Examiner's commentary

Interestingly a visit to a solar panel manufacturer inspires the candidate's clear and focused research question itself complemented by the title. The influence of two parameters, wavelength, and temperature, on the output power of three different types of solar panel is considered. For each panel, a high quality and reasonable amount of data is collected. Also, the candidate makes an effective selection of sources. The candidate introduces the micro-physics of a cell, P-N junction, bandwidth energy, action of photon and types of cell. An in-depth theoretical development follows with key figures from sources well identified. The candidate investigates the effect of wavelength on spectral response and ideal performance of cell, quantum efficiency depending on bandwidth. Also considered is the negative effect of temperature on bandwidth (reduced) hence power decreasing. The candidate takes advantage of an exceptional bibliography with understanding. The candidate's research is appropriate to the research question, with an answer in line with results obtained for the three different types of panels. The analysis includes uncertainty and significant figures well manipulated as well as a correct propagation of error. Clear graphs present best-fit equations for each variable and panel. The candidate applies theory systematically in the analysis of graphs of each type of panel and independent variable. The analysis and discussion, of high quality, reveals general trends and specifics for each type of photovoltaic panel. An evidence-supported conclusion is given and limitations of the investigation are considered. The presentation, of very good quality, is supported by a complete title page, chapters and headings, tables and graphs all well-organized. The clear labelling and regular font reflect a very good layout. There is an excellent presentation of references as footnotes in the core and sources in the bibliography. The constant commitment shown in exploring a new and relevant theory, facing challenges in collecting data and seriously analysing results is inspiring, a reflection of a very high standard achievement.

International Baccalaureate

Extended Essay

Physics

Topic: To find the best semi-conductor and its structure for the construction of solar cells.

Research Question: Does the electrical output of a solar cell depend on the type of semi-conductors used for construction at various operating temperatures and wavelengths of light incident on it?

Word Count : 3969

Table of Contents

CHAPTER 4 – Conclusion, Evaluation and Citations

1. Introduction

A recent visit to solar panel manufacturing company aroused my curiosity about solar panels. There were so many types of solar panels on show. Some were tiny, while others were large. This aroused a question in me - "Do each of these solar panels have their own unique uses?" I wanted to analyse this experimentally and reach my own conclusion. The performance of each type of solar panel can be found at different points on the electromagnetic spectrum, which could determine the best-suited uses for each of solar panel.

Hence this research question was formulated:

DOES THE ELECTRICAL OUTPUT OF A SOLAR CELL DEPEND ON THE TYPE OF SEMI-CONDUCTORS USED FOR CONSTRUCTION AT VARIOUS OPERATING TEMPERATURES AND WAVELENGTHS OF LIGHT INCIDENT ON IT?

After further thinking, I reflected upon my initial question "Do each of these solar panels have their own unique uses?". These panels have their unique purposes and each of them operate best under certain light conditions. Keeping in mind the former statement it was decided that wavelength and intensity of light incident on the panel can be used to simulate various light conditions. Also the temperature at which these solar panels operate might vary. Therefore, it was further decided that changing the temperature of operation would also be considered. Therefore, by answering the sub-questions in this introduction, I think the answer to principle research question can be and with adequate justification.

2. Background Information

The solar panel operation is similar to that of a P-N junction. The P-N junction consists of 2 types of extrinsic semiconductor placed horizontally above each-other. This device that converts light energy to electrical energy through photoelectric effect. Photoelectric effect, phenomenon in which electrically charged particles are released from or within a material when it absorbs electromagnetic radiation. [1]A more complex application of the photoelectric effect is seen in the P-N junction.

The most important parameter in the solar panels that determines the voltage and current generated is the band-gap. Each structure of solar panel have different band-gap lengths, therefore different band-gap energies. The voltage is the work done required by electrons to cross the band-gap and current generated is directly proportional to the number of electrons that cross the band-gap.

Figure 1: Monocrystalline, Polycrystalline and Amorphous Panels

Energy from the sun is emitted in the form of electromagnetic waves in range of wavelengths. White light from the Sun includes all colours of the visible spectrum and ranges in wavelength from about 400 nm to about 780 nm. The order of energy of waves with different frequencies starts from violet and descends through at the redder end of the spectrum. The energy of the photons is determined by their frequency and their relation is given by the formula[2]:

$$E = hf \quad ---------- (1)$$

where f is the frequency of photons and h is the Planck's constant which has a value of $6.63 \times 10^{-34}\ Js^{-1}$.

[1] Britannica, The Editors of Encyclopaedia. "Photoelectric Effect." Encyclopædia Britannica, Encyclopædia Britannica, Inc., 19 Jan. 2018, www.britannica.com/science/photoelectric-effect. Date Accessed - 08/07/18

2 R. Abd Elgani, et al. Impact of the Light Intensity Variation on the Performance of Solar Cell Constructed from (Muscovite/TiO2/Dye/Al) . 9 Aug. 2013, file.scirp.org/pdf/NS_2013092914301980.pdf. Date Accessed - 08/07/18

But the through qualitative analysis it can be determined that the optimum range of wavelengths lie towards the red end of the visible light spectrum (spectral response). [3] The spectral response describes the sensitivity of the photosensor to optical radiation of different wavelengths.[4]

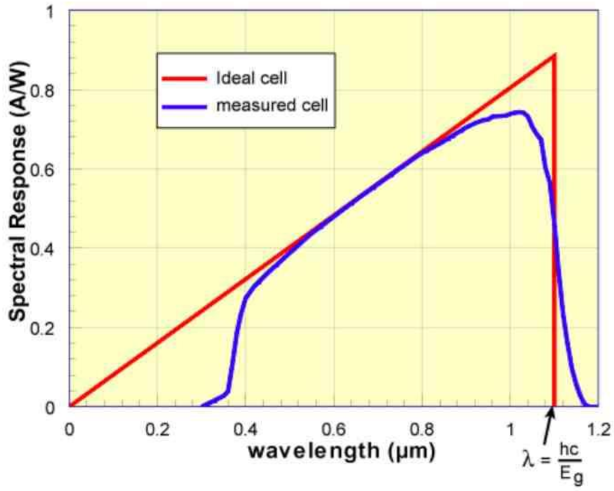


Figure 2: Spectral Response vs Wavelength[5]

The trend in Fig.1 suggests that shorter wavelengths (less than 400 nm) are absorbed by the panel's glass, resulting in low cell response. On the other hand, ideal performance is attained at intermediate wavelengths and is close to null at wavelengths close to 1000 nm. Silicon is an indirect band-gap semiconductor so there is not a sharp cut off at the wavelength corresponding to the band-gap (1.12).

Photons of longer wavelengths, unable to knock electrons off due to insufficient energy offer limited ideal spectral response. At smaller wavelengths, photons have energy larger than the band-gap requirement, therefore excess energy is goes into heating the panel. Because the aforementioned factors, there is significant power loss in solar cells[6].

The quantum efficiency can be determined from the spectral response by replacing the power of the light at a particular wavelength with the photon flux for that wavelength. [7]This gives:

3 V.Jafari Fesharaki, et al. The Effect of Temperature on Photovoltaic Cell Efficiency. 20 Nov. 2011, research.iaun.ac.ir/pd/jjfesharakiold/pdfs/PaperC_4124.pdf. Date Accessed - 17/07/18
4 "Photosensor Tutorial." Lighting Research Center | Education | Learning | Terminology | Spectral Power Distribution, Lighting Research Center, www.lrc.rpi.edu/programs/nlpip/tutorials/photosensors/spectral.asp. Date Accessed - 17/07/18
5 "PVEducation." Properties of Light | PVEducation, www.pveducation.org/pvcdrom/solar-cell-operation/spectral-response. Date Accessed – 12/07/18
6 Dan Thomas. "The Photoelectric Effect." Types of Chemical Bonds, University of Guelph, 5 July 1996, dwb4.unl.edu/Chem/CHEM869B/CHEM869BLinks/www.chembio.uoguelph.ca/educmat/chm386/rudiment/tourexp/photelec.htm Date Accessed- 28/ 09/18
7 "Solar Cell Operation." Solar World, 14 Jan. 2018, www.solarworldpower.com.au/solar-cell-operation/.

$$\mathcal{E} = \frac{q\lambda}{hc}\eta \text{ ----------(2)}$$

$$\mathcal{E} = \text{Spectral Response}$$

$$q = \text{charge}$$

$$\lambda = \text{wavelength of light}$$

$$h = \text{Planck's constant}$$

$$c = \text{speed of light}$$

$$\eta = \text{quantum efficiency}$$

Increases in operating temperatures of solar cells negatively affects the band-gap; it reduces and also affects other semi-conductor parameters. The band-gap decreases because increasing temperature results in higher electron energy, in turn bond-energy requirement. As the bond energy reduces, the band-gap of the semiconductor also reduces. Therefore increasing the temperature reduces the band gap.

