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Characterisation of a solar roof tile (SunSlates™)

With focus on local applicability and conditions

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Project report presented in partial fulfilment of the requirements for the degree of Master of Engineering at the University of Stellenbosch

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Department of Mechanical and Mechatronic Engineering

Characterisation of a solar roof tile (SunSlates™)

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Masters of Engineering Project

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Executive Summary

Three SunSlates™ where investigated to predict the performance of a fully installed system.

The three slates were mounted on a fixed tilt of 30˚, but with different orientations. The tilt is close to latitude of the Stellenbosch site, which is 33.92˚. The one faces due east, another due west and last due north. This is to determine the effect that orientation has on the energy from the SunSlates™.

Another slate, also facing north, was mounted on an adjustable framework. The framework was used to adjust the tilt angle of the slate, the orientation of the slate was constantly north. This slate was used to determine the effect of tilt on the total daily energy produced by the slate.

To determine the performance of the slates daily measurements of temperature, solar insolation and wind was taken. These where used to investigate the effects on the SunSlates™.

During the test period, which scheduled from September to November, the results show a difference, smaller than commonly believed, in the daily and annual energy delivered from the differently orientated slates. The slates facing east and west, however, have similar energy outputs, even though the power profiles differ. The north facing slate has the highest annual energy output, as expected.

It was found that during the months of summer, November to January, the optimal tilted slate (Slate tilted to have a incidence angle of 0˚ from solar rays at noon) had a slightly lower energy output, but higher maximum power output per day than the 30 degree tilted slate. This is in contrast to the energy output predictions for the winter months where in the winter the energy can be as much as double that of the 30 degree tilted slate.

The thorough testing and expert installation of the SunSlates™ is essential. From the case study it can be seen that some problems during installation, possibly a single faulty slate or shadowing, can cause a complete system to lose 30% of its efficiency.

Declaration

I, the undersigned, hereby declare that the work contained in this assignment is my own original work and that I have not previously in its entirety or in part submitted it at any university for a degree.

____________________ ____________________

Signed Date

Acknowledgements

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Nomenclature

PV - Photovoltaics

BIPV - Building integrated photovoltaics

W/m^2 - Watts per square meter

I_{sc} - Short-circuit current (Ampere)

I_o - Rated short-circuit current (at 25˚ C) (Ampere)

ΔT - Change in temperature

V_{oc} - Open-Circuit voltage (Volts)

V_o - Voltage at reference temperature (at 25˚ C) (Volts)

α, β - temperature coefficients

P_{max} - maximum possible power with change in temperature (Watts)

P_o - Rated power at reference temperature (Watts)

I_{ph} - Photo current (Ampere)

I_{max} - Rated current (same as I_{sc}) (Ampere)

$\emptyset$, φ - Incident angle

A/D - Analogue to Digital converter

STC - Standard test conditions

MPP - Maximum power point

MPPT - Maximum power point tracker

ST - Standard Time

LST - Local solar time

AM - Air Mass

NREL - National Renewable Energy Laboratory (America)

I_D - Direct insolation on perpendicular surface (W/m^2)

I_G - Global insolation on perpendicular surface (W/m^2)

δ - Declination angle

kWh - kilo Watt hour, measure of energy

Ω - Ohm, measure of resistance

R_x - Resistor number x

V_{in} - Control voltage from A/D

V_V - Measured voltage from PV panel

V_I - Amplified voltage from op-amp

T_1, T_2 - Transistors (T_2 – 2N2222 and T_1 – Tip41C)

C - Capacitor

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1 Introduction

World Energy Outlook

Energy is one of the buzz words in the world today. With increasing discussion about the oil peak and other fossil fuel production problems, people are looking into different ways to keep to their home comforts without having to pay the increased fees for these comforts. The world energy council (WEC) has been busy since the mid 1930's publishing statistical year-books. These year books were an attempt to publish international statistics of power resources (World Energy Council 2007, 2007). The 2007 survey is primarily concerned with energy reserves and the future outlook of energy usage. The 2007 energy report sketches a positive future for fossil fuel reserves, contrary to the other published papers, in the light of this the environmental reasons for energy saving should be considered more vigorously.

The rise in energy costs as well as a new environmental awareness has awakened the attractiveness of renewable resources. The renewable energy market has seen tremendous growth in the last few years and promises to be a good investment for future developments. The biggest growth in the group of renewable resources has been the production of photovoltaic modules. This industry has grown about 50% per year for the last 5 years. This growth has the positive effect of decreasing the cost per watt for the produced PV panels, stimulating the acceptance of this technology by the general public. (Earth Policy Institute, 2007)

PV in world markets

PV has been used in more extensively in Europe than in the rest of the world, with Japan, USA and China entering the market recently. China has now become one of the main PV producers in the world. One of the reasons for the acceptance of PV in Europe, which does not have ideal conditions for PV, has been mainly due to feed in tariffs resulting in the creative and practical use of PV by integrating it into a building. This is called Building Integrated Photovoltaics (BIPV).

Building integrated PV

BIPV has been developed and used in some European countries, Germany and Sweden especially, with great success. BIPV describes the use of PV panels and other products being used during construction of a building and forming part of the building itself and not being retrofitted to the building as in the past. This means that the panels have multiple usages, which reduces the lifetime costs of the panel.

Figure 1-1: BIPV Examples, buildings in Germany

BIPV has the potential to become one of the main uses of PV next to utility scale power generation. It can be used dynamically in almost any building design. This report investigates one of the BIPV innovations to evaluate its use in the South African context.

South African outlook

Currently South Africa has no incentives, like feed in tariffs or tax breaks, in place for any form of renewable energy technology. This is one of the main barriers in the widespread use of photovoltaic systems. Currently the main commercial energy distributor in South Africa is ESKOM. The cost of ESKOM generated electricity is another barrier to PV usage. Due to the low grid electricity costs the payback time on PV systems are substantial and do not warrant investment.

The current electricity problems in South Africa may be an advantage for PV systems. ESKOM has reached their peak generation capacity and the country is plagued with mandatory power cuts. This has placed a massive strain on the growth of the economy. ESKOM has gone as far as placing a moratorium on new developments which will require electricity from ESKOM.

Due to the electricity crisis in South Africa investigations are being made into renewable energy resources. The most abundant of these resources is solar energy. South Africa has one of the highest annual solar insolation levels in the world, making it an appropriate country for all solar technologies. The following map from the renewable energy database illustrates the spread of solar insolation in South Africa. It should be noted that the Northern Cape Province has the highest insolation levels in South Africa. (ESKOM, 2006)

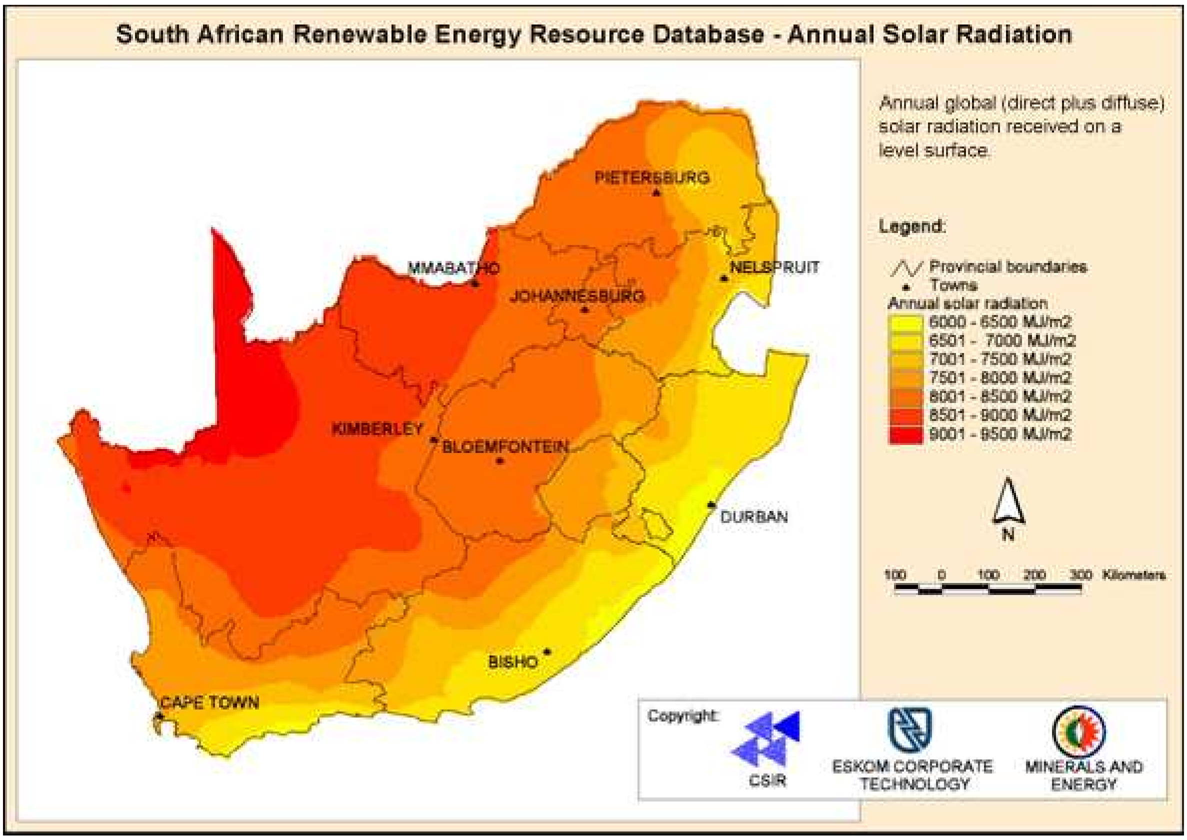


Figure 1-2: S.A. Annual Solar Radiation (ESKOM, 2006)

Regardless of the fact that South Africa has an abundant solar resource, the PV market has never grown more than rural or far off-grid applications. This is due to the relative high costs of PV systems, as mentioned before.

Market trends, however, have shown that the price of PV modules is coming down and grid parity has been reached in some countries, like Spain and California. If this trend continues and the electricity crisis in South Africa has not been solved, PV will become a viable option for most home owners, especially BIPV systems for new developments.

BIPV can be used with sustainable design to reduce the total energy needs of a house or development. This will assist developers to circumvent the problems with grid supply and will also assist the growing economy.

The use of BIPV will stimulate a new market in South Africa. The spin offs from the new market will have the added benefit of job creation, one of the main priorities of the South African government.

BIPV Product

An American company called Atlantis Energy System has entered the new BIPV market. This company manufactures roof slates with a PV module integrated on it, thus the slate has the multiple purpose of acting as a roof and generating electricity. The picture below is an illustration from an installation manual for the SunSlates™.

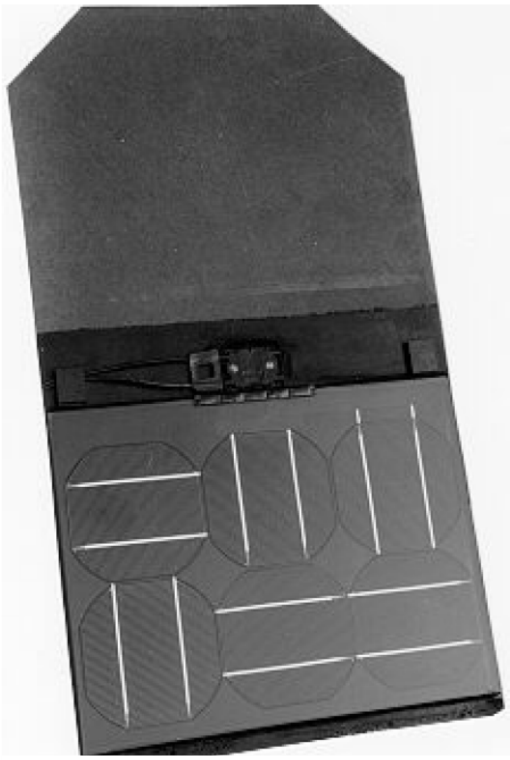


Figure 1-3: SunSlate™ from Atlantis Energy Systems

As can be seen from this picture of the panel, the design is simple and can be easily reproduced for South African condition and building regulations.

This report investigates the SunSlate™ and attempts to characterise it's parameters to some degree. A model will be developed to predict the performance of these slates in real world conditions under varying solar intensities and orientations.

Definition of terms used in this report:

Table 1-1: List of definitions used in project

Insolation [kW/m^2]	The power incident on a surface measured in W/m^2. Solar Insolation is thus the power received from the sun on a surface.
Irradiance [kWh/m^2/day]	Irradiance is the measured insolation on a surface for a period of time. This is in essence the *energy* received from the sun.
Air Mass	Air Mass is known as the path length the solar rays must travel to the surface of the earth.
Efficiency	Efficiency refers to the conversion of solar energy or power to electrical

	energy or power of the PV panel.
Tilt angle	This is the angle a slate or surface is tilted from the horizontal.
Zenith angle	This is the angle which indicates the sun's vertical position from the vertical, looking from a fixed point.
Altitude angle	Altitude angle is 90˚ minus the zenith angle.
Azimuth angle	This is the angle which indicates the sun's horizontal position from north, looking from a fixed point.
Incidence angle	The angle between solar rays and the Normal to a surface.
Standard Test Condition (STC)	The standard test condition refers to the standard conditions under which PV cells are specified. These conditions are at a solar intensity of 1000W/m^2 and at 25˚C and at AM1.5 solar spectrum.
Maximum Power Point	The point at which the combination of voltage and current from a panel results in the maximum possible power from that panel.
Optimal Tilt	Optimal tilt refers to the tilt angle at which the incidence angle of the solar rays is equal to 0˚. (Solar rays perpendicular to surface)
Diffuse component	This is the component of the insolation due to light reflection from surrounding area. During cloudy days the diffuse component can make up the most of measured insolation.

2 Objectives and motivation

Motivation

BIPV is becoming more important in the construction of buildings worldwide. However, there is limited data on the performance of these installations. BIPV systems will not always be installed at the optimal tilt or orientation. The lack of performance data needed to identify PV power output has motivated the need for this project to test a specific type of BIPV system, i.e. SunSlates™ from Atlantis Energy Systems.

These SunSlates™ consist of an integrated PV panel and roof slate, thus the PV system doubles as the roof of a building. The PV slates are individually connected in series and/or parallel and the string is then coupled to an inverter.

Due to the addition of a roof slate to the back of the PV cells the characteristics of the cells will differ from laboratory test conditions. The slate will increase in temperature and other operating parameters of the PV cells need to be investigated.

Further, limited data is available of real system performance at different orientations. When installing a system, previous performance information is required or accurate predictions are needed. This project attempts to address these problems by evaluating the SunSlates™ at different tilt angles as well as different orientations. The motivation for this was that not all roofs are built to face due north, but most are at different orientations and tilt angles.

Meteorological data are available for Stellenbosch, but what is required is data on the performance of the SunSlates™. With this information models can be developed for other installations.

Choice of Slate

Before choosing a product to install on the roof at the Sustainability Institute, various products on offer was evaluated. It was found however that most of the products on offer was not an integrated solution.

The SunSlate™ was the only product which incorporated a PV module with a roof slate. The other products where either normal PV modules stacked on the roof in stead of roof tiles or the product was an addition to the current roof. The following is pictures of the various products available:

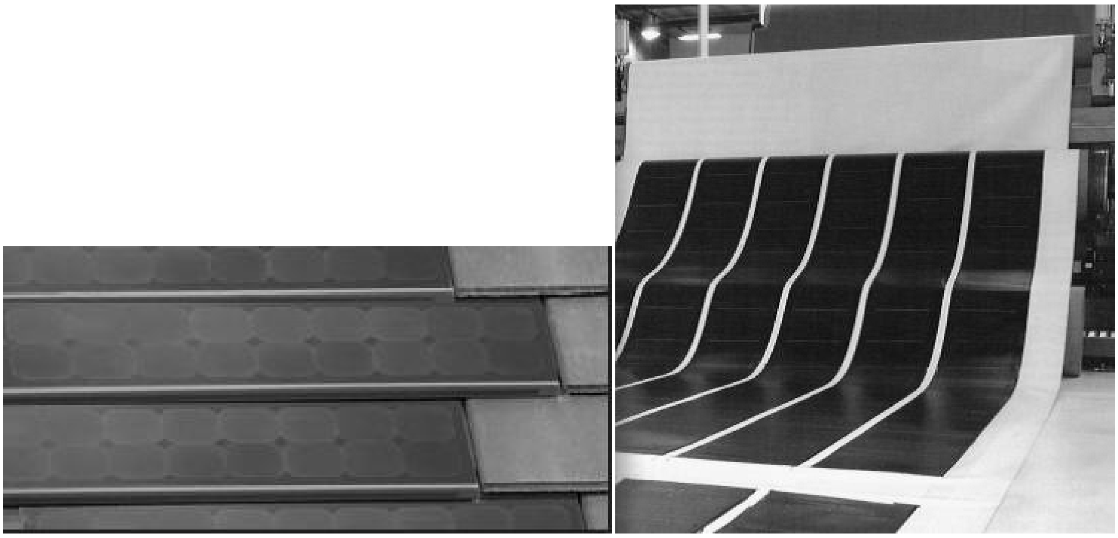


Figure 2-1: Solarcentury - 'complete solar roof' tile and UNISolar’s Solar Laminate

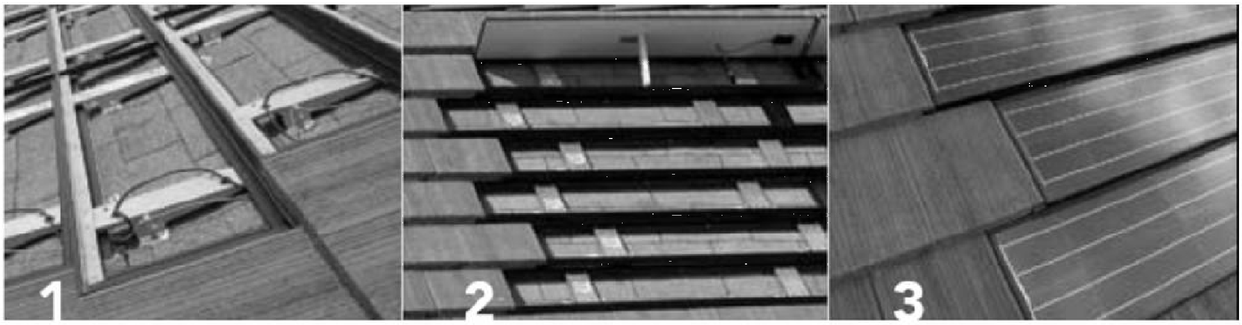


Figure 2-2: MyGen Meridian by Kyocera

Most of the other products available are in the same style as these illustrated in figure 2-1 and 2-2.

Objectives

The characteristics of three SunSlates™ were analysed, tests were done by mounting the slates at fixed angles with each of the slates facing a different direction (East, West and North) and another slate was set up facing north on a adjustable stand so that it’s tilt angle could be adjusted. This was done to determine the effect the change of season will have on the performance of the slate and the total energy produced versus that of a fixed slate.

Solar intensity was measured in watts per square meter as this directly relates to the amount of power a solar panel produces. Solar cell power output is specified for a solar insolation of 1000 W/m^2. This is not always attainable in practice and a study was made of the proposed installation site so that the amount of power from the panels can be theoretically determined. The power output increases with increase in to the solar intensity, but the efficiency of the panel will be approximately the same with the change of solar intensity (Schenk). At lower insolation the short-circuit current will be lower than at higher insolation. The same is true for the open-circuit voltage, as seen in Figure 2.3

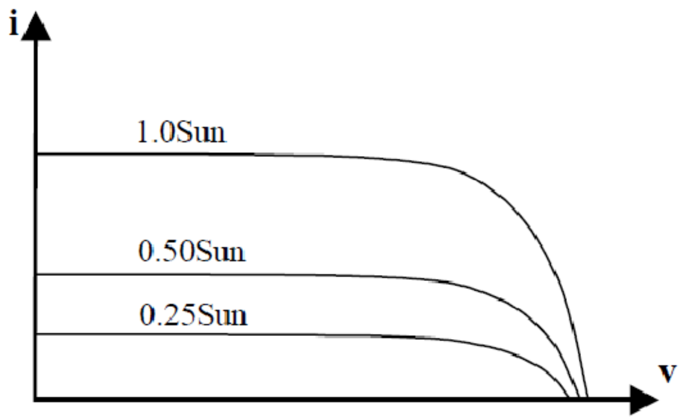


Figure 2-3: Change in I-V curve with regards to insolation, (Schenk)

The effect of temperature changes was tested. Temperature has a large effect on the efficiency of a solar cell and panel. Efficiency drops with the increase in temperature from the reference temperature (25˚C). A decrease in temperature would theoretically increase the efficiency. (King & Kratochvil, 1997)

In most cases the short circuit current will increase and the open-circuit voltage will drop as temperature increases. The drop in V_{oc} is usually more than the increase of I_{sc}, thus reducing the power delivered by the solar cell. (King & Kratochvil, 1997)

Open circuit voltage and short circuit current can be approximated by the following formulae:

$$I_{sc} = I_o(1+\alpha\Delta T) \tag{2.1}$$

$$V_{oc} = V_o(1+\beta\Delta T) \tag{2.2}$$

where I_{sc} is the short circuit current of the PV cell, I_o current at reference temperature (25˚C), ΔT change in temperature, V_{oc} open-circuit voltage, V_o voltage at reference temperature and α and β are temperature coefficients for the short circuit current and open-circuit voltage, with β usually negative and larger than α.

Manufacturers, in most cases, document the amount of power change associated with temperature change.

The maximum power can be calculated by combining (2.1) and (2.2):

$$P_{max} = I_o(1+\alpha\Delta T) * V_o(1+\beta\Delta T) \qquad (2.3)$$

Ignoring quadratic terms:

$$\begin{aligned} P_{max} &= I_o(1+\alpha\Delta T) * V_o(1+\beta\Delta T) \\ &= P_o(1 + (\alpha + \beta)\, \Delta T) \end{aligned} \qquad (2.4)$$

where P_{max} is the maximum possible power with change in temperature and P_o the power delivered at 25˚C under the same illumination.

The term ($\alpha + \beta$) is usually negative and thus the increase in temperature will decrease the maximum power and thus the efficiency of the cell in total.

The following figure illustrates the effect of temperature on power output.

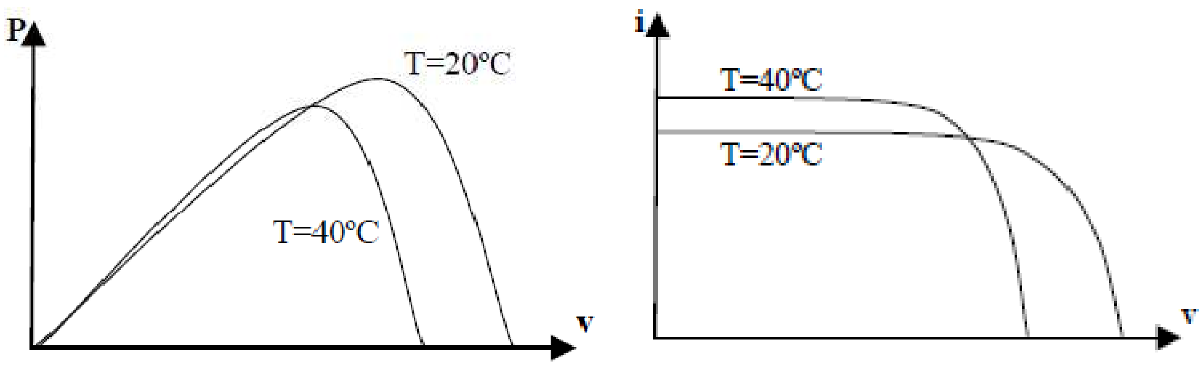


Figure 2-4: Illustration of the effect of temperature on power of a PV cell and the I-V curve

The effect of tilt angle was investigated by means of the panel mounted on the adjustable structure. The optimal power output from a PV cell is obtained when the cell faces the sun and the incident angle of the solar rays is 0˚ (perpendicular to the cell). As the incident angle changes so too does the maximum photo current of PV cell, (Kacira, 2003). The change can be calculated by use of the following equation:

$$I_{ph} = I_{max} * \cos(\theta) \qquad \text{, where } \theta \text{ is the incident angle} \qquad (2.5)$$

The tilt angle is of importance especially when it comes to designing of a BIPV system. Optimal angles can not always be realised and tracking is not always an option. Knowing the effect of off angle installation of this specific product will lead to a model that can be used when determining installation parameters like maximum power output for a specific site. If a PV panel has a fixed tilt the optimal angle towards the sun will only be realised twice a year, while at the other times of the year the maximum power will not always be realised.

To determine what effect the orientation has on total energy produced, 2 slates were mounted facing east and west. The energy produced by these 2 slates was compared to the slate facing north. As with the tilt angle this resulted in a usable model when a north facing orientation is not possible.

A comparison was done between the total energy production from the PV panels using a fixed load and using maximum power point tracking. The maximum power point tracking was realised by utilising an electronic circuit connected to a computer. This computer has, by means of software, determined the maximum power point from a custom built measurement circuit.

All data and results were compared to current available data in the literature. All data in combination was used to construct a model, which can be used for commercial installations predictions.

Summary of objective

1) Characterising the slate: Measured power in comparison to specification.
2) Effect of intensity and environment on the temperature and power of a slate facing north.
3) To determine the effect orientation has on the output of the slates.
4) The effect of tilt on output of slates.
5) Comparison between measured values and predicted values.
6) A practical case study at Lynedoch.

3 Literature study

Discussion of literature reviewed

Various sources of literature exist regarding photovoltaic systems. Doing a search on Google.com under 'Building Integrated PV' yields numerous results. The one thing which is lacking is performance tests of these BIPV systems. The lack of performance testing has been addressed by the America's National Institute of Standards and Technology, (Fanney, Dougherty, & Davis, 2002).

The paper by *Fanny et al.* (2002) from the NIST describes how they constructed a test bed facility on the NIST building south wall. The experiment used various technologies of PV modules and not just crystalline silicon. This was done to compare the results of different types of PV cells used in BIPV applications. The temperature of each of the panels where measured and the modules where kept at their maximum power point. The MPP was obtained by using a multi-curve tracer, operating at 15 second intervals. The I-V curves of the modules where measured every 5 minutes. A meteorological station was also set up close to the south facing wall where the experiment was taking place. The measurements taken were solar radiation, wind and ambient temperature. The results from this experiment can be useful for those who work in the field of BIPV and perhaps assist in reducing some of the limitations on BIPV.

Limited data exist describing technical statistics of BIPV. It should be noted that PV cells in BIPV has the same characteristics as free panel mounted PV, with the addition of other materials which may cause the cells to operate at higher temperatures or cause other effects.

