Influence of the sun position on the efficiency and Shockley-Queisser limit of solar panels

Marjolein Gelauff and Ilja van Voorst

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Supervisors: Bruno Ehrler and Moritz Futscher

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Abstract

Looking in the research field of solar panels, most research is done around the measuring and improving of the efficiency of solar cells. In this thesis the influence of the position of the sun on the efficiency of six different type of solar cells will be researched. Each cell type has its own solar panel which has been used to collect data. As the angle of the sun changes, the air mass, which is the path length of the sunlight, changes too. When the position of the sun changes, the angle of the sun compared to the solar panels changes too. The efficiency is plotted against the angle to examine this influence. The Shockley-Queisser limit, which gives the highest possible efficiency at the given circumstances, will be compared to the observed efficiency to observe the influence further. It can be concluded that the efficiency decreases as the angle of the sun increases due to more air mass.

In future research, the influence of the sun can be researched with more detail. When done with more data and more accurate weather conditions, the decrease of efficiency and Shockley-Queisser limit due to the changing sun position can be quantified. It can also be possible to research if the sun position is the only factor for the decrease or other factors too, such as reflection of light.

Contents

Chapter 1

Introduction

Society struggles with exhausted fossil fuels. Alternative resources are needed for the future energy supply. The existing solar panels, one of the sustainable alternatives, are already use-ready, installed and in use by companies and households. However, sustainable resources are still more expensive than fossil fuels [1]. This makes sustainable energy, such as solar panels, an important research area. To make these sources less expensive, the efficiency and production and installation cost are the most important factors to be improved with research. In this thesis the influence of position of the sun on existing solar panels is highlighted.

As the sun position changes, its angle compared to the solar panels changes too. With a higher angle, the air mass will increase. Air mass is the path length of the sun, so more air mass means the sunlight travels through more air. This causes more absorption of light and a lower efficiency. This thesis will test this theory by plotting the observed efficiency against the angle. The plotting will be done in $Wolfram\ Mathematica$. Furthermore, the results of the efficiency

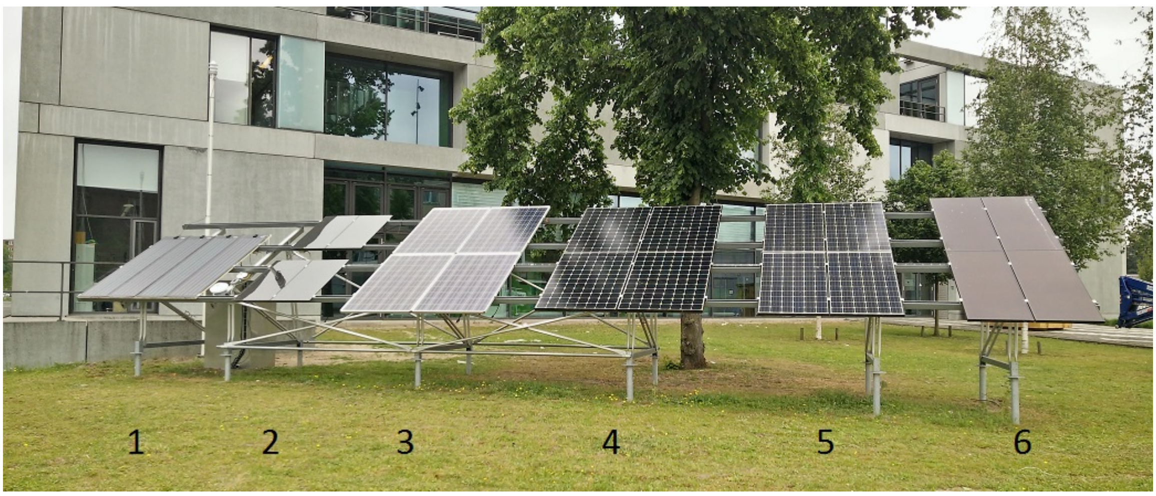


Figure 1.1: The set-up of the installed solar panels at AMOLF. The panels face South and are located next to a tree. In order from panel $1 - 6$: CIGS, CdTe, Poly-Si, IBC Si, HIT Si and CIGSm.

will be compared to the Shockley-Queisser limit. This limit gives the highest possible efficiency with a certain temperature and spectrum of the incoming light at the moment of measurement. We will take a look at the trend in the change in efficiency in comparison to the angle of the solar panel with the sun.

The research took place at the FOM institute AMOLF (further referred as AMOLF) and is done with the data of six different types of solar cells taken over the months March, April and May. The six different types of solar cells are shown at figure 1.1. This research is inspired by other research done with these solar panels at the AMOLF [2].

CHAPTER 2

Research Background

2.1 Semi conductors

A solar cell is made of a material of crystals where the electrons in the material have split into two electron bands: the valence band and the conduction band, as can be seen in figure 2.1 [2]. The valence band houses all the electrons, while the conduction band is empty. There is a band gap between the bands, which is different for each material. When electrons receive enough energy, they will be excited from the valence band to the conduction band as shown in figure 2.1. It leaves a hole in the valence band, which behaves as an positive charged electron. As there are more holes, electrons will be able to move through the material and doing so the material will conduct electricity [3].