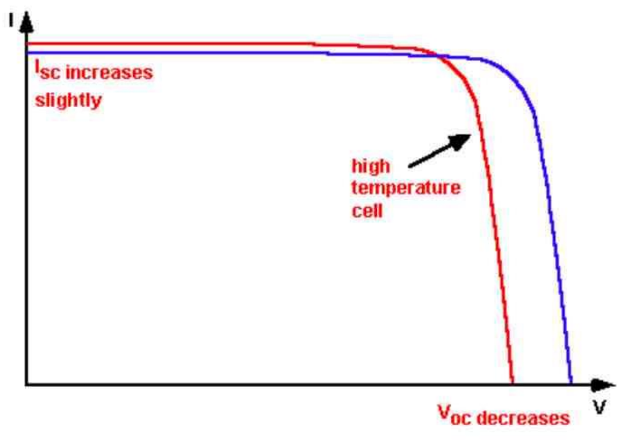


Figure 3: Current vs Voltage with varied temperature[8]

The equation for I_0, reverse saturation current, from one side of a *p-n* junction is given by[9]:

$$I_0 = qA\left(\frac{Dn_i^2}{LN_D}\right) \text{ -------------- (3)}$$

Date Accessed-29/09/18

[8] "PVEducation." Properties of Light | PVEducation, www.pveducation.org/pvcdrom/solar-cell-operation/effect-of-temperature. Date Accessed 05/01/19

[9] Tobnaghi, Davud Mostafa, and Rahim Madatov. "The Effect of Temperature on Electrical Parameters of Solar Cells." Research & Reviews: Journal of Agriculture and Allied Sciences, Research and Reviews, www.rroij.com/open-access/the-effect-of-temperature-on-electricalparameters-of-solar-cells.php Date Accessed - 18/10/18

q = electronic charge

A = area of exposure

D = diffusivity of minority carrier

L = minority carrier diffusion length

N_D = doping constant

n_i = intrinsic carrier concentration

$$n_i^2 = 4\left(\frac{2\pi kT}{h^2}\right)^3 (m_e \times m_h)^{\frac{3}{2}} e^{-\frac{E_{G0}}{kT}}$$

$$n_i^2 = BT^3 e^{-\frac{E_{G0}}{kT}}$$

where $B = 4\left(\frac{2\pi k}{h^2}\right)$, which is independent of temperature

T is the temperature

h and k are constants

m_e and are the effective masses of electrons and holes respectively

E_{GO} is the band-gap linearly extrapolated to absolute zero

Substituting for n_i^2 in. equation (3) gives

$$I_0 = qA\frac{D}{LN_D}BT^3 e^{-\frac{E_{G_O}}{kT}}$$

Since $qA\frac{D}{LN_D}$ is not temperature dependent, the equation can be re-written as:

$$I_0 \approx B'T^{\gamma} e^{-\frac{E_{G0}}{kT}} \text{ ------------ (a)}$$

In order to find the relation between temperature and voltage, equation (a) should be substituted into the following equation[10]:

[10] S. Bensalem, et al. "Band Gap Dependence with Temperature of Semiconductors from Solar Cells Electrical Parameters." Current Applied Physics, Elsevier, www.sciencedirect.com/science/article/pii/S1567173916302875. Date Accessed – 12/07/18

$$V_{oc} = \frac{kT}{q} \ln\left(\frac{I_{sc}}{I_0}\right) \text{------------- (4)}$$

$K -$ Botlzmann Constant

$T -$ Temperature in Kelvin

$I_{sc} -$ Short circuit current

$$= \frac{kT}{q} \ln I_{sc} - \frac{kT}{q} \ln I_0$$

Substituting for I_0 in equation (4):

$$= \frac{kT}{q} \ln I_{sc} - \frac{kT}{q} \ln\left[B'T^{\gamma}\, e^{-\frac{E_{G0}}{kT}}\right]$$

As $E_{G0} = qV_{G0}$, E_{G0} can be substituted as:

$$V_{oc} = \frac{kT}{q} \ln I_{sc} - \frac{kT}{q} \ln\left[B'T^{\gamma}\, e^{-\frac{qV_{G0}}{kT}}\right]$$

By property of logarithms that $\ln(a \times b) = \ln a + \ln b$, the following can be arrived at:

$$V_{oc} = \frac{kT}{q}\left(\ln I_{sc} - \ln B' - \gamma \ln T + \frac{qV_{G0}}{kT}\right) \text{--------------- (c)}$$

Upon implicitly differentiating the equation (c),

$$\frac{dV_{oc}}{dT} = \frac{(V_{oc} - V_{Go})}{T} - \gamma \frac{k}{q} \text{ ------------- (5)}$$

The relation derived above gives the temperature sensitivity of PV cells and it is heavily dependent on V_{oc}, open circuit voltage.

3. Methodology

As the experiment aims to determine the best possible semi-conductor for solar panels, the different parameters under which the panels function had to looked into. The most significant parameters were found to be wavelength of incident light and temperature of operation. Therefore, for this extended essay specific experiments were designed to accommodate the various parameters and analyse them individually. After comparison of data and standardise the effect of each parameter (which parameter has the greatest influence and which does not), the optimum semi-conductor material for solar panel construction could be determined.

4. Hypothesis

4.1 Hypothesis for experiment 1 – Voltage, Current vs Color Filters (varied wavelengths)

All the solar panels will have the same, or almost similar, performances under bluish lighting conditions. The aforementioned assertion is based upon the fact that bluish light has higher frequency and therefore will ensure that the most of the electrons cross the band-gap. On the other hand, at yellowish lighting conditions the polycrystalline panels will have a better performance because they have a lower band-gap as compared to the other types of solar panels[11].

4.2 Hypothesis for experiment 2 – Voltage, Current vs Temperature

The solar panels' voltage would ideally have a downward slope with an increase in temperature, but their current generation will have increasing trend. The voltage drops at higher temperatures because the band-gap of solar panels drops.[12] This is given by:

$$E_g(T) = E_g(0) - \frac{\alpha T^2}{T+\beta} \text{ ------------ (6)}$$

The current, on the other hand, increases with temperature, because the intrinsic carrier concentration increase with temperature and so does carrier diffusivity. Diffusivity and intrinsic carrier concentrations are given by[13]:

$$D_n = \left(\frac{kT}{q}\right)\mu_n\ ,\ D_p = \left(\frac{kT}{q}\right)\mu_p \text{------------(7)}$$

$$n_i^2 = 4\left(\frac{2\pi kT}{h^2}\right)^3 (m_e \times m_h)^{\frac{3}{2}}\, e^{-\frac{E_{G0}}{kT}} \text{ -------------- (8)}$$

This can be further simplified to:

$$n_i^2 = BT^3\, e^{-\frac{E_{G0}}{kT}}$$

where $B = 4\left(\frac{2\pi k}{h^2}\right)$, which is independent of temperature

T is the temperature

h and k are constants

m_e and are the effective masses of electrons and holes respectively

E_{GO} is the band-gap linearly extrapolated to absolute zero

---

11 Aakash KhatterAakash Khatter 11. "What Is the Relation between Photoelectric Current and Frequency of Incident Light?" Physics Stack Exchange, physics.stackexchange.com/questions/128964/what-is-the-relation-between-photoelectric-current-and-frequency-of-incident-lig. Date Accessed – 12/12/18

12 Joseph Amajama. Effect of Solar ILLuminance (or Intensity) on Solar (Photovoltaic) Cell's Output and the Use of Converging Lenses and X or Gamma Rays to Enhance Output Performance. University of Calabar, 4 July 2016, oaji.net/articles/2016/786-1472705473.pdf. Date Accessed - 21/11/18

13 Sharun ShajiSharun Shaji 1. "Why Doesn't Photoelectric Current Increase with Frequency of the Incident Wave?" Physics Stack Exchange, physics.stackexchange.com/questions/222359/why-doesnt-photoelectric-current-increase-with-frequency-of-the-incident-wave. Date Accessed - 07/01/19

5. Variables

Experiment 1

4.1 Independent variables

1. Light with different wavelength incident on the all types (amorphous, monocrystalline, polycrystalline) solar cells – (red, yellow, green, blue, purple)

5.2 Dependent variables

1. Current generated by the solar cells
2. Voltage generated by the solar cells

Experiment 2

5,3 Independent variables

1. Operating Temperature of the all (amorphous, monocrystalline, polycrystalline) the solar panels – $(15^0C, 25^0C, 35^0C, 45^0C, 55^0C, 65^0C)$

5.4 Dependent variables

1. Current generated by the solar cells
2. Voltage generated by the solar cells

5.5 Controlled Variables

1. Intensity (& angle of incident light)

   HOW IT WAS CONTROLLED -All readings were taken at the same time of the day (1:00pm – 2:00pm), thereby controlling angle of incident light and therefore intensity.

2. Wavelength of the light incident on the solar panels

   HOW IT WAS CONTROLLED -The wavelength of light coming out of the filter remains constant because the filters are diffraction grating with fixed grating on it.

3. The area of solar panels that is exposed to sun light

HOW IT WAS CONTROLLED -The solar panels are all not of the same size, therefore the area of exposure must be equal for all solar panels, so that the data is reliable. This is achieved by covering the extra parts of the solar cell using opaque black material.

