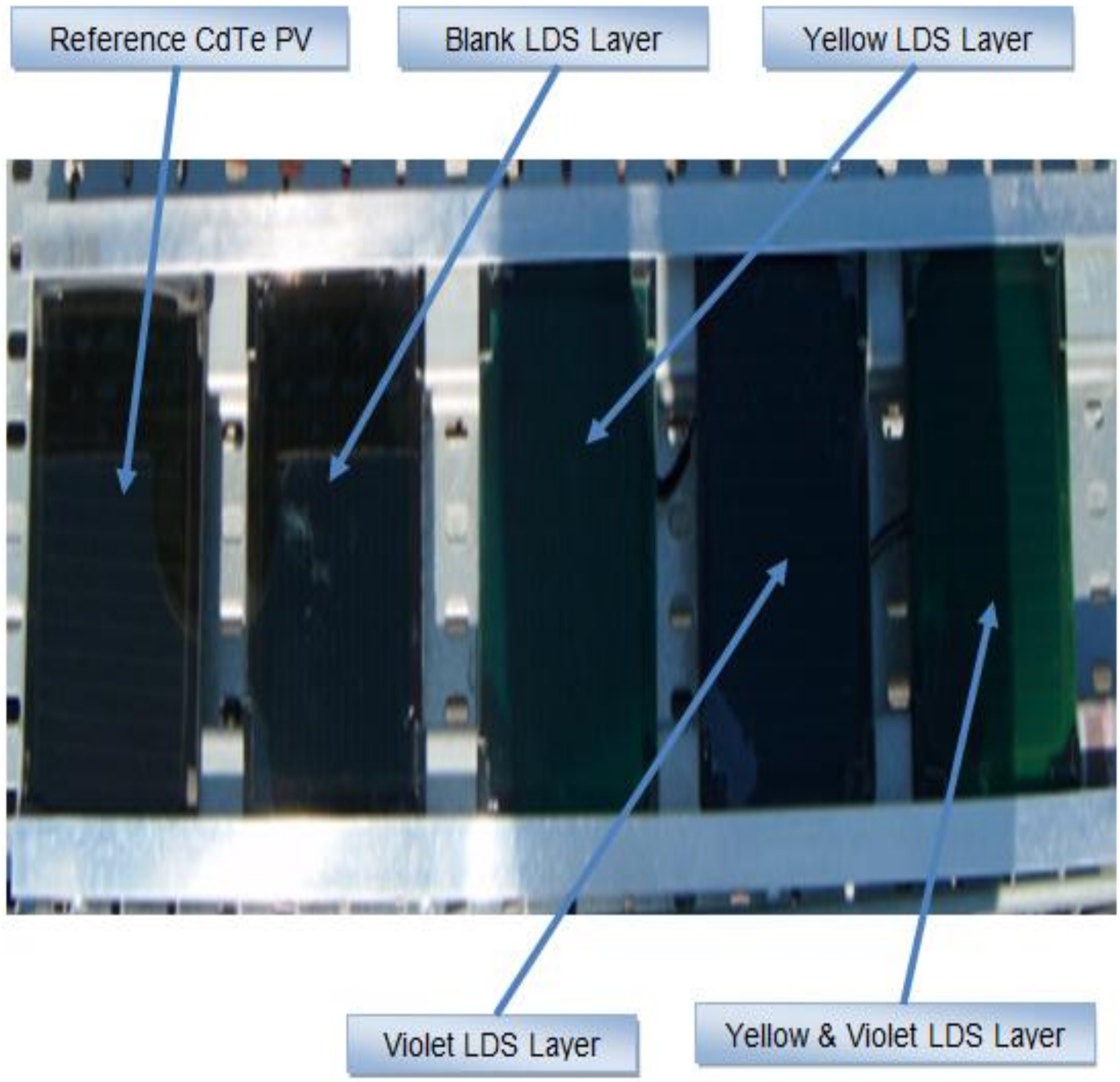

Figure 46 Outdoor Testing Setup

The PV cells are individually connected to a National Instruments PXI-1033 dada logger. The National Instruments PXI-1033 is designed for remote control applications. The PXI-1033 provides a transparent remote link up, which makes it ideal for both portable and desktop systems therefore the data, could be viewed anywhere via the internet. The National Instruments PXI-1033 dada logger was connected to a hard drive computer in a external meter box of the roof of Kevin St building. The remote connection provided a user interface (Labview 2010), to adjust setting, monitor and record the output readings.

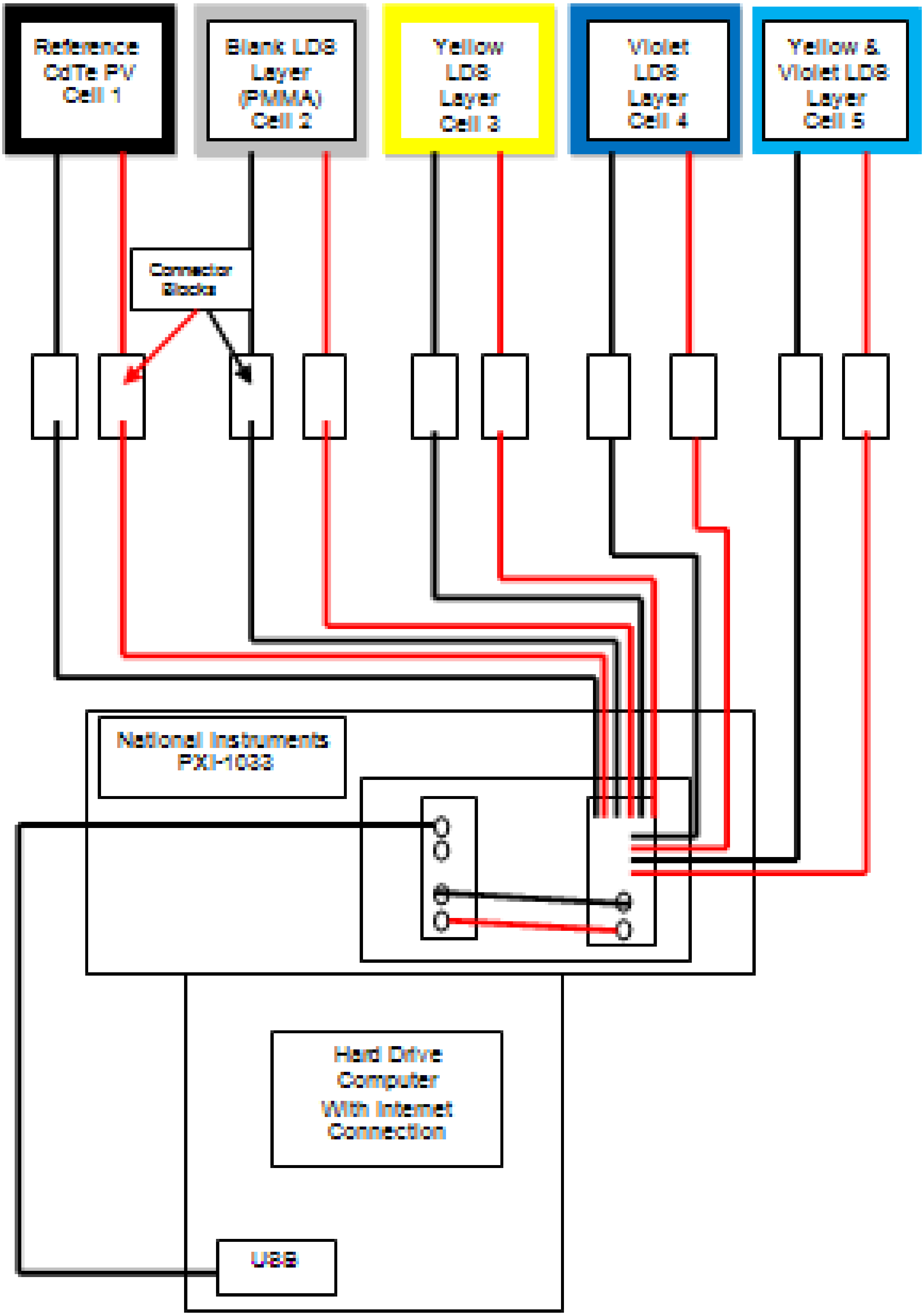

Figure 47 Schematic Diagram of the outdoor Test Setup

Figure 48 Cable connections and the data logger

5.4.1 Parameter Settings

Number of Channels = 5

Voltage Start Level = 0 Vdc

Voltage Stop level = 20 Vdc

Points = 50

Samples per Points = 300

Display between Points = 10.15

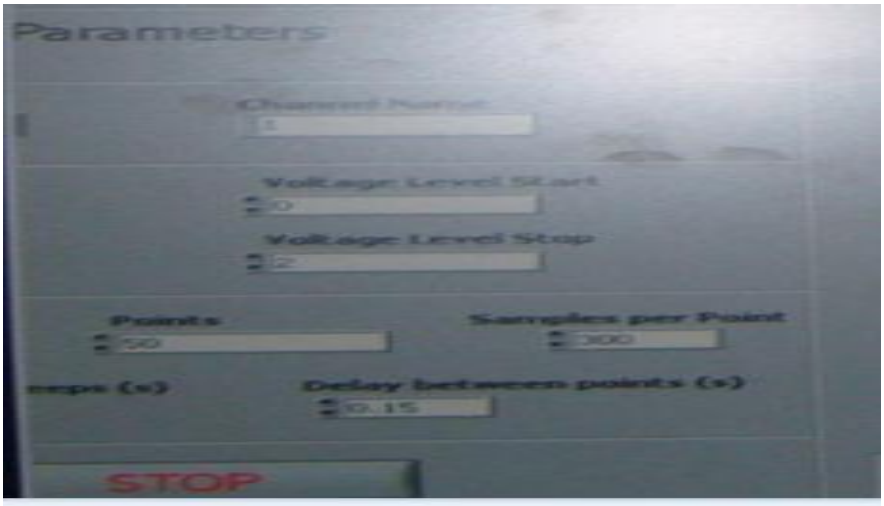

Figure 49 Parameter Settings

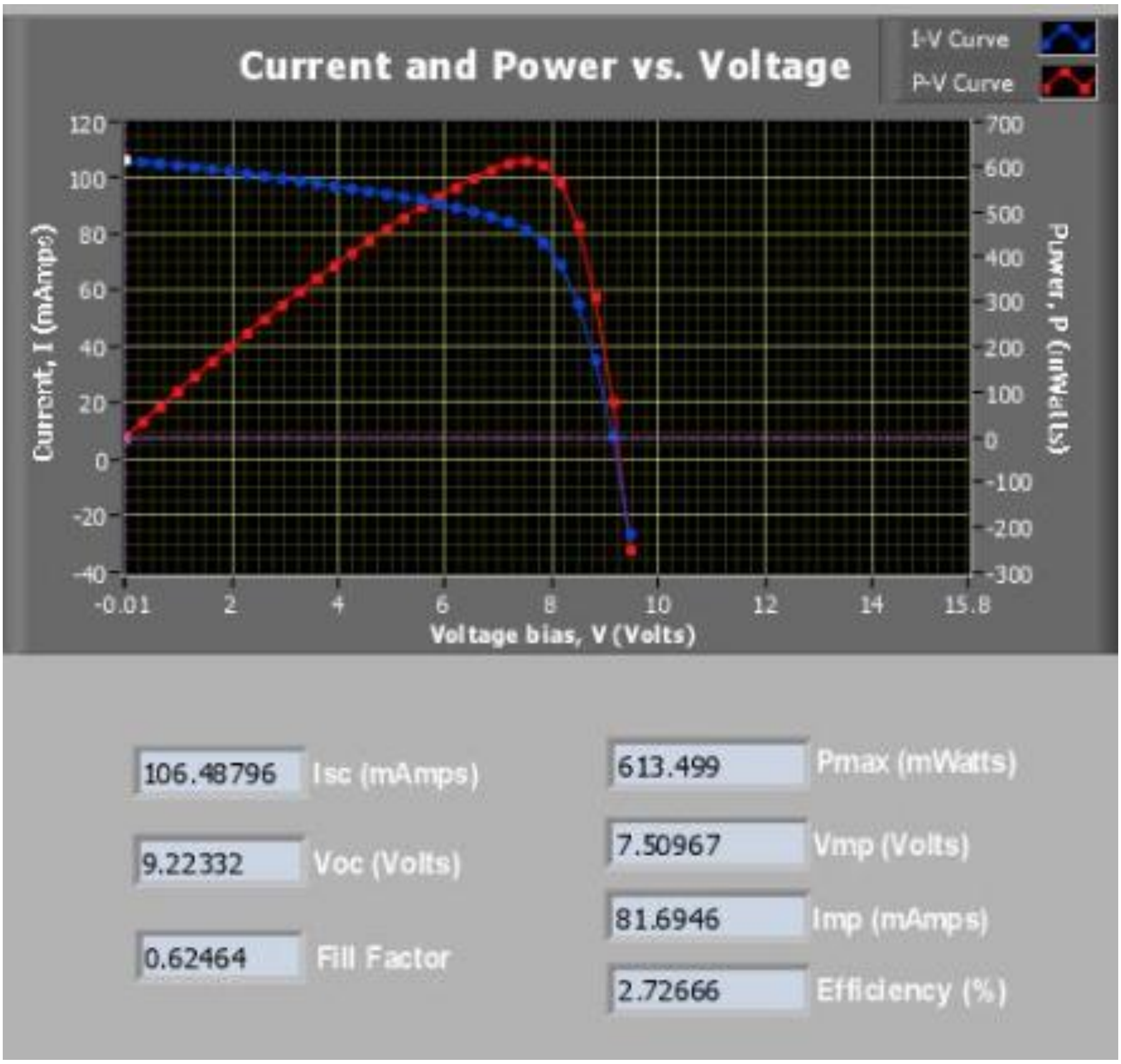

Figure 50 “Expected” Labview interface output reading

The data is logged using Labview interface, allowing values to be recorded every 15 seconds. Once Labview interface settings were set to the test conditions, the program displayed the IV and PV curve for the cells and widgets (text boxes) containing the Fill factor, open circuit voltage, short circuit current, and point of maximum power. This process would record every PV cell simultaneously every 15 seconds and the data would be recorded. The data is saved to a Microsoft Excel sheet where it could be analyzed and the data could then be plotted in graphs.

5.5 Weather Data

Weather data is vital information when measuring the CdTe PV cells performances The PV cells are expected to perform best in conditions where sun light is at its peck. Therefore, the PV cells output will be effected in cloudy conditions and will work best in clear natural sun light. The PV cells work more efficiently on lower temperature. The output of the PV cell is better when it’s clear and cold rather than when it’s sunny and warm. This is not likely to be a factor for this project as the ambient temperature in Dublin during the summer months is 17°C to 20°c. Mist and fog will also affect the output of the PV cells as the mist and fog will reduce the amount of sun light reaching the surface area of the PV cells. When analyzing the data on the PV cells the different outputs of the PV cells can be compared to the different weather conditions at that time, this will give a more informative indication of how the PV cells are behaving.

There is a Davis Vantage Pro2 wireless weather station is installed on the roof of the DIT Kevin St building. The weather station features forecasting, on-screen graphing, integrated sensor suite, which combines a rain collector, temperature and humidity sensors, and anemometer.

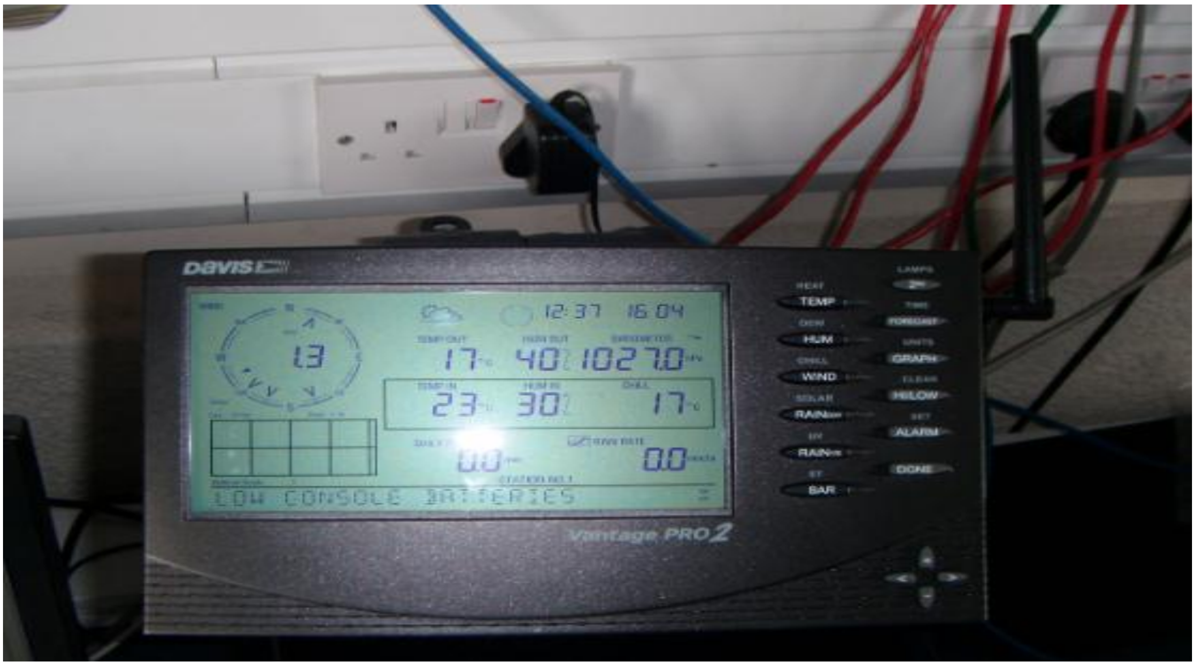

Figure 51 Davis Vantage Pro2 Indoor Unit

Figure 52 Davis Vantage Pro2 Outdoor Unit

The Electronic components are housed in a weather-resistant shelter. The Sensor suite is solar powered. The temperature and humidity sensors are housed inside a radiation shield for improved accuracy. The shield protects against solar radiation and other sources of radiated and reflected heat. The console screen has quick view icons show the forecast at a glance sunny, partly sunny, cloudy, rain or snow while a moving ticker tape display gives more details. The data is saved to a Microsoft Excel sheet where it could be analyzed and the data could then be plotted in graphs. (Instruments, 2014)

5.6 Problems Encountered

The biggest challenge of this dissertation was the problem that arose with the National Instruments PXI-1033 data logger. The National Instruments PXI-1033 is designed for remote control applications, it provides a transparent remote link up, which makes it ideal for the roof on the Kevin St building because the data can be view from anywhere. The National Instruments PXI-1033 data logger had been previously used by the PhD student for a project last year and the logger proved very successful and user friendly. The one thing that was over looked by the PhD student was the voltage range of this logger. The max voltage PXI-1033 data logger could log is 6 volts dc. The CdTe PV cells voltage range exceeds the voltage range of PXI-1033 data logger, therefore the XI-1033 could not log the data from the CdTe PV cells. When the PXI-1033 data logger was logging the output of the CdTe PV cells the data user interface was displaying corrupted data. This data was unusable for this reason.

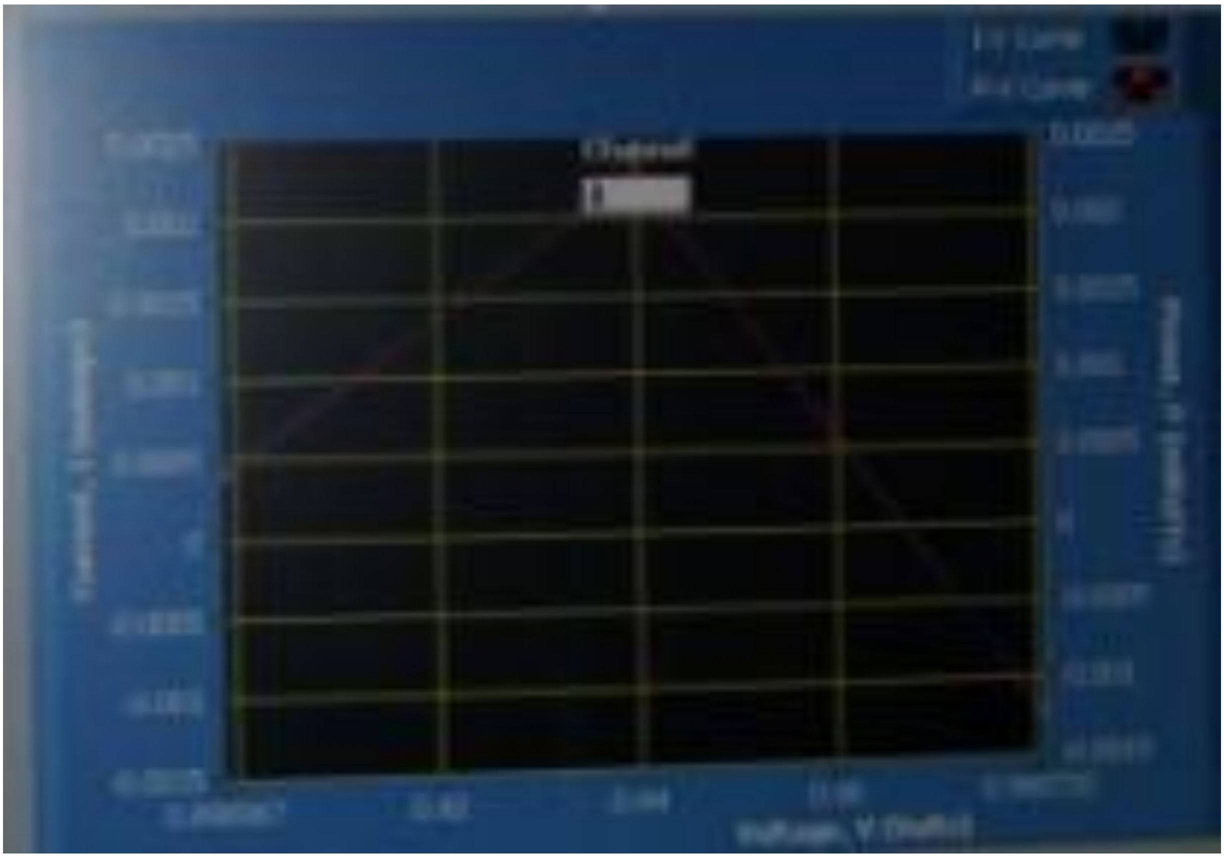

Figure 53 Corrupted data

The data logger was the responsibility of the PhD student's and it was not within the author's part project to have such equipment or acquire large equipment, therefore it was outside the author's scope of the project and there was nothing the author could do about this problem. When this problem became known, it was too late to get a new data logger because of the cost involved and the time it would to go through the necessary channels involved in acquiring one. For this reason different ideas were used to try solve the problem such as resistors multiplier.