King et al. (1997) has done an in-depth study of the temperature coefficient of PV cells. In this paper they discuss the misconceptions of how the temperature coefficients are applied and how they should be used. Fundamentally the temperature coefficient for an individual cell should apply to the module as a whole, but this is stated not to be the case as non-uniform temperature distribution in the module would affect the final performance of the cells. The application of the coefficients to the power delivered by the panel is given by a simple formula. This formula is given as

$$P_{mp} = I_{mp}(T).[1 - \alpha_{mp}(T - T_{ref})].V_{mp}(T) - \beta_{mp}V_{mp}^{STC}(T\text{-}T_{ref}) \qquad 3.1$$

The formula makes the assumption that the open-circuit Voltage coefficient as well as the maximum power point voltage coefficient is independent from the solar insolation. It states that in practice the V_{oc} coefficient only varies with up to 5% from the STC V_{oc}. This paper states that at low insolation and temperature levels the maximum power delivered can be higher than stated in the data sheets of the solar cell due to the effect of the temperature coefficients. The increase in module temperature leads to a decrease in power output. This has significant implications in the design and implementation of PV systems.

Due to the change in insolation and the power characteristics of a PV cell during operation it is suggested that a maximum power point tracker be used. In *Bekker et al*. (2004) different types of MPPT algorithms are investigated. A maximum power point tracker can be expensive to implement and should be considered only if it is economically viable and the energy gained over a period of time justifies the addition of a MPPT. For accurate testing of any panel during actual operating conditions, it is essential to implement maximum power point tracking. If the load does not dissipate the maximum power from the panel, some of the power will need to be dissipated in the panel. This will cause the cells to heat up and affect the performance. *Kamath et al*. also investigates the use of different algorithms do determine the maximum power output from a panel. The basic principle of the MPP tracking is to monitor the voltage and current from the panel and then alter the load to determine the optimal voltage/current relationship which would give the maximum power. Most reviewed literature agrees that the energy delivered by the PV module can be increase by 20% to 30% if a MPPT is used. The maximum power point for a silicon PV cell is mostly obtained when the voltage delivered by the PV module to the load is about 80% that of the open-circuit voltage of the panel.

Crucial to any placement of PV panels is the orientation. As explained in *Bekker et al.* the orientation and tilt of the panels directly relates to the annual energy yield of the panels. Computer modelling is used to determine the best possible position.

The most important factor when considering the power output from a PV panel is the solar insolation at a site. Solar insolation differs from site to site, but PV panels are certified for insolation of 1000 W/m^2. To accurately determine the annual energy output from PV panels the seasonal variation of the insolation should also be taken into account. Winter months will have a lower insolation than summer months, due to the inclination of the earth. The power delivered by a PV cell is approximately proportioned to the solar insolation. Higher insolation levels will result in higher current from the cell leading to higher to power delivered. Site specific data is required for any installation or test.

Kacira et al. (2003) describes how optimal tilt angles can be determined at a specific site. Due to the cost of trackers it is often needed to mount PV panels at fixed orientations and tilt. There are various opinions of what the optimal tilt angle should be. It varies from ±15˚ from latitude angle to latitude angle + 30˚. It was found that the optimal angle to mount the panel differs from month to month, due to the seasonal shift of the sun. From this paper it can be seen that for designing and implementing a PV system it is critical to determine the application beforehand. The applications can vary from maximum energy capture throughout the year or maximum power output during a specific month. The tilt angle determines the amount of solar insolation the panel will receive during a specific month. *Bekker et al* take it further to develop mathematical model of the movement of the sun to determine the optimal positioning. These models consider the movement of the sun and with this it is possible to determine the tilt angle of solar panel to obtain the maximum energy capture per month.

Standard test conditions are defined at AM1.5. The increase of air mass has the effect of decreasing the solar irradiance from the sun. This explains why the insolation changes with the season. *Honsburg et al.* use the movement of the sun and the relation between air mass and insolation to predict the amount of solar insolation on a surface.

From most of the literature reviewed it was found that the local solar resource should be well established before any installation can be considered. Standard time or mean time as seen on a watch is not the same as the Local Solar Time (LST). The difference between standard time and LST is used to determine the time of day when maximum power is delivered by a PV system. The difference between LST and mean time is shown by formula 4.6.

From the position of the sun the insolation on a surface can be predicted. The predicted insolation data can be used to estimate the power and energy output from a PV panel.

4 Solar Resource

It is of great importance to know the local solar resource available and how it changes throughout the year and also throughout the day, so that the energy captured can be calculated. The knowledge of the sunshine hours is also required to estimate the potential output of a system.

Historical data can be obtained from meteorological institutes or other online resources like RETScreen™ or NREL models. RETScreen uses data from NASA weather satellites over a historical period of 5 years.

Theory

In PV applications a global standard of insolation has been selected. The global standard has been chosen as the spectrum of AM1.5 and an insolation of 1000 W/m^2. The air mass however changes as the season changes and throughout the day as the sun moves trough the sky.

Air Mass is a measure of the path length the solar rays must travel through the atmosphere to the surface of the earth. If the sun is directly above the surface the air mass would be 1. As the earth moves and the incidence angle changes so to does the air mass with the following relationship:

$$AM_X \text{ ,where } X = 1/\cos\varphi \qquad 4.1$$

The following figure illustrates the concept of air mass:

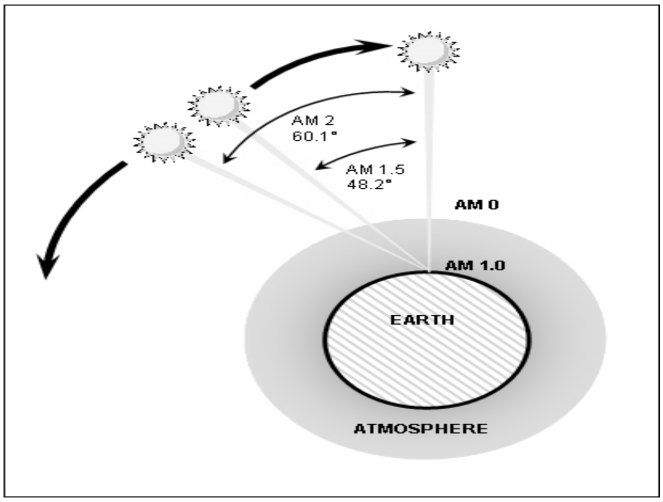


Figure 4-1: The path length, in units of Air Mass, changes with the zenith angle, *www.dur.ac.uk/~dph0www5/am1_5.html*

To mathematically predict the solar insolation at a specific site for a specific time the following analysis is required: understanding the movement of the sun and the change in daytime position, causing changes in insolation. A mathematic program can be compiled to predict the power output from a PV module if the area and the efficiency are known.

Insolation is related to air mass, as AM increases the insolation decreases. This relationship has been experimentally derived by *Meinel*, this relation is as follows, (Honsberg & Bowden, 2008) :

$$I_D = 1.353 \times 0.7^{AM \times 0.679} \quad 4.2$$

Thus by determining the Air Mass at a certain time of the day one can predict the direct insolation for that time of day on a perpendicular surface. In formula 4.2 I_D is the direct solar insolation on a perpendicular surface to the solar rays. The assumption made here is that there is no cloud cover on the specific day. Literature (Honsberg & Bowden, 2008) states, that even on a day of clear skies the diffuse component will still be around 10% of the direct component of insolation, thus one can determine the global insolation from

$$I_G = 1.1 \times I_D \quad 4.3$$

It should be noted that the diffuse component is dependant on the surrounding area. In the case of desert areas the diffuse component can increase.

To determine AM the Zenith angle or altitude angle of the sun is required for the specific time of the day. To determine the Zenith of the sun for a particular hour of a particular day of the year some astronomical knowledge is required. Before calculating the Zenith the declination of the earth is required. The declination of the earth can change from 23.45˚ to – 23.45˚ depending on the time of the year due to the tilt angle of the earth towards the sun. The solar declination angle, the angle between the solar rays and vertical, at noon on the equator, is a maximum or minimum on the winter and summer solstices (21 June and 21 December).

The solar declination angle can be determined by the following equation and yields the following result:

$$\delta = 23.45° \times \left[\left(\frac{360}{365}\right)(N + 284)\right] \quad \text{,where N is the day of the year} \qquad 4.4$$

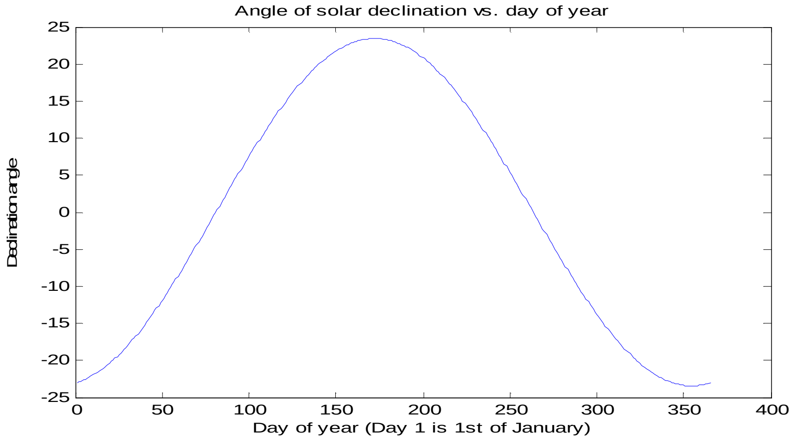


Figure 4-2: Angle of solar declination vs. day of year

To further determine the Zenith of the sun one should use solar time. Solar time differs from normal clock time, which is based on mean time. This difference is due to the elliptical orbit of the earth around the sun as well as the movement of the sun relative to the equator (declination of sun).

The difference between Solar time and clock time can for a specific day of the year can be expressed with the following equation (Equation of Time) yielding the results shown in figure 4.3.

$$EoT = 2.292(0.0075 + 0.1868\cos\beta - 3.2077\sin\beta - 1.4615\cos2\beta - 4.089\sin2\beta) \qquad 4.5$$

where $\beta = \frac{2\pi}{365}(N - 1)$ and N the day of the year.

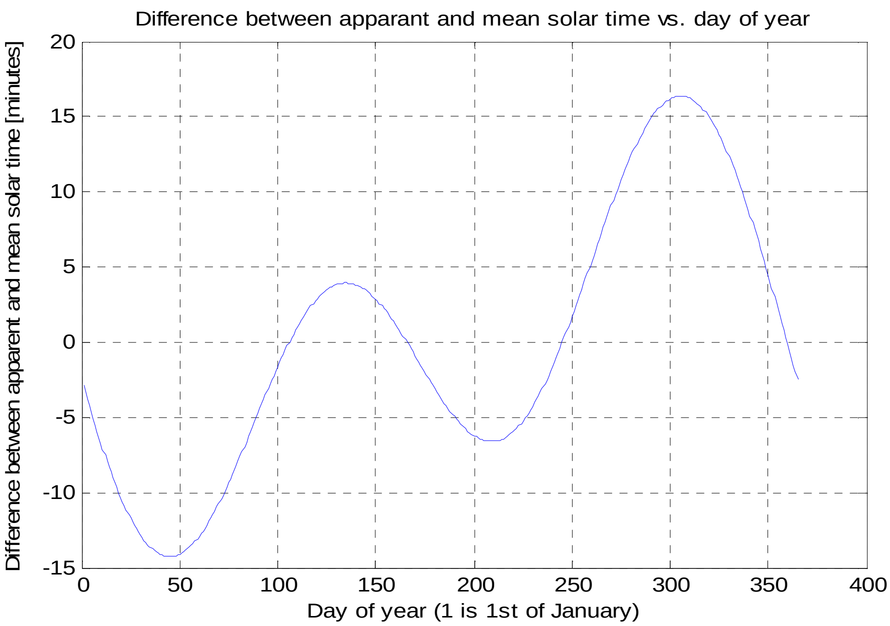


Figure 4-3: Difference between apparent and mean solar time as function of day of the year

Using the above equation of time, one can determine the Local Solar Time. It is this time which is used to determine the position of the sun and hour angle of the sun. Local apparent solar time is, like mean time, based on longitude. The following equation is used to convert from clock time to local solar time, (Honsberg & Bowden, 2008)

$$LST = ST + 4(L_{longitude} - L_{sm}) + EoT \qquad 4.6$$

L_{sm} is the standard meridian for the local time zone, this is 15˚ for every +1 hour away from GMT (Greenwich Mean Time) and -15˚ for every -1 hour away from GMT. $L_{longitude}$ is the longitude of the specific site, Stellenbosch is as 18.5˚ east. The EoT is the correction element from the equation of time, in minutes.

Using the local solar time one can calculate the hour angle of the sun, (Bekker, 2004). The hour angle is a way to determine the position of the sun relative to noon solar time. At noon the angle will be 0˚. The hour angle changes with 15˚ for every hour towards or away from the noon zenith. This hour angle can be determined by the following equation (Bekker, 2004):

$$hourangle = 15(SolTime - 12) \qquad 4.7$$

With the sun declination and the hourangle calculated one can calculate the Zenith of the sun for a specific day, at a specific time. This calculation is used to determine the AM of a specific time of day, (Honsberg & Bowden, 2008).

$$Zenith\_Angle = \arccos(\sin(Latitude).*\sin(Declination) + \cos(Latitude)\cos(Declination)\cos(hourangle)) \qquad 4.8$$

The resulting air mass can now be calculated by eq 4.1 by using the Zenith_Angle for φ

To determine the insolation on a tilted surface the following equation can be used:

$$B_{Tilted} = I_D[\cos(elevation\_angle)\sin(slope)\cos(azimuth - solar\_azimuth) + \sin(elevation\_angle)\cos(slope)] \qquad 4.9$$

Where I_D is the insolation on a surface perpendicular to the sun, *slope* is the angle of the tilted surface from the horizontal, thus a horizontal surface will be a 0˚ and a vertical surface will be at 90˚. The elevation_angle is 90˚ - Zenith_angle. The *azimuth* is the angle the surface makes from north, thus if it faces north it will be 0˚ and if it faces west it will be 90˚. The *solar azimuth* can be calculated by using the following equation:

$$\text{solar\_azimuth} = \arctan[\cos(\textit{declination})\sin(\textit{hourangle}) / (\sin(\textit{latitude})\cos(\text{declination})\cos(\textit{hourangle}) - \cos(\textit{latitude})\sin(\textit{declination}))] \quad 4.10$$

Site Analysis

Historical data for the specific site at Stellenbosch suggests that the total energy received on a horizontal surface differs from January to June. The following is data retrieved from RETScreen data sources (http://eosweb.larc.nasa.gov/sse/RETScreen/).

Table 4-1: RETScreen data, energy available on horizontal surface

Month:	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	**Average**
kWh/m^2/d	8.17	7.3	5.91	4.3	3.09	2.64	2.85	3.67	4.92	6.46	7.68	8.18	**5.26**

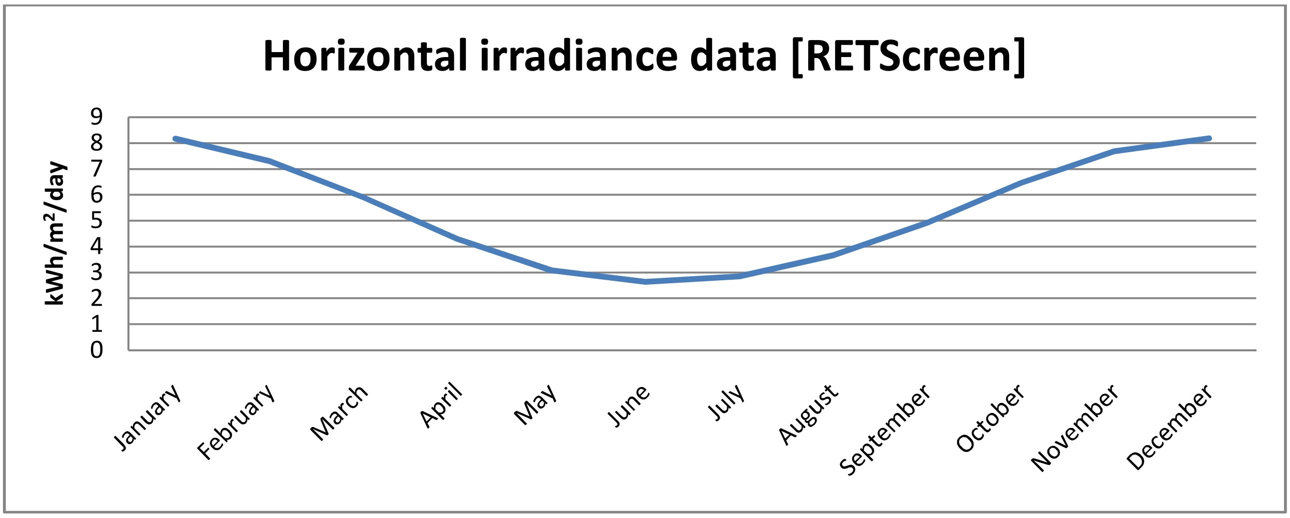


Figure 4-4: Horizontal Irradiance data [RETScreen]

From this data the total possible energy on a horizontal surface for the year is about 2MWh/m^2/year or 7200 MJ/m^2 per year. This corresponds to data obtained from Eskom about the local solar resources available at Stellenbosch, (ESKOM, 2006).

The following data obtained from RETScreen estimates the amount of energy per day at Stellenbosch on a tilted surface. The difference between 30˚, 34˚ and 60˚ are given:

Table 4-2: RETScreen data, energy available on tilted surfaces

Month:	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	**Average**
$kWh/m^2/d$ @ 30˚	7.36	6.95	6.23	5.12	4.23	3.92	4.14	4.67	5.46	6.45	7.07	7.30	**5.73**
$kWh/m^2/d$ @ 34˚	7.17	6.84	6.21	5.18	4.33	4.04	4.26	4.75	5.47	6.37	6.90	7.09	**5.71**
$kWh/m^2/d$ @ 60˚	5.38	5.53	5.53	5.08	4.57	4.43	4.60	4.80	5.06	5.33	5.30	5.23	**5.07**

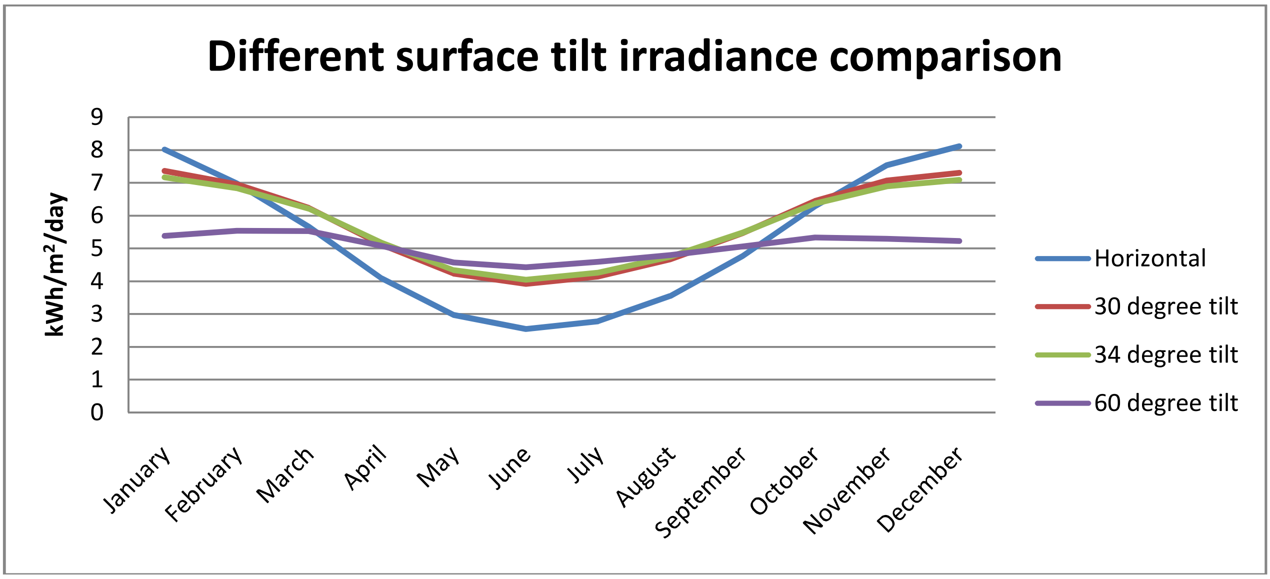


Figure 4-5: Irradiance data [RETScreen] on tilted surfaces compared to horizontal

From the historical data one can see that a latitude tilt differs little from a 30˚ tilt and that up to a 60˚ tilt the energy output still averages to above $5kWh/m^2$ per day. The averaged energy generated per year for the 30˚ tilt is 2.09 MWh/m^2 and for the 60˚ tilt 1.85 MWh/m^2. The difference is 240 kWh/m^2 per year or 11.5%. This difference should be taken into account when installing a PV system.

The optimal annual energy will be obtained if the surface faces the sun perpendicularly throughout the year. To ensure that a surface is facing the sun the angle of incidence is required, this can be obtained from the Zenith of the sun. The following table and graph is the mathematically calculated change of incidence angle as function of day in the year with a summary of the optimal angle for each Month of the year to ensure that a surface is perpendicular to the rays of the sun at solar noon.

The required tilt angle can be calculated by subtracting the Zenith angle from 90˚. The optimal angle is given as the angle on or around the 21^{st} of the month.

Table 4-3: Optimal tilt angle for surface to be perpendicular to solar rays

Month:	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Zenith	75	67	56	45	34	32	34	43	55	65	75	80
Tilt angle	15	23	34	45	56	58	56	47	35	23	14	10

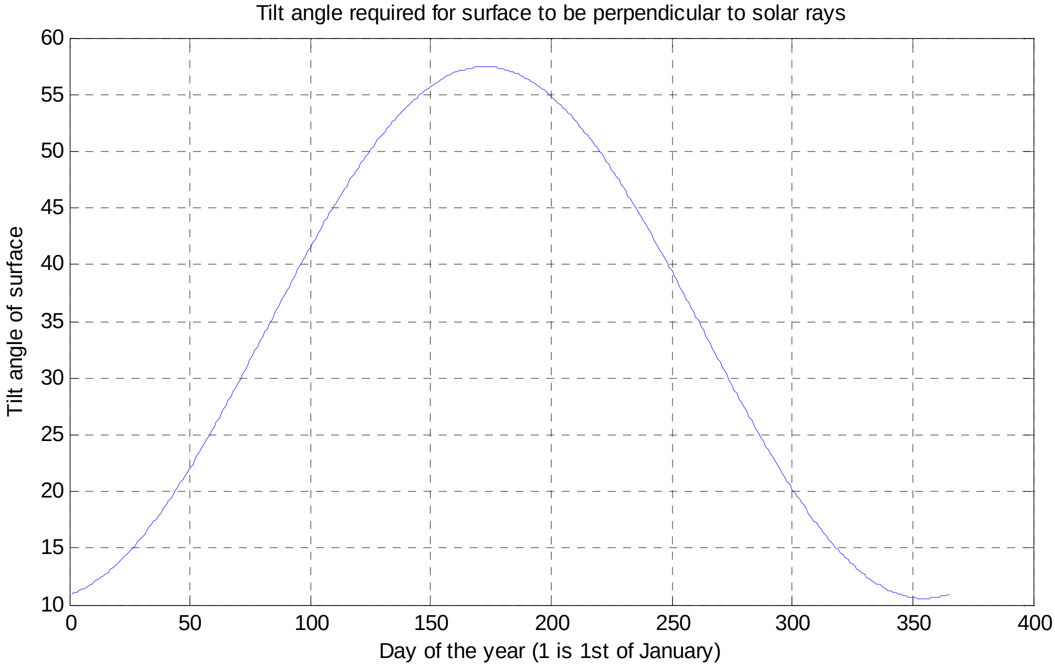


Figure 4-6: Zenith position at solar noon vs. day of the year

Using the Zenith as reference and changing the tilt angle once per month on or around the 21st of the month the following results are obtained for energy generation:

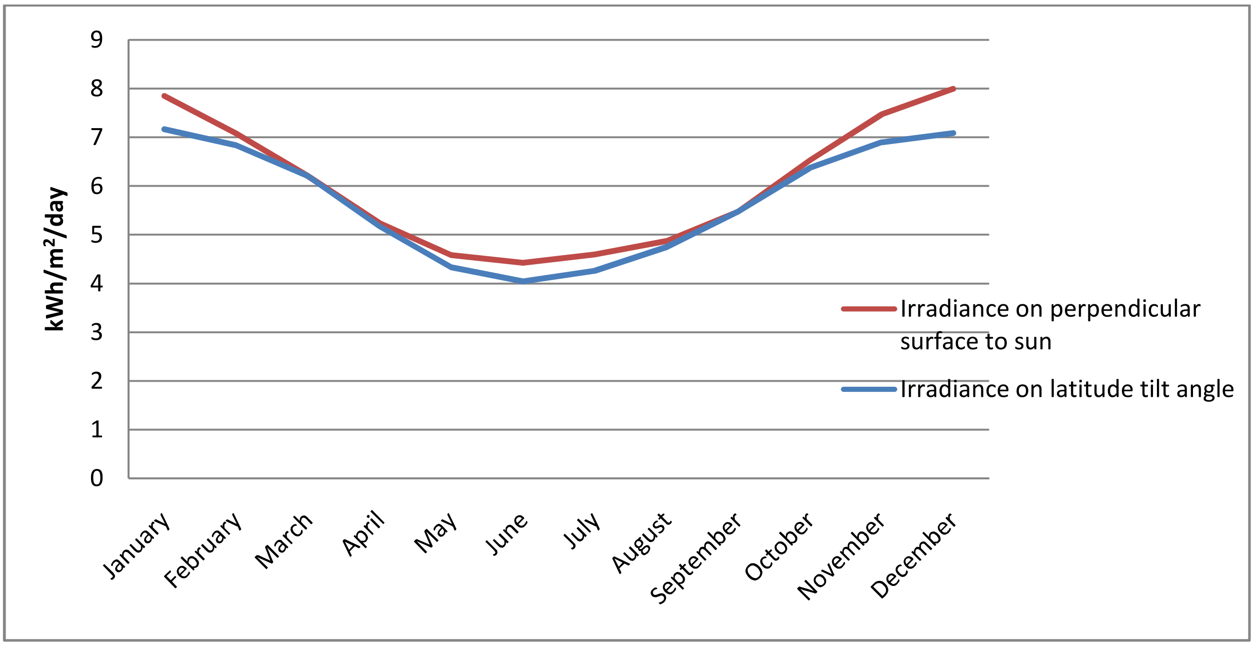


Figure 4-7: Irradiance on a tilted surface perpendicular to solar rays compared to irradiance on latitude tilted surface.

