The general working of solar cells and the correlation between diffuseness and temperature, irradiance and spectral shape

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Abstract

The efficiency of solar cells is mostly measured under standard test conditions. In reality, the temperature and sunlight is not always the same. In The Netherlands there is on average only 1650 hours of sunshine per year[2], the rest of the daytime per year is without direct sunlight radiating the solar cells. The light captured is diffuse. In this work we discuss the basics of how solar cells work and we investigate the correlation between diffuseness of the sunlight and temperature, irradiation and spectral shape. We find correlations due to weather conditions. Furthermore we verify correlations between efficiency and temperature, and efficiency and irradiation.

Introduction

Since the discovery of the photovoltaic effect - explaining how electricity can be converted from sunlight - by Alexandre Edmond Becquerel in 1839, and the invention of solar cells by Russell Ohl in 1941, the quality and production of solar panels has improved enormously. Research institute AMOLF in Amsterdam has four research groups doing fundamental research to improve the efficiency of solar panels. Research on improving the quality of solar panels is of great importance, due to the growing demand of energy worldwide, in particular renewable energy. Nowadays around 1.3% of the total energy produced is generated by solar energy conversion [4]. With the global warming caused by energy production using fossil fuels, the need for green energy like wind- and solar energy is growing even faster. This review/research is done at AMOLF under supervision of dr. Ehler and dhr. Futscher for the course Research Practicum as part of the Bachelor Physics and Astronomy. We give a short background of the theory behind solar panels, the parameters affecting the efficiency of solar panels and results of an experiment to explore the correlation between efficiency and temperature, irradiance and APE, and the correlation between diffuseness and the other main parameters. Often scientists use the terms diffuseness and low light intensity interchangeable. Aim of this work is to differentiate between the effect of diffuseness and low intensity on the efficiency. Being able to include diffuseness as a main parameter for efficiency would bring clarification and demands for further experiments to verify this parameter.

Theory

Solar cells are made of different layers of materials. They have a protective glass plate, thin films as moisture barriers and the actual solar cells which convert the energy.

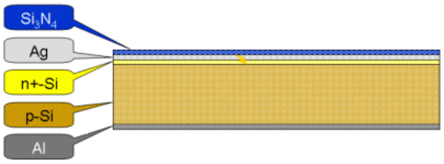

Figure 1: Schematic representation of a silicon solar cell. The blue layer is an anti reflective and protective layer, the grey layers are the cathode and anode, the yellow layers are the silicon semiconductor. (From: crystec.org)

The heart of the solar cell is the semiconducting photovoltaic layer (the yellow and brown layers in Figure 1). This is a material made up of atoms bonded together forming an uniform structure. This bond is called a covalent bond, whereby two atoms share a electric bond (pveducation.org, 2017). Crystalline Silicon (Si) is the most used semiconductor material in solar cells. It consists of a crystal lattice of Si atoms with surrounding electrons (see Figure 2). The surrounding electrons are part of covalent bonds, which is the binding of atoms by sharing electrons. Each atom forms four covalent bonds with its 4 surrounding atoms. In this way, each atom is surrounded by eight electrons. The semiconductor works as an insulator at low temperatures and as a semiconductor at temperatures at which solar cells work. When the bound electrons gain enough energy, they get excited. The vacancy left behind by the excited electron can be viewed as a positive charge, which is called a hole. It can be treated similar to an electron but has a positive charge. The energy needed to excite the electron from its bound state energy to its free state is called the band gap, which is the energy difference (E_G) between the low energy valence band

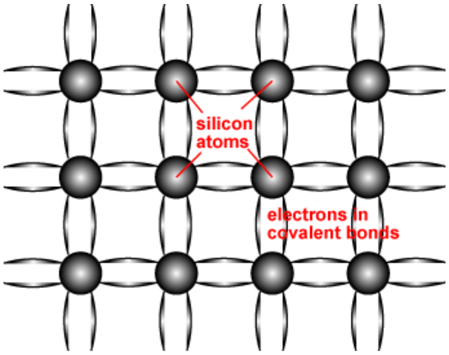

Figure 2: Schematic representation of a crystal lattice. The lines connecting the Silicon atoms represent the shared electrons, which are covalent bonds. (From: pveducation.org)

(E_V) and the conduction band (E_c). If the incident light has an energy greater than the band gap, the electron can be excited from the valence band to the conduction band, and thus generate a free charge carrier. It is possible to change the balance of electrons and holes in the lattice by doping it. Doping is the injection of impurities, to modify the properties (number of electrons and holes) of the material. When doping a semiconductor of group IV atoms with group V atoms, a n-type material is created (Fig. 3). Doping of group IV material semiconductor with group III atoms creates a p-type. The n-type has high electron concentration and the p-type has a high hole concentration. Combining p-type and n-type semiconductor materials makes a pn-junction (Figure 4.