A multiplier resistor was put in series with the data logger to reduce the voltage by a ratio of 10:1 with the idea that the data logger could than record the output of the CdTe PV cells then. The multiplier resistor in series with the logger creates a voltage divider with the loggers internal resistor, reducing the voltage which basically gives the logger a larger range, therefore the multiplier resistor is in actuality multiplying the range of the data logger and allowing the data logger to record a higher voltage.

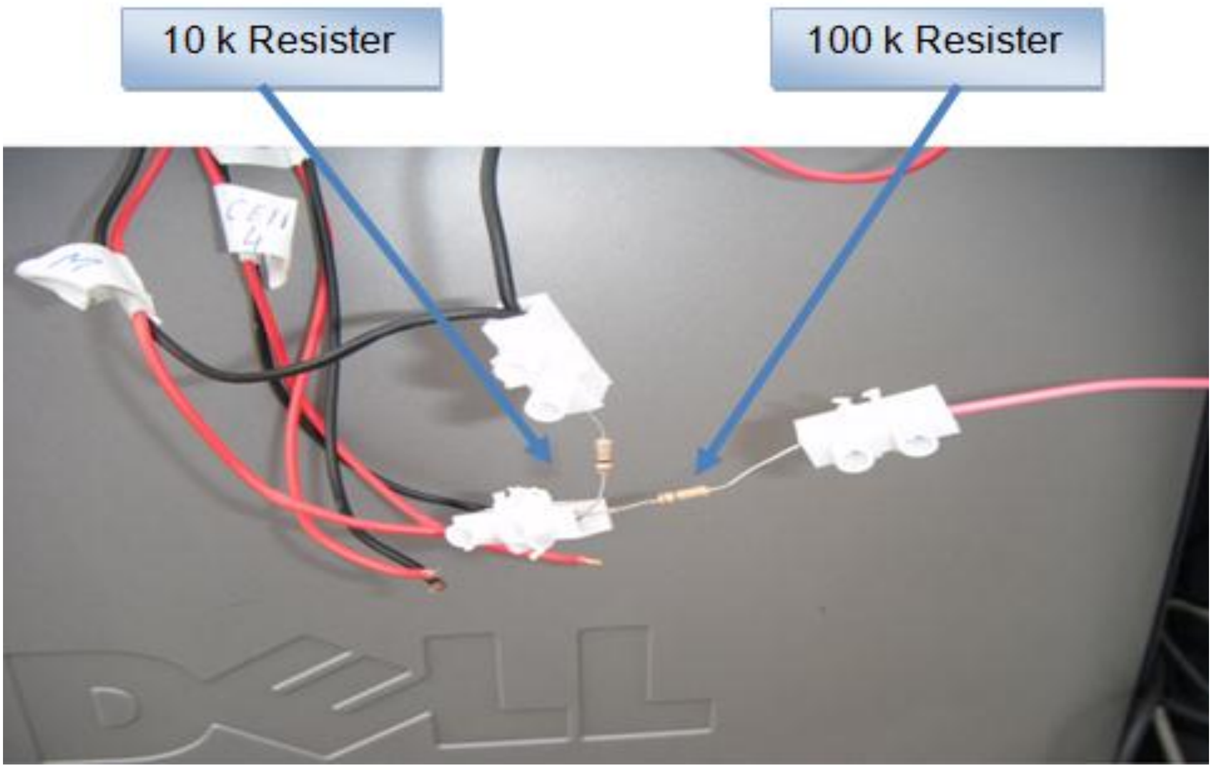

Figure 54 Multiplier Resistor with 100kΩ:10KΩ Ratio

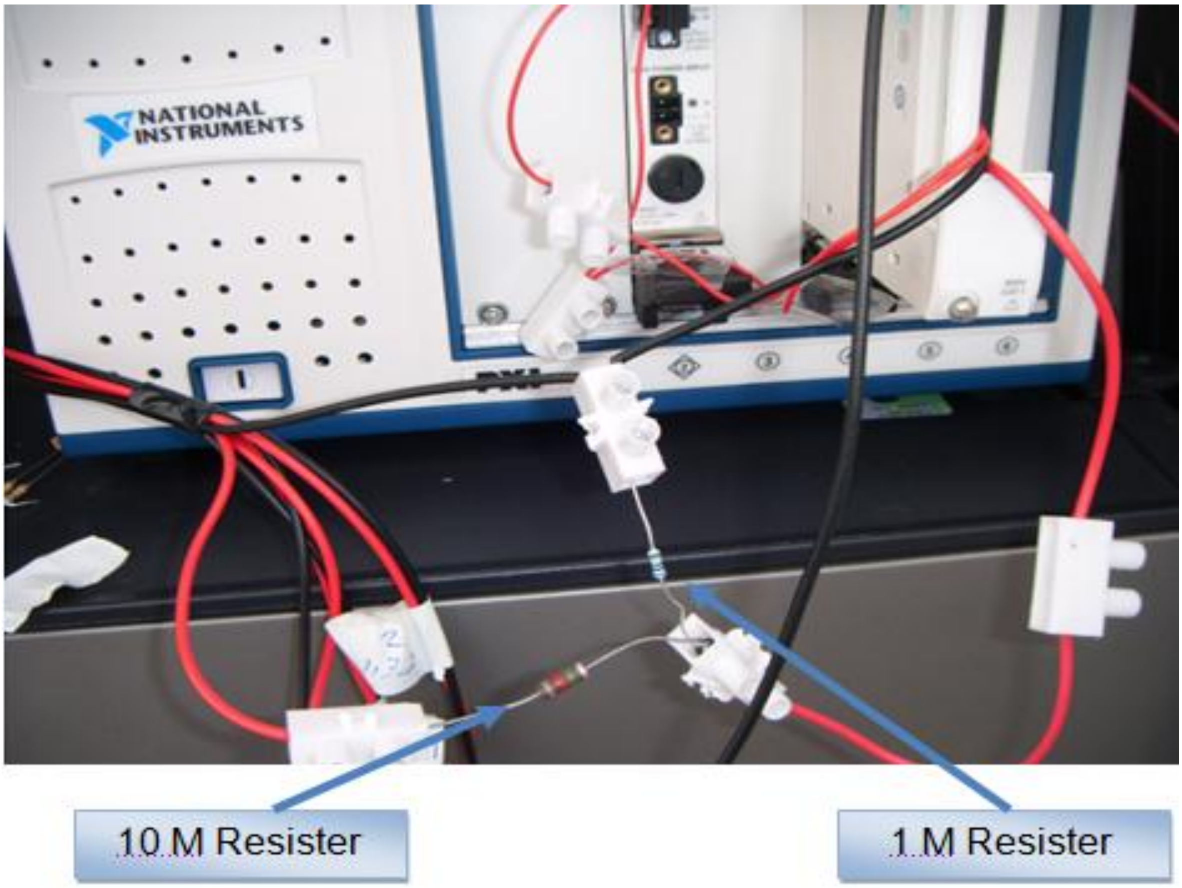

Figure 55 Multiplier Resistor with 10MΩ:1MΩ Ratio

Even with the multiplier resistor in series with the data logger to reduce the voltage the PXI-1033 data logger was logging the output of the CdTe PV cells the data user interface was displaying corrupted data. There was insufficient time to explore other solutions. Including placing a load in the circuit and a Shunt to measure the current.

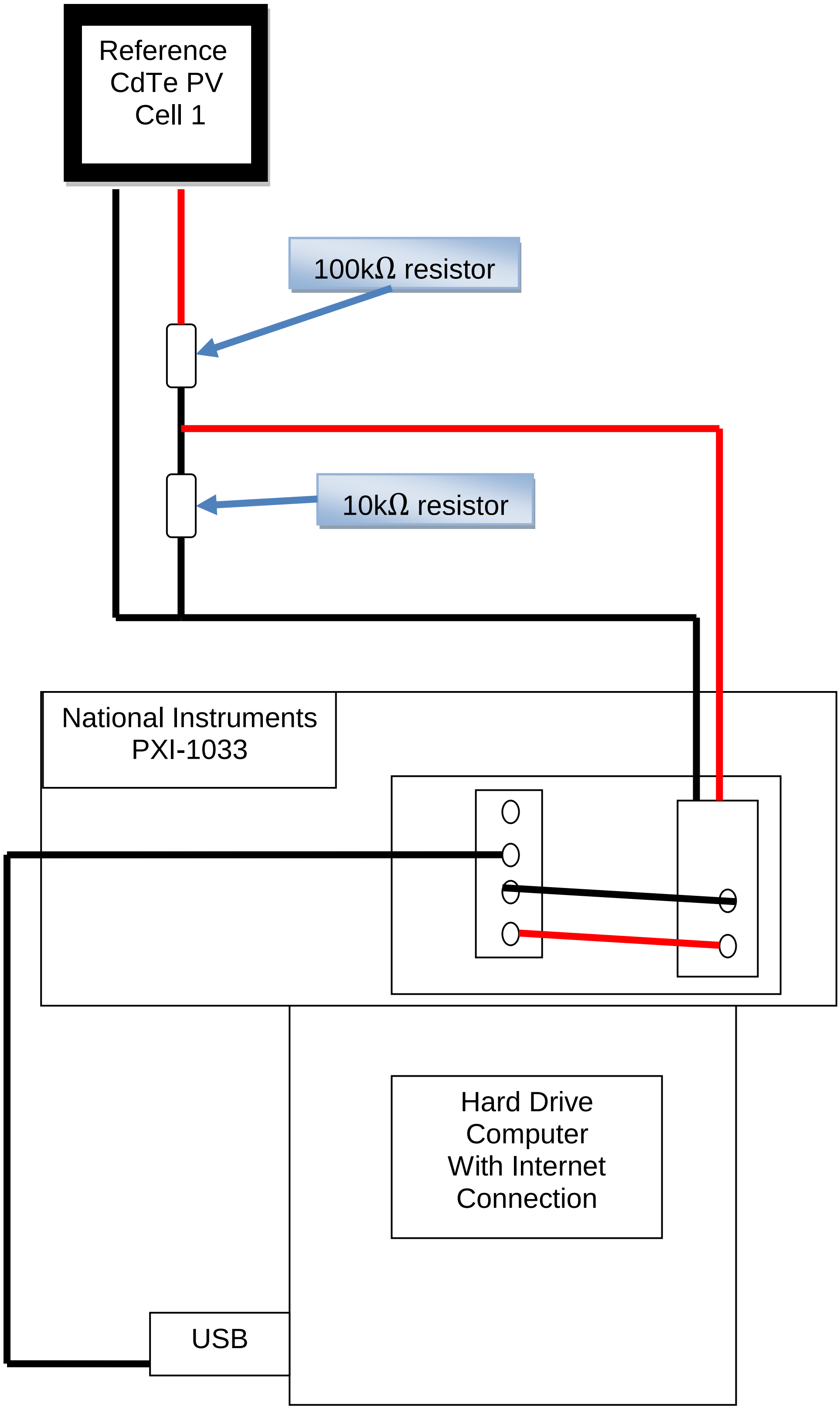

Figure 56 Schematic Diagram of the Multiplier Resistor with 100kΩ:10KΩ Ratio

6 Results and Analysis

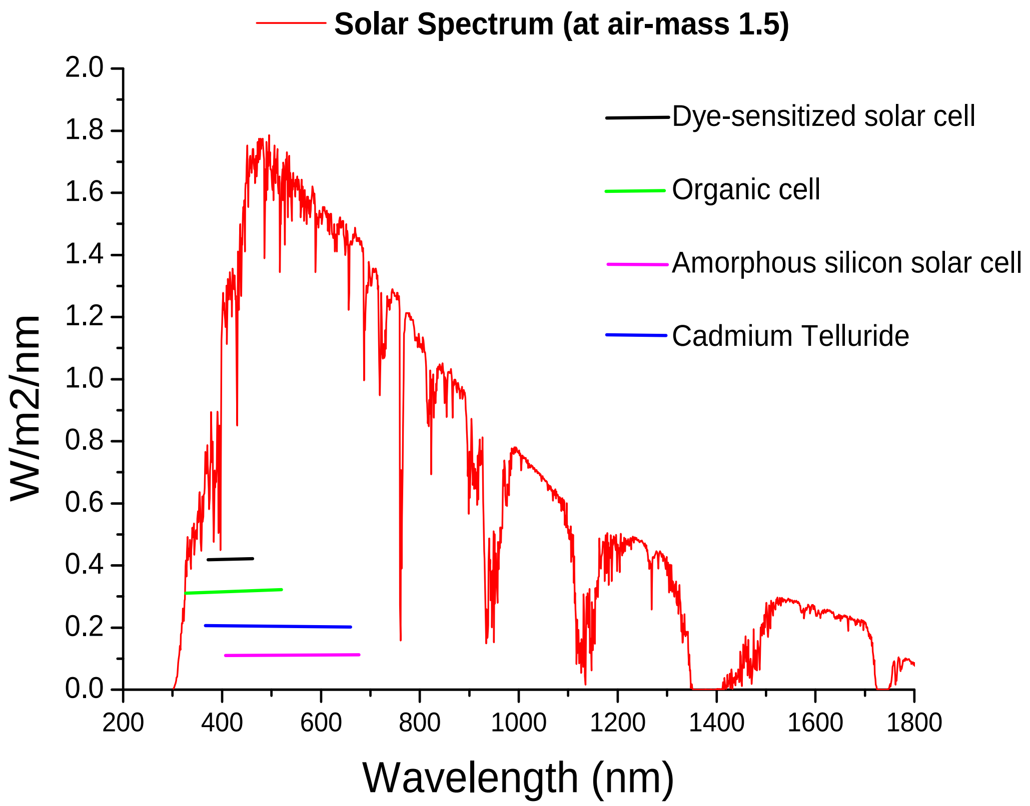

Figure 57 Solar Spectrum

(Ahmed, 2013)

The figure above shows the solar spectrum in red and the solar optical response for the four different solar cells are shown as horizontal the lines in the graph. The solar optical response for CdTe cells is 390nm to 650nm, which starts, in the UV region and ends in the visible region of the solar spectrum. The CdTe Cell is only active within this area.

Data Analysis

During the absorption and emission, testing per installed software was used to compile the data, all this data was stored to Excel spreadsheet. Using the Excel spreadsheet and the software program Origin, the following graphs were complied.

6.1 Absorption of the LDS Layers

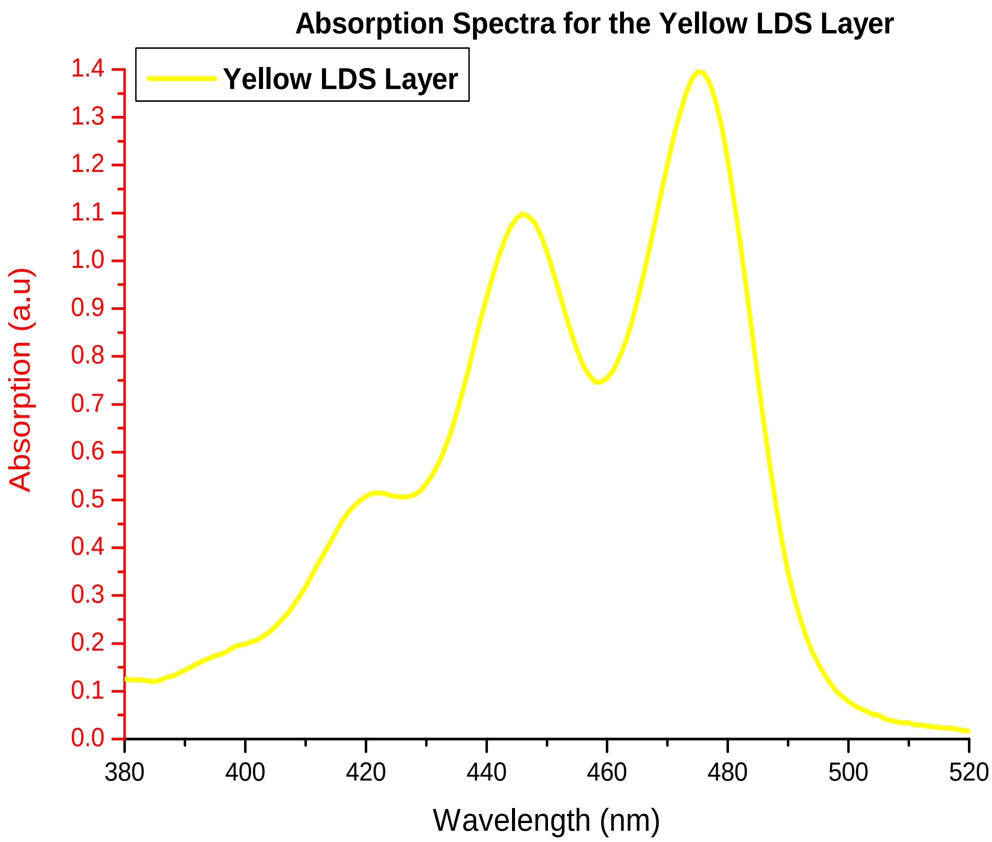

Figure 58 Absorption Results of the Yellow LDS Layer

The figure above shows the absorption of the yellow LDS layer measured to be in the range of 380nm to 520nm, which is mostly in the visible region of the solar spectrum. The peak absorption measured for the yellow LDS layer is 472nm.

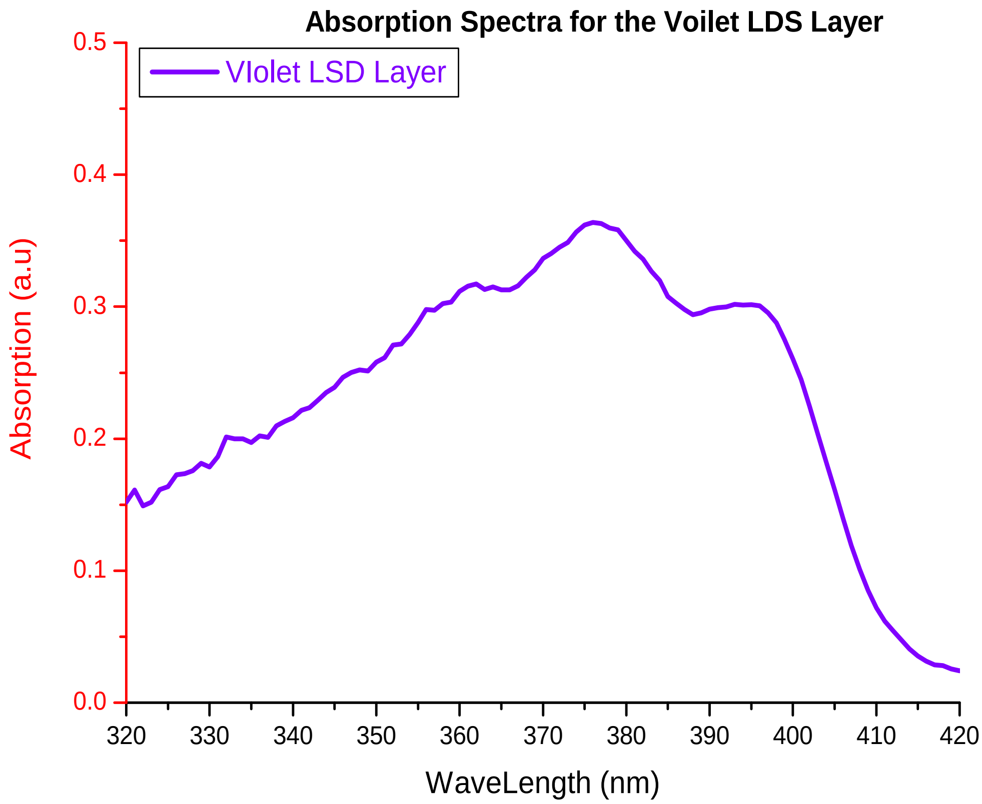

Figure 59 Absorption Results of the Violet LDS Layer

The figure above shows the absorption of the Violet LDS layer measured to be in range of 320nm to 420nm, which is in the UV region of the solar spectrum. The peak absorption measured for the Violet LDS layer is 376nm.