4. Structure of solar panel

HOW IT WAS CONTROLLED -The same solar panel is used to collect readings while the colour filters are being changed.

5. Duration of time interval for collection of each reading

HOW IT WAS CONTROLLED - All readings will be taken for 1 minute and the mode value will be chosen as the value of the trial to account for fluctuations.

6. Procedure

6.1 Apparatus Required

Apparatus used	Quantity	Used In Exp 1:	Used in Exp 2:
Black sheets of paper	4	✓	✓
Monocrystalline silicon solar panel	1	✓	✓
Polycrystalline silicon solar panel	1	✓	✓
Amorphous silicon solar panel	1	✓	✓
Multimeters (uncertainty $\pm$ 0.01)	2	✓	✓
Connecting cables	6	✓	✓
Crocodile clips	6	✓	✓
Logger pro ($\pm$0.01)	1	✓	✓
Light intensity meter ($\pm$10 lx)	1	✓	✓
Stopwatch ($\pm$0.01 secs)	1	✓	✓
Grated Colour filters	6	✓	×
Temperature Controller (self-made)	1	×	✓

6.2 Procedure for equalising solar panel area

1. Paper to match the dimensions of area of solar panels that will be under sunlight exposure and was placed on the panel
2. Black duct tape was used to cover all but the area under black paper.
3. Then the paper was removed and the panel had uniform area.
4. Repeat steps for the other solar panels

6.3 Procedure for experiment 1 – Voltage and Current vs Wave Length of incident light

1. Two functional multimeters were connected in series and parallel.
2. The multimeter in series was to collect the readings of current and the one in parallel was to collect readings of voltage.
3. A load was attached using crocodile clips and connectors.
4. The circuit was placed directly under the sun with no obstruction in the vicinity.
5. A light intensity meter was used ensure uniform intensity of light.
6. The filters were placed consecutively and current and voltages were recorded for respective filters.
7. 3 trials for each panel and colour filter were conducted to minimise random error.

6.4 Procedure for experiment 2 – Voltage and Current vs Temperature

1. Two functional multimeters were connected in series and parallel.
2. The multimeter in series was set to collect the readings of current and the one in parallel was set to collect readings of voltage.
3. A load was attached using crocodile clips and connectors.
4. To vary the temperature of the solar panel, an insulating box was used and the solar panel and the lamp were placed in the box.
5. A heater was used for maintaining higher temperatures $(15^0\text{C}, 25^0\text{C}, 35^0\text{C}, 45^0\text{C}, 55^0\text{C}, 65^0\text{C})$, whereas for the colder temperature is cooled the box down to 5^0C and the solar panel and the lamp were placed inside it waited for the temperature around the solar panel to reach 15^0C.
6. By adjusting the temperature of the heater, the voltage and current readings for specific temperatures were noted.

7. Conduct 3 trials for each solar panel at each temperature to minimise the effects of random errors.

6.5 Diagrams of the setup

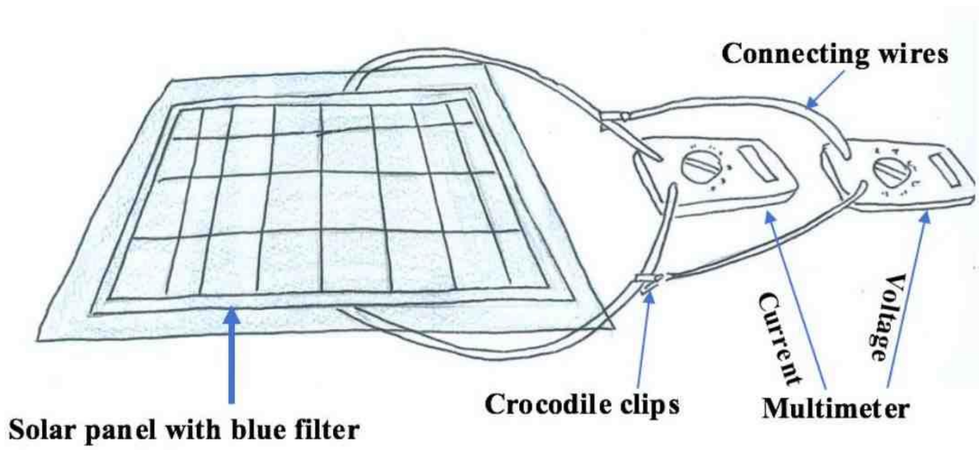


Figure 4: Hand-drawn diagram of experiment 1

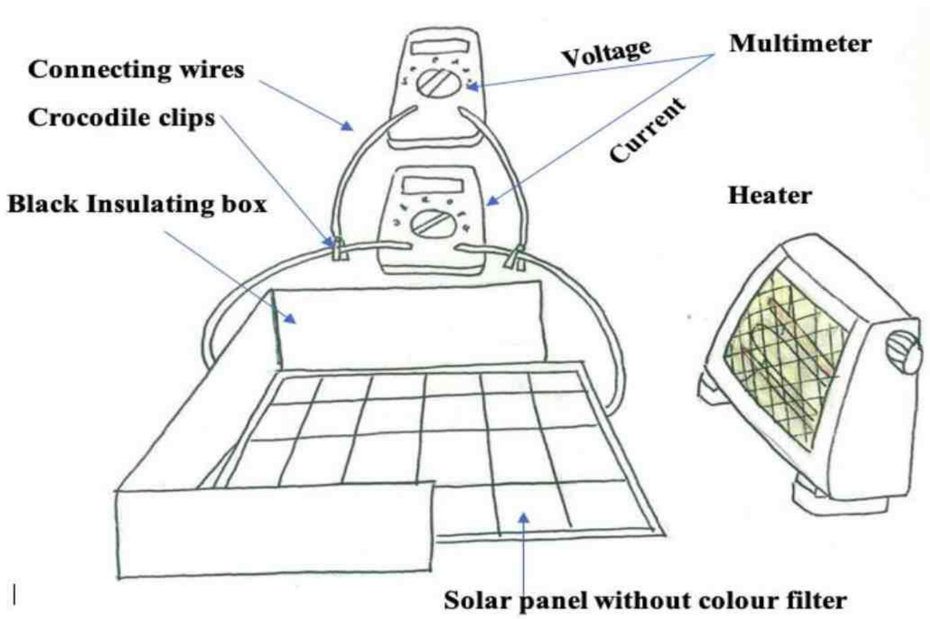


Figure 5: Hand-drawn diagram of experiment 2

7. Data collection

7.1 Raw Data

7.1.1 Raw Data for Changing Colour Filters

Table 1: Voltage and Current data for Amorphous Panel for changing colour filters

Amorphous								
	Trial 1		Trial 2		Trial 3		Trial 4	
Filter	Voltage	Current	Voltage	Current	Voltage	Current	Voltage	Current
None	12.63	84.39	12.59	84.53	12.72	84.48	12.74	84.55
Red	12.03	74.65	12.09	74.69	12.09	74.75	12.07	74.73
Yellow	11.69	63.92	11.78	63.96	11.73	63.81	11.81	67.79
Green	11.35	52.84	11.39	52.71	11.31	52.68	11.33	52.81
Blue	11.19	41.25	11.16	41.38	11.17	41.36	11.13	41.29
Violet	10.76	28.83	10.72	28.74	10.74	28.76	10.73	28.79

Table 2: Voltage and Current data for Polycrystalline Panel for changing colour filters

Polycrystalline								
	Trial 1		Trial 2		Trial 3		Trial 4	
Filter	Voltage	Current	Voltage	Current	Voltage	Current	Voltage	Current
None	8.94	255.3	8.96	255.33	8.95	255.27	8.96	255.36
Red	8.75	159.84	8.73	159.85	8.7	160.03	8.71	160.04
Yellow	8.59	96.78	8.57	96.86	8.54	96.79	8.58	96.81
Green	8.38	58.86	8.37	58.84	8.34	58.95	8.43	58.92
Blue	8.21	37.06	8.26	37.09	8.23	37.13	8.26	37.16
Violet	8.16	24.13	8.19	24.09	8.13	24.05	8.15	24.04

Table 3: Voltage and Current data for Monocrystalline Panel for changing colour filters

Monocrystalline								
	Trial 1		Trial 2		Trial 3		Trial 4	
Filter	Voltage	Current	Voltage	Current	Voltage	Current	Voltage	Current
None	10.36	119.58	10.39	119.52	10.41	119.57	10.31	119.53
Red	10.09	79.076	10.07	79.079	10.02	79.075	10.04	79.081
Yellow	9.69	63.64	9.63	63.65	9.72	63.67	9.66	63.71
Green	9.36	43.28	9.43	43.24	9.41	43.26	9.41	43.24
Blue	9.07	29.19	9.15	29.26	9.18	29.25	9.12	29.22
Violet	8.96	19.72	9.02	19.76	8.96	19.78	8.98	19.72