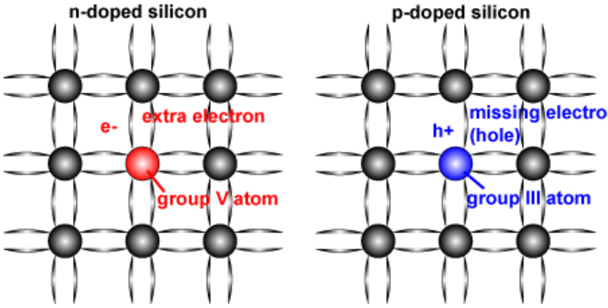

Figure 3: Schematic of n-doped (left) and p-doped (right) silicon lattice. Doping the lattice with a group V atom gives an extra electron, and doping with a group III atom creates a hole. (From: pveducation.org)

Inside the pn-junction the charges (i.e., electrons and holes) move freely in the junction, and thus can diffuse to the other side. Because the holes and electrons have positive and negative charge, they leave behind negative and positive ions, respectively. This induces an electric field between the positive ions in the n-type side and negative ions in the p-type. In this region are no mobile charges present. This region is called the depletion region, because it opposes the electron flow from the n- to the p-type and the holes from the p- to the n-type. Carrier transport following the electric field is called drift. When an external voltage is applied, which is bigger than the voltage over the depletion region, an electric current starts flowing through the junction.

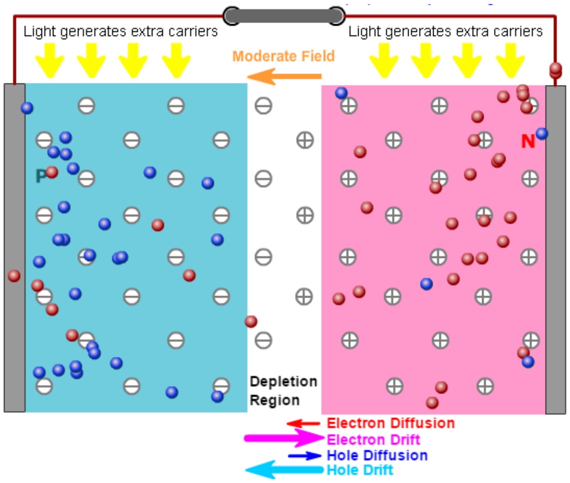

Figure 4: A schematic overview of a pn-junction when the sun radiates on the solar cell and current is generated. On the left side are the negatively charged ions with (positive) holes and on the right side the positively charged ions with (negative) electrons. Between the p- and n-side is the depletion region with the electric field, which makes diffusion of the electrons and holes to the other side less likely. Because the carriers can be collected when there is a short-circuit, the diffusion is low and drift - caused by the moderate electric field - is high. (From: pveducation.org)

Generation rate

The generation rate describes the amount of ”generated” electrons as a function of depth of the solar cell. The intensity of light in the cell can be formulated as:

$$I(x) = I_0 \, e^{-\alpha(\lambda)x}, \tag{1}$$

where I_0 is the light intensity at the surface, $\alpha(\lambda)$ the absorption coefficient and x the depth at which the intensity is calculated. The decrease in light intensity - equal to the absorption of photons - is related to the generation of electron-hole pairs by differentiating equation 1:

$$G = \alpha(\lambda) \; N_0 \, e^{-\alpha(\lambda)x}, \tag{2}$$

where N_0 is the photon flux at the surface. Equations 1 and 2 show that the generation rate is highest at the surface, where the intensity is highest. The generation rate varies for different wavelengths. Short wavelength photons (blue light, high energy) have small absorption depths and are absorbed first, large wavelength photons (red light, lower energy) are absorbed at greater depths.

Collection probability

The collection probability is the probability that a carrier will be collected by the junction and contributes to the current. For a carrier generated in the depletion region, the collection probability is one since the electron-hole pair are instantly separated by the electric field and are collected in the junction. Away from the depletion region, the collection probability drops. If the carrier is generated at a distance equal to or larger than the diffusion length, then the collection probability is very low. The diffusion length is the average length a carrier moves between generation and recombination. Carriers generated at the surface have higher recombination rate, because of dangling bonds at the edges. Figure 5 illustrates the dependence of collection probability on diffusion length and surface passivation.