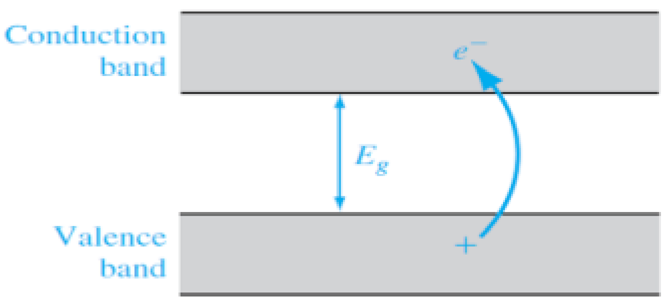


Figure 2.1: Band structure of a solar cells with a band gap energy E_g. If the electron receives enough energy, it will be excited from the valence band to the conduction band. The electron leaves a gap which behaves as a positive charged electron.

Between the two bands all states are forbidden, so electrons can't be between the bands. So an electron can be excited if it receives enough energy. That is, when the energy is equal as or higher than the band gap energy. When the band gap is zero or the bands even overlap, the material will always conduct electricity. These are called conductors. When the band gap is around $2\ eV$, thermal or photonic excitations are possible. These are called semi-conductors. When the band gap is too large for thermal or photonic excitations, the material is called an insulator. These have band gap energies between $3 - 6\ eV$. In figure 2.2 a schematic representation can be seen [2].

Within solar cells the energy of the incoming light is used to excite electrons. Light consists of photons, which have energy equal to [2]

$$E = hf = \frac{hc}{\lambda}. \tag{2.1}$$

When a photon hits an electron, the electron absorbs this photon and thus its energy. If the photon has enough energy, for example $E_{photon} = 1.12eV$ within silicon solar cells, the electron will be excited. If the energy of the photon is higher than the band gap energy, the electron will be excited above the band gap. The energy of the electron will then be decreased until the band gap energy and the lost energy will be transformed to heat. This heat doesn't contribute to the energy generated by the solar panel, so the heat energy is unused energy. This means this process lowers the efficiency of the solar panel [2].

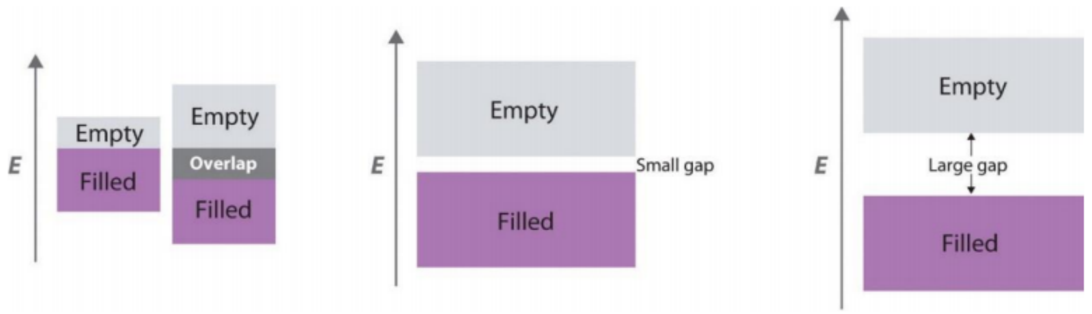


Figure 2.2: The difference between metals, semi-conductors and insulators. A metal (left) has no band gap and will always conduct eletricity. A semi-conductor (middle) has a band gap around 2 eV and will conduct electricity with thermal or photonic excitations. A insulator (right) with a band gap around $3 - 6\ eV$ can't use thermal or photonic excitations and won't conduct eletricity [2].

To enhance the efficiency, doping is used in solar cells. Doping consists of impurities with either more or less electrons than the semi-conductor material. The binding energy of these impurities is small compared to the band gap and thus creates an additional energy level, as can be seen in figure 2.3 [2].

Donors - with one more electron - give an extra energy level just below the conduction band, while acceptors - with one electron less - add an extra energy level just above the valence band. Now less energy is needed to excite the electrons and the efficiency of the cells will be higher [3].

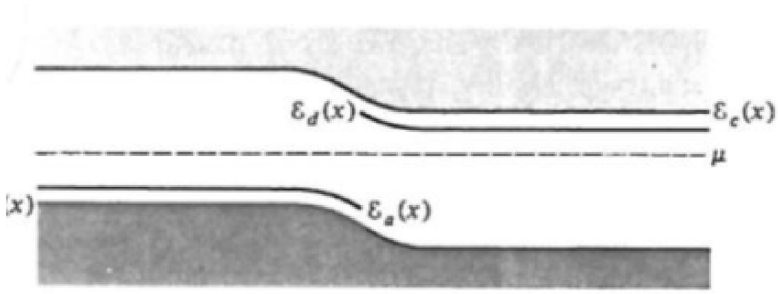


Figure 2.3: The band gap structure with doping. The donor gives an extra energy level ϵ_d just below the conduction band, while the acceptor gives an extra energy level ϵ_a just above the valence band [2].