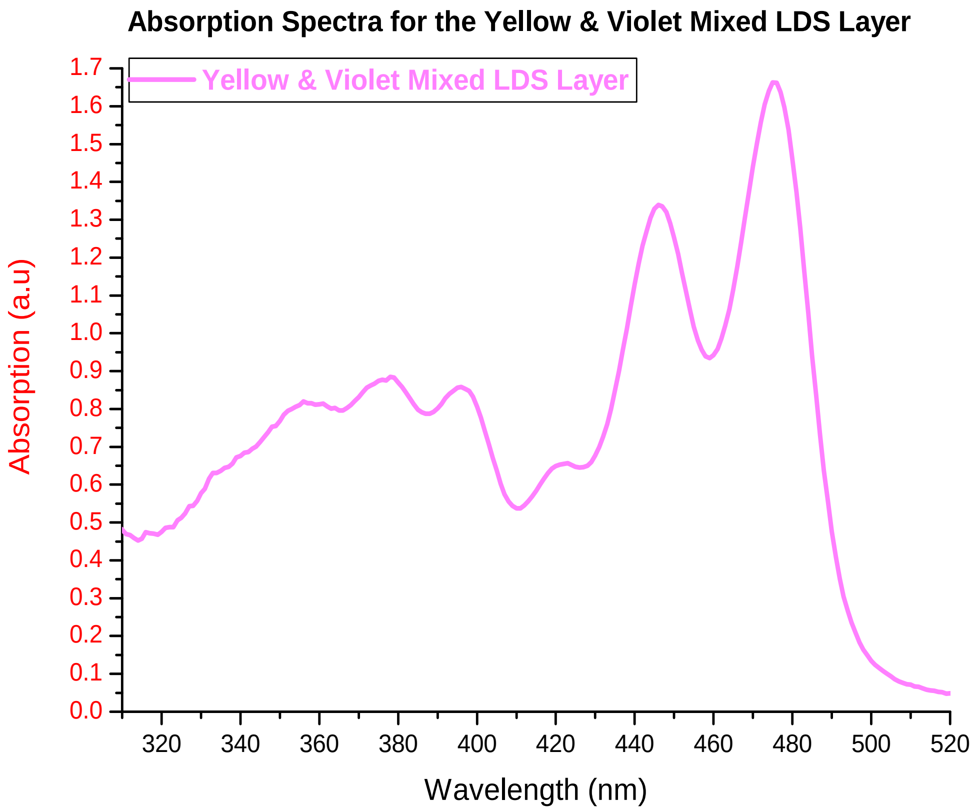

Figure 60 Absorption Results of the Mixed Yellow & Violet LDS Layer

The LDS layer containing the mixture of the Yellow 083 and Violet 570 dyes measured to have an absorption range of 320nm to 500nm. The mixture of the Yellow 083 and Violet 570 dyes are both in the UV region and the visible region of the spectrum. The peak absorption measured for the Yellow and Violet LDS layer is 472nm.

This result shows using the mixtures of Yellow 083 and Violet 570 dyes organic dyes did increase the absorption range of the LDS layer allowing more light to be absorbed. This shifts the light to higher wavelengths where the PV cell operates more efficiently.

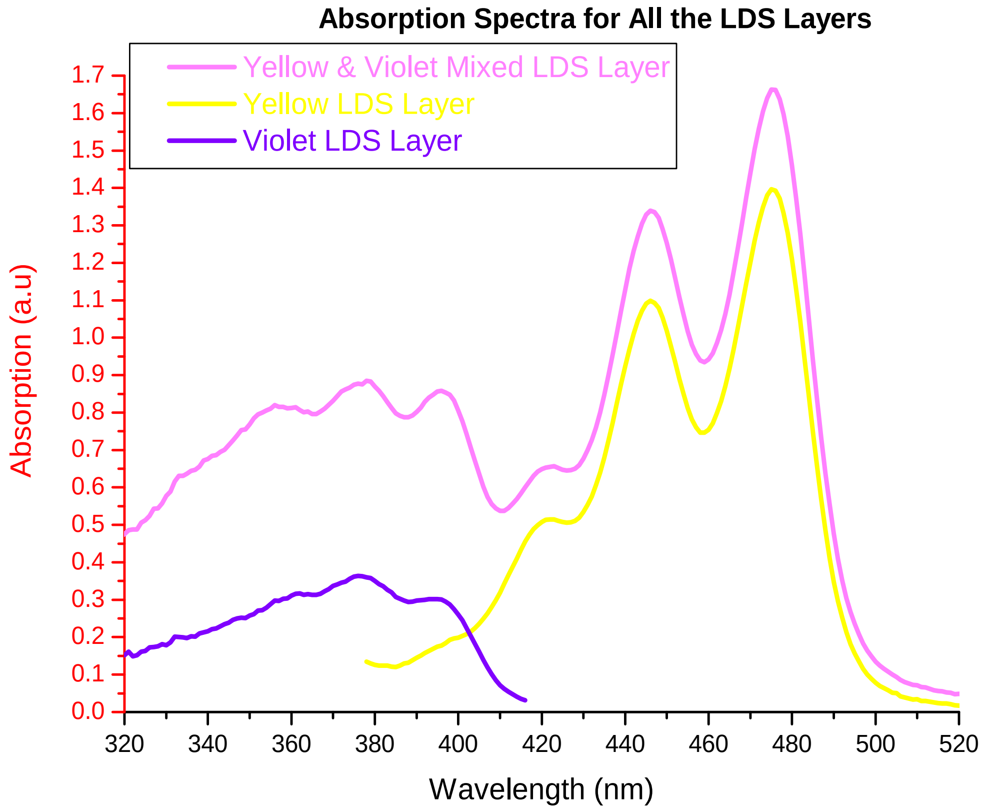

Figure 61 The Absorption Results for all Three LDS Layers

The figure above shows the absorption measurement of the of the three LDS layers, it shows the variation in the absorption spectra of the different LDS layers. From the figure the above, it can be seen that there is a benefit of mixing the two dyes. The mixture of Yellow and Violet has an increased absorption range compared to either one of the two single LDS layers.

6.2 Emission of the LDS Layers

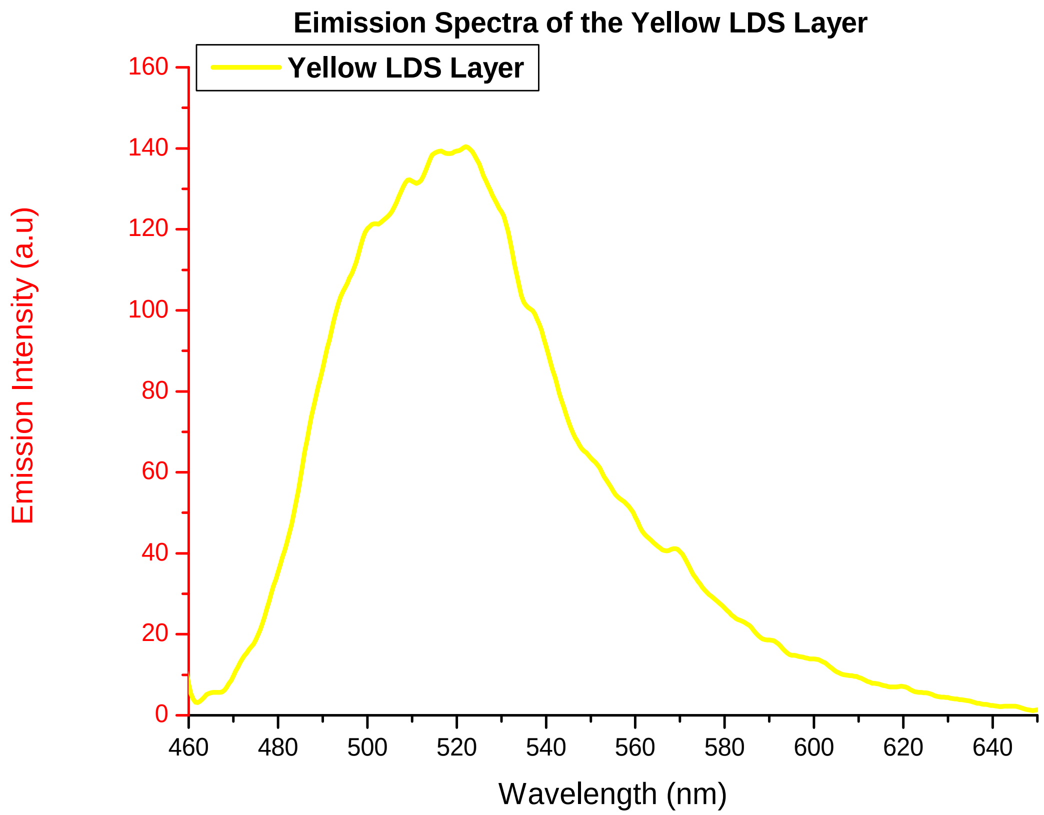

Figure 62 Emission Results of the Yellow LDS Layer

The figure above shows the emission measurement of the of the Yellow LDS layer. The Yellow LDS layer has an emission region of 460nm to 640nm, which is in the visible region of the solar spectrum. The emission peak for the Yellow LDS layer is 528nm. The Yellow LDS layer peak absorption is 472nm, therefore from peck to peck the Yellow LDS layer downshifts photons from 472nm to 528nm.

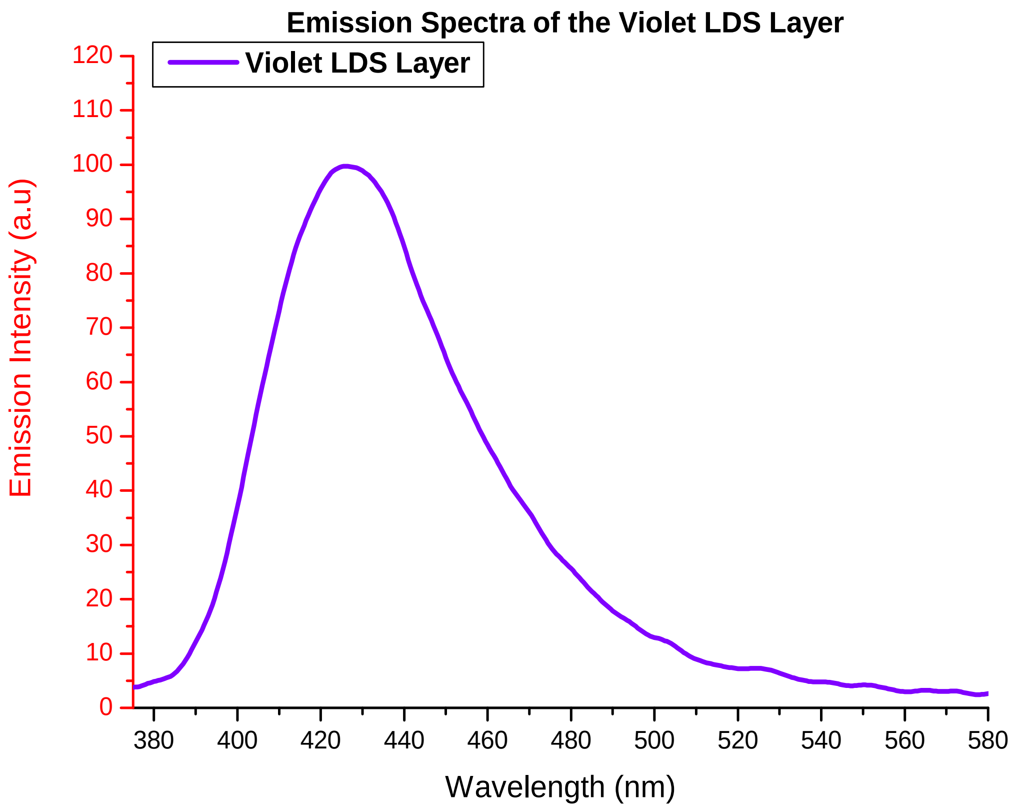

Figure 63 Emission Results of the Violet LDS Layer

The figure above shows the emission measurement of the of the Violet LDS layer. The Violet LDS layer has an emission region of 377nm to 580nm, which is in the visible region of the solar spectrum. The emission peak for the Violet LDS layer is 428nm. The Violet LDS layer peak absorption is 376nm, therefore from peck to peck the Violet LDS layer downshifts photons from 376nm to 428nm.

It is clear that the Violet LDS layer has suitable spectral properties for luminescent downshifting, as it absorbs in the UV region and downshifts to the visible region.

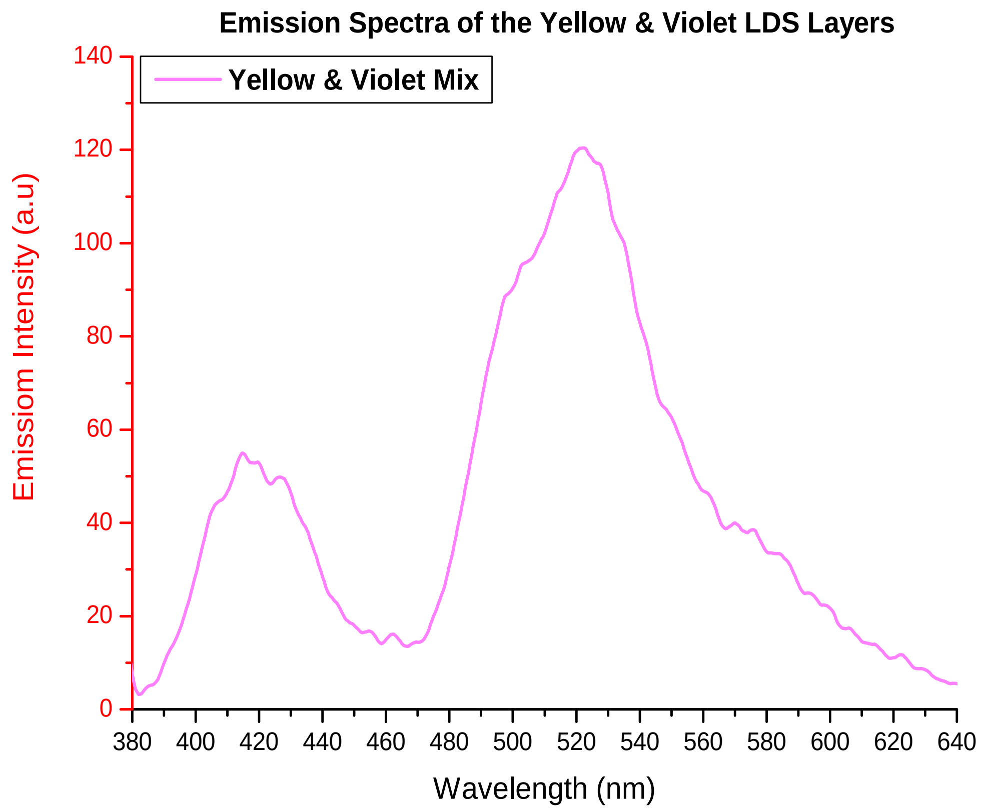

Figure 64 Emission Results of the Mixed Yellow Violet LDS Layer

The figure above shows the emission measurement of the mixed Yellow and Violet LDS layer. The mixed Yellow and Violet LDS layer has an emission region of 377nm to 640nm, which is in the visible region of the solar spectrum. The emission peak for the mixed Yellow and Violet LDS layer is 528nm. The mixed Yellow and Violet LDS layer peak absorption is 476nm, therefore from peck to peck the mixed Yellow and Violet LDS layer downshifts photons from 476nm to 228nm.

It is clear that the mixed Yellow and Violet LDS layer has suitable spectral properties for luminescent downshifting, as it absorbs in the UV region and downshifts to the visible region.

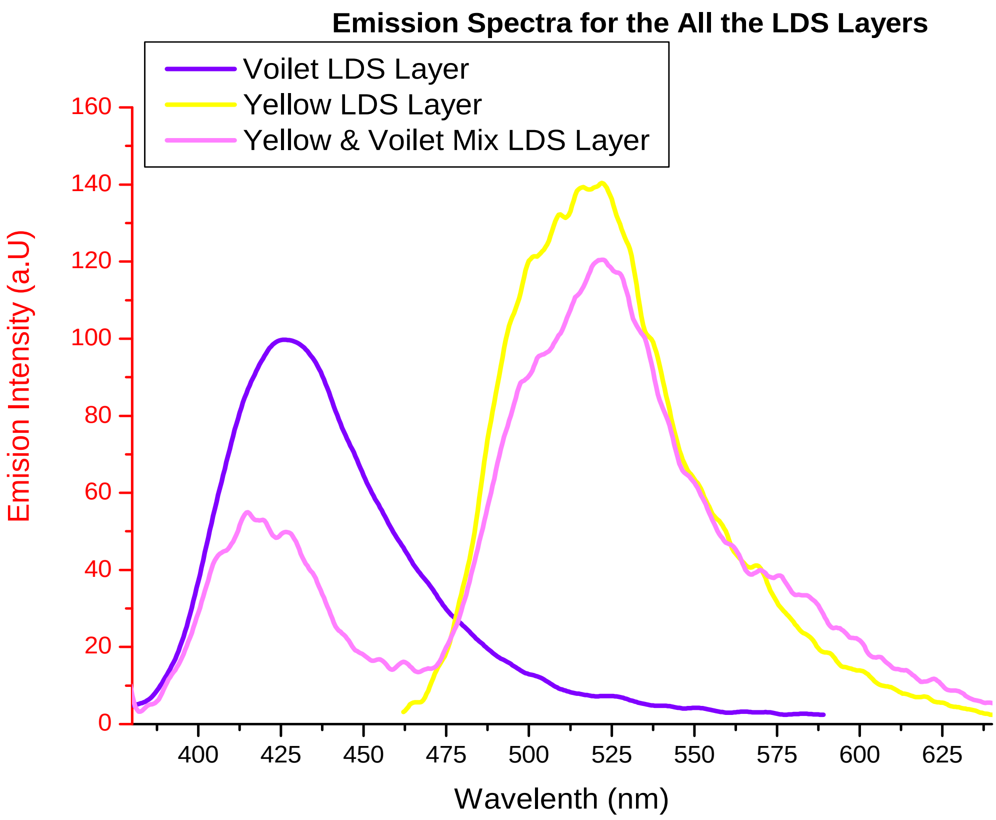

Figure 65 The Emission Results for all Three LDS Layers

The emission spectra of the Yellow 083 and Violet 570 dyes show the benefit of mixing the two dyes to create the mixed Yellow and Violet LDS layer. The mixture has an increased absorption range compared to single dyes. The Violet 570 dye can downshift the photons from 380nm to 580nm thus enabling these down shifted photons to be absorbed by the Yellow 083 dye and downshifting the photons to 640nm. These photons are than within the visible region of the solar spectrum and this will allow the PV cell to utilise the light more efficiently.

6.3 Indoor characterization

Data Analysis

During the indoor testing the software used was Solar cell IV sweep modified NI-DC power' software and the user interface was Labview, all the data was stored to Excel spreadsheet. The software provided the Photovoltaic Cells output, current, voltage, the Isc (short circuit current A) values, the Voc (open circuit voltage V) values, the Pmax (max power W) and the FF (fill factor). Using the Excel spreadsheet and the software program Origin, the following graphs were complied.

6.4 The CdTe PV Cell

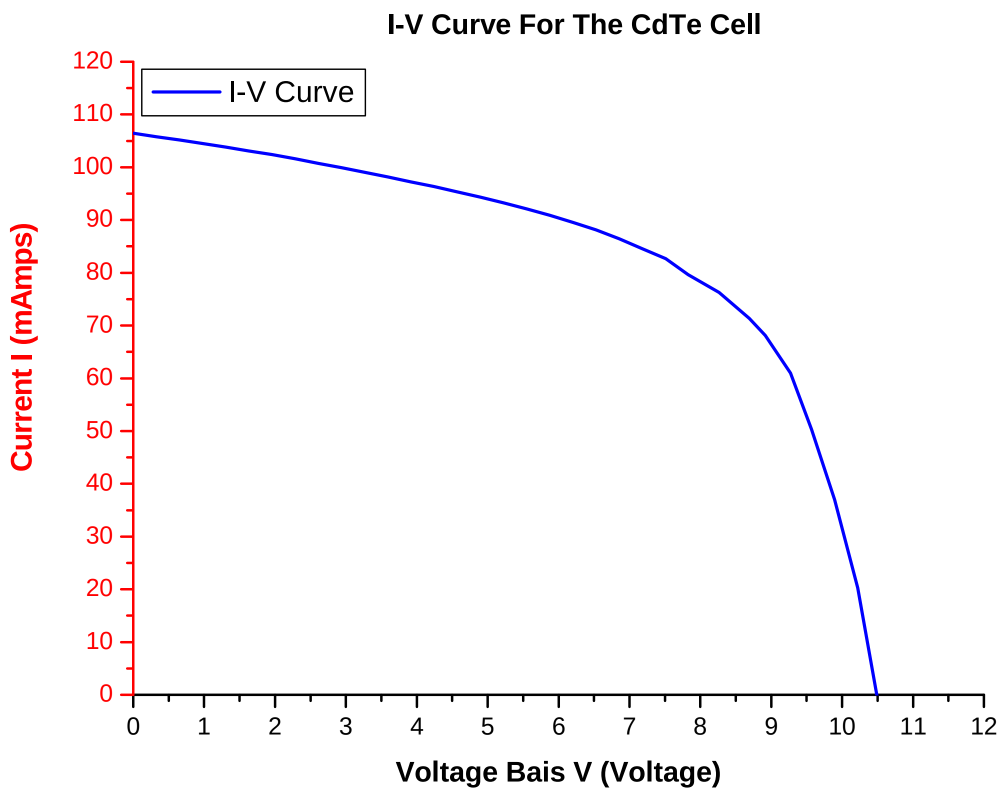

Figure 66 The Plot of Electrical Output Characteristics of the Current and Voltage

The figure above shows the I-V curve for the reference CdTe PV cell. The results show a short circuit current of 106.48mA and an open circuit voltage of 10.5Vdc.