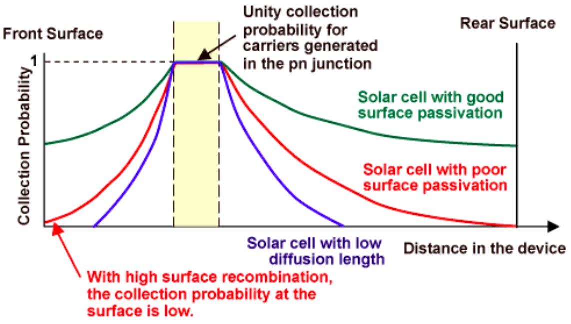

Figure 5: Illustration of the collection probability against the depth in the solar cell. (From: pveducation.org)

IV-characteristic

The performances of solar cells are indicated by four parameters. These are the open-circuit voltage V_{OC}, the short-circuit current I_{SC}, the fill factor FF and the maximum power point P_{MP} ([1] and [3]). It is summarized in an IV-characteristic. An example of an IV-characteristic is shown in Figure 6.

The IV-characteristic plots the measured current against the applied voltage over the solar cell. When there is no voltage applied to the solar cell the current is called the I_{SC}. When there is no net current flowing, the voltage is called V_{OC}, which is a property of the junction and the material itself. From this curve, a power output can be plotted using

$$P = V \cdot I. \tag{3}$$

This curve has a maximum at P_{max}. The voltage corresponding to this point (V_{MP}) has to be applied for maximum power. The ratio of the area under the rectangle formed by the axes and the P_{MP} to the product of I_{SC} and V_{OC} is called the Fill Factor (FF):

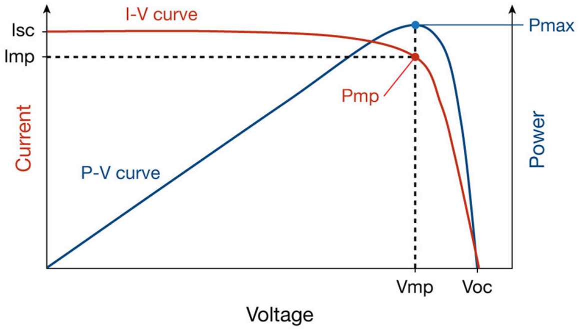

Figure 6: Example of an IV-characteristic (red) and its corresponding power curve (blue). (From: solarproffesional.com)

$$FF = \frac{V_{MP}\, I_{MP}}{V_{OC}\, I_{SC}} \tag{4}$$

The fill factor measures the squareness of the IV curve. The more the IV-characteristic is rectangle-shaped, the bigger the fill factor is. Hence, higher efficiency.

Efficiency

The efficiency of a solar cell is defined as the maximum power output divided by the total power of light that radiates on the solar cell:

$$\eta = \frac{V_{OC}\, I_{SC}\, FF}{P_{in}} \tag{5}$$

The numerator is the maximum power output from the solar cell,

$$P_{max} = V_{OC}\, I_{SC}\, FF. \tag{6}$$

The maximum efficiency that could be reached is limited by the Shockley-Queisser (SQ) limit. This is a theoretical limit to the maximum achievable efficiency of a solar cell with a single pn-junction. The losses of energy which can not be converted into electrical power is caused by different factors:

- Photons below the band gap energy cannot be absorbed;
- Photons with high energies also excite an electron, but it ends up at the bottom/lower limit of the conduction band. The part of the energy $> E_G$ is lost as heat;
- Radiative recombination of electron-hole pairs. This releases a photon and thus energy.

In real devices there is also non-radiative recombination.

Parameters which influence the efficiency

At outdoor operating conditions, there are three main parameters which influence the efficiency of a solar cell: Intensity, temperature and spectral shape.

Intensity If the intensity of light changes on a solar panel, the IV-characteristic, as shown in Figure 6, will change. The outer bounds V_{oc} and I_{sc} change logarithmically and linearly with the intensity, respectively. The change of V_{oc} is given by

$$V'_{oc} = V_{oc} + \frac{nkT\ln(X)}{q}. \tag{7}$$

where X denotes the rate of change in intensity, n denotes mole, k denotes the Boltzmann constant, q denotes electronic charge and T the temperature. An increase in intensity gives an increase in number of photons at each wavelength. The current density $J(x)$ (I per unit area) is given by:

$$J(x) = q\int\int \alpha(\lambda)\ H_0\ e^{\alpha(\lambda)x}\ d\lambda\ cp(x)\ dx, \tag{8}$$

where $cp(x)$ denotes the collection probability as a function of x (depth material), H_0 the intensity and $\alpha(\lambda)\ H_0\ e^{\alpha(\lambda)x}$ the generation rate. From equation 8 follows that I changes linearly with the intensity.