2.2 Angle of the sun and air mass

The air mass is the path length of the sunlight. As the angle of the sun compared to the solar panel increases, the air mass increases too. A larger air mass means the light travels through more dust and air that can absorb the light. Those particles will only absorb photons which have energies close to their binding energy, which are the higher energy photons. If more high energy photons are absorbed, the light reaching the solar panel will be more red. So a higher air mass and thus absorption leads to lower energy photons to reach the solar panels. This leads to less photons that can excite electrons and a lower efficiency [4].

The angle with the sun is dependent of the position of the sun compared with the location of the solar panel. This gives a triangle as pictured in figure 2.4. The angle of the sun compared to the surface of the earth can then be calculated with

$$\alpha = \tan^{-1}\left(\frac{d(latitude)}{d(longitude)}\right), \qquad (2.2)$$

where $d(langitude)$ is the difference between the langitude coordinates of the sun and the solar panels and $d(longitude)$ is the difference between the longitude coordinates of the sun and the solar panels.

Once this angle is calculated, the angle between

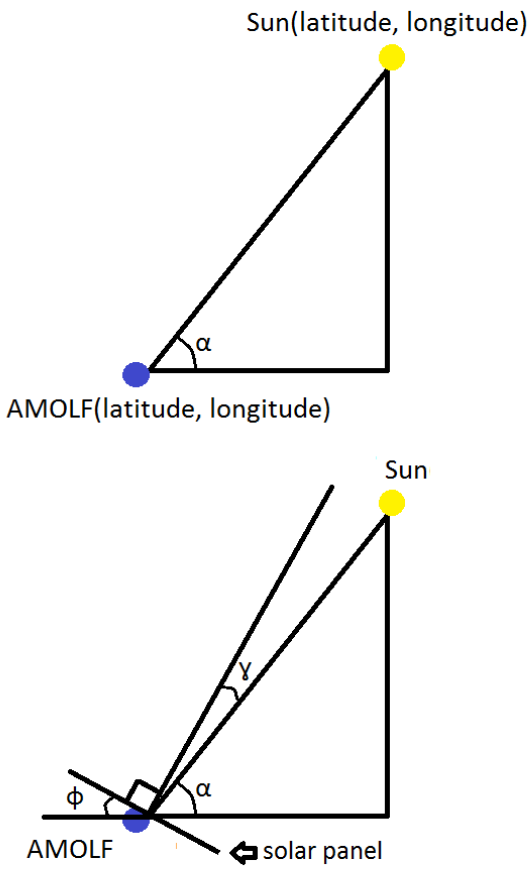


Figure 2.4: Schematic representation of the positions of the solar panels and the sun. Here α is the angle between the sun and the surface of the earth, ϕ is the angle between the solar panel and the surface of the earth and γ is the angle between the sun and the solar panel.

the sun and the solar panels can be calculated with

$$\gamma = \phi + \alpha - 90°. \quad (2.3)$$

Here ϕ is the angle between the solar panels and the ground and γ the angle between the sun and the solar panel. γ is the angle that will be used in measurements.

2.3 Efficiency and Shockley-Queisser limit

The efficiency and the Shockley-Queisser limit will be plotted against the angle γ, which is calculated above in equation 2.3. The efficiency is defined as

$$\eta = \frac{gain}{cost}. \quad (2.4)$$

In this formula is the cost the energy received by the solar panel. This is the incoming power from the sun, which is called the irradiance. This irriadiance can be measured by the measuring equipment. The gain is the power generated by the solar panel. Power is defined as

$$P = IV, \quad (2.5)$$

with I the current and V the voltage. The generated power can thus be calculated with the current and voltage in the solar panel at maximum power point. These can be measured as well with the measurement equipment.

The Shockley-Queisser limit gives the theoretical maximum efficiency for the solar cell. If the energy of the sun consists of low energy particles, the efficiency will lower because less electrons will be excited. But if the energy of the incoming irradiance will be higher, the electrons will be excited above the band gap. As explained in section 2.1, the electrons will fall back to the band gap. This is called thermalization. The energy lost this way will also lower the efficiency. Another limiting factor is the black body radiation caused by the temperature of the solar panel. These combined losses result in a maximum possible efficiency, which is called the Shockley-Queisser limit. A summary of these losses can be found in figure 2.5 [5]. The Sockley-Queisser limit is defined by

$$\eta_{max}(V) = \frac{J(V) \cdot V}{P}, \quad (2.6)$$

where J is the current, V the voltage and P the irradiance. [2].