7.1.2 Raw Data for Changing Operating Temperature

Table 4: Voltage and Current data for Amorphous Panel for changing temperatures

Amorphous								
	Trial 1		Trial 2		Trial 3		Trial 4	
Temperature	Voltage	Current	Voltage	Current	Voltage	Current	Voltage	Current
15^0	12.32	80.68	12.36	80.61	12.37	80.73	12.33	80.7
25^0	12.83	88.18	12.79	88.11	12.81	88.22	12.79	88.2
35^0	12.22	92.18	12.24	92.11	12.26	92.22	12.27	92.2
45^0	11.98	97.38	12.01	97.31	11.96	97.42	11.97	97.4
55^0	11.76	102.78	11.73	102.71	11.78	102.82	11.77	102.8
65^0	11.53	107.08	11.56	107.01	11.49	107.12	11.52	107.1

Table 5: Voltage and Current data for Polycrystalline Panel for changing temperatures

Polycrystalline								
	Trial 1		Trial 2		Trial 3		Trial 4	
Temperature	Voltage	Current	Voltage	Current	Voltage	Current	Voltage	Current
15^0	8.83	247.8	8.79	247.85	8.8	247.78	8.81	247.77
25^0	9.29	255.3	9.27	255.35	9.26	255.28	9.25	255.27
35^0	9.03	259.3	9.00	259.35	8.99	259.28	9.02	259.27
45^0	8.86	264.5	8.82	264.55	8.83	264.48	8.84	264.47
55^0	8.48	269.9	8.45	269.95	8.44	269.88	8.46	269.87
65^0	8.25	274.2	8.21	274.25	8.22	274.18	8.23	274.17

Table 6: Voltage and Current data for Monocrystalline Panel for changing temperatures

Monocrystalline								
	Trial 1		Trial 2		Trial 3		Trial 4	
Temperature	Voltage	Current	Voltage	Current	Voltage	Current	Voltage	Current
15^0	9.82	111.91	9.86	111.94	9.87	111.86	9.83	111.9
25^0	10.33	119.41	10.29	119.44	10.31	119.36	10.29	119.4
35^0	10.02	123.41	10.07	123.44	10.04	123.36	10.03	123.4
45^0	9.79	128.61	9.82	128.64	9.84	128.56	9.86	128.6
55^0	9.48	134.01	9.44	134.04	9.47	133.96	9.48	134
65^0	9.24	138.31	9.25	138.34	9.19	138.26	9.25	138.3

7.2 Processed Data

7.2.1 Processed Data for Changing Colour Filters

Table 7: Voltage, Current, Intensity, and Power data for Amorphous Panel for changing colour filters

Amorphous					
Colour	Voltage(V) ±0.01	Current (mA) ±0.01	Intensity (lx)±10	Power(W)	$\pm\Delta P$
None	12.67	84.47	5809	1.070	0.001
Red	12.05	74.70	5790	0.900	0.009
Yellow	11.75	63.87	5788	0.750	0.008
Green	11.34	52.77	5690	0.600	0.006
Blue	11.16	41.33	5823	0.460	0.005
Violet	10.73	28.78	5799	0.310	0.004

Table 8: Voltage, Current, Intensity, and Power data for Polycrystalline Panel changing colour filters

Polycrystalline					
Colour	Voltage(V)±0.01	Current (mA) ±0.01	Intensity(lx)±10	Power(W)	$\pm\Delta P$
None	8.98	255.31	5668	2.290	0.002
Red	8.72	159.90	5714	1.390	0.001
Yellow	8.57	96.80	5736	0.830	0.001
Green	8.38	58.90	5698	0.490	0.007
Blue	8.23	37.10	5640	0.310	0.005
Violet	8.14	24.07	5647	0.200	0.003

Table 9: Voltage, Current, Intensity, and Power data for Monocrystalline Panel changing colour filters

Monocrystalline					
Colour	Voltage(V) ±0.01	Current (mA) ±0.01	Intensity(lx)±10	Power(W)	$\pm\Delta P$
None	10.36	119.55	5705	1.240	0.001
Red	10.05	79.08	5743	0.790	0.009
Yellow	9.67	63.67	5685	0.620	0.007
Green	9.40	43.25	5751	0.410	0.005
Blue	9.13	29.23	5762	0.270	0.004
Violet	8.98	19.74	5751	0.180	0.003

7.2.2 Processed Data for Changing Temperature

Table 10: Voltage, Current, and Power data for Amorphous Panel for changing temperatures

Amorphous				
Temperature(C)	Voltage(V) ±0.01	Current (mA) ±0.01	Power(W)	$\pm\Delta$P
15^0	12.35	80.68	0.995	0.002
25^0	12.81	88.18	1.130	0.001
35^0	12.25	92.18	1.128	0.003
45^0	11.98	97.38	1.166	0.005
55^0	11.76	102.78	1.209	0.002
65^0	11.53	107.08	1.233	0.001

Table 11: Voltage, Current, and Power data for Polycrystalline Panel for changing temperatures

Polycrystalline				
Temperature(C)	Voltage(V) ±0.01	Current (mA) ±0.01	Power(W)	$\pm\Delta$P
15^0	8.81	247.80	2.180	0.006
25^0	9.27	255.30	2.370	0.006
35^0	9.01	259.30	2.340	0.007
45^0	8.84	264.50	2.340	0.007
55^0	8.46	269.90	2.280	0.008
65^0	8.23	274.20	2.260	0.008

Table 12: Voltage, Current, and Power data for Monocrystalline Panel for changing temperatures

Monocrystalline				
Temperature(C)	Voltage(V) ±0.01	Current (mA) ±0.01	Power(W)	$\pm\Delta$P
15^0	9.85	111.90	1.100	0.012
25^0	10.31	119.40	1.230	0.013
35^0	10.04	123.40	1.240	0.013
45^0	9.83	128.60	1.260	0.014
55^0	9.47	134.00	1.270	0.014
65^0	9.23	138.30	1.280	0.015

7.3 Uncertainty Calculations

The uncertainty values for current and voltage were considered to 0.01mA and 0.01V because they were measured using a digital multi-metre with least count 0.01. The uncertainty in intensity was considered to be 10 lux, despite the prescribed uncertainty value of intensity probe being 1 lux. This was due to the fact that the intensity was fluctuating a lot and this generally occurred in the ten's place. The uncertainty in power was calculated using the rules of uncertainty of multiplication. The formula created is:

$$\Delta power = \left(\frac{\Delta V}{V} + \frac{\Delta I}{I}\right) \times power$$

Sample Calculation

This calculation is for the power reading of the amorphous panel in condition 1: power vs changing colour filters.

$$V = 12.67 \ \pm 0.01 \text{ V}$$
$$I = 84.47 \pm 0.01 \text{ mA}$$
$$Power = 1.07 \text{ W}$$

Applying the formula deduced to calculate the uncertainty:

$$\Delta power = \left(\frac{0.01}{12.67} + \frac{0.01}{84.47}\right) \times 1.07$$

That yields a ΔP value of = 0.001 W

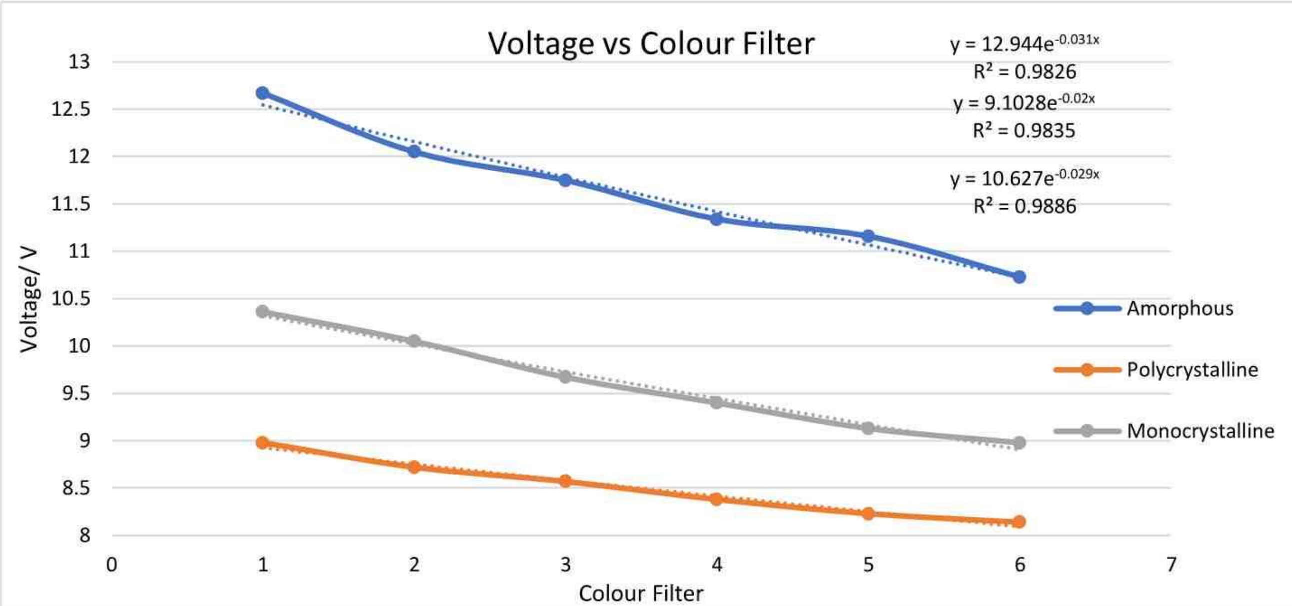
This calculation is for the power reading of the amorphous panel in condition 2: power vs changing operating temperature.