Table 4-4: : Irradiance on a tilted surface perpendicular to solar rays

Month:	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	**Average**
$kWh/m^2/d$	7.85	7.08	6.21	5.24	4.58	4.43	4.59	4.87	5.47	6.53	7.47	8.00	**6.03**

The annual energy obtained from keeping the surface perpendicular to the solar rays is 2.2 MWh/m^2. This is an increase of 300 kWh/m^2 or 13% per year from the horizontal and 110 kWh/m^2 or 5% per year from latitude tilt. This data shows that single axis tracking or seasonal sun tracking only increases total the energy output of a system by a small amount.

Using historical data from RETScreen the effect of orientation on the annual energy was analysed. The annual energy generation for a west orientation is the same as that of an east orientation, when using RETScreen data. In practice the amount of energy captured by a west facing slate should be higher by a small margin.

The following is a graph of energy from east orientation compared to north orientation at an angle of 30˚

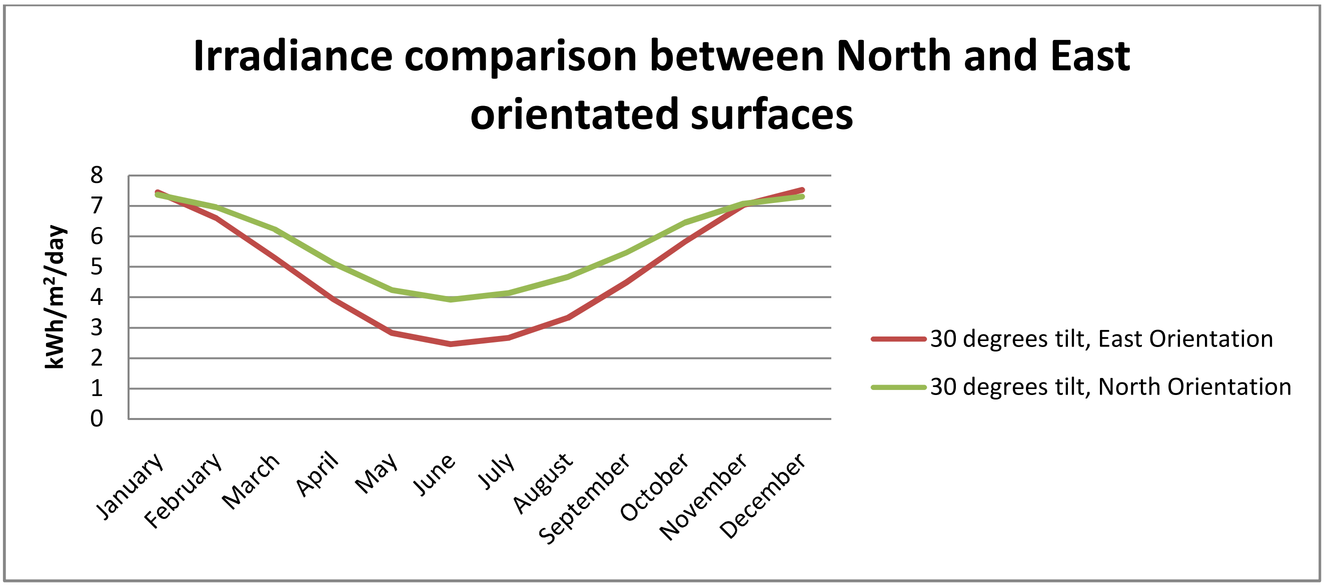


Figure 4-8: Daily solar irradiance, orientation comparison

The amount of energy captured by an east or west orientated surface is somewhat less than the energy captured by a north facing surface at the same tilt angle of 30˚. The annual energy obtained from an east of west orientated surface is equal to 1.8 MWh/m^2. This is 290 kWh/m^2 or 14% less than north orientation for the year. Which is smaller than expected.

Looking at daily insolation for north and east orientated surfaces the following can be observed between a north facing surface at 30˚ tilt and an east facing surface at 30˚. The insolation data was predicted using a mathematical model.

North East

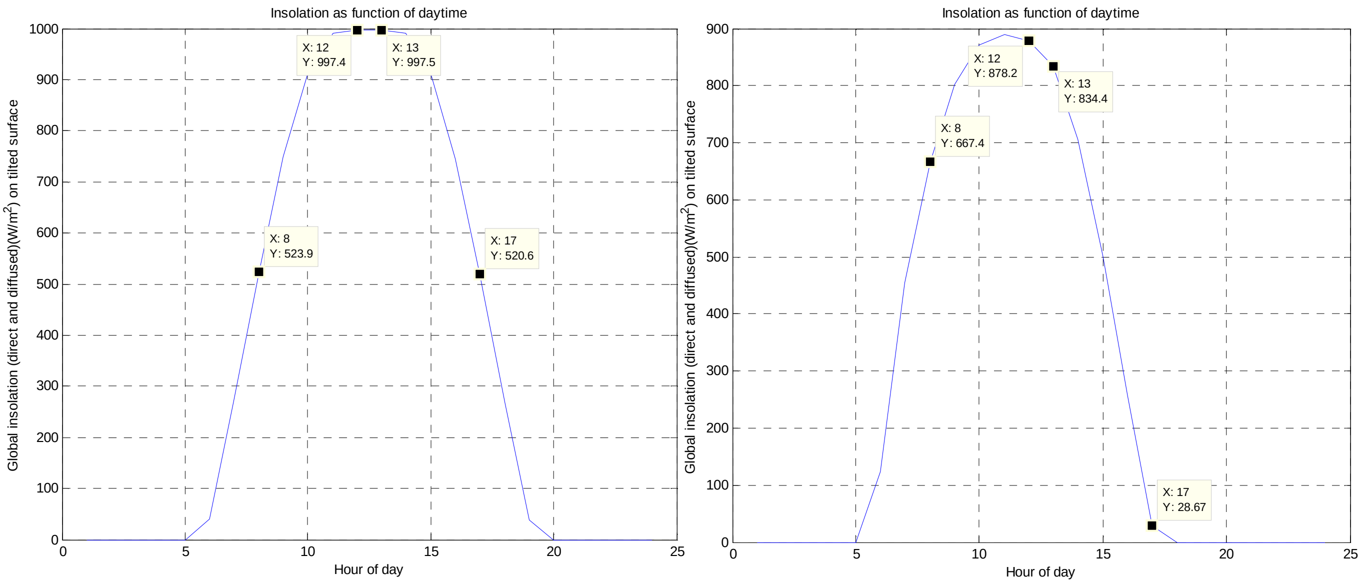


Figure 4-9: Insolation comparison between a north facing surface and an east facing surface, on day 320

The insolation on the surface differs somewhat due to orientation. The east orientation has fewer sunshine hours and also does not receive the same maximum insolation as the north orientated surface. From the predicted insolation data one can see that the north facing surface has a symmetrical form. The east facing slate has higher insolation earlier in the day, but the insolation drops more rapidly after the solar noon.

5 Experimental Setup

Mechanical Design

To mount the SunSlates™, a framework had to be designed. The design of the framework was such that two slates would face away from a central middle tile. This was done to have one tile facing north and the other facing east and west. The framework was built using cost effective materials and mounting of the tiles were done by clamping them to the framework.

It was decided that the angle to the horizontal of the mountings of the individual slates should be 30˚. This is 4 degrees less than the latitude of the Stellenbosch site (34.2 S), which would have been optimal. Most roofs are not built at the angle equal to the latitude of the site and for this reason 30 degrees will fall in the range of the angle of a real roof and is still in the optimal range for fixed angle PV installations in regions around Stellenbosch.

The following picture and diagram illustrates the design and the setup on the roof at the Solar Energy Testing Facility:

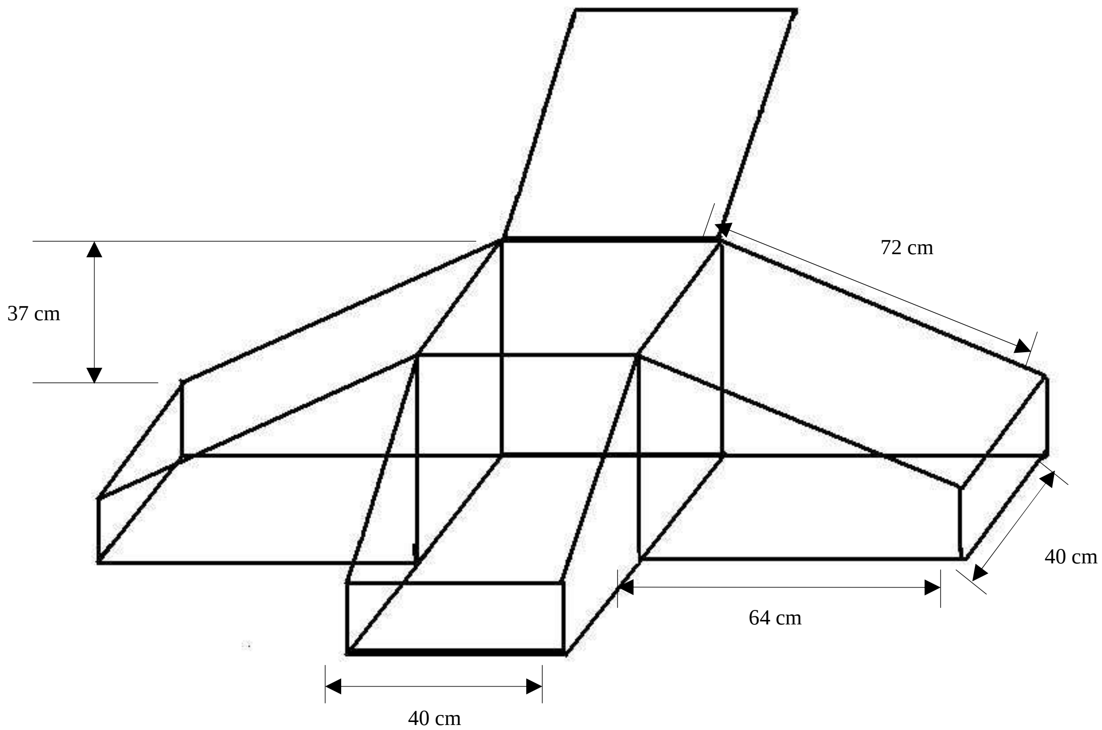


Figure 5-1: Diagram of Frame for mounting of SunSlates

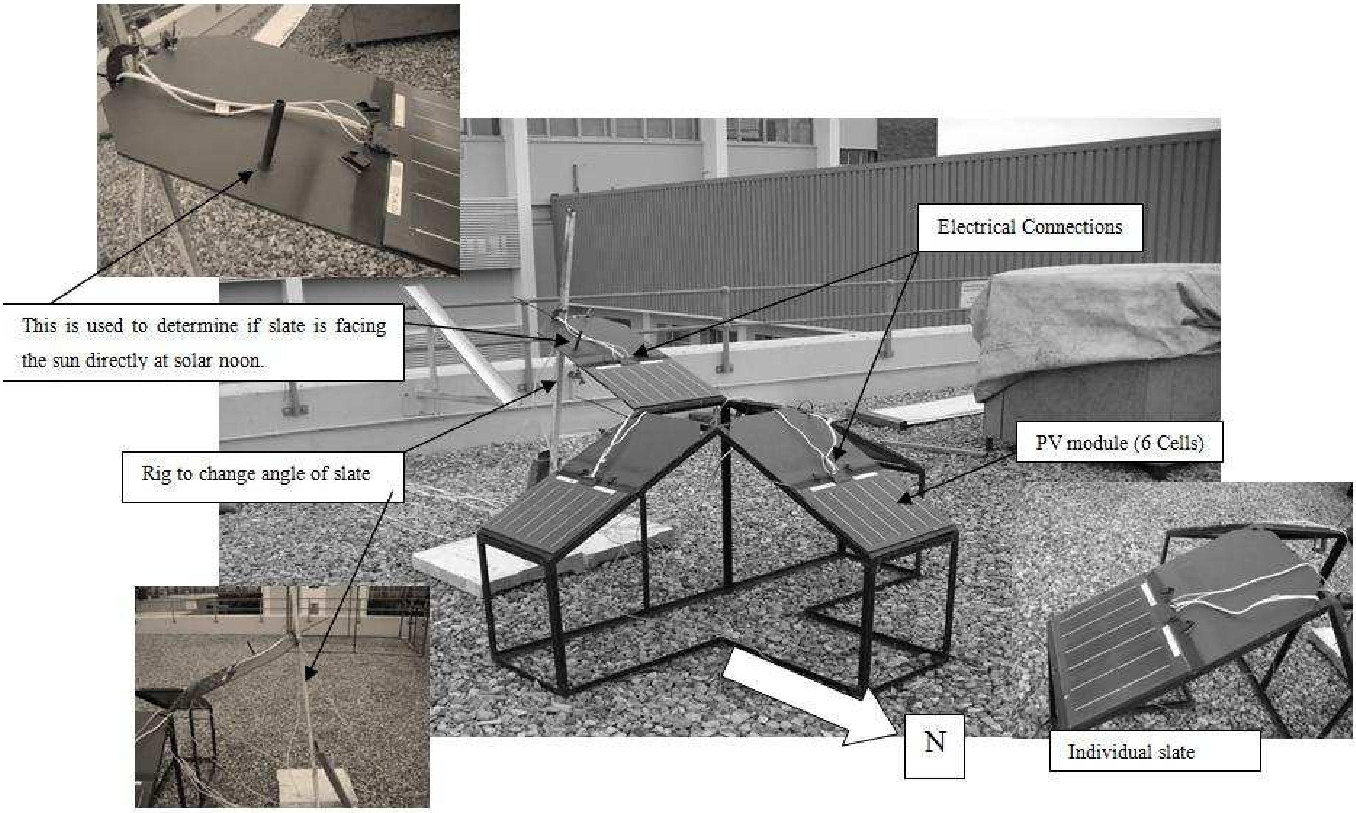


Figure 5-2 : Setup on the Solar Energy Test Facility Roof

Site

The frame was placed on the roof of the Mechanical Engineering building at the Solar Testing Facility. This area has limited to no shading which allows for solar research. The frame was placed so that the adjustable and the centre slate both face north. This resulted in the side slates facing east and west. Figure 5-2 is a picture of the framework with slates attached. The day the picture was taken was overcast and no shadows will be visible. The adjustable slate was initially set to 30 degrees, the same as the fixed slate.

All data processing and measurements was done in the lab directly below the setup. This was done by connecting everything on the roof trough a hole in the roof to the lab.

The following pictures illustrate the area where the system was placed.

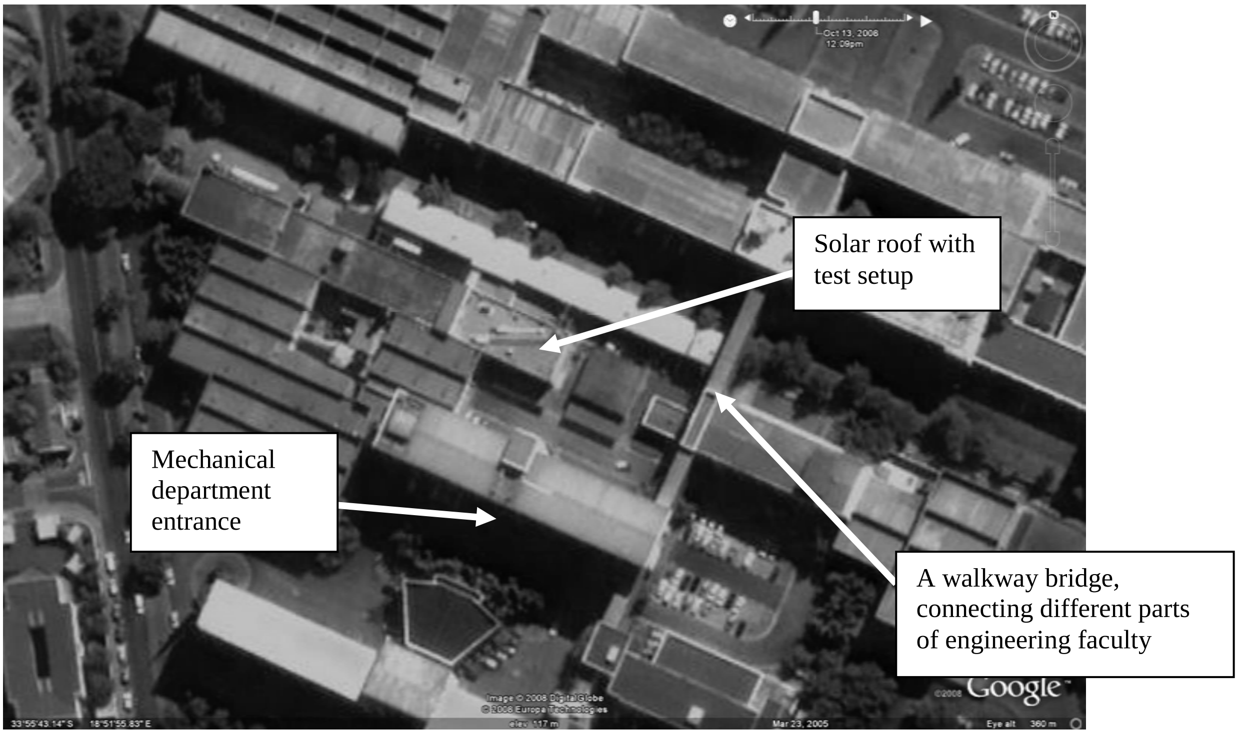


Figure 5-3: Engineering faculty seen from GoogleEarth at 360m

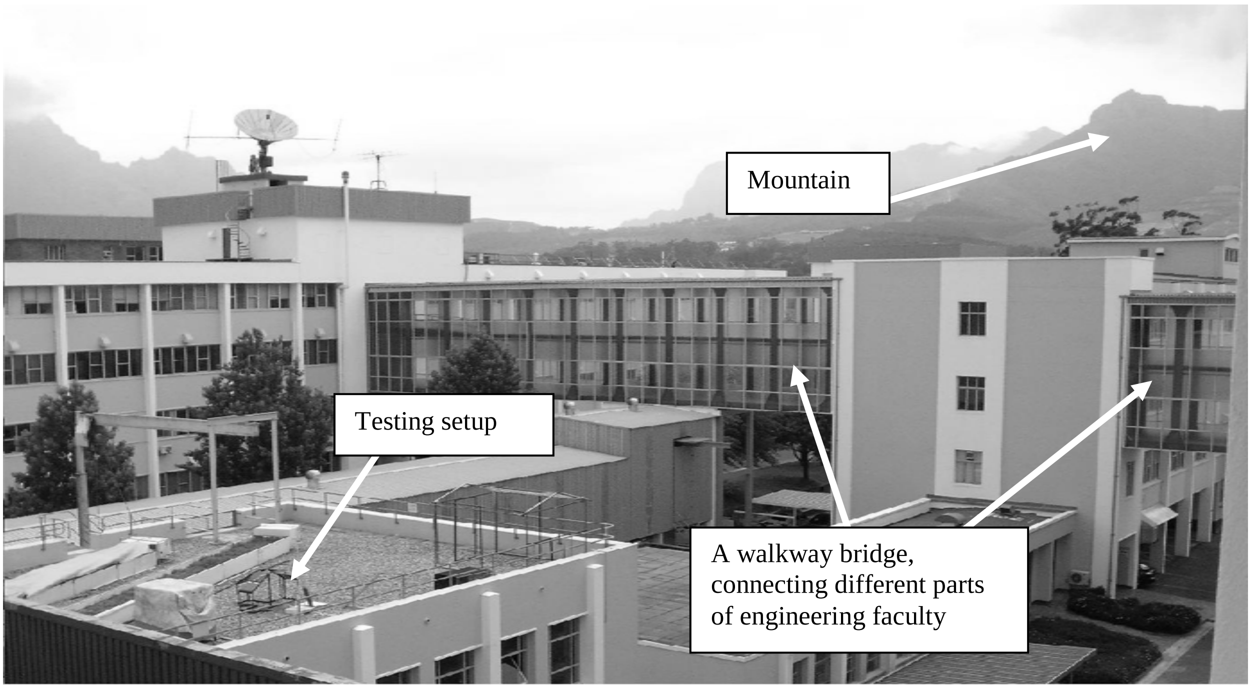


Figure 5-4: Panoramic view of setup

Electronic design

To obtain the most accurate results a maximum power point tracker was designed and built using an electronic circuit connected to an analogue to digital converter (A/D) and a computer. The computer was used to do the data processing and determining the maximum power point (MPP). This process repeated every 5 minutes to ensure that the slates would operate at their maximum power point at all times.

Hardware

A circuit was designed which utilises a power transistor on a heat sink as a dynamic load. All the power of the slate was dissipated trough the transistor and the cables connecting the slate with circuit.

The slate voltage was measured directly from the slate to avoid voltages losses in the connecter cables. The cables where also selected to ensure that losses where minimum.

A current resistor (0.1 Ω) was placed in the power loop to determine the amount of current flowing in the system. This was measured by first amplifying the voltage over the current resistor with an op-amp with a gain factor of 9.3 (selected to be as close to 10 as possible).

The following is a schematic diagram of the circuit used to measure the current and voltage. This circuit is also used to maintain the maximum power point by charging the capacitor to the selected operating voltage and then discharging trough an op-amp designed to be a high-impedance input to the circuit, this allows the capacitor to maintain its charge for an indefinite period.

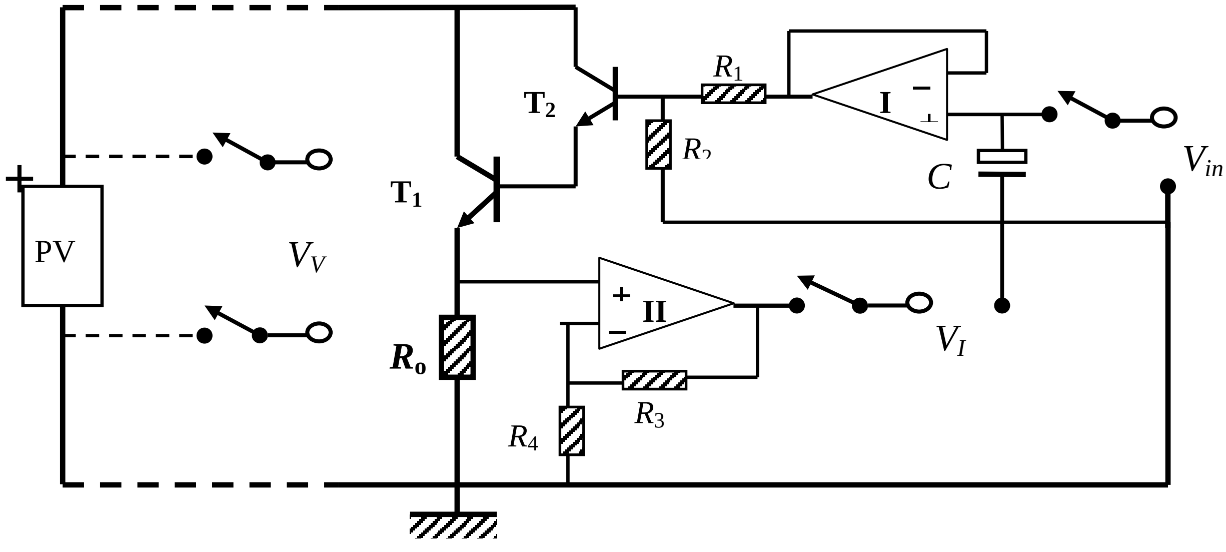


Figure 5-5: Schematic diagram of measuring circuit

R_1 and R_2 were used as a voltage divider. This was initially done to give the output of the A/D a larger range. In this project it was found however that the accuracy and range of the A/D was sufficient and R_1 and R_2 were not necessary.

R_3 and R_4 were selected to have a positive gain of 9.3. This was done to amplify the low voltage over the 0.1Ω resistor (R_0) in the current loop. This voltage is measured by the A/D and data logger and converted to a current measurement with software.

V_{in} determines the voltage delivered to the base of T_2. T_2 is used in a Darlington pair to deliver the base current which is required for full operation of T_1. By manipulating V_{in} the amount of power dissipated by the transistor (T_1) can be varied. By sweeping V_{in} the maximum power point can be determined by measurements of V_v and V_I.

The capacitor (C) was used to sustain V_{in} while the A/D was sweeping trough the other circuits or in between the 5 minute intervals of MPP detection. The size of C was selected in such a way that it would discharge trough the A/D as soon as the A/D closes the relay switch, so that the capacitor would not affect the MPP measurements. The capacitance was chosen to be 1000µF.

Four identical circuits were built to connect each of the mounted SunSlates™. Due to the limit of output and input channels from the A/D, switches where used to optimise the use of the A/D converter. Using 5V relay switches and switching them with the digital output all four circuits could be connected to the computer.

V_v was connected to channel 0 (Pin 1 and 2) of the A/D converter, V_I to channel 1 (Pin 4 and 5, with 5 to ground) and V_{in} to OUT 0 (pin 13).

The A/D converter used was a product of Measurement computing called USB-1208LS, this A/D converter connects to the computer via USB and has 4-differential inputs or 8 single-ended inputs, but only 2 analogue outputs.

The following are pictures of the built circuit and the A/D converter from the datasheet.

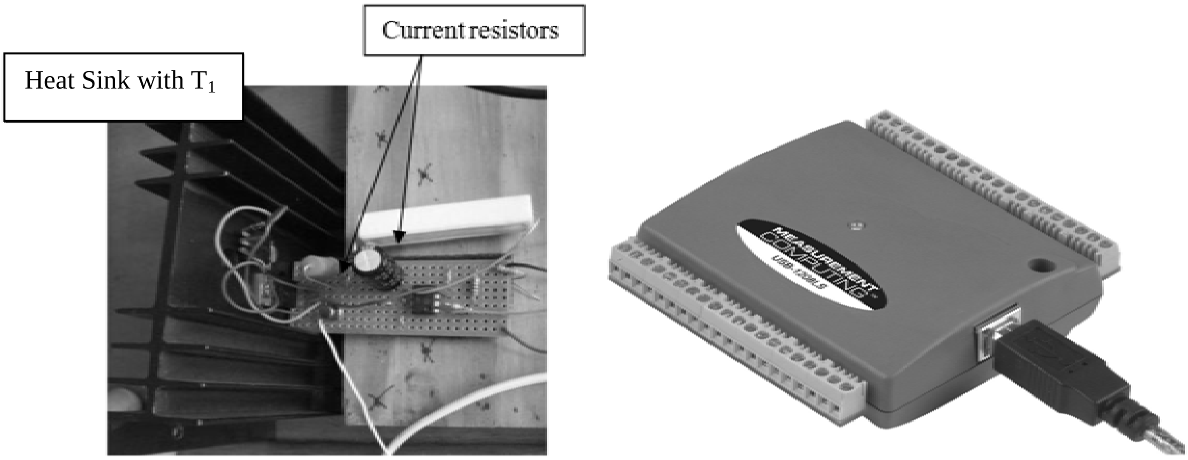


Figure 5-6: A/D converter and built circuit for MPP tracking

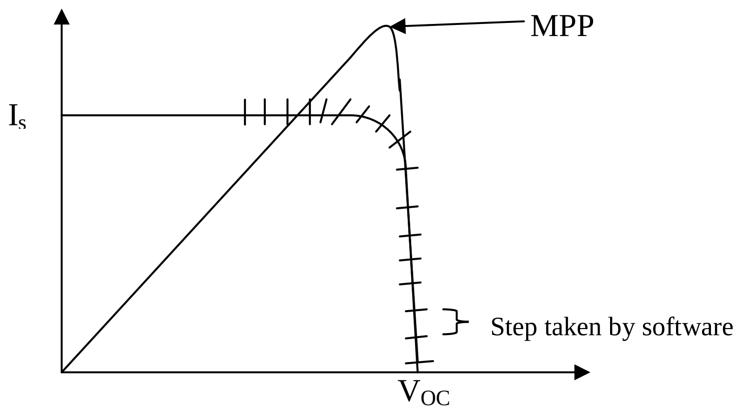
Software

MATLab with its data acquisition toolbox was used to communicate with the A/D converter. A program was set up to determine the MPP every 5 minutes. This was done by setting V_{in} to 0 and measuring the PV voltage and current through the use of the circuit. V_{in} was swept between 1V and 2.5V, the operating range for the transistors. At less than 1V the open-circuit voltage of the slate was measured as no current flows through the transistor and at over 2.5V the transistor would be fully on and the current (almost equal to the short-circuit current) would flow trough the current resistor.