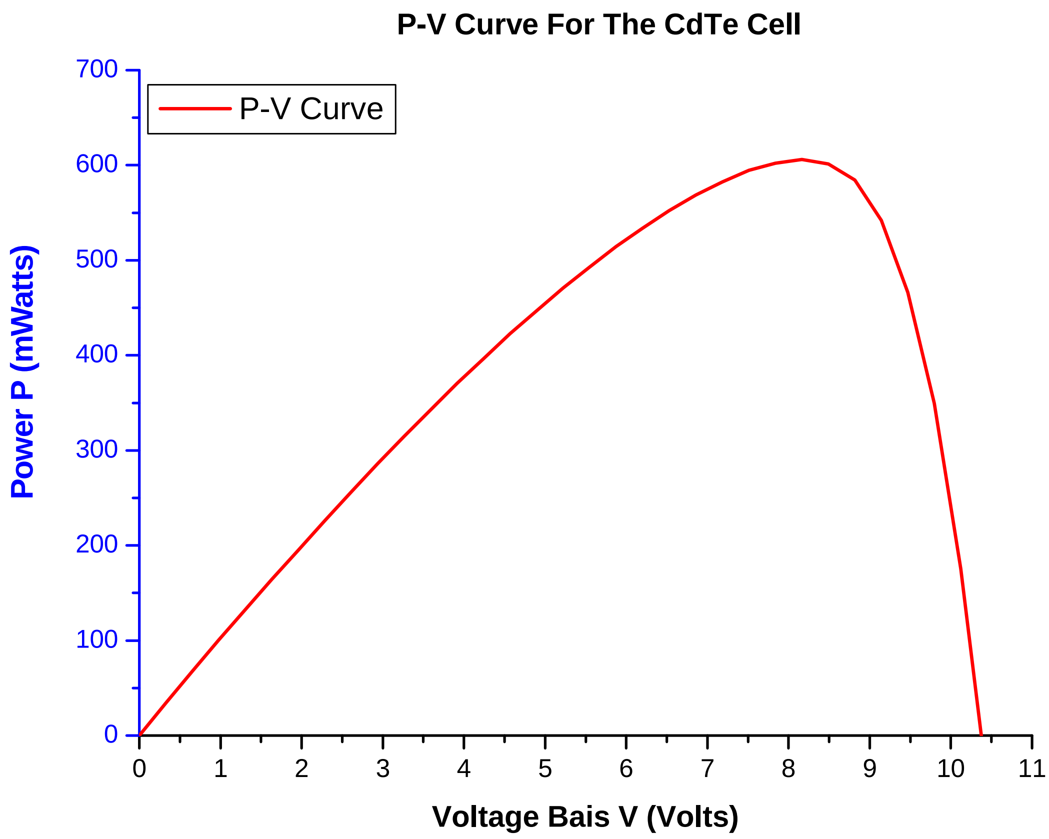

Figure 67 The Plot of Electrical Output Characteristics of the Power and Voltage

The figure above shows the P-V curve for the reference CdTe PV cell. The results show that the reference CdTe PV cell has a maximum power point of 613.499mwatts, the maximum power voltage is 7.5Vdc and an open circuit voltage of 10.48Vdc.

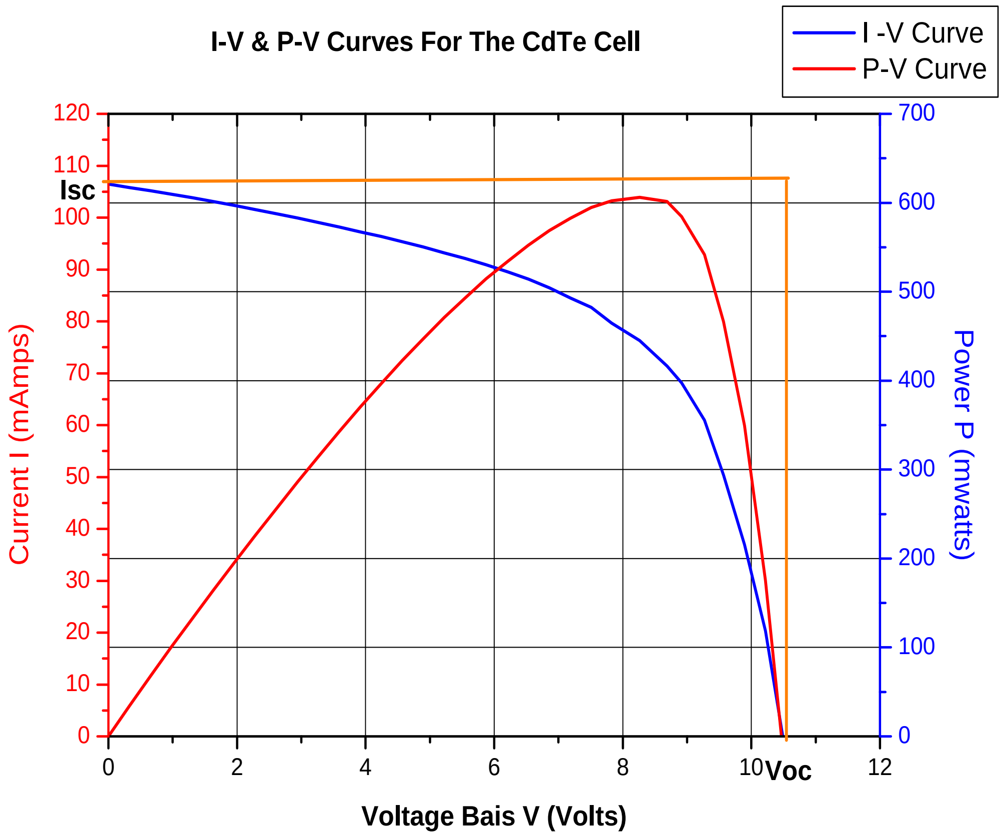

Figure 68 Electrical Output Characteristics of the Current, Power and Voltage

The figure above shows the I-V and the P-V curves for the reference CdTe PV cell. The results show the reference CdTe PV cell has a maximum power point of 613.499mwatts, the maximum power voltage is 7.5Vdc and a maximum power current of 81.69mA. This is the point when the reference CdTe PV cell operates at its highest efficiency of 2.726 %.

- Short Circuit Current (mAmps) = 106.48mA
- Voltage (Volts) = 10.5Vdc
- Fill Factor = 0.62
- Maximum Power (mWatts) = 613.499mWatts
- Optimum Power Voltage Vmp (Volts) = 7.50Vdc
- Optimum Operating Current Imp (mAmps) = 81.69mA
- Efficiency (%) = 2.726%

6.5 The Blank LDS Layer

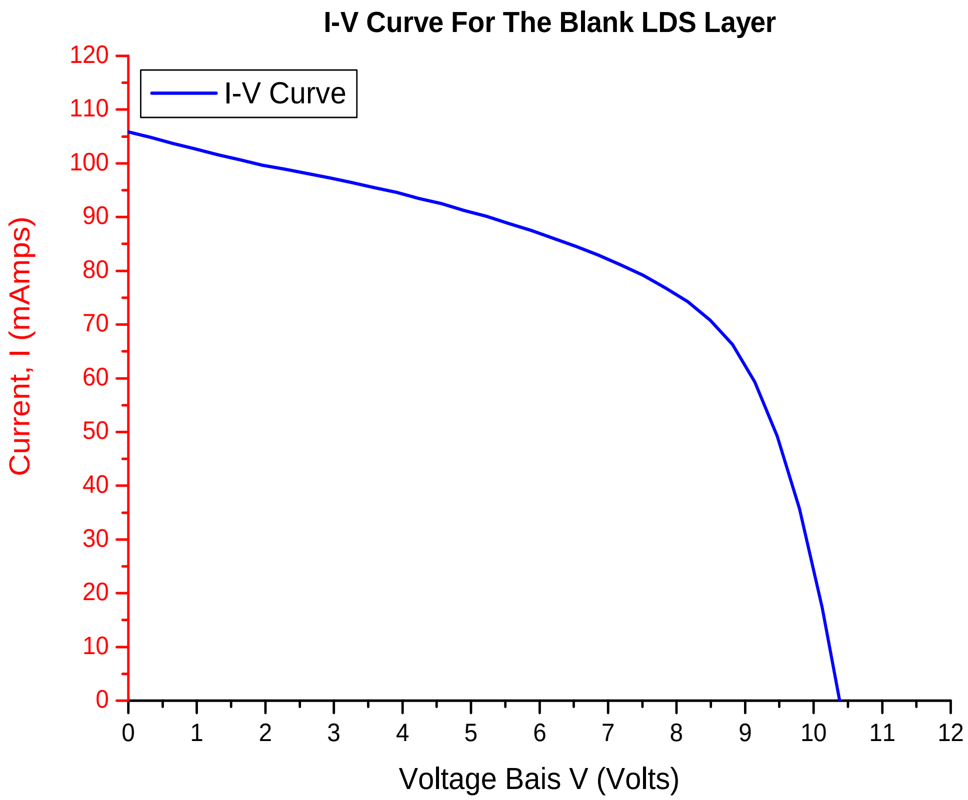

Figure 69 The Plot of Electrical Output Characteristics of the Current and Voltage

The I-V curve for the CdTe PV cell with the blank LDS (PMMA) layer presented in the figure above shows a short circuit current of 105.83mA and an open circuit voltage of 10.37Vdc. This shows that the host material (PMMA) negative affect the output of the CdTe PV cells. These results also show a short circuit current decrease of 0.65mA and an open circuit voltage reduction of 0.13Vdc compared to the reference CdTe PV Cell.

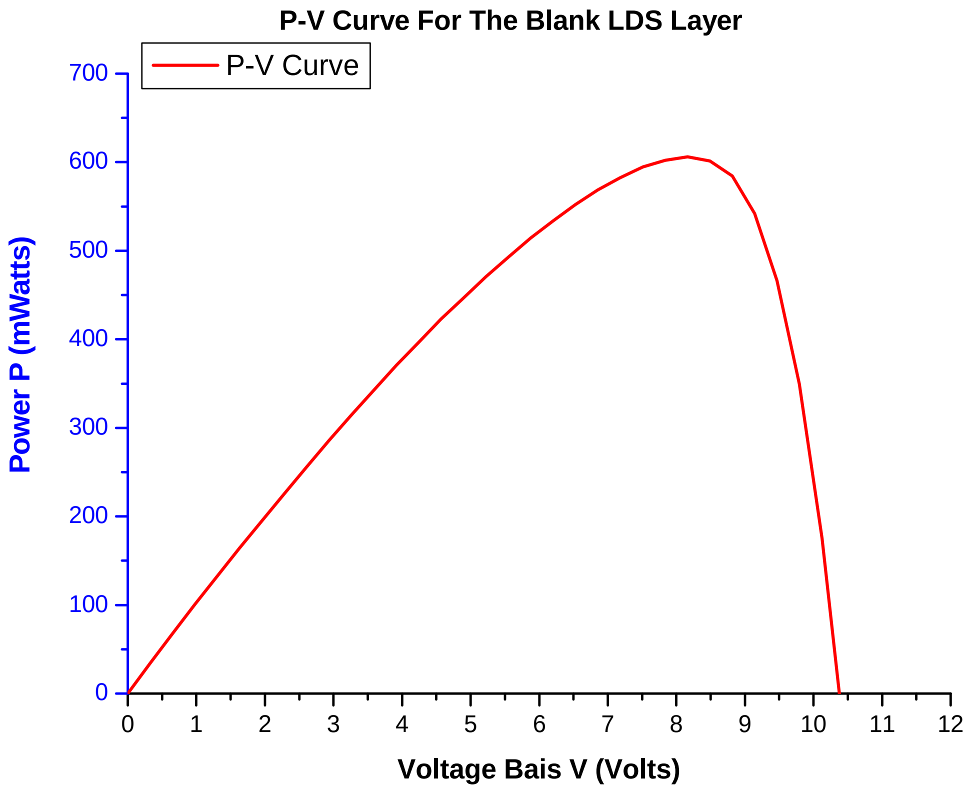

Figure 70 The Plot of Electrical Output Characteristics of the Power and Voltage

The P-V curve for the CdTe PV cell with the blank LDS (PMMA) layer presented in the figure above a maximum power point of 606.034mwatts, the maximum power voltage is 8.16Vdc and an open circuit voltage of 10.37Vdc.

This shows that the host material (PMMA) has a negative effect the output of the CdTe PV cells. These results show a maximum power point decrease of 7.465mwatts and a maximum power voltage reduction of 0.13Vdc compared to the reference CdTe PV Cell.

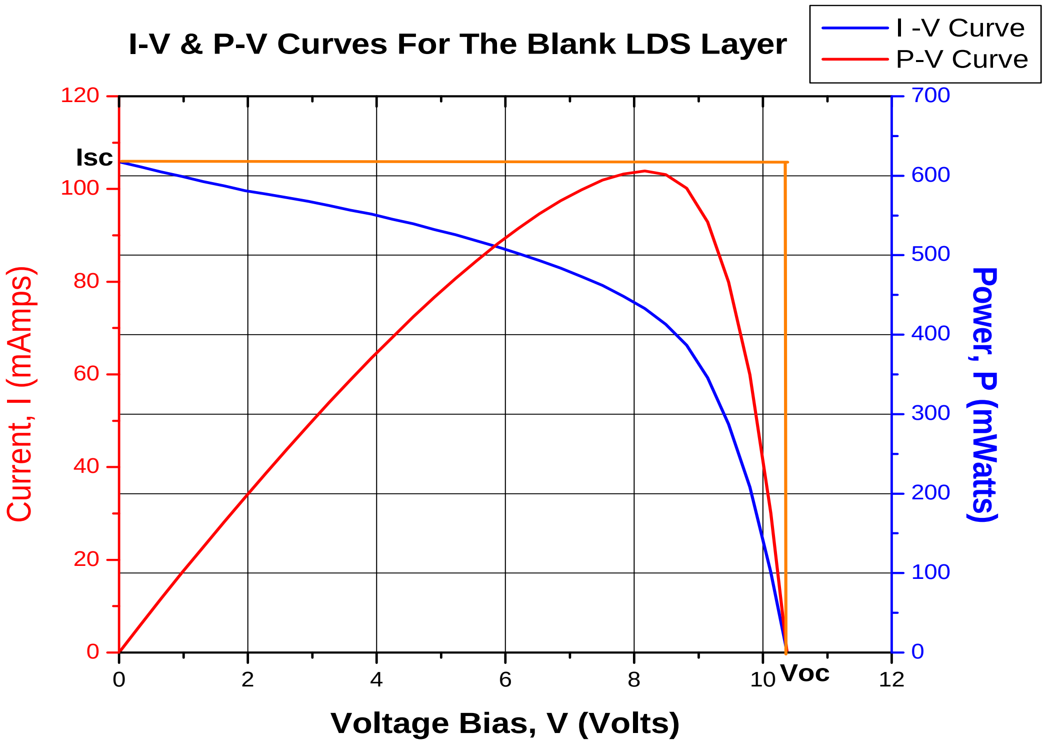

Figure 71 Electrical Output Characteristics of the Current, Power and Voltage

The figure above shows the I-V and the P-V curves for the CdTe PV cell with the blank LDS (PMMA). The results show a maximum power point of 606.034mwatts, the maximum power voltage is 8.16Vdc and a maximum power current of 74.23mA. This is the point when the reference CdTe PV cell operates at its highest efficiency of 2.693 %.

Percentage Improvement = $\frac{Scc\ of\ LDS\ Layer\ CdTe - Scc\ of\ Reference\ CdTe\ PV\ Cell}{Scc\ of\ Reference\ CdTe\ PV\ Cell}$ X 100%

$$\frac{105.83 - 106.48}{106.48}$$ x 100 % = 0.61% Reduction

- Short Circuit Current (mAmps) = 105.83mA
- Voltage (Volts) = 10.37Vdc
- Fill Factor = 0.55
- Maximum Power (mWatts) = 606.034mWatts
- Optimum Power Voltage Vmp (Volts) = 8.16Vdc
- Optimum Operating Current Imp (mAmps) = 74.23mA
- Efficiency (%) = 2.693%

6.6 The Yellow LDS Layer

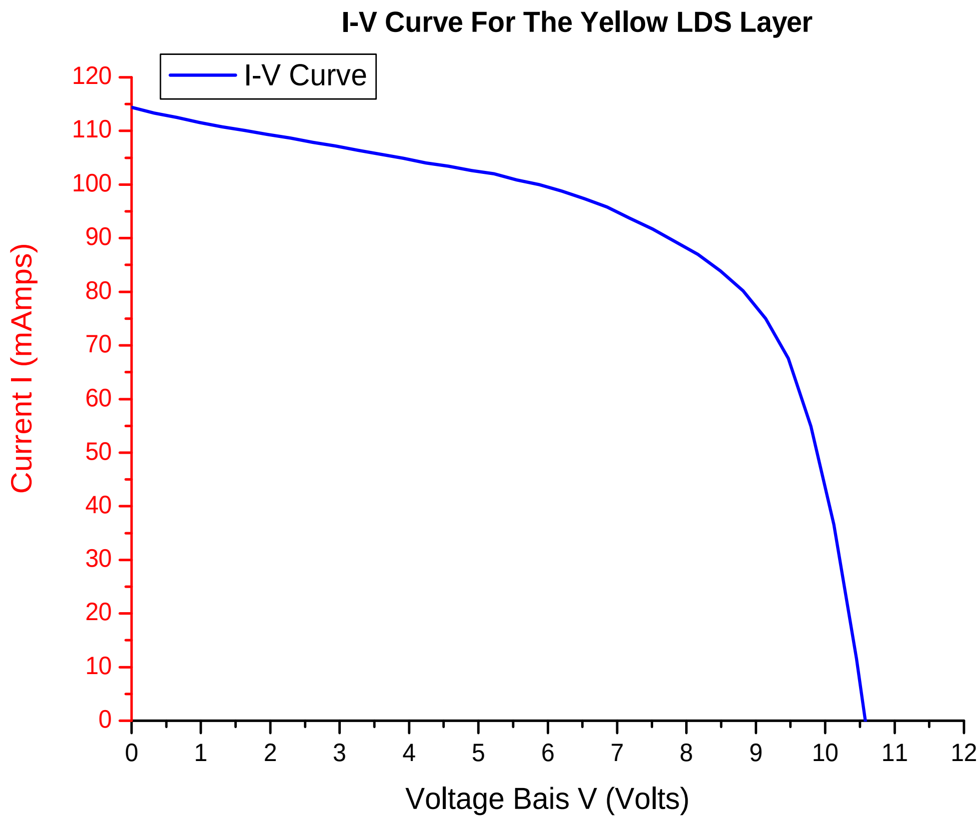

Figure 72 The Plot of Electrical Output Characteristics of the Current and Voltage

The I-V curve for the CdTe PV cell with the Yellow LDS layer presented in figure above shows a short circuit current of 114.39mA and an open circuit voltage of 10.6Vdc. This shows a short circuit current improvement of 7.91mA and an open circuit voltage improvement of 0.1Vdc compared to the reference CdTe PV Cell.

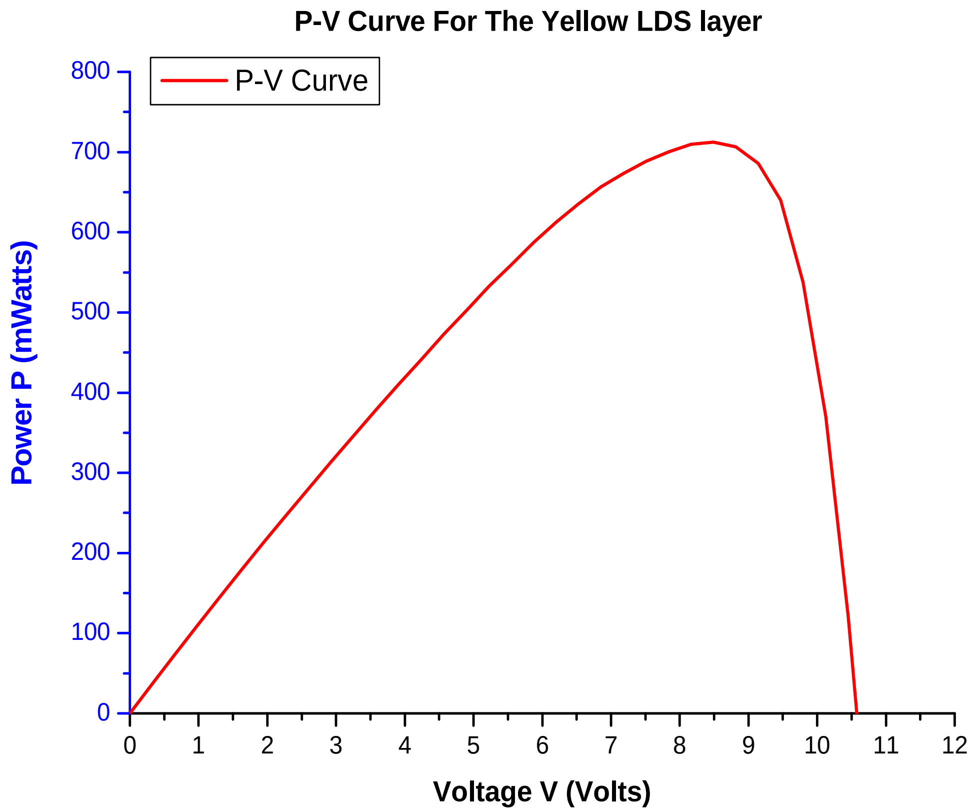

Figure 73 The Plot of Electrical Output Characteristics of the Power and Voltage

The P-V curve for the CdTe PV cell with the Yellow LDS layer presented in the figure above shows a maximum power point of 712.29mwatts, the maximum power voltage is 8.48 Vdc and an open circuit voltage of 10.6Vdc.

These results show a maximum power point increase of 98.79mwatts and a maximum power voltage improvement of 0.1Vdc compared to the reference CdTe PV Cell.