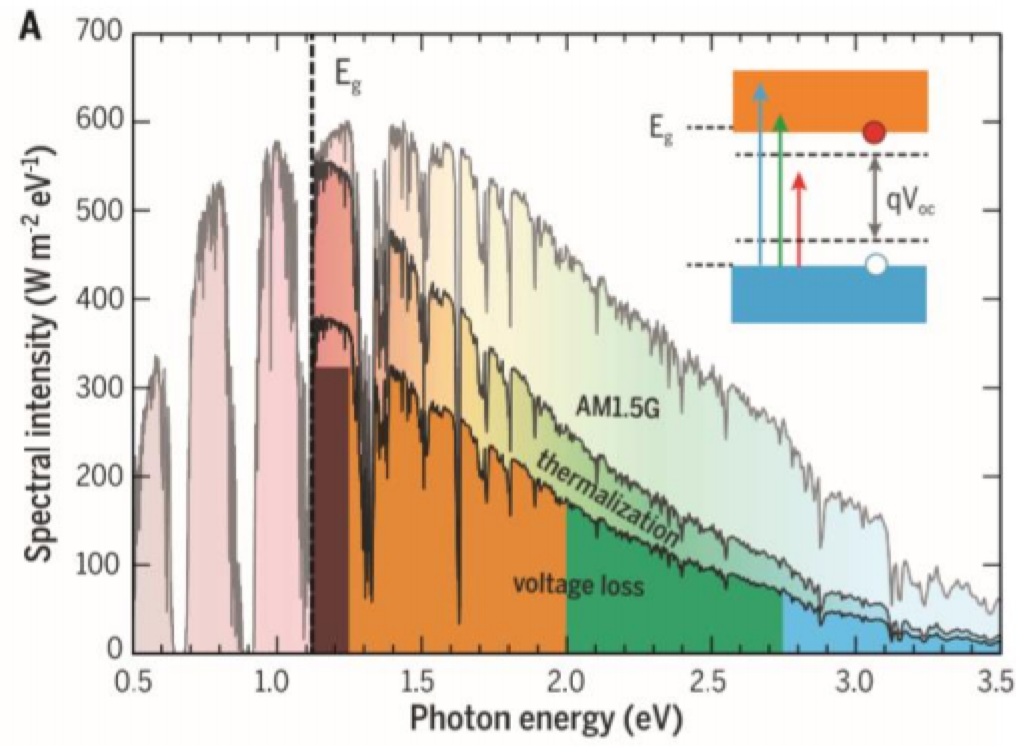


Figure 2.5: Limitations of the efficiency for the $AM1.5$ spectrum [5].

CHAPTER 3

Experimental Set-up and Methods

The data used in this research has been collected by the Hybrid Solar Cells team at the AMOLF, where the data are stored. The data comes from the solar field at AMOLF. This solar field is described further on.

3.1 Solar Panels

There are six different modules installed, each with a different solar panel. They are set up as shown in the picture in image 3.1. The properties of these six modules the Area, band gap and efficiency as stated by the manufacturer are shown in table 3.2 [2].

The solar panels are set up on one frame. The frame is shown in figure 3.1. This frame has an angle with the ground of $\phi = 30°$. The angle of the sun compared to the earth is α, as defined in equation 2.2. This angle of the sun compared to the earth depends on the time and date and changes with the position of the sun.

The panels face South. Of each type of panel, there are four panels installed, but only one of these four are connected, so we are using the data of only one panel of each type [2].

Figure 3.1: The set-up of the installed solar panels.

Module #	Name	Area (m^2)	Band Gap (eV)	Efficiency as stated by manufacturer (%)
1	Copper Indium Gallium Selenide (CIGS)	2.017 x 0.494	1.2 (NREL record)	12.7
2	Cadmium Telluride (CdTe)	1.200 x 0.600	1.45 (NREL record)	12.0
3	Polycrystalline Silicon (Poly-Si)	1.675 x 1.001	1.12	15.5
4	Integrated Back Contact Monocrystalline Silicon (IBC Si)	1.559 x 1.046	1.12	21.5
5	Heterojunction Intrinsic Layer Monocrystalline Silicon (HIT Si)	1.580 x 0.798	1.12	19.4
6	Copper Indium Gallium Selenide with back mirror (CIGSm)	1.656 x 0.656	1.2 (NREL record)	14.7

Figure 3.2: Area, band gap and efficiency as stated by the manufacturer for each type of solar panel used in this research [2].

3.2 Measurements

The solar panels are connected with different measurement equipment. The main groups measured are solar module parameters and current-voltage curves, weather data and spectra. The first group is collected with PV-$scan$ 13 $software$. It collects open-circuit voltage, short-circuit current, power at maximum power point, voltage at maximum power point, current at maximum power point, Fill Factor and module temperature. The open-circuit voltage and short-circuit current are calculated by extrapolation. The maximum power point is calculated by multiplying the current and voltage.

There is also a $Compact\ Weather\ Station\ WS600 - UMB$ from Lufft GmbH. It collects the temperature, dew point, relative humidity, air pressure, air density, wind speed and wind direction.

The spectra are measured with a $MS - 711\ Spectrometer$ by EKO Instruments. It measures between $300 - 1100\ nm$, which leaves out the tail-end of the infrared and part of the high energy photons. They still contribute to the incoming irradiance, so the incoming power of the sun is underestimated. This causes the Shockley-Queisser limit to be overestimated. To resolve this issue, an interpolation based on the STC spectrum is done from $1100 - 4000\ nm$.

All the measurements are done with a time step of five minutes, during daylight. The parameters of the solar panels are done one by one. A full overview of the Data Collection Circuit and Software System can be found in Appendix A.

All calculations and figures made with this data were done in Wolfram Mathematica. The full code can be seen in Appendix B.