From this sweep the maximum power point would be determined by multiplying the true current with the measured PV voltage. V_{in} would be saved in a variable as soon as the maximum power point was detected. This value of V_{in} was set on the capacitor to keep the slate operating at MPP until the next sweep.

The measured power, PV voltage and current was saved in an excel sheet for later use.

The concept of the program is illustrated in the following figure:



With every step the program takes, it determines the power delivered by the slate for the step. As the steps proceed the consequent power is determined until a maximum power point is determined.

Figure 5-7: Figure illustrating the concept of the MATLAB program

The following is the block diagram of how the software functions:

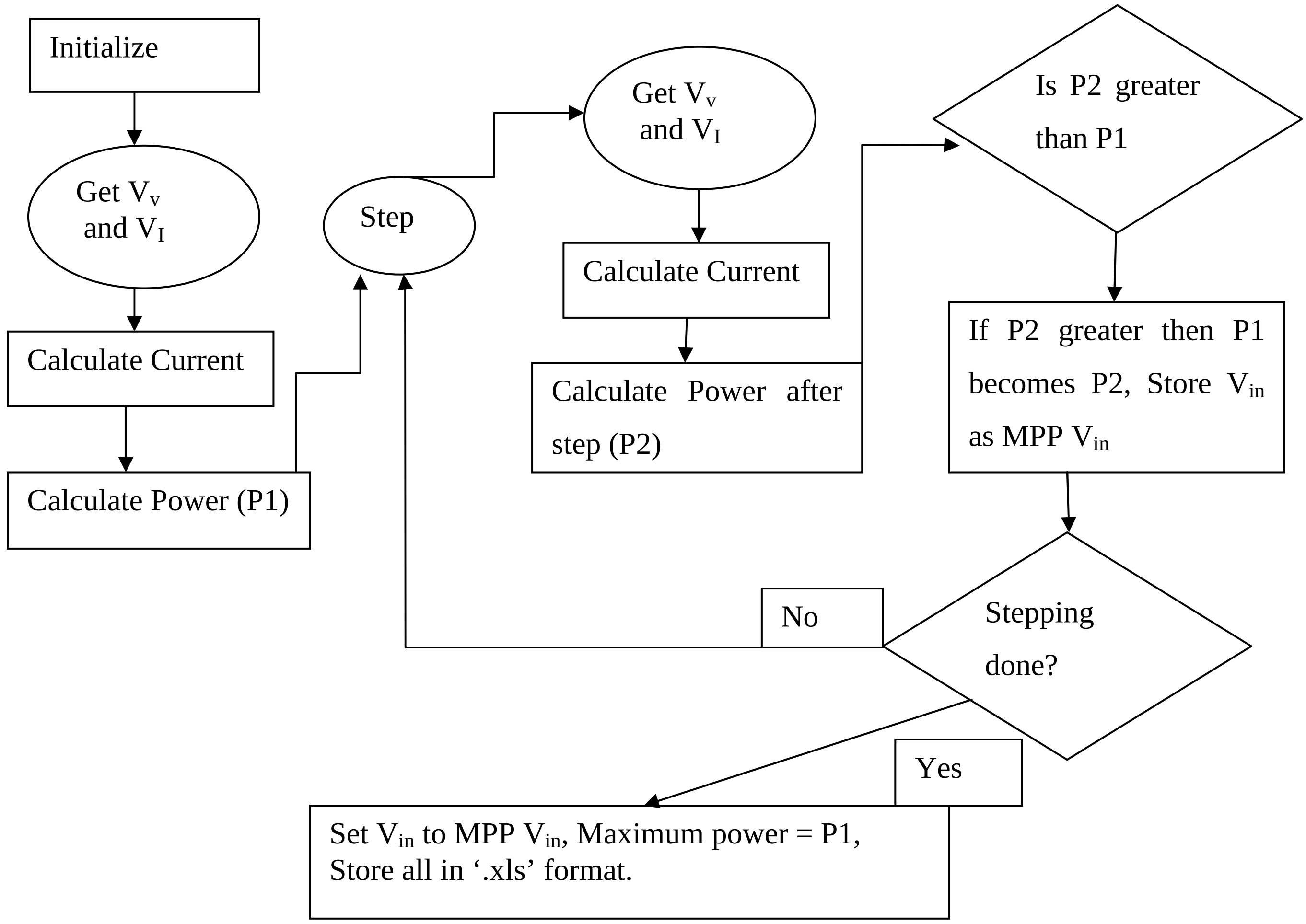


Figure 5-8: Block diagram of how the software functions

Measuring instrumentation

The temperature of the four slates were measured individually. The temperature probes (type K thermocouples) were placed between the PV module and the back panel of the slate to accurately determine the cell temperatures. A temperature probe was also placed in the shade under the north facing slate to determine the ambient temperature in the specific environment of the setup. The temperature probes, PV voltage and the current measurement were connected to an Agilant Data Logger. This used 14 of the 16 available channels. The data was logged, by the data logger, on 10 minute intervals, where as the software sweeps for the MPP every 5 minutes. The data from the data logger was used to determine the temperature of the slate and the power delivered at 10 minute intervals.

Due to the MPPT the power measured by the data logger will always be a maximum for the given time. The power measured from the data logger can be used to calculate the energy generated by the slate. The energy of a slate can be determined by integrating the P(t) curve over time.

The climatic conditions of the Solar Testing Facility were measured by a weather station set up on the roof. This weather station is connected to a Davis Vantage PRO console and data logger. The solar insolation and daytime temperatures where measured at 10 minute intervals to correspond to the data taken by the Agilent Data Logger. The data from the data logger was saved on a computer in the Solar Energy Laboratory and also uploaded to an internet site.

The weather station data is also available online at: http://students.ee.sun.ac.za/~weather/

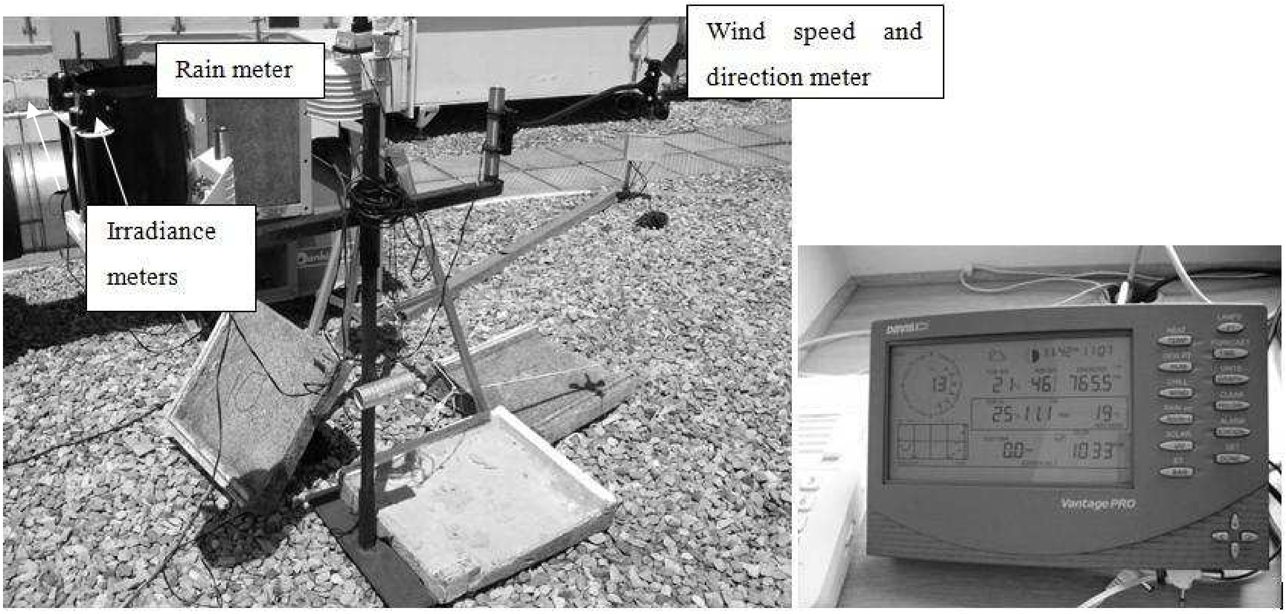


Figure 5-9: Weather Station and Davis Vantage PRO console

6 Results

The slate

The slate used was manufactured by Atlantis energy systems and uses mono-crystalline silicon cells manufactured by Q-Cells. The manual obtained from Atlantis Energy System does not contain any I-V characteristics and does not list the model name under the parameters given. Thus the manual is not strictly compatible with the slates received from Atlantis energy systems.

The cell type used is the Q5M150. Six cells are used in the manufacturing of the slates. Datasheets for the specific cells could not be obtained. This type of cell is no longer manufactured by Q-Cells and little information is available about the characteristics of this cell.

SunSlate™ Specifications as given on the Slate:

Table 6-1: Summary of Slate Specifications

Slate Length	72cm
Slate width	40cm
PV glass covered area	30cm by 40cm
Total PV area	$0.09m^2$
Cell efficiency	±15.5%
Voltage and current rated at STC	
V_{oc}	3.7V
I_{sc}	5.07A
V_{mpp}	2.96V
I_{mpp}	4.89A
P_{mpp}	14W ± 10%

Measured Data

Large amounts of raw data were obtained. This data was logged by the Agilant Data Logger, the software coupled to the A/D and the Davis Vantage Pro console and weather link. The data was stored on 10 minute intervals. The data obtained were panel voltage and current, the panel temperature, solar insolation, wind speed and ambient temperature.

Power and energy differences between MPPT and fixed load

Two different slate connections where investigated. The first was to connect the slate directly to a fixed load, setup in such a way that maximum power from the panel was obtained during noon. The other was to connect the slate to a MPPT to keep the slate functioning at maximum power throughout the day.

The following results where obtained. The results where measured on the 16th of October and the 16th of November. The power was normalised to STC, this was done by using the linear relation between power and insolation. Only the north facing panel was investigated.

Power from North facing slate:

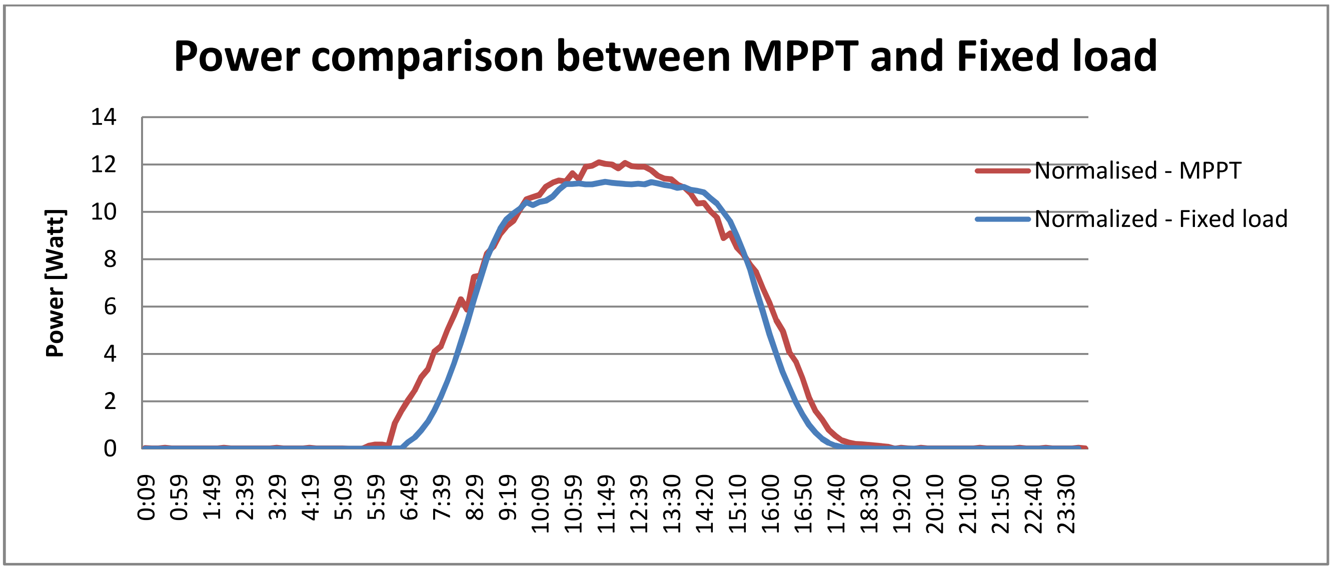


Figure 6-1: Power comparison between MPPT and Fixed load

Power output at noon:	MPPT panel	: 12W
	Fixed load	: 11.2W
	Difference	: 0.8W
Daily energy:	MPPT panel	: 91Wh
	Fixed load	: 83 Wh
	Difference	: 8 Wh (9%)

The difference between MPPT and fixed load is quite small for a slate with a low power rating (Under 50W).

Effect of orientation on temperature

From the data the effect of orientation can be obtained.

Data from the 16th of September, 16th of October and 16th of November are used: 16th September ambient temperature, wind speed and insolation levels:

Data obtained on the 16th of September:

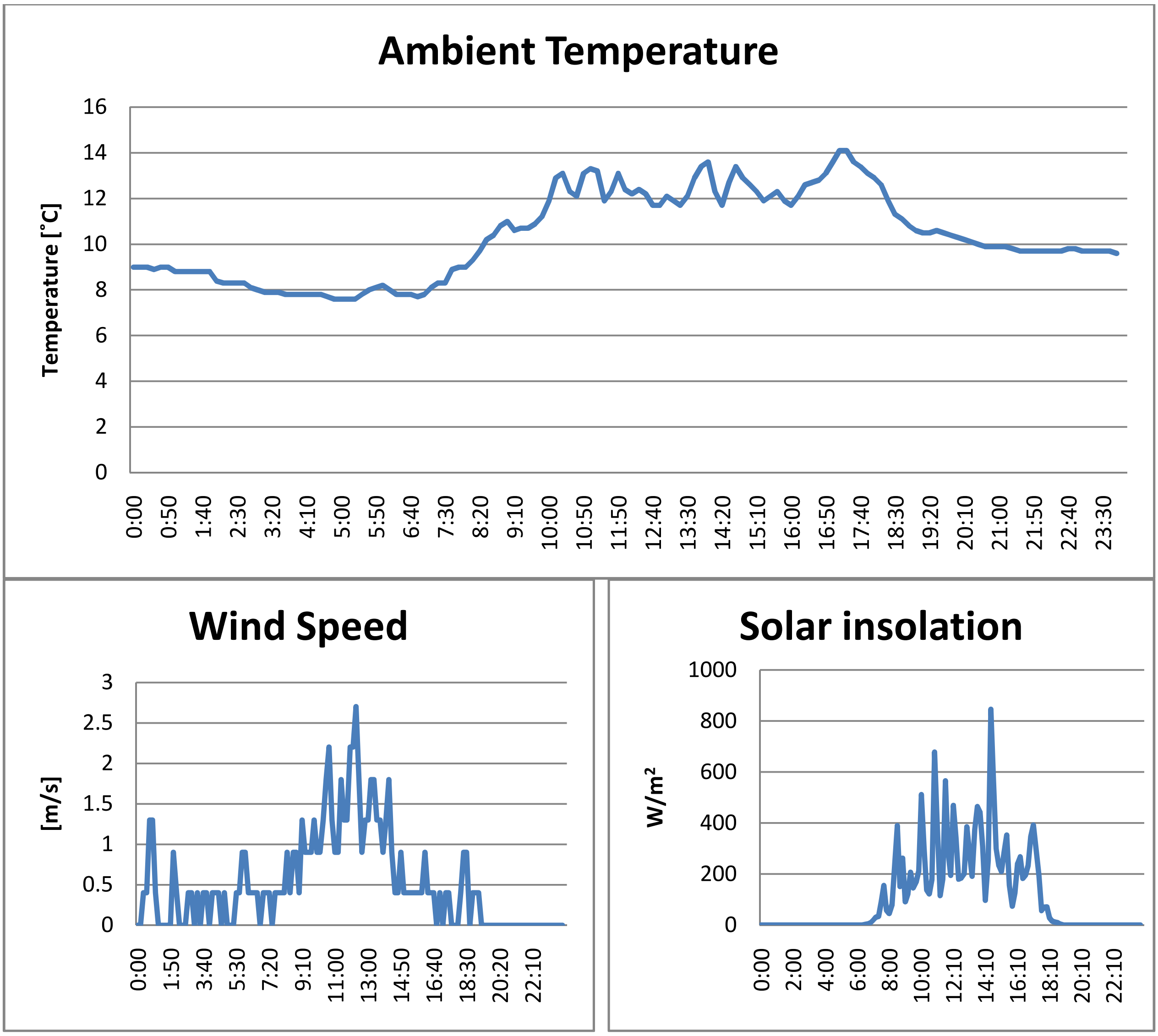
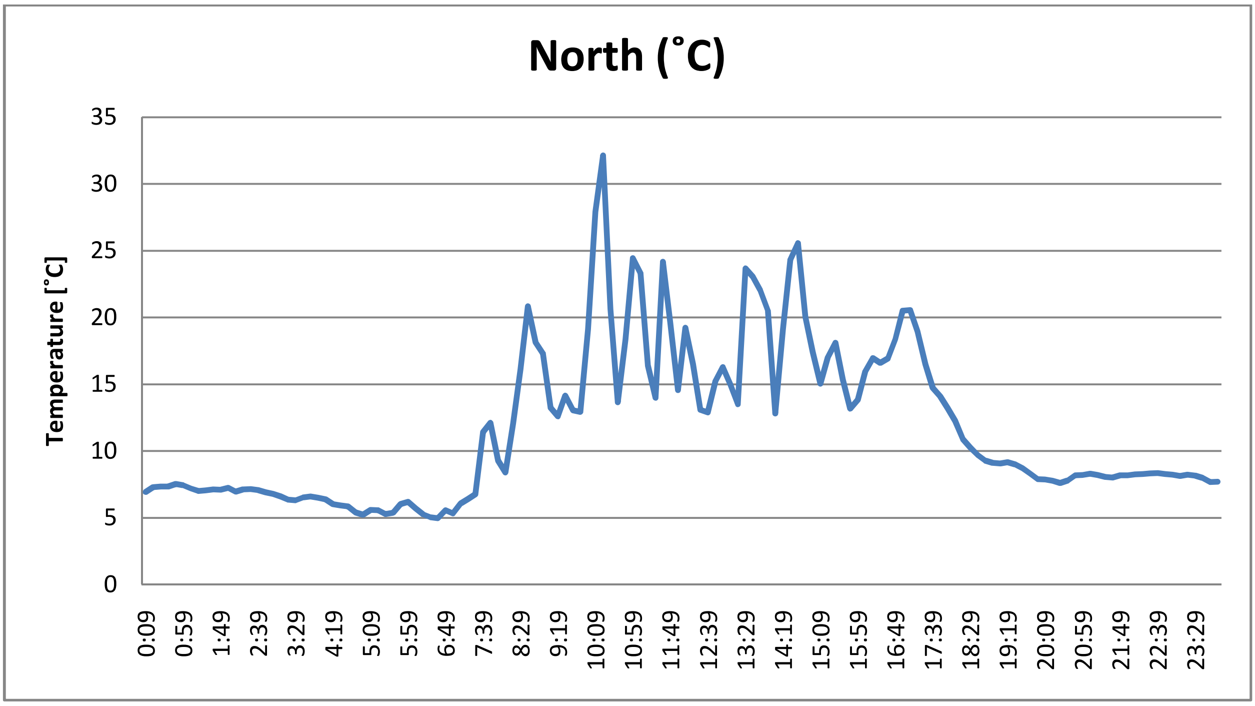


Figure 6-2: Temperature, wind speed and solar insolation of the 16th of September

From this weather data one can see that the 16th of September was a particular cold day with a cloudy sky and some wind. This is ideal to see how the SunSlates™ react on such days.



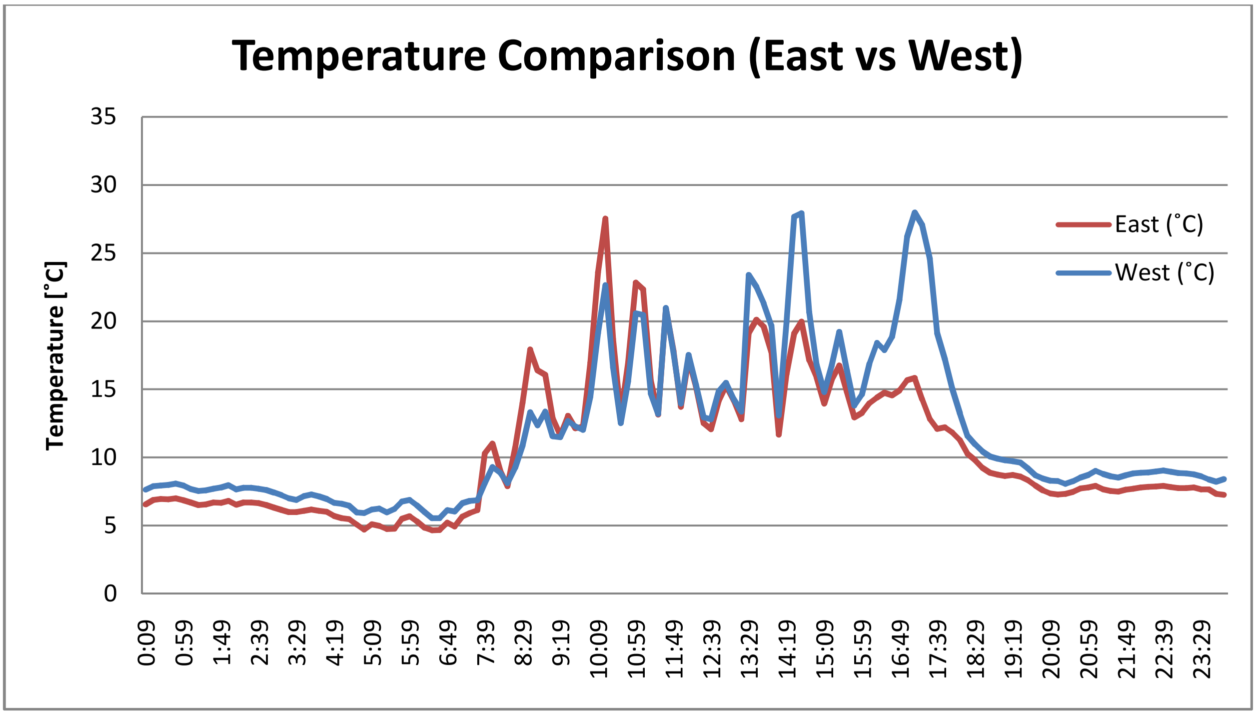


Figure 6-3 Temperature comparison between east and west orientations 16th September

These results indicate that even on a cloudy and cold day the temperature profiles of the Slates differ due to orientation. These results where obtained while the panels where connected to a fixed load and not operating at the MPP.