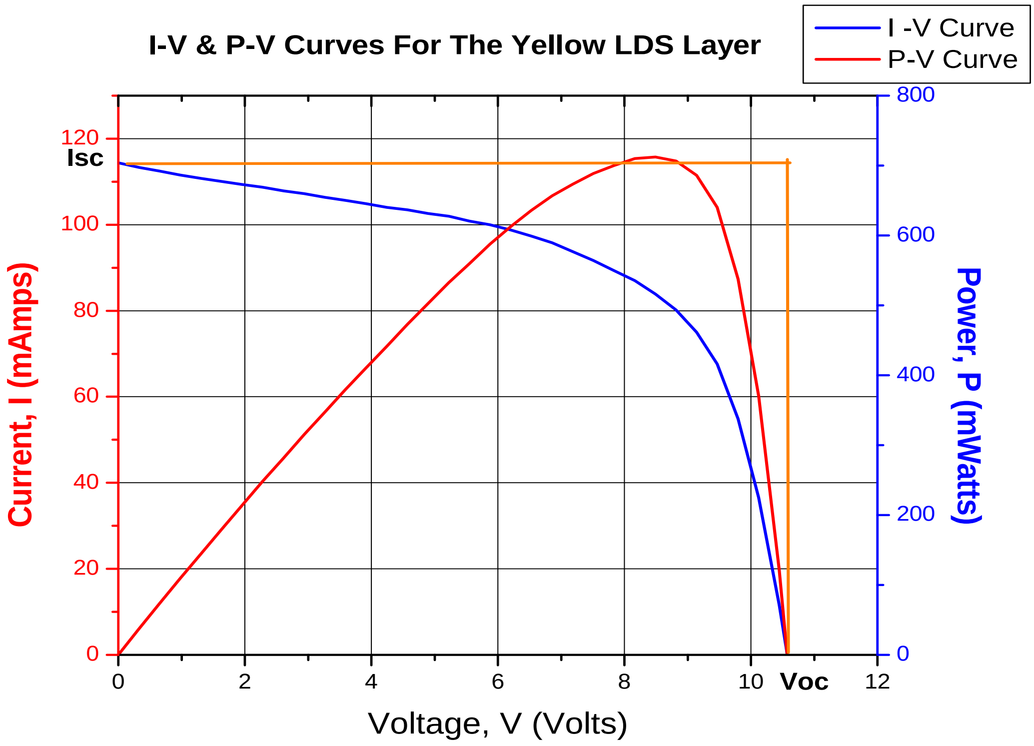

Figure 74 Electrical Output Characteristics of the Current, Power and Voltage

The figure above shows the I-V and the P-V curves for the CdTe PV cell with the Yellow LDS layer. The results show a maximum power point of 712.29mwatts, the maximum power voltage is 8.48Vdc and a maximum power current of 83.9mA. This is the point when the reference CdTe PV cell operates at its highest efficiency of 3.165 %.

Percentage Improvement = $\frac{Scc\ of\ LDS\ Layer\ CdTe - Scc\ of\ Reference\ CdTe\ PV\ Cell}{Scc\ of\ Reference\ CdTe\ PV\ Cell}$ X 100%

$$\frac{114.39 - 106.48}{106.48} \times 100\ \% = 7.42\%\ \text{improvement}$$

- Short Circuit Current (mAmps) = 114.39mA
- Voltage (Volts) = 10.6Vdc
- Fill Factor = 0.588
- Maximum Power (mWatts) = 712.29mWatts
- Optimum Power Voltage Vmp (Volts) = 8.48Vdc
- Optimum Operating Current Imp (mAmps) = 83.9mA
- Efficiency (%) = 3.165%

6.7 The Violet LDS Layer

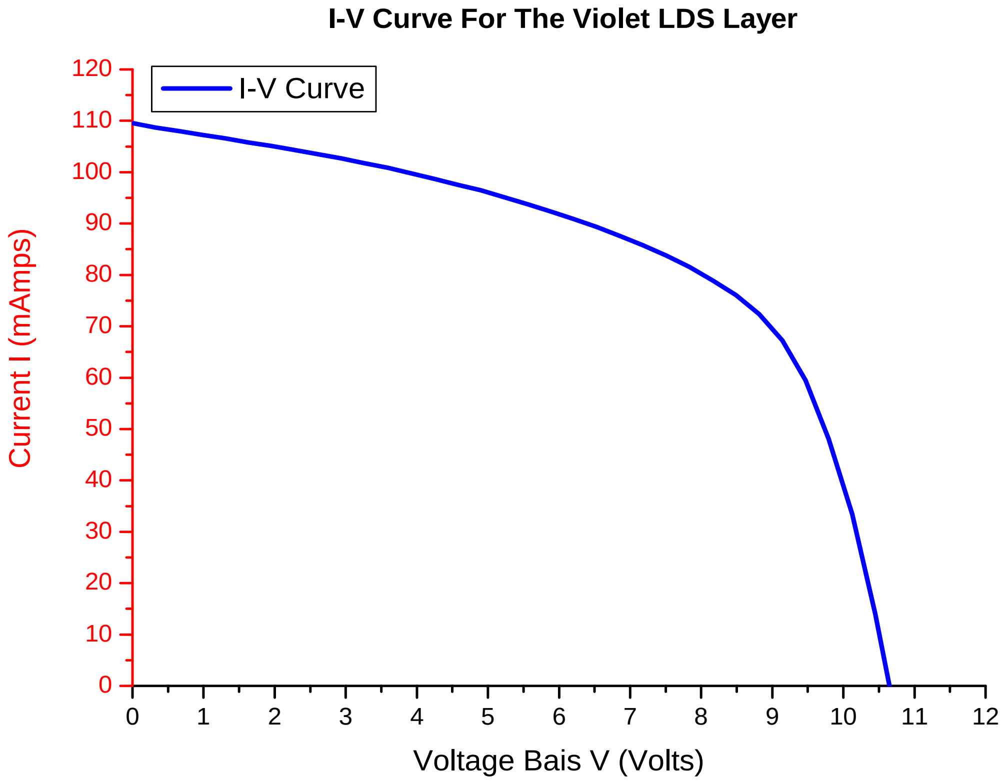

Figure 75 The Plot of Electrical Output Characteristics of the Current and Voltage

The I-V curve for the CdTe PV cell with the Violet LDS layer presented in figure above shows a short circuit current of 111.84mA and an open circuit voltage of 10.69Vdc. This shows a short circuit current improvement of 5.36mA and an open circuit voltage improvement of 0.19Vdc compared to the reference CdTe PV Cell.

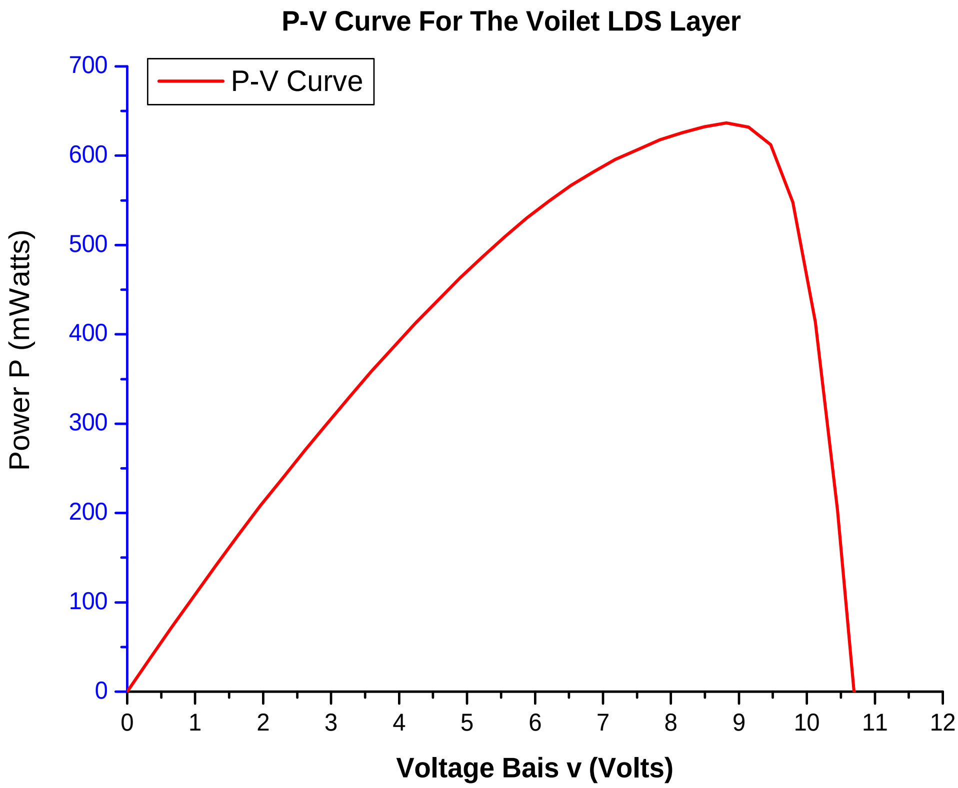

Figure 76 The Plot of Electrical Output Characteristics of the Power and Voltage

The P-V curve for the CdTe PV cell with the Violet LDS layer presented in the figure above shows a maximum power point of 636.52mwatts, the maximum power voltage is 8.81Vdc and an open circuit voltage of 10.69Vdc. These results show a maximum power point increase of 23.03mwatts and a maximum power voltage improvement of 0.19Vdc compared to the reference CdTe PV Cell.

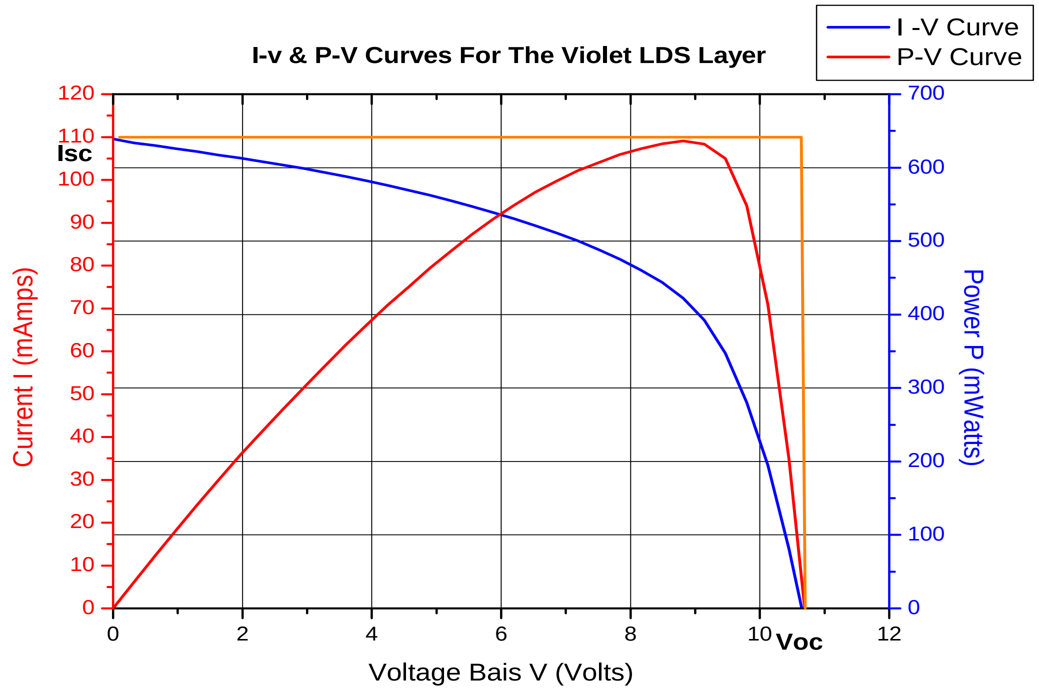

Figure 77 Electrical Output Characteristics of the Current, Power and Voltage

The figure above shows the I-V and the P-V curves for the CdTe PV cell with the Violet LDS layer. The results show a maximum power point of 636.52mwatts, the maximum power voltage is 8.81 Vdc and a maximum power current of 72.2mA. This is the point when the reference CdTe PV cell operates at its highest efficiency of 2.829%.

Percentage Improvement = $\frac{Scc\ of\ LDS\ Layer\ CdTe - Scc\ of\ Reference\ CdTe\ PV\ Cell}{Scc\ of\ Reference\ CdTe\ PV\ Cell}$ X 100%

$$\frac{111.84 - 106.48}{106.48} \text{ x } 100\ \% = 5.03\% \text{ improvement}$$

- Short Circuit Current (mAmps) = 111.84mA
- Voltage (Volts) = 10.69Vdc
- Fill Factor = 0.532
- Maximum Power (mWatts) = 636.52mWatts
- Optimum Power Voltage Vmp (Volts) = 8.81Vdc
- Optimum Operating Current Imp (mAmps) = 72.2mA
- Efficiency (%) = 2.829%

6.8 The Yellow & Violet LDS Layer

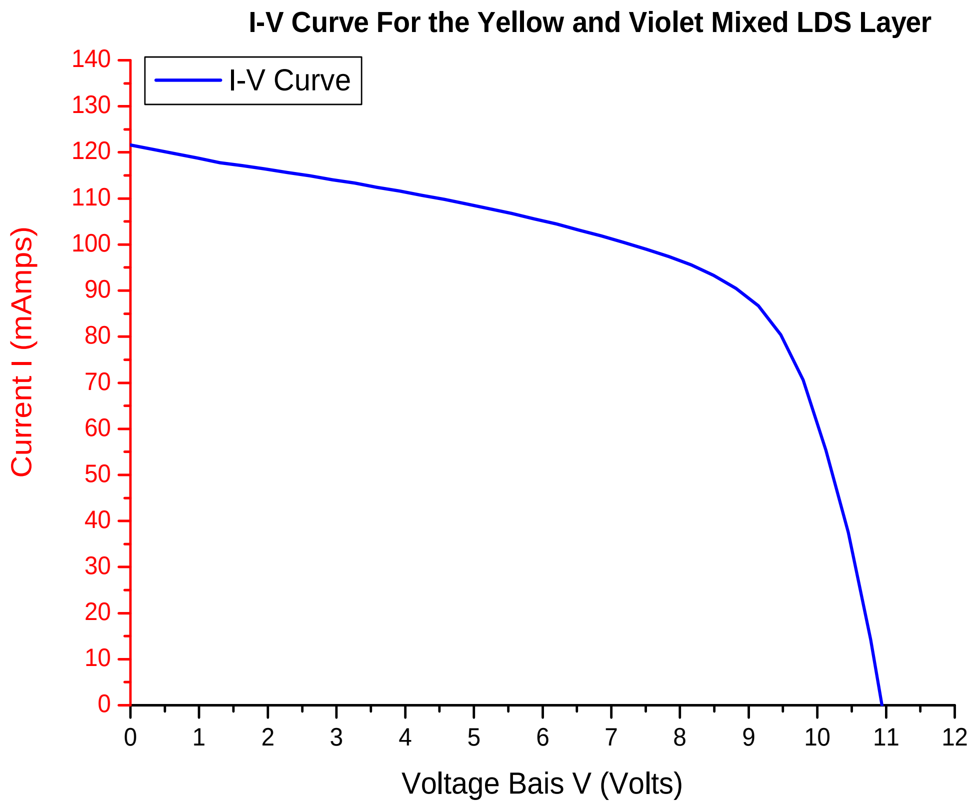

Figure 78 The Plot of Electrical Output Characteristics of the Current and Voltage

The I-V curve for the CdTe PV cell with the Yellow and Violet LDS layer presented in figure above shows a short circuit current of 121.64mA and an open circuit voltage of 10.94Vdc. This shows a short circuit current improvement of 15.16mA and an open circuit voltage improvement of 0.44Vdc compared to the reference CdTe PV Cell.

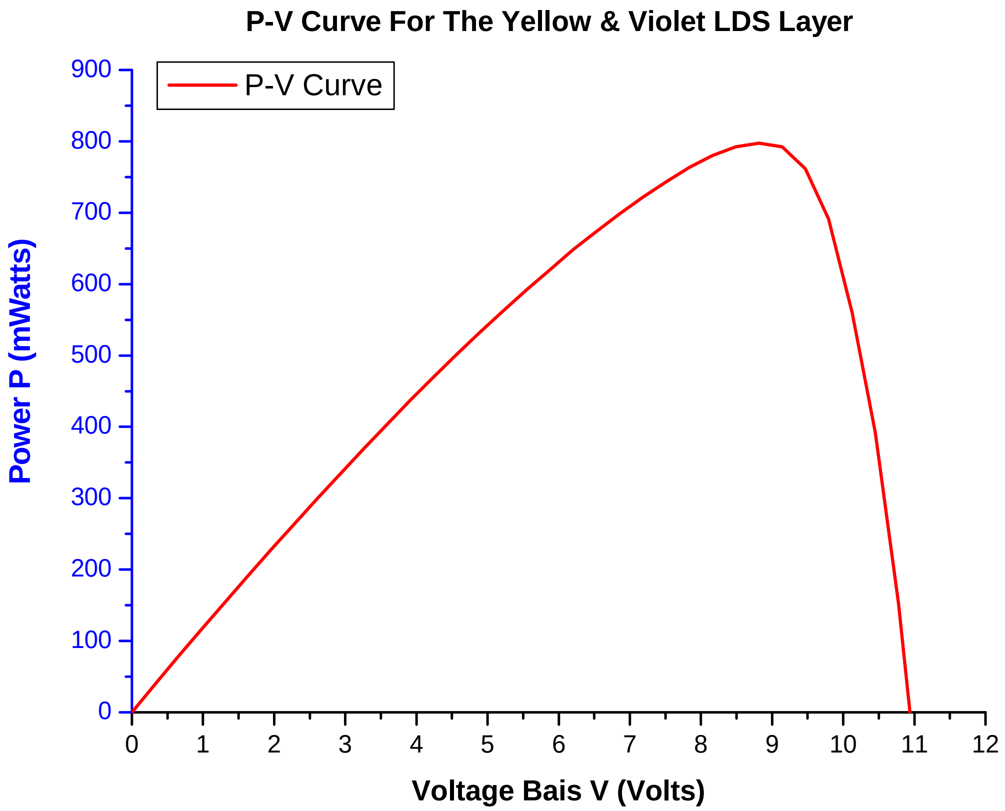

Figure 79 The Plot of Electrical Output Characteristics of the Power and Voltage

The P-V curve for the CdTe PV cell with the Yellow and Violet LDS layer presented in the figure above shows a maximum power point of 797.45mwatts, the maximum power voltage is 8.81Vdc and an open circuit voltage of 10.94Vdc. These results show a maximum power point increase of 183.951mwatts and a maximum power voltage improvement of 0.44Vdc compared to the reference CdTe PV Cell.

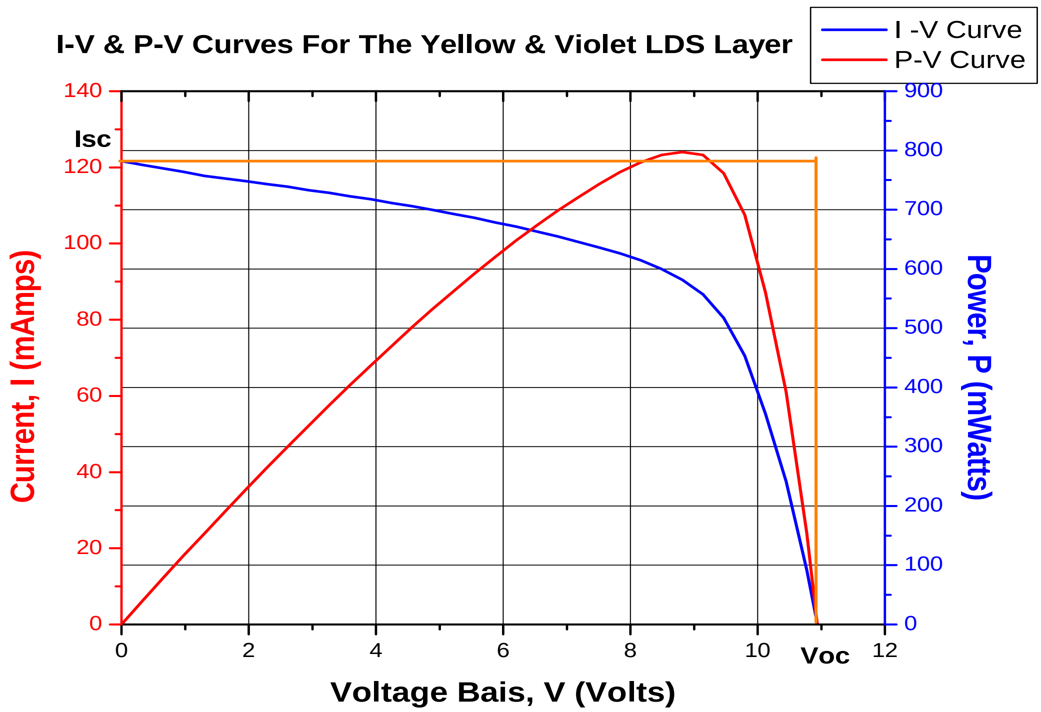

Figure 80 Electrical Output Characteristics of the Current, Power and Voltage

The figure above shows the I-V and the P-V curves for the CdTe PV cell with the Yellow LDS layer. The results show a maximum power point of 797.45mwatts, the maximum power voltage is 8.81Vdc and a maximum power current of 90.45mA. This is the point when the reference CdTe PV cell operates at its highest efficiency of 3.54%.