3.3 Weather conditions

As the climate of the measurements is unpredictable and variable, it is a difficult process to decide which days are used as data points in the calculations. The complexity factor comes from the weather conditions, in lab conditions they should be constant for a precise measurement so the efficiency will only change of the changing sun position and not because of other weather factors. In this research we have chosen to take the daily weather information of the Royal Netherlands Meteorological Institute (KNMI) measured at the weather station located at Schiphol, which is the closest weather station located to our measuring location at AMOLF [6]. This data is used to find days were the VVN value (minimum visibility in the sky) is found between 62 $(12 - 13km)$ and 69 $(19 - 20km)$. This way the used measuring days would be as cloudless as possible and by that definition probably cloudless at our used measuring time and location.

A factor that we shouldn't forget is that the VVN value is determined for a different location, a location close to AMOLF, but still a different location. This can give a false indication of cloudiness if the clouds are very local.

Beside clouds, other weather conditions apply. The temperature of the module, which increases with higher temperature of the air, affects the efficiency. Another factor would be the humidity. By picking cloudless data, a lot of data was excluded from the experiment. By choosing days which have also the same humidty and temperature, too little data would be left, so clouds were chosen as the most important changing factor.

3.4 Finding the position of the sun

As the rotation and location of the sun can be calculated on advance and afterwards, we have used the calculation program $Sun\ Position$ that makes calculation of the sun's position in the sky for each location on the earth at any time of day [7]. With the position, given by the program, in latitude and longitude coordinates the position of the sun at the day and time of measurements could be determined and noted. Once the position of the sun is found the formulas 2.2 and 2.3 will calculate the angle of the sun compared to the solar panels.

CHAPTER 4

Results

With the measured data the observed efficiency is calculated for the different days of measurement with Mathematica as shown in Appendix B. These calculations are done for all six modules. This observed efficiency is plotted against the angle of the sun (β), which is defined in figure 2.4. These plots are shown in the figures 4.1 to 4.3. The Shockley-Queisser limit is plotted as well against the angle β. These can be seen in figure 4.4 to 4.6.

As seen in figure 4.1 to 4.3, the observed efficiency decreases as β increases for all solar panels. This can easily be seen with the linear fit through the data, which gives the average decrease of observed efficiency per degree.

The Shockley-Queisser limit is plotted against β and the result can be seen in figure 4.4 to 4.6. A linear fit was made again to see that the Shockley-Queisser limit on a average decreases.

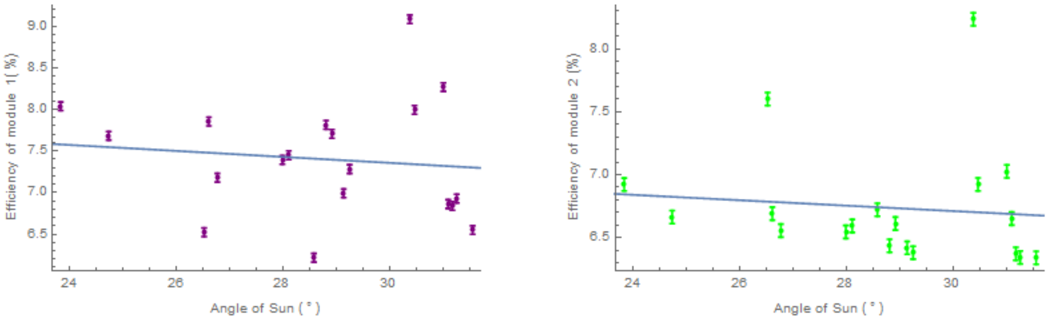


Figure 4.1: The observed efficiency against the angle of the sun of module 1 (left) and module 2 (right). The error of the observed efficiency is 0.05%. With the linear fit can be easily seen that the efficiency on average decreases.

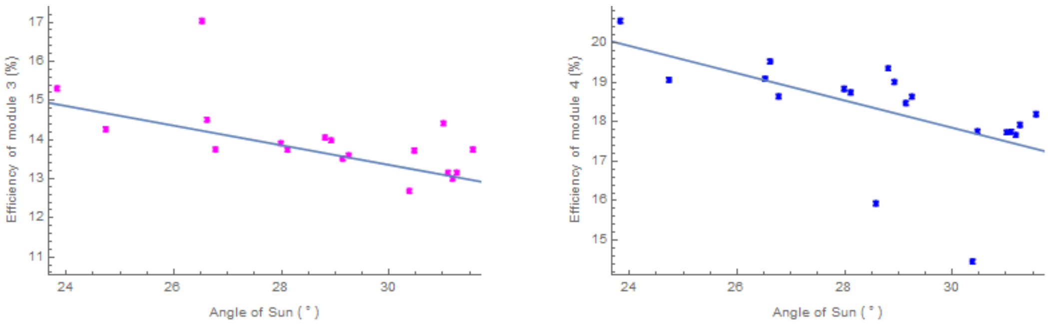


Figure 4.2: The observed efficiency against the angle of the sun of module 3 (left) and module 4 (right).The error of the observed efficiency is 0.05%. With the linear fit can be easily seen that the efficiency on average decreases.