Data obtained 10th October:

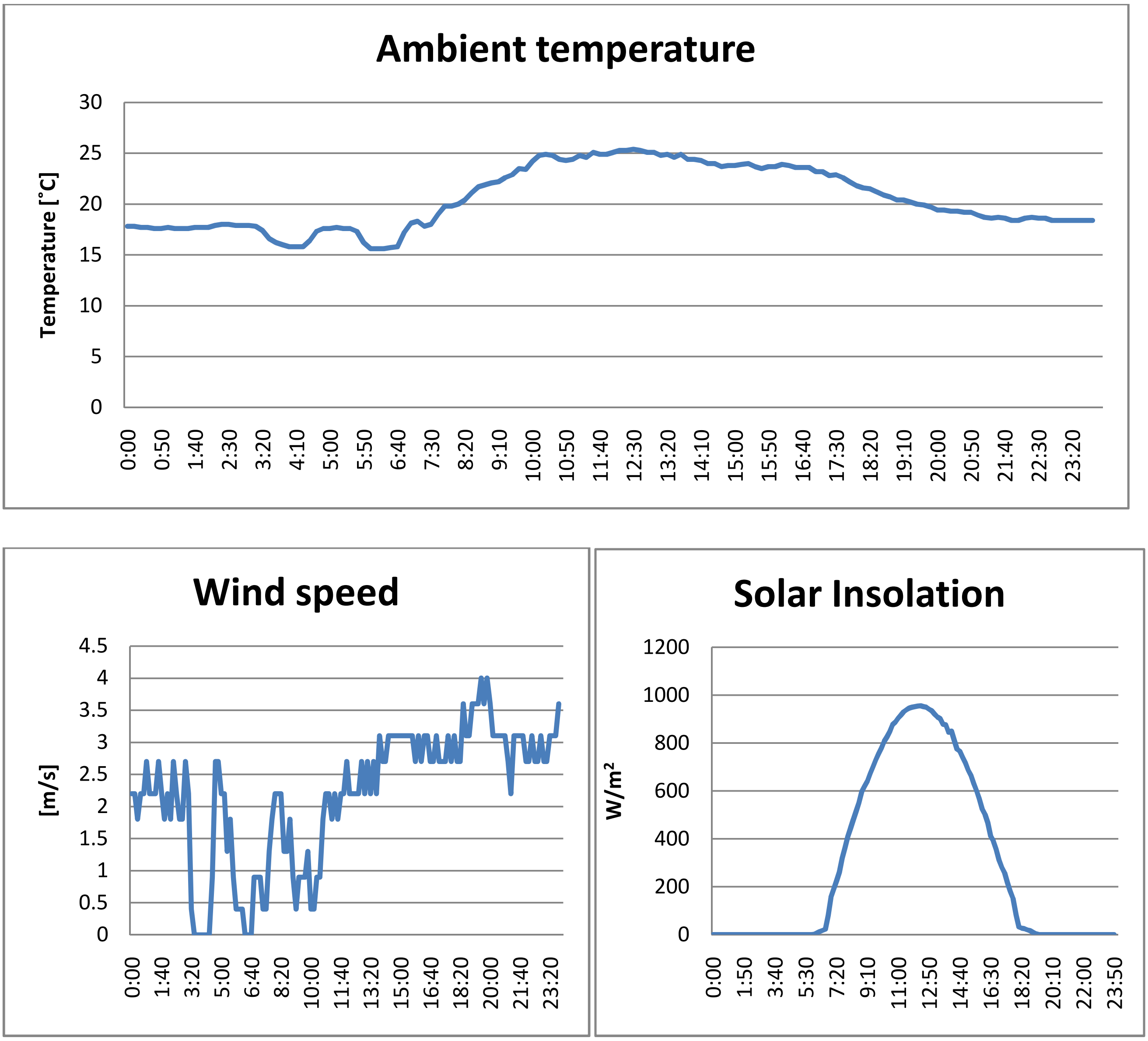
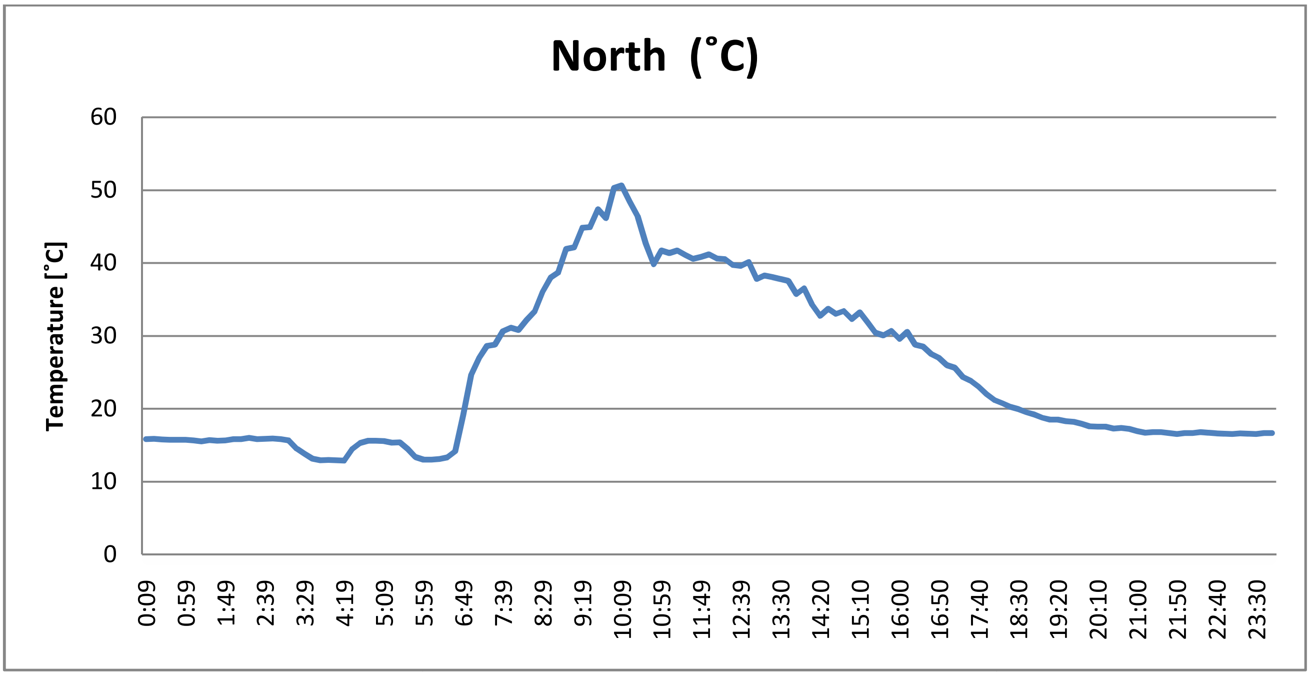


Figure 6-4: Temperature, wind speed and solar insolation of the 10th of October

From the weather data one can see that the 16th of October was a cloudless day with light to medium winds. The temperature profile and solar insolation profiles are typical for a cloudless October day.



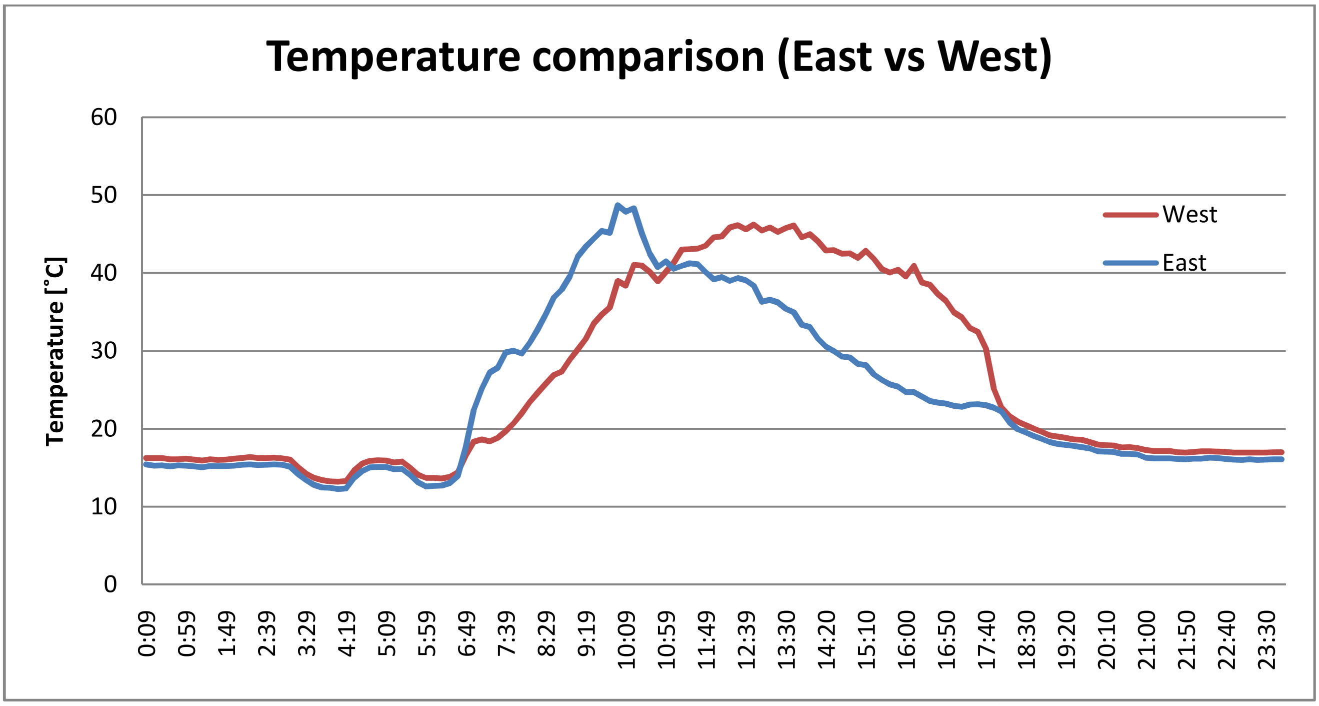


Figure 6-5: Temperature comparison between east and west orientations 10th of October

These results indicate that each slate has a distinct temperature profile due to the orientation. These results where obtained while the panels where connected to a fixed load and not operating at the MPP.

Data obtained 16th November:

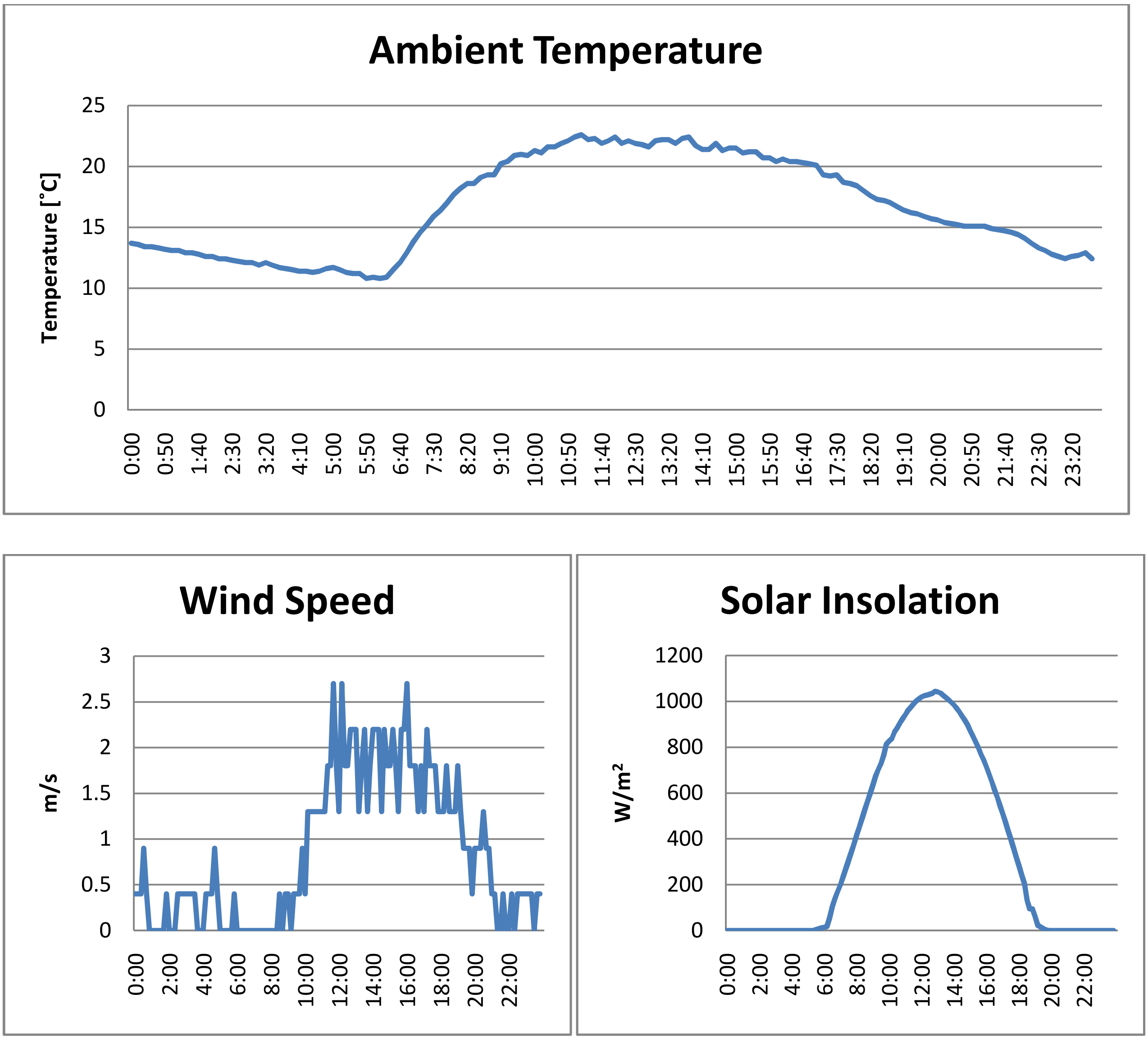
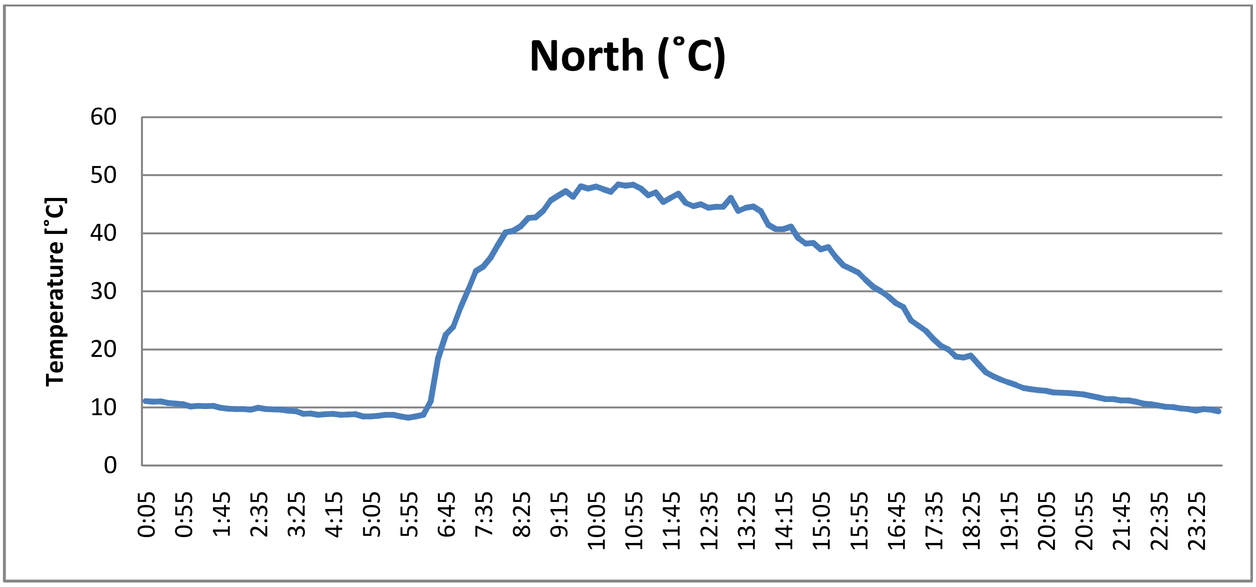


Figure 6-6: Temperature, wind speed and solar insolation of the 16th of November

This day is similar to the 16th of October, a cloudless day with some wind. The ambient temperature, however, was somewhat lower that that measured on the day in October, but the solar insolation was higher.



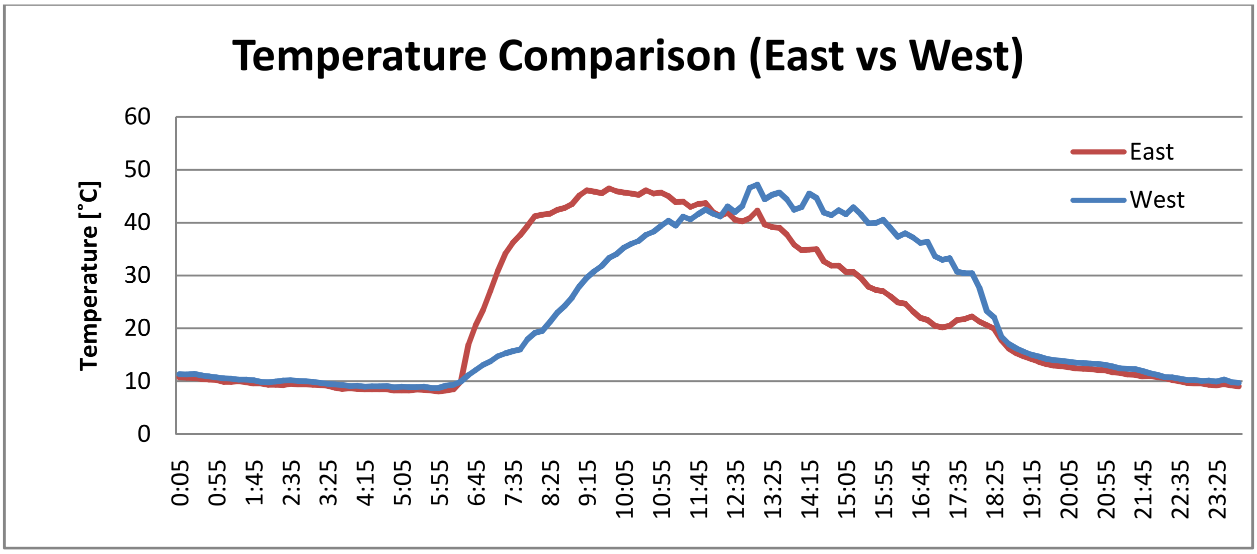


Figure 6-7: Temperature comparison between east and west orientations 16th of November

These profiles are similar to those on the 16th of October with some differences. The effect of solar insolation can be clearly seen on the increase of temperature.

From these measurements it can be seen that the maximum temperature of the North facing slate is about 5˚C higher than the east or west slates at their respective maximums. The maximum temperature for the north facing slate is 50˚C and the maximums for the east and west facing slates are 46˚C.

Effect of temperature on power output of panels

To investigate the effect of the temperature on the power output of the panels three consecutive days with the same insolation levels, but different day time temperatures were used. Only the north facing panel was used in this analysis.

The following is obtained from the Vantage Pro Console trough the Weather Link program:

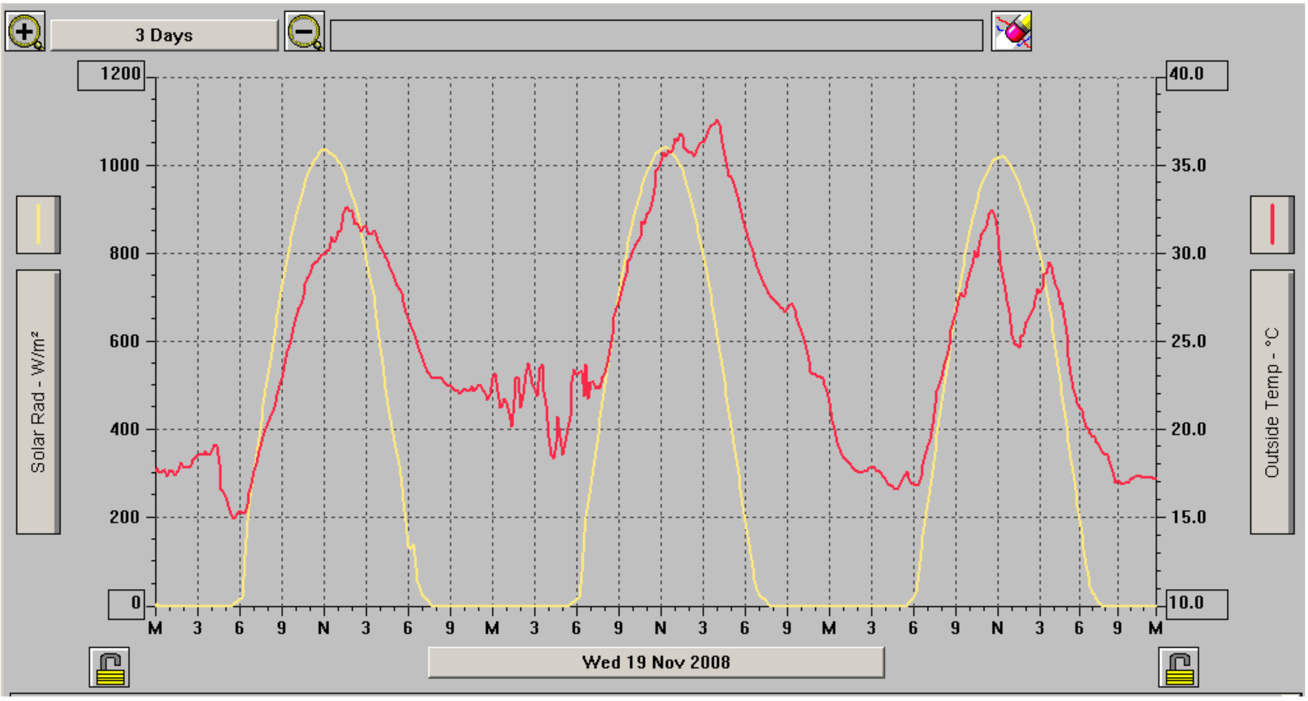


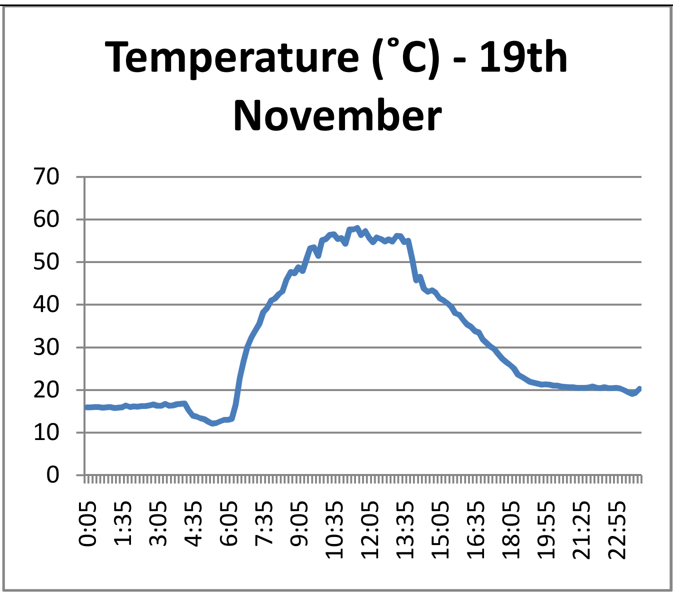
Figure 6-8: 3 Day Irradiance and ambient temperature data, begining 19th of November

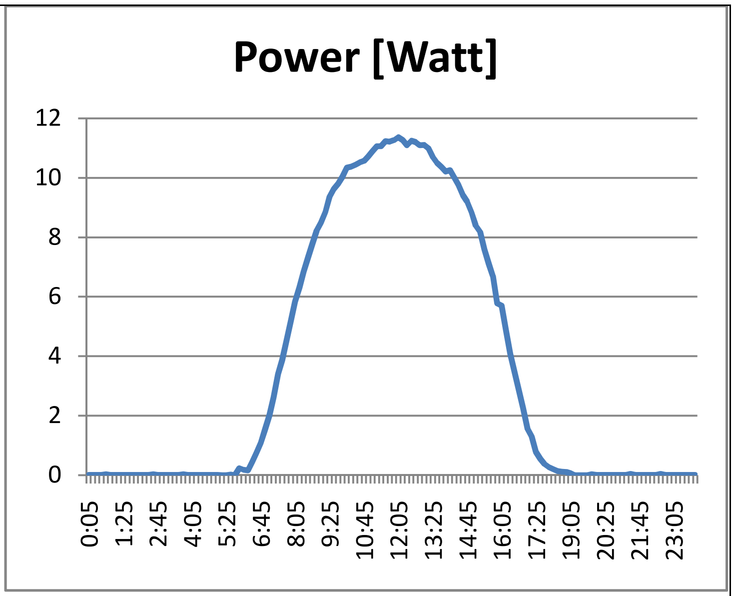
From figure 6-8 one can see that the 20th of November was a warmer day than the 19th or 21st of November, but the insolation is exactly the same as the other days.

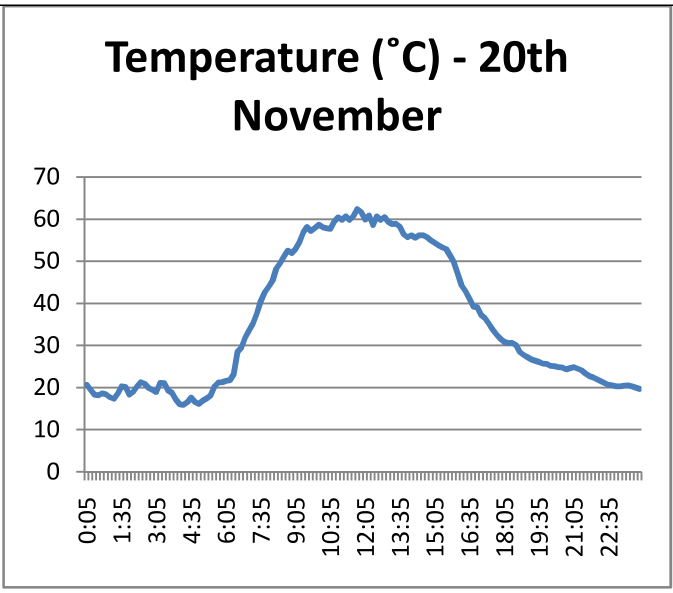
The change in temperature can be attributed to the wind speed.

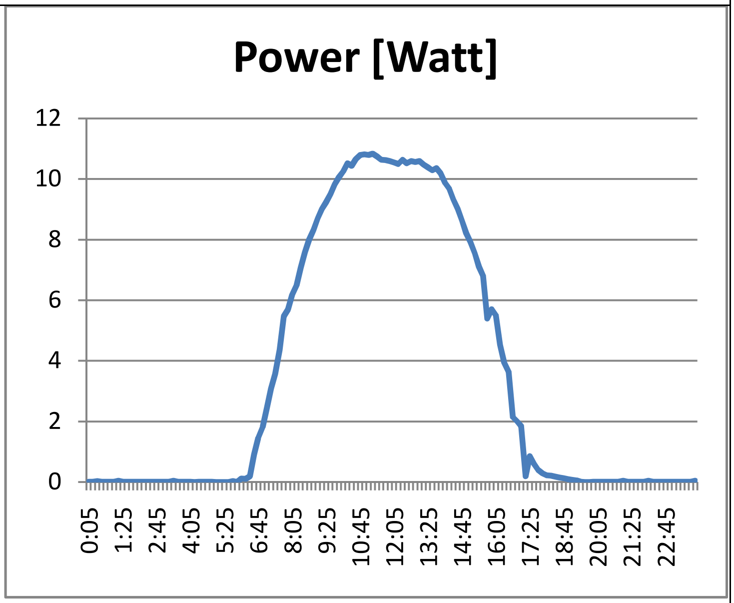
The temperature and power of the panel on the individual days is given in the following table:

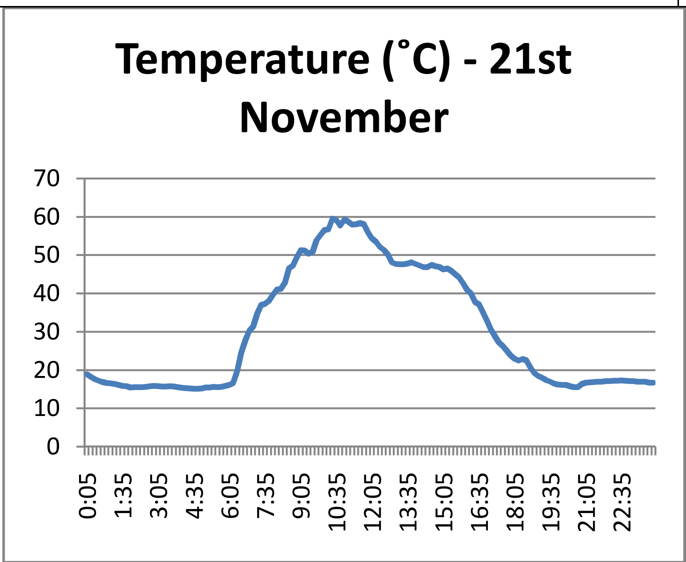
Table 6-2: 3 Day comparison between power and temperature

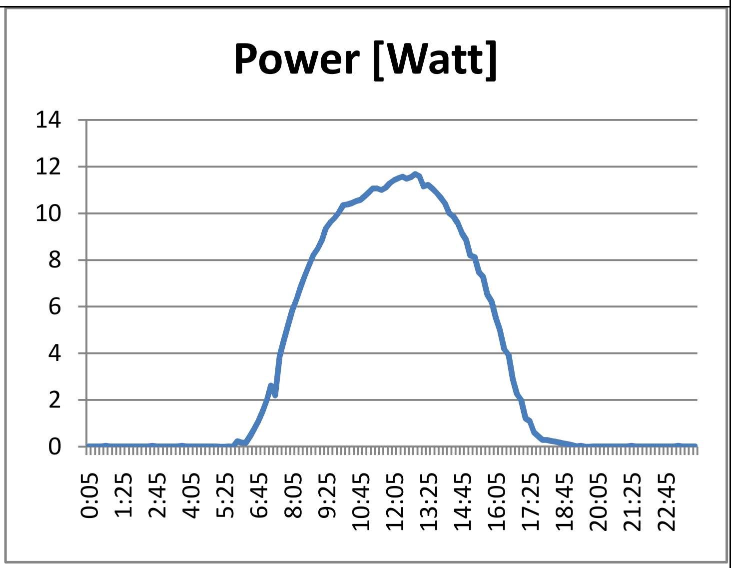












Summary of power delivered at 10am, 11am, 12pm, 1pm and 2pm

Table 6-3: Power delivered at different times and temperature

Time	**Slate Temperature (˚C)**			**Slate Power (Watt)**		
	19 Nov	**20 Nov**	**21 Nov**	**19 Nov**	**20 Nov**	**21 Nov**
10am	55.1	58.7	56.5	10.5	10.25	10.3
11am	54.3	59.8	58.6	11.05	10.7	10.8
12pm	55.7	59.9	54.3	11.36	10.5	11.4
1pm	54.8	59.3	47.6	11.11	10.6	11.5
2pm	45.7	56.1	47.2	10.26	9.87	10.4

Energy can be calculated by integrating the power delivered by the slate over the amount of sunshine hours in the specific day.