$$V = 12.35 \pm 0.01 \text{ V}$$
$$I = 80.68 \pm 0.01 \text{ mA}$$
$$P = 0.995 \text{ W}$$
$$\Delta P = \left(\frac{\Delta V}{V} + \frac{\Delta I}{I}\right) \times \text{P}$$
$$\Delta P = \left(\frac{0.01}{12.35} + \frac{0.01}{80.68}\right) \times 0.995$$

That yields a ΔP value of = 0.002 W

8. Graphical Analysis

8.1 Condition 1: Colour (Wavelengths) of Lights vs Voltage, Current, Power



Graph 1: Voltage vs Colour filter for all panels

The trend in Graph.1 indicates the band-gap width of all the solar panels. By generating the highest voltage, amorphous solar panels have the largest band-gap width and therefore need photons of higher energy levels to interact with electrons. Polycrystalline solar panels have the smallest band-gap and will accept the photons of lowest wavelength of generate voltage and current.

Despite blue and violet light having higher energy photons, the voltage drops at the blue end of spectrum is due to the fact that, generating voltage and current is not only dependent on the energy of photons, but also their detectability, that is, on the spectral response of each colour[14].

By substituting the energy in Equation 2 we get:

$$\varepsilon = \frac{q\lambda}{hc}\eta \text{ -----------(2)}$$

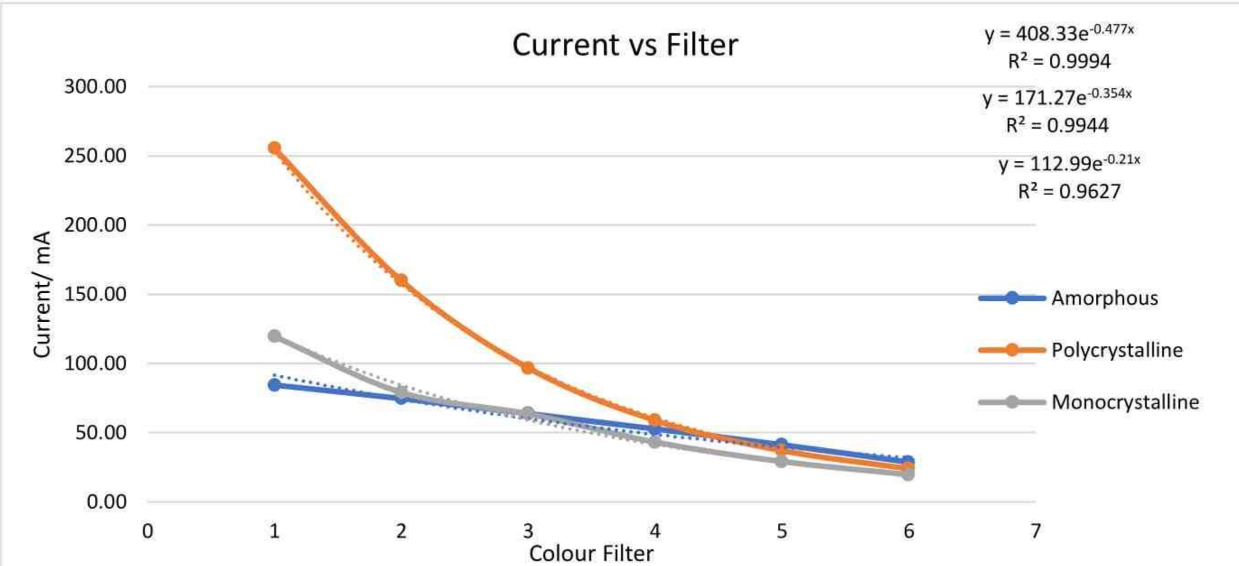
Since:

$$E_{BG} = \frac{hc}{\lambda}$$

[14] Md. Shazzadul Islam, et al. Solar PV Output under Different Wavelength of Light: A Simulation Based Study. 6 Feb. 2018, www.ijser.org/researchpaper/Solar-PV-output-under-different-wavelength-of-light-A-Simulation-Based-Study.pdf. Date Accessed - 27/12/18

$$\mathcal{E} = \frac{q}{E_{BG}} \eta \text{ ----------(8)}$$

This equation suggests the inverse relation between spectral response and band-gap energy of solar panel.



Graph 2: Current vs Colour filter for all panels

Graph.2 displays an exponential decrease. This is mainly because of the spectral response of solar cells to different coloured lights. As current also depends of the number of electrons crossing the band-gap of various solar panels, hence polycrystalline panel will generate the largest current.

Another factor contributing to the exponential trend of current is sunlight. As sunlight reaching the earth generally consists of photons towards of the red end of the spectrum, number of high-wavelength photons is much higher than low-wavelength photons due to the scattering of light with smaller wavelengths. This can be called intensity deficit. As current varies with intensity (photon flux) as suggested by the formula:

$$\Phi = \frac{P'}{E} \text{ -------------(9)}$$

$\Phi -$ photon flux

$P' -$ Power

$E -$ Energy

If $f > f_o$ (threshold frequency) and photon efficiency of the semiconductor is $\eta\%$, then the number of photoelectrons emitted per second is given by:

$$n = \frac{\Phi\eta}{100}\left(\frac{P}{4\pi r^2} \times \frac{A}{hf}\right) \text{ ---------- (10)}$$

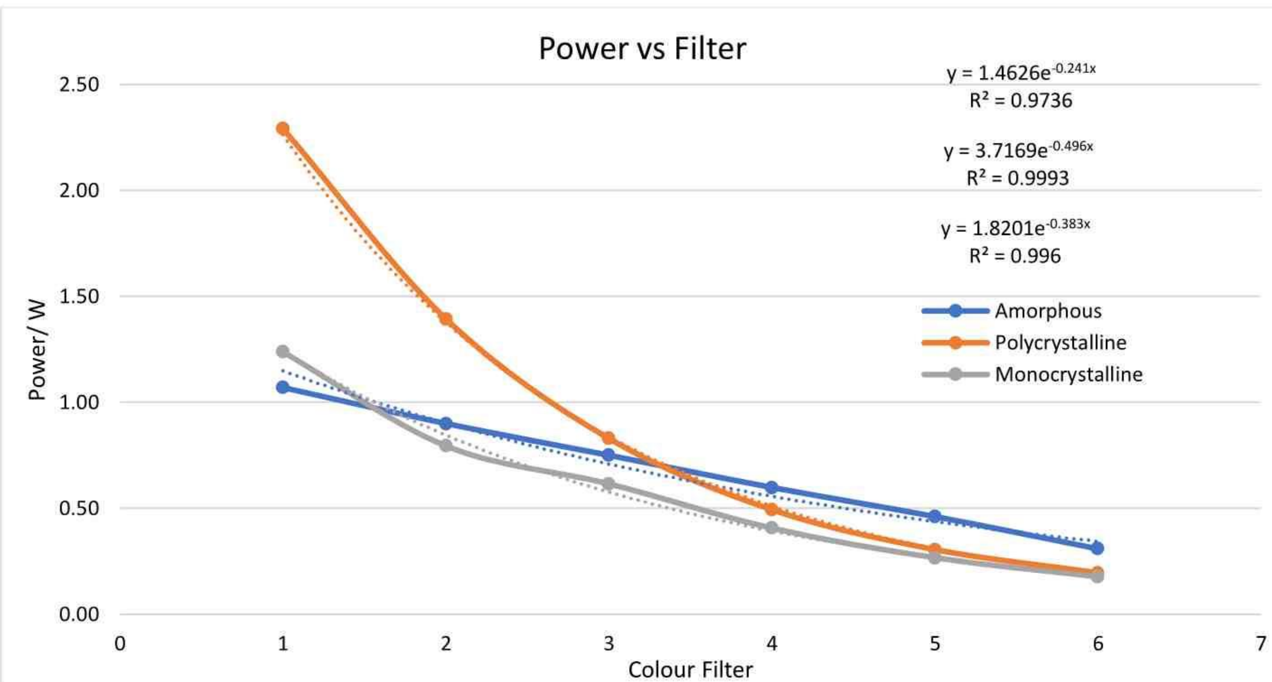
Finally the photocurrent generated by the panel is given by:

$$I = ne$$

$$I = \frac{\Phi\eta}{100}\left(\frac{P}{4\pi r^2} \times \frac{A}{hf}\right)e \text{ ----------- (11)}$$

Therefore current depends on the quantum efficiency and frequency of light. All other parameters mentioned in the equation, remain constant for every condition. Therefore, it can be seen that the current (I) is inversely related to the wavelength as an increase in frequency will reduce the current generated. Also, an increase frequency also reduces the quantum efficiency, there is an exponential decrease in the current, and in turn in the voltage.