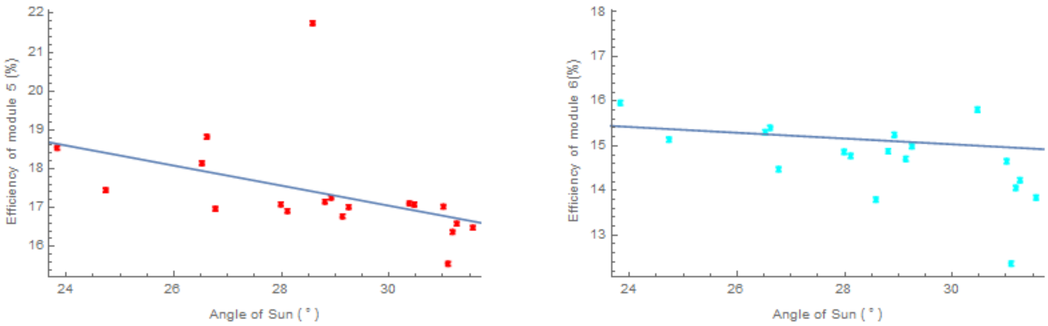


Figure 4.3: The observed efficiency against the angle of module 5(left) and module 6(right). The error of the observed efficiency is 0.05%. With the linear fit can be easily seen that the efficiency on average decreases.

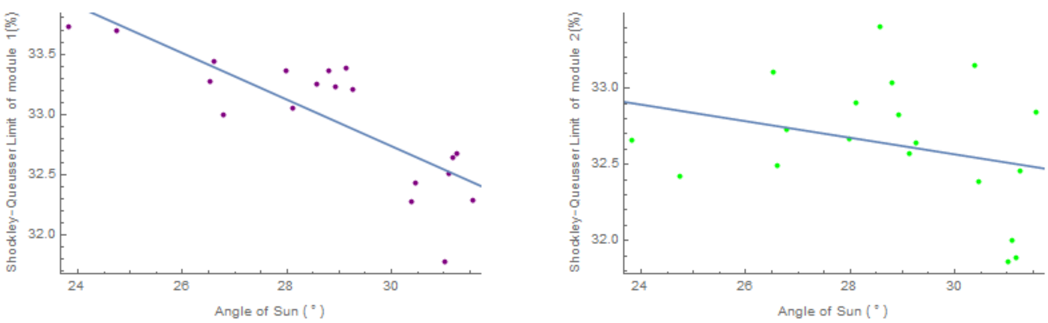


Figure 4.4: The Shockley-Queisser limit against the angle of the sun of module 1 (left) and module 2 (right). With the linear fit can be easily seen that the efficiency on average decreases.

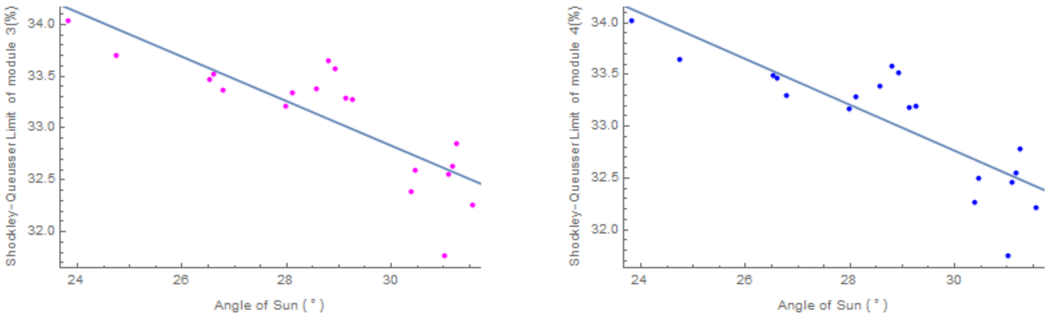


Figure 4.5: The Shockley-Queisser limit against the angle of the sun of module 3 (left) and module 4 (right).With the linear fit can be easily seen that the efficiency on average decreases.

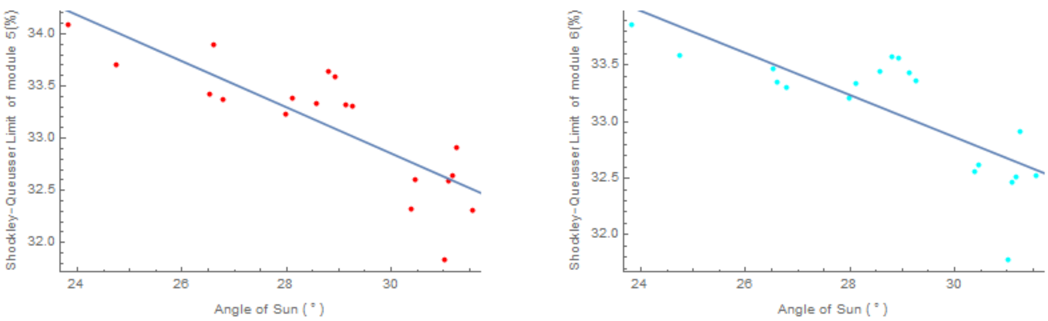


Figure 4.6: The Shockley-Queisser limit against the angle of the sun of module 5 (left) and module 6 (right). With the linear fit can be easily seen that the efficiency on average decreases.