Percentage Improvement = $\frac{Scc\ of\ LDS\ Layer\ CdTe - Scc\ of\ Reference\ CdTe\ PV\ Cell}{Scc\ of\ Reference\ CdTe\ PV\ Cell}$ X 100%

$$\frac{121.64 - 106.48}{106.48}$$ x 100 % = 14.23% improvement

- Short Circuit Current (mAmps) = 121.64mA
- Voltage (Volts) = 10.94Vdc
- Fill Factor = 0.599
- Maximum Power (mWatts) = 797.45mWatts
- Optimum Power Voltage Vmp (Volts) = 8.81Vdc
- Optimum Operating Current Imp (mAmps) = 90.45mA
- Efficiency (%) = 3.54%

6.9 Comparison of the PV Cells

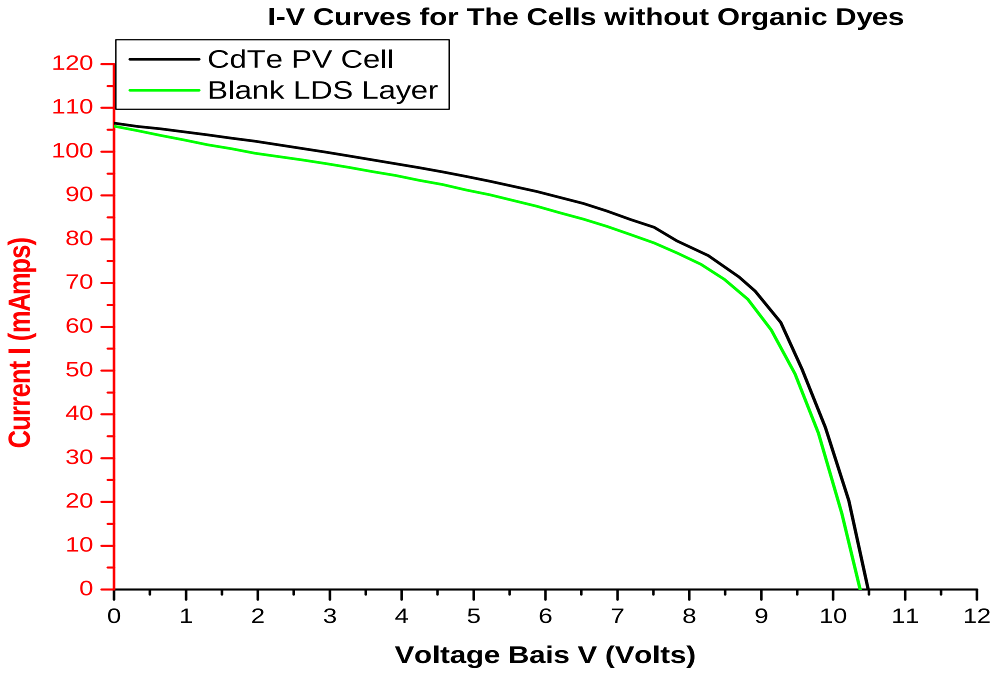

Figure 81 A Comparison of Electrical Output Characteristics of the Current and Voltage of the PV Cells without Organic Dyes

The figure above is the I-V curves for the reference CdTe PV cell and the CdTe PV cell with the blank LDS (PMMA) layer. The short circuit currents and the open circuit voltages are presented in the graph. The graph shows that the reference CdTe PV cell performs better that the CdTe PV cell with the blank LDS (PMMA) layer.

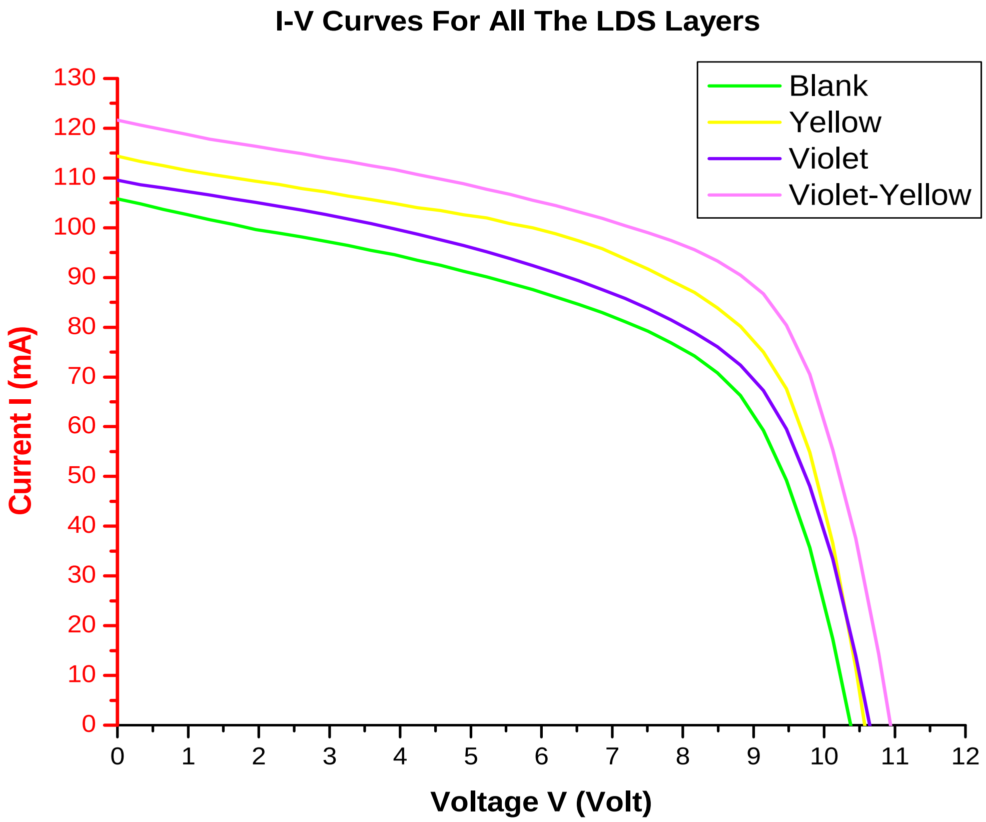

Figure 82 Comparison of Electrical Output Characteristics of the Current and Voltage of the PV Cells with LSD Layers

The figure above is the I-V curves the PV Cells with LSD Layers. The short circuit currents and the open circuit voltages are presented in the graph. The graph shows that the layers contain organic dyes performs better than the blank LDS (PMMA) layer. The mixed Yellow and Violet LDS layer performs better that the single dye LDS layers.

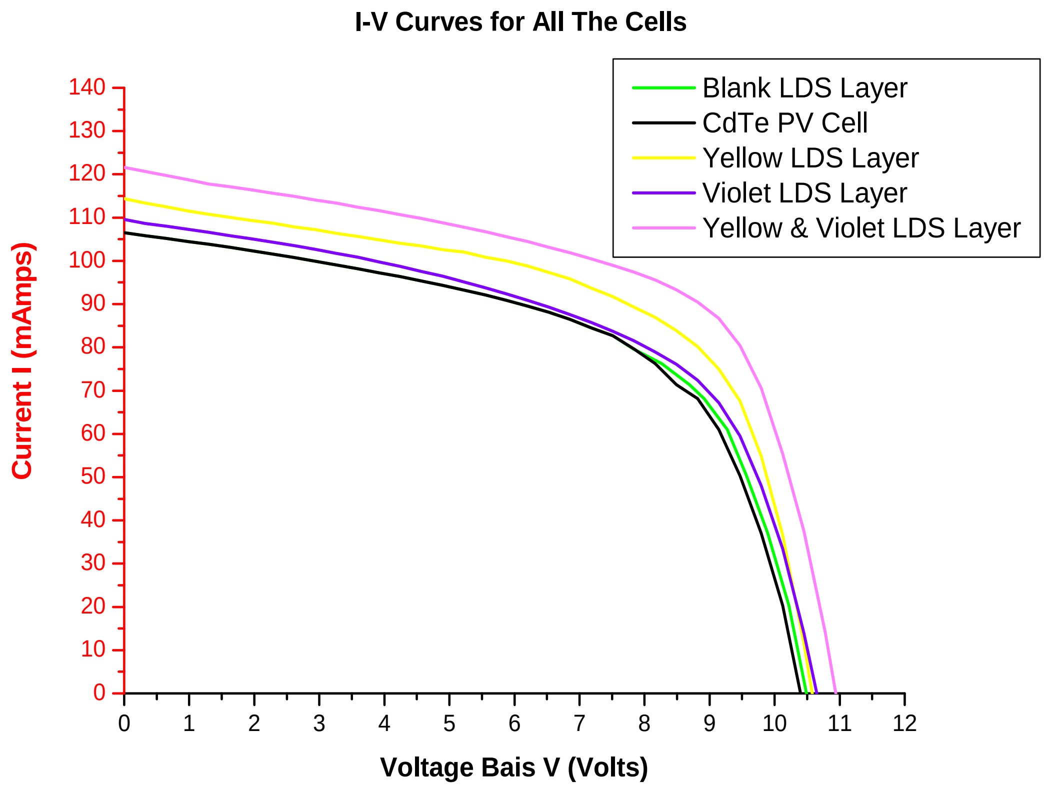

Figure 83 A Comparison of Electrical Output Characteristics of the Current and Voltage of All the PV Cells

The Reference CdTe PV Cell

- Short Circuit Current (mAmps) = 106.48mA
- Open Circuit Voltage = 10.5Vdc

The Blank LDS (PMMA) Layer

- Short Circuit Current (mAmps) = 105.83mA
- Open Circuit Voltage = 10.37Vdc

The Yellow LDS Layer

- Short Circuit Current (mAmps) = 114.39mA
- Open Circuit Voltage = 10.6Vdc

The Violet LDS Layer

- Short Circuit Current (mAmps) = 111.84mA
- Open Circuit Voltage = 10.69Vdc

The Yellow and Violet LDS Layer

- Short Circuit Current (mAmps) = 121.64mA
- Open Circuit Voltage = 10.94Vdc

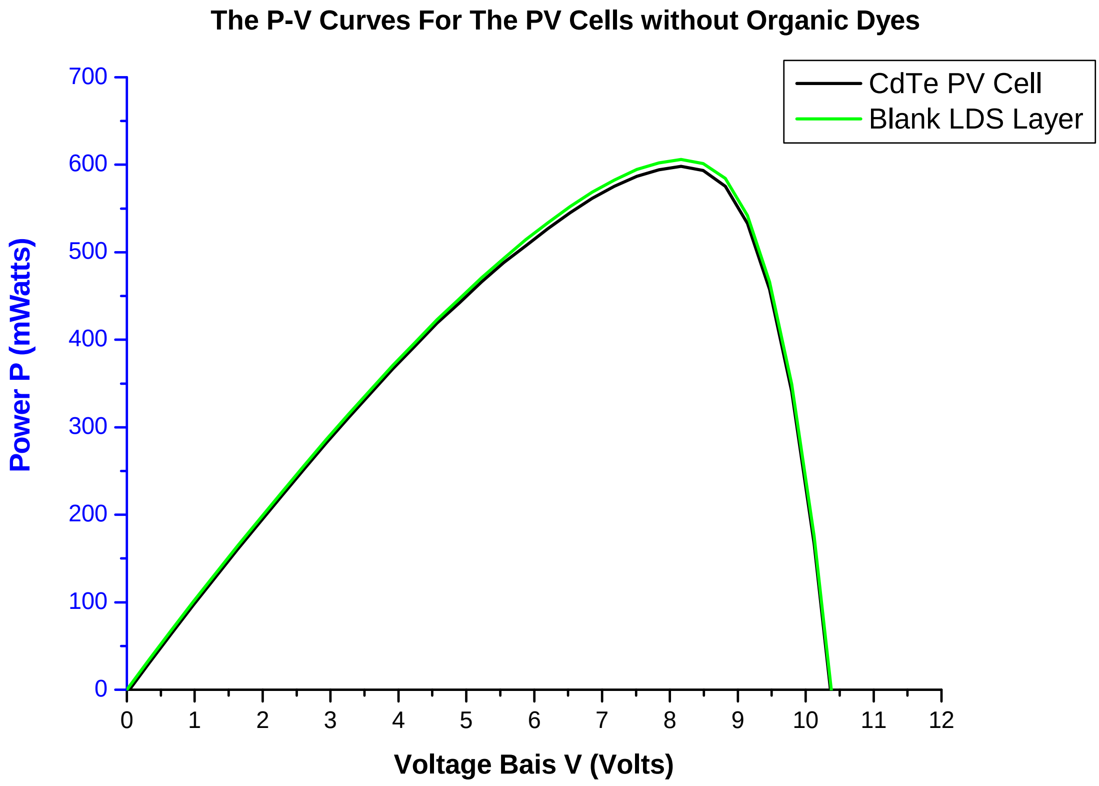

Figure 84 A Comparison of Electrical Output Characteristics of the Power and Voltage of the PV Cells with no Organic Dyes

The figure above is the P-V curves for the reference CdTe PV cell and the CdTe PV cell with the blank LDS (PMMA) layer. The maximum power point, the maximum power voltage and the open circuit voltage are presented in the graph. The graph shows that there is little difference between the reference CdTe PV cell and the CdTe PV cell with the blank LDS (PMMA) layer.

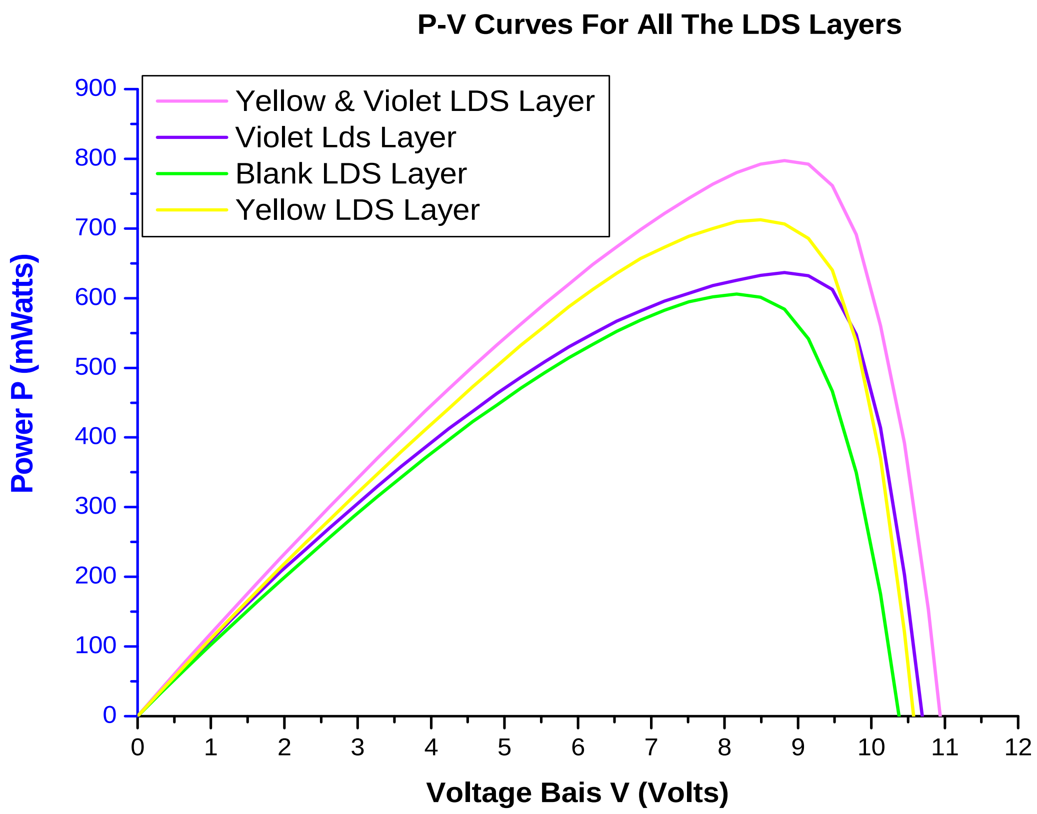

Figure 85 A Comparison of Electrical Output Characteristics of the Power and Voltage of the PV Cells with LDS layers

The figure above is the P-V curves for the reference CdTe PV cell and the CdTe PV cell with the blank LDS (PMMA) layer. The maximum power point, the maximum power voltage and the open circuit voltage are presented in the graph. The graph shows that the layers contain organic dyes performs better than the blank LDS (PMMA) layer. The mixed Yellow and Violet LDS layer performs better that the single dye LDS layers.

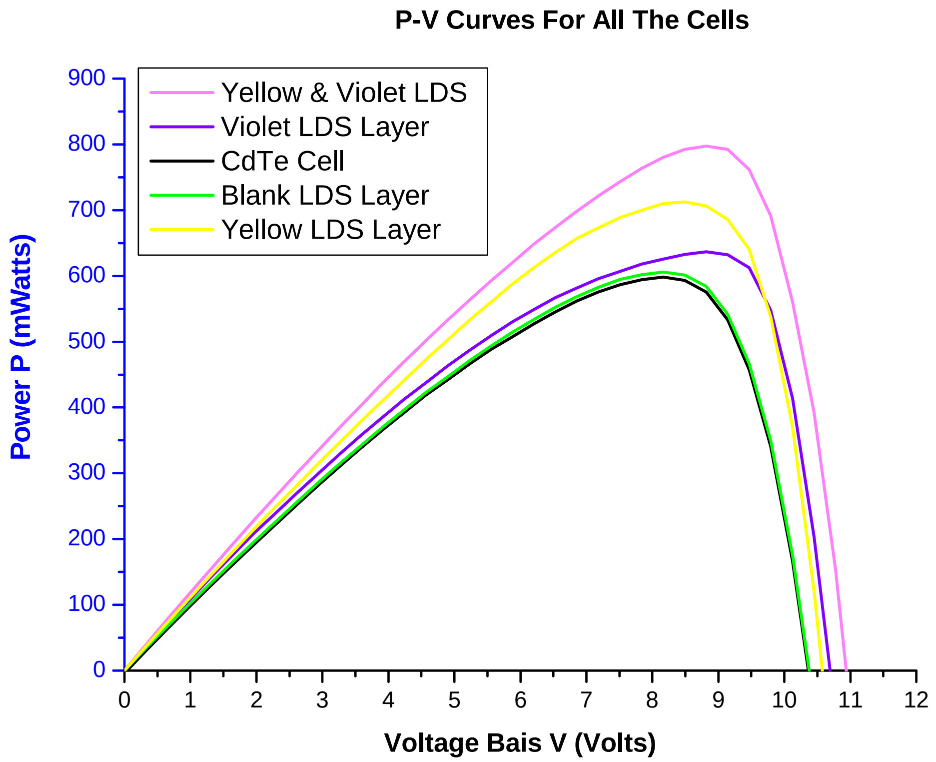

Figure 86 A Comparison of Electrical Output Characteristics of the Power and Voltage of All the PV Cells

The Reference CdTe PV Cell

- Maximum Power (mWatts) = 613.499mWatts
- Maximum Power Voltage Vmp (Volts) = 7.5Vdc

The Blank LDS (PMMA) Layer

- Maximum Power (mWatts) = 606.034mWatts
- Maximum Power Voltage Vmp (Volts) = 8.16Vdc

The Yellow LDS Layer

- Maximum Power (mWatts) = 712.29mWatts
- Maximum Power Voltage Vmp (Volts) = 8.48Vdc

The Violet LDS Layer

- Maximum Power (mWatts) = 636.52mWatts
- Maximum Power Voltage Vmp (Volts) = 8.81Vdc

The Yellow and Violet LDS Layer

- Maximum Power (mWatts) = 797.45mWatts
- Maximum Power Voltage Vmp (Volts) = 8.81Vd

6.10 Findings

6.10.1 Adsorption and Emission

Table 1 Adsorption Characteristics of the CdTe PV Cells

CdTe PV Cells	Absorption Range (nm)	Absorption Peck Range (nm)
Yellow LDS Layer	380nm to 520nm	472nm
Violet LDS Layer	320nm to 420nm	376nm
Mixed Yellow & Violet LDS Layer	320nm to 520nm	472nm

The Yellow LDS layer absorbs light in the range of 380nm to 520nm, which is mostly in the visible region of the solar spectrum. The Yellow LDS layers peak absorption is 472nm.

The Violet LDS layer absorbs light in the range of 320nm to 420nm, which is mostly in the UV region of the solar spectrum. The Violet LDS layers peak absorption is 376nm.

The Yellow and Violet LDS layer absorbs light in the range of 320nm to 520. This is in both the UV region and the visible region of the spectrum. The Yellow and Violet LDS layers peak absorption is 472nm.

This result shows using the mixtures of Yellow 083 and Violet 570 dyes organic dyes did increase the absorption range of the LDS layer allowing more light to be absorbed. This shifts the light to larger wavelengths where the PV cell operates more efficiently.

Table 2 Emission Characteristics of the CdTe PV Cells

CdTe PV Cells	Emission Range (nm)	Emission Peck Range (nm)	Downshifting Range (nm)	Peck Downshift Range (nm)
Yellow LDS Layer	460nm to 640nm	528nm	380nm to 640nm	472nm to 528nm
Violet LDS Layer	377nm to 580nm	428nm	320nm to 580nm	376nm to 428nm
Mixed Yellow & Violet LDS Layer	377nm to 640nm	528nm	320nm to 640nm	376nm to 528nm

The Yellow LDS layer has an emission region of 460nm to 640nm The emission peak for the Yellow LDS layer is 528nm. The Yellow LDS layer downshifts photons from peck to peck at 472nm to 528nm. The complete downshifting range is 472nm to 528nm

The Violet LDS layer has an emission region of 377nm to 580nm. The emission peak for the Violet LDS layer is 428nm. The Violet LDS layer downshifts photons from peck to peck at 376nm to 428nm. The complete downshifting range is 376nm to 428nm.

The mixed Yellow and Violet LDS layer has an emission region of 377nm to 640nm. he emission peak for the mixed Yellow and Violet LDS layer is 528nm. The mixed Yellow and Violet LDS layer downshifts photons from peck to peck at 476nm to 228nm. The complete downshifting range is 376nm to 528nm.

It is clear that the Violet LDS layer and mixed Yellow and Violet LDS layer has suitable spectral properties for luminescent downshifting, as it absorbs in the UV region and downshifts to the visible region.

6.10.2 Electrical Findings

Table 3 Indoor Electrical Characteristics of the CdTe PV Cells

CdTe PV Cells	Open Circuit Voltage Voc (Volts) V	Max Power (mWatts)	Max Power Voltage Vmp (Volts) V	Max Power Current (mAmps)	Short Circuit Currents (mAmps)
Reference CdTe PV cell	10.5	613.499	7.5	81.69	106.48
Blank LDS (PMMA) Layer	10.37	606.034	8.16	74.23	105.83
Yellow LDS Layer	10.6	712.29	8.48	83.9	114.39
Violet LDS Layer	10.69	636.52	8.81	72.2	111.84
Mixed Yellow & Violet LDS Layer	10.94	797.45	8.81	90.45	121.26

The table above is a summary of the electrical results of the indoor testing. The following bar charts put the findings into perspective.