Energy for specific day: 19 Nov - 86 Wh

20 Nov - 83 Wh

21 Nov - 87 Wh

Difference in percentage between specific days:

Difference between 19th and 20th: 4.3%

Difference between 20th and 21st: 5%

From these results it can be concluded that the difference in temperature has an effect on the total energy output from the SunSlates™. This should be taken into consideration when designing a system.

The tiles can be kept cool by introducing some ventilation into the roof space, this can be done by adding vents to the roof space or a Whirly-bird.

Effect of orientation and tilt on power and energy output

Power delivered by North facing slates at different tilts, measured at solar noon with insolation of 1020W/m^2, on the 25th of November:

Table 6-4: Maximum power output at specified angles and predicted daily and annual energy output

Tilt	0	30	45	60	Optimal angle for November (15˚C)
Power	12.3W	12.2W	11.5W	10W	12.5W
Daily energy (predicted)	85Wh	93Wh	89Wh	79.8Wh	91Wh
Annual energy (predicted)	26.8kWh	29.1kWh	27.5kWh	25.8kWh	30.7kWh

The daily predicted values were obtained from the mathematical model developed in Chapter 4. The annual energy predictions were done by using NASA historical data by means of RETScreen.

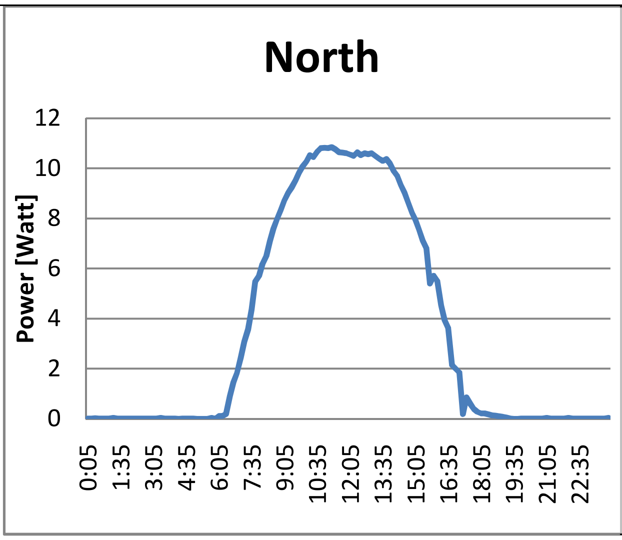
From this table of results it can be seen than a single-axis tracking system would benefit only slightly from following the seasonal path of the sun compared to a fixed tilted system of 30˚. The difference in predicted annual energy production between a system with single axis tracking and a fix mount of 30˚ tilt is about 1.6kWh or 5%.

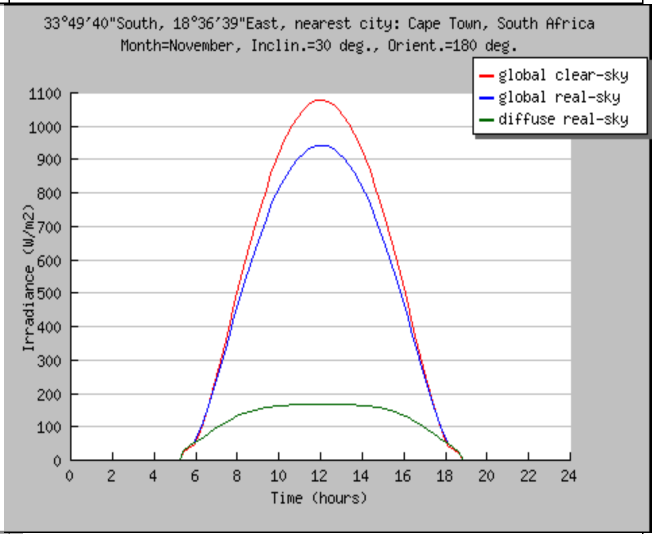
Even though the optimal angle slates have higher power output at noon, the total energy output per day, during the summer, is slightly lower than a 30˚ fixed angle system. The single-axis tracking will have a higher annual energy production.

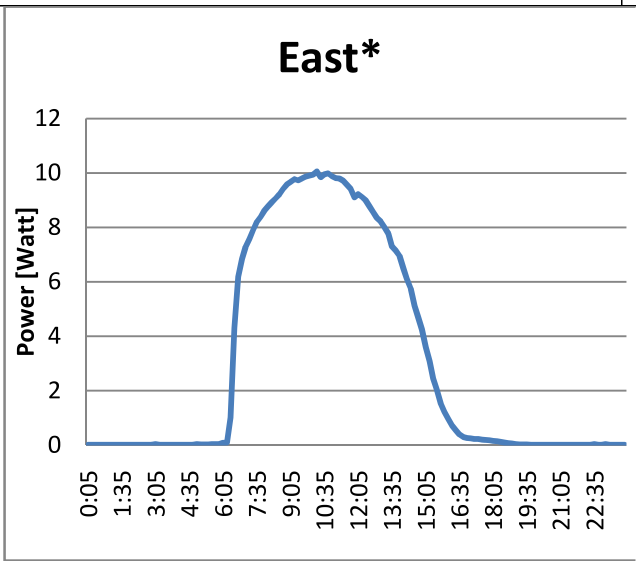
Differences in power delivered by differently orientated slates measured on 20th November are given in the following table:

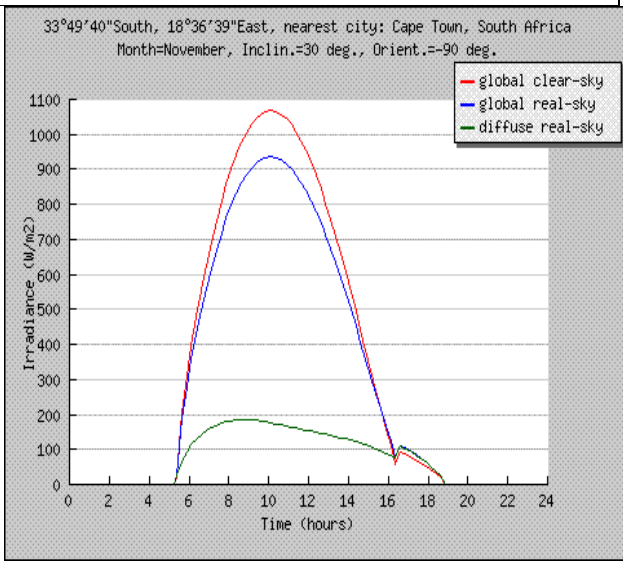
Table 6-5: Different power delivered due to orientation compared to predicted insolation on surface

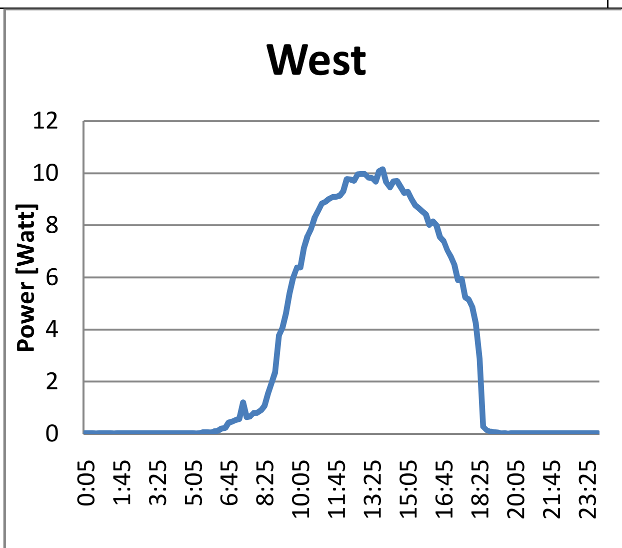
Measured Power on 20th November	Data obtained from: Photovoltaic Geographical Information System - Interactive Maps, (European Commission, Joint Research Centre, 2008)

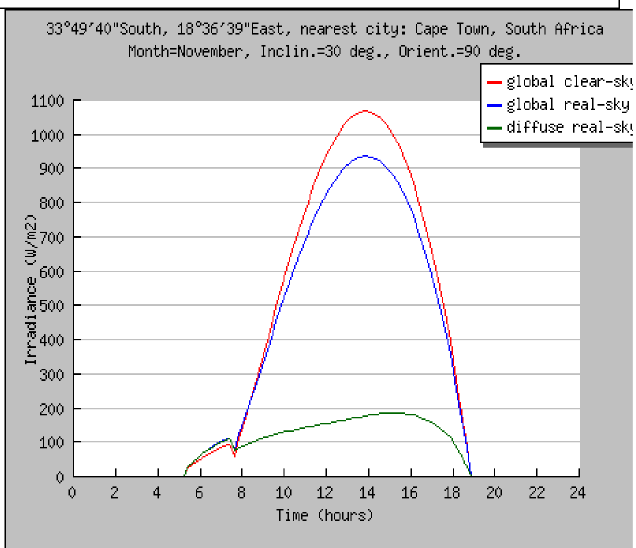












Total energy produced on specific day:

North	:	84 Wh
East	:	75 Wh
West	:	78 Wh

The placement of the system is so that additional reflected sunlight falls onto the panels. This part of the diffuse component is small enough to ignore for most of the day, the only small effect it has is on the early morning measurements.

*From the measurements obtained one can see that there is some shading in the morning. This shading can be attributed to the surroundings of the system setup. From physical inspection it was found that the difference between predicted insolation (from the PVGIS, (European Commission, Joint Research Centre, 2008)) and measured power output can be attributed to a mountain range due east from the system, as well as a walkway to the east. The mountain and the walkway has the effect of "delaying" the sunrise for 30 to 45 minutes and this affects the power curve of east facing slate. Figure 5-4 is picture of the setup. From the picture it can be seen that the walkway and mountain can obstruct the sun in the early mornings.

Using mathematical modelling with a temperature coefficient of -0.4 %/˚C and assuming the cell temperature to be 55˚C maximum the following predicted values are obtained:

West facing Slate, tilt 30˚, 25th November

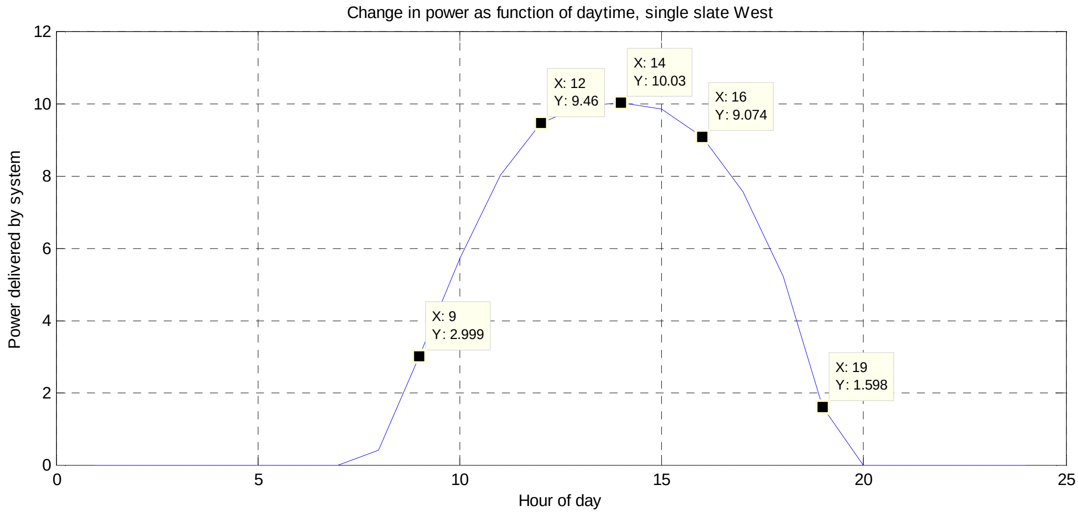


Figure 6-9: Predicted power from West facing slate

North Facing slate, tilt 30˚

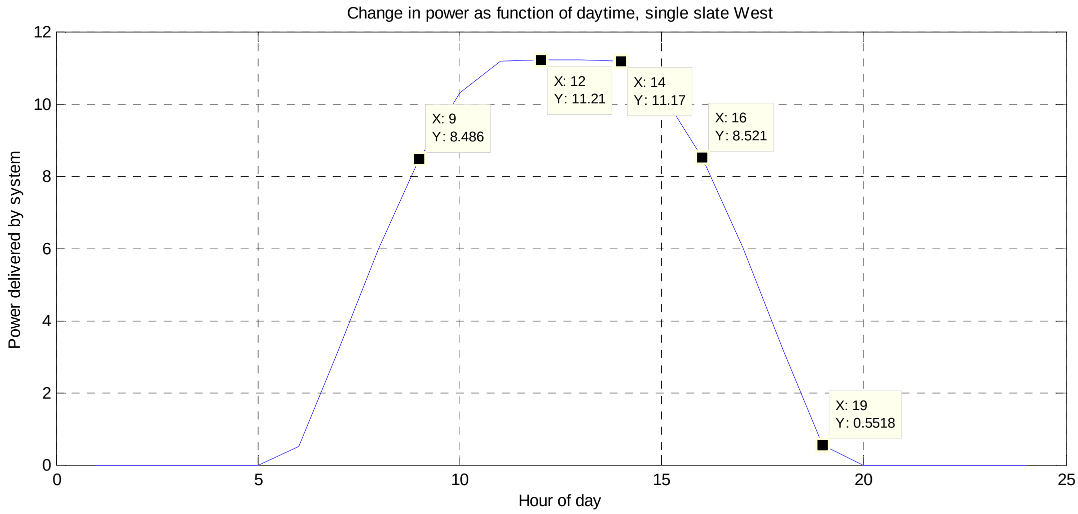


Figure 6-10: Predicted power from North facing slate

The following table compared the predicted energy with measured energy.

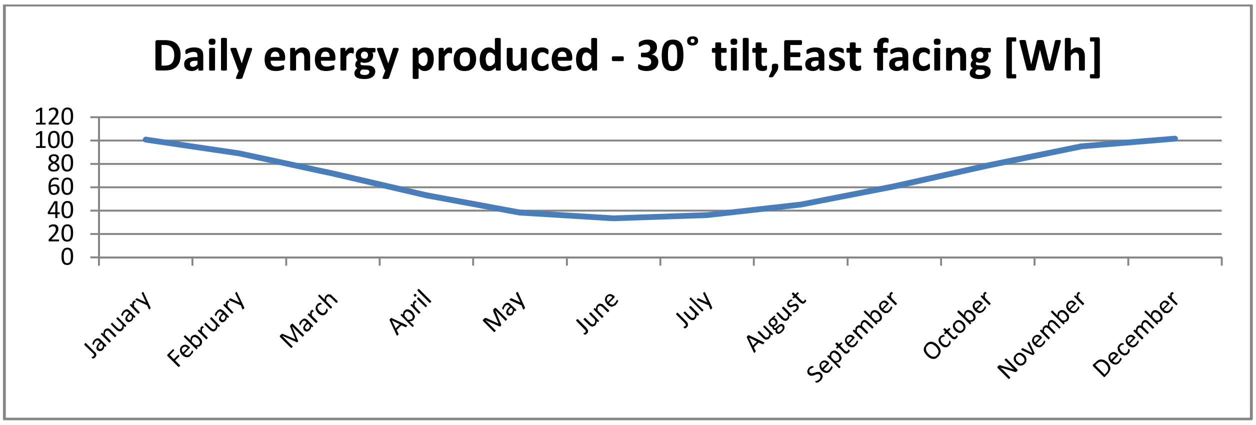
Table 6-6: Measured energy compared to predicted energy

Orientation	North	East	West
Measured Energy	84Wh	75Wh	78Wh
Predicted Energy	91Wh	79Wh	79Wh
Difference	7Wh	4Wh	1Wh

The difference between the measured data and the predicted data can be attributed to the following:

1) The difference in the North predicted and North measured is due to the temperature changes. The predicted value uses a temperature value of 55˚C. The temperature of the measured north facing slate can be as high as 60˚C and this would cause the difference in energy produced
2) The difference between East predicted and East measured can be attributed to the fact that the measured slate does not receive sunlight in the early morning, due to shading from a nearby walkway and a mountain due east from the test setup.

Annual energy prediction from historical data, taking into account slate PV area and efficiency, ***but not taking into account temperature variations***:



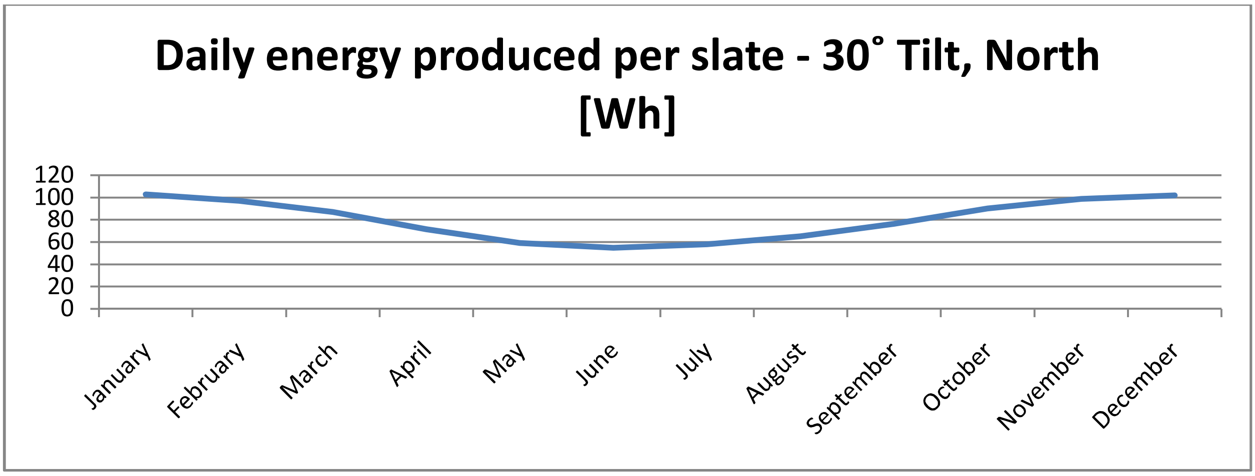


Figure 6-11: Annual energy predictions for a single slate

If temperature variations where taken into consideration the overall energy produced during the months of October to February would have been lower than what is predicted in Figure 6-10, 11.

7 Case Study

SunSlates™ in practice, a Lynedoch case study.

Introduction

It is widely known that South Africa is the midst of a power crisis. ESKOM can no longer supply peak demand at certain times of the day. Due to this scenario some South Africans have started to look into generating and supplying their own power in times of need.

Some of the generating options are renewable energy sources, like solar power and wind power. In South Africa, solar power is one of the most abundant sources of renewable energy, with South Africa having one of the highest annual insolation levels in the world.

With access to international markets South Africa has the potential to grow into one of the biggest photovoltaic users in the world. The growth in this market however will only become viable if the government introduces some form of incentive or if South Africa's traditionally low electricity costs increase to where PV can achieve grid parity.

Even though grid parity is presently far from being reached in South Africa the Lynedoch Sustainability Institute has decided to invest into some research into a BIPV system. The Sustainability Institute is part of a unique setup within South Africa. The Sustainability Institute forms part of a sustainable community/village built on rural land just outside Stellenbosch. The village is comprised of residential units as well as a school and a pre-school. The village and school are built up around a hotel, which now functions as a guest house.

All of the houses have solar water heating and use gas for cooking. The solar water heaters are paid off by the owners by paying a premium on their electricity until the price for the SWH's have been paid in full.

Currently most of the electricity is supplied by ESKOM trough a central 6kV feed line. The power is then locally distributed throughout the village. The village pays by means of pre-paid meters. The pre-paid electricity can be bought from the Body Corporate of the village and this is where the premium is added to the price.

Due to a local grid, the Sustainability Institute decided to experiment with a BIPV system. This system was installed on a part of the guest house roof and supplies electricity to the local grid. In the case of an ESKOM power outage this system will also automatically switch off to prevent 'islanding' from occurring.

Islanding is a term used to describe the effect when power is still available to a part of a distribution grid after it has been shut down for repairs. This happens if someone connected to this distribution grid supplies the grid with privately generated power.

The purpose of this experiment is to see if it will be possible to build up the generating capacity within the local grid, so that it might eventually stand independent from ESKOM and use ESKOM as a back-up supply.

Lynedoch SunSlate™ System Setup

Location and orientation

Lynedoch is located just outside Stellenbosch on the R310, about 9km. The geographic location is 33.98˚ South latitude by 18.76˚ East longitude. This is similar to that of Stellenbosch and most of the data applicable to Stellenbosch is also applicable to Lynedoch.

The site chosen to install the system is on the roof of the guest house. The roof is orientated in a North-West direction at almost 45˚. The roof itself has a tilt of ±35˚.

The following is a Google Earth™ image of the site.

Figure 7-1: Google Earth image of the sustainable village at Lynedoch

System Size and related costs

The size of the installed system is 1.7kW$_p$. This is equivalent to the output of 120 SunSlates™. The slates are connected in 2 series strings of 60 slates each and then connected to a SMA SunnyBoy inverter. This inverter is coupled to the local grid. The SMA inverter is of high quality and ensures that the power delivered matches the grid standards and also prevents islanding situations when the grid shuts down.

To install the SunSlates™ on the guest house roof, the roof had to be reinforced, as the weight of the slates are more than the weight of the corrugated iron roof which was installed. This added to the costs of the retrofit.

A summary of the costs:

Table 7-1: Summary of costs

120 SunSlates @ $102 (exchange $1 = R7.5)	R91 800
Retrofit Costs	R 5 000
Engineering and installation costs	R15 000
Inverter costs	R23 000
Total	**R134 800**

All costs are rounded for convenience with some estimation done and exchange rate of August 2007 used.

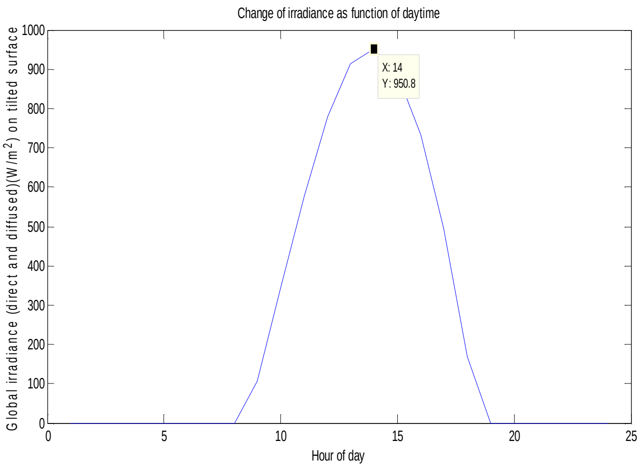
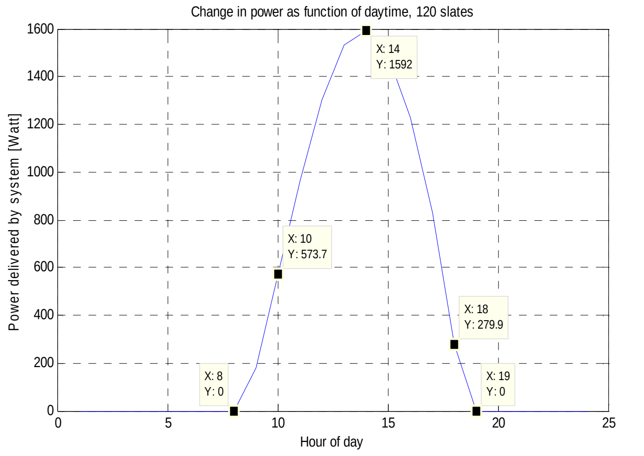
This relates to an installed cost of R80/W$_p$, which is higher than the average of R60/W$_p$

Predicted output from system

Using historical data from NREL and mathematical calculations, the performance of the system was predicted.

To estimate maximum performance capabilities three days have been chosen where with no cloud cover. The days chosen where 13 September, 10 October and 16 November. These days are relatively one month apart. The 13th of September was the 2nd day the system was online.