Deriving the change in efficiency with a growth in intensity, gives a positive change in V_{oc} and I_{sc}. While the general formula for the IV-characteristic stays

$$I = I_0\ (e^{\frac{qV}{nkT}} - 1) - I_L, \tag{9}$$

where V denotes voltage and I_L light generated current. It indicates that $I_{sc} \cdot V_{oc} \cdot FF$, or the area under the IV-characteristic gets bigger, while P_{in} also gets bigger. But due to the linear and logarithmic growth of I_{sc} and V_{oc}, the efficiency will grow (Eq. 5). That is why there are concentrator solar cells, whereby mirrors or lenses are used to concentrate the incident solar light on a small area. For this, special materials are used for the solar cells.

Temperature If the temperature rises the atoms within the material start to vibrate faster. This causes the carriers to suffer significantly more collisions due to phonon scattering, and thus recombinations occur [5]. Therefore the lifetime will decrease. Hence the electrical mobility and conductivity will decrease, causing an increase in resistance in the semiconductor. On the other hand, the band gap narrows as the temperature increases. This makes it possible for more electrons to be excited. Combined, I will increase little with risen temperature.

Because the band gap narrows with an increase in temperature, V and V_{oc} will decrease. Deriving V_{oc} gives:

$$\frac{dV_{oc}}{dT} = -\frac{k\gamma}{q} * \ln(T) - \frac{k\gamma}{q}, \tag{10}$$

showing V_{oc} decreases with an increasing temperature.

Looking at the efficiency (equation 5), it will decrease with a rise in temperature, since the contribution of V is larger than I.

Spectral shape; spectral irradiance Electrons in the solar cell can only be excited when an incoming photon has higher energy than the band gap. If the spectral shape has more high energy photons which correspond to the energy of the band gap or bigger, a relative larger part of the spectrum can excite electrons which eventually leads to more converted energy.

Method

The measurements are done with the sensors located at the AMOLF Solar Field. The measured temperature is of the solar cell itself. The spectral shape is quantified by measuring the average photon energy (APE). At the website of Light Management in New Photovoltaic Materials[1] (LMPV) is a list of all data collected at the Solar Field.

The diffuseness is measured with the illumination meter made by Toon Maassen as part of his Bachelor Project at AMOLF. This measurement system is a cube with a sensor on all six sides that measures light intensity. The diffuseness is quantified by models described by Xia et al. [6].

The solar cell data is obtained from the Copper Indium Gallium Selenide (CIGS) solar panels. It contains thin film solar cells with a nominal efficiency of 12.7%[2]. The basic operation of this solar cell is the same as the silicon solar cell, as previously described. The data is taken from the CIGS solar cell because it may have higher efficiency at cloudy days (with diffuse light)

Results and discussion

In this section we show the results we obtained from the data of the CIGS solar panels, all the sensors, and the diffuseness sensor made by Toon Maassen. The data of these results are of the last 8 days of the month May in 2017. We plot the raw data to verify correlations between efficiency and temperature, irradiance and APE according to theory. Furthermore we plot diffuseness against the other main parameters to exclude correlations between diffuseness and other main parameters. Hence, to investigate diffuseness as a parameter for efficiency at low irradiance. In the end we discuss the results and recommend for future research.

Temperature, irradiance and APE vs. efficiency

The efficiency compared to the measured temperature of the solar panels is shown in Figure 7. A certain decay in efficiency is apparent with rising temperature, when neglect-

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[1] Website LMPV: `lmpv.nl/solar-field`

[2] Specifications of the CIGS flexible solar cell can be read at `http://www.lmpv.nl/wp-content/uploads/2016/11/Hanergy_CIGS_Flex.pdf`

ing the points where low irradiance influences the efficiency (this is the increase in efficiency between ∼ 20-25°C). This coincides to the theory.