CHAPTER 5

Discussion

Both the observed efficiency and the Shockley-Queisser limit are decreasing as the angle β increases. As explained in chapter 2.2, this is caused by corresponding increasing of the air mass. By an increasing angle β, the air mass increases too. This causes a higher amount of absorption of the higher energy photons by dust and air particles. The light that reaches the solar panels is more shifted to the red spectrum. This means there are less electrons excited because the sun rays have more photons with less energy than the band gap. This causes to lower the efficiency. The decrease can be seen in figure 4.1 - 4.6.

If we compare the observed energy to the Shockley-Queisser limit, they both decrease. This makes the results consistent and believable. However, there was not enough data to see how big the decrease is and we can only speak of a trend. It is likely that the decrease in both the observed efficiency and Shockley-Queisser limit is caused by increasing the angle β compared to the solar panels. But it is not known if this is the only source causing this trend. One other important source could be the reflection of light.

As can be seen, the observed efficiency of module 2 is very low and differs a lot from the efficiency from the manufacturer. This is because the glass of the solar panel was broken during the installation of the panel on the frame. Except for the lower efficiency, the solar panel should still behave as expected. Though this is an error for the actual values of that type of solar panels.

Another factor to influence the results are the weather conditions. The data of the weather conditions are from Schiphol. So we used general clear days, but it can still be clouded at Science Park while it is a clear day at Schiphol. The other weather conditions, like temperature and humidity, are also not included. This is because too little data would be left when included. This causes the noise in the graphs of the Shockley-Queisser limit and observed efficiency. But despite the noise, the decreasing trend is still visible.

It should also be noted that these possible explanations are for this short time period. When this experiment would be done over a whole year and with more data, this research can be done with a higher accuracy, more data would make it possible to account for the weather conditions. There would also be less outliers in the figures. This would give a higher accuracy. It would then also be possible to quantify the decrease in efficiency and research which solar panel would be the most efficient to use with a significant variance in the angle of the sun. This future research would bring results for solar panels are used by households and companies, making solar energy less expensive.

CHAPTER 6

Conclusion

The input of this research was measured current and voltage at maximum power and the incoming power of the sun over three months. With this information the observed efficiency has been calculated. The Shockley-Queisser limit is calculated with the measured spectrum and temperature and the band gap energy for each solar panel specific given by the manufacturer. Both the observed efficiency and Shockley-Queisser limit were plotted against the angle of the sun compared to the solar panels (β).

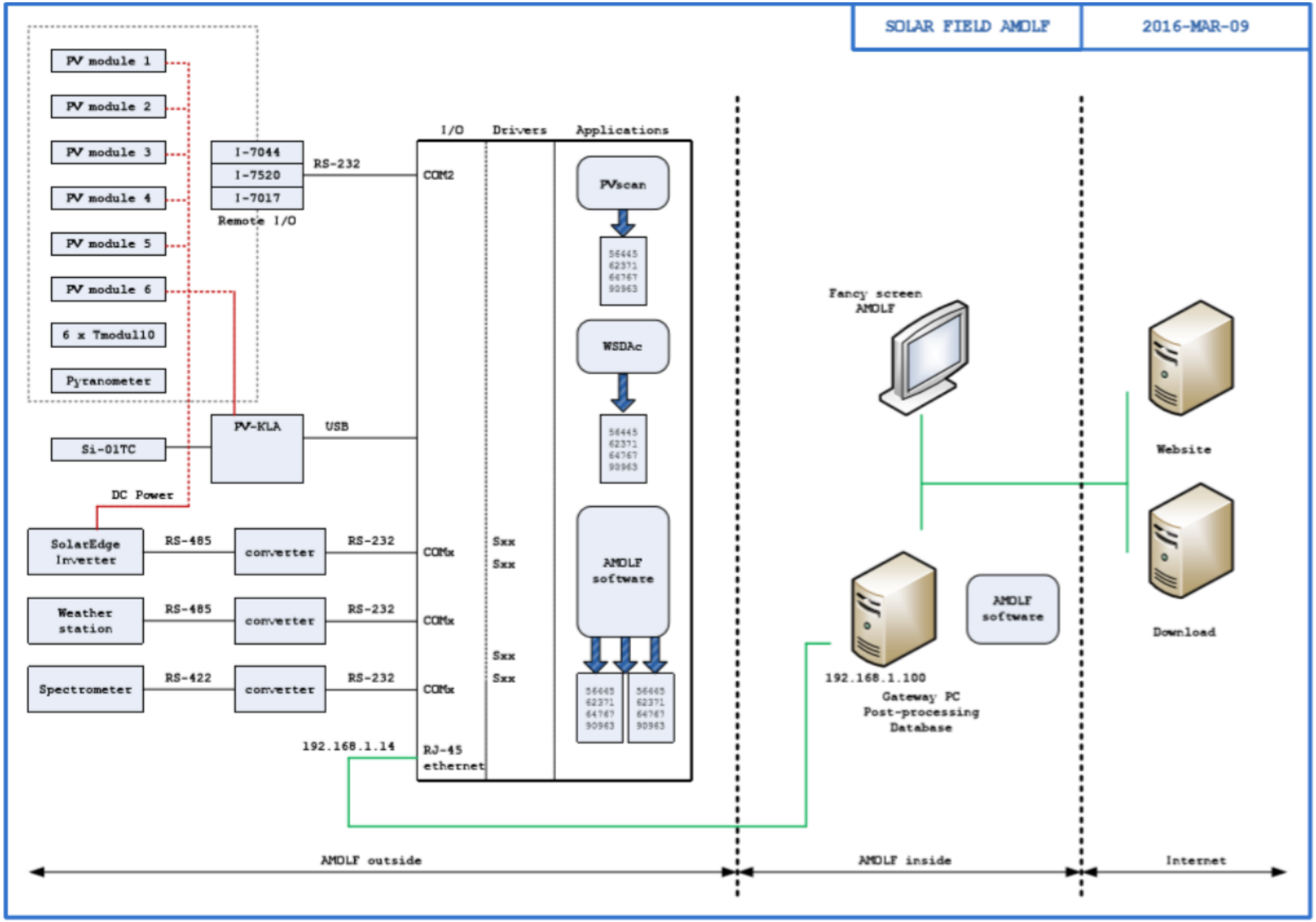
As seen in figures 4.1 to 4.6, the observed efficiency and Shockley-Queisser limit decreases as the angle β increases. This was expected from the background theory, as the air mass increases when the angle increases. It is very likely that the decrease in efficiency is caused by the changing angle β and not because of other factors. However, it is possible that the angle is not the only influence. It could be caused by the angle and some other factor, for example the reflection of light. All these components in countered, this overlap means that we can speak of a trend.