And the existence of fewer number of high energy photons in sunlight that reaches earth, the electronic energy is insufficient to make substantial leaps across larger band-gaps. Therefore, the current produced by the polycrystalline cells is higher than monocrystalline and amorphous due to their high band-gap energy requirement.



Graph 3: Power vs Colour filter for all panels

The Power vs Colour filter graph shows an exponential trend for the polycrystalline and monocrystalline solar panels, whereas there is an almost linear trend for the amorphous solar panel. For all the solar panels, the power output is maximum under red-yellow lighting conditions. This trend is due to the fact that spectral response maximises at the wavelengths 600nm – 700nm. Spectral Response is given by:

$$SR = \frac{q\lambda}{hc}\eta \text{ ----------(2)}$$

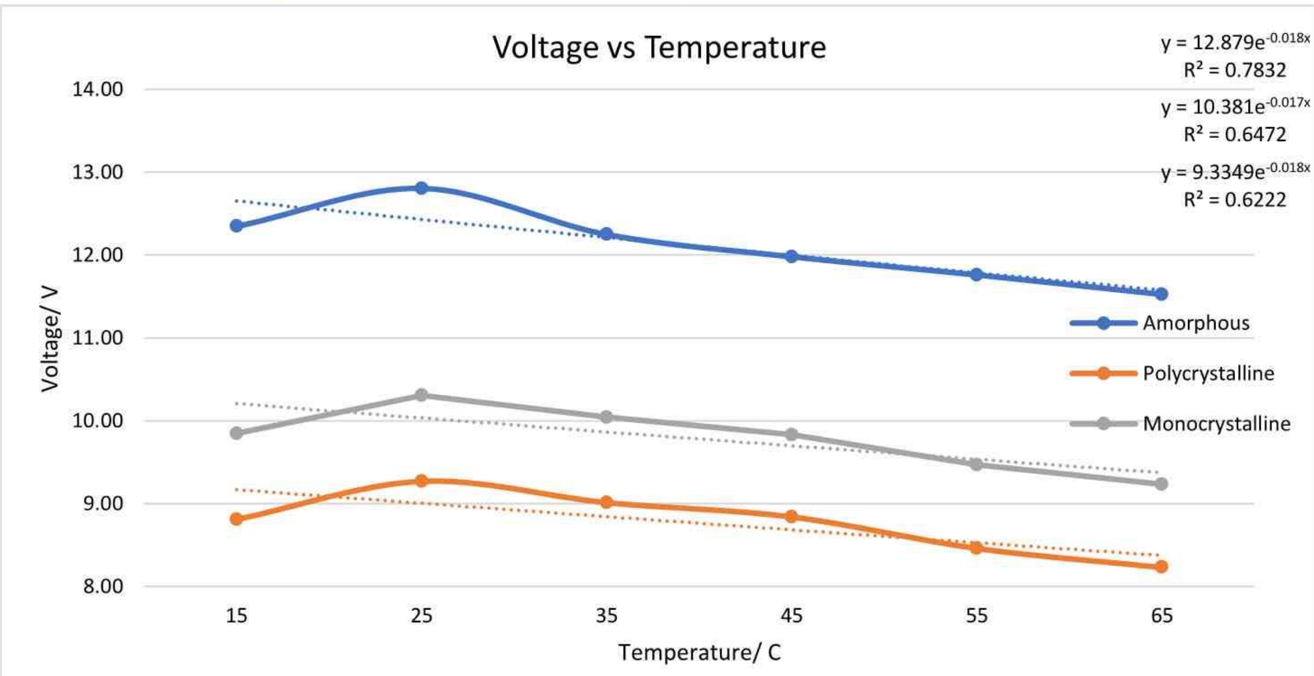
So it can be seen that there exists an directly proportional relation between Spectral Response and Wavelength, while all other parameters remain constant for all lighting conditions. When spectral response is high, the photocurrent generated is also high, therefore power output is high.

Maximum Power is given by the formula[15]:

$$P_{max} = V_{oc} I_{sc} FF \text{ ----------(12)}$$

With I_{sc} increasing with wavelength and V_{oc} dipping at lower wavelengths (as seen in next part), the power output peaks towards the red end of visible light spectrum.

8.2 Condition 2: Temperature of operation vs Voltage, Current, Power



Graph 4: Voltage vs Temperature for all panels

The voltage decreases with temperature for all the solar panels as hypothesised by the Varshini Equation. The peak appears at 25^0C because at temperatures lower than that electrons move less freely than they do at regular temperature. Therefore, some amount photonic energy is used up to increase the potential energy as well (break force that holds the electrons). As mentioned earlier, the decrease in band-gap causes a dip in the voltage output of the panel. With increase in temperature reduce the band-gap of a semiconductor.

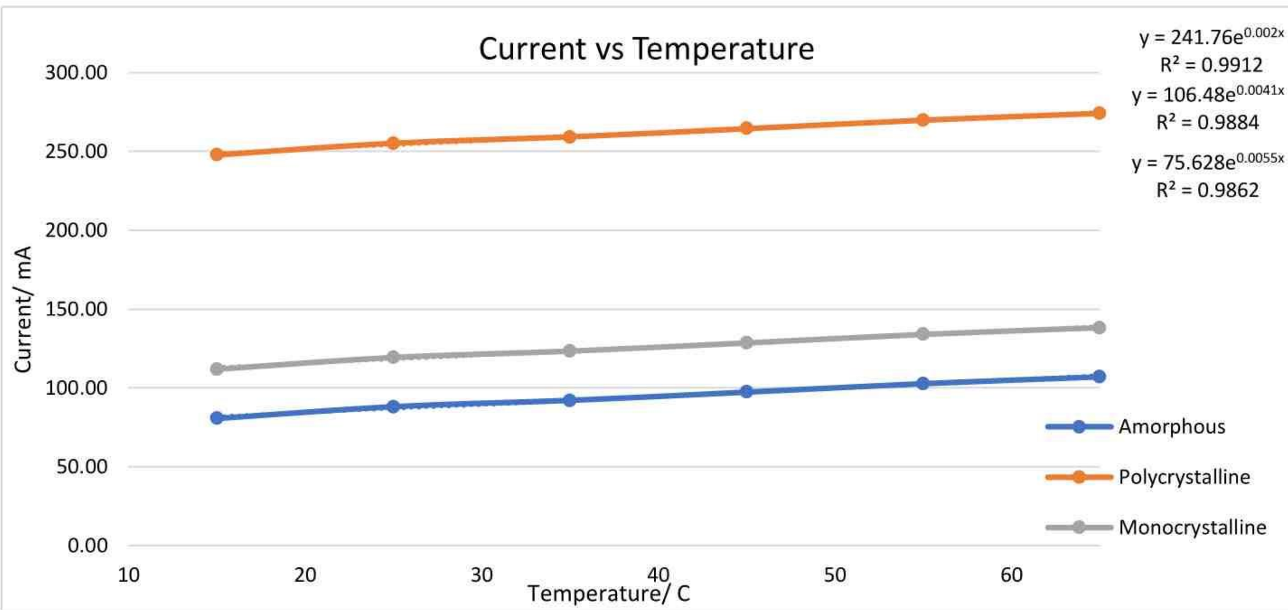
[15] Pukhrem, Shivananda. "Solar Cells: Solar Cell Model & What Affects Solar Cell Performance & Efficiency." Solar Love 3D Printed Trees Harvest Energy From Sun Wind Temperature Comments, solarlove.org/solar-cell-model-and-its-characteristics/. Date Accessed - 22/12/18

In a solar cell, the parameter most affected by an increase in temperature is the open-circuit voltage.[16]

The voltage vs temperature is given by:

$$V_{oc} = \frac{KT}{q} \ln\left(\frac{I_{sc}}{I_0}\right) \text{ ---------- (4)}$$

Despite V_{oc} is directly proportional to the temperature by the given equation, the more dominant factor is the reverse saturation current (I_0). The relation between the V_{oc} and I_0 is inversely proportional and the increase in temperature is accompanied by the an exponential increase in the reverse saturation current, therefore results in a drop in the voltage.



Graph 5: Current Temperature for all panels

The increase in temperature gives rise to a positive linear increment in the short-circuit current of the PV cell. This trend can be hypothesised by the equation:

$$I_{sc} = qG(L_n + L_p) \text{ ---------- (14)}$$

where G is the generation rate and L_n *and* L_p are electron and hole diffusion lengths.