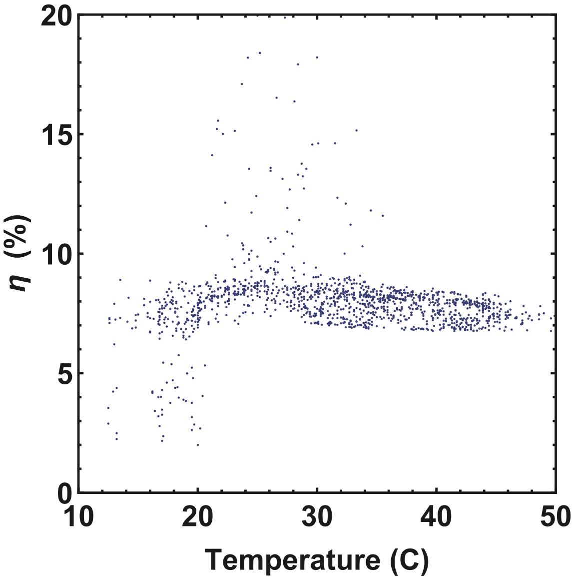

Figure 7: The efficiency plotted against the temperature of the solar cell. The increase in efficiency from 19 to 21 °C is due to increase in irradiance. This plot uses all data points, so the points up untill ∼ 21 °C are coming from the data with low irradiance.

The efficiency against the irradiance is shown in Figure 8. When the irradiance rises, the efficiency also rises. This corresponds to the theory. After the positive slope, the data shows a small decay, probably due to higher temperatures influencing the efficiency, caused by increasing recombination rate.

The efficiency against the APE is shown in Figure 9. A big cloud of data points is clearly visible with a small slope downwards for higher APE. One would expect a higher efficiency for higher APE, as discussed in the section about spectral shape. Higher APE means more diffuse light. The possibility of lower light intensity at diffuse light can explain this downward slope.

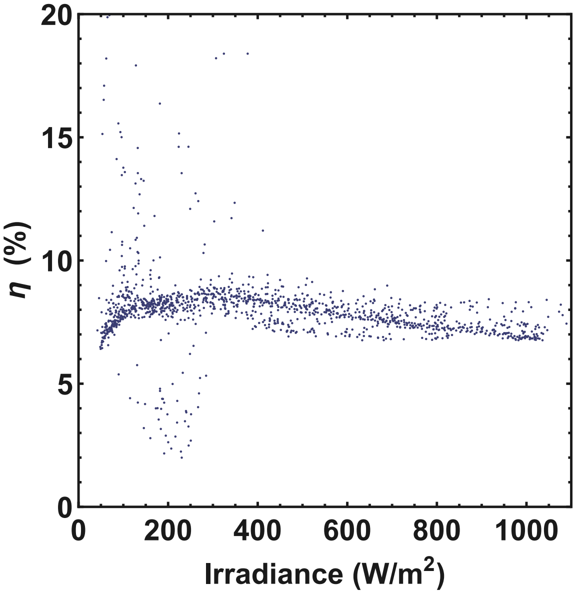

Figure 8: The irradiance plotted against the efficiency of the solar cell. All data is used for this graph.

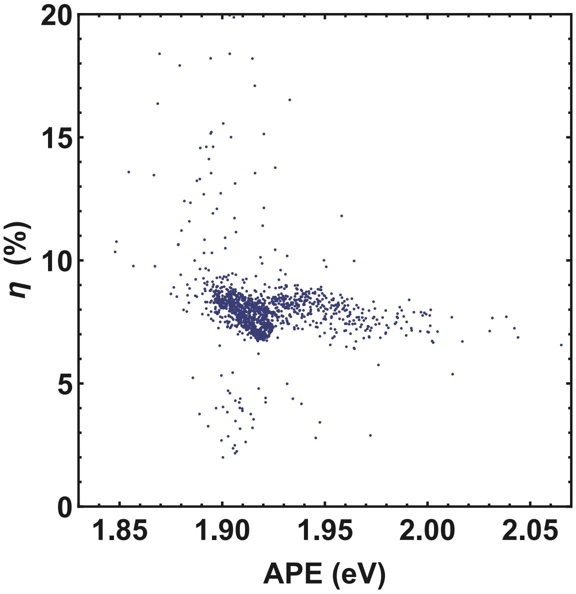

Figure 9: The average photon energy (APE) plotted against the efficiency of the solar cell. All data is used for this graph.

Temperature, irradiance and APE vs. diffuseness

In this section we plot the diffuseness measurements against the other main parameters. Figure 10 shows the measured diffuseness against the temperature of the solar cell. It is clear that with higher temperature there is less diffuseness, indicating more direct sunlight. Figure 11 shows the measured diffuseness against the irradiation of the sunlight.

With higher intensities, the diffuseness tends to be lower. This also seems realistic with directer sunlight. Figure 12 shows the measured diffuseness against the average photon energy. Neglecting the cloud of data points from diffuseness higher than ~ 0.5, we can see an upwards slope with higher diffuseness. This is due to blue shift in the spectrum of the sunlight corresponding to higher diffuseness.