The outcome of the trend gives a lot of openings of future research as discussed in chapter 5. For future research on these six types of solar panels, this research could be done for the whole year. This would give the influence of the angle of the sun for solar panels in The Netherlands with a higher accuracy. It would be possible to quantify the decrease in efficiency and Shockley-Queisser limit and see if the angle is the only influence or not. It is then also possible to see what solar panel is most efficient to use in The Netherlands in relation to the changing sun position. The errors and other influences such as the temperature factor could be taken into account too. Results of such research could give consumers a higher efficiency, which would make solar energy less expensive and more accessible.

APPENDIX **A**

Data Collection Circuit and Software System Overview

On the next page can the Data Collection Circuit and Softer System be seen in full detail.



SOLAR FIELD AMOLF
2016-MAR-09
PV module 1
PV module 2
PV module 3
PV module 4
PV module 5
PV module 6
6 x Tmodul10
Pyranometer
Si-01TC
I-7044
I-7520
I-7017
Remote I/O
RS-232
PV-KLA
USB
DC Power
SolarEdge Inverter
Weather station
Spectrometer
RS-485
RS-485
RS-422
converter
converter
converter
RS-232
RS-232
RS-232
I/O
Drivers
Applications
COM2
COMx
COMx
COMx
RJ-45 ethernet
192.168.1.14
Sxx
Sxx
Sxx
Sxx
PVscan
WSDAc
AMOLF software
Fancy screen AMOLF
192.168.1.100
Gateway PC
Post-processing
Database
AMOLF software
Website
Download
AMOLF outside
AMOLF inside
Internet

APPENDIX **B**

Mathematica Code

On the next page is the Mathematica code to be found to calculate the observed efficiency and Shockley-Queisser limit.

In[128]:=

SQ

```
SQ[Eg1_, Temp_, spectrum_, irradiance_, number_] := Quiet[{
    Γ[En_] := Interpolation[makeFlux[spectrum]][En];
    powerofsun := irradiance[[number]] * 1000;
    JG[Eg_] := NIntegrate[Γ[En], {En, Eg, 4.0}];
    JR[Eg_, V_] := q 2 Pi / (c^2 h2^3) NIntegrate[ En^2 / (Exp[(En - V) / (k Temp)] - 1), {En, Eg, 4.1}];

    jg = JG[Eg1];
    d = Table[{v1, jg - JR[Eg1, v1]}, {v1, 0, Eg1, .005}];
    iv = Interpolation[d];
    voc = FindRoot[iv[v], {v, .5}][[1, 2]];
    jsc = JG[Eg1] - JR[Eg1, 0];

    (* Finding the maximum conversion efficiency *)
    NMaximize[{100 iv[V] V / powerofsun, d[[1, 1]] < V < d[[-3, 1]]}, V]} * 1000][[1, 1]]
```

In[107]:=

Experimental Efficiency Calculation

```
ObsEff [Pmpp_, Area_, Gpyranometer_] := Pmpp / Area / Gpyranometer * 100
(*ObservEfficiency = Pmpp / Gpyranometer * 100*)
ObsEffTime [parametertime_, ExperEff_] := Table[{parametertime[[i, 1]], ExperEff[[i, 1]]}, {i, 1, Length[parametertime]}]
(*observed efficiency against time*)
```

Bibliography

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