Table 7-2: Predicted daily performance of system

<table>
<tr><th>Predicted insolation on roof surface</th><th>Mean power in kWh delivered</th></tr>
<tr><td>
</td><td>
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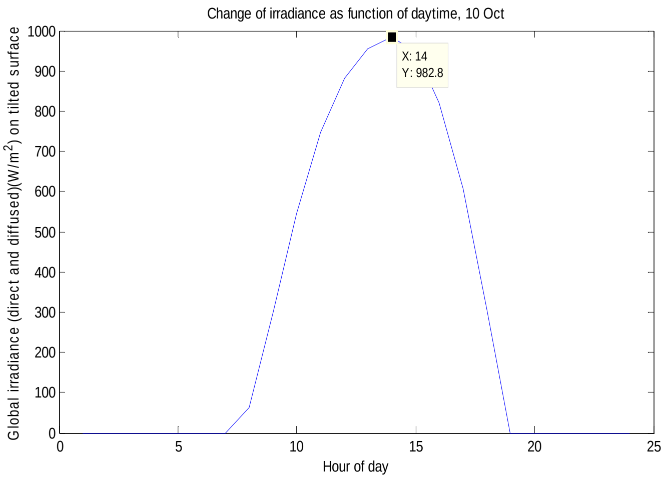
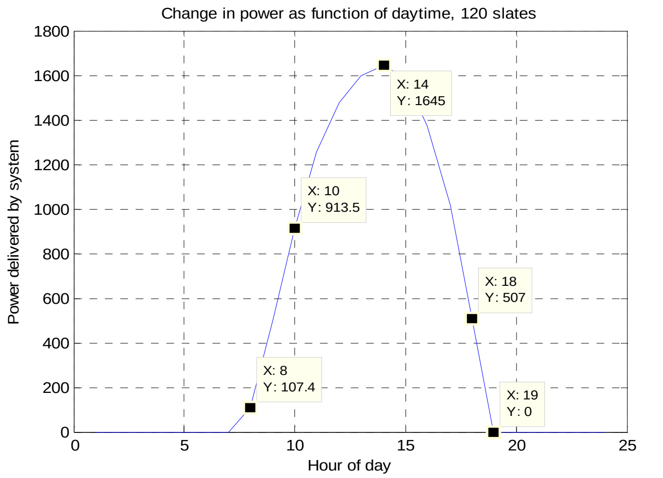
<tr><td>
</td><td>
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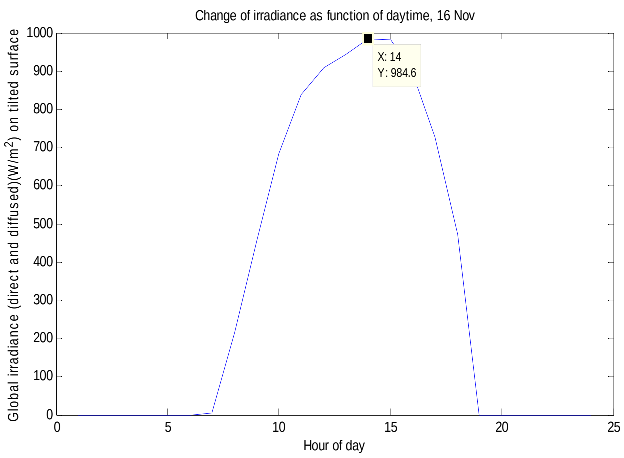
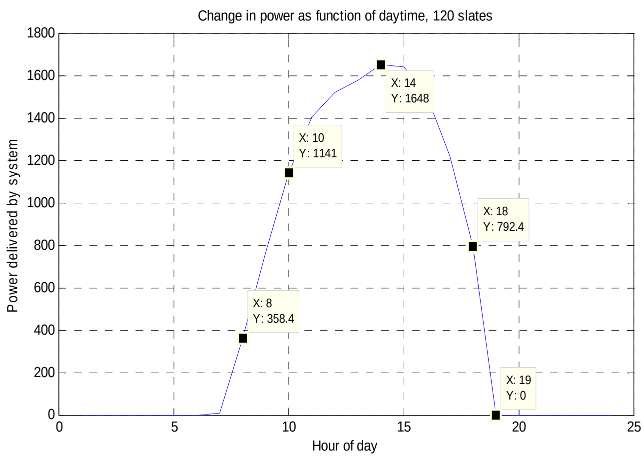
<tr><td>
</td><td>
</td></tr>
</table>

The total area used was 10.8m^2 and the cell efficiency was taken to be 15.5%. The energy was calculated by integrating the power delivered by the system over the available sunshine hours in the day.

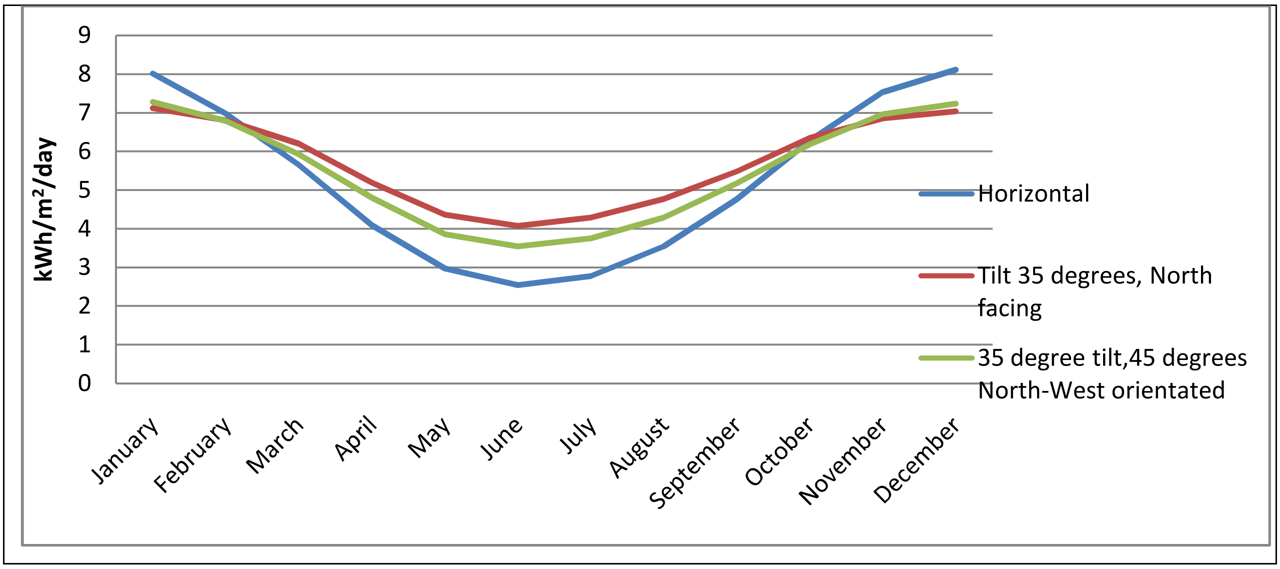
Predicted energy generated on the specific day:

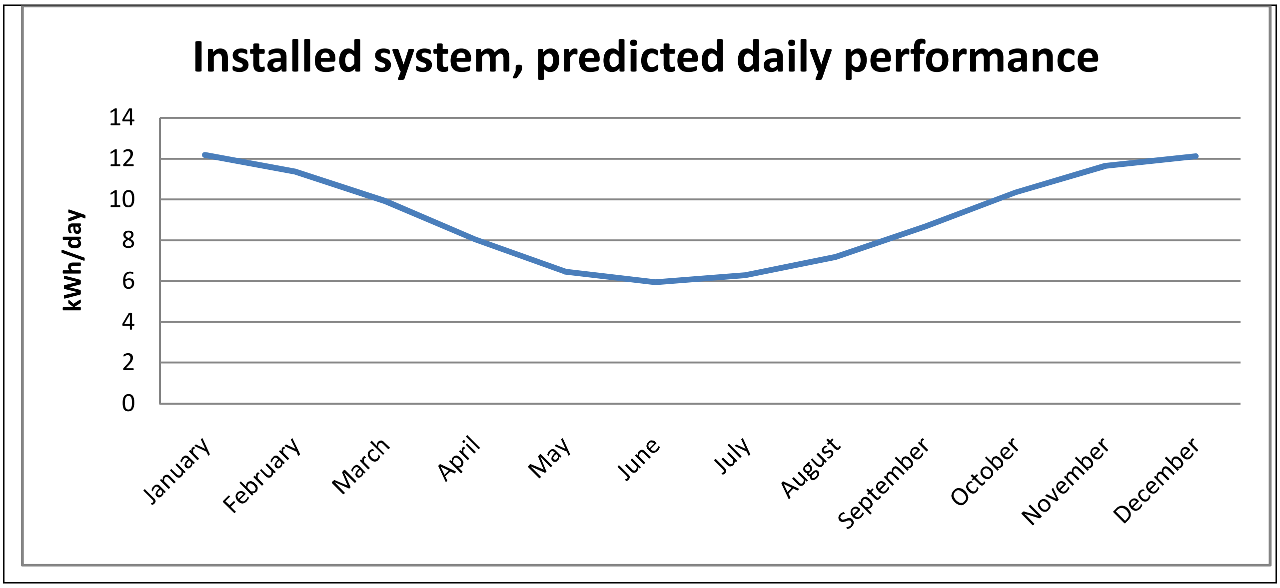
13 September	:	9.67 kWh
10 October	:	11.97 kWh
16 November	:	13.76 kWh

Using historical data to predict the annual energy production, the following where obtained:

The first graph indicates the average solar energy per day per square meter available on a tilted surface per day and the second is an estimation of the amount of electrical energy the system will generate given the historical data:

Table 7-3: Historical data of insolation on different surface and Predicted annual performance of system





From the historical data predictions it was found that the annual average energy produced by the system should be 3350kWh per year for the specific orientation and tilt.

The difference in energy produced between the 45˚ N-W orientation and direct north facing at a tilt of 35˚ is about 4% per year. A total energy increase of 134kWh per year can be achieved if the roof where to face north.

The historical data used was obtained from RETScreen. This data uses information from a NASA historical database. The difference between daily insolation levels from the historical data and from the specific day predicted values is due to the weather effects included in the historical data.

The predicted data is only valid for cloudless days.

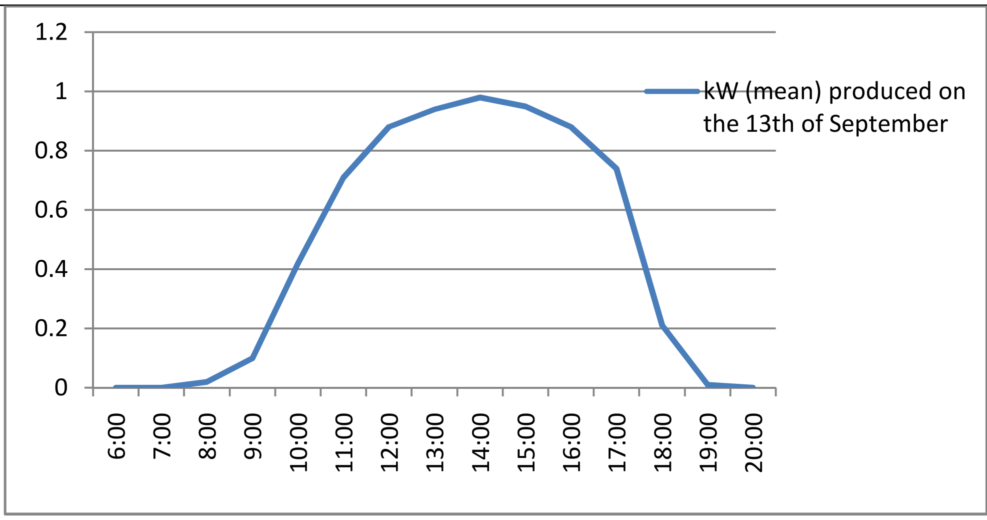
Measured system performance

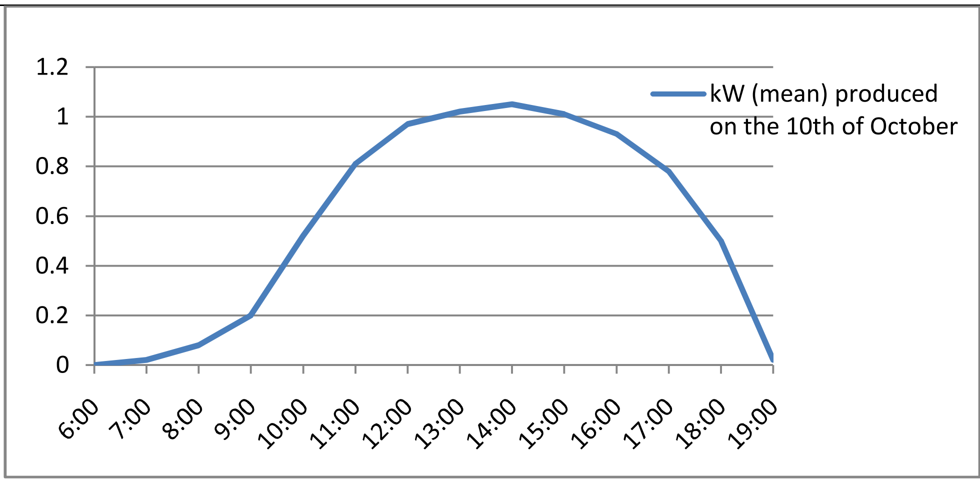
Practical performance data was obtained from an installed SunnyBoy Web Box. This web box logs the mean hourly data from the SunnyBoy inverter. Some of the data can presently be obtained from: http://www.sieckmann.biz/content/ProjectsSustanabilityInstituteReports.html

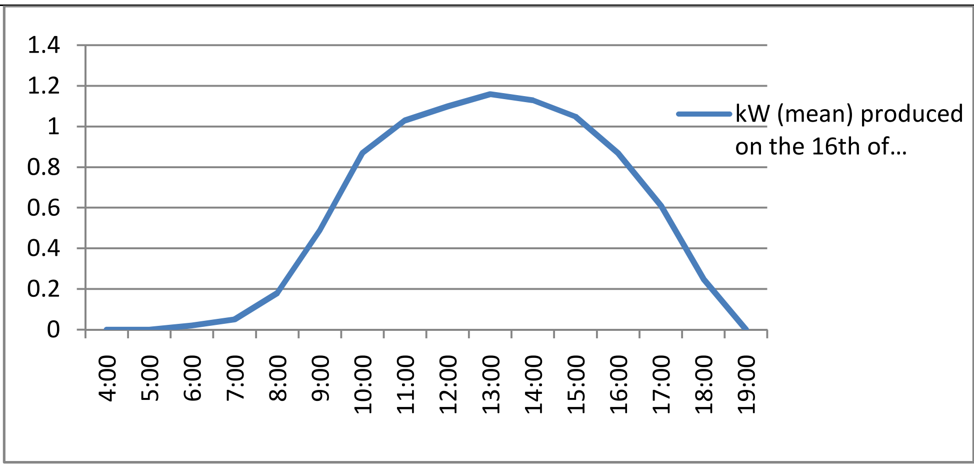
Power and Energy

Using data from the specified days the following was obtained:

Table 7-4: Data graphs of daily performance of system







In the following table the maximum power delivered and the difference between the predicted and the practical values are given:

Table 7-5: Summary of daily power delivered

Day	Maximum power by system	Difference from predicted value [Table 7.2]	Percentage difference
13 September	0.98 kW	0.612 kW less	38%
10 October	1.05 kW	0.595 kW less	36%
16 November	1.16 kW	0.488 kW less	30%

The following table is a summary of the amount of energy for the specific day produced and the difference from the predicted values:

Table 7-6: Summary of daily energy delivered

Day	Energy delivered	Difference from predicted value [Table 7.3]	Percentage difference
13 September	6.84 kWh	2.83 kWh	30%
10 October	7.91 kWh	4.06 kWh	34%
16 November	8.81 kWh	4.95 kWh	36%

From this analysis it can be seen that the system is underperforming. The average performance difference is 33%.

The poor performance will be explained in a subsequent paragraph.

Financial and environmental benefit

Money is saved due to the fact that less ESKOM power is used by the sustainable village, in addition to this green house gas emissions are reduced. The total energy produced if the situation was ideal would have been 3350kWh per year, due to certain performance issues the energy produced is adapted 33% lower and is estimated to be 2245 kWh per year.

The reduction in green house gas emissions up to this date is 301 kg, as determined by the installer of the product. Working on the possible energy this project could save during its operation this total will increase to 44 900 kg, the estimated life time of the project is 20 years. To calculate the net savings in GHG emissions the amount of GHG emissions during manufacture and transport should be subtracted from the total. This could be substantial as the cells had to be transported from Europe to America and then the slate has to be transported to

South Africa. The transporting will have increased the total carbon footprint of this product. This can, however, be seen as acceptable as this is a research project and the main concern for this project is not total savings in GHG emissions.

The concern of this project is the long term savings and contribution to the local grid. A simple financial analysis shows that with no debt it will take 20 years worth of electricity savings for a simple payback on the system, a simple payback only takes into account the capital costs and the saving from the investment. The payback includes an annual increase of 15% in the electricity price. Just looking at this, it can be seen that financially this type of project will not be viable for the South African market. With the low tariffs on electricity this will not be a good financial investment for a retrofit under present (2008) conditions.

Known problems affecting performance

Orientation

The orientation of the roof has an effect on the total energy produced by the system. If the roof was facing due north the system will have an increase in the total energy produced per anum of about 4%. The inclination of the roof (about 35˚) has the added benefit of producing more energy during the winter months than would be produced with a horizontal roof. The difference in orientation has less effect on the total energy produced than the tilt of the roof in this case as can be seen from Table 7-3.

The difference between predicted values and practical values are due to certain performance issues of the system.

Shading

The first problem is due to a shading effect. The shadow from the chimney of the guest house kitchen falls on the PV area of the roof from sunrise until just before noon. This reduces the total amount of power delivered and the energy produced. The shading effect can be seen in the measured result. The shading occurs in the mornings.

The following picture was taken early morning (8h30, 06 October 2008). The shadow of the chimney is clearly visible on the slates.

Figure 7-2: Shadow of chimney on PV panels

It is possible that when the slates where installed the sun rose at a different angle, than when the measurements where taken. If this is the case the installer did not anticipate the movement of the sun.

Faulty Slates

The largest factor contributing to the 30% performance deficit could be one or two faulty SunSlates™. These faulty slates would have the effect of absorbing some of the power from the other slates and releasing it as heat. This fault can be rectified but with difficulty. The design of the roofing system is such that in theory it should be easy to remove an individual slate, but in practice it is not easy to do or to locate the faulty slate in the series line. The electrical coupling is also hidden from access, thus easy fault finding is not an option.

If a slate is faulty it would heat up more than the slates around it. This characteristic can be used to determine the faulty slate by taking an infrared picture of the roof. From the picture the faulty slate could be located.

Case conclusion

From this case study one can conclude that SunSlates™ are not a good financial investment in current South African market conditions, this is no different from any other PV or other renewable energy investments. The total cost of transport, installation and maintenance would probably be more than the benefit from the electricity savings from the slates. Thus this investment will cost you more than what you would gain in savings.

Other factors that influence the feasibility of this type of project are the orientation and the tilt of a roof. If the tilt and orientation is not best suited for the area of such a project energy losses will occur. This losses or reductions could lead to reduced returns on the investment or make the investment unfeasible, it was shown in this case however that orientation losses only amount to about 4% and would not have such a significant effect on the feasibility.

In this case the tilt results in maximum energy per year as it is close to the latitude of the site, it was also found that at this specific tilt the orientation has a small effect on the total energy produced.

It can also be seen from this case study that the individual slates must be tested before use. If a single slate is faulty it will affect the entire system and power reduction, as in this case, can be as high as 30% of installed capacity.

Even though the SunSlates™ are a novel idea it will not benefit a South African client under current market conditions. From this one can see that the time for BIPV is not yet here for South Africa, but the situation might change in the near future.

8 Discussion and conclusion

Discussion

From the measured results and the predictive model it can be seen that the power and energy output of a PV panel can be easily predicted from given data.

The temperature measurements indicate that orientation has an effect on the temperature profile of the slates. The temperature profile is closely linked to the wind speed and the solar radiation received. One of the more interesting points in the measurements is the fact that the slate temperature decreases to below ambient temperatures during night time (see figures 6-3, 5, 7). This effect is due to the heat radiated by the slate during night times. This has an added effect of increasing efficiencies during the mornings, but the temperature of the slate increases rapidly when the first rays of the sun hit the slate.

When looking at the daytime temperatures of the slates it can be seen that the slate's temperature, on average, increase to 25˚C to 30˚C above ambient temperatures. This is a disadvantage to any PV module as this decreases the maximum power output. From the data sheet of a new version of the Q-Cell it was found that the power lost in relation to increase in temperature is 0.43%/K. This will result in a power loss of up to 15% during a warm summer day. From the results obtained it can be seen that these specific cells are sensitive to changes in temperature, where a 5˚C increase in temperature can reduce total energy output by up 5% per day (Table 6.3).

Another factor that might contribute is the placing of the temperature probe. This probe is placed between the glass of the module and the slate, thus the temperature probe does not measure the direct cell temperature and can only be used as an indicator of the effect of the temperature. The cell temperature might be even higher than measured, due to the insulating effect of the glass lamination.

Table 6.2 illustrates the effect temperature has on the output of the slates. From this one can conclude that the ambient temperature, determined also by wind speed and direction, can have some impact on the total power delivered. From the data a difference in 5˚C ambient temperature can lead to 3.5% less energy delivered on the specific day.

The winter temperatures of Stellenbosch would seldom drop so low that the slate temperature will be reduced to less than 25˚C. Thus an increase in power above rated power will not easily occur.

The temperature profiles of east facing slates are not the same as west facing slates. From the results (see figure 6-7) one can see that the temperature of the east facing slate increases rapidly at first and then steadily cools down, unlike the west facing slate which has a more even temperature profile.

The temperature profile of the North facing slate is almost the same as the east facing slate. The east facing slate, however, does not reach the same maximum temperature as the north facing slate. This does not benefit the total energy production of the orientated slates. The solar incidence angle on the slates will not be perpendicular and maximum insolation will not be obtained on the slates. This explains the effect that the orientated slates never produce equal amounts of power compared to the north facing slate. This also explains why the temperature of the orientated slates are constantly lower than the north facing slate, solar insolation is closely related to the temperatures of the slates.

The power output of the slates under test never reaches the rated output of the slates. This is due to the temperatures of the slates reaching as high as 60˚C. As seen from the results the increase in temperature decreases the performance. To maximise the performance of the slates, some cooling would be required.

Looking at the orientation of the slates it was found that orientating the slates east or west resulted in almost equal amounts of energy. This is due to the symmetrical movement of the sun during the day. There is, however, one factor which can influence a change between the generation capabilities. This would be the difference in morning and afternoon temperatures of the slates. If weather patterns in an area result in regular afternoon winds or perhaps morning winds, the temperature of the slates will differ a few degrees from morning to afternoon, this effect as mentioned earlier, is small enough to ignore when sizing a system.

Changing the orientation from north will reduce the total energy produced throughout the year. West or east orientation can only utilise partial sunshine hours per day, unlike north orientation which benefits maximally from the sunshine hours of the day. As soon as the sun pasts its zenith it will reduce the radiation on an east facing slate and only then start radiating a west facing slate. This effect of reduced insolation during the day can result in a reduction of up to 30% energy production during a winter day, but has a small effect during summer (figure 6-11). The total loss in energy production due to orientation was estimated to be about 10% per year.

From the case study it can be seen that the environmental effect of the panels throughout the life time of the system can be considerable, the cost however is still very prohibitive in the South

African context. With a simple payback term of 20 years it will not be a wise financial investment.

In the case study it was suggested by the installer of the system that some of the installed slates could be faulty. A single faulty slate would have a dramatic effect on total system performance. In practice this will need to be addressed by actively testing each slate before installation. This will have an effect on the total cost of such a system as it will increase the installation time and man-hours required to complete a system installation.

From the case study it can be seen that orientation reduces the power produced during the winter the most. This is similar to the findings of the slates under test. The amount however is negligible.

Conclusion

Through predictions and measurement it was found that a north orientated slate with a tilt of 30˚ has a higher annual energy production than an East facing slate at the same tilt angle. The difference between energy produced between the north and east/west orientated slates are smaller than anticipated.

The tilt angle is of more importance when designing a BIPV system, as this has the largest effect on the total energy produced. From analysing the local solar resource it was found that a latitude tilt can produce 10% more energy per anum, than a 60˚ tilt or horizontal installation.

The combination of the effect of tilt and orientation should be considered when installing a system. If the orientation and tilt is not optimal the losses in the system could be high.

When designing a system it is important to factor in the temperature coefficients of the PV panels. In the case of BIPV the mountings of the panel should be closely investigated to determine what type of temperature variations certain additions to the slates might cause. In the case of a SunSlate™ installation it is suggested that ventilation be added to the roof space. The additional ventilation could reduce the overall cell temperature, increasing the efficiency of the system.

It is important to have the system connected to a MPPT. The MPPT will increase the total energy produced per day by the system. Because maximum available power is delivered to the load it will reduce the power dissipated in the cells, preventing the cells to heat up.

Overall the SunSlates™ performed well under different orientations and tilt. For current South African condition however it is still not a sound financial investment.