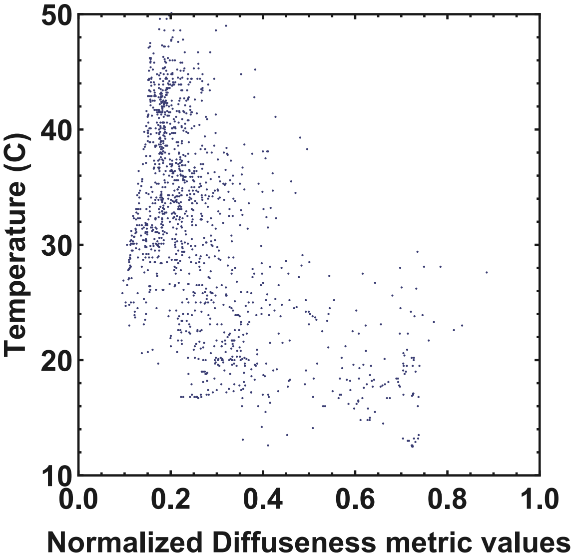

Figure 10: The measured diffuseness against the temperature of the solar cell. All data is used for this graph.

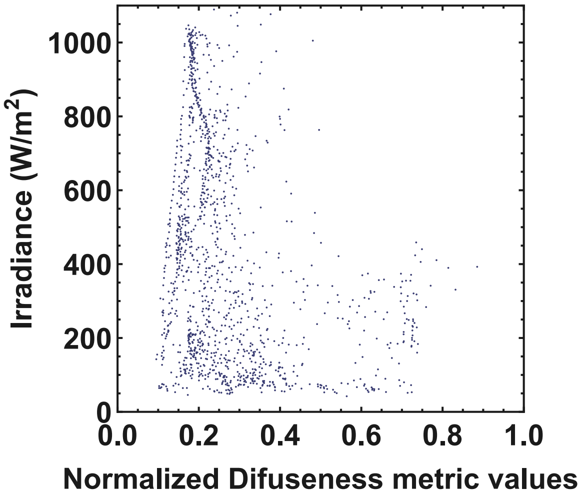

Figure 11: The measured diffuseness against the irradiance. All data is used for this graph.

Determining diffuseness correlation

The diffuseness against the efficiency is shown in Figure 13. There is no real correlation visible in this graph without mean and variance. To be able to figure out a correlation, we should search in smaller ranges of parameters and add mean and variance.

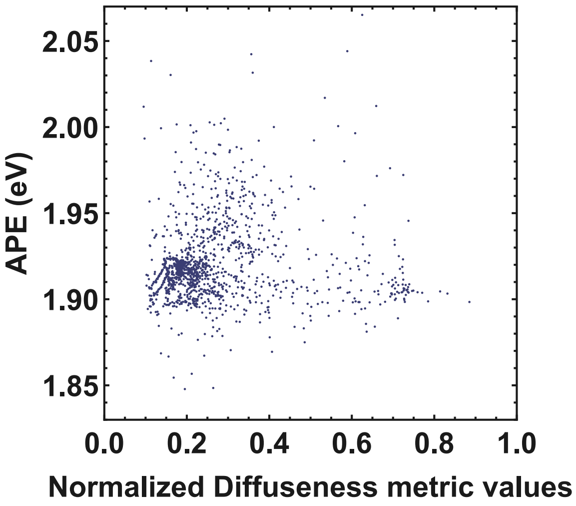

Figure 12: The measured diffuseness against the average photon energy. All data is used for this graph.

During our research, we used and improved the Mathematica program made by Elio Monaco with which we can instantly plot only a chosen range - called bins - of units of diffuseness against efficiency, holding three parameters constant and differing one. Examples are Figures 14 and 15 in the appendix. Unfortunately, you can not see a correlation or clear trend due to the very little data points we have. Correlation and trends between parameters in this research, especially in the appendix, are speculations since there are too few data points.

Future research

For future research it would be interesting to look at small bins of the parameters and plotting efficiency against diffuseness. Therefore we need more data. Though data points would have much noise, it would also be interesting to make 3D plots of diffuseness, an other main parameter and efficiency, holding three parameters constant and differing one. We fit the data for the efficiency vs. APE plot and got a function with a negative slope: $46.5402 - 19.9769x$. For a more precise result, the incorrect data points can be filtered out. For this, we need more data and more time. It could be a follow-up research for other Bachelor students.