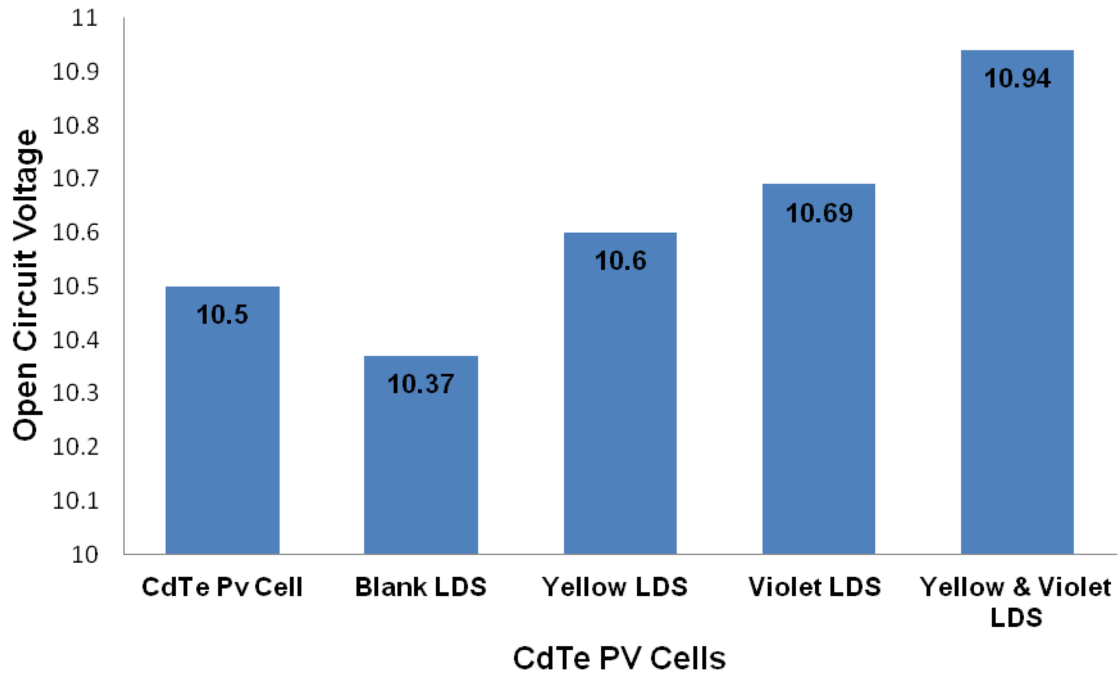

Figure 87 Bar Chart of the Open Circuit Voltage

The bar chart above shows the results of the open circuit voltage results for all the cells. The reference CdTe cell has an open circuit voltage of 10.5Vdc. The mixed Yellow and Violet LDS Layer has the greatest open circuit voltage of 10.94Vdc, this is an increase of 0.49Vdc. It should be noted that the blank LDS layer has a reduction in open circuit voltage of 0.13Vdc.

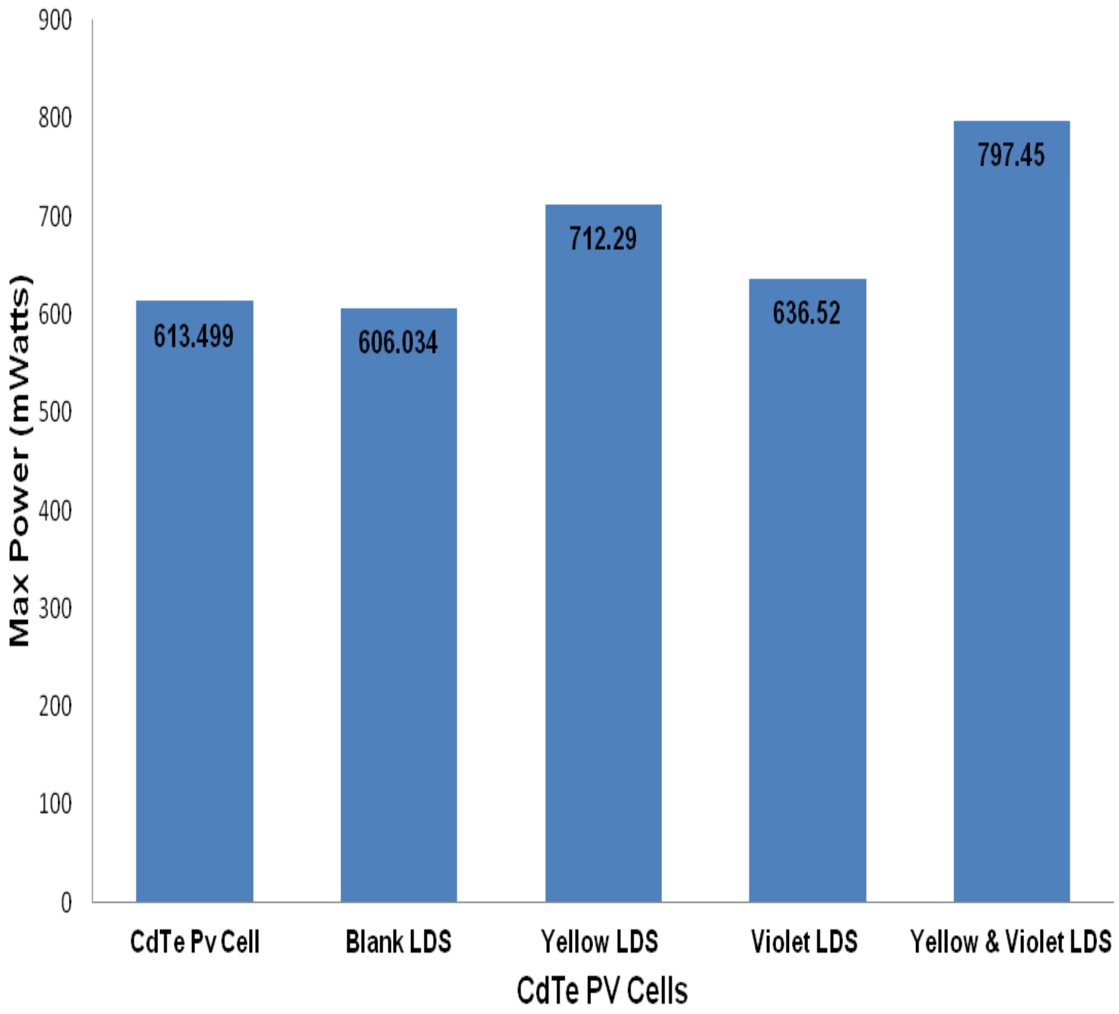

Figure 88 Bar Chart of the Maximum Power

The bar chart above shows the results of the maximum power results for all the cells. The reference CdTe cell has a maximum power of 613.499mWatts. The mixed Yellow and Violet LDS Layer has the greatest maximum power of 797.45mWatts, this is an increase of 183.951mWatts. It should be noted that the blank LDS layer has a reduction in maximum power of 7.456mWatts.

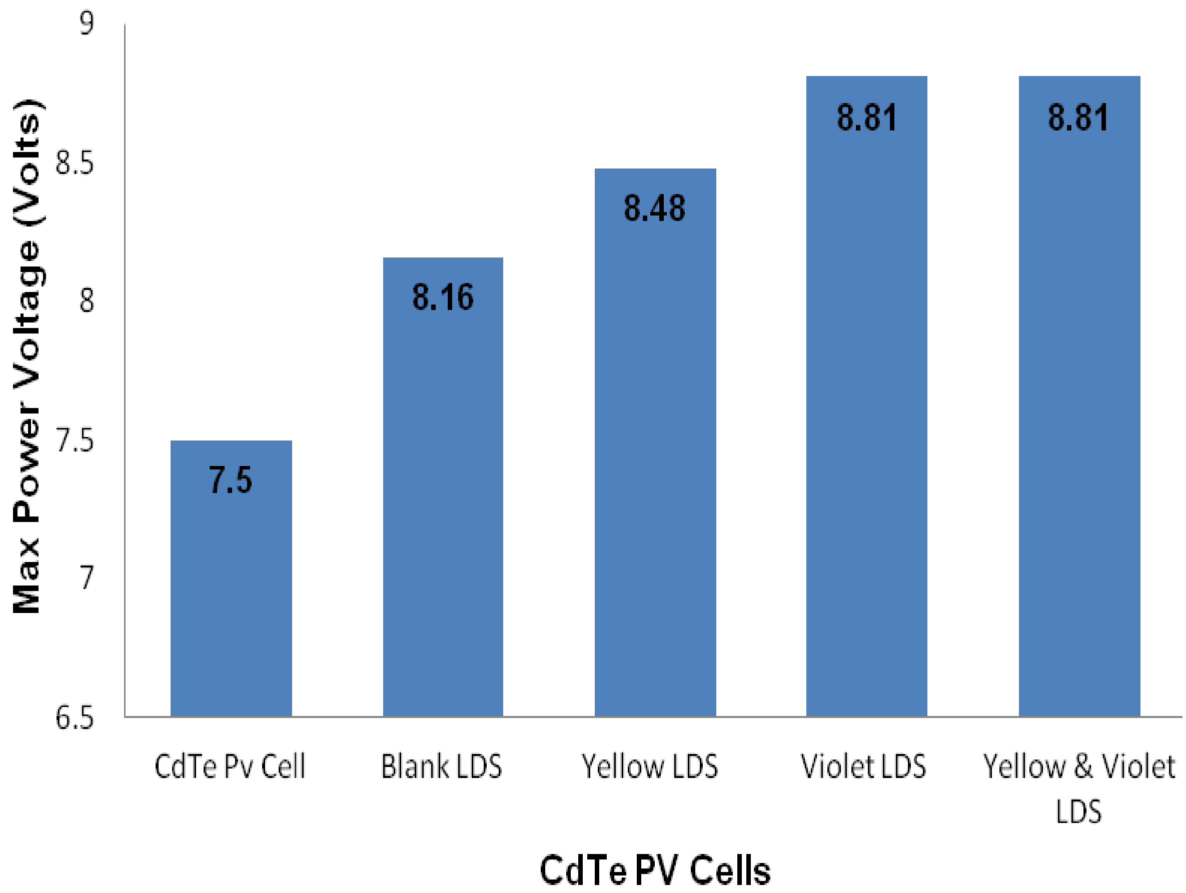

Figure 89 Bar Chart of the Maximum Power Voltage

The bar chart above shows the voltage of the cells at maximum power. The reference CdTe cell has a maximum power voltage of 7.5Vdc. The Violet LDS layer and the mixed Yellow and Violet LDS Layer t have the greatest maximum power voltage of 8.81Vdc, this is an increase of 1.31Vdc. It should be noted that all the LDS layers including the blank LDS layer have an increased maximum power voltage.

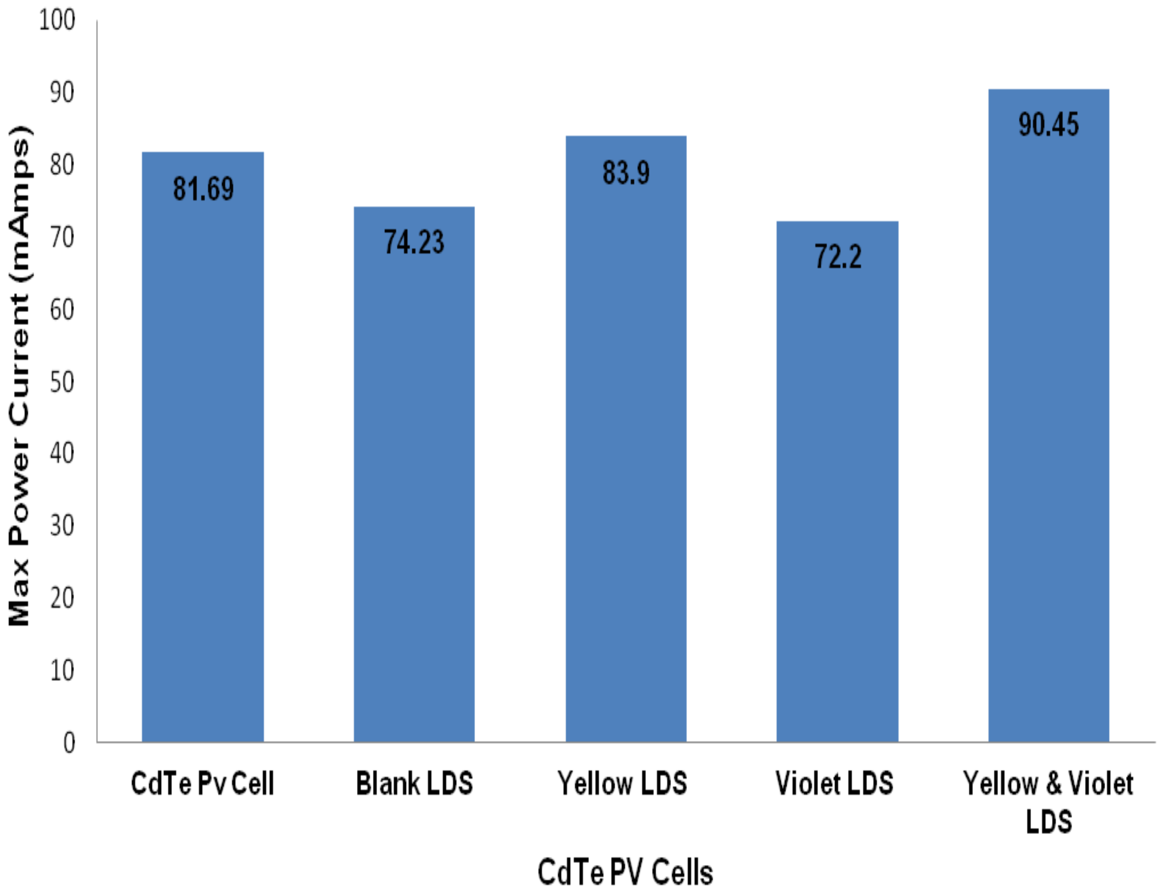

Figure 90 Bar Chart of the Maximum Power current

The bar chart above shows the current of the cells at maximum power. The reference CdTe cell has a maximum power current of 81.69mA. The mixed Yellow and Violet LDS Layer has the greatest maximum power current of 90.45mWatts, this is an increase of 8.76mA. It should be noted that the blank LDS layer has a reduction in maximum power current of 7.46mA.

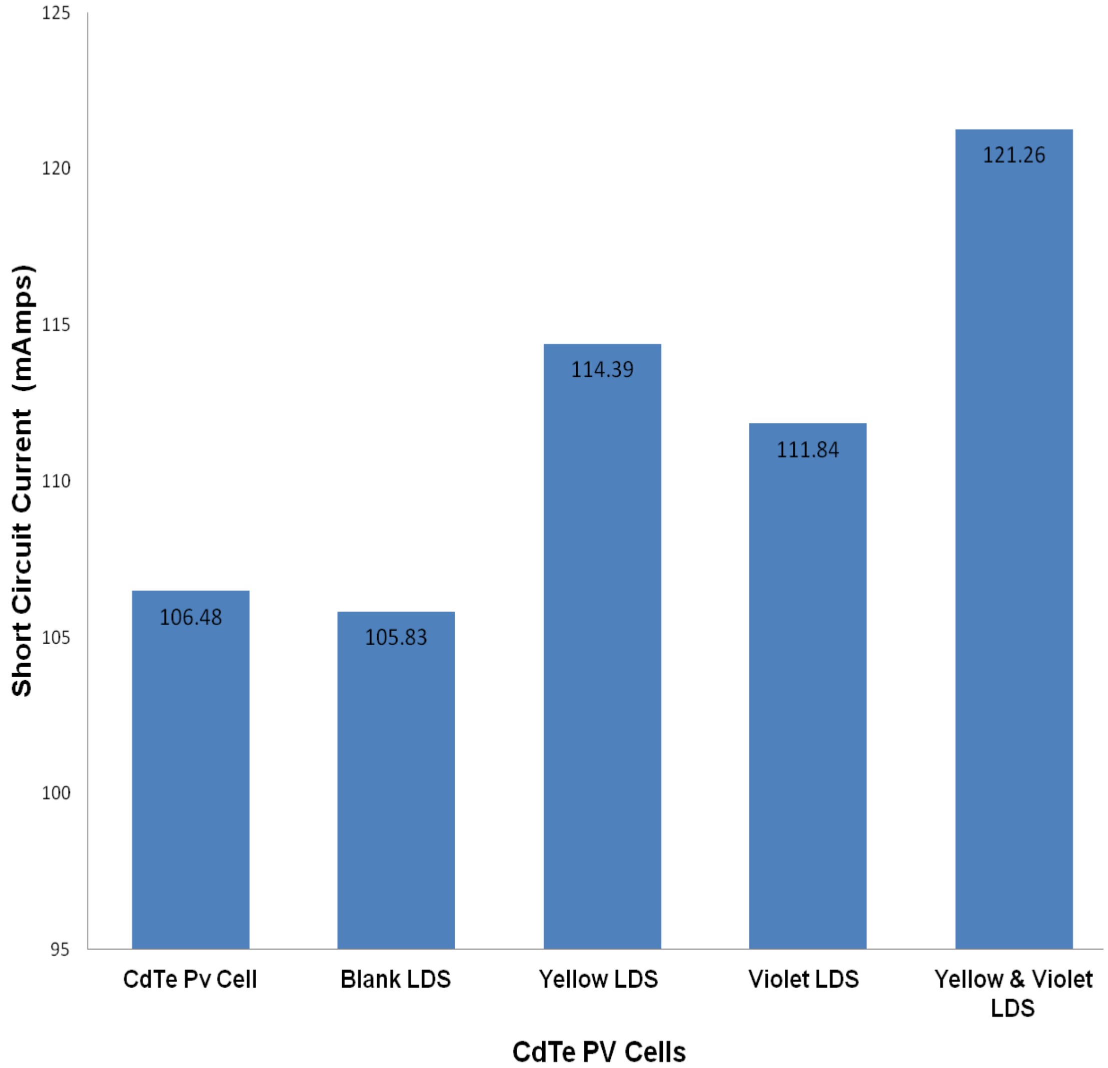

Figure 91 Bar Chart of the Short Circuit Currents

The bar chart above shows the results of the short circuit currents for all the cells. The reference CdTe cell has a short circuit current of 106.48mA. The mixed Yellow and Violet LDS Layer has the greatest short circuit currents of 121.26mA, this is an increase of 13.73mA. This is a percentage increase of 14.23%. It should be noted that the blank LDS layer has a reduction in its short circuit current of 0.65mA, This is a percentage reduction of 0.61%.

Table 4 Indoor Efficiency characteristics of the CdTe PV Cells

CdTe PV Cells	Efficiency (%)	Fill Factor (FF)	Percentage Improvement (%)
Reference CdTe PV cell	2.73%	0.62	0%
Blank LDS (PMMA) Layer	2.69%	0.55	0.61% Reduction
Yellow LDS Layer	3.17%	0.588	7.42%
Violet LDS Layer	2.83%	0.532	5.03%
Mixed Yellow & Violet LDS Layer	3.54%	0.599	14.23%

The table above shows the efficiency, fill factor and the percentage improvement of the cells with the interdiction of luminescent down shifting. The following bar charts put the findings into perspective.

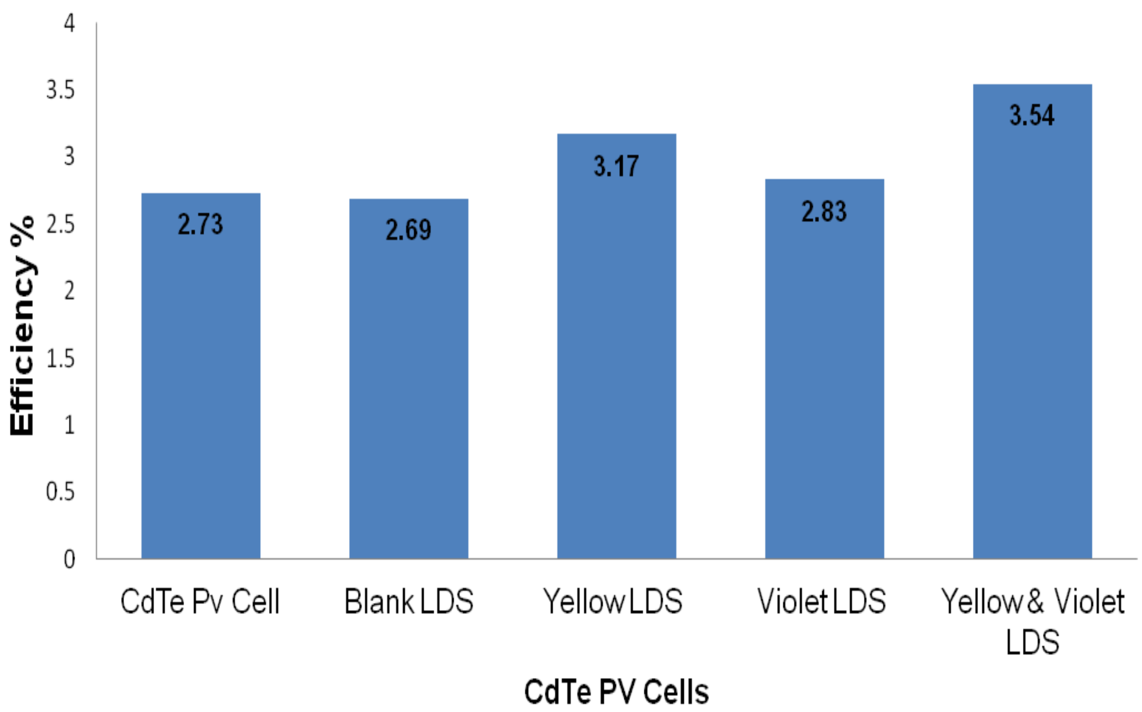

Figure 92 Bar Chart of the Efficiency of the CdTe PV Cells

The bar chart above shows the efficiencies of the CdTe PV Cells. The reference CdTe PV cell has an efficiency of 2.73%. All the LDS layers containing organic dyes improve the efficiency of the CdTe PV cell. The mixed Yellow and Violet LDS Layer has the greatest efficiency of 3.54% this is an improvement of 0.81%. The blank LDS layer containing PMMA has an efficiency of 2.69%, this is a reduction of 0.04%.