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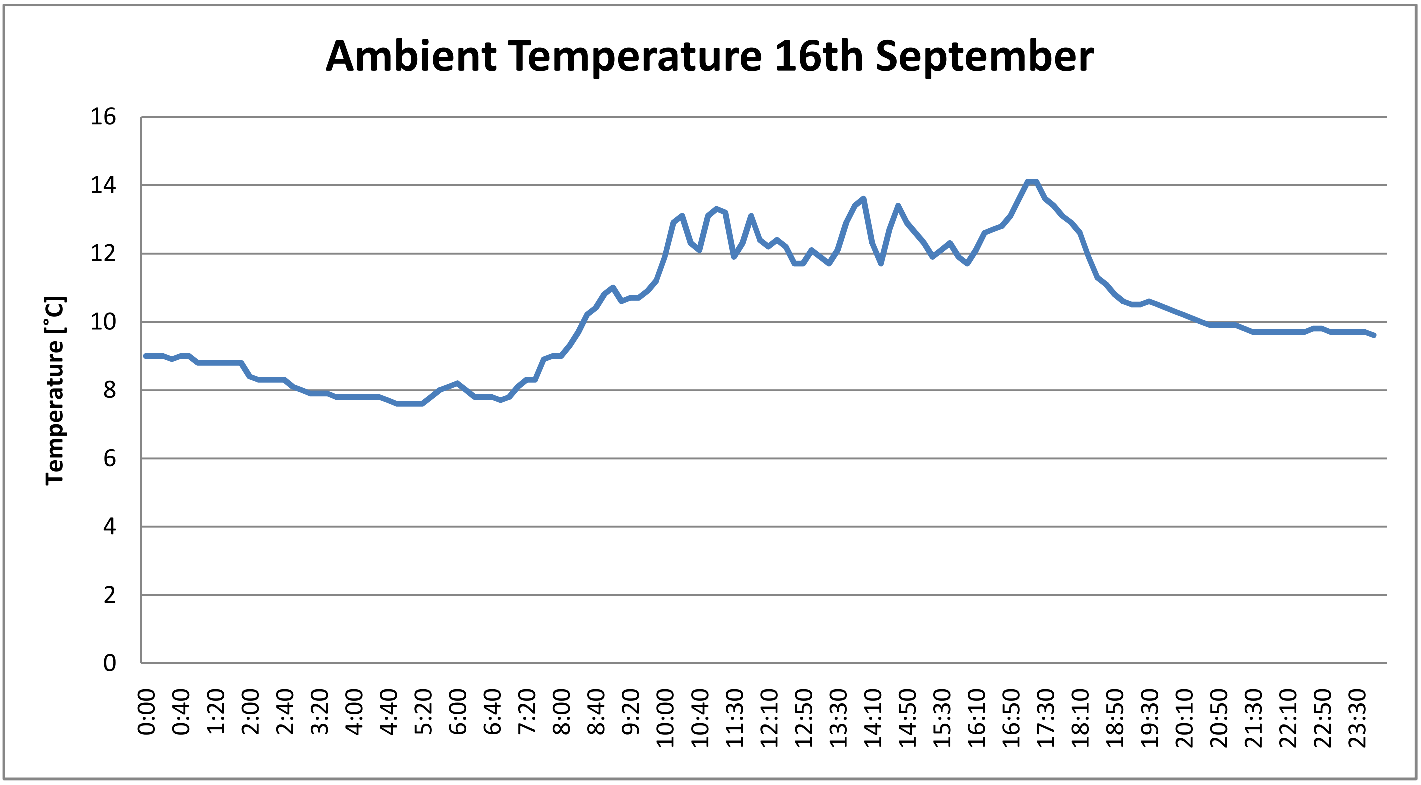
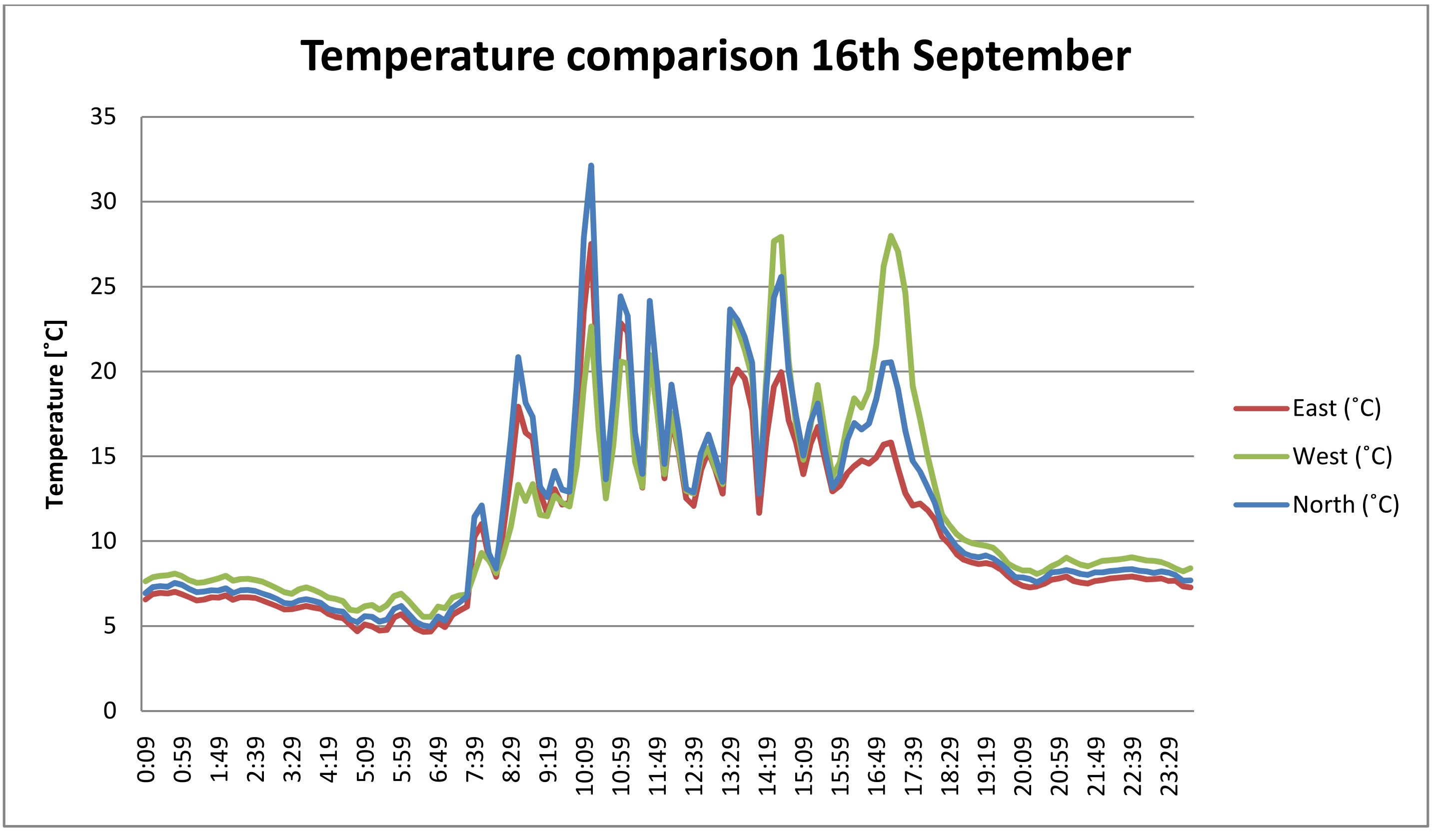
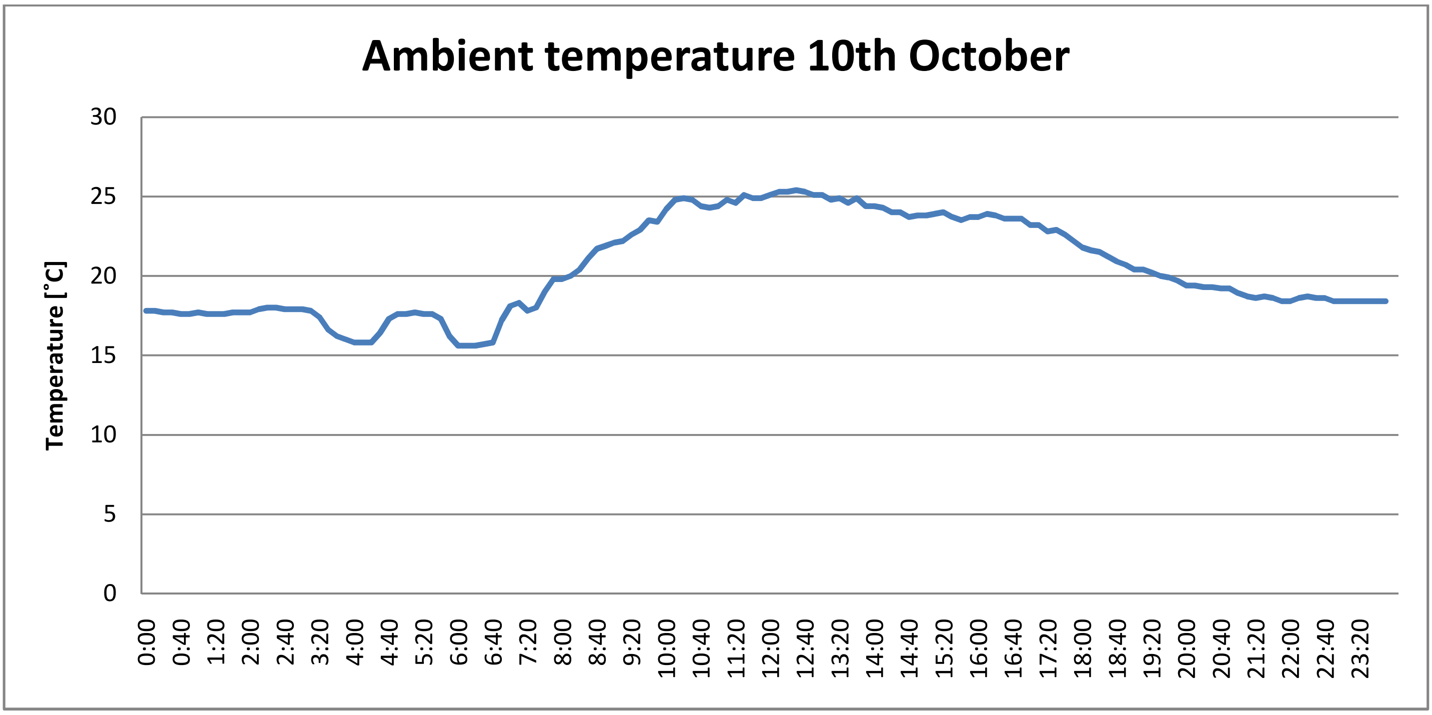
Appendix A

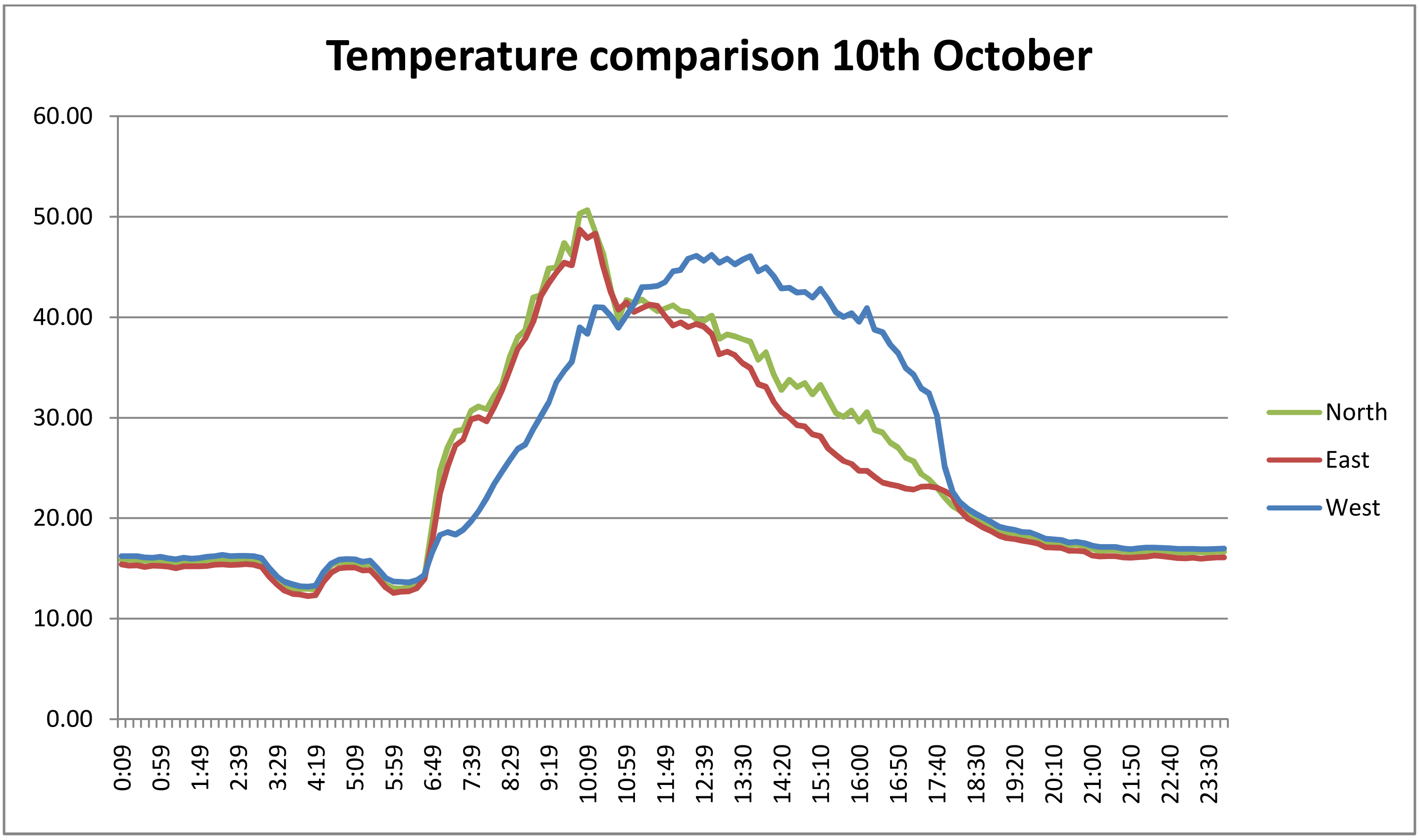
Combination of obtained temperature data:



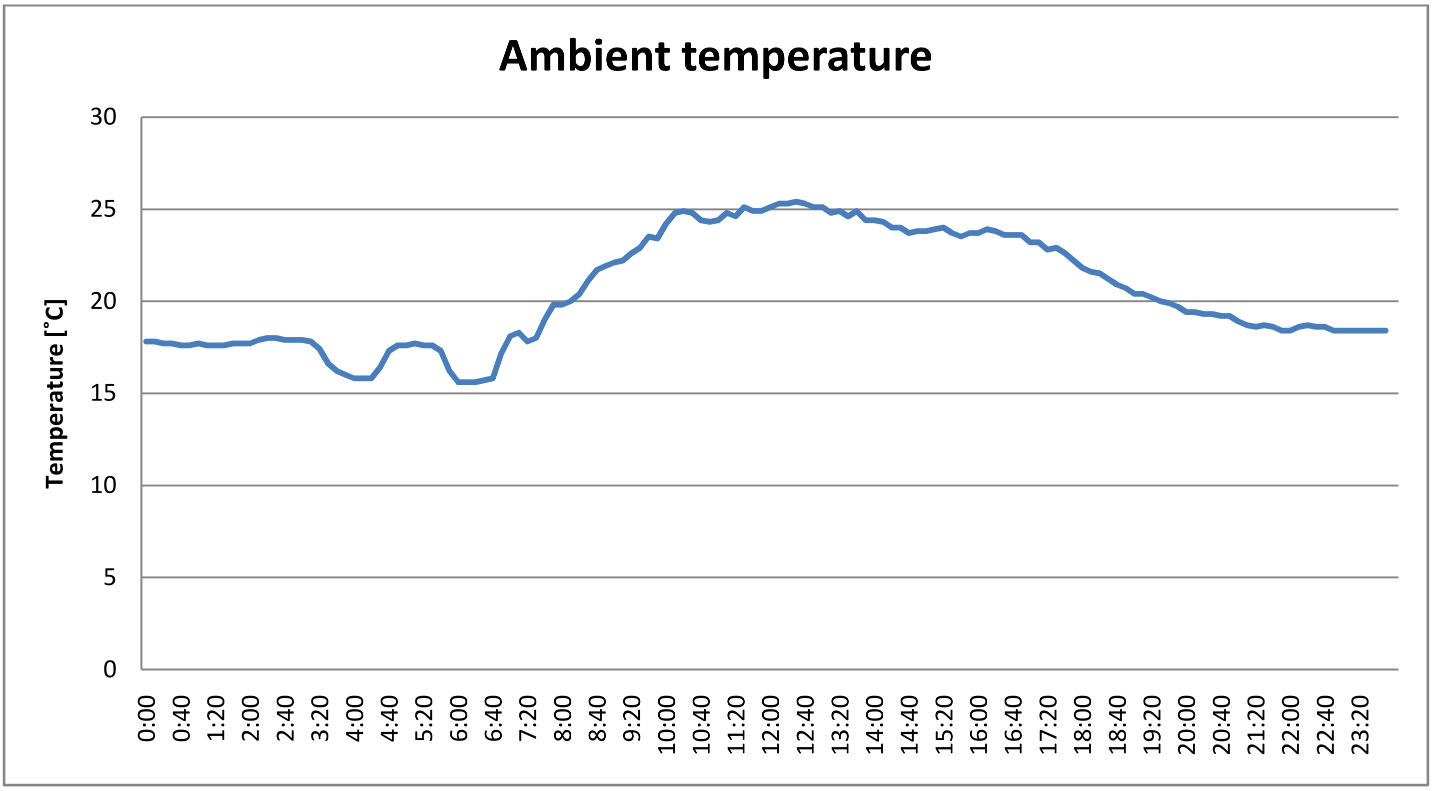




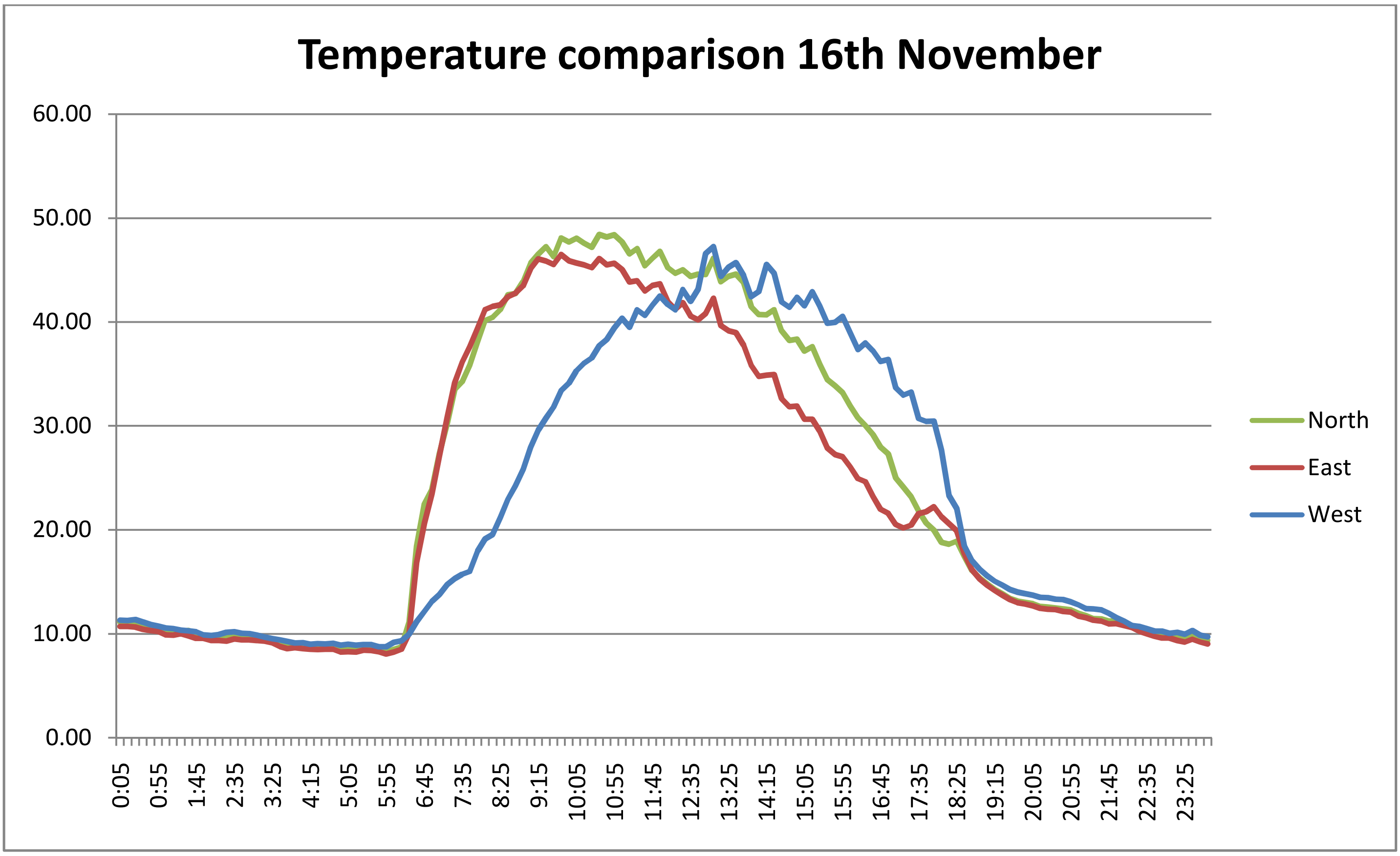
Ambient temperature 10th October
Temperature [˚C]
30
25
20
15
10
5
0
0:00
0:40
1:20
2:00
2:40
3:20
4:00
4:40
5:20
6:00
6:40
7:20
8:00
8:40
9:20
10:00
10:40
11:20
12:00
12:40
13:20
14:00
14:40
15:20
16:00
16:40
17:20
18:00
18:40
19:20
20:00
20:40
21:20
22:00
22:40
23:20



Temperature comparison 10th October
60.00
50.00
40.00
30.00
20.00
10.00
0.00
0:09
0:59
1:49
2:39
3:29
4:19
5:09
5:59
6:49
7:39
8:29
9:19
10:09
10:59
11:49
12:39
13:30
14:20
15:10
16:00
16:50
17:40
18:30
19:20
20:10
21:00
21:50
22:40
23:30
North
East
West



Ambient temperature
Temperature [˚C]
30
25
20
15
10
5
0
0:00
0:40
1:20
2:00
2:40
3:20
4:00
4:40
5:20
6:00
6:40
7:20
8:00
8:40
9:20
10:00
10:40
11:20
12:00
12:40
13:20
14:00
14:40
15:20
16:00
16:40
17:20
18:00
18:40
19:20
20:00
20:40
21:20
22:00
22:40
23:20



Temperature comparison 16th November
60.00
50.00
40.00
30.00
20.00
10.00
0.00
0:05
0:55
1:45
2:35
3:25
4:15
5:05
5:55
6:45
7:35
8:25
9:15
10:05
10:55
11:45
12:35
13:25
14:15
15:05
15:55
16:45
17:35
18:25
19:15
20:05
20:55
21:45
22:35
23:25
North
East
West

Appendix B

The following is the MATLAB code used to calculate the movement of the sun and predict the Insolation at a certain time of day:

```
%EOT
function EoT = EOT(day)
n = day;
b = (2.*pi/365).*(n-1);
EoT = 2.292.*(0.0075 + 0.1868.*cos(b)-3.2077.*sin(b) - 1.4615.*cos(2*b) -
4.089.*sin(2*b));

function [SolTime,hour] = LSt(day)

EoT = ET(day);
hour = 1:1:24;
Lm = 30;
Long = 18.86;
ST = hour.*60;

LST = ST + 4.*(Long - Lm)+ EoT;

SolTime = LST./60;

%hourangle
function hourangle = hang(day)

SolTime = LSTime(day);
% hourangle2 = (((LST - 720)./60).*15);
hourangle = ((SolTime - 12).*15)*pi/180;

%Zenith
function [AltAng,Zen] = zenithf(day)
DECL = declination(day);
hourangle = hourang(day);
%hourangle = 0;
LAT = -34*pi/180;
Zen = acos(sin(LAT).*sin(DECL) +cos(LAT).*cos(DECL).*cos(hourangle));
Zend =  Zen.*180/pi;
AltAng = 90 - Zend;
alt = AltAng.*pi/180;

figure(1)
plot(Zend);
xlabel('Day of the year (1 is 1st of January)');
ylabel('Tilt angle of surface');
title('Tilt angle required for surface to be perpendicular to solar rays');

% Solar azimuth
DECL = DEC.*pi/180;
%hourangle = ((SolTime - 12)*15*pi/180);  %rads
hourangle = 0*pi/180;
LAT = 34 * pi / 180;
% s_azi =
atan(cos(DECL).*sin(hourangle)./(sin(LAT).*cos(DECL).*cos(hourangle)-
cos(LAT).*sin(DECL)));
% azi = s_azi*180/pi;
HRA = hourangle;
t = sin(DECL)*sin(LAT);
u = cos(DECL)*cos(LAT)*cos(HRA);
```

```
ALT = asin(t+u);
Altd = ALT*180/pi;

%calculate AirMass
%
% To calculate air mass - Go to Declination and select day
%                  - Go to zenith and claculate
%                 - Run airmass claculator - Results AM
%                                           Irradiance
function [Id,Ig,Itot] = amf(day)

declination(day);
[AltAng,Zen] = zenith(day);

% angle = 0:1:85;
% am = 1./cos(angle.*pi./180);
c = 1;
cm = [];
am = 0;
zen2 = 0;
Itot = 0;
for m = 1:1:24
     if AltAng(m) > -1
%      zen2(c) = Zen(m);
     am(c) = 1./cos(Zen(m));
     Id(c) = 1350.*(0.7.^(am(c).^0.678));
     cm = [cm m];
     Itot = Itot + Id(c);
     else
        am(c) = 0;
        Id(c) = 0;
        Itot = Itot + Id(c);
%      zen2(c) = 0;
     end
    c = c + 1;
 end
% am = 1./cos(zen2)
[b,hour] = LSTime(day);
figure(2)
plot(hour,am)
xlabel('Hour of day');
ylabel('Airmass');
title('Change of airmass as function of daytime');


Ig = 1.1.*Id;



%Tilted measurement

% tilt describes the angle from vertical and not horizontal!
function [Btot, Power] = tilt(day,tilt2,ori2,temp)
sazim = azimuth(day);
[Id,Ig,Itot] = airmass(day);
[AltAng,Zen] = zenith(day);
tilt = tilt2*pi/180;
ori = ori2*pi/180;
alt = AltAng.*pi/180;
if tilt2 == 0
err = 0;
```

```
erra = 0;

    if day < 184
    erra = 2.5 + day*0.082;
    end
    if day > 183
    erra = 30 - day*0.082;
    end
err = (100 - erra)/100
Bnorm = Id./err;
    else
    Bnorm = Id;
end

% Btilt = Bnorm.*(cos(Zen).*sin(tilt).*cos(ori - sazim) +
sin(Zen).*cos(tilt));
Btilt = (Bnorm.*(cos(alt).*sin(tilt).*cos(ori - sazim) +
sin(alt).*cos(tilt)));
% u = cos(tilt).*cos(Zen);
% y = sin(tilt).*sin(Zen).*cos(sazim);
% Btilt = Bnorm.*(u + y);



Btot = Btilt*1.1;%./err; %Added 5% for accuracy
[b,hour] = LSTime(day);

for n = 1:1:24
    if Btot(n) < 0
        Btot(n) = 0;
    end
end



%Btilt = Bnorm*((cos(tilt).*cos(Zen) + sin(tilt).*sin(Zen).*cos(sazim)));
figure(6)
plot(hour,Btot);
xlabel('Hour of day');
ylabel('Global insolation (direct and diffused)(W/m^2) on tilted surface');
title('Insolation as function of daytime');

PowerA = Btot.*(0.09).*(0.155);
PowerLoss = PowerA*(temp*0.43/100);
Power = PowerA-PowerLoss;

figure(7)
plot(hour,Power);
xlabel('Hour of day');
ylabel('Power delivered by system');
title('Change in power as function of daytime, single slate West');

Btest = 0;
PowerT = 0;
for m = 1:1:24
    Btest = Btest + Btot(m);
    PowerT = PowerT + Power(m);
end
Btest
PowerT
```

Appendix C

Datasheets of A/D converter and SunSlate™