We used the raw data for the analysis of the parameters. For more reliable results, it is interesting to calculate means or variances.

The method of measuring diffuseness with the cube should be investigated on its accuracy, by comparing its data to data of professional weather stations. Also the dependence of the orientation of the cube can be investigated by

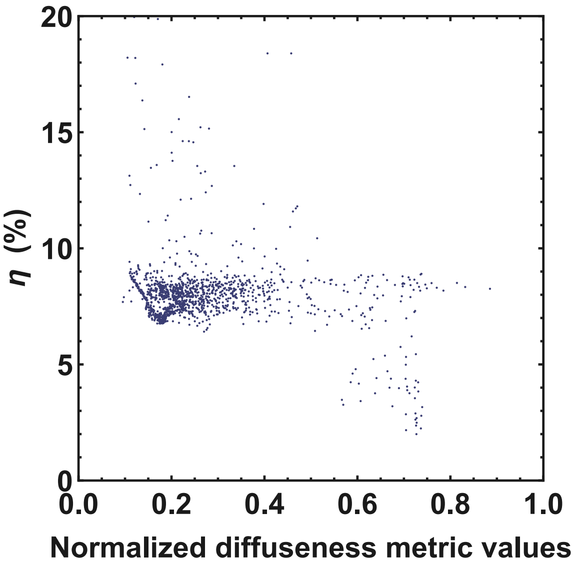

Figure 13: The efficiency against the measured diffuseness. All data is used for this graph.

turning it under constant weather conditions.

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Appendix

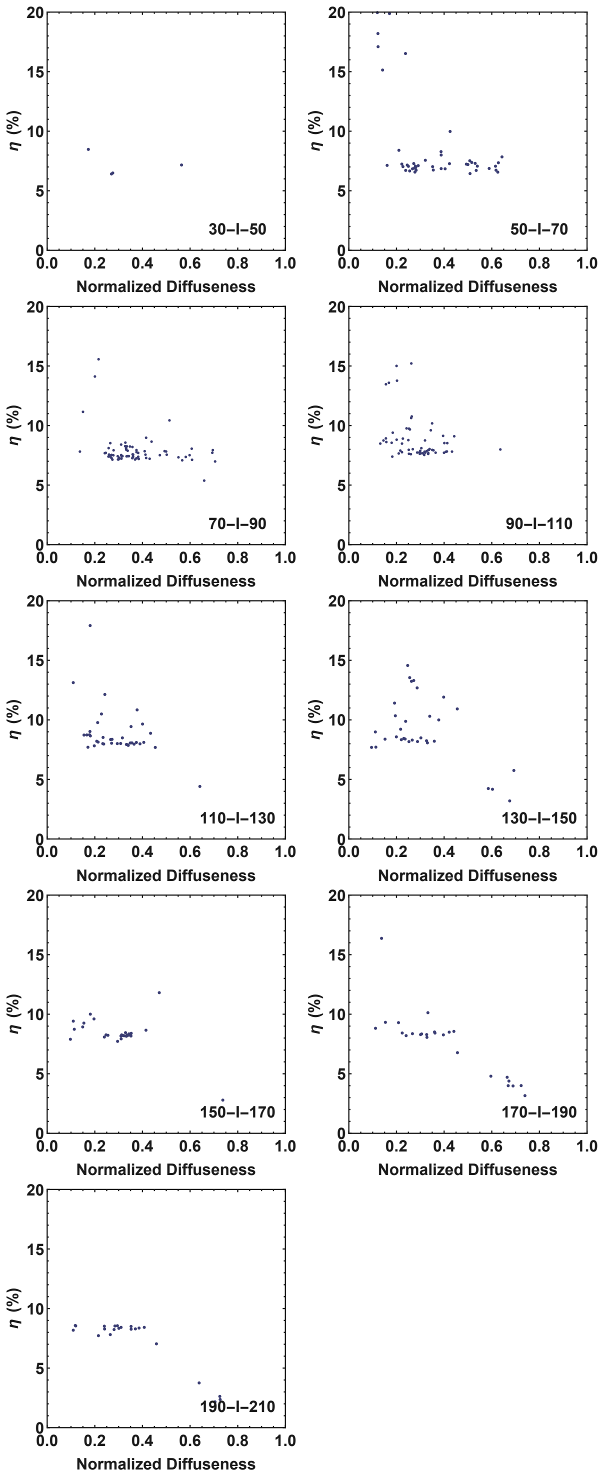

Figure 14: The efficiency plotted against the diffuseness. For these graphs, only data is used where the temperature is between 15 and 35°C and the APE between 0 and 3 (which is the whole range). The irradiance is varying from 70-90 W/m^2 in the first plot, to 190-210 W/m^2 in the last plot, using bins of 20 W/m^2.