An increase in temperature positively affects the electron and hole diffusion lengths (Diffusion length is the average length a carrier moves between generation and recombination)[17], that is, the lengths become shorter as a result of a smaller band-gap. This results in lower energy electrons, but more number of electrons are able

16 Appl. Phys. Lett. 58, 2924 (1991); doi: 10.1063/1.104723 Date Accessed – 15/01/19

17 "PVEducation." Properties of Light | PVEducation, www.pveducation.org/pvcdrom/diffusion-length. Date Accessed 22/12/18

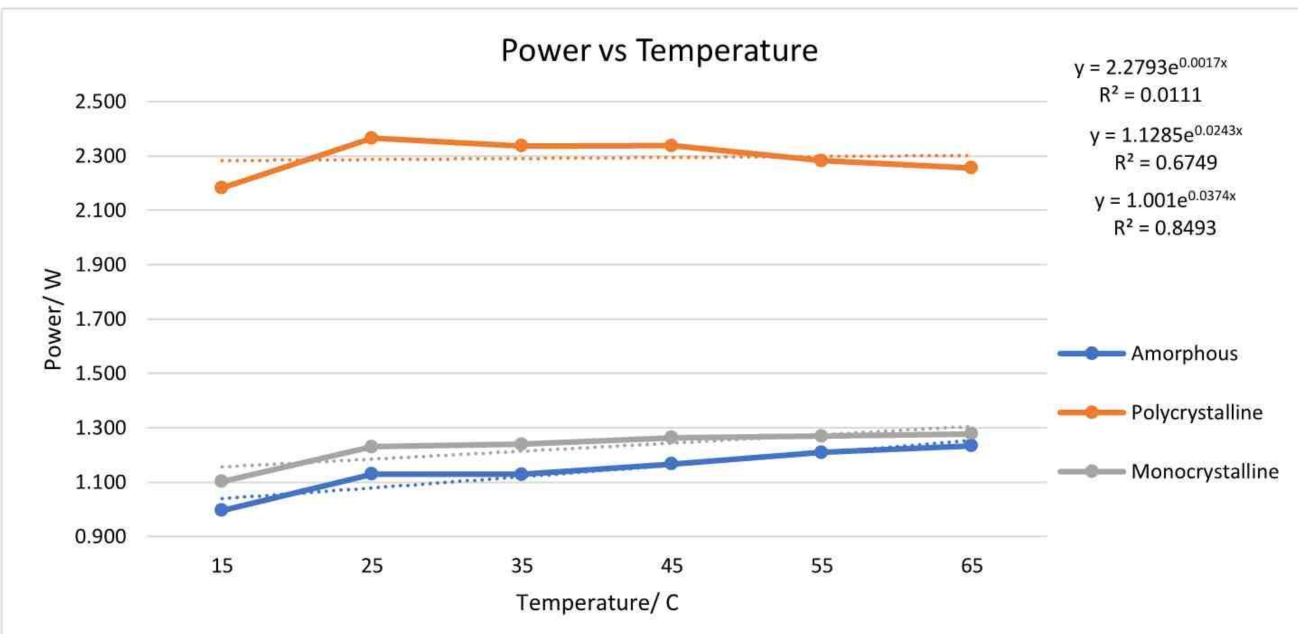
to cross the band-gap. And as current is direct proportional to number of electrons, it can be concluded that the current in a PV cell increases with temperature.

An increase in temperature also results in the increase of ,I_0, reverse saturation current[18] which is given by the Eqn.6 :

$$I_0 = \frac{qADn_i^2}{L_N D} \text{ --------- (3)}$$

many of the parameters have some temperature dependence, but the most significant effect is due to the intrinsic carrier concentration n_i. The intrinsic carrier concentration depends on the band-gap energy (with lower band-gaps giving a higher intrinsic carrier concentration), and on the energy which the carriers have (with higher temperatures giving higher intrinsic carrier concentrations).

The current is generation is lower for the monocrystalline and amorphous panels because their levels of purity. Polycrystalline being the most pure of all silica structures has a higher carrier lifetime, which are in turn responsible for the generation of reverse saturation current. The monocrystalline and amorphous panels are second-most and least impressive due to lower quality and smaller carrier lifetime[19].



Graph 6: Power vs Temperature for all panels

[18] Davoud Mostafa Tobnaghi, et al. Investigation of Light Intensity and Temperature Dependency of Solar Cells Electric Parameters . ena.lp.edu.ua/bitstream/ntb/26855/1/031-090-093.pdf. Date Accessed – 05/01/19

[19]Gianluca Coletti. "Impurities in Silicon and Their Impact on Solar Cell Performance." ResearchGate , Sept. 2011, www.researchgate.net/publication/239854077_Impurities_in_silicon_and_their_impact_on_solar_cell_performance. Date Accessed - 21/10/18

The power vs temperature graph has decreasing trend in general and the maxima of the graph occurs at 25^0C. It generally reaches the maximum value at 25^0C because the band-gap decreases with temperature. The Varshini Equation [20]gives the relation:

$$E_g(T) = E_g(0) - \frac{\alpha T^2}{T+\beta} \text{ ---------- (6)}$$

At temperatures lower than 25^0C, the power generation is also low because the kinetic energy of the electrons is lower and force between the electrons (inter-electronic force) increases. Therefore, more energy is required to break bonds and knock off electrons from the panel. The following equation gives the energy requirement for lower temperatures.

$$hf = \phi + \frac{h^2k^2}{2m} + E_p \text{ ----------(17)}$$

$$hf = \phi + \frac{h^2 {k_\lambda}^2}{2m} + \frac{kq_1q_2}{r}$$

ϕ – work function

k_λ – wave number

m – mass of electron

k – coulomb's constant

q_1, q_2 – electronic charge

r – distance between electrons

Therefore, even if the kinetic energy of the electrons reduces at lower temperatures, the addition of potential energy results in larger energy requirement to knock off the electron.[21] The trend in Amorphous and Monocrystalline panels, unlike that of Polycrystalline, shows a slight upward trend with increase in temperature. Both of these solar panels have a band-gap that is larger than that of the polycrystalline panel, and the current level of heat wasn't enough to significantly shorten the band-gap of the 2 panels. The slight decreases in voltage the temperature has a more dominant effect on the current. Therefore as $Power = VI$, the domination of current over the voltage results in the slight increases in the power output.

[20] M. Cardona, and R.K. Kremer. "Temperature Dependence of the Electronic Gaps of Semiconductors." Elsevier, www.fkf.mpg.de/565362/I_01_09.pdf. Date Accessed - 21/01/19

[21] "Chapter 2: Semiconductor Fundamentals." None, ecee.colorado.edu/~bart/book/book/chapter2/ch2_3.htm. Date Accessed - 05/01/19

9. Discussion

The graphical analysis shows that as the temperature increases the voltage and power decrease exponentially whereas the current increases linearly. The general trend of the wavelength of incident is that the power output is maximised at the red end of the spectrum and is lowest towards the violet end. After further assessment of the trends, the following can be deduced:

An amorphous cell is better-suited to environments that are darker and have lower power requirements. Its large band-gap and stability at lower intensities/coloured light make it an ideal option for indoor equipment like calculators. Because it needs high energy photons to generate current, the higher temperatures actually help the amorphous panel. Overall, the amorphous cell being the least purest and cheapest form of silicon, is ideal for cheaper and less powerful devices

Monocrystalline cells are the intermediate between polycrystalline and amorphous cells. They generate less power than the polycrystalline cells, but more than amorphous. It is not heavily dependent on either the band-gap or the number of electrons, unlike the amorphous and polycrystalline respectively. Therefore, monocrystalline cells can be good intermediate option for power and stability.

Polycrystalline cells have the best performance, especially under high intensity conditions because it has a small band-gap and power generation is dependent on the number of electrons knocked off. It is ideal for large scale power generation, like in deserts where the long-wavelength radiation is plentiful. Being very expensive, it is not viable for small scale power generations and small electrical appliances.

10. Conclusion

DOES THE ELECTRICAL OUTPUT OF A SOLAR CELL DEPEND ON THE TYPE OF SEMI-CONDUCTORS USED FOR CONSTRUCTION AT VARIOUS OPERATING TEMPERATURES AND WAVELENGTHS OF LIGHT INCIDENT ON IT?

The answer to this had already been hypothesised and later justified in the discussion. The electrical output of solar panels does depend on the material there are constructed with. This is because each of the three panels have a slightly different way of generating current, power and voltage. For example, power generation is heavily dependent on band-gap in amorphous, but in polycrystalline cells, it is dependent on number of electrons. Due to such differences that are inherent to the panels due to slight variations in structure result in there being no best semiconductor to build solar panels with.

11.1 Evaluation – Limitations of the experiments and possible solutions

1. Solar panel temperature: The solar panels would get very hot under the sun, which could affect their efficiency. This systematic error could be solved by covering the tape in reflective material, like aluminium foil.
2. The filter used for the experiment was only capable of filtering out light from the visible range spectrum. Therefore, the unfiltered ultra-violet and infrared rays may have affected the readings of the experiment.
3. The process of collecting the readings could have been improved using software to calculate the mean voltage and current values over a period of a minute, rather than roughly estimating the mode of the fluctuations of the multimeter readings.
4. The intensity of light falling on the solar panel. Despite conducting all the experiment at almost the same time of the day, the intensity of sunlight had been fluctuating. In order to correct this error, we can mathematically adjust the intensity and the respective values of current and voltage by using ratios.