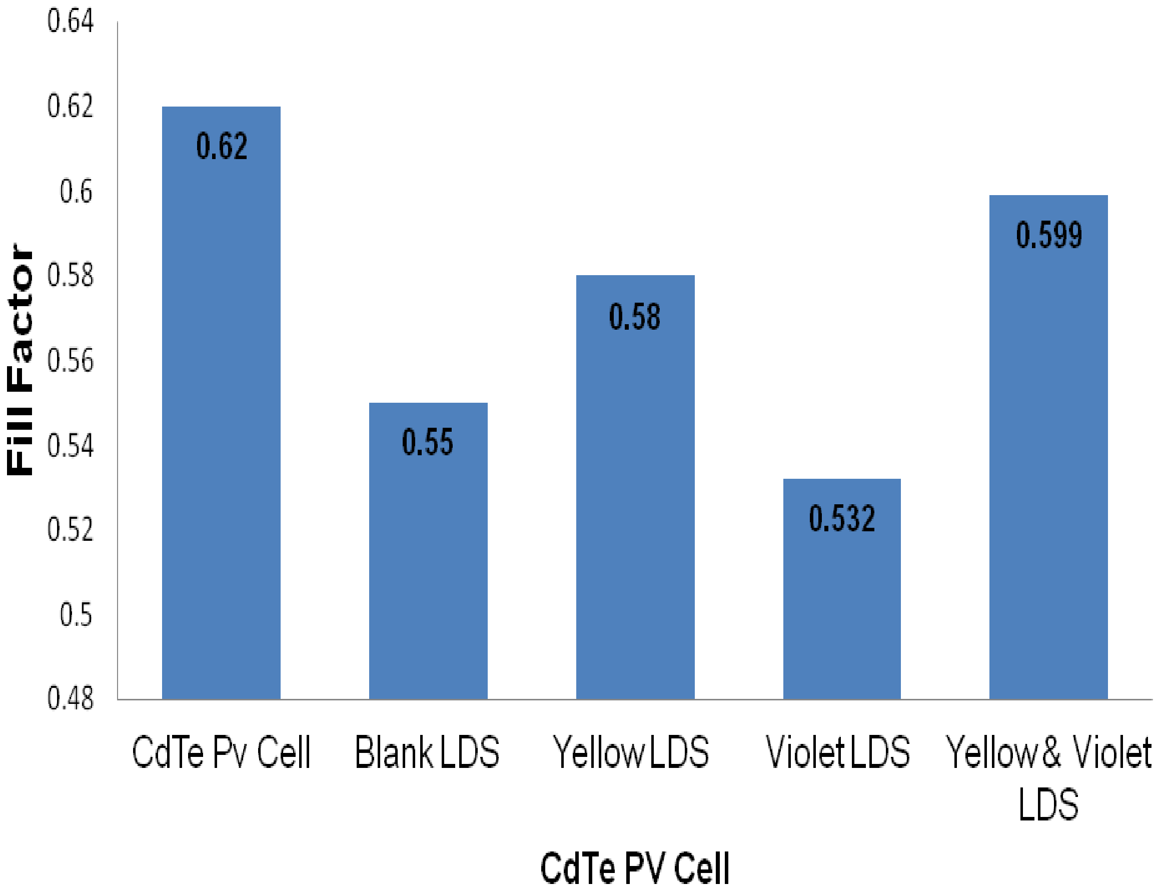

Figure 93 Bar Chart of the Fill Factor for the CdTe PV Cells

The bar chart above shows the Fill Factor for all the CdTe PV Cells. The reference CdTe PV cell has a Fill Factor of 0.62. All the CdTe PV cells with LDS layers have a reduction in Fill Factor.

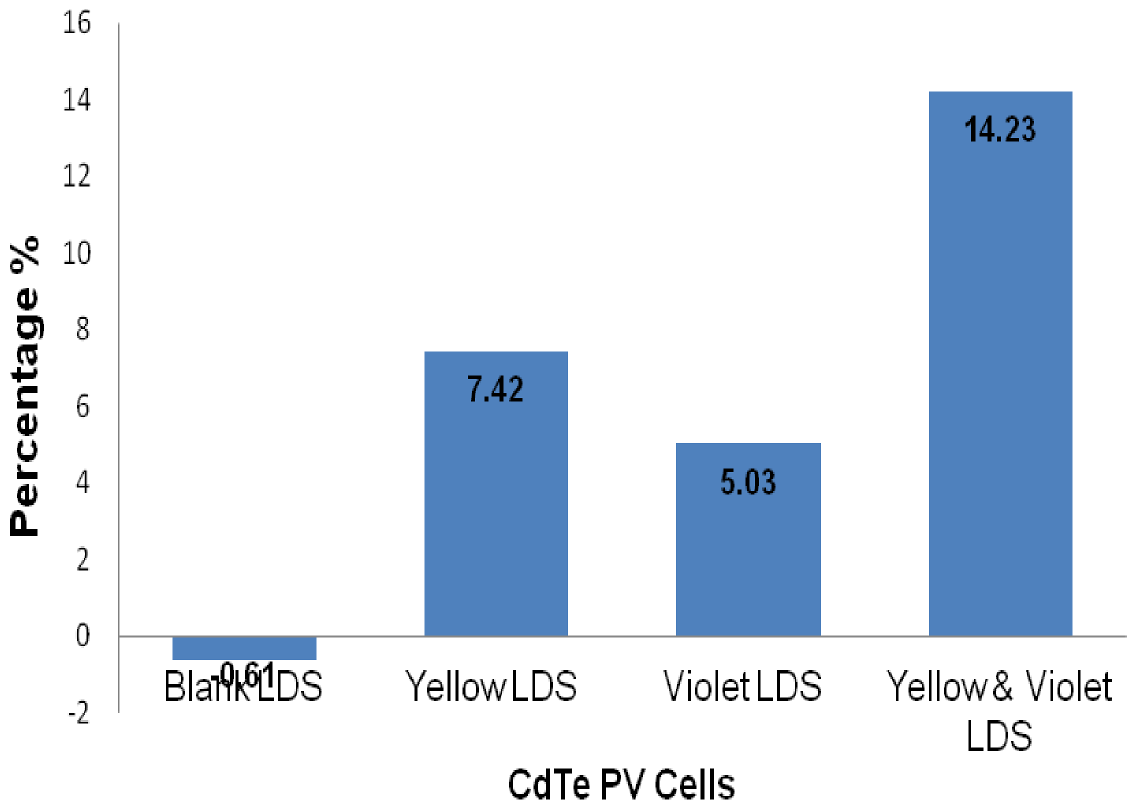

Figure 94 Bar Chart of the Percentage Improvement of the CdTe PV Cells

The bar chart above shows the Percentage Improvement for the short circuit current of the CdTe PV Cells. The percentage improvement figures were found using the following formula,

$$\text{Percentage Improvement} = \frac{Scc\ of\ LDS\ Layer\ CdTe - Scc\ of\ Reference\ CdTe\ PV\ Cell}{Scc\ of\ Reference\ CdTe\ PV\ Cell}\ \text{X}\ 100\%$$

The reference CdTe PV cell is understood to be 0%, therefore anything above 0% is an improvement and anything below 0% is a reduction. All the LDS layers containing organic dyes improve the efficiency of the CdTe PV cell. The mixed Yellow and Violet LDS Layer has the greatest improvement of 14.23%. The blank LDS layer containing PMMA has a reduction in efficiency of 0.61%, therefore the host material in the LDS layers PMMA can reduce the efficiency of the LDS layers and the efficiency of the CdTe PV cells.

7 Conclusions

7.1 Introduction

The study of this dissertation set out to explore the concept that the spectral losses due to limited spectral response can affect the performance of Cadmium Telluride photovoltaic cells. By improving the utilization of the CdTe PV cells, spectral response the potential exists to increase CdTe PV cells efficiency by making better use of short wavelength light. Luminescent organic dyes such as Lumogen yellow 083 and Lumogen Violet 570 can convert high energy photons to lower energy photons. The process of applying a thin layer of luminescent organic dye to the CdTe PV cells is referred to as luminescent down-shifting. This dissertation provides a comparative performance analysis of cadmium telluride photovoltaic cells in indoor testing conditions and in real life conditions. The tests were performed on reference CdTe PV cells and on CdTe PV cells containing luminescent down-shifting layers. The reason for performing these tests was to find the following research questions.

1) How did the luminescent downshifting layers perform in the absorption and emission tests?

2) How the CdTe PV cells perform in terms of energy production and efficiency?

3) Did luminescent downshifting can increase the efficiency of CdTe PV cells?

4) What is CdTe PV cells electrical behaviour, performance and characterization of CdTe PV cells in indoor test conditions?

5) What is CdTe PV cells electrical behaviour, performance and characterization of CdTe PV cells on the Kevin St building?

6) What is the difference between the indoor tests conditions to the real life conditions?

7) Which Organic dyes perform best as luminescent downshifting layers?

7.2 Empirical Findings

1) How did the luminescent downshifting layers perform in the absorption and emission tests?

The Yellow LDS layer absorbs light in the range of 380nm to 520nm, the Yellow LDS layers peak absorption is 472nm. The Yellow LDS layer has an emission region of 460nm to 640nm, the emission peak for the Yellow LDS layer is 528nm. The Yellow LDS layer downshifts photons from peck to peck at 472nm to 528nm. The complete downshifting range is 472nm to 528nm

The Violet LDS layer absorbs light in the range of 320nm to 420nm, the Violet LDS layers peak absorption is 376nm. The Violet LDS layer has an emission region of 377nm to 580nm. The emission peak for the Violet LDS layer is 428nm. The Violet LDS layer downshifts photons from peck to peck at 376nm to 428nm. The complete downshifting range is 376nm to 428nm.

The Yellow and Violet LDS layer absorbs light in the range of 320nm to 520, the Yellow and Violet LDS layers peak absorption is 472nm. The mixed Yellow and Violet LDS layer has an emission region of 377nm to 640nm. The emission peak for the mixed Yellow and Violet LDS layer is 528nm. The mixed Yellow and Violet LDS layer downshifts photons from peck to peck at 476nm to 228nm. The complete downshifting range is 376nm to 528nm.

This result shows using the mixtures of Yellow 083 and Violet 570 dyes organic dyes did increase the absorption range of the LDS layer allowing more light to be absorbed. This shifts the light to larger wavelengths where the PV cell operates more efficiently. It is clear that the Yellow LDS layer absorbs light in the visible range reemitted it in the visible range. The Violet LDS layer and mixed Yellow and Violet LDS layer has suitable spectral properties for luminescent downshifting, as it absorbs in the UV region and downshifts to the visible region witch makes better use of the spectral response.

2) How the CdTe PV cells perform in terms of energy production and efficiency?

The energy input to the CdTe PV cells was light energy at a light Intensity / Irradiance of 1000 W/m².

The reference the CdTe PV cell had a energy production of 613.499mWatts with an overall efficiency of 2.73%.

The CdTe PV cell with the blank layer had an energy production of 606.034mWatts with a overall efficiency of 2.69%.

The CdTe PV cell with the Yellow LDS layer had an energy production of 712.29mWatts with a overall efficiency of 3.17%.

The CdTe PV cell with the Violet LDS layer had an energy production of 636.52mWatts with an overall efficiency of 2.83%.

The CdTe PV cell with the mixed Yellow and Violet LDS layer had an energy production of 712.29mWatts with an overall efficiency of 3.54%.

3) Did luminescent downshifting can increase the efficiency of CdTe PV cells?

To evaluate the if the luminescent downshifting had any effect on efficiency a reference CdTe PV cell underwent the same test as the CdTe PV cells containing LDS layers in order to compare them. The reference CdTe PV cell had a power output of 613.499mWatts and a short circuit current of 106.48mAmps. The percentage increase of the CdTe PV cells was acquired using the following formula.

$$\text{Percentage Improvement} = \frac{Scc\ of\ LDS\ Layer\ CdTe - Scc\ of\ Reference\ CdTe\ PV\ Cell}{Scc\ of\ Reference\ CdTe\ PV\ Cell}\ \text{X } 100\%$$

The CdTe PV cell with the blank LDS layer had an energy reduction of 7.456mWatts, with a percentage reduction of 0.61%.

The CdTe PV cell with the Yellow LDS layer had an increase in energy production of 98.791mWatts with a percentage improvement of 7.42% over the reference CdTe PV cell.

The CdTe PV cell with the Violet LDS layer had an increase in energy production of 23.021mWatts with a percentage improvement of 5.03% over the reference CdTe PV cell.
The CdTe PV cell with the Yellow and Violet LDS layer had an increase in energy production of 183.951mWatts with a percentage improvement of 14.23% over the reference CdTe PV cell.

These results show that the introduction of luminescent downshifting does increase the efficiency of CdTe PV cells. The host material (PMMA) actually decreases the efficiency of the CdTe PV cells.

4) What is CdTe PV cells electrical behaviour, performance and characterization of CdTe PV cells in indoor test conditions?

The CdTe PV cells were characterized in terms of the I-V curves and P-V curves.
The reference CdTe PV cell has a short circuit current of 106.48mA, an open circuit voltage of 10.5Vdc, a maximum power point of 613.499mwatts, a maximum power voltage of 7.5Vdc and a maximum power current of 81.69mAmps.

The CdTe PV cell with the blank LDS layer has a short circuit current of 105.83mA, an open circuit voltage of 10.37Vdc, a maximum power point of 606.034mwatts, a maximum power voltage of 8.16Vdc and a maximum power current of 74.23mAmps.

The CdTe PV cell with the Yellow LDS layer has a short circuit current of 114.39mA, an open circuit voltage of 10.6Vdc, a maximum power point of 712.29mwatts, a maximum power voltage of 8.48Vdc and a maximum power current of 83.9mAmps.

The CdTe PV cell with the Violet LDS layer has a short circuit current of 111.84mA, an open circuit voltage of 10.69Vdc, a maximum power point of 636.52mwatts, a maximum power voltage of 8.81Vdc and a maximum power current of 72.2mAmps.

The CdTe PV cell with the mixed Yellow and Violet LDS layer has a short circuit current of 121.26mA, an open circuit voltage of 10.94Vdc, a maximum power point of

797.45mwatts, a maximum power voltage of 8.81Vdc and a maximum power current of 90.45mAmps.

5) Which Organic dyes perform best as luminescent downshifting layers?

The Organic dyes used were Lumogen yellow 083 layer and Lumogen Violet 570 to make the LDS layers. As a single Organic dye Lumogen yellow 083 performed better than Lumogen Violet 570. The mixture of the two Organic dyes proved to be the best LDS layer and outperforming the two single organic dyes. The LDS layers are made using a host material PMMA. A blank Layer was made containing only the host material, this layer proved to decrease the electrical output and efficiency of the CdTe PV cell.

7.3 Research Limitations

1) What is the difference between the indoor tests conditions to the real life conditions?

This question could also not be answered due to a problem with the National Instruments PXI-1033 data logger. As no outdoor data was logged, it was impossible to compare the outdoor data to the indoor. It was expected that the outdoor CdTe PV cells would be exposed to a larger amount of ultra/Violet light. It was expected that this exposure to ultra/Violet light would show a greater improvement in electrical output and efficiency of the CdTe PV cells with the LDS layers.

2) What is CdTe PV cells electrical behaviour, performance and characterization of CdTe PV cells on the Kevin St building?

This question could not be answered due to a problem with the National Instruments PXI-1033 data logger. The max voltage PXI-1033 data logger is designed to log 6 volts dc as a maximum voltage. The CdTe PV cells voltages ranged from 10.37Vdc to 10.96Vdc this exceeds the voltage range of PXI-1033 data logger. When the PXI-1033 data logger was logging the output of the CdTe PV cells, the data user interface was displaying corrupted data. The data logger was the responsibility of the

PhD student's and it was not within the author's scope of the project to have such equipment or acquire large equipment.

This was also the problem when it came acquiring an oven large enough to bake the LDS layers for the large CdTe PV cells. At present the DIT do not have a oven large enough to accommodate this process. This problem was related to the PhD student's scope of the project.

7.4 Conclusion of the Conclusion

The aim of this dissertation was to find out if spectral losses due to limited spectral response of Cadmium Telluride photovoltaic cells could affect their performance.

The question was answered by performing a comparative performance analysis of CdTe PV cells with the introduction of luminescent downshifting. This study provides the results that the potential does exists to increase CdTe PV cells efficiency by luminescent downshifting. The simulation results have shown that, increases in the short-circuit current and in the percentage improvement of 5.03% 7.42%, and 14.23% respectively was achieved by using an organic dyes Yellow 083 and Violet 570 to make the three different LDS layers.

8 Further Research

8.1 Continued Development of the Host Material PMMA

This dissertation demonstrates results that the electrical output and efficiency of the CdTe PV cells can be improved by means of luminescent downshifting with organic dyes. The host material PMMA was shown to reduce the possible efficiency of the LDS layers, this leads to the question does The volume of PMMA used with the dye solution affect the efficiency? Is less or more better? Are there better host materials that could be used with the organic dyes?

8.2 Continued Development of Organic Dyes

An ideal LDS layer would have a broad absorption range to utilize the solar spectrum efficiently, 100% emission of light from the absorbing luminescent species, A large shift between the absorption and emission spectra to reduce absorption losses, and long term stability. To work towards making the organic LDS layers idea further research will be required. This research found that Lumogen Yellow and Violet dye was found to be the most suitable LDS layer.

Lumogen Yellow dye was found to be the most suitable organic dye LDS layer. Solar cell has poor optical response up to 470nm. Lumogen Yellow, absorbing between 380 to 520nm, can be therefore, used as to enhance the solar cells efficiency.

Organic photovoltaic cells are promising in terms of their lightweight, mechanically flexibility, ease of processing and low cost. They have poor optical response therefore, further research on the development of organic dye with Organic photovoltaic cells may have a promising outcome.

The two organic dyes Violet 570 and Yellow 083 have a great contribution in this dissertation, the results could be compared to another organic dye, Orange 240 to see how it would perform and if mixing the organic dye with Orange 240 would be of benefit.

8.3 The Manufacturing Process LDS layers

The cost of the manufacturing process is outside the scope of this study.
Cost effectiveness of the LDS layers is therefore a idea of future work. How much does it cost to make the LDS layers? Does the cost outweigh the savings on using the LDS layers? Does production process of LDS layers generate more Co2 emissions than they reduce while they are been used?

8.4 Solar Concentrators

A solar concentrator uses lenses, which take a large area of sunlight and direct it towards a specific spot (i.e. a solar cell) by bending the rays of light and focusing them. This makes the light more focused on the solar cell, making the cells vastly more efficient. Concentrators work best when there is a single source of light and the concentrator can be pointed right at it. The solar concentrators also have the advantage that the solar cells can be spaced farther apart since light can be focused on each cell. This means fewer solar cells need to be made and the panels cost less to construct. There research scope for using solar concentrator with LDS layer to see how they perform. An idea would be a comparative study to see what performs the best. Use a reference PV cell, a PV cell with a LDS layer, a PV cell with a solar concentrator and a PV cell with both a LDS layer and a solar concentrator and compare them all to one another.

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10 Log of Correspondence with Supervisor

Student-Supervisor Log Record	
Date:	Meeting 1 - 26/11/2013
Attendees:	Mark Gleeson & Kevin O Farrell
Items Discussed:	Petty cash option and claim the money back for materials for the project
Tasks to be completed:	Design of the PV cells Frame.
Tasks Completed:	N/A for this meeting.
Signatures:	

Student-Supervisor Log Record

Date:	Meeting 2 - 29/01/2014
Attendees:	Mark Gleeson & Kevin O Farrell
Items Discussed:	Safety training
Tasks to be completed:	Safety training
Tasks Completed:	N/A for this meeting.
Signatures:	

Student-Supervisor Log Record	
Date:	Meeting 3 - 30/01/2014
Attendees:	Mark Gleeson & Kevin O Farrell
Items Discussed:	General Introduction Web courses Project Dissertation Module ES & EM Project Guidance Document Student Writing Guide Masters Template Project Proposal Issues
Tasks to be completed:	Re-think overall research question to reduce vagueness. Reduce number of objectives to five (maximum) and ensure that new objectives don't include main thesis components such as methodology, literature review, etc.
Tasks Completed:	N/A for this meeting.
Signatures:	

Student-Supervisor Log Record	
Date:	Meeting 5 - 4/03/2014
Attendees:	Mark Gleeson & Kevin O Farrell
Items Discussed:	methodology,
Tasks to be completed:	methodology.
Tasks Completed:	N/A for this meeting.
Signatures:	

Student-Supervisor Log Record	
Date:	Meeting 5 - 27/01/2014
Attendees:	Mark Gleeson & Kevin O Farrell
Items Discussed:	literature review
Tasks to be completed:	literature review, etc.
Tasks Completed:	N/A for this meeting.
Signatures:	

Student-Supervisor Log Record	
Date:	Meeting 6 - 08/04/2014
Attendees:	Mark Gleeson & Kevin O Farrell
Items Discussed:	Problems with dissertation
Tasks to be completed:	Solar Concentrators
Tasks Completed:	N/A for this meeting.
Signatures:	