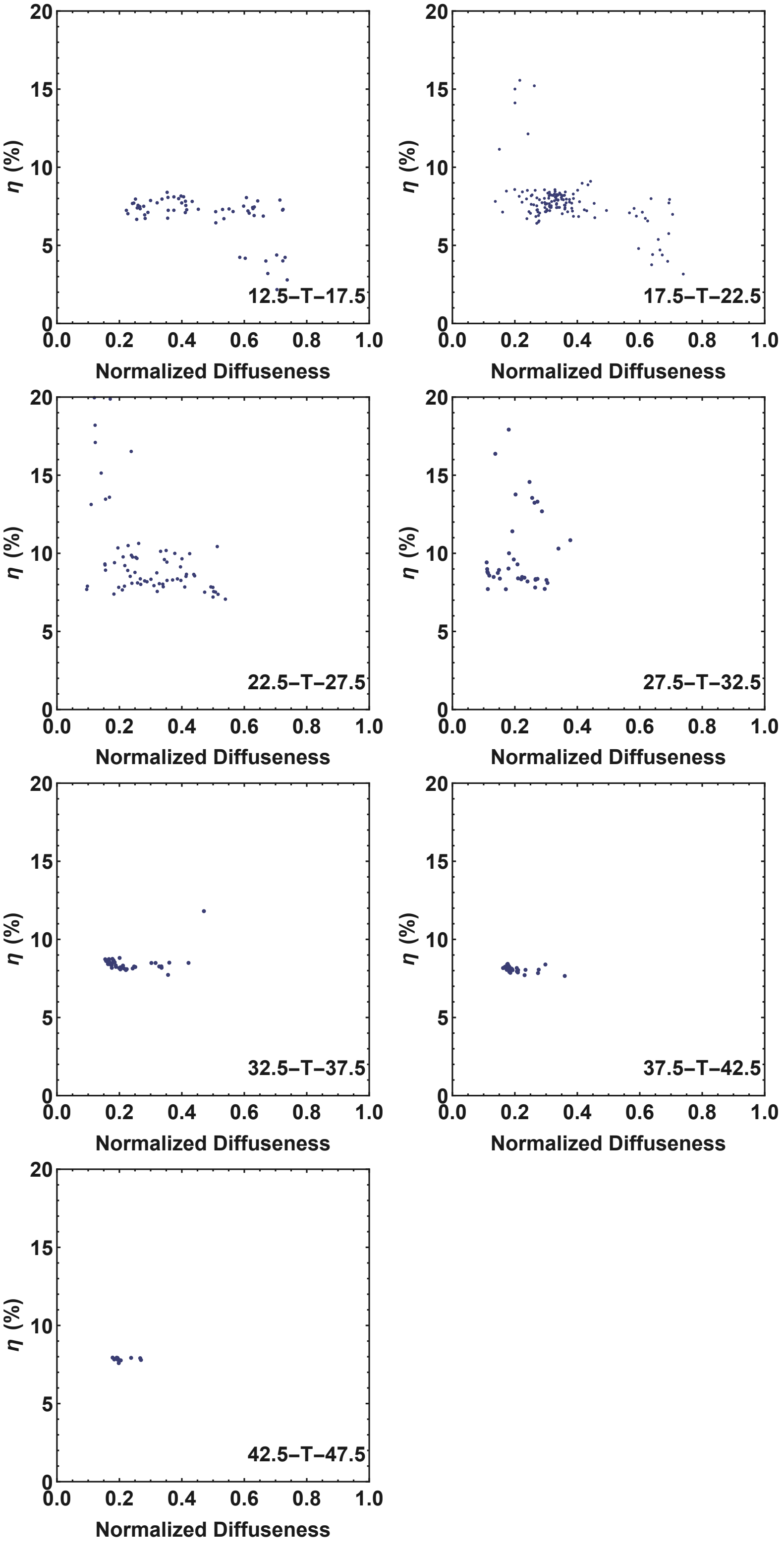

Figure 15: The efficiency plotted against the diffuseness. For these graphs, the data which has irradiance less than 200 W/m^2 and an APE between 0 and 3 (which is the whole range). The temperature of the solar cell is varying from 17.5-22.5°C in the first plot, to 37.5-42.5°C in the last plot, using bins of 5°C.