11.2 Scope for further research

1. The experiment could be further modified by bringing in the concept of spectral irradiance.
2. The experiment could use solar panels with semi-conductors of different elemental identity like gallium, arsenide or even hybrid solar panel material like perovskites.

11.Bibliography

1. Aakash KhatterAakash Khatter 11. "What Is the Relation between Photoelectric Current and Frequency of Incident Light?" *Physics Stack Exchange*, physics.stackexchange.com/questions/128964/what-is-the-relation-between-photoelectric-current-and-frequency-of-incident-lig. Date Accessed – 12/12/18
2. Appl. Phys. Lett. 58, 2924 (1991); doi: 10.1063/1.104723 Date Accessed – 15/01/19
3. Britannica, The Editors of Encyclopaedia. "Photoelectric Effect." *Encyclopædia Britannica*, Encyclopædia Britannica, Inc., 19 Jan. 2018, www.britannica.com/science/photoelectric-effect. Date Accessed 08/07/18
4. "Chapter 2: Semiconductor Fundamentals." *None*, ecee.colorado.edu/~bart/book/book/chapter2/ch2_3.htm. Date Accessed - 05/01/19
5. Dan Thomas. "The Photoelectric Effect." *Types of Chemical Bonds*, University of Guelph, 5 July 1996, dwb4.unl.edu/Chem/CHEM869B/CHEM869BLinks/www.chembio.uoguelph.ca/educmat/chm386/rudiment/tourexp/photelec.htm. Date Accessed- 28/ 09/18
5. Davoud Mostafa Tobnaghi, et al. *Investigation of Light Intensity and Temperature Dependency of Solar Cells Electric Parameters* . ena.lp.edu.ua/bitstream/ntb/26855/1/031-090-093.pdf. Date Accessed – 05/01/19
6. Gianluca Coletti. "Impurities in Silicon and Their Impact on Solar Cell Performance." *ResearchGate* , Sept.2011,www.researchgate.net/publication/239854077_Impurities_in_silicon_and_their_impact_on_solar_cell_performance. Date Accessed - 21/10/18
7. Joseph Amajama. *Effect of Solar ILLuminance (or Intensity) on Solar (Photovoltaic) Cell's Output and the Use of Converging Lenses and X or Gamma Rays to Enhance Output Performance*. University of Calabar, 4 July 2016, oaji.net/articles/2016/786-1472705473.pdf. Date Accessed - 21/11/18
8. M. Cardona, and R.K. Kremer. "Temperature Dependence of the Electronic Gaps of Semiconductors." *Elsevier*, www.fkf.mpg.de/565362/I_01_09.pdf. Date Accessed - 21/01/19
9. Md. Shazzadul Islam, et al. *Solar PV Output under Different Wavelength of Light: A Simulation Based Study*. 6 Feb. 2018, www.ijser.org/researchpaper/Solar-PV-output-under-different-wavelength-of-light-A-Simulation-Based-Study.pdf. Date Accessed - 27/12/18

10. "Photosensor Tutorial." *Lighting Research Center | Education | Learning | Terminology | Spectral Power Distribution*, Lighting Research Center, www.lrc.rpi.edu/programs/nlpip/tutorials/photosensors/spectral.asp. Date Accessed - 17/07/18

11. "PVEducation." *Properties of Light | PVEducation*, www.pveducation.org/pvcdrom/solar-cell-operation/effect-of-temperature. Date Accessed 05/01/19

12. "PVEducation." *Properties of Light | PVEducation*, www.pveducation.org/pvcdrom/solar-cell-operation/spectral-response. Date Accessed – 12/07/18

13. "PVEducation." *Properties of Light | PVEducation*, www.pveducation.org/pvcdrom/diffusion-length. Date Accessed 22/12/18

14. R. Abd Elgani, et al. *Impact of the Light Intensity Variation on the Performance of Solar Cell Constructed from (Muscovite/TiO2/Dye/Al)* . 9 Aug. 2013,file.scirp.org/pdf/NS_2013092914301980.pdf. Date Accessed - 08/07/18

15. S. Bensalem, et al. "Band Gap Dependence with Temperature of Semiconductors from Solar Cells Electrical Parameters." *Current Applied Physics*, Elsevier, www.sciencedirect.com/science/article/pii/S1567173916302875. Date Accessed – 12/07/18

16. Sharun ShajiSharun Shaji 1. "Why Doesn't Photoelectric Current Increase with Frequency of the Incident Wave?" *Physics Stack Exchange*, physics.stackexchange.com/questions/222359/why-doesnt-photoelectric-current-increase-with-frequency-of-the-incident-wave. Date Accessed - 07/01/19

17. "Solar Cell Operation." *Solar World*, 14 Jan. 2018, www.solarworldpower.com.au/solar-cell-operation/. Date Accessed-29/09/18

18. Tobnaghi, Davud Mostafa, and Rahim Madatov. "The Effect of Temperature on Electrical Parameters of Solar Cells." *Research & Reviews: Journal of Agriculture and Allied Sciences*, Research and Reviews, www.rroij.com/open-access/the-effect-of-temperature-on-electricalparameters-of-solar-cells.php?aid=42871. Date Accessed - 18/10/18

19. V.Jafari Fesharaki, et al. *The Effect of Temperature on Photovoltaic Cell Efficiency*. 20 Nov. 2011, research.iaun.ac.ir/pd/jjfesharakiold/pdfs/PaperC_4124.pdf. Date Accessed - 17/07/18

EE/RPPF

For use from May/November 2018

International Baccalaureate
Baccalauréat International
Bachillerato Internacional

Candidate personal code: ___________

Extended essay - Reflections on planning and progress form

Candidate: *This form is to be completed by the candidate during the course and completion of their EE. This document records reflections on your planning and progress, and the nature of your discussions with your supervisor. You must undertake three formal reflection sessions with your supervisor: The first formal reflection session should focus on your initial ideas and how you plan to undertake your research; the interim reflection session is once a significant amount of your research has been completed, and the final session will be in the form of a viva voce once you have completed and handed in your EE. This document acts as a record in supporting the authenticity of your work. The three reflections combined must amount to no more than 500 words.*

The completion of this form is a mandatory requirement of the EE for first assessment May 2018. It must be submitted together with the completed EE for assessment under Criterion E.

Supervisor: *You must have three reflection sessions with each candidate, one early on in the process, an interim meeting and then the final viva voce. Other check-in sessions are permitted but do not need to be recorded on this sheet. After each reflection session candidates must record their reflections and as the supervisor you must sign and date this form.*

First reflection session

Candidate comments:

After my first reflection session, i got an insight into the various plausible areas of study for my Physics Extended Essay. The one I was very interested about was: Photovoltaics. This interest stemmed from my undying passion for nuclear and particle physics. Fascinated by einstein's photoelectric effect and the significance of photovoltaics in the future, i decided to research a little bit more about them. Having found, solar panels come with different semi-conductor constructs, i pondered why not decide on the best semi-conductor and only produce those rather than producing substandard versions. After further discussion with my EE supervisor, I decided on a topic: TO DETERMINE THE BEST SEMI-CONDUCTOR FOR PV CELLS". Thanks to my supervisor, i completed the target of my first reflection session: Choose and research on an EE topic.

Date: 27/3/2018

Supervisor initials:

International Baccalaureate
Baccalauréat International
Bachillerato Internacional

Interim reflection

Candidate comments:

After further discussing and trial experimentation, i deduced the various numbers of factors that affect PV performance. The most influential ones were the Intensity and Colour (wavelength) of the incident light. I was also surprised to notice that temperature played an important role in the PV performance. Deduction of these variables was followed by collection of experimental apparatus. Another challenge faced was that the school laboratory only had one type of PV cell; therefore i had to conduct a fair share of experimentation outside.

After collecting 540 readings of voltage and current (dependent variables) by varying the type of solar panel (polycrystalline, mono-crystalline and amorphous), the intensity (6 discrete) and colour (6 discrete wavelengths) of light, and finally the temperature of operation (6 discrete), I began my data processing and analysis.

Date: 23/11/2018

Supervisor initials:

Final reflection - Viva voce

Candidate comments:

In my viva voce, I discussed my entire EE journey with my supervisor – challenges, outcomes and implications of my research.

The biggest challenge I faced during my EE journey was designing my setup for the changing the temperature of the panel. I couldn't directly heat the panel nor could I use a water bath, as the solar panel could be damaged by both. Therefore, I created another setup with a 4 sided black insulated box in which I place a solar panel and room heater. Through this setup I increase the temperature and not cause any damage to the panel.

In the end, I feel confident in the work that I put into my extended essay. I think my approach to the topic was comprehensive and the analysis of the topic was as deep as it could be given the constrictions of the word count. With solar cells being a topic that is not very deeply discussed in the IB diploma, all the extensive research I put into this Extended Essay seemed give me so much knowledge about this section of physics. This knowledge that I gained through my research might prove to be very beneficial as photovoltaics is the future of energy sources and having such in-depth knowledge about the topic may provide the perfect foundation to further build upon my interest and conduct research on this topic in the future.

Date: 15/04/2019

Supervisor initials: