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Performance evaluation of a rooftop solar photovoltaic power plant in the Gävle Arenaby (Gävle, Sweden): Installation testing

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Abstract

The current energy situation is taking a turn towards renewable energies, due to the new pacts to curb global warming. These agreements, together with governmental aid, are facilitating an escalation in the production and improvement of new energy systems and the price decrease due to a larger-scale production.

Within these energy alternatives, solar energy is found, specifically the subject to be treated in this project is photovoltaic energy, due to its exponential growth in the last 10 years, new tools are being developed for its monitoring and modelling.

Therefore, the main objective of this thesis is to develop a method for installation testing of a PV-system. The method should give the installed nominal power of the system and show if the maximum power point trackers work as expected.

A large PV-system was installed on the roof of Gävle Arenaby during 2017. A measurement system for monitoring of the power of the system and of the solar irradiance was installed.

Different parameters have been taken into account for the adjustment of the model that vary the performance of the system. These factors are: the irradiance received, the module temperature and the angle of incidence.

It has been concluded that the results obtained indicate a correct adjustment of the theoretical power against the real power, which means, a correct operation of the generated model. Besides, the expected power follows a linear trend, reaching the power set by the manufacturer for Standard Test Conditions. The results show that the monitored modules-strings fulfill the promised performance and the method for installation testing work as expected. The linear correlation between corrected power and irradiance means that the maximum power point tracker in the inverter works independent of the power.

Key words: Installation test, module temperature, angle of incidence, solar irradiation, PV system.

Preface

I would like to say a few words to my supervisor Björn Karlsson. My choice of Gävle as an Erasmus destination was based on developing my knowledge of renewable energies. During the beginning of the course, I was surprised by the dedication of our teacher Björn.

Although it has been difficult for me to express myself on certain occasions, I have been very fortunate to have him as a supervisor, since he has explained to me and had the patience to continue teaching me when I did not understand a concept. I hope to continue my career on solar energy, and one day, be able to teach someone like you have done with us.

I do not want to forget about Mikael Sundberg and Mattias Gustafsson who have helped me with the installation of the measuring devices, and they have offer themselves at any time to help me and give me information about the installation.

Finally, to thank my family for the support during these years to study abroad, and my friend Pedro Horno, for his Visual Basics classes that have helped me develop the model.

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1 Introduction

1.1 Solar energy overview

The new treaty discussed in the congress conducted in Paris in December 2015, in which an agreement was reached. The treaty specifies that the global average temperature increases at most 2°C compared to the pre-industrial temperature [1].

During the years 2004 to 2014, the energy consumed by fossil fuels increased by 21.3% [2], especially in the Asia-Pacific area. Currently 81% of the total energy consumed comes from this type of energy sources, 29% coal, 31% of oil and 21% of natural gas, which in turn are the main sources of CO_2 emissions and of greenhouse gases [3].

Due to these factors, policies are drifting towards a more sustainable system, and that is why different renewable energies come into play such as biomass, hydroelectric, geothermal, wind, or solar, in which the study will be focus on.

Solar energy is determined by the radiation received from the Sun, the radiation changes according to the location of the installation. It is a clean energy and simple to install, which can be adapted both to reduce the energy consumption of a home, and to make a plant of several megawatts to provide energy to the energy network.

Solar energy is divided into photovoltaic and thermal, and it is possible to combine both. Photovoltaics is characterized by using solar radiation and converting this energy into direct current (DC). Whereas, the thermal uses the energy received from the Sun to heat a fluid (For example, water that can be used directly in the domestic water). But, it can also be used with molten salts to store energy and then use that energy stored when there is a shortage of solar radiation, to start a power cycle.

Regarding photovoltaic solar energy, its performance depends a lot on the weather conditions. The power that can be extracted vary greatly depending on some parameters such as ambient temperature, solar irradiation or the module temperature. However, the performance of the PV-system can also be affected by other environmental aspects such as shadows: produced by a tree, a building, other modules or clouds.

Even with the problems that affect PV-systems, the market has grown fast since 2000. Increasing 200 times the volume of production and prices have plummeted. In the following figure it can be seen how prices have fallen since 2009 for different types of cells and photovoltaic installations [4].

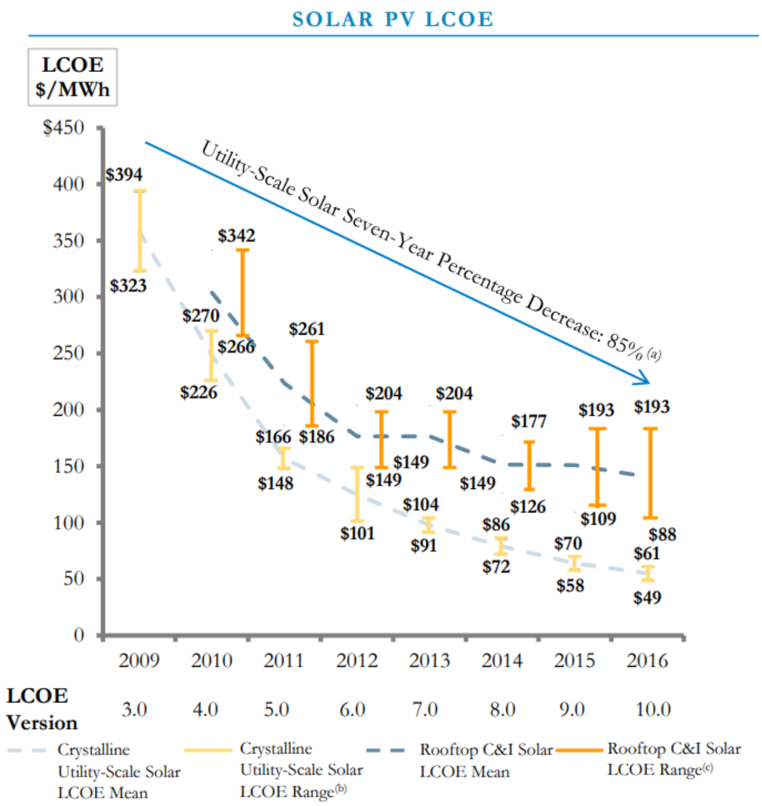

Figure 1. Solar price [5].

The drop-in price has resulted in an increase in the number of installed Gigawatts; the following figure shows the increase in installed capacity from 2007 to 2016.

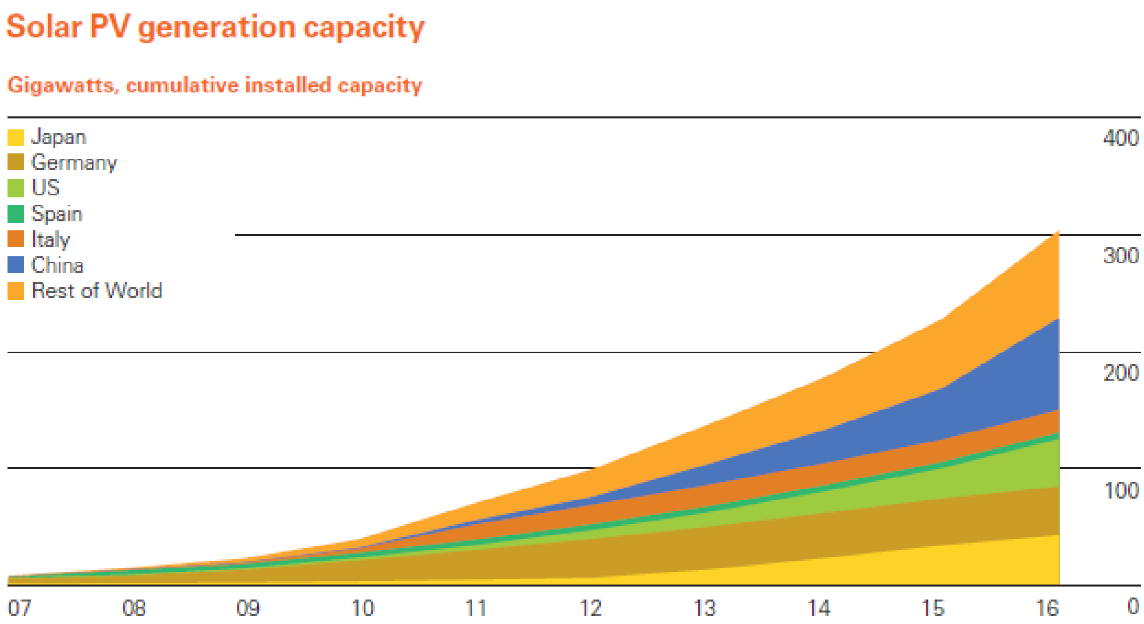

Figure 2. Cumulative solar installed capacity [3]

1.2 Objectives and limitations

The objective is to monitor and model the performance of a photovoltaic installation located on the rooftop of the Gävle Arenaby (Gävle, Sweden).

It will try to develop a correlation between real and theoretical performance through corrections in different parameters that will be explained. Due to the characteristics of the solar modules are given under the standard conditions of measurement (STC), it is intended to develop a method for instalaltion testing of a PV-system.

For this purpose, a correction factor will be applied on the module temperature and solar irradiation, in order to develop a standardized methodology to calculate the performance of PV-systems.

To achieve the objective, the PV-system will be monitored for several days and its performance will be evaluated. A measuring system will be installed to collect the intensity and voltage values of the modules. Also, the different parameters collected by the pyranometer and the reference solar cell that will be explained in the thesis.

1.3 Literature review

The characterization of photovoltaic installations is booming, there is a clear growth in the use of this technology, and therefore new methods are being developed to model and simulate photovoltaic installations.

According to [6], where the power is predicted theoretically and compared with a real measure in your equipment as in the case of this project, two methods are used to estimate the temperature of the cell, the Sandia, which comes from the Sandia National Laboratories; and the NOCT (Nominal Operating Power of the Cell). But in this case they cannot adjust the model when they have shadows. However, in this project it will be observed that when having inclement weather, the model follows the real power curve.

Moreover, since solar panels are usually characterized under the standard test conditions (STC), they present problems in relation to module temperature and environmental variables [7]. Therefore, it is required to verify that the power expected by the manufacturer is adjusted to a simple model, in this case a linear regression.

All these concepts will be explained and expanded in the following chapters.

2 Theoretical Background

2.1 PV systems

In this chapter, it will be explained the types of solar panels on the market, as well as the operation of a solar cell. Also the power and efficiency of a photovoltaic module and, finally, the different factors that affect the correct performance of a photovoltaic system.

2.1.1 Types of solar cells

The photovoltaic conversion is based on the photovoltaic effect, that is, on the conversion of the light energy coming from the Sun into electrical energy. To carry out this conversion, devices called solar cells are used, constituted by semiconductor materials in which, artificially, a constant electric field has been created (through a union p-n). Explained in the following section.

The most used material is silicon, because it is found in large quantities in the Earth, about 60% of the Earth's crust contains silica [8].

At present, the market is dominated by monocrystalline and polycrystalline solar cells, with almost 95% of the market. As can be seen in the following figure:

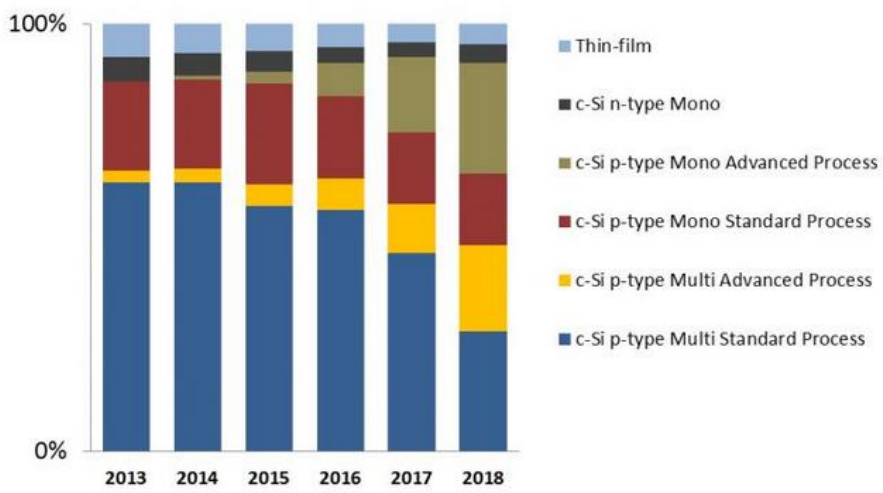

Figure 3. PV cell production by technology. [9]

This is due to its high efficiency, which can reach maximum efficiencies of 24% [8] in the case of monocrystalline, while polycrystalline can reach maximum efficiencies of 17% [10]. But the monocrystalline for manufacturing than polycrystalline cells.

On the other hand, it is found the thin film solar cells, which are solar panels that reduce the amount of material used, since several semiconductors are combined in thin layers to create a series of thin films. They are also flexible and have already arrived at the laboratory to achieve efficiencies of 20.1% [11]; it is also much cheaper to manufacture than other modules. Against it, it takes more space to get the same power and is more sensitive to the effect of heat and shadows, effects that will be explained later.

Finally, it is found the Amorphous Silicon Solar Cells, which are solar panels that are used on a small scale, as in calculators or travel lights, these cells usually reach maximum values of 9% [11].

Finally, a summary table is presented with the different types of cells, the range of efficiencies and the area required for 1 kWp in m^2.

Cell material	Module efficiency	Surface area required for 1kWp in metres squared
Monocrystalline silicon	14–20%	5–7m^2
Polycrystalline silicon	13–15%	6.5–8.5m^2
Amorphous silicon thin film	6–9%	11–16.5m^2
CdTe thin film	9–11%	9–11m^2
CIS/CIGS thin film	10–12%	8.5–10m^2

Figure 4. Comparison between different solar technologies. [11]

2.1.2 Principle of operation of a solar cell

When the light strikes a solar cell that is connected to an external load, there will be a potential difference in that load and a current flow that leaves the external circuit through the positive terminal and returns to the cell through the negative.

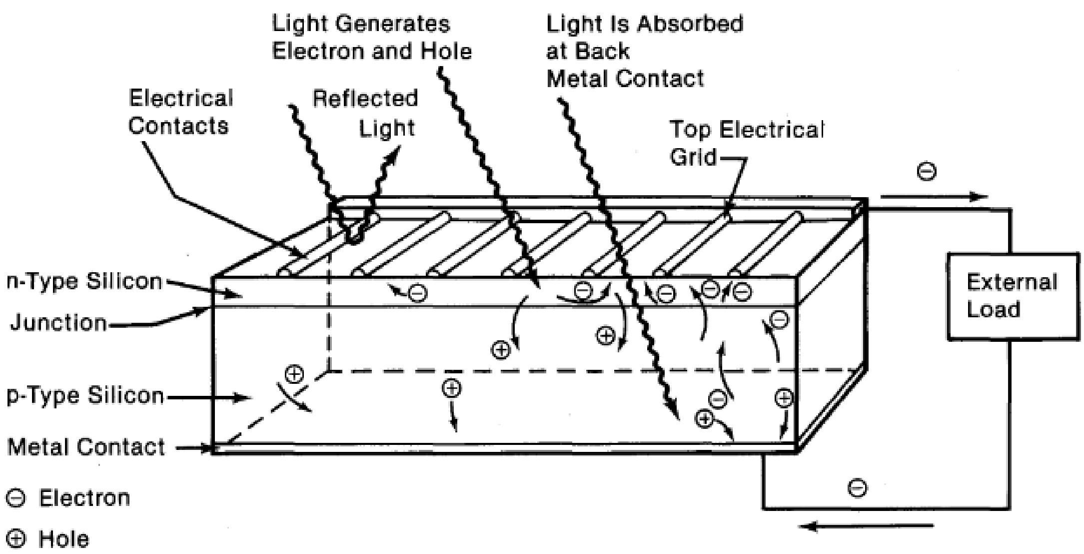

Figure 5. Light strikes on the solar cell. [12]

In these operating conditions the cell performances like an energy. The phenomena that take place inside the device can be described as follows: The photons that strike the cell with energy equal to or greater than the width of the band gap are absorbed in the semiconductor volume and generate hollow electron pairs that can act as current carriers [13].

The electric field, or the potential difference, produced by the p-n junction is the cause of the separation of the carriers before they can recombine again and, therefore, the cause of the flow of the current by the difference of external potential, thus supplying power to the load [13].

In summary, the current delivered to a load by an illuminated semiconductor diode is the net result of two internal components of current that oppose:

a) I_L is the current generated by the photovoltaic effect.
b) I_D is the diode current.

The following figure shows the intensity and voltage values that can be given in a diode, when the diode is receiving light and when it is in the dark.

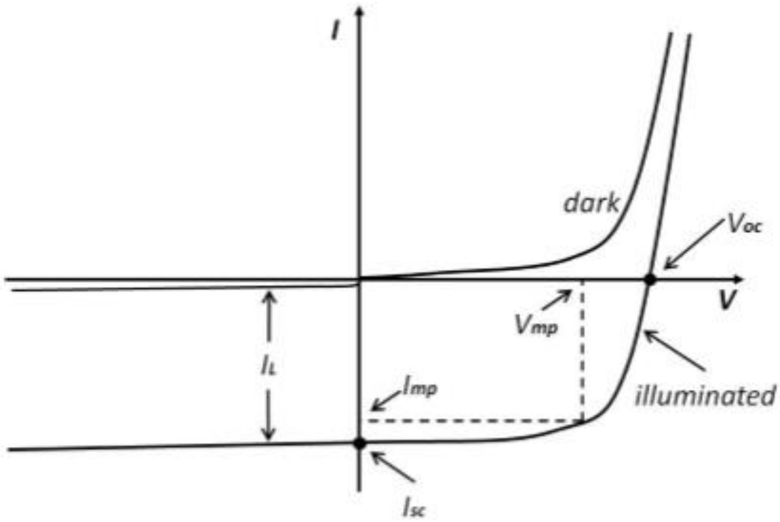

Figure 6. Characteristics of a diode solar cell when is non-illuminated (dark) and illuminated [14].

Usually, to study a photovoltaic cell the polarity references are changed. Being I_L current positive, it is obtained the characteristic equation of the solar cell:

$$\mathrm{I} = I_L - I_D \qquad (1)$$

Regarding the electric model that is represented in the following figure:

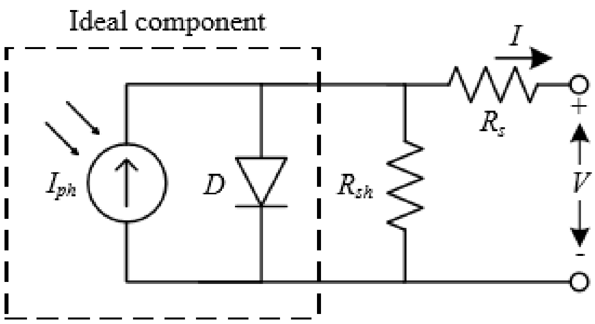

Figure 7. PV cell single-diode electrical equivalent circuit [15cite13].

Being I_{PH}= I_L and the current that passes through the diode, I_D. It is obtained mathematically, that the current of the diode can be expressed as by the model of an exponential, being the characteristic equation of the device:

$$\mathrm{I} = I_L - I_D\,(V) = \; I_L - I_O \cdot [e^{\frac{e \cdot V}{n \cdot K \cdot T}} - 1] \qquad (2)$$

Parameters:

I: Current [A]

I_L: Current generated by the photovoltaic effect [A]

I_D: Diode current [A]

I_O: Saturation current of the diode [A]

e: Electron Charge [C]

n: Dimensionless Diode factor. Value between [0;1].

K: Boltzmann constant [J/K]

T: Cell temperature [K]

Observing the previous electrical diagram, it can be observed that the highest current value is obtained when the voltage becomes zero, obtaining the short-circuit current (I_{SC}), which will be equal to that caused by the photovoltaic effect:

$$I_{SC} = I(V = 0) = I_L \qquad (3)$$

Therefore, if the circuit keeps open, with the circulating current equal to zero, the open circuit voltage (V_{OC}) value is obtained, with the maximum voltage value in the solar cell being:

$$V_{OC} = \frac{nkT}{e} \ln(\frac{I_L}{I_O} - 1) \qquad (4)$$

The area enclosed under the graph, between I_{SC} and V_{OC} corresponds to the operation of the cell. For each point of the I-V curve, a power value is obtained.

$$\mathrm{P} = \mathrm{V} \cdot \mathrm{I} \qquad (5)$$

Parameters:

P: Power [W]

V: Voltage [V]

I: Current [A]

The power curve can be seen in the following figure, where is the operating point (V_{MP}, I_{MP}) for which the maximum power value (MPP) is obtained.

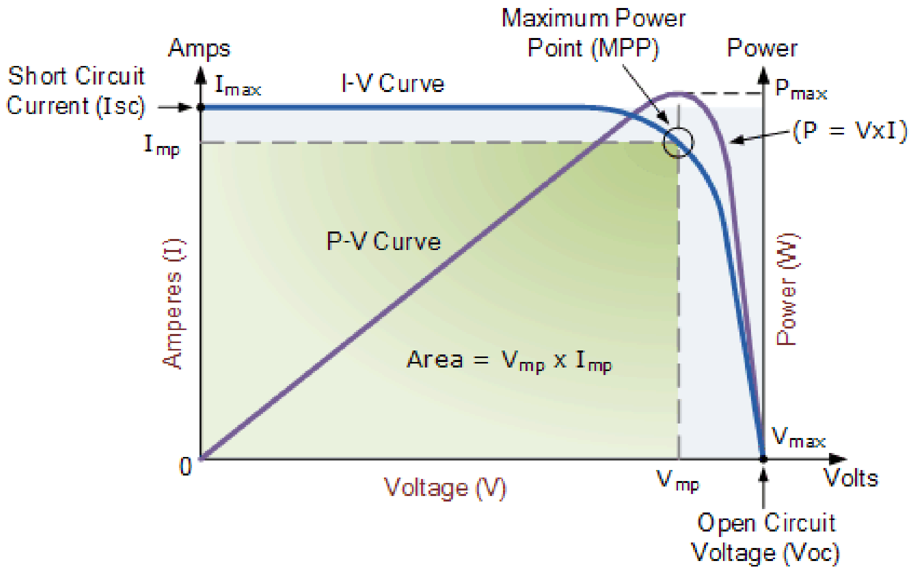

Figure 8. Solar Cell I-V characteristic curve [16].

The area enclosed under the graph between the I_{MP} and V_{MP} points gives the fill factor.

$$FF = \frac{I_{MP} \cdot V_{MP}}{I_{SC} \cdot V_{OC}} \tag{6}$$

Using the above formula, it can be obtained the maximum power delivered by the solar cell.

$$P_{MP} = FF \cdot I_{SC} \cdot V_{OC} \tag{7}$$

The representation of the fill factor is shown graphically in the following figure.

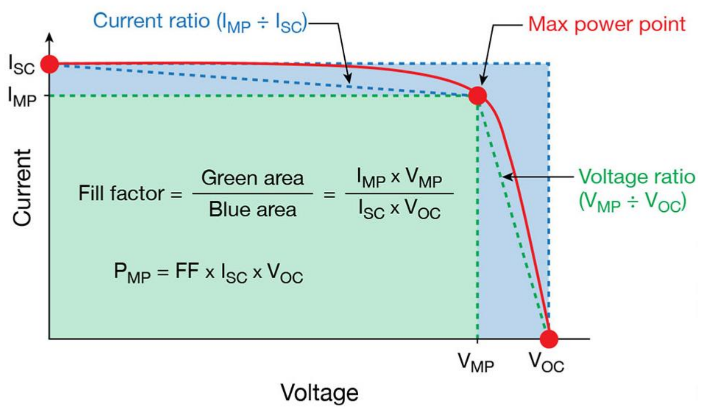

Figure 9. Fill Factor. [17]

2.1.3 PV module efficiency

The characteristic curve of I-V of a photovoltaic cell depends on different environmental conditions, to be able to compare the different existing technologies, several methods have been established to test them.

The most common is the Standard Test Conditions (STC), in which the module temperature is 25°C, the solar irradiation (G) is 1000W/m^2 and the angle of incidence (θ) is 0°.

The characterization of the module is completed with the measurement of the Nominal Operating Temperature of the Cell, NOCT, defined as the temperature reached by the solar cells when the module is subjected to the following operating conditions: an irradiance of 800W/m^2, an ambient temperature of 20°C, normal irradiance and a wind speed of 1 m/s [18].

The value of the efficiency or performance of the cell will depend on external parameters that it cannot be controlled, such as temperature, solar irradiation or materials that can be deposited on top of our structure. Regarding the materials, these can be waste such sand or dust; also the drops of water since not only the day when it rains there is less solar radiation due to the clouds, but it can also carry waste residues that will later produce shadows in the module. All these external agents will be explained in more detail in sections *2.1.6*, *2.1.7* and *2.1.8*.

Therefore, under the Standard Test Conditions, the efficiency (η) of a solar cell is:

$$\eta = \frac{P}{G \cdot \mathrm{A}} \tag{8}$$

Parameters:

P: Power [W]

G: Irradiance [W/m^2]

A: Area [m^2]

Knowing the conditions of the STC, in this case the power is equal to the maximum power P_{Peak} [Wp]. Therefore, the peak power for a defined area and a determined efficiency is:

$$P_{Peak}[W_p] = \eta \cdot \mathrm{A} \cdot 1000 \tag{9}$$

Being the solar irradiance 1 kWp, it can be written that:

$$\eta = \frac{P_{Peak}}{A} \tag{10}$$

2.1.4 PV module output power

In the previous section it has been explained how it is possible to obtain the peak power value under standard conditions. But the reality tell that the received solar radiation almost never be under standard conditions, therefore, an adjustment must be made to obtain the theoretical output power, since the theoretical output power is directly proportional to the irradiance received.

Being the solar irradiance 1 kWp, it can be written that:

$$P_{Theoretical} = P_{Peak} \cdot \frac{G}{1000} \tag{11}$$

Parameters:

$P_{Theoretical}$: Theoretical output power given by the module [W]

P_{Peak}: Peak power of the module [W]

G: Irradiance [W/m^2]

But, the theoretical output power is not only influenced by the received radiation, but also by the angle of incidence of the irradiation and the temperature of the module, the influence of these parameters will be explained in sections 2.1.5 and 2.1.6 respectively. Therefore, under the influence of these variables, the theoretical power can be written as:

$$P_{theoretical}(\mathrm{T},\theta) = P_{peak}(25) \cdot \frac{[K_b(\theta) \cdot G_b + K_d \cdot G_d] \cdot [1 + (T_m - 25) \cdot \alpha]}{1000} \tag{12}$$

Parameters:

K_b: Correction factor of the angle of incidence for the power

G_b: Beam irradiance on the module [W/m^2]

K_d: Correction factor for diffuse radiation [%]

G_d: Diffuse radiation on the module [W/m^2]

T_m: Temperature of the module [°C]

α: Correction factor for the temperature [%/°C]

Once the theoretical power has been calculated, the energy that a module gives us during a period of time can be calculated.

$$E = \varphi \cdot \eta \cdot \mathrm{A} \cdot \mathrm{H} \tag{13}$$

The equation *13* can be written as:

$$E = \varphi \cdot P_{Peak} \cdot H \tag{14}$$

Parameters:

E: Output energy [kWh]

φ: Performance factor

H: Average annual solar radiation [kWh/m^2]

Where the parameter φ is a factor that allows to adjust the model to conditions outside the standard. It usually has a value between 0.85 to 0.95 [19].

2.1.5 Effect of Solar irradiance

The amount of radiation per unit area that the Earth receives at the top of the atmosphere is almost a constant, it can vary slightly throughout the year because the Earth's orbit around the Sun is elliptical, so it presents approaches or distances of the star, and because of solar activity whose cycle is 11 years. The updated value and more accurate is 1360.8 W/m^2; this value is known in the engineering literature as the "solar constant" [20].

The photovoltaic applications used in space, in satellites or spacecraft, have available solar radiation different from that of terrestrial photovoltaic applications. Radiation outside the atmosphere is distributed over different wavelengths in a manner like the radiation of a "black body", according to Planck's law, while at the surface of the Earth the atmosphere selectively absorbs the radiation of certain wavelengths. The radiation emitted by the surface of the Sun has a spectral distribution that resembles that of a black body at 5778 K. When crossing the atmosphere there is a reduction in the amount of energy that is finally received in the Earth's crust, around 1000 W/m^2[11], as seen in the figure:

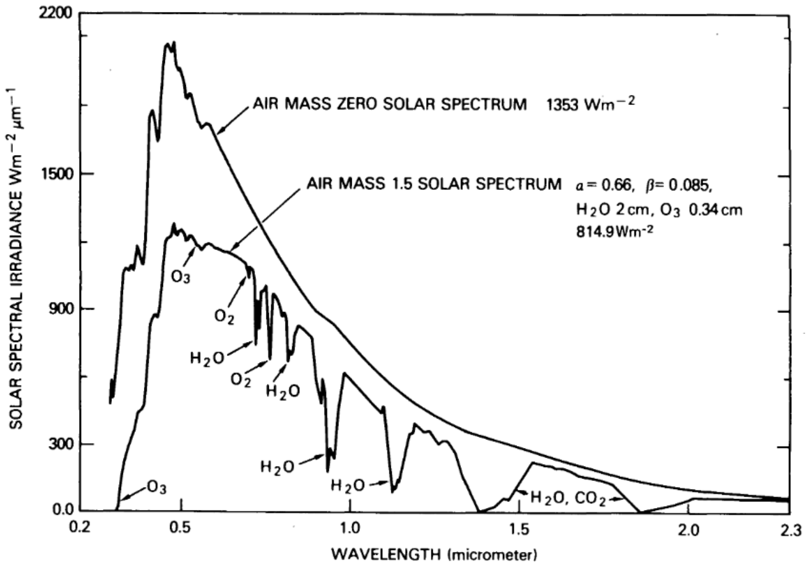

Figure 10. Irradiance of the Sun versus wavelength [21].

Irradiation is a combination of direct radiation and diffuse radiation, and depends on the location where it is located. It is shown in the following figure a scheme of both types of radiation.

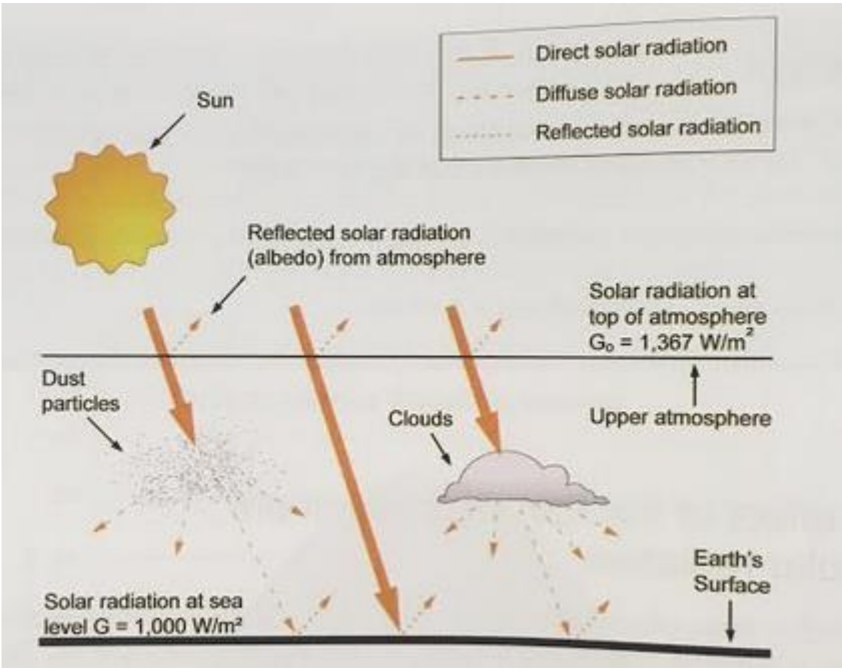

Figure 11. Solar Radiation comprises diffuse and direct radiation [11].

As has been explained in section *2.1.3*, for STC conditions, the air mass must be 1.5; here it is shown an outline of the air mass, as it can be seen the regions outside the tropics cannot have air mass one. The air mass is defined as the relative path length of the solar radiation as it passes the atmosphere.

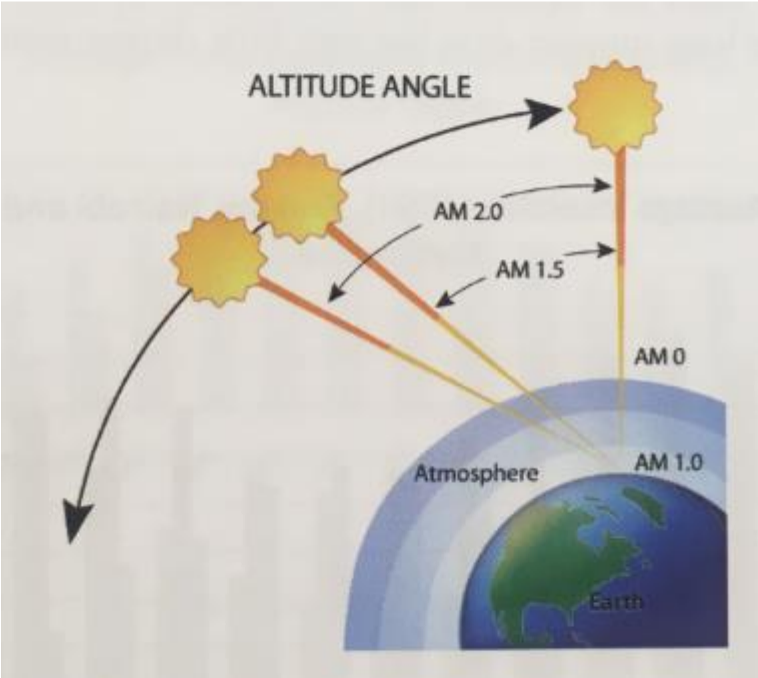

Figure 12. Air mass is directly related to the altitude of the Sun. [11]

The impact of solar irradiation is very important for our photovoltaic system, for this it is used the angle of incidence, which is the angle that is formed between the normal surface and the Sun's rays.

The angle of solar incidence is very useful, since it allows a relatively simple calculation of the incidence of radiation on a surface. The angular relationships between the incident of direct solar radiation on a plane, such as a surface area of wall or glass, arbitrarily oriented in relation to the Earth can be described in terms of various angles [22]. The angle of incidence is defined by the following equation:

$$\cos(\theta) = \cos(\delta)\sin(\omega)\sin(\beta)\sin(\gamma) + \cos(\delta)\cos(\omega)\sin(\lambda)\sin(\beta)\cos(\gamma) + \sin(\delta)\cos(\lambda)\sin(\beta)\cos(\gamma) - \cos(\delta)\cos(\omega)\cos(\lambda)\cos(\beta) + \sin(\delta)\sin(\lambda)\cos(\beta) \quad (15)$$

Parameters:

θ: Angle of incidence [°]

δ: Declination [°]

ω: Hour angle [°]

β: Tilt [°]

γ: Azimuth [°]

λ: Latitude [°]

The angles that define the angle of incidence are shown in the following figure:

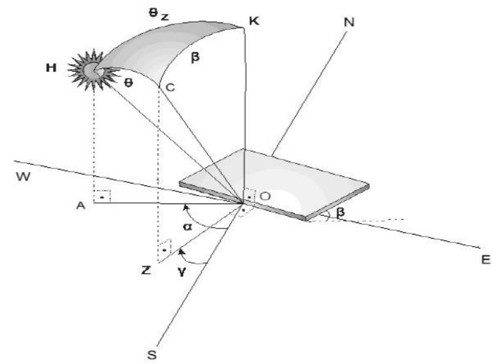

Figure 13. Representation of the zenith angle (θ_Z), the angle of incidence (θ), the surface azimuth angle (γ) and the tilt (β); between the Sun and the Earth on an inclined plane [22].

A summary of its definitions:

- Azimuth surface (γ) is the angle between the South and the projection of the normal in the horizontal plane of the surface. This angle is positive if the normal is to the South-West and negative if to the South-East.
- Tilt (β) is the angle at which the surface is inclined with respect to the horizontal and is taken positive for surfaces facing South.

- Latitude (λ) is an angle whose value goes from 0 ° to 90° and specifies the position of a point on the Earth's surface.

Therefore, as can be extracted from the previous information, solar radiation is received at different latitudes and at different times of the year, it varies because the axis of rotation of the Earth is not perpendicular to the ecliptic plane, but inclined at a fixed angle of 23.45°.

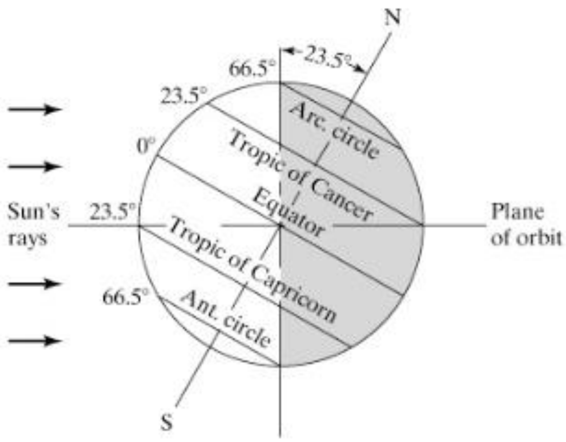

Figure 14. Position of the Earth in relation to the Sun´s rays in the winter solstice [23].

Hence, the solar declination is the angle between the Sun's rays and the equator's plane of the Earth. It varies by an angle between -23.45 to 23.45. Reaches its maximum value, (+23.45 °) on June 21, this day is called summer solstice. While the minimum value, (-23.45 °) is reached on December 20, this day marks the winter solstice. The declination is zero at the spring equinox (March 21) and at the fall equinox (22 September) [24].

The decline can be assumed as constant during the period of one day, for its calculation, proceed with the following formula:

$$\delta = 23.45 \cdot \sin[360 \cdot (\frac{284 + d}{365})] \tag{16}$$

Parameters:

δ: Declination [°]

d: Day of the year in the Julian calendar [day]

It is also found, the hour angle which is the angular distance between the circle of the hour of the Sun and the meridian of the site. It can be calculated as:

$$\omega = 15 \cdot [(hh_s - 12) + \frac{mm_s}{60}] \tag{17}$$

Parameters:

ω: Hour angle [°]

hh_s: Solar hour [h]

mm_s: Solar minutes [min]

For an observer on Earth the Sun seems to move around the Earth at the rate of 360° in 24 h or 15° per hour. The hour angle is set as negative before solar noon and positive after solar noon. To calculate the hour angle it is important to use the solar time and not the clock time [25]. Due to the specific time the Sun does not match the local clock time for two reasons:

The first is the changes in the rotational and orbital angular velocity of the Earth. To correct this factor, the equation of time (E) is used and can be expressed in minutes as:

$$E = 229.2 \cdot [0.000075 + 0.001868 \cdot \cos(\mathrm{B}) - 0.032077 \cdot \sin(\mathrm{B}) - 0.014615 \cdot \cos(2B) - 0.04089 \cdot \sin(2\mathrm{B})] \tag{18}$$

In this equation, our unknown B, is defined as:

$$B = (d - 1) \cdot \frac{360}{365} \tag{19}$$

Parameters:

d: Day of the year in the Julian calendar [day]

The second is the difference in the longitude between the location (local meridian, L_l) and the standard meridiam (L_{ST}). This correction has a magnitude of 4 minutes for each degree of difference in the longitude. Therefore, the solar time can be calculated as:

$$Solar\ time - Local\ Time = 4 \cdot (L_{ST} - L_l) + \mathrm{E} \tag{20}$$

Parameters:

L_{ST}: Standard meridian [°]

L_l: Local meridian of the location [°]

E: Correction factor of solar time [min]

To obtain the hour angle accurately, it is necessary to combine equation *18* and equation *20*:

$$\omega = 15 \cdot (hh - 12) + \frac{mm + E}{60} + (L_{ST} - L_l) \tag{21}$$

Finally, once all the parameters that define the angle of incidence have been obtained, it can be proceeded to its calculation, and therefore apply the correction factor of the angle of incidence as shown in equation ***12*** for module performance in section *2.1.4*. This correction factor (K_b) can be expressed as:

$$K_b(\theta) = 1 - b_0 \cdot (\frac{1}{\cos(\theta)} - 1) \tag{22}$$

Parameters:

$K_b(\theta)$: Correction factor of the angle of incidence

b_0: Correction factor of the angle of incidence for K_b

θ: Angle of incidence [°]

The correction factor of the angle of incidence for K_b can be observed in the following figure. When θ=60°, then K_b=1-b_0, the values of b_0 usually oscillate between 0.1 to 0.2.

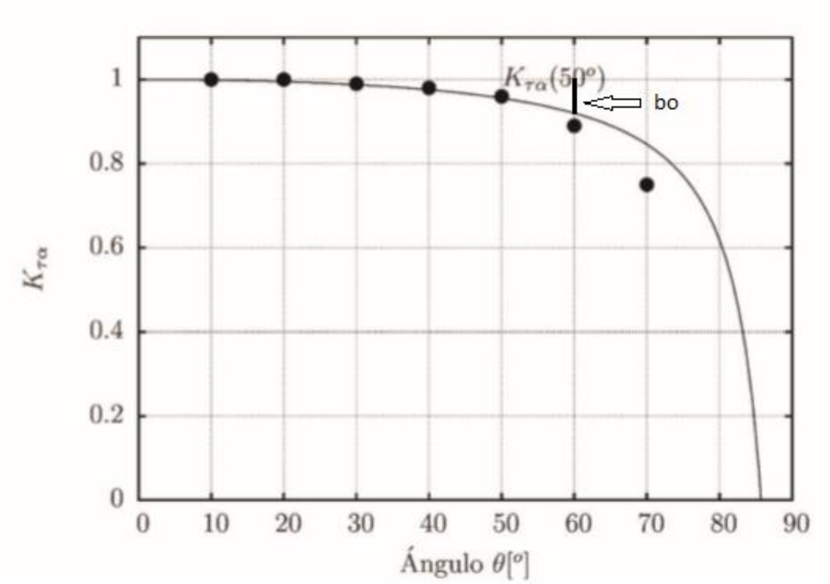

Figure 15.Correction factor for the angle of incidence. [20]

2.1.6 Effect of temperature

Another parameter that affects the performance of photovoltaic modules is the influence of the module temperature. Manufacturers perform tests under standard conditions (STC), maintaining the temperature of the cells at 25 °C. But with this temperature increasing: the open-circuit voltage (V_{OC}), the fill factor and the maximum output power decrease, while the short-circuit current (I_{SC}) increases slightly. Therefore, it can be said that the parameter, temperature coefficient, will be positive for the short circuit current and negative for the other three parameters affected [26].

In the following figure, the influence of temperature on the characteristic curve I-V is observed.

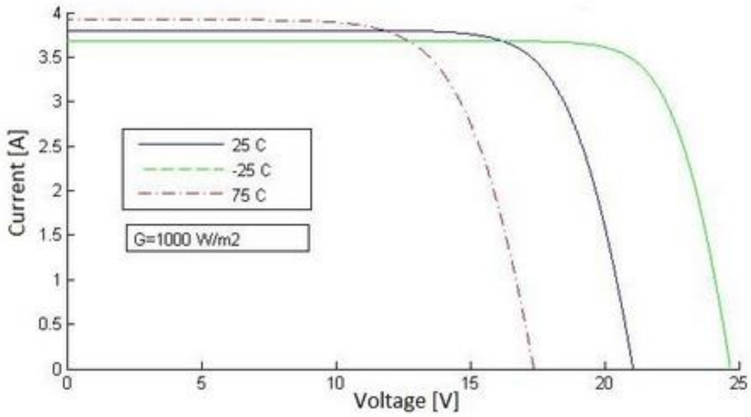

Figure 16. Temperature effect on the I-V curve. [27]

2.1.7 Effect of irradiance

In the case of the effect of the variation of solar irradiation; the most affected parameter is the short circuit current, which is directly proportional to the received irradiance [28]. In this case the value of the open circuit voltage is reduced, but not as drastically as with the effect of the increase in temperature. By varying the short circuit current, the maximum output power is also affected. The variation of the short-circuit current is shown in the next figure.

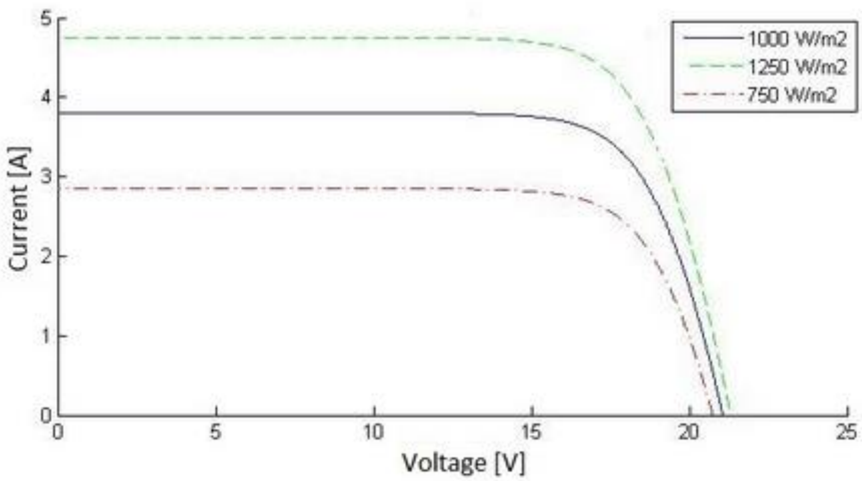

Figure 17. Irradiance effect on the I-V curve [29]

As it has been explained, the maximum output power is also affected, and is shown in the following figure.

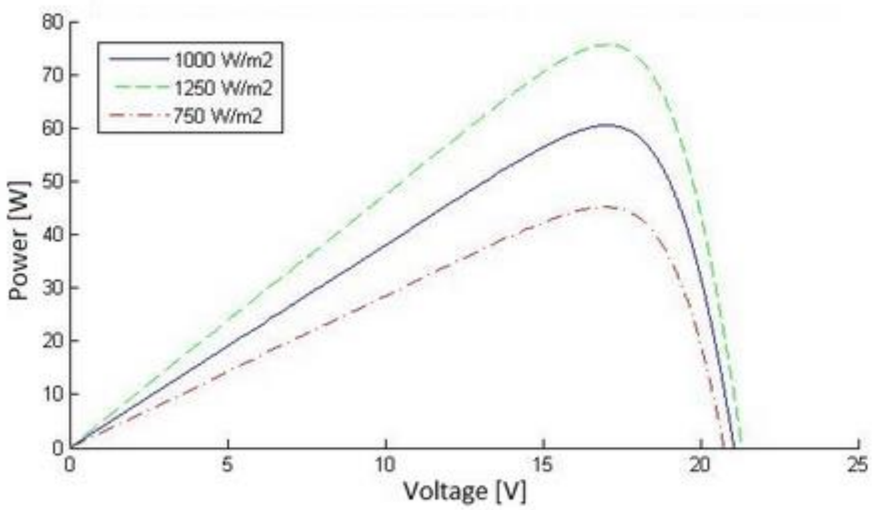

Figure 18. Irradiance effect on the P-V curve. [29]

2.1.8 Effect of shadows

Finally, the most significant environmental parameter that affects the performance the solar modules are shadows. These shadows can come from buildings, vegetation, clouds or objects that can generate a shadow on the solar panels, when they indicate sunlight.

It is possible to find two serious problems: the first is the reduction of the output power of our system, since there is a reduction in the solar radiation received. And the second is the possible destruction of our module due to overheating. At this point, it is called Hot Spot, there is a decrease in the current in the area affected by the shadow, becoming a reverse diode for the rest of the cells connected in series [30cite28].

To avoid this phenomenon and protect the system, the diode bypass is chosen, that is, when the sum of the positive voltages of the rest of the cells associated in series with the shaded cell exceeds the negative voltage of the cell in an amount equal to the activation voltage of the bypass diode. Then, the bypass diode starts to conduct, offering an alternative path for the current, and thus preventing the shaded cell from being damaged [31]. It can be seen in the following figure:

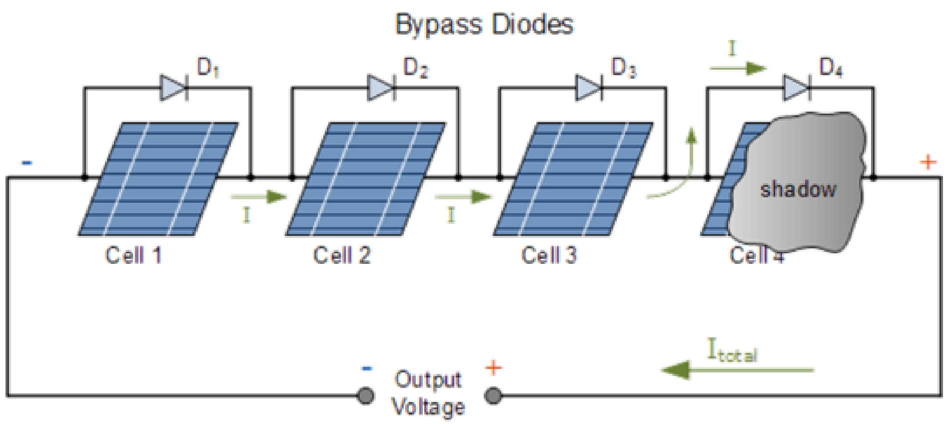

Figure 19. Current flow in bypass diode when the cell is shaded [32].

Regarding the maximum output power, in a system of modules in which part of one of them is shaded, as shown in the following figure.

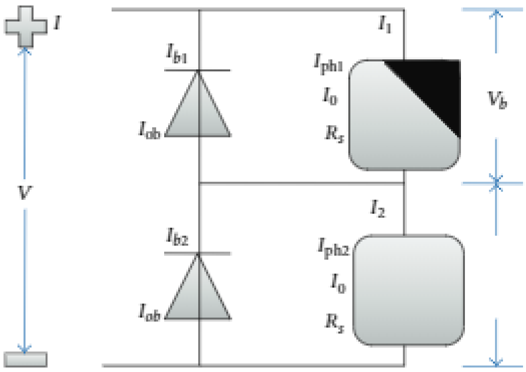

Figure 20. PV module equivalent circuit [30].

The power generated by the system will be highly affected by the shadows, the higher the percentage of the module affected, the greater the reduction in power generated.

In these cases, the characteristic curve I-V shows some variations that allow us to detect the presence of shadows in the system, these variations are presented in the following figure, where the curve I-V and P-V are observed for two strings of 18 cells each connected with two bypass diodes, and a single cell is affected by shadows:

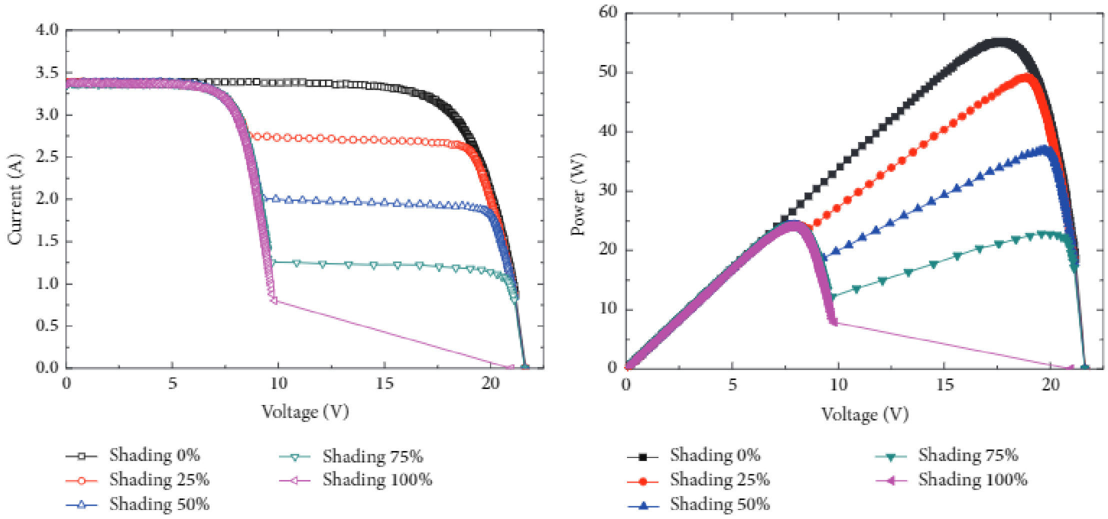

Figure 21. I-V curve and P-V curve [30]

3 Methodology

In this chapter, the procedures to carry out the thesis will be analysed. It will begin by explaining the installation and the measurement equipments used to acquire the data that allow analysing the system. Then, the irradiance on the modules where corrrected for the different tilts of the modules. Finally, it is described how the calculations have been carried out to obtain the relevant results.

3.1 Installation

The installation consists of 988 PV panels, half of which is oriented to the South-East and the other half to the North-West. For the transformation of direct current into alternating current, there are 10 inverters, 8 of them are connected to 138 PV panels and the other 2 are connected to 80 panels. The following image shows the installation.

Figure 22. PV installation

The following table reflects the characteristics of the complete installation divided into the 3 parts that are composed.

Table 1. Installation features.

A	Peak power per module	0,26	kWp					
		Part I		Part II		Part III		
		Input A	Input B	Input A	Input B	Input A	Input B	
B	Number of inverters	3		3		2		
C	Number of strings	3	3	3	3	2	2	
D	String per inverter	6		6		4		
E	PV Modules per string	23	23	23	23	20	20	
F	PV Modules per input	69	69	69	69	40	40	
G	PV Modules per inverter	138		138		80		
H	PV modules per part (B*G)	414		414		160		
I	Total PV Modules installation	988						
J	Peak power per string (A*E)	5,98	5,98	5,98	5,98	5,2	5,2	kW
K	Total power per input (C*J)	17,94	17,94	17,94	17,94	10,4	10,4	
L	Total power per inverter (Input A+ Input B)	35,88		35,88		20,8		
M	Total power per part (B*L)	107,64		107,64		41,6		
N	Total power installation	256,88						

Input A: North West Orientation
Input B: South East Orientation

Each PV panel contains 60 cells, counting a total of 59280 cells throughout the installation, they are manufactured with polycrystalline silicon from ShineTime Solar. The following table shows the technical datasheet of the PV panels.

Table 2. Technical Datasheet of Shinetime PV panel [33]

DataSheet STC			
Product type	Shinetime Solar XTM6-60-260		
Peak Power	Ppeak	260	[Wp]
Nominal Power Voltage	Vmp	30.6	[V]
Nominal Power Current	Imp	8.5	[A]
Open Circuit Voltage	Voc	38	[V]
Short Circuit Current	Isc	9.03	[A]
Module efficiency	η	15.98	[%]

As it has been explained in section *2.1.6*, the increase in temperature is a parameter that negatively affects our system, therefore, the manufacturer also indicates in the technical datasheet the temperature correction coefficients that must be applied for get more reliable results. These parameters are shown in the following table.

Table 3. Temperature coefficients for the Shinetime PV panel [33].

Temperature rattings			
Nominal Operating Cell Temperature	NOCT	45±3	[°C]
Temperature coefficient of	Pmax	-0.402	[%/°C]
Temperature coefficient of	Voc	-0.344	[%/°C]
Temperature coefficient of	Isc	-0.052	[%/°C]

In order to carry out the necessary measurements for the modelling of the installation, the voltages and currents from eigth strings have been collected by a junction box connected to a data logger, as well as the signals of the devices for monitoring the irradiance (reference solar cell and pyranometer) and the ambient temperature. In the following sections each device will be explained in more detail, figure 24 and 25 show the measurement system.

3.1.1 Inverter

The inverters in the photovoltaic system are used for the conversion of direct current into alternating current. Another of its properties is the optimization of energy, maximizing the energy of the solar panels [34].

In this installation the inverters type string have been used. These inverters are connected to several chains of solar panels in serie, this is an effective system since they are easy to maintain and are located in accessible areas. A string of series connected modules are sensitive to shading, since the module generating the lowest current limits the current in the string.

The inverters installed are from the SMA Company, in this case the model is the STP 25000 TL-30, an inverter with a maximum capacity of direct current input of 25550W and output in alternating current of 25000 W, with a maximum efficiency of 98.1% for European standards [35].

Each inverter has the capacity to connect to 6 strings. Eight inverters are installed, 6 of them are connected to 6 strings each, 3 strings come from the South-East orientation, and the other 3 from the North-West orientation. The other two are only connected to 4 strings, two of each orientation. The following figure shows an outline of the installation.

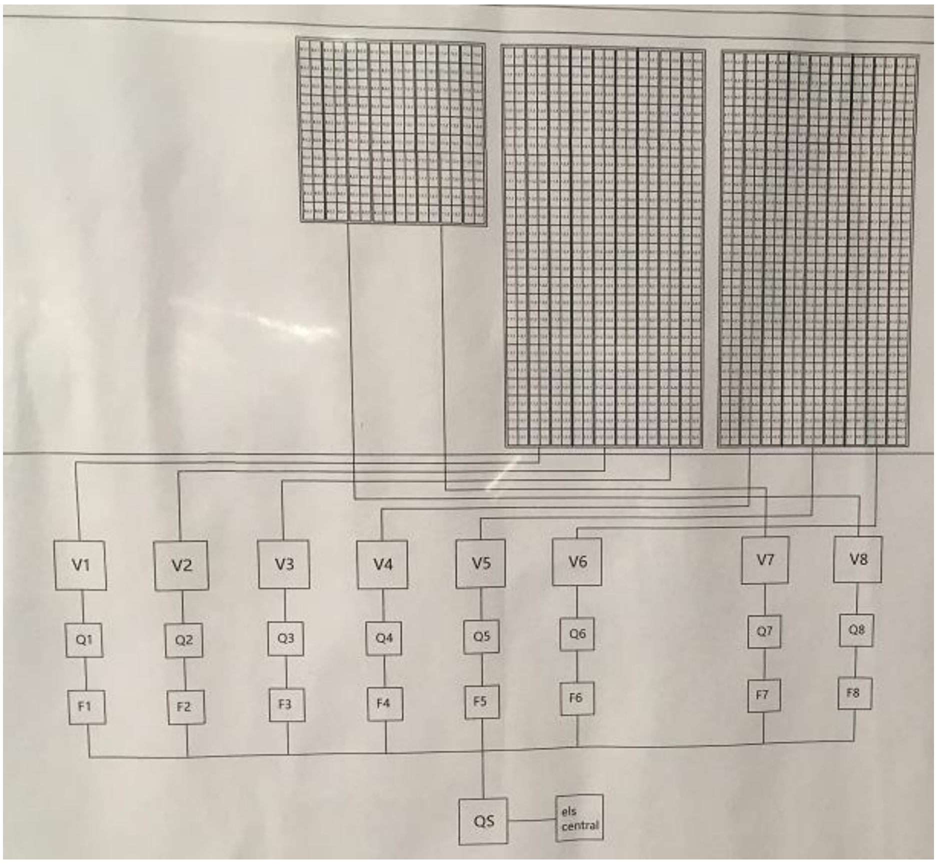

Figure 23. Electrical diagram of PV installation.

The junction box will be connected to the inverter, which will be explained in the next section.

3.1.2 Junction box

The junction box consists of an electrical box in which 10 electronic circuits have been installed, of which 8 will be used, since it will measure 8 strings.

The junction box is connected to the output of each string and to the inverter, in between, are the electronic circuits that are responsible for measuring the voltage and current through a resistor, these signals are sent to the logger.

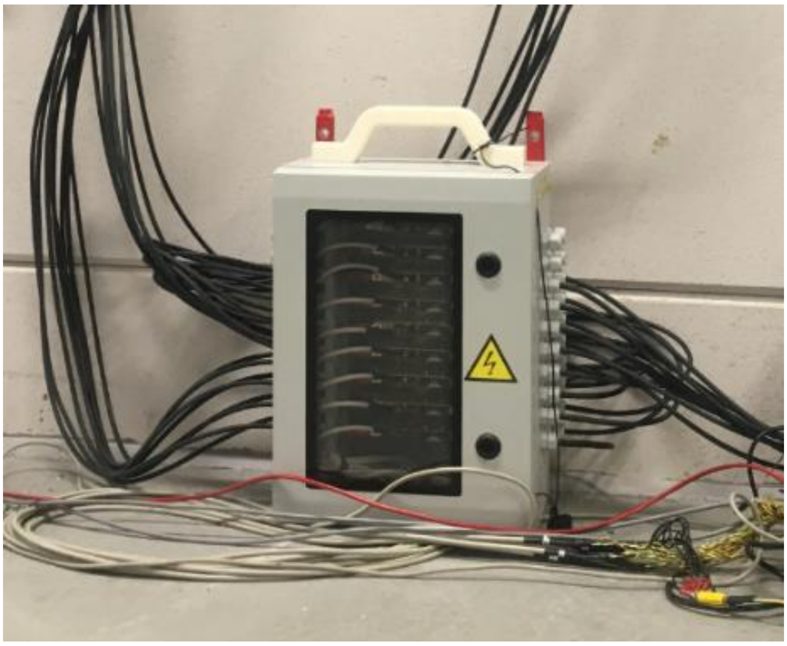

Figure 24. Junction Box.

3.1.3 External parameters

As it has been explained in chapter 2, there are external factors which seriously affect the functioning of the system, such as solar irradiation or module temperature, which will depend on the ambient temperature. In order to correctly model the installation and know its real performance, these parameters must be measured. The measuring devices will be explained in the following subsections.

The following figure shows the different measuring devices used, observe that the ambient temperature meter has been placed separately from the rest of the measuring devices to avoid shadows that affect them.

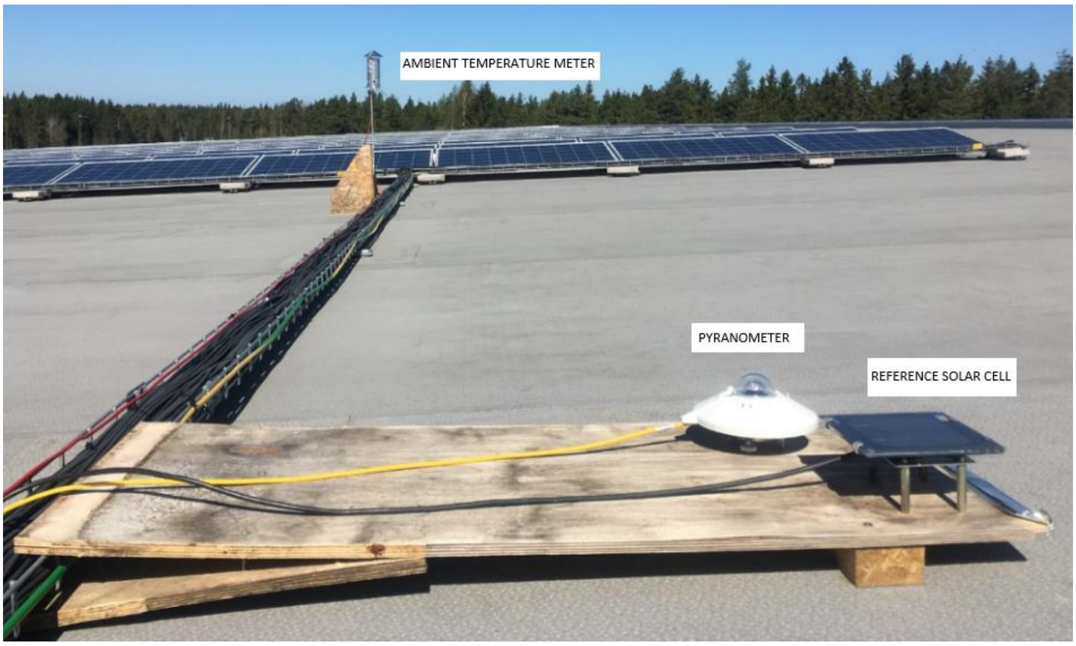

Figure 25. Devices on horizontal surface for measuring external parameters.

3.1.3.1 Pyranometer

A pyranometer is a measuring device that is used to determine the solar radiation received on a surface, it is made to measure global solar radiation at a view angle of 180° [36].

The pyranometer gives a signal in mV with a sensitivity factor of 13.11 mV for an irradiance of 1000 W/m^2.

3.1.3.2 Reference solar cell

The reference solar cell consists of two independent cells. One monitor the short circuit current which is proportional to the irradiance. The other cell monitor the open circuit voltage which gives the cell temperature. In the case of the reference solar cell, the cell generates a current (I_{SC}) that is measured as a voltage over a small resistance. The voltage is proportional to the irradiance. The following table shows the technical datasheet of the reference solar cell [37].

Table 4. Technical Datasheet of the Reference Solar Cell [38].

Reference solar cell		
Voc signal	586.7 per 1000	[mV/(W/m2)]
Isc signal	28.7 per 1000	[mV/(W/m2)]
β	-2.17	[mV/°C]

3.1.3.3 Ambient temperature meter

As it has been explained in section 2.1.6, temperature is a factor that negatively influences the system. To do this, the second parameter will be measured, which is the ambient temperature, by means of a temperature sensor enclosed in a metal box to avoid the solar irradiance and contact with the water since it is directly connected to the logger, which is an electronic device and could be damaged. Likewise, holes have been made in the box to cool the inside of the box and prevent overheating that could affect the taking of measurements.

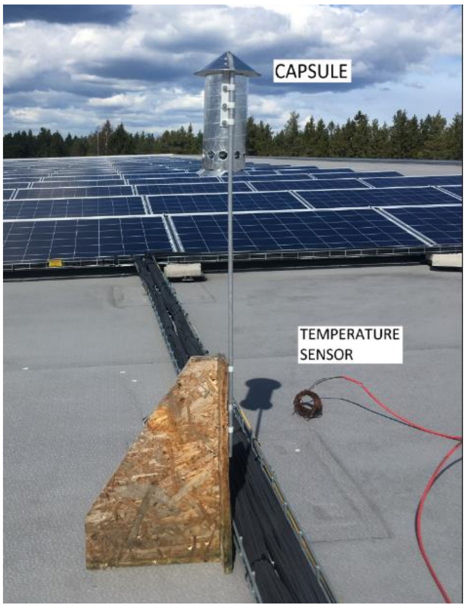

Figure 26. Ambient temperature meter.

3.1.4 Logger

To obtain the data that will allow the study of the installation requires the use of a data logger, this electronic device allows to record data in real time, with the period that is indicated, within a range assigned to each data logger, can measure both by own and external sensors.

The Agilent company's data logger model 34970A [39] was used to study this installation.

Figure 27. Data Logger Agilent 34970A.

It must be taken into consideration that the logger works in solar time. Therefore, an adjustment of one hour will have to be made to convert it to normal time.

3.1.5 Program data

Once all the devices are connected to the logger, the data is recorded using the connection between the logger and a computer. To record the data, the LabVIEW program (Laboratory Virtual Instrument Engineering Workbench) is used, a program that allows to control and measure systems with a quick access to the data [40].

In this study the program will collect the data of: current and voltage of each string, the short-circuit current and the open-circuit voltage of the reference solar cell, a voltage from the pyranometer that will allow the calculation of the irradiance, and finally, the ambient temperature recorded by the temperature sensor. The logger collects the data every 10 seconds and returns an average every minute of the 6 measurements that have been taken.

3.2 Geographical coordinates and correction angles.

The solar irradiation depends on the place of the planet the installation is located. Therefore, the installation site must be defined. In this case, the installation is located in Gävle (Sweden), with coordinates of: Latitude: 60°41'35.277'' N; Longitude: 17°08'12.395" E [41].

As the modules are oriented in two ways, half in the South-East direction and the other half in the North-West direction, there will be two different azimuth angles according to the orientation being -45° for the South-East and 135° for the North-West.

Because the pyranometer is located horizontal and the panels have a tilt of 10°, a correction must be made to calculate the irradiance for each orientation of the panels.

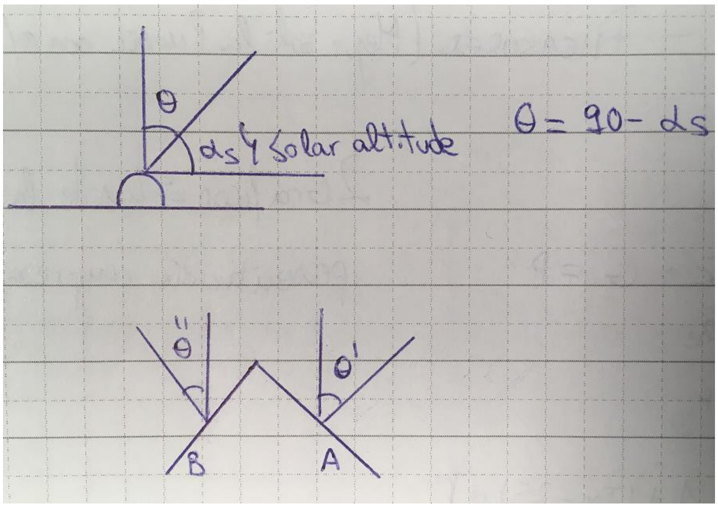

Figure 28. Angles for correction irradiance.

$$G_{(A)} = G \cdot \frac{\cos(\theta')}{\cos(\theta)} \qquad (23)$$

$$G_{(B)} = G \cdot \frac{\cos(\theta'')}{\cos(\theta)} \qquad (24)$$

Parameters:

G_A: Irradiance corrected for panels facing South-East [W/m^2]

G_B: Irradiance corrected for panels facing North-West [W/m^2]

G: Irradiance calculated by parameters measured with the pyranometer

θ: Angle of incidence on the pyranometer [°]

θ': Angle of incidence. South-East orientation [°]

θ'': Angle of incidence. North-West orientation [°]

3.3 Steps for resolution

For the resolution of the system, a code has been programmed in Visual Basics (Microsoft Excel) to accelerate the visualization of results, through a faster processing of data thanks to programming. The main objective has been to monitor the real performance of the photovoltaic installation and compare it with a previously simulated model, in order to verify that the simulated model is close to real. For this, the following steps have been carried out.

3.3.1 Monitored power

It will be measured in the 2 inverters with 4 strings each, with 20 modules per string, explained in subsection 3.1.1. The nominal powerof each string is 20*0.260=5,2kWp

To calculate the output power that the system is generating, a matrix is generated with the measured voltage and current data, explained in section 3.1.2. The installation joins 10 panels in series and each two blocks of 10 panels in parallel. Therefore, in each string there are have 20 modules.

With the collected data, the power of each string is calculated in the period of time selected for data collection. For this, the equation of the power, reflected in equation *5*, is used.

Once the powers of each string are calculated, the total power produced in each inverter is obtained by summing the powers of each string, and the energy produced each day in kWh/day for each string is programmed on the screen, and the maximum power peak of each string is obtained.

3.3.2 Simulation power

To calculate the theoretical power that the system will give, equation *12* should be used, explained in section *2.1.4*. The calculation of the parameters that compose it, is described in the following subsections.

3.3.2.1 Peak power

Table 1 shows the different characteristics of the solar panels installed, including the value of P_{peak}. This value is 260 Wp per module. By having 20 modules for each string, the value of the peak power can be written as:

$$P_{peak} = N_{modules} \cdot P_{peak}(one\ module) \tag{25}$$

Parameters:

$N_{modules}$: Number of modules in one string

3.3.2.2 Solar irradiance

Regarding irradiance, values are obtained through the pyranometer and the reference solar cell. In equation *12*, it is observed that the solar irradiance is divided into direct and diffuse radiation. But diffuse radiation only cannot be measured with the available devices. Therefore, it is assumed that all radiation is direct. Obtaining the following formula.

$$P_{theoretical}(\mathrm{T}, \theta) = N_{modules} \cdot P_{peak}(one\ module) \cdot \frac{[K_b(\theta) \cdot \mathrm{G}] \cdot [1 + (T_m - 25) \cdot \alpha]}{1000} \tag{26}$$

For the calculation of the irradiance, it must be calculated for each measurement device, since each of them has different characteristics. In the case of the pyranometer, the sensitivity it has, explained in subsection *3.1.3.1*, is 13.11 mV for an irradiation of 1000 W/m^2. Being the calculation for irradiance:

$$Irradiance_{pyranometer}(\frac{W}{m^2}) = \frac{V_{pyranometer} \cdot 1000}{13.11} \tag{27}$$

In the reference solar cell as explained in subsection 3.1.3.2, a resistor is used to obtain the short circuit current in mV. In Table 3, it can be observed that the signal for an irradiation of 1000 W/m^2 is 28.7 mV. In previous works, it has been observed that a correction factor of 1.02 has to be applied to adjust the values between the pyranometer and the reference solar cell. Obtaining the following equation:

$$Irradiance_{reference\ solar\ cell}(\frac{W}{m^2}) = 1.02 \cdot \frac{I_{SC} \cdot 1000}{28.11} \tag{28}$$

3.3.2.3 Angle of incidence

During the day, the Sun goes orbiting, changing its position with respect to the solar panels, this change has a great effect on the irradiance received by the panels. Therefore, an adjustment of this parameter must be made by means of the correction factor of the angle of incidence, explained in section *2.1.5*, which is reflected in equation 22.

To calculate the angle of incidence a program created by Björn Karlsson has been linked to the main Visual Basics program. In the first step, the following parameters are requested for the calculation of the angle of incidence: latitude, longitude, tilt angle, azimuth, standard meridian, and the day and month of the year in which the data were obtained.

The program has been debugged to avoid operations with K_b values greater than 1.2 or negatives values, and to avoid that if there is an angle of 90° it is operated to avoid an indeterminate form in the equation, since cos (90°) = 0.

3.3.2.4 Module temperature

The characteristic curve of a solar module is severely affected by the increase in temperature, as explained in section *2.1.6*. Therefore, equation *12* must be adjusted, with the temperature of the module and the temperature coefficient (α).
As with the irradiance, there are two measuring devices, and the module temperature must be calculated differently. For the reference solar cell, the data used are: the open circuit voltage and a decrease value of this voltage for each degree centigrade that is called β, these parameters are found in Table 3. The following equation is given:

$$T_{module} = \frac{V_{OC}(STC) - V_{OC}}{\beta} + T_{STC} = \frac{586.7 - V_{OC}}{2.17} + 25 \qquad (29)$$

Parameters:

T_{module}: Temperature of the module [°C]

$V_{OC}(STC)$: Open circuit voltage in Standard Conditions [mV]

V_{OC}: Open circuit voltage measured by the reference solar cell [mV]

β: Temperature coefficient for V_{OC} [mV/°C]

T_{STC}: Temperature of Standard Conditions [°]

In the case of the pyranometer, the temperature of the module must be calculated by the ambient temperature measured by the temperature sensor, and a ratio between the measured irradiance with the pyranometer and the heat transfer coefficient. Obtaining the following formula:

$$T_{module} = T_{ambient} + \frac{G}{h} \qquad (30)$$

Parameters:

$T_{ambient}$: Ambient temperature measured by the temperature sensor [°C]

G: Irradiance calculated from pyranometer measurements [W/m^2]

h: Heat transfer coefficient [W/m^{2}K]

Once the calculations have been made, the heat transfer coefficient should be adjusted in a range of 20 to 30 W/m^2K to find the value that allows us to obtain the smallest error in the difference between the temperature of the module calculated with the reference solar cell and the pyranometer. In this case, 20 W/m^2K has been the chosen value, since it is the value that makes the model adjust more the real values obtained with the different measuring devices.

3.3.2.5 Losses

Due to the losses produced in the cables and measurement systems, an efficiency of 95% has been considered. Therefore, equation 12, finally turns out to be:

$$P_{theoretical}(\mathrm{T},\theta) = \eta \cdot N_{modules} \cdot P_{peak} \cdot \frac{[K_b(\theta) \cdot G_b] \cdot [1 + (T_m - 25) \cdot \alpha]}{1000} \qquad (31)$$

Parameters:

η: Efficiency due to losses in the system

3.3.3 Nominal power

Apart from comparing the real and the simulated power, the other point to evaluate in this study is to know if the installation can be adjusted to a linear regression of the power that it should deliver in standard conditions.

In the case of this study, there are 8 strings, and each of them contains 20 modules. Therefore, for an irradiation of 1000W/m^2, the power input for each string should be 5.2 kW.

To observe this regression, it is necessary to calculate the nominal power for each measuring device, with the different considerations regarding the module temperature and the angle of incidence. Obtaining the following equations:

$$P_{nominal\ string}(\text{Pyranometer}) = \frac{I \cdot \mathrm{V}}{K_b(\theta) \cdot [1 + (T_m - 25) \cdot \alpha]} \qquad (32)$$

$$P_{nominal\ string}(\text{Reference Solar Cell}) = \frac{I \cdot \mathrm{V}}{[1 + (T_m - 25) \cdot \alpha]} \qquad (33)$$

No angular correction is done for the reference solar cell, since it is assumed to have the same angular dependence as the PV-modules.

3.3.4 Reliability of the measurement system

Once everything necessary for studying the system has been calculated, it must be verified that the measurements have been correct. Therefore, for each string it is calculated:

$$Reliability = \frac{P_{string}}{Irradiance} \qquad (34)$$

If the data and the information treated is correct, this relationship should be represented as a straight line, because the power is proportional to the solar irradiance.

4 Results

In this chapter the results obtained after the analysis of the raw data are presented. Results have been obtained for days with different weather conditions: rain, cloudy or sunny days. The 9th of May was chosen as a reference due to the fact that it was a day without inclement weather and the results are more adjusted to the theoretical model. The remaining days are represented in Appendix I, II, III, IV and V.

Because there are panels with different azimuths, the results will show the string 7 and 8, the string 7 located in the North-West direction, and the string 8 in the South-East direction.

4.1 Reliability of measurement system

Once the raw data was analysed, in subsection *3.3.4*, it was mentioned that the reliability of the system should be observed. In the following figures it is observed that the system follows the same linear trend, with peaks due to failures in the model system, but which ensure that the results are reliable.

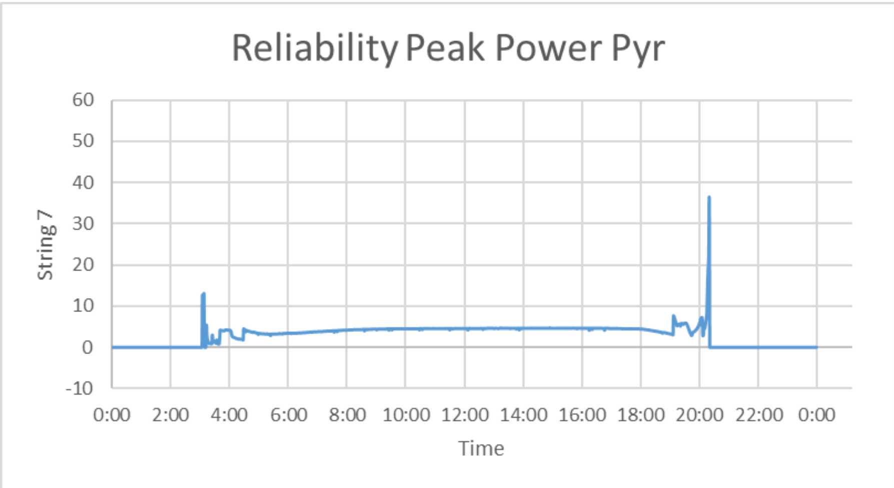

Figure 29. Reliability of the measurement system for String 7 using the Pyranometer 9th of May.

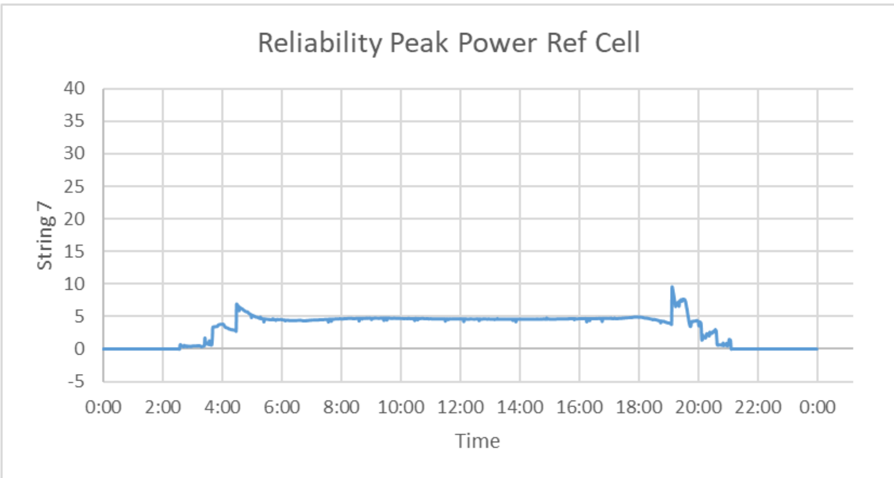

Figure 30. Reliability of the measurement system for String 7 using the Reference Solar cell 9th of May.

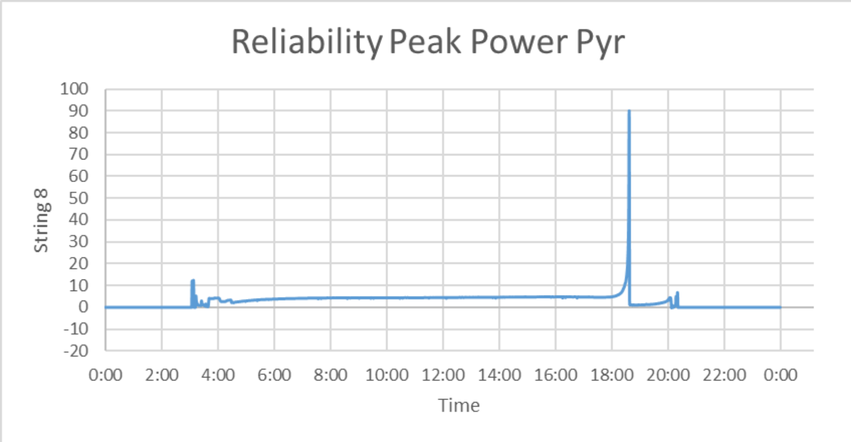

Figure 31. Reliability of the measurement system for String 8 using the Pyranometer 9th of May.

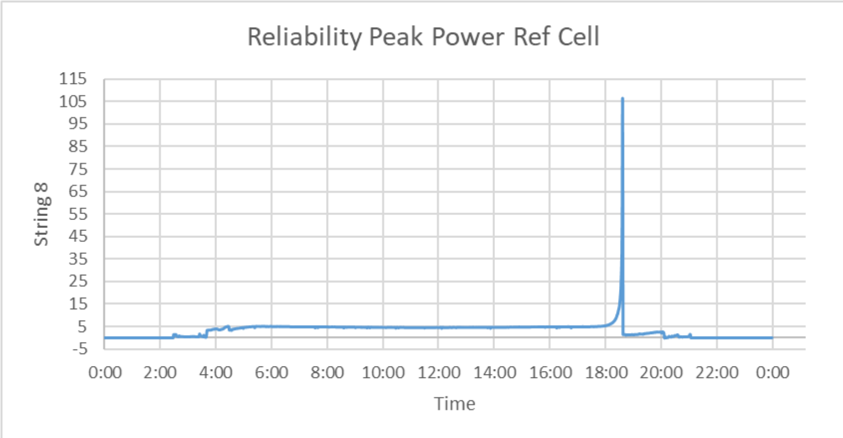

Figure 32. Realibility of the measurement system for String 8 using the Reference Solar cell 9th of May.

4.2 Output Power

Assured the reliability of the model, the relationship between the power of the strings and the irradiance obtained with the pyranometer and the reference solar cell are shown in the figures 33-36.

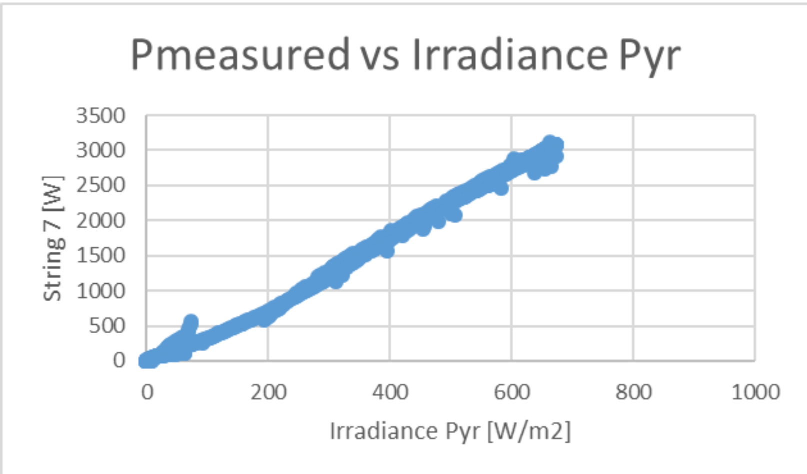

Figure 33. Relation between the irradiance measured with the Pyranometer and the output power of the String 7, 9th of May.

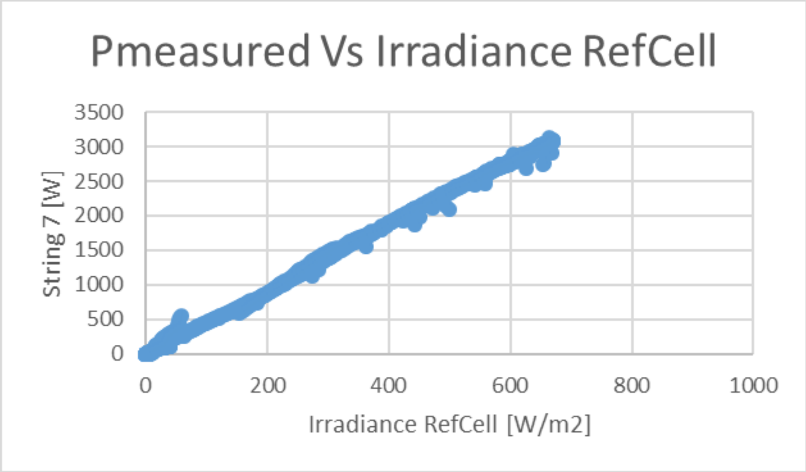

Figure 34. Relation between the irradiance measured with the Reference Solar cell and the output power of the String 7, 9th of May.

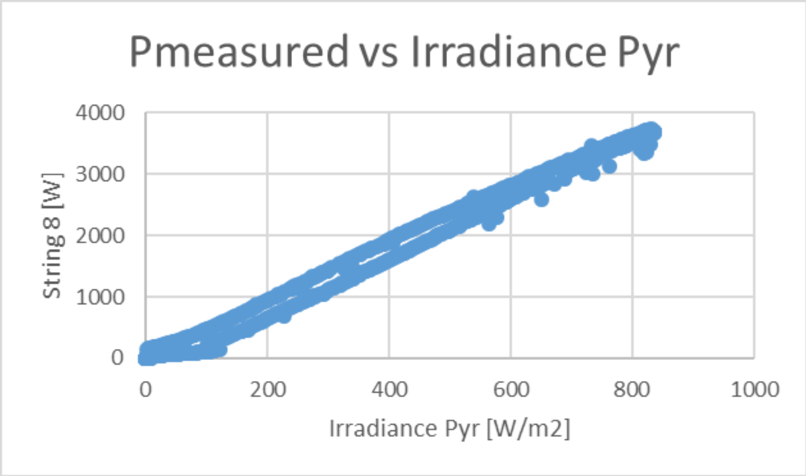

Figure 35. Relation between the irradiance measured with the Pyranometer and the output power of the String 8, 9th of May.

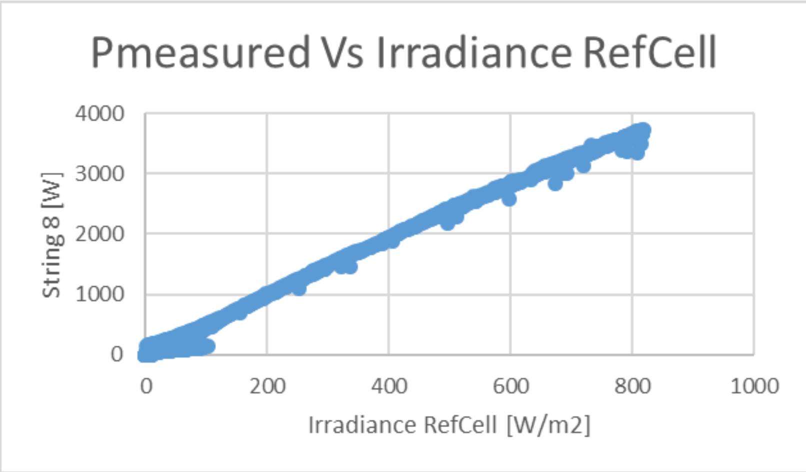

Figure 36. Relation between the irradiance measured with the Reference Solar cell and the output power of the String 8, 9th of May.

The data must be filtered to obtain a more optimal result for the model as will be observed in the following sections.

4.3 Comparison Theoretical and Real Power

Two different measuring devices have been used to calculate the irradiance. Therefore, two theoretical powers have been obtained, one regarding the pyranometer and the other regarding the reference solar cell.

In the following figures, it can be seen how the differences between the measured power and the power of the theoretical model is reduced when the corrections of the angle of incidence and temperature are applied.

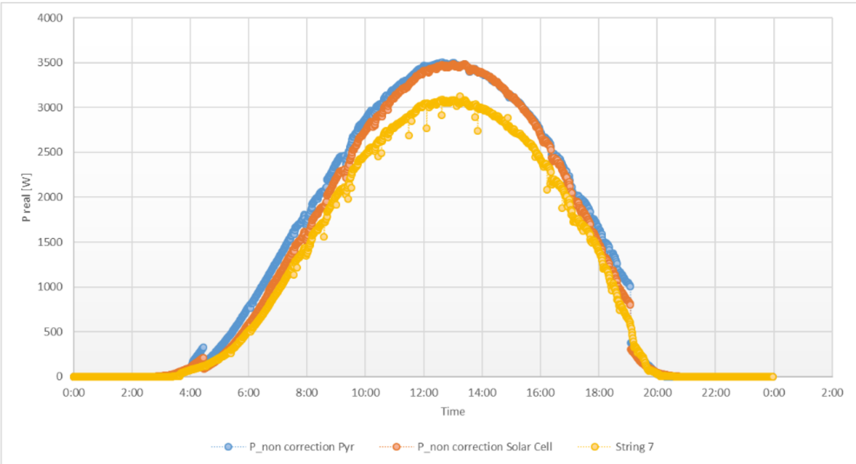

Figure 37. Gmodule x Ppeak. String 7, 9th May.

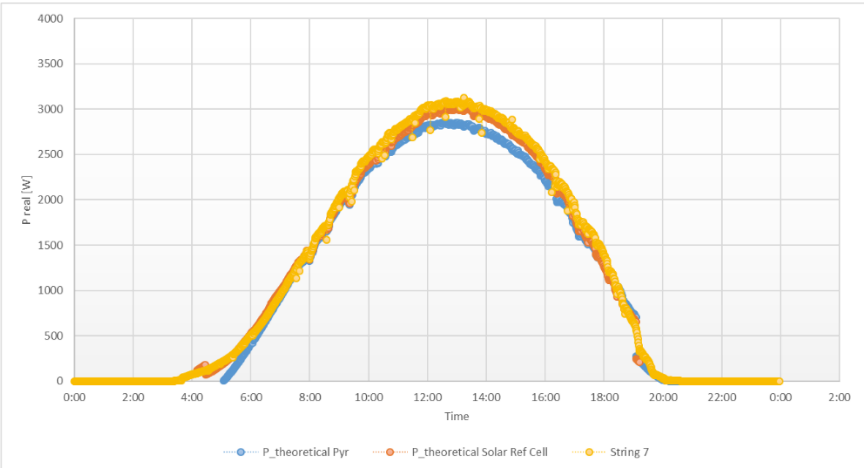

Figure 38. Performance of the Theoretical and Real Power. String 7, 9th May.

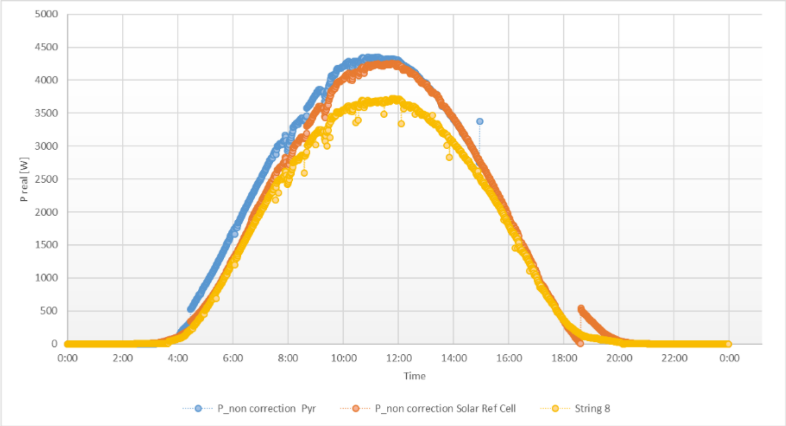

Figure 39. Gmodule x Ppeak. String 8, 9th May.

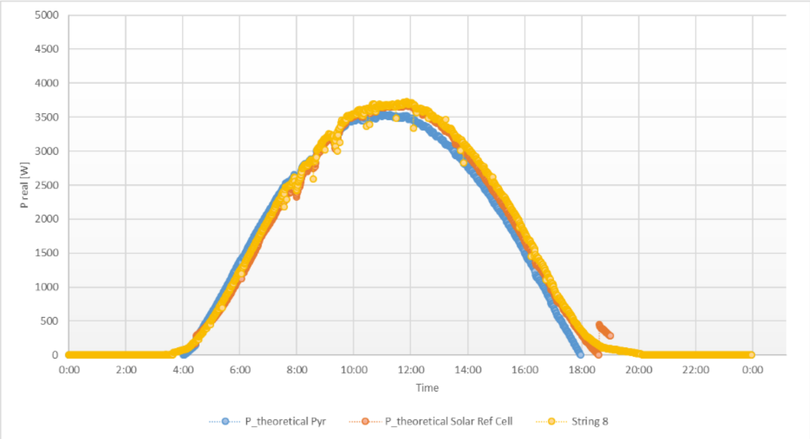

Figure 40. Performance of the Theoretical and Real Power. String 8, 9th May.

Figures 37-40 show the real power curve versus those generated by the data obtained with the pyranometer and the reference solar cell. Without applying the corrections of the angle of incidence and the module temperature (Figure 37 and 39) and applying those corrections (Figure 38 and 40). Whereas the following figures 41-44, decompose figures 38 and 40, to observe clearly the difference between the curve generated with the pyranometer and the reference solar cell.

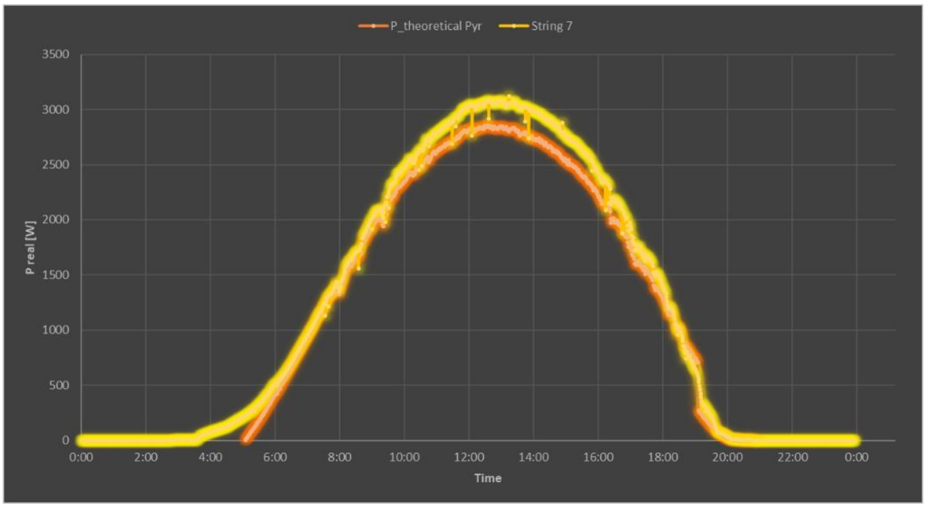

Figure 41. Pyranometer power vs Real Power. String 7. 9th May.

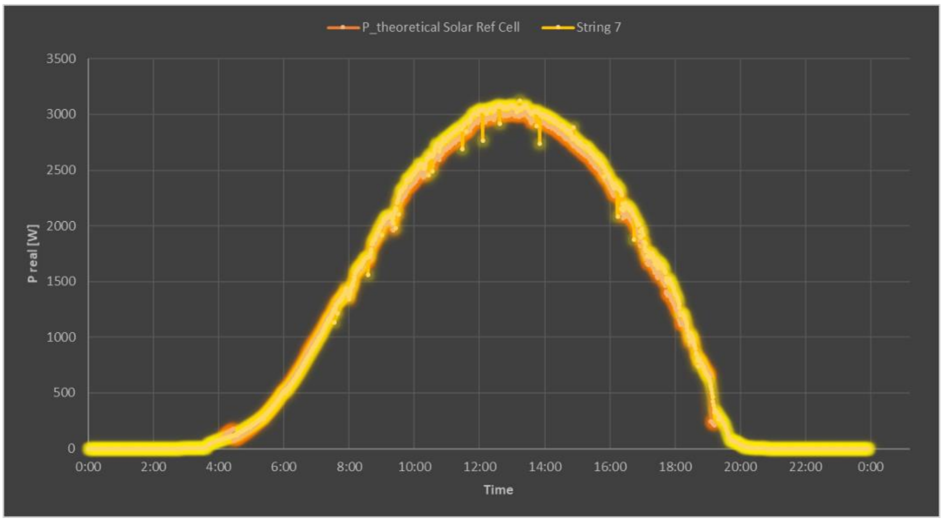

Figure 42. Reference Solar cell power vs Real Power. String 7. 9th May.

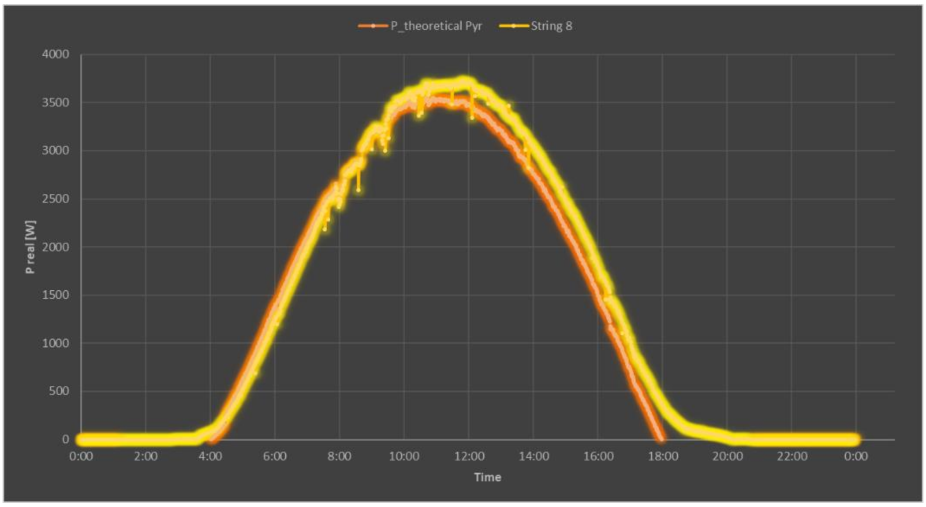

Figure 43.Pyranometer power vs Real Power. String 8. 9th May.

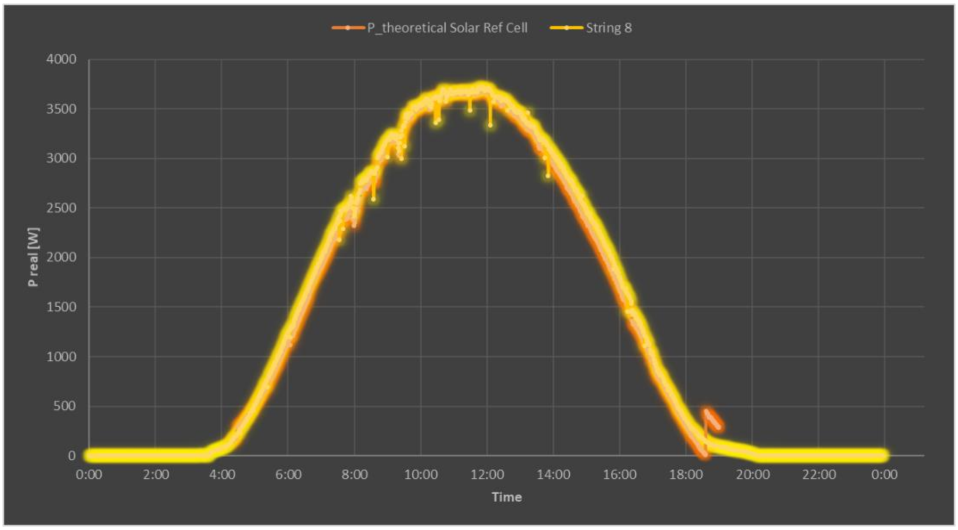

Figure 44.Reference Solar cell power vs Real Power. String 8. 9th May.

4.4 Expected power

To observe if the model will work correctly, the expected power must also be observed, because if a linear regression can be approximated, the created model could be validated.

The data of the nominal power have been filtered to avoid incoherent data due to the correction of the angles, since irradiances were obtained above 5000 W/m^2 or negative, even reaching negative values of -12000 W/m^2. In the following figures, the nominal power versus irradiance is represented.

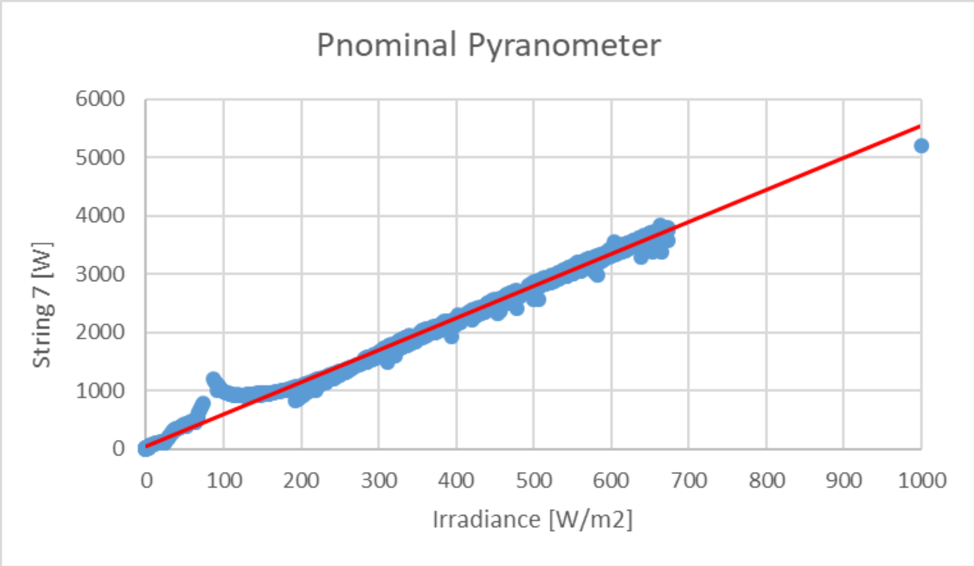

Figure 45. Relation between the nominal power and the irradiance of the Pyranometer. String 7, 9th May.

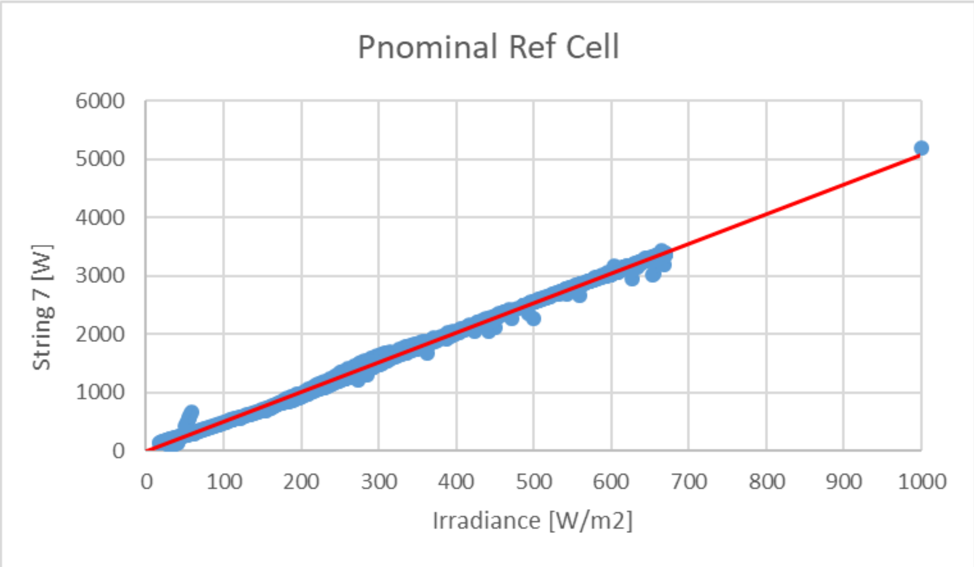

Figure 46. Relation between the nominal power and the irradiance of the Reference Solar cell. String 7, 9th May.

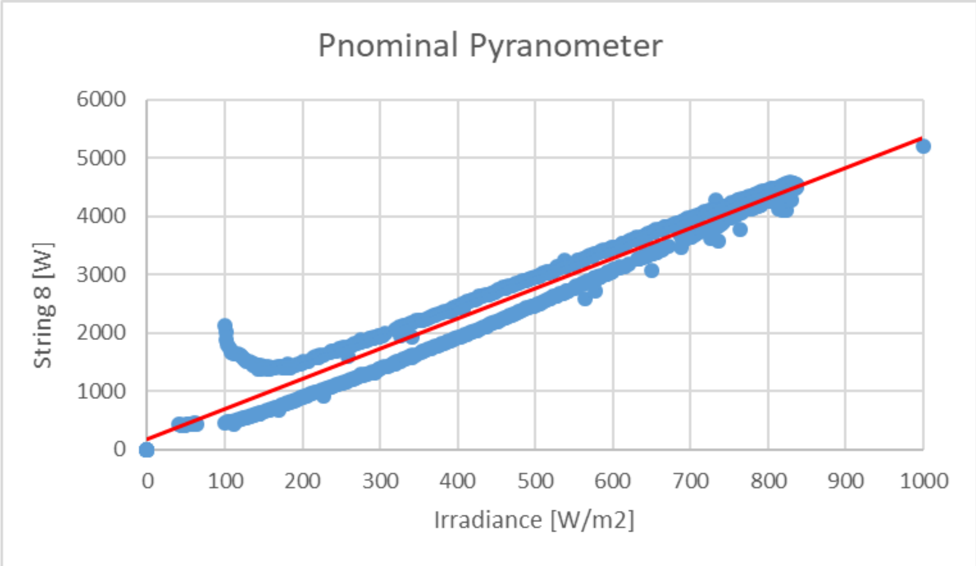

Figure 47. Relation between the nominal power and the irradiance of the Pyranometer. String 8, 9th May.

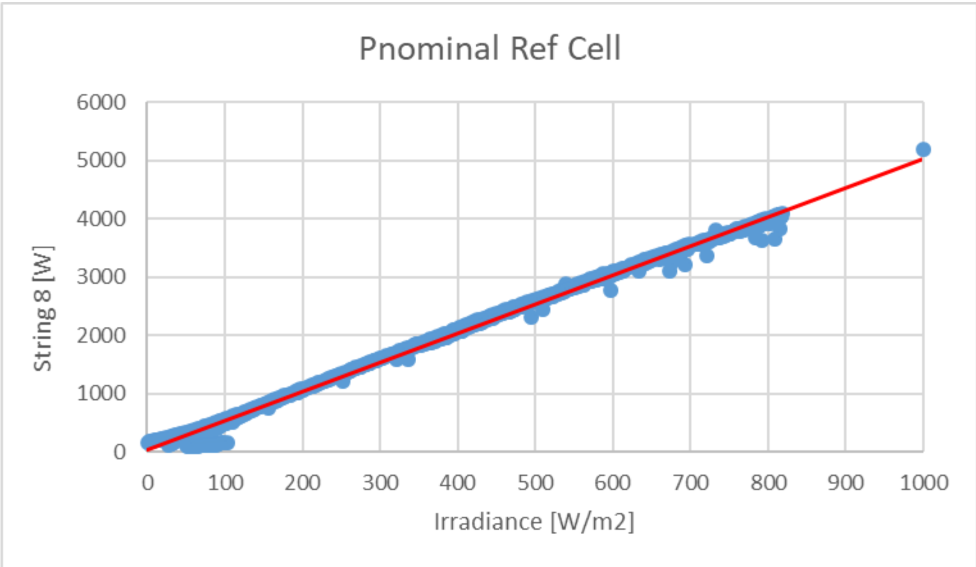

Figure 48. Relation between the nominal power and the irradiance of the Reference Solar cell. String 8, 9th May.

As can be seen, it is possible to reach the target of the expected power at 5,2kW. String 7 even exceeds that power, this may be due to calibration problems in the pyranometer. This problem can also be seen in section 4.3; since the pyranometer can not follow the real curve of the measured power.

The linear dependence between the nominal power and the irradiance on the modules in figures 45-48 indicates that the maximum power point trackers works properly for all solar intensities.

4.5 Total power

Due to the orientation of the panels, the following figure shows the variation of total power during one day and the average of kWh delivered by each string. The odd number strings is oriented to the North-West, while the even stringss are oriented to the South-East.

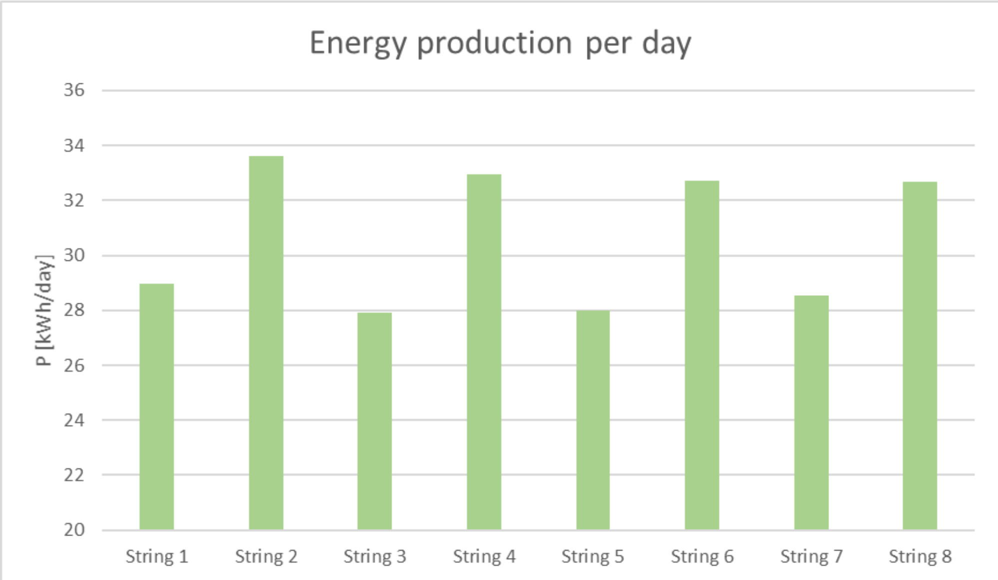

Figure 49. Energy production in kWh delivered by each string, 9th May.

A clear decrease can be observed in the panels oriented North-West with respect to those oriented to the South-East, this is due to the greater amount of solar radiation received by the latter, since the solar trajectory makes them more exposed to the irradiation. The differences between strings with the same orientation are minimal.

5 Discussion

5.1 Reliability of measurement system

Although the step of observing the reliability of the measurement system has been the last to be presented in the methodology to be followed. It must be the first to be presented, as it indicates whether the system is working correctly.

As indicated previously in subsection *3.3.4*, the relationship between the power of each string and the irradiance must follow a constant straight line.

Normally, in the panels facing South-East, the relationship is usually constant, except for peaks at the beginning and end of production, around 4:00 and towards 9:00 p.m. This is due to the corrections that have been made due to the position of the measuring devices, obtaining very high or negative values of the correction factor (K_b). These values have been treated, so that they do not intervene in obtaining the final results.

In the case of North-West facing panels, records are also recorded at the beginning of production, around 4:00 and between 6:00 pm and 9:00 pm; As in the other panels, the data has been treated to avoid influencing the final results.

5.2 Output Power

Regarding the measured output power of each string, in the case presented in the results it can be observed that for the same irradiance in the range between 0 to 200 W/m^{2}K it is obtained two different powers. The power values for the same irradiance gives greater power in the case of string 7 (figure 33 and 34), and lower for string 8 (figure 35 and 36), is due to the angle of incidence of that radiation in the panels due to its orientation and its correction, the measuring devices do not work accurately at low irradiation. It is very difficult to align the pyranometer, reference cell and the modules in exact angulars.

This phenomenon can be observed more clearly, in the sunniest days: 9th, 14th and 15th of May, but in those in which there has been rain or there have been clouds during the day. It is obtained a scatter of points on the graph that prevents you from observing this system characteristic that can be observed in Appendix II.

5.3 Comparison Theoretical and Real Power

The comparison between real and theoretical power is one of the most important points of the thesis, since it is one of the parameters that shows that the model that has been used is valid.

As can be seen in figures 37 and 39, respectively for the string 7 and 8, the curves of the theoretical power with the data of the pyranometer and the reference solar cell, differ greatly from the power value that the plant is delivering.

While using the method proposed in this project, by means of a correction in the received irradiance and in the temperature of the module and its correction, a much more adjusted graph with respect to reality is obtained as shown in figures 38 and 40, for the string 7 and 8 respectively. It does not matter if the day was sunny or there were inclement weather, the model acts according to the received values and offers a much more real response to what is measured directly from the installation. Although, in the case of the pyranometer, as can be seen in figures 41-44. The curve does not adjust as much as that of the reference solar cell, this may be due to the fact that the global radiation is measured. But, only a corrective fatcor is applied to direct radiation. In addition, as discussed in section *5.2*, it is very difficult to align the measuring devices with the modules, which has led to measurement errors.

5.4 Expected power

In this section, it can be seen how both configurations of panels, either North-West or South-East; as shown in figures 45 and 46 for the North-West panels and figures 47 and 48 for the South-East panels. They approach practically a linear regression until reaching 5200 W under standard conditions.

Although it must be emphasized, panels oriented to the North-West generate less amount of energy per day due to their lower exposure to solar irradiation during the period of time that the system has been evaluated.

5.5 Total power

Regarding the power generated by each string, it can be observed in section *4.5* how the North-West oriented strings generate less energy than those oriented to the South-East. As reflected in the following two figures, at the maximum irradiation peak, panels oriented North-West receive around 700 W/m^{2}K, while those oriented to the South-East receive 800 W/m^{2}K.

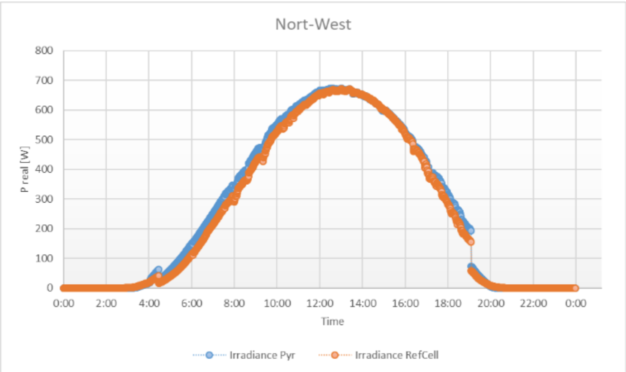

Figure 50. Irradiation received string 7

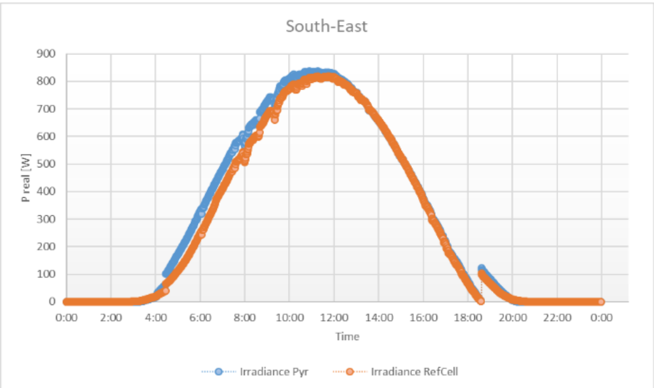

Figure 51. Irradiation received string 8

6 Conclusions

A work of modelling, characterization and monitoring of a photovoltaic system has been carried out, and after its analysis, the following conclusions have been extracted.

6.1 Study Results

Regarding the results obtained, it can be seen that the measurements have been reliable. Although if another reference solar cell and another pyranometer were available, each orientation of the panels could have been studied, thus avoiding a correction that could introduce certain errors in the final results.

Considering the output power of the system, emphasize that panels oriented to the North-West produce less than those oriented to the South-East, due to the amount of radiation received during the day.

One of the tools that allowed to validate the model has been the comparison between the theoretical curve and the real, a great adjustment is observed when introducing the corrections of irradiation and temperature; and that the model maintains its adjustment even when affected by rain or clouds. Note that the pyranometer has a greater error than the reference solar cell, this may be because it was calibrated for the last time in 2013 or the alignment with the modules.

The proposed method for installation testing of a PV-system works as expected. The eight strings investigated fulfill the expected performance and reach the promised nominal power.

The linear correlation between corrected power and irradiance means that the maximum power point tracker in the inverter works independent of the power.

6.2 Outlook

Once the installation has been studied and analysed, having deepened in solar energy, it is concluded that this method could be used in future studies of photovoltaic energy.

It should be able to be tested in more facilities and places on the planet for a longer period because the results obtained have been made only for 8 days, and in a place with a low ambient temperature compared to other countries with higher solar irradiance.

6.3 Perspectives

The project developed can help to be more precise when choosing the installed power in a solar installation. Previously a large deployment should be done to take irradiation and temperature data to be able to map and obtain results from many areas and develop a tool that could be very powerful.

By being able to choose the installed power better, it would not be necessary to oversize the installations, helping a more responsible consumption and production of energy and the products to manufacture the panels. This reduction in the dimensioning of the installation would allow to reduce costs and improve the profitability of the installation buyer, being able to be more accessible to a larger number of people, helping to achieve more sustainable communities.

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Appendix I: Reliability of measurement system

8th May

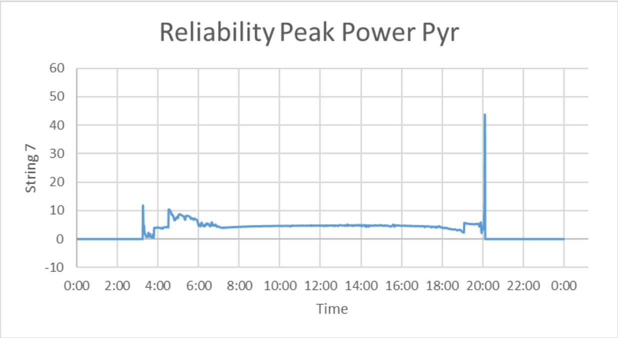

Figure 52. Reliability of the measurement system for String 7 using the Pyranometer

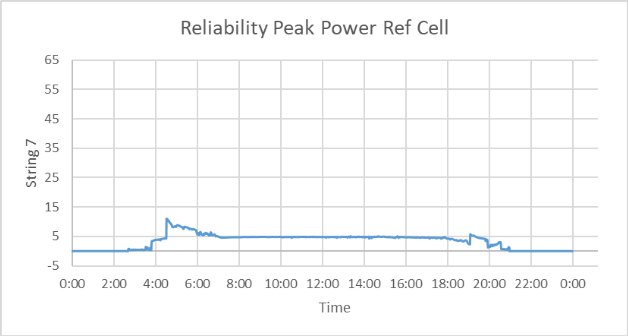

Figure 53. Reliability of the measurement system for String 7 using the Reference solar cell

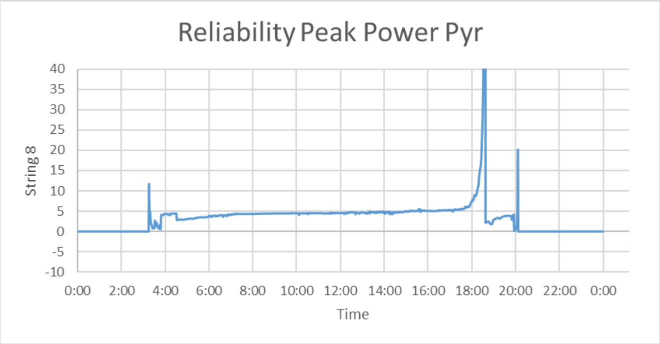

Figure 54. Reliability of the measurement system for String 8 using the Pyranometer

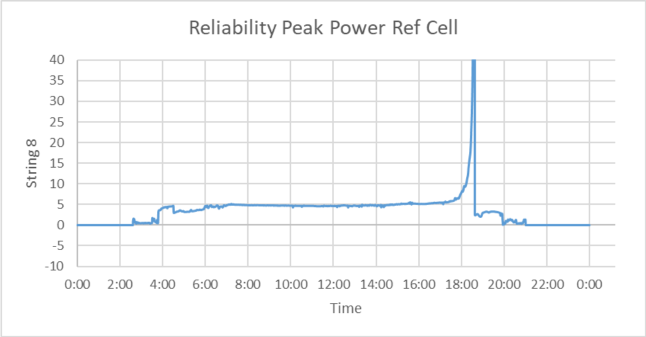

Figure 55. Reliability of the measurement system for String 8 using the Reference Solar cell

10th May

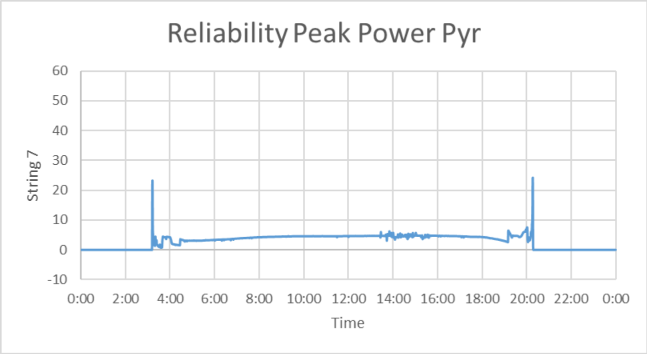

Figure 56. Reliability of the measurement system for String 7 using the Pyranometer

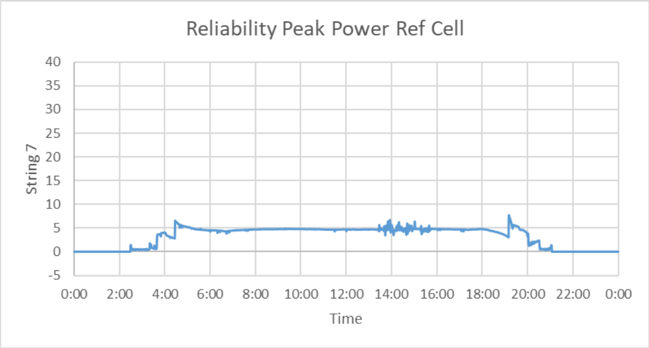

Figure 57. Reliability of the measurement system for String 7 using the Reference solar cell

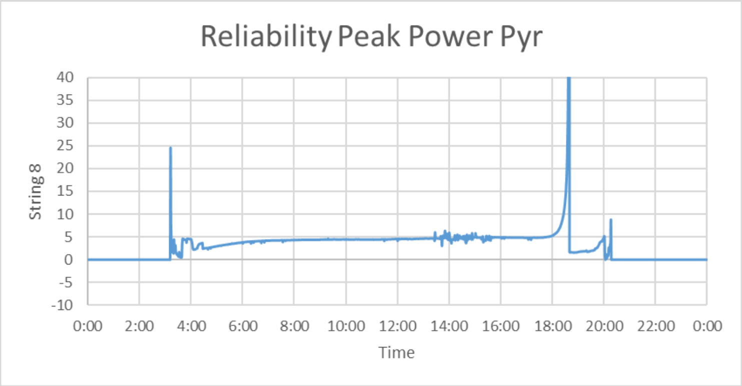

Figure 58. Reliability of the measurement system for String 8 using the Pyranometer

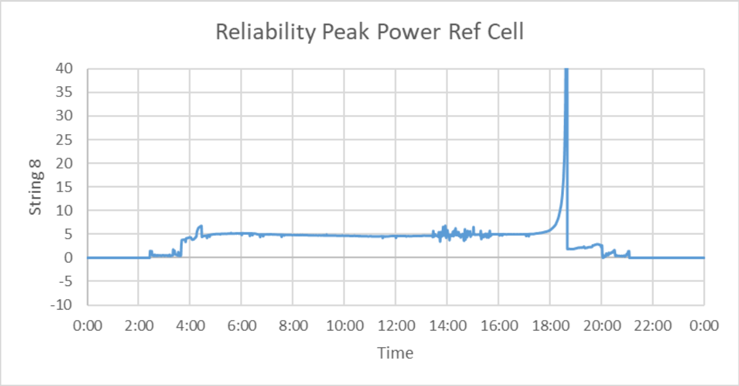

Figure 59. Reliability of the measurement system for String 8 using the Reference Solar cell

11th May

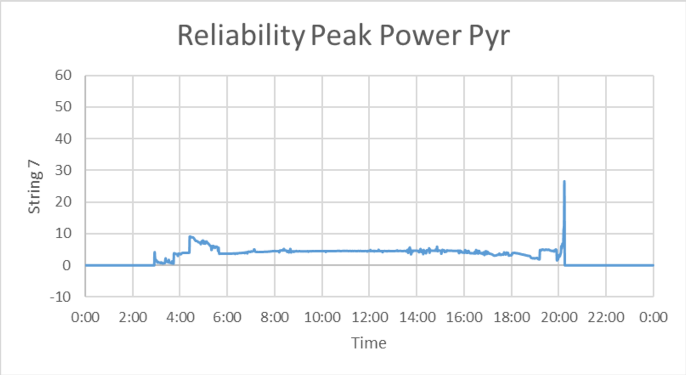

Figure 60. Reliability of the measurement system for String 7 using the Pyranometer

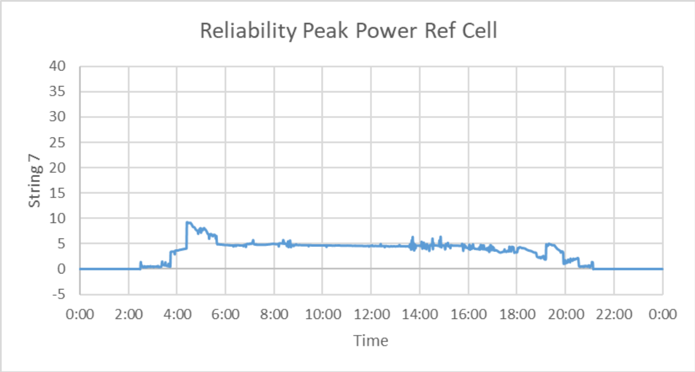

Figure 61. Reliability of the measurement system for String 7 using the Reference solar cell

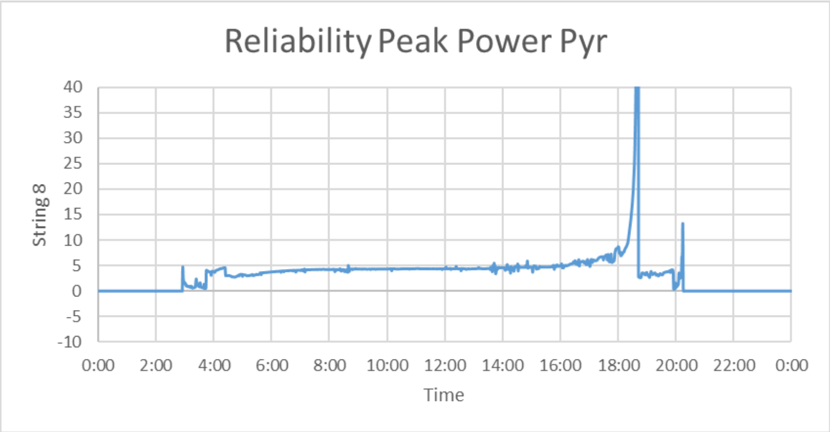

Figure 62. Reliability of the measurement system for String 8 using the Pyranometer

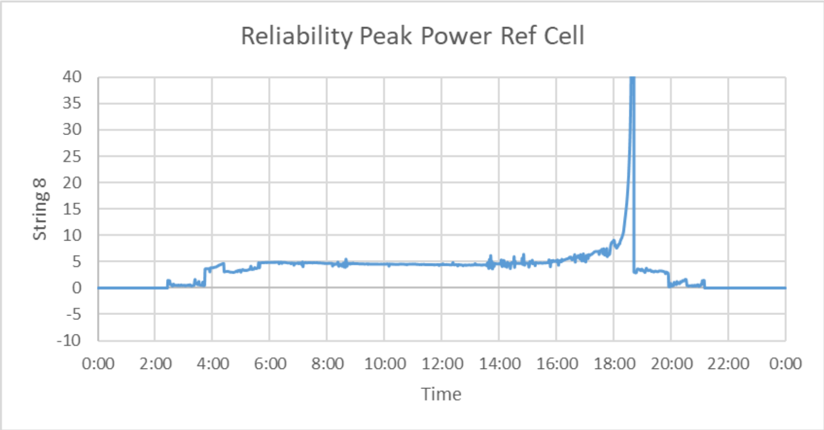

Figure 63. Reliability of the measurement system for String 8 using the Reference Solar cell

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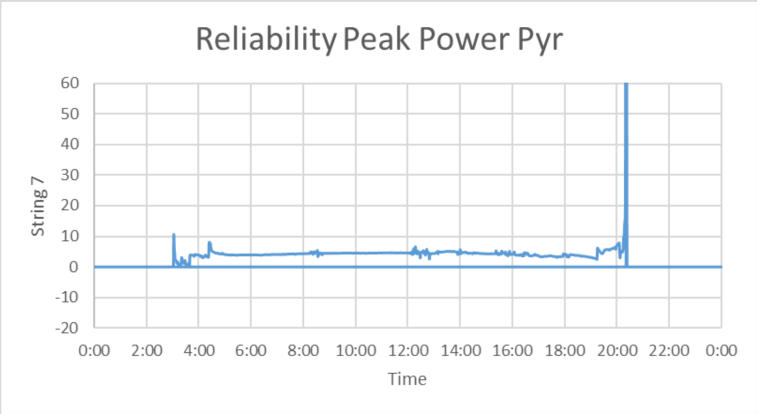

Figure 64. Reliability of the measurement system for String 7 using the Pyranometer

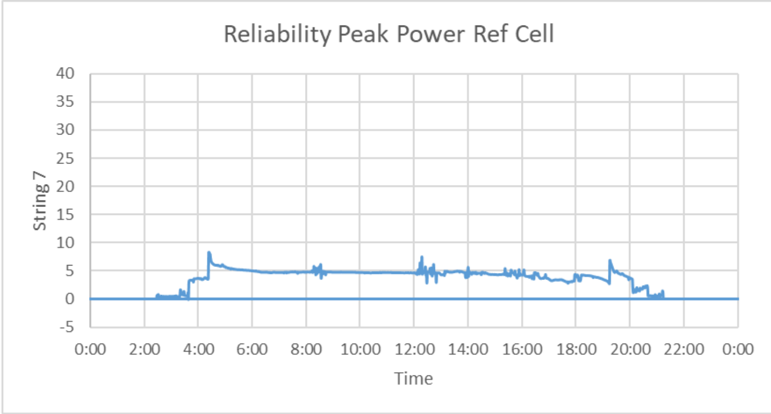

Figure 65. Reliability of the measurement system for String 7 using the Reference solar cell

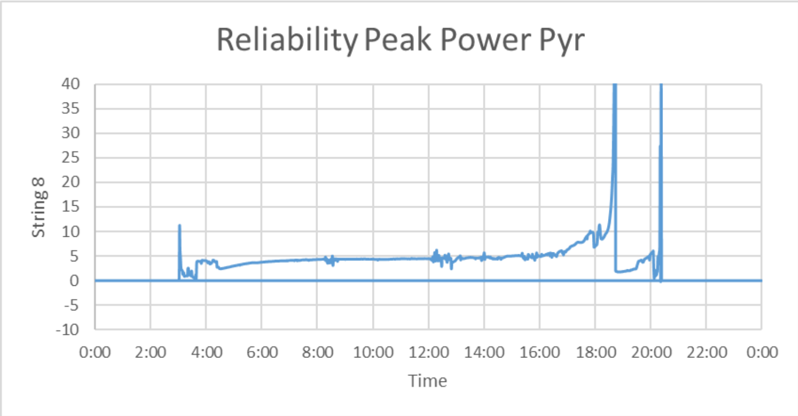

Figure 66. Reliability of the measurement system for String 8 using the Pyranometer

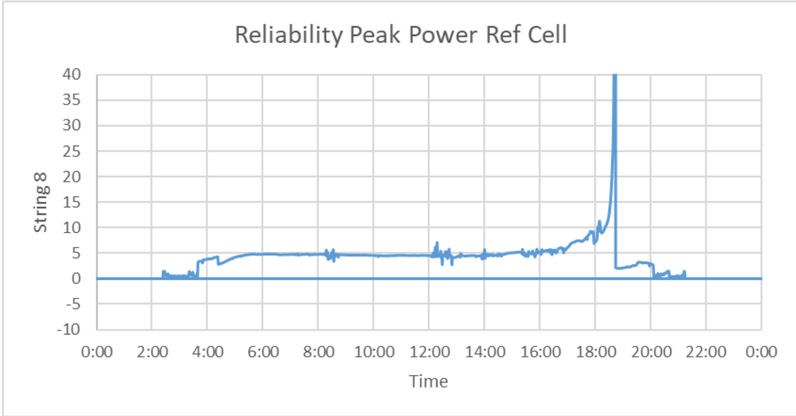

Figure 67. Reliability of the measurement system for String 8 using the Reference Solar cell

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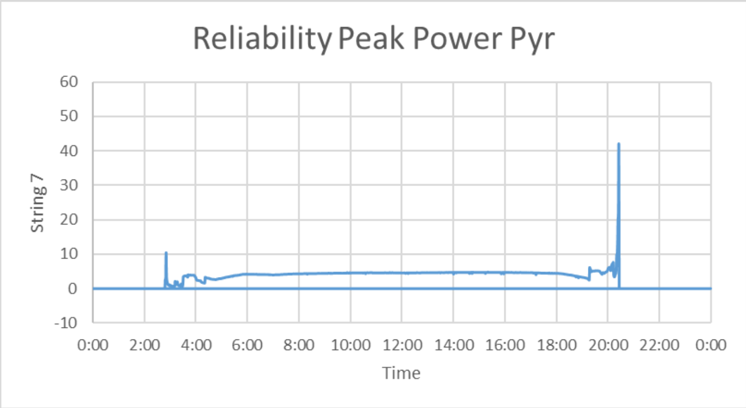

Figure 68. Reliability of the measurement system for String 7 using the Pyranometer

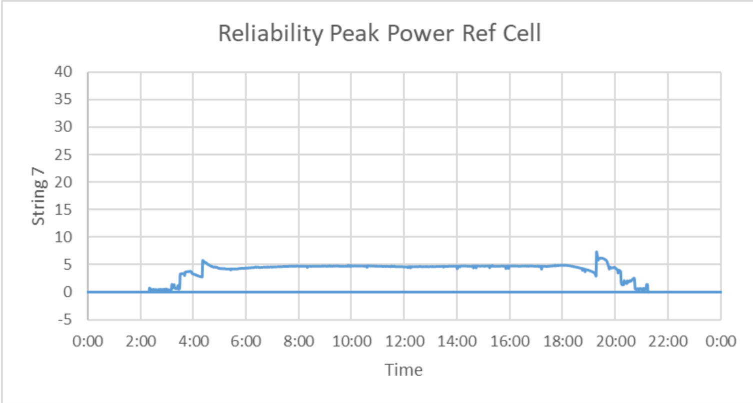

Figure 69. Reliability of the measurement system for String 7 using the Reference solar cell

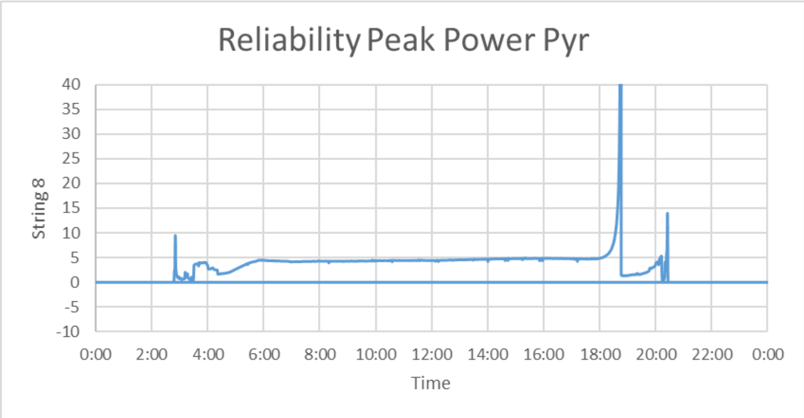

Figure 70. Reliability of the measurement system for String 8 using the Pyranometer

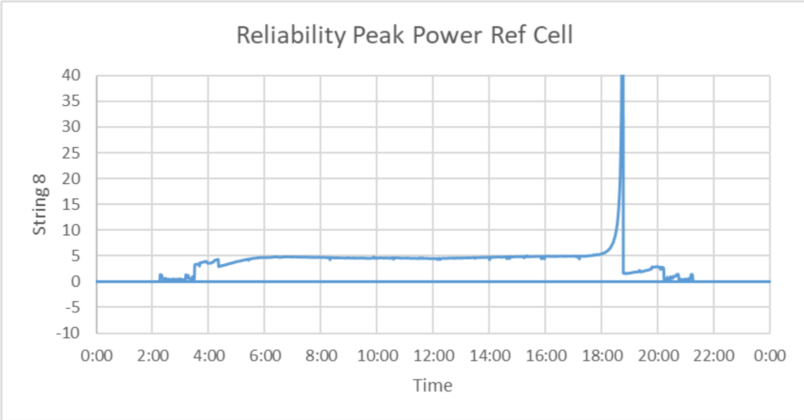

Figure 71. Reliability of the measurement system for String 8 using the Reference Solar cell

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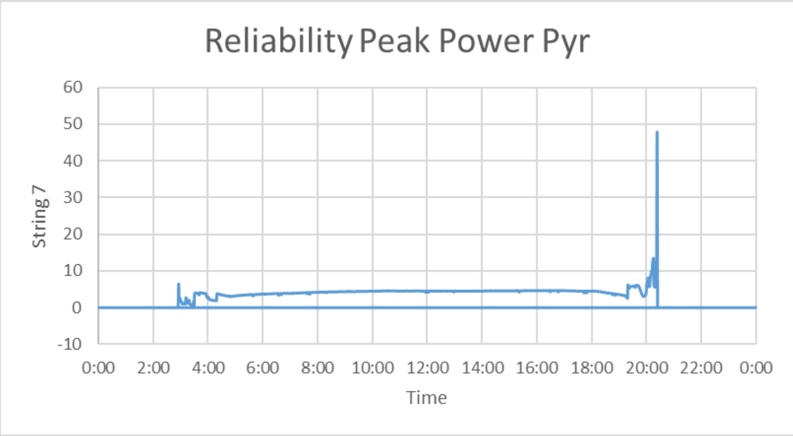

Figure 72. Reliability of the measurement system for String 7 using the Pyranometer

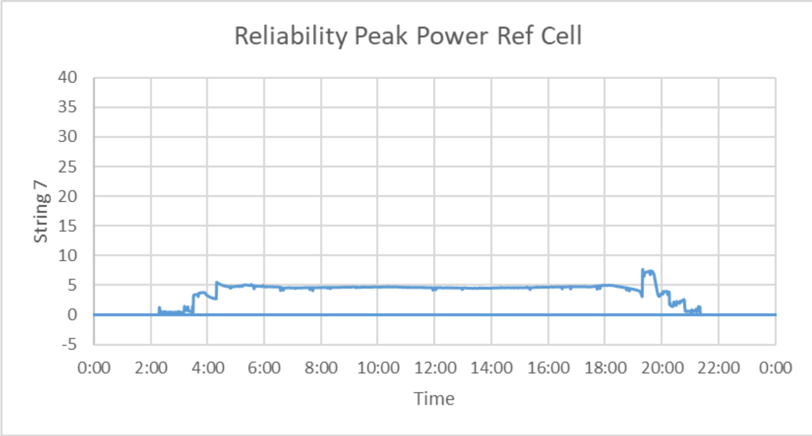

Figure 73. Reliability of the measurement system for String 7 using the Reference solar cell

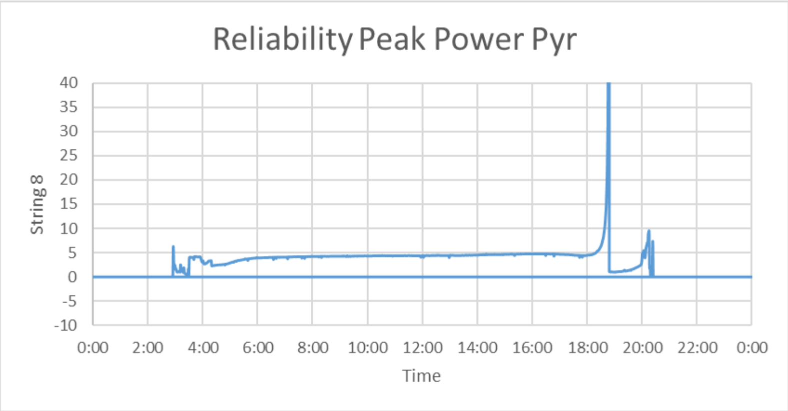

Figure 74. Reliability of the measurement system for String 8 using the Pyranometer

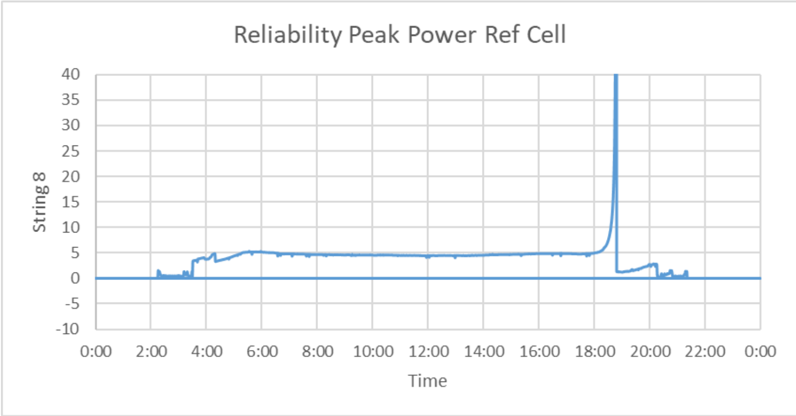

Figure 75. Reliability of the measurement system for String 8 using the Reference Solar cell

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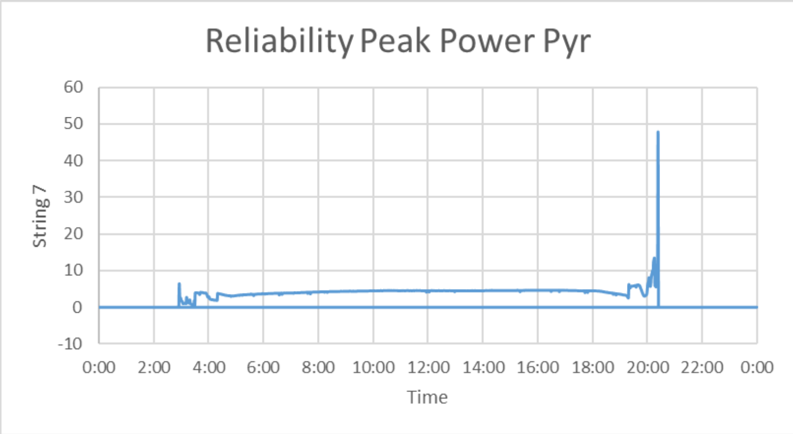

Figure 76. Reliability of the measurement system for String 7 using the Pyranometer

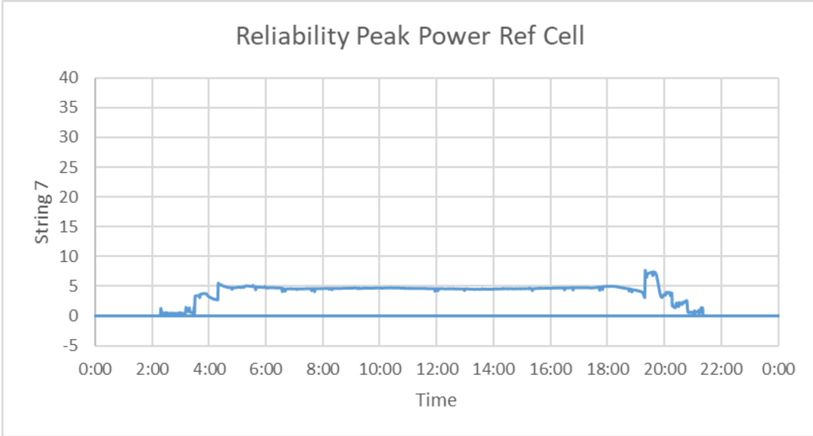

Figure 77. Reliability of the measurement system for String 7 using the Reference solar cell

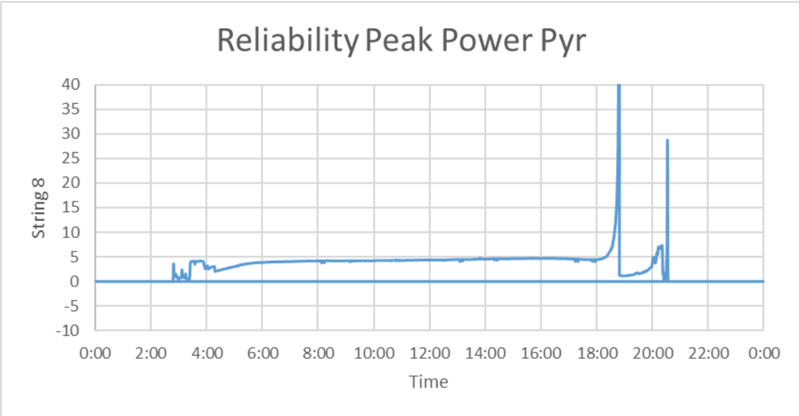

Figure 78. Reliability of the measurement system for String 8 using the Pyranometer

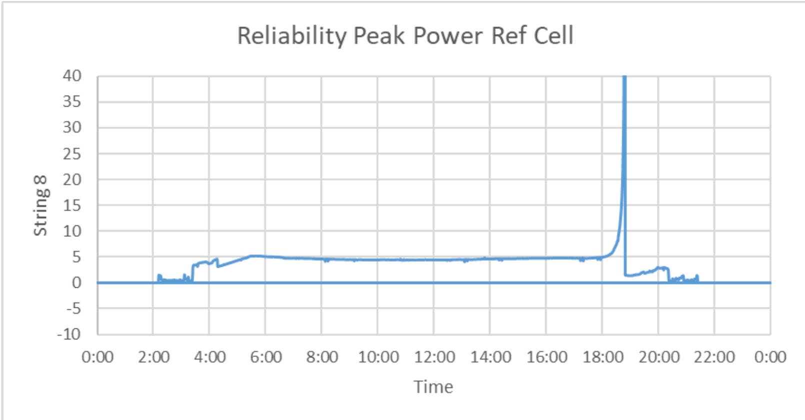

Figure 79. Reliability of the measurement system for String 8 using the Reference Solar cell

Appendix II: Output Power

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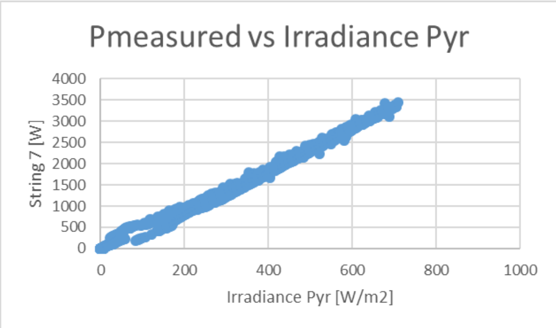

Figure 80. Relation between the irradiance measured with the Pyranometer and the output power of the String 7

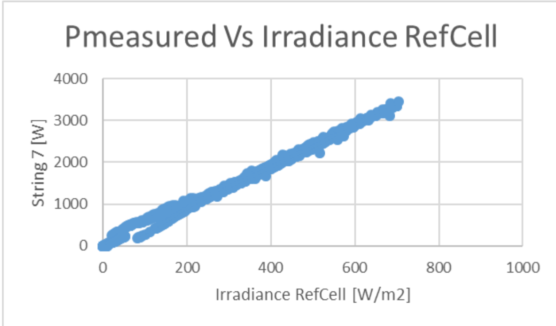

Figure 81. Relation between the irradiance measured with the Reference Solar cell and the output power of the String 7

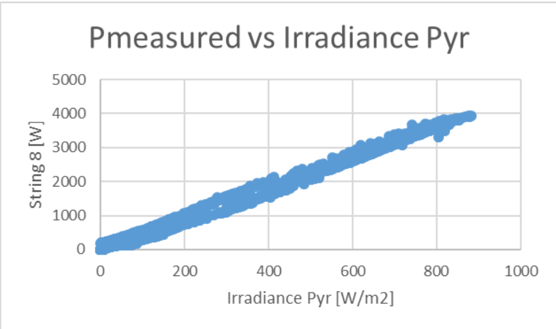

Figure 82. Relation between the irradiance measured with the Pyranometer and the output power of the String 8

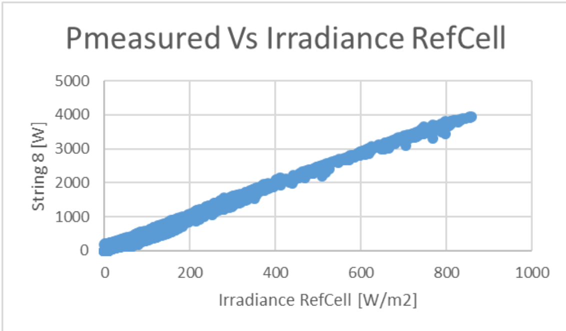

Figure 83. Relation between the irradiance measured with the Reference Solar cell and the output power of the String 8

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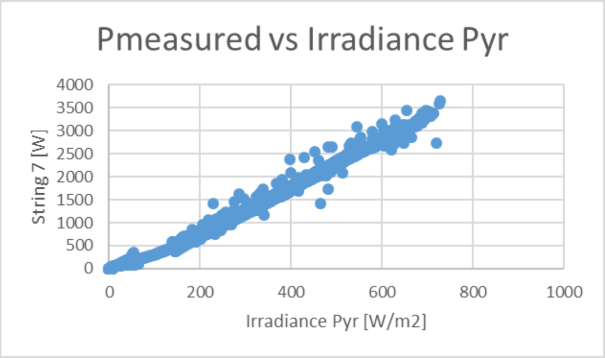

Figure 84. Relation between the irradiance measured with the Pyranometer and the output power of the String 7

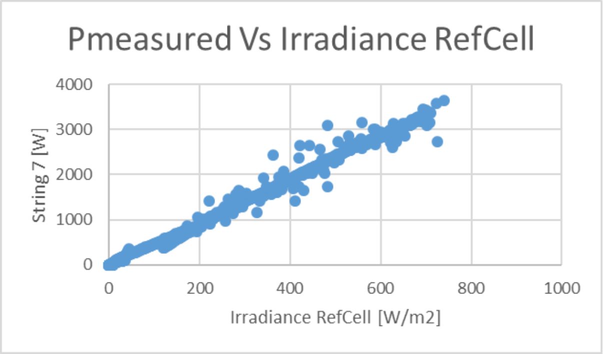

Figure 85. Relation between the irradiance measured with the Reference Solar cell and the output power of the String 7

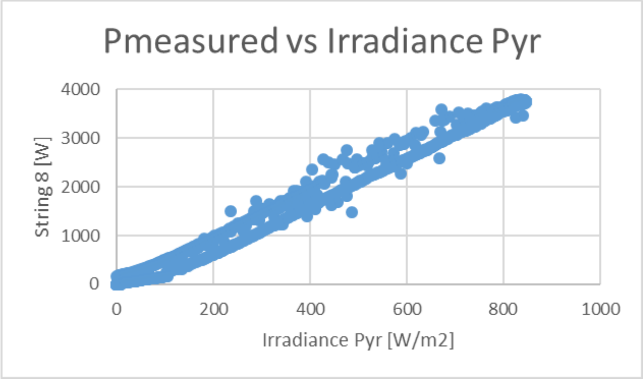

Figure 86. Relation between the irradiance measured with the Pyranometer and the output power of the String 8

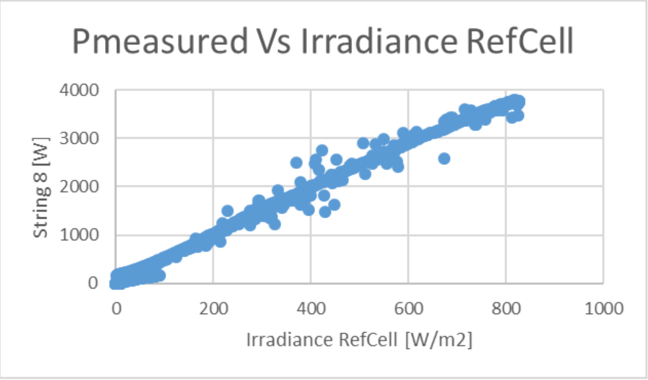

Figure 87. Relation between the irradiance measured with the Reference Solar cell and the output power of the String 8

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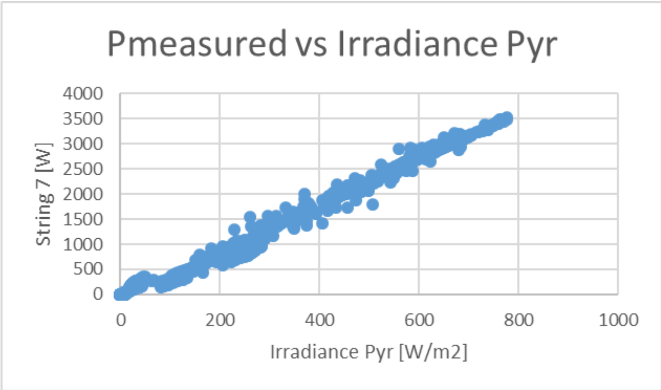

Figure 88. Relation between the irradiance measured with the Pyranometer and the output power of the String 7

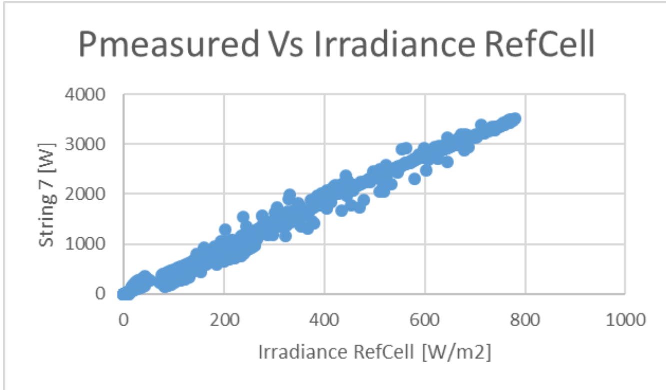

Figure 89. Relation between the irradiance measured with the Reference Solar cell and the output power of the String 7

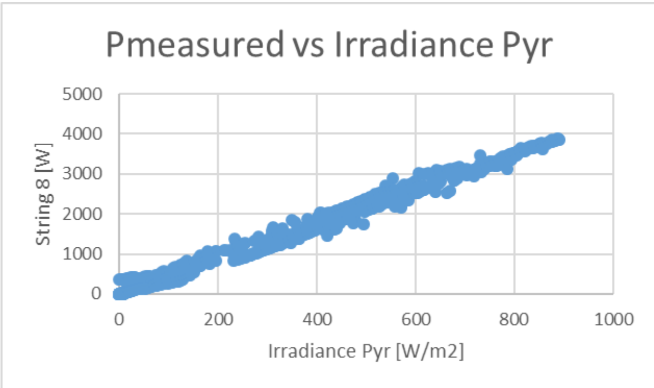

Figure 90. Relation between the irradiance measured with the Pyranometer and the output power of the String 8

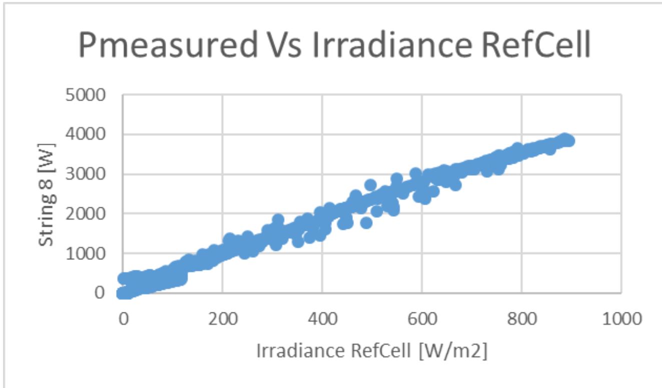

Figure 91. Relation between the irradiance measured with the Reference Solar cell and the output power of the String 8

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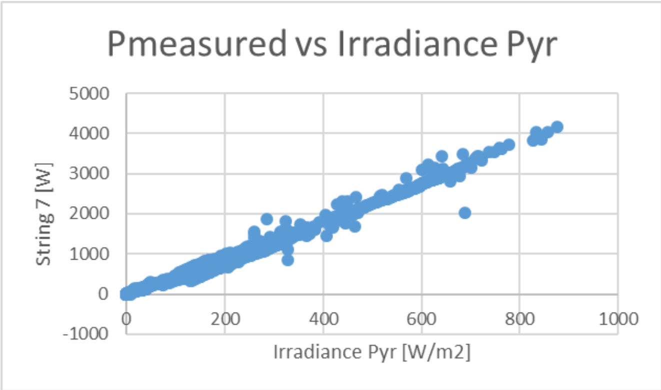

Figure 92. Relation between the irradiance measured with the Pyranometer and the output power of the String 7

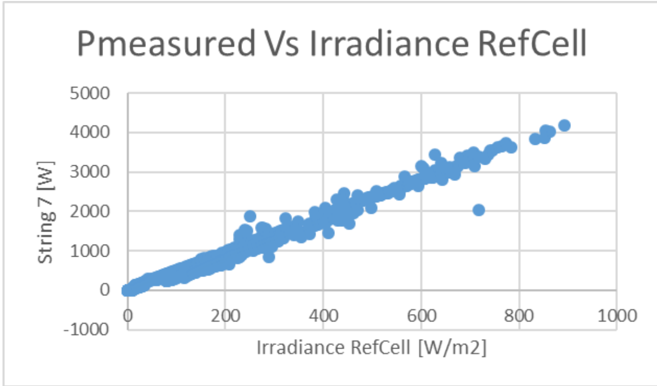

Figure 93. Relation between the irradiance measured with the Reference Solar cell and the output power of the String 7

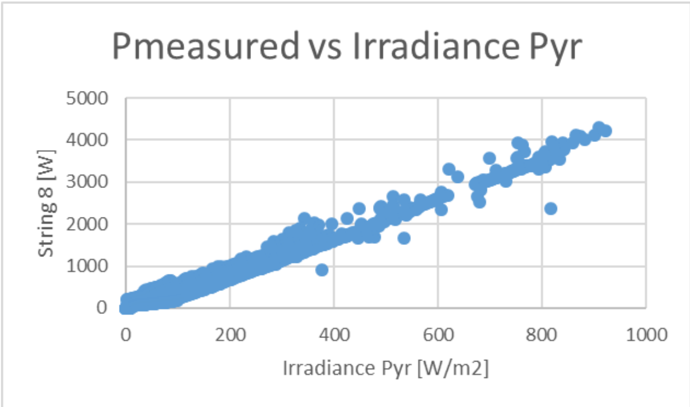

Figure 94. Relation between the irradiance measured with the Pyranometer and the output power of the String 8

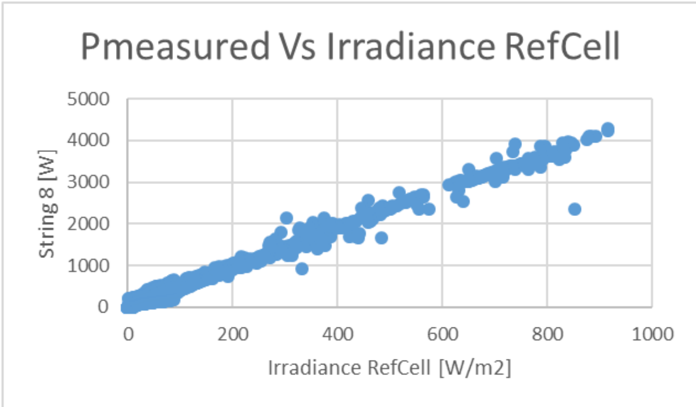

Figure 95. Relation between the irradiance measured with the Reference Solar cell and the output power of the String 8

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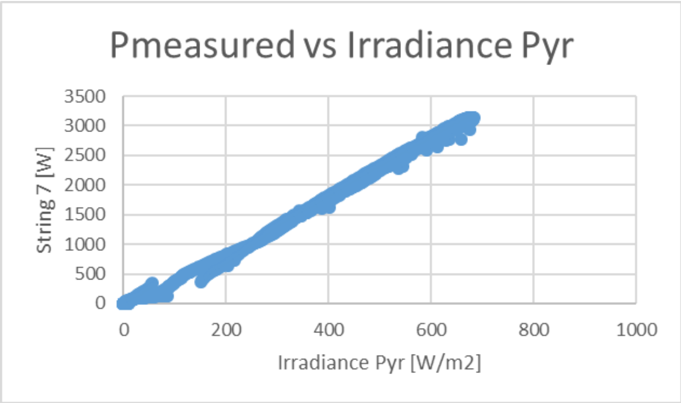

Figure 96. Relation between the irradiance measured with the Pyranometer and the output power of the String 7

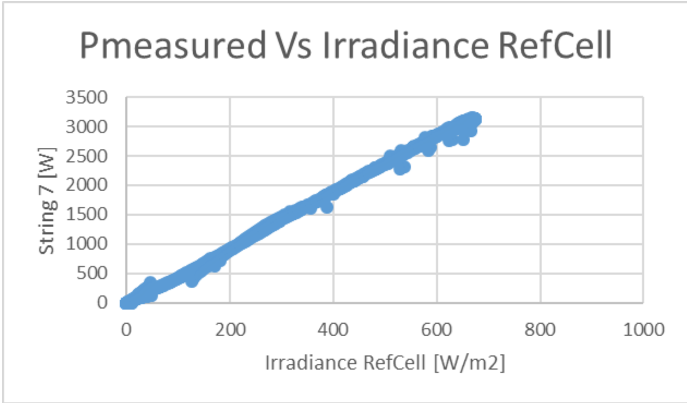

Figure 97. Relation between the irradiance measured with the Reference Solar cell and the output power of the String 7

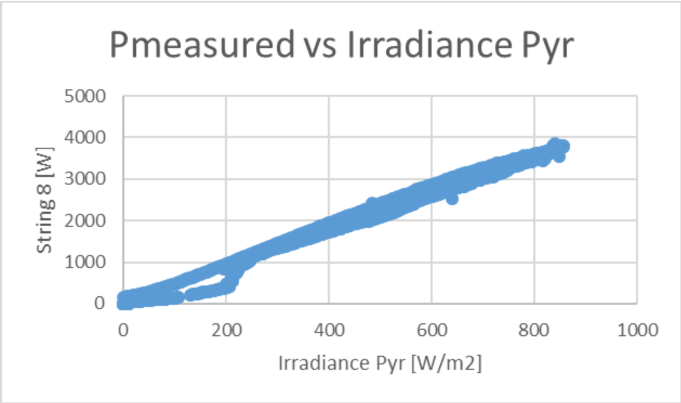

Figure 98. Relation between the irradiance measured with the Pyranometer and the output power of the String 8

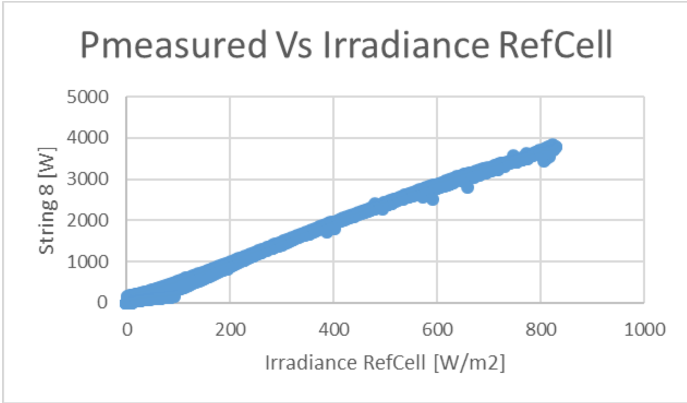

Figure 99. Relation between the irradiance measured with the Reference Solar cell and the output power of the String 8

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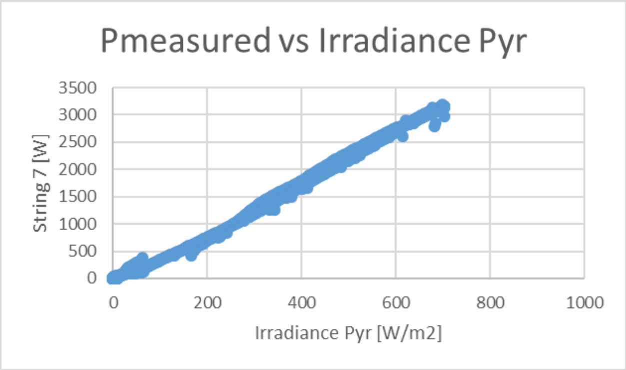

Figure 100. Relation between the irradiance measured with the Pyranometer and the output power of the String 7

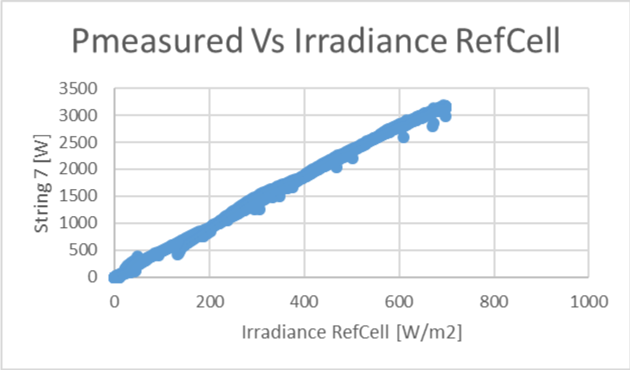

Figure 101. Relation between the irradiance measured with the Reference Solar cell and the output power of the String 7

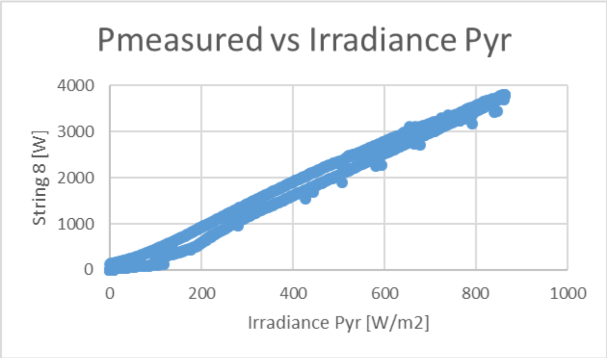

Figure 102. Relation between the irradiance measured with the Pyranometer and the output power of the String 8

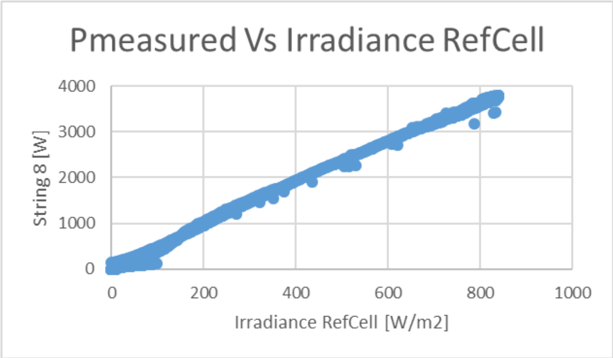

Figure 103. Relation between the irradiance measured with the Reference Solar cell and the output power of the String 8

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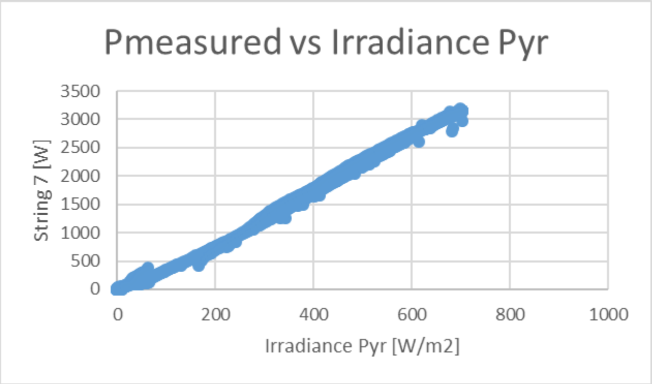

Figure 104. Relation between the irradiance measured with the Pyranometer and the output power of the String 7

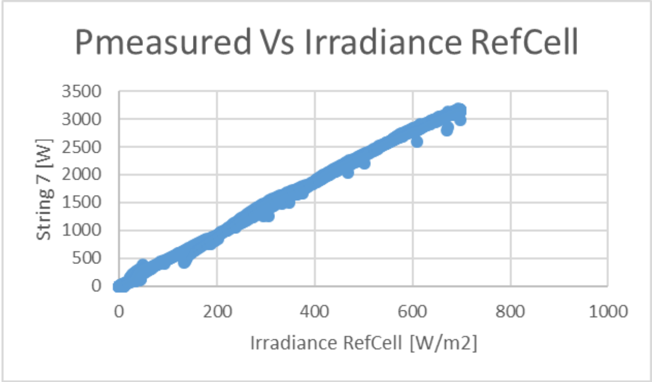

Figure 105. Relation between the irradiance measured with the Reference Solar cell and the output power of the String 7

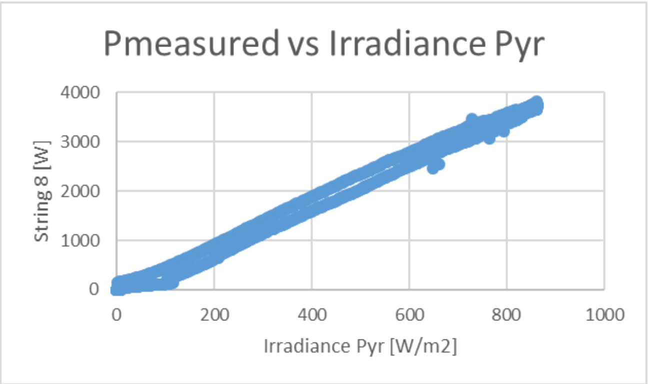

Figure 106. Relation between the irradiance measured with the Pyranometer and the output power of the String 8

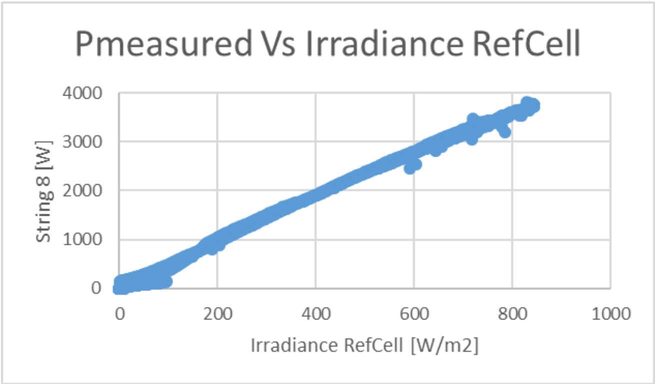

Figure 107. Relation between the irradiance measured with the Reference Solar cell and the output power of the String 8

Appendix III: Comparison Theoretical and Real Power

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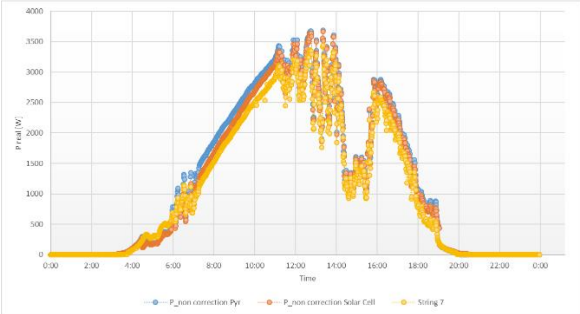

Figure 108. Gmodule x Ppeak. String 7

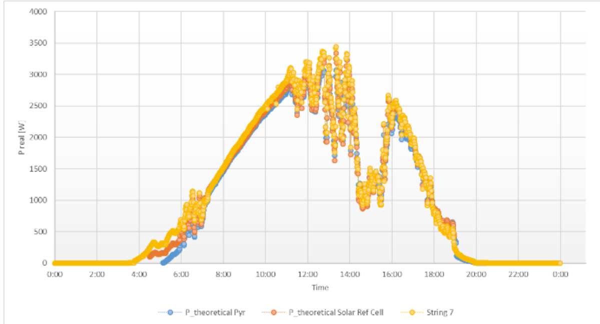

Figure 109. Performance of the Theoretical and Real Power with corrections. String 7

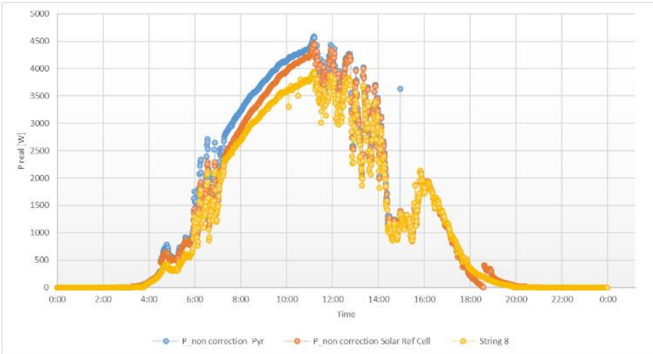

Figure 110. Gmodule x Ppeak. String 8

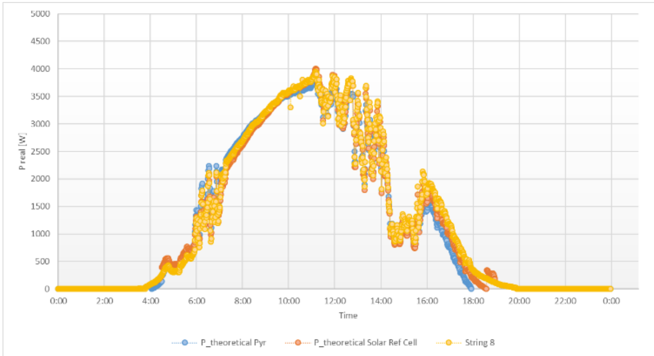

Figure 111. Performance of the Theoretical and Real Power with corrections. String 8

10th May

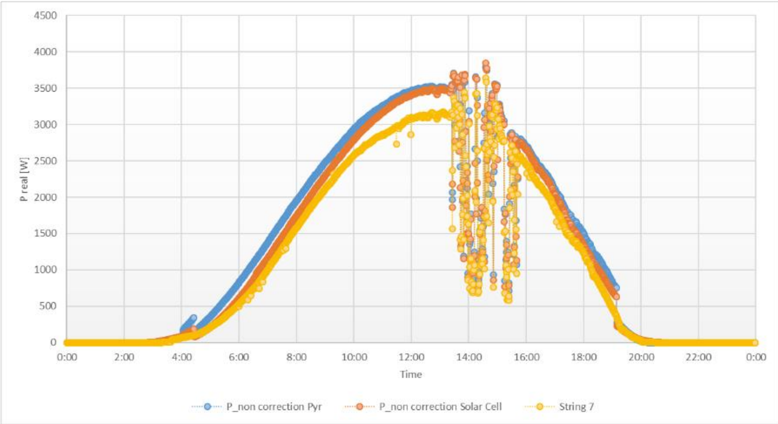

Figure 112. Gmodule x Ppeak. String 7

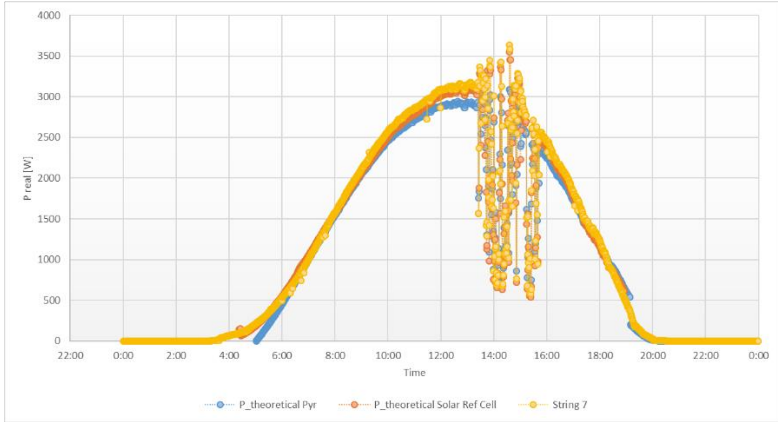

Figure 113. Performance of the Theoretical and Real Power with corrections. String 7

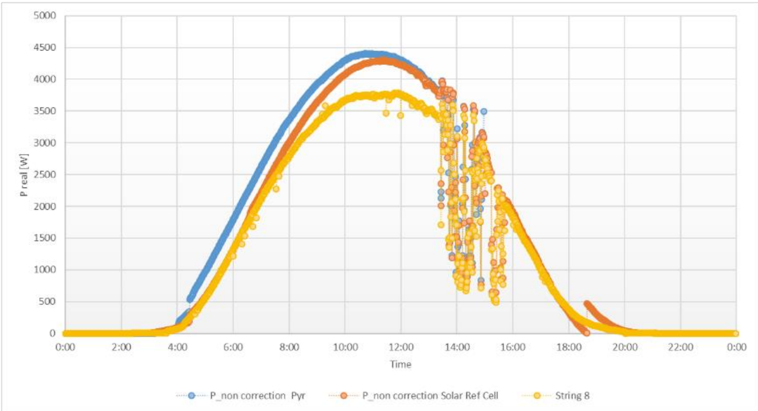

Figure 114. Gmodule x Ppeak. String 8

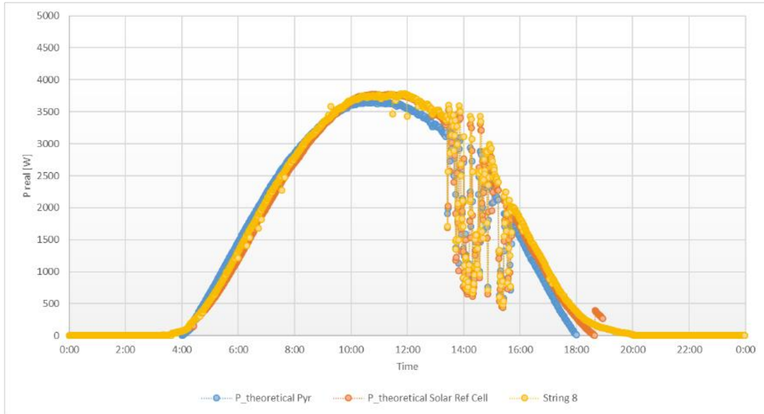

Figure 115. Performance of the Theoretical and Real Power with corrections. String 8

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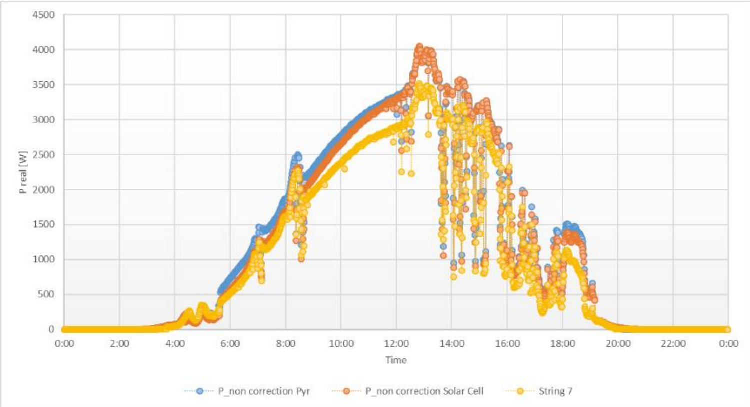

Figure 116. Gmodule x Ppeak. String 7

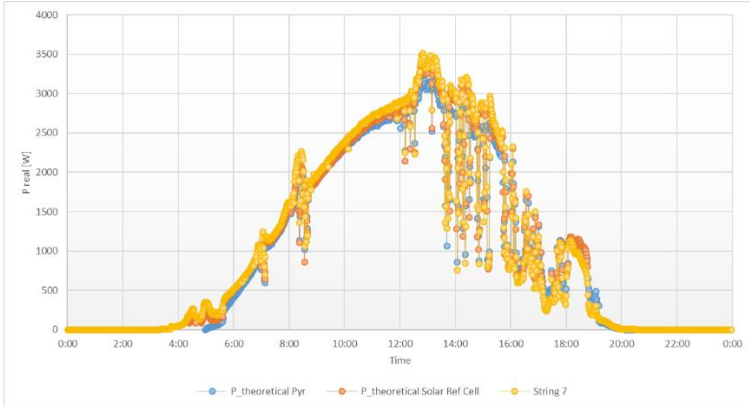

Figure 117. Performance of the Theoretical and Real Power with corrections. String 7

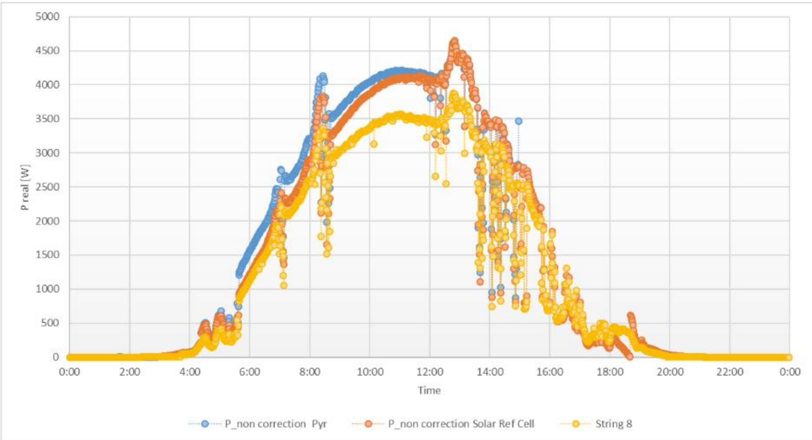

Figure 118. Gmodule x Ppeak. String 8

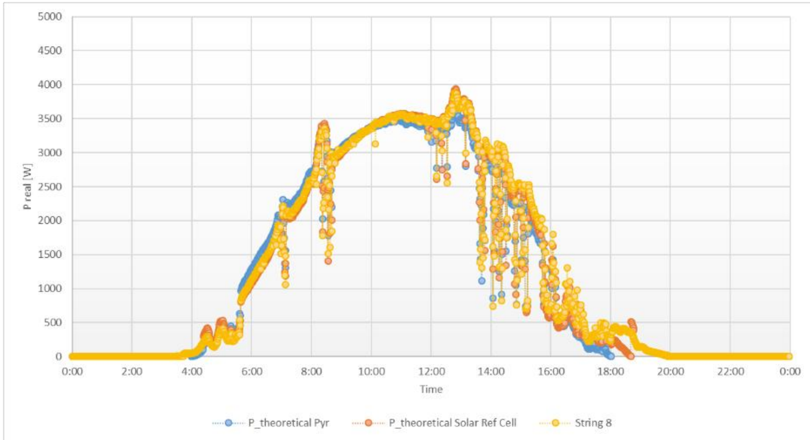

Figure 119. Performance of the Theoretical and Real Power with corrections. String 8

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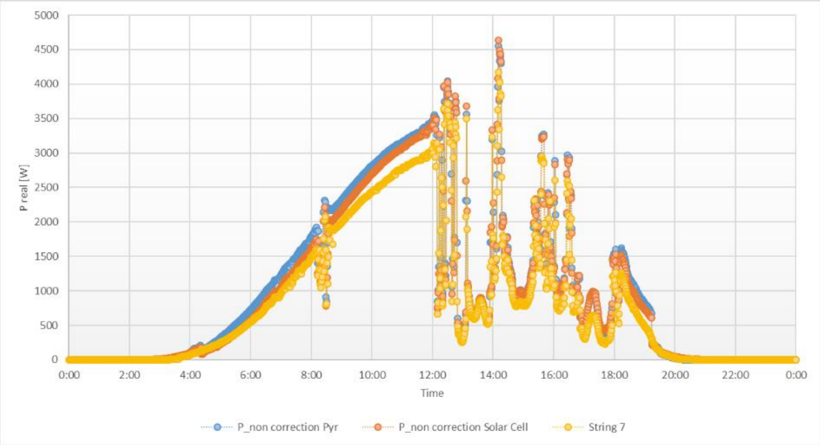

Figure 120. Gmodule x Ppeak. String 7

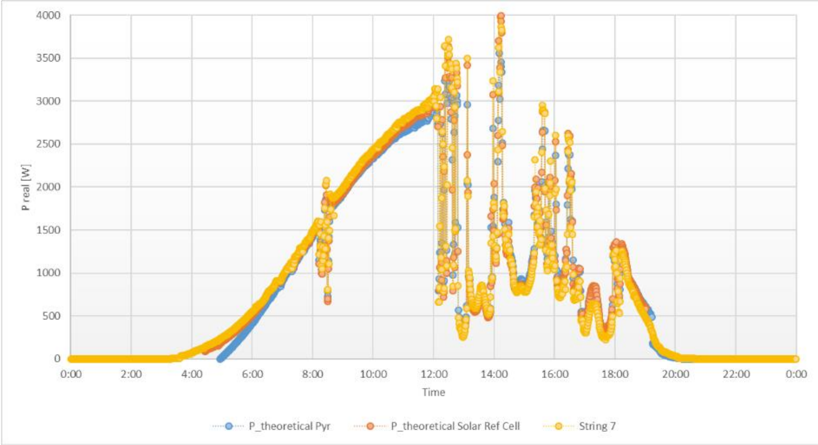

Figure 121. Performance of the Theoretical and Real Power with corrections. String 7

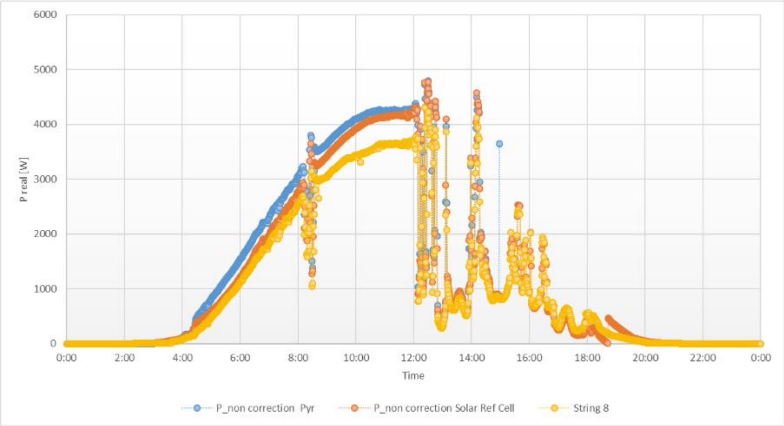

Figure 122. Gmodule x Ppeak. String 8

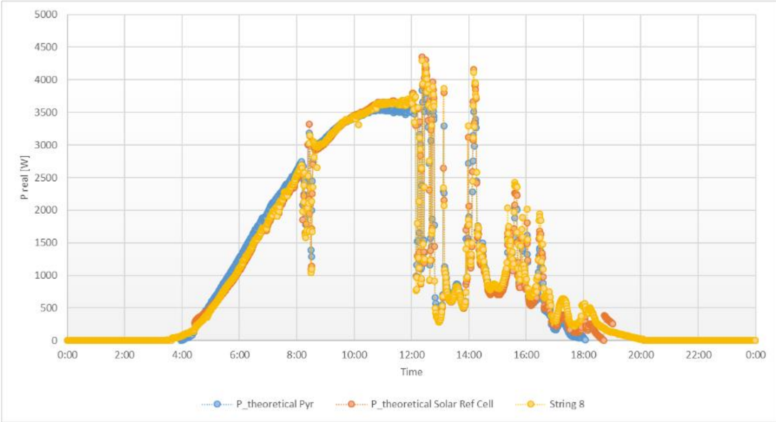

Figure 123. Performance of the Theoretical and Real Power with corrections. String 8

13th May

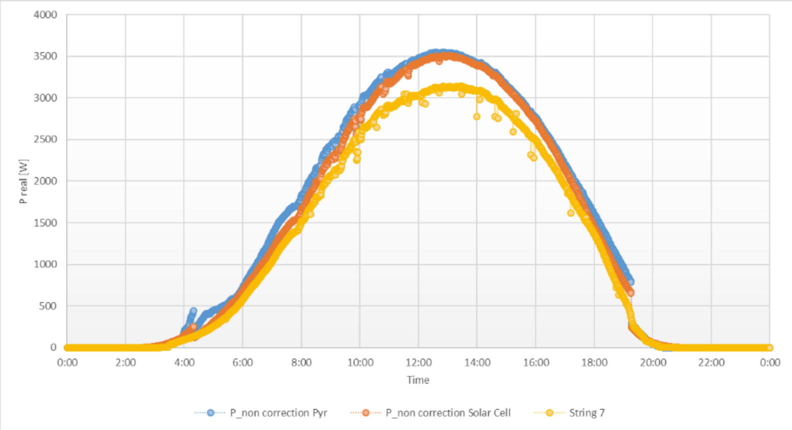

Figure 124. Gmodule x Ppeak. String 7

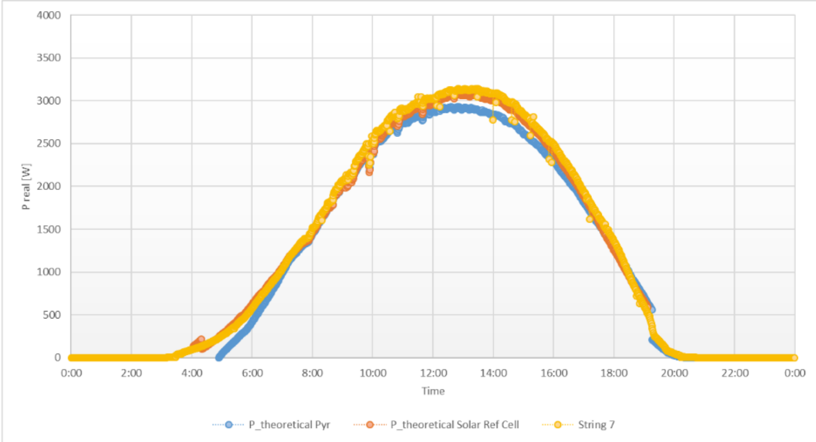

Figure 125. Performance of the Theoretical and Real Power with corrections. String 7

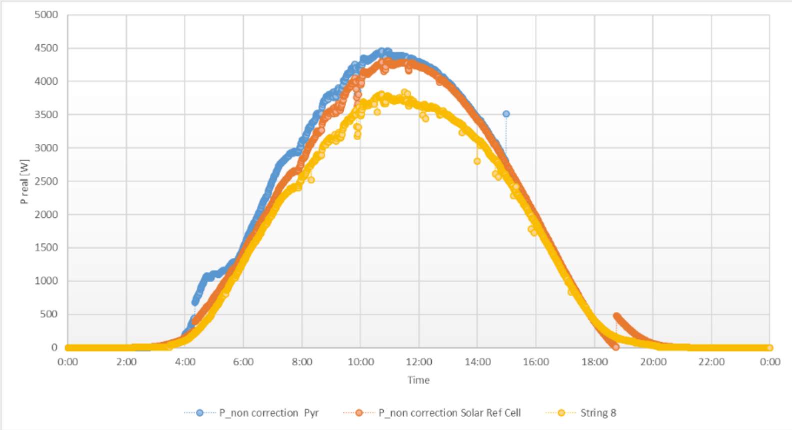

Figure 126. Gmodule x Ppeak. String 8

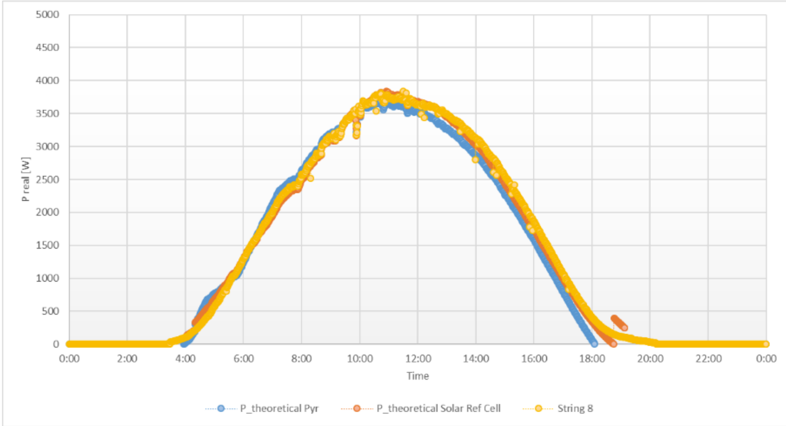

Figure 127. Performance of the Theoretical and Real Power with corrections. String 8

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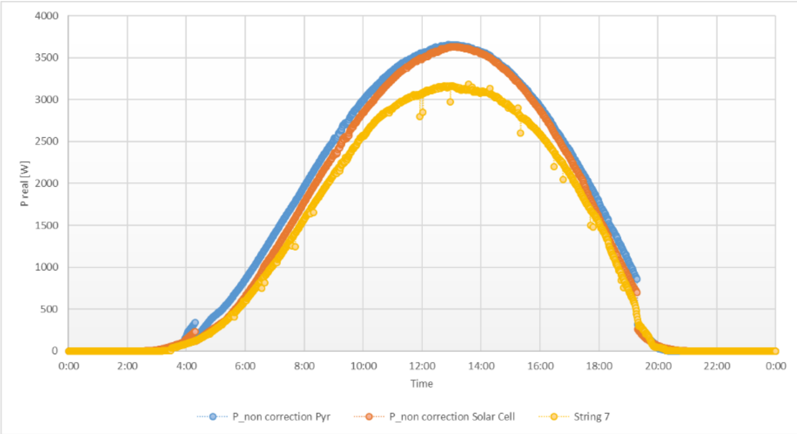

Figure 128. Gmodule x Ppeak. String 7

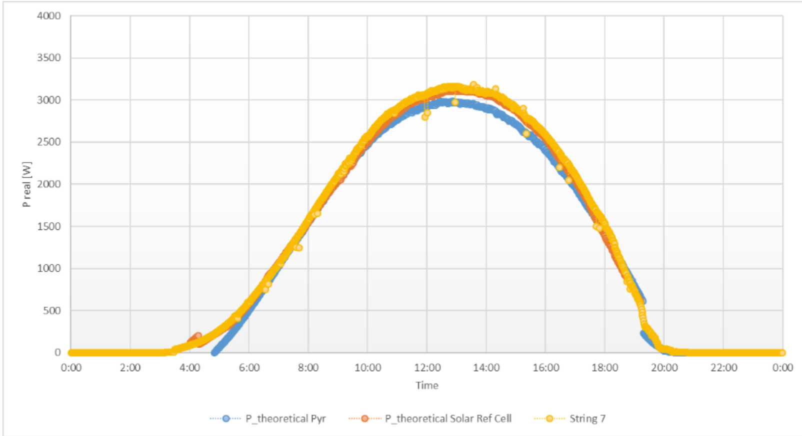

Figure 129. Performance of the Theoretical and Real Power with corrections. String 7

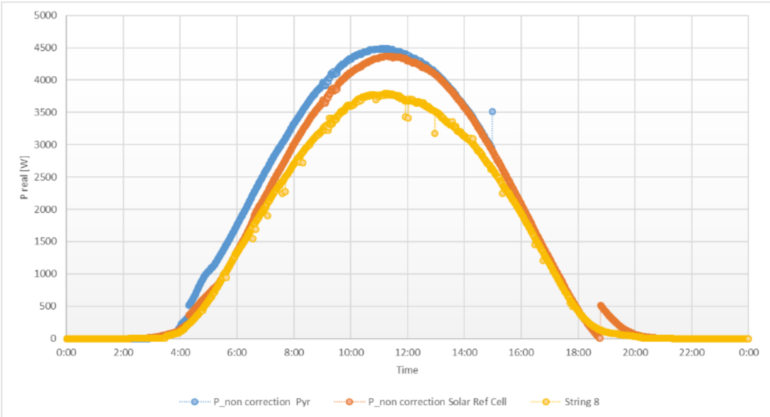

Figure 130. Gmodule x Ppeak. String 8

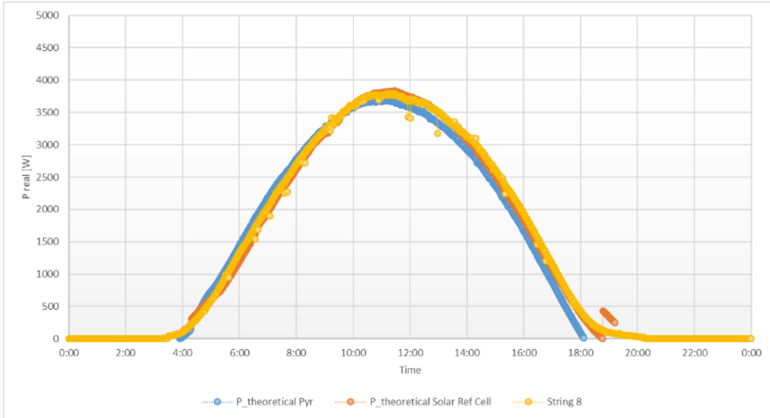

Figure 131. Performance of the Theoretical and Real Power with corrections. String 8

15th May

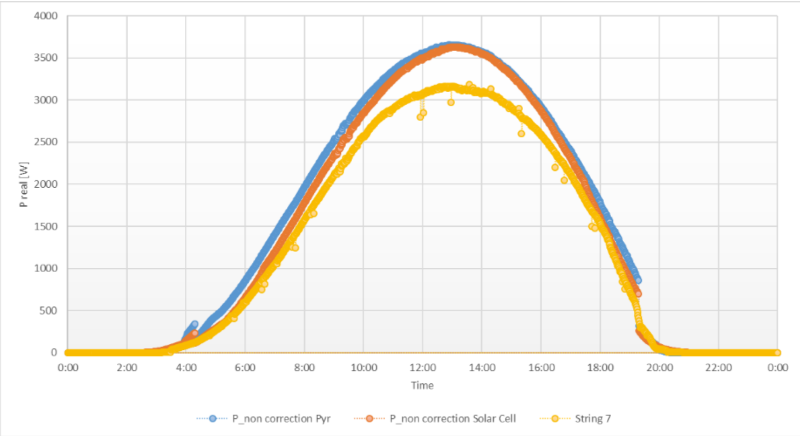

Figure 132. Gmodule x Ppeak. String 7

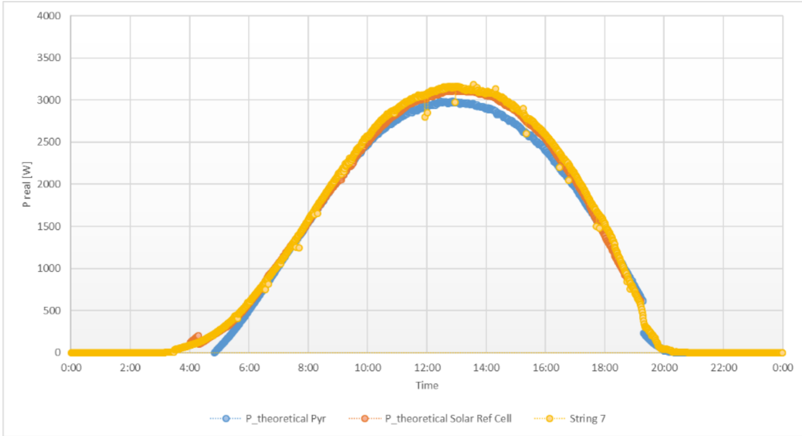

Figure 133. Performance of the Theoretical and Real Power with corrections. String 7

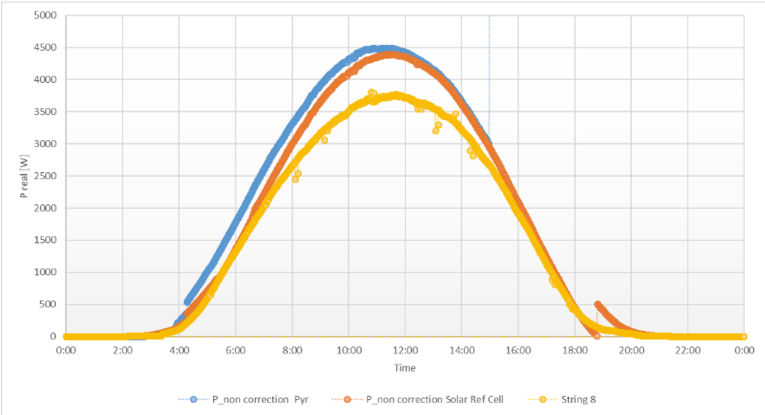

Figure 134. Gmodule x Ppeak. String 8

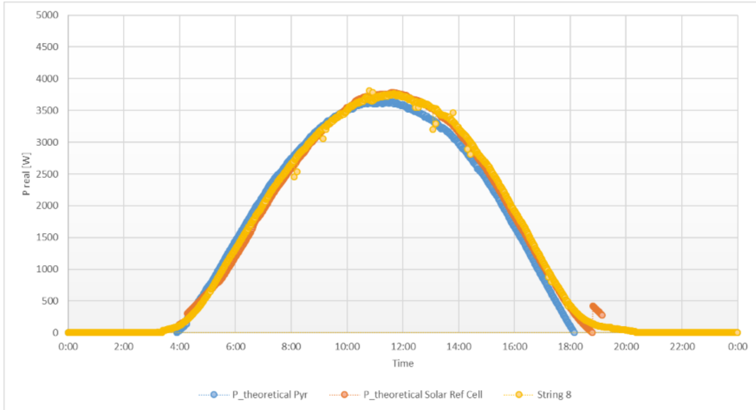

Figure 135. Performance of the Theoretical and Real Power with corrections. String 8

Appendix IV: Expected Power

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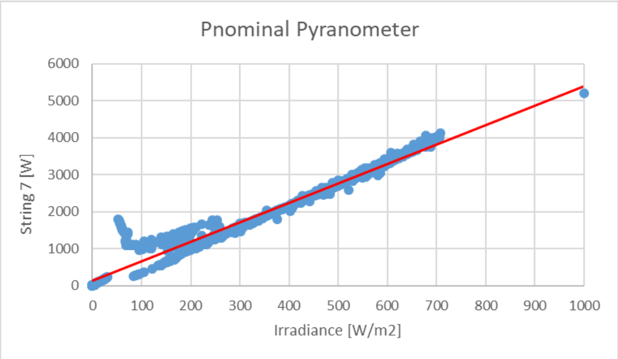

Figure 136. Performance of the Theoretical and Real Power without corrections. String 7

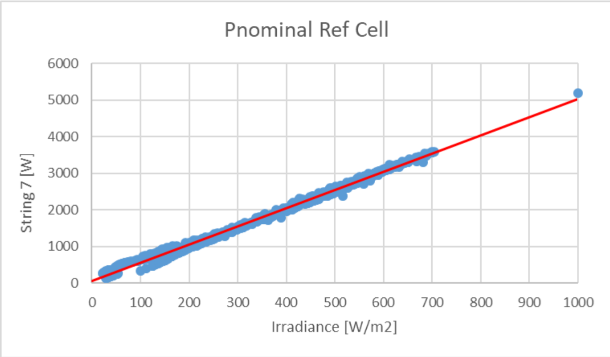

Figure 137. Performance of the Theoretical and Real Power with corrections. String 7

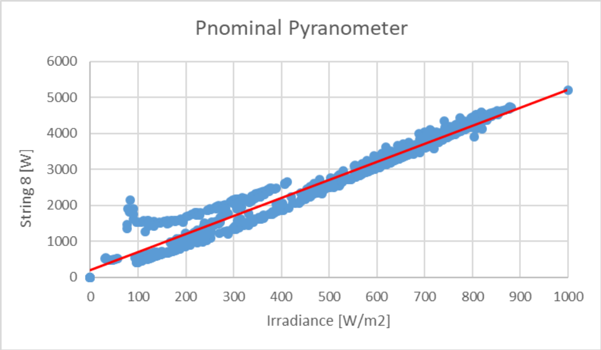

Figure 138. Performance of the Theoretical and Real Power without corrections. String 8

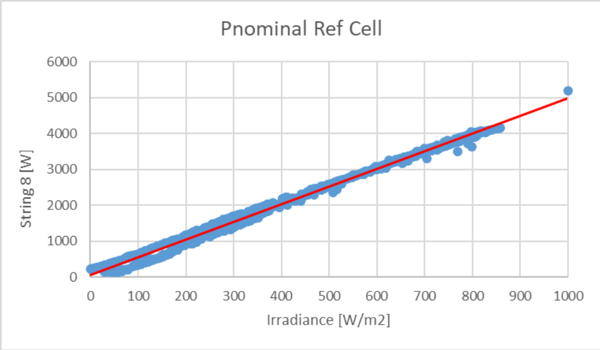

Figure 139. Performance of the Theoretical and Real Power with corrections. String 8

10th May

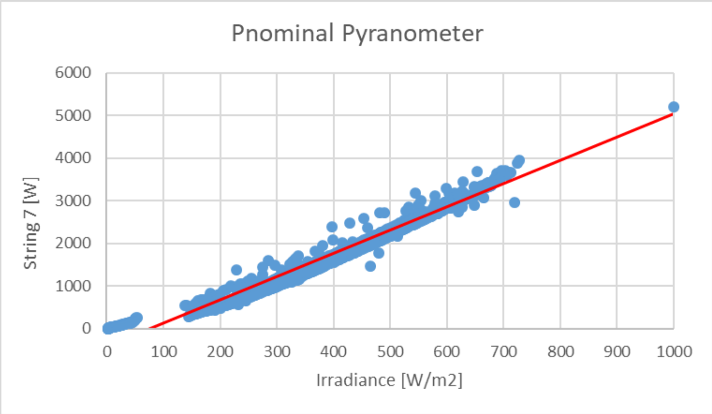

Figure 140. Performance of the Theoretical and Real Power without corrections. String 7

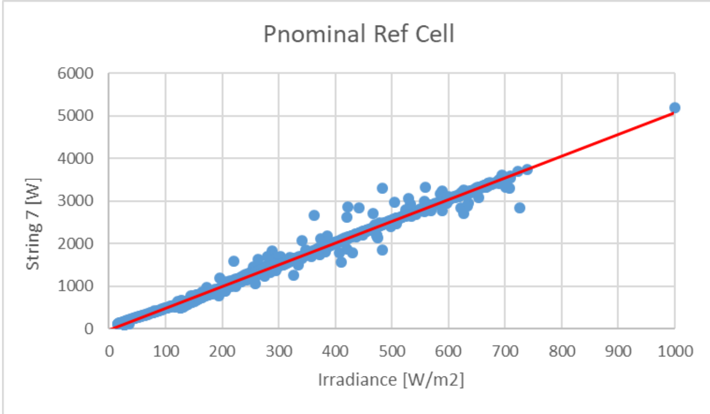

Figure 141. Performance of the Theoretical and Real Power with corrections. String 7

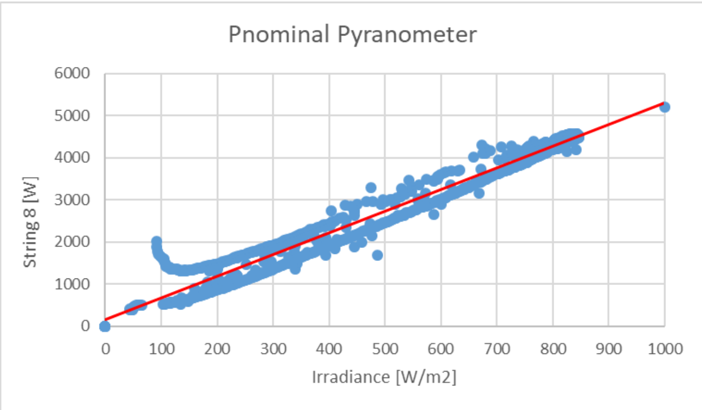

Figure 142. Performance of the Theoretical and Real Power without corrections. String 8

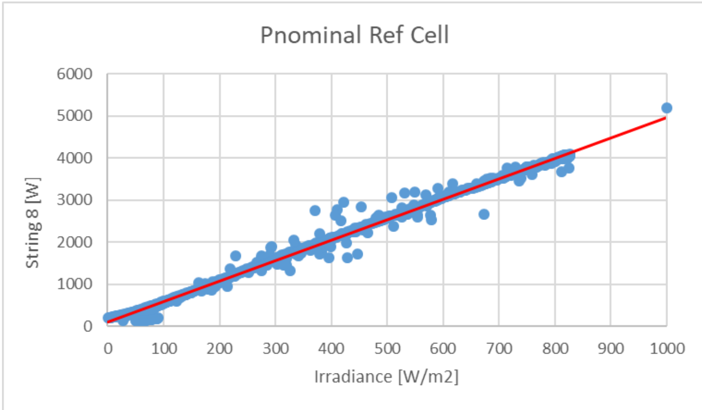

Figure 143. Performance of the Theoretical and Real Power with corrections. String 8

11th May

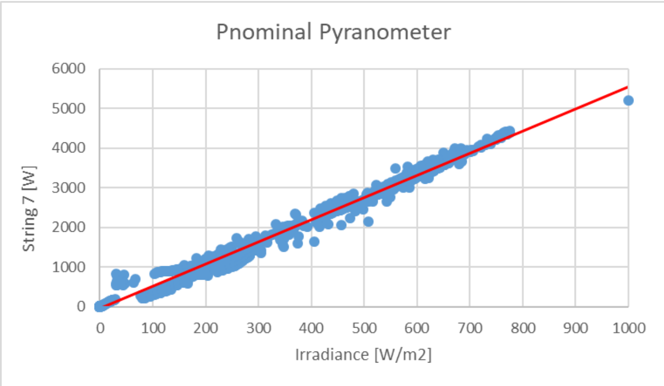

Figure 144. Performance of the Theoretical and Real Power without corrections. String 7

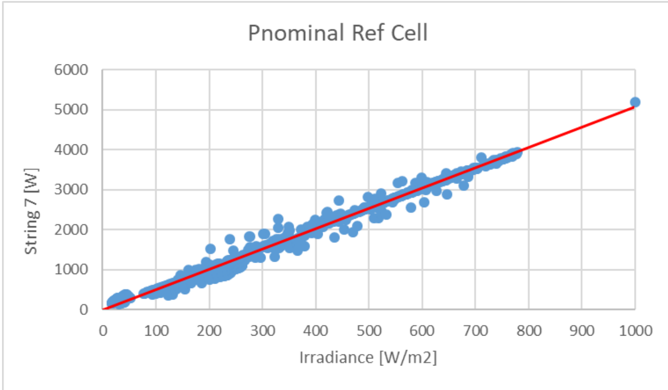

Figure 145. Performance of the Theoretical and Real Power with corrections. String 7

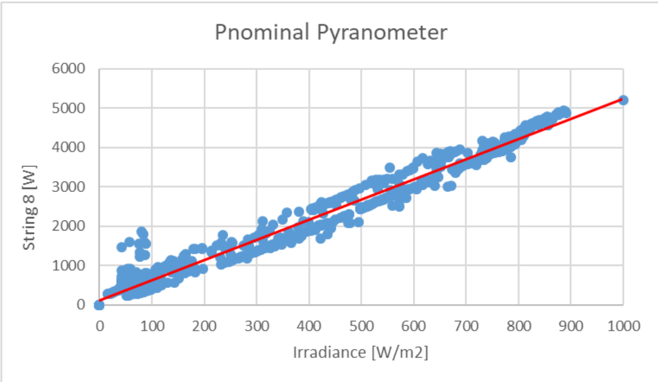

Figure 146. Performance of the Theoretical and Real Power without corrections. String 8

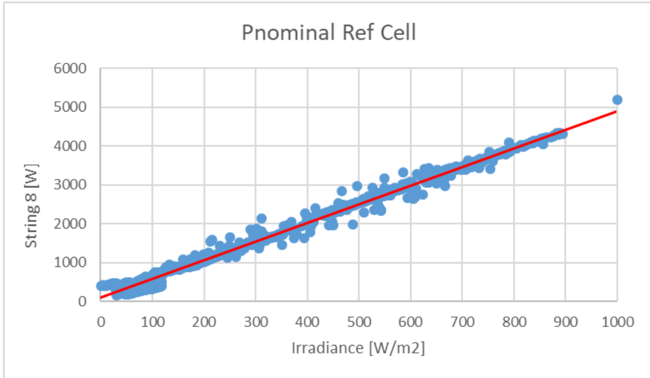

Figure 147. Performance of the Theoretical and Real Power with corrections. String 8

12th May

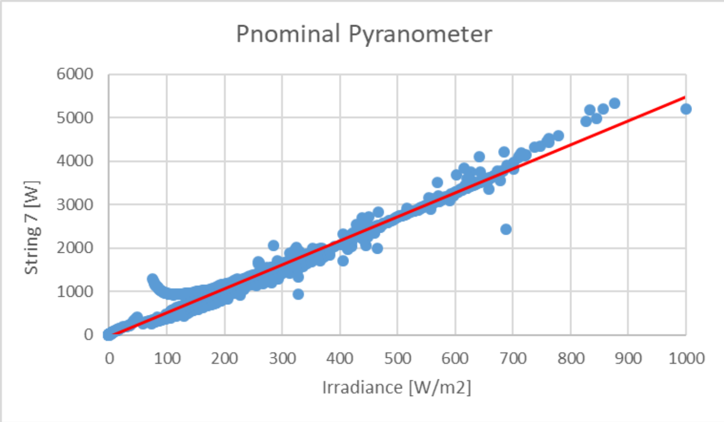

Figure 148. Performance of the Theoretical and Real Power without corrections. String 7

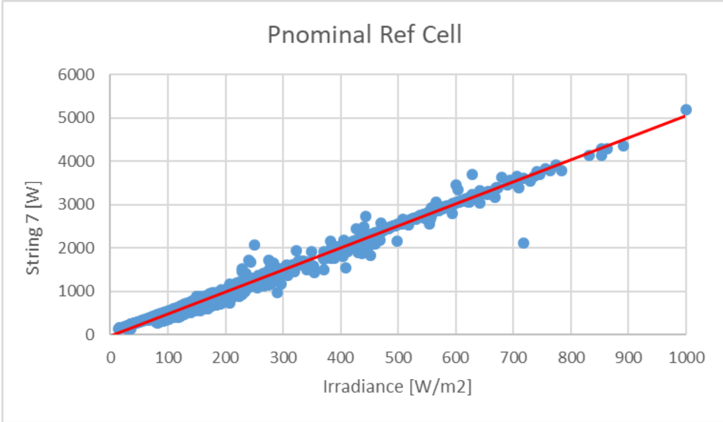

Figure 149. Performance of the Theoretical and Real Power with corrections. String 7

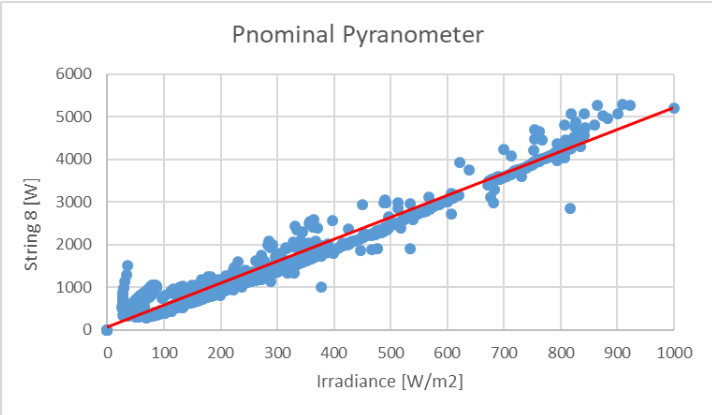

Figure 150. Performance of the Theoretical and Real Power without corrections. String 8

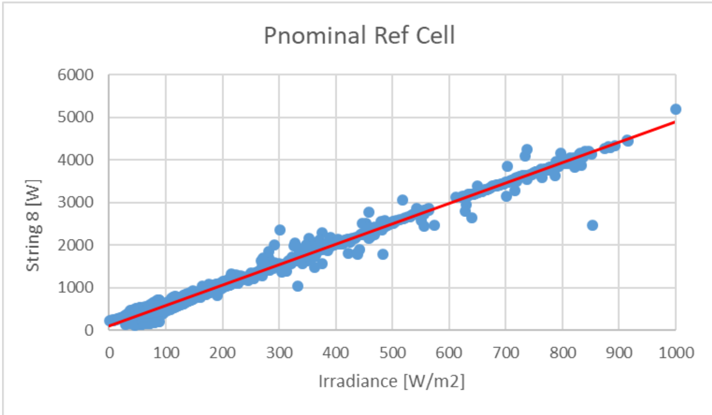

Figure 151. Performance of the Theoretical and Real Power with corrections. String 8

13th May

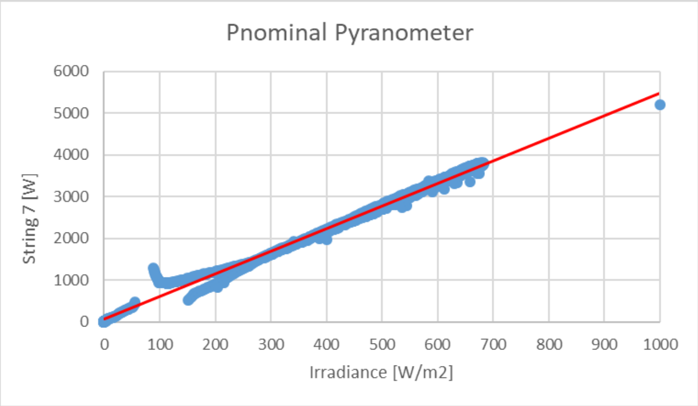

Figure 152. Performance of the Theoretical and Real Power without corrections. String 7

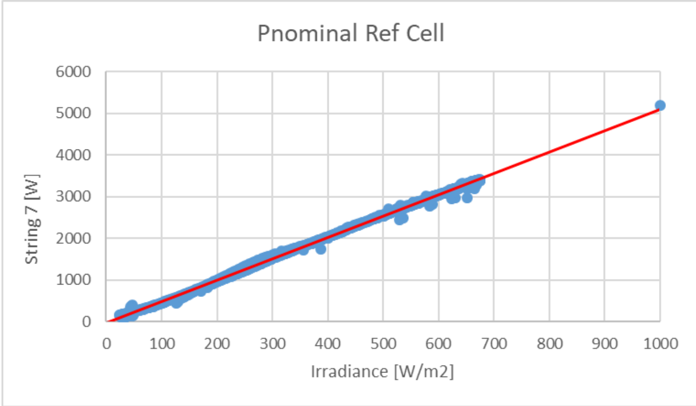

Figure 153. Performance of the Theoretical and Real Power with corrections. String 7

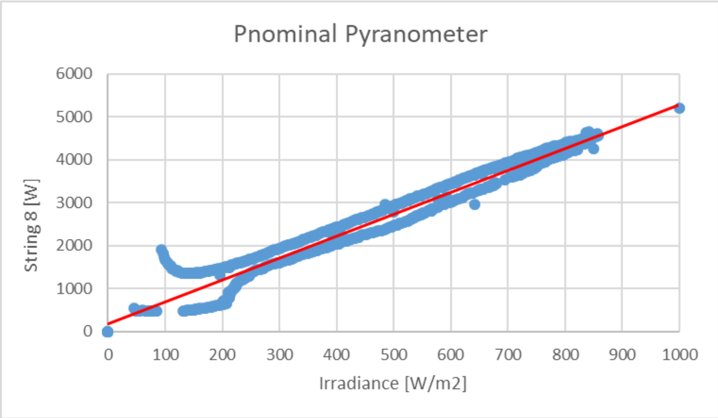

Figure 154. Performance of the Theoretical and Real Power without corrections. String 8

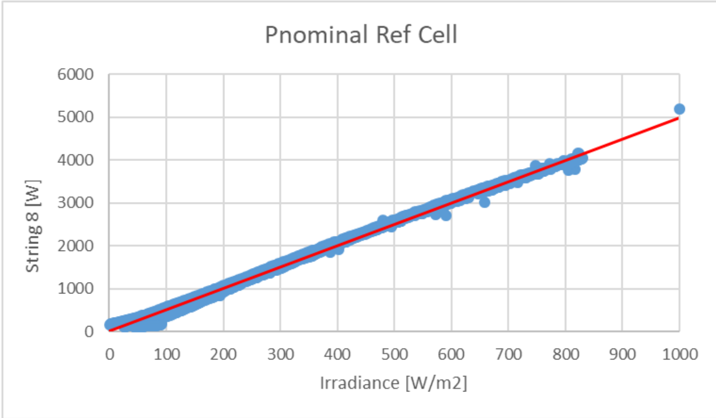

Figure 155. Performance of the Theoretical and Real Power with corrections. String 8

14th May

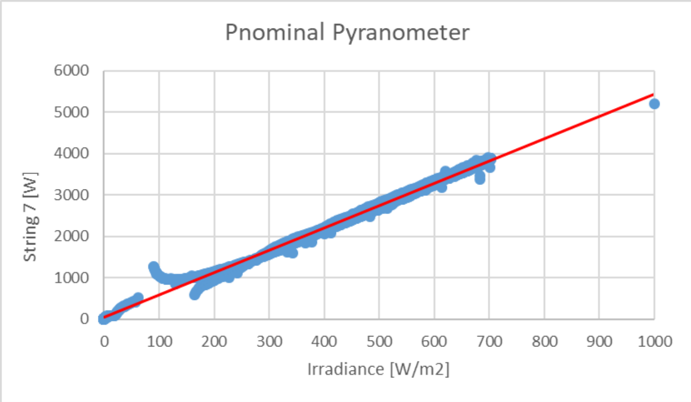

Figure 156. Performance of the Theoretical and Real Power without corrections. String 7

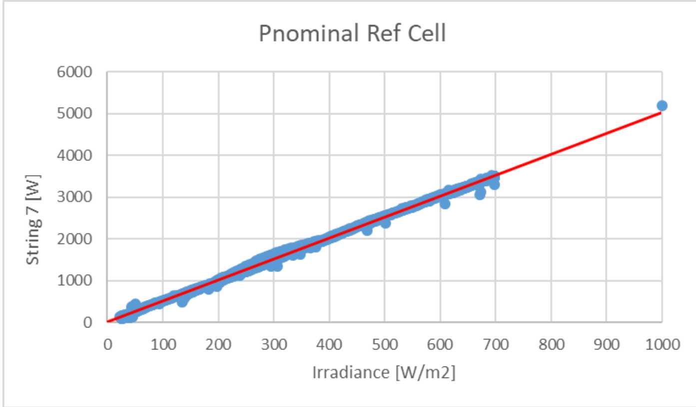

Figure 157. Performance of the Theoretical and Real Power with corrections. String 7

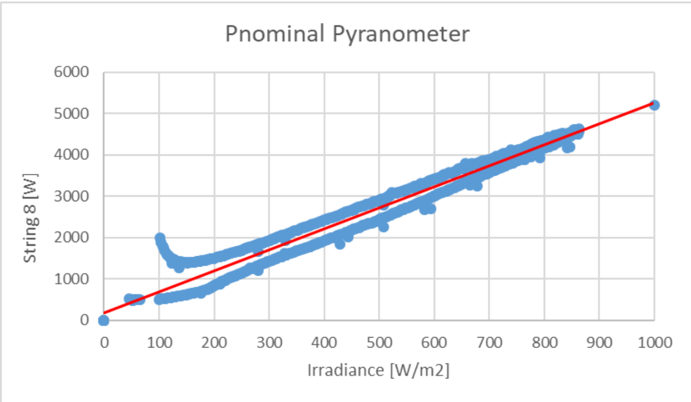

Figure 158. Performance of the Theoretical and Real Power without corrections. String 8

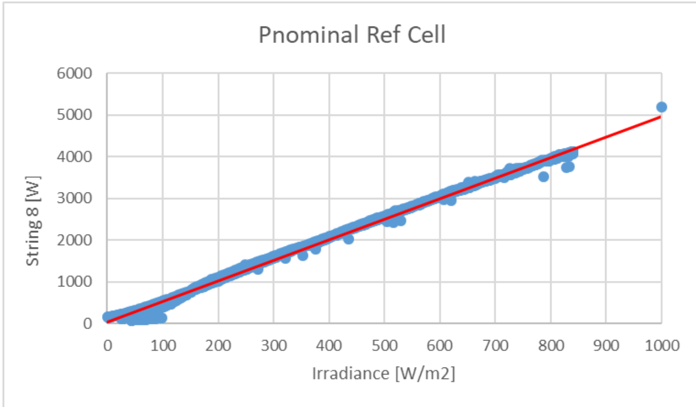

Figure 159. Performance of the Theoretical and Real Power with corrections. String 8

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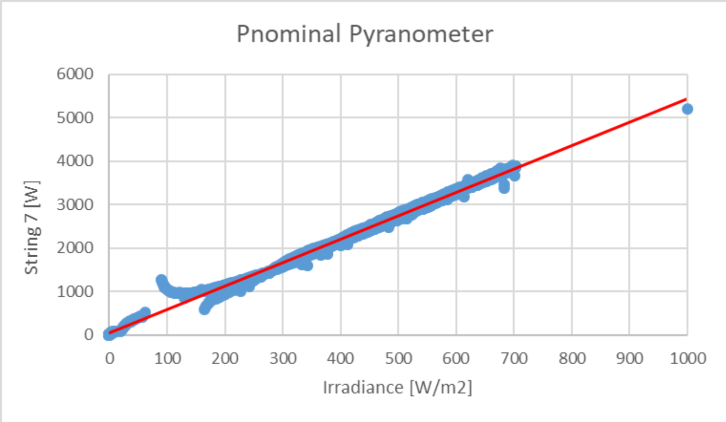

Figure 160. Performance of the Theoretical and Real Power without corrections. String 7

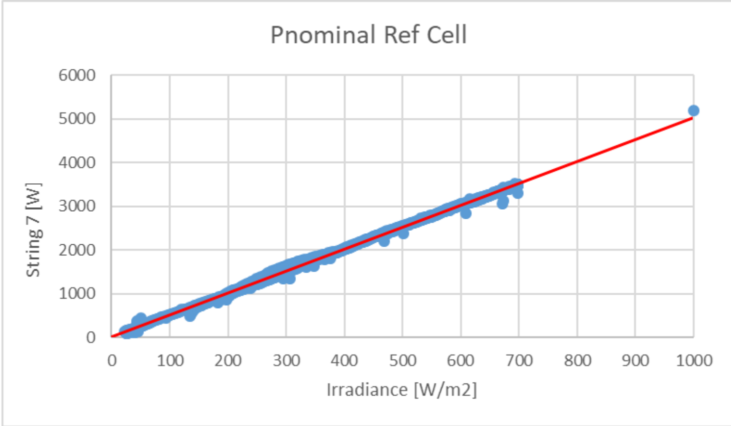

Figure 161. Performance of the Theoretical and Real Power with corrections. String 7

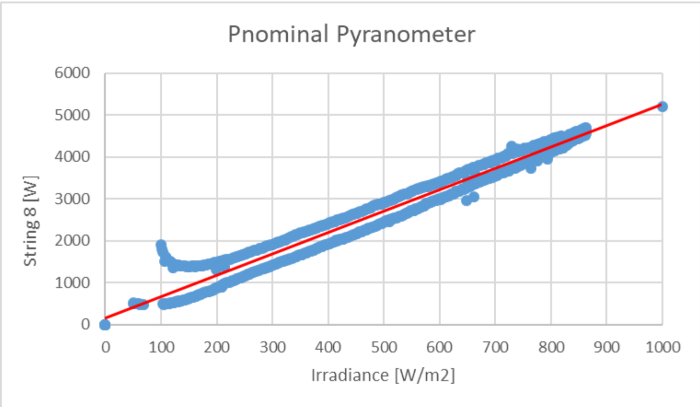

Figure 162. Performance of the Theoretical and Real Power without corrections. String 8

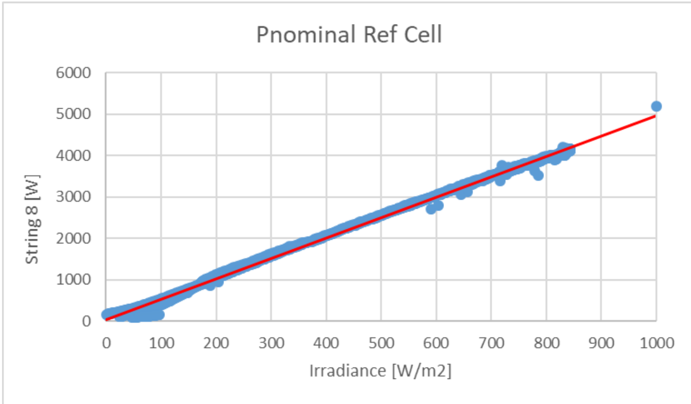

Figure 163. Performance of the Theoretical and Real Power with corrections. String 8

Appendix V: Total Power

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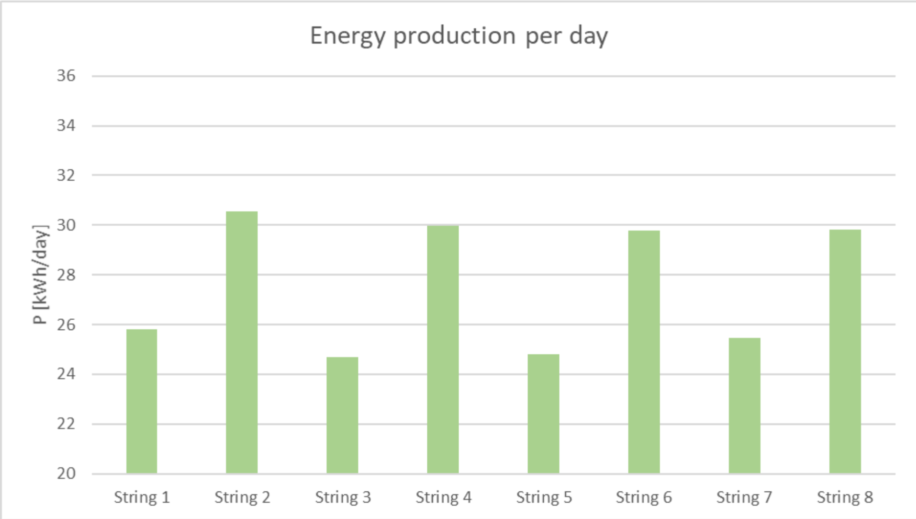

Figure 164. Energy production in kWh delivered by each string

10th May

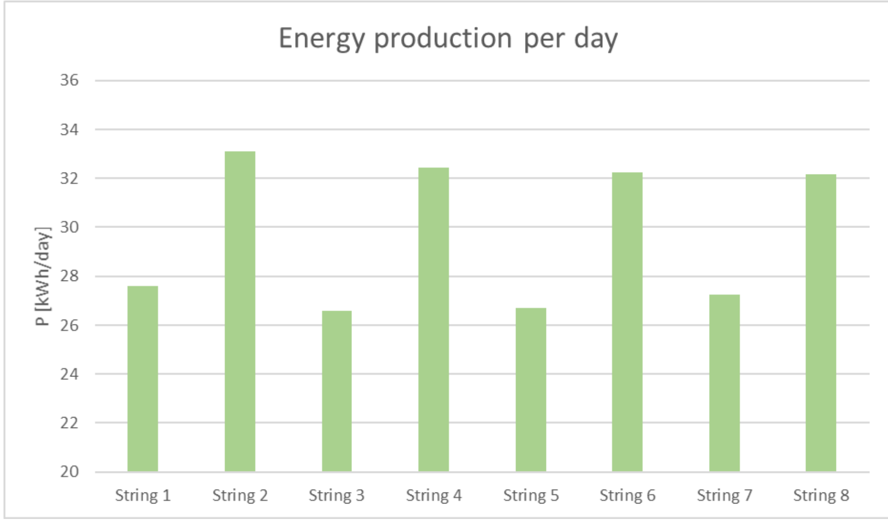

Figure 165. Energy production in kWh delivered by each string

11th May

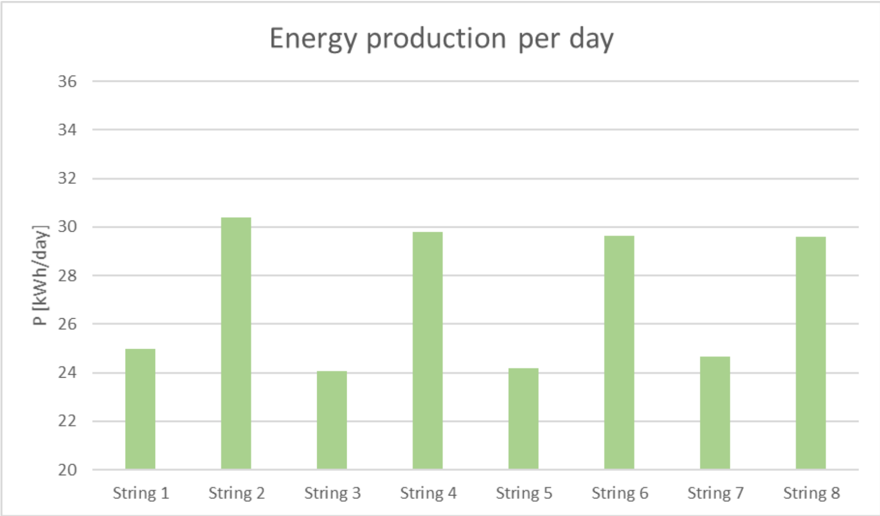

Figure 166. Energy production in kWh delivered by each string

12th May

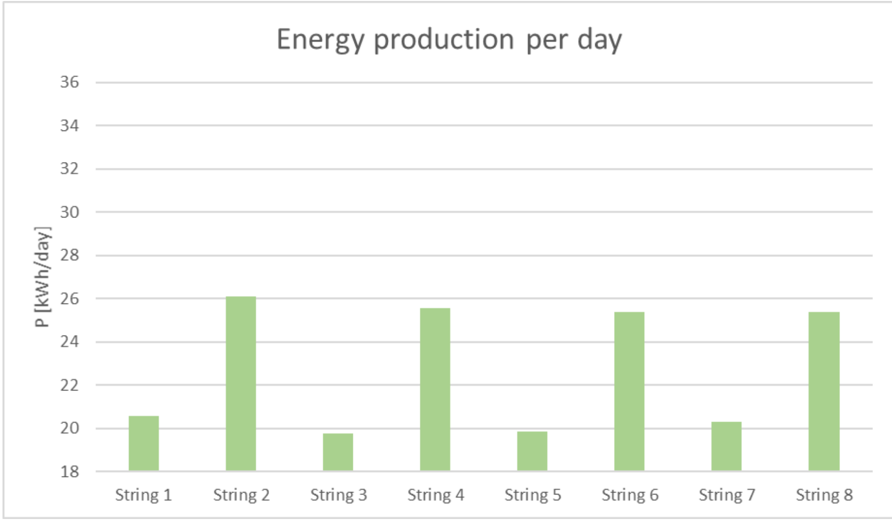

Figure 167. Energy production in kWh delivered by each string

13th May

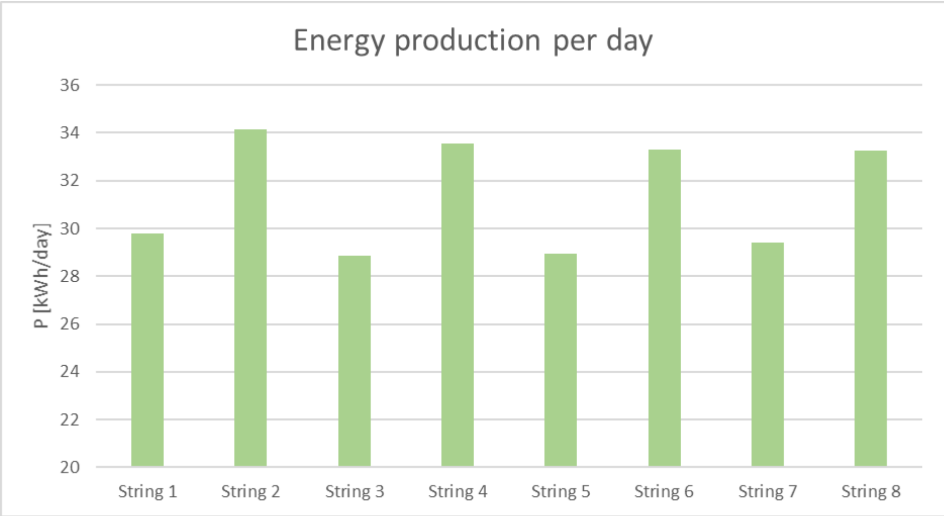

Figure 168. Energy production in kWh delivered by each string

14th May

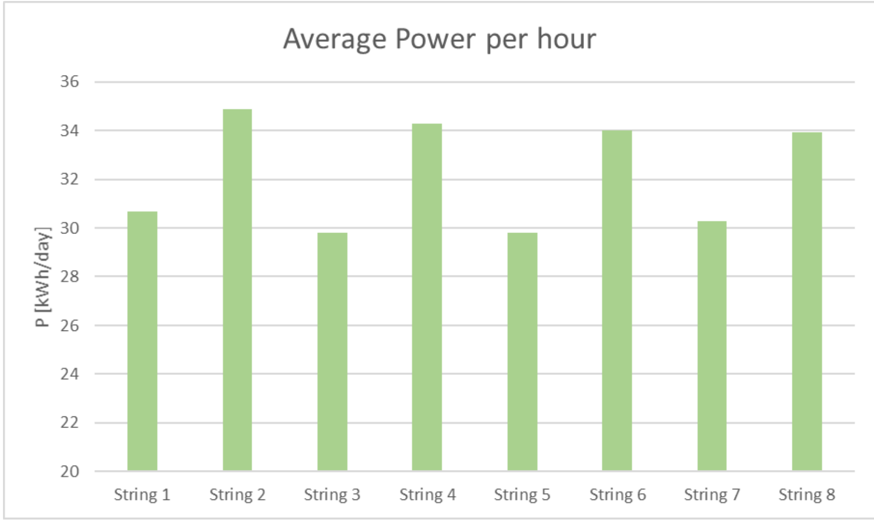

Figure 169. Energy production in kWh delivered by each string

15th May

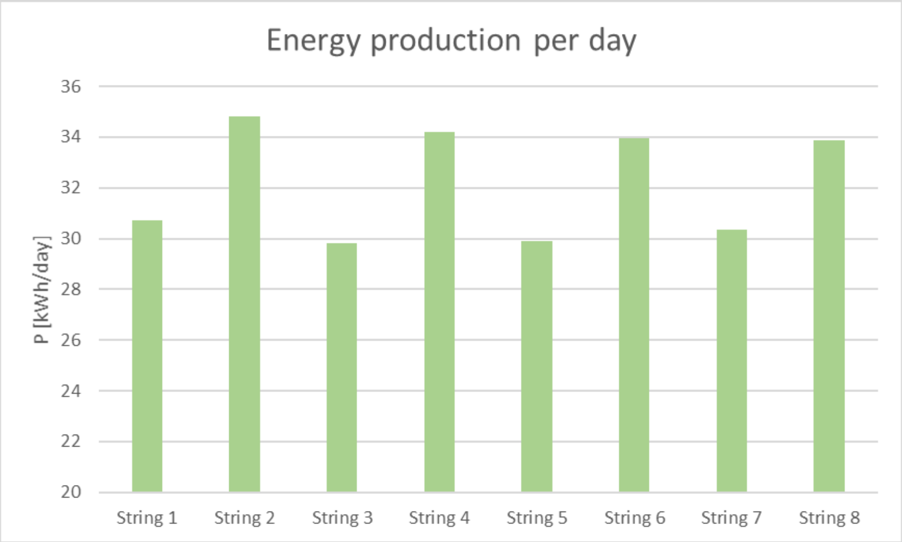

Figure 170. Energy production in kWh delivered by each string

Appendix VI: Irradiation

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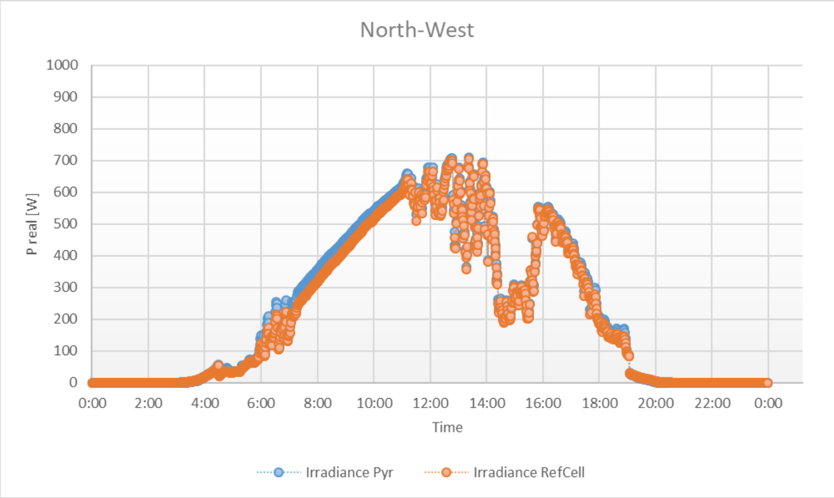

Figure 171. Irradiation received string 7

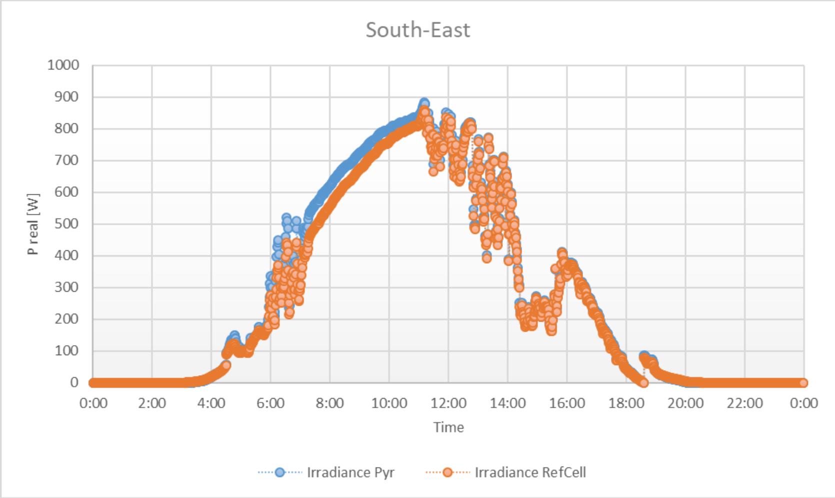

Figure 172. Irradiation received string 8

10th May

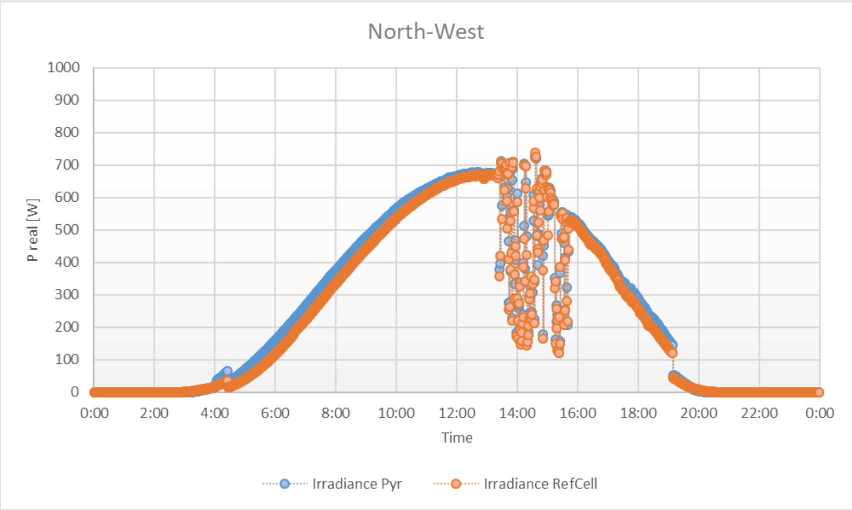

Figure 173. Irradiation received string 7

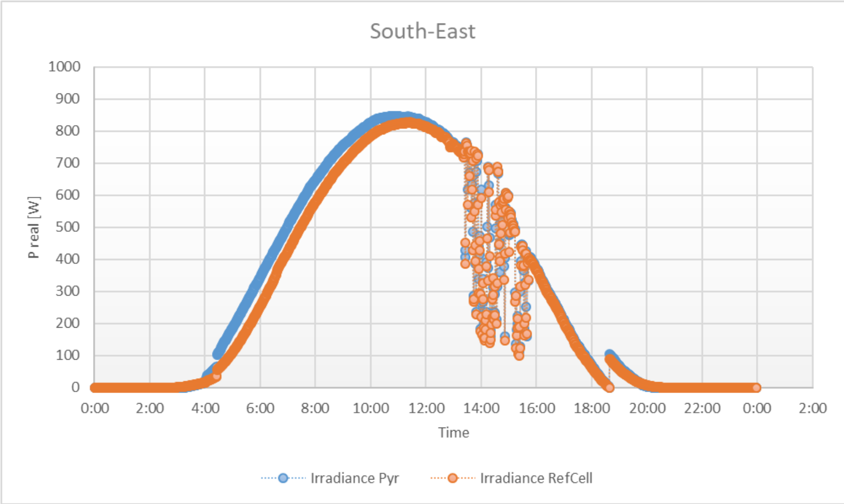

Figure 174. Irradiation received string 8

11th May

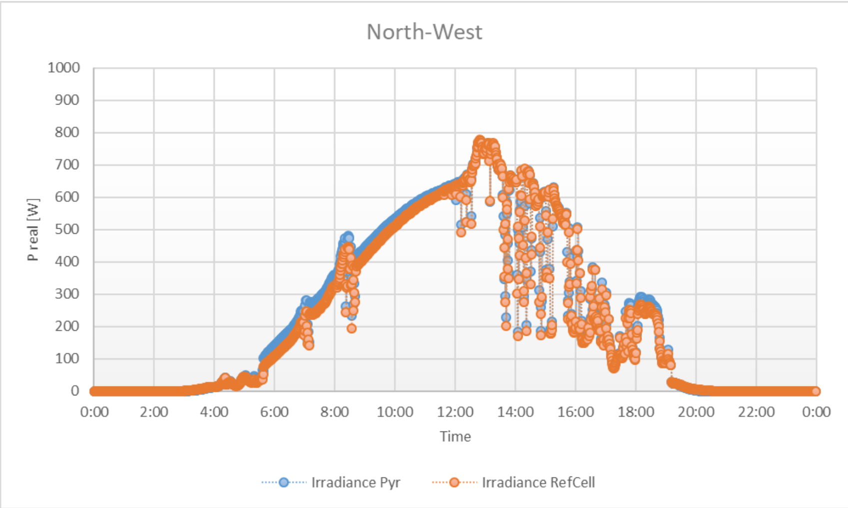

Figure 175. Irradiation received string 7

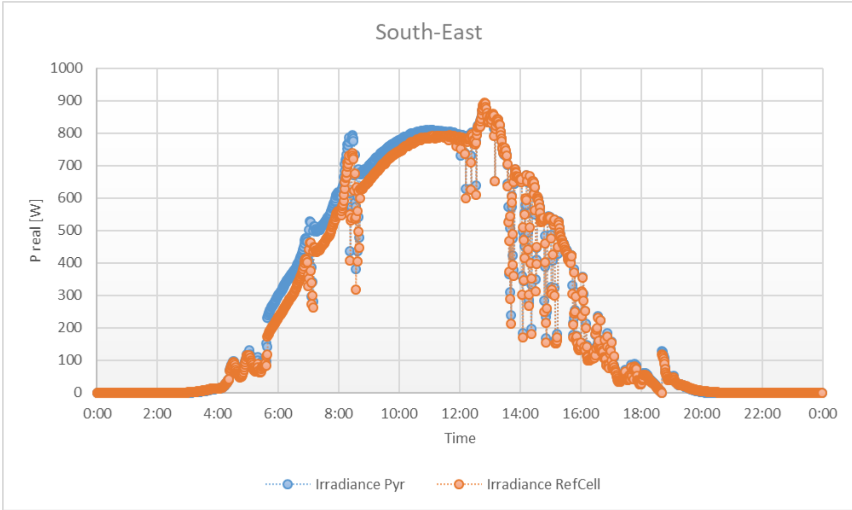

Figure 176. Irradiation received string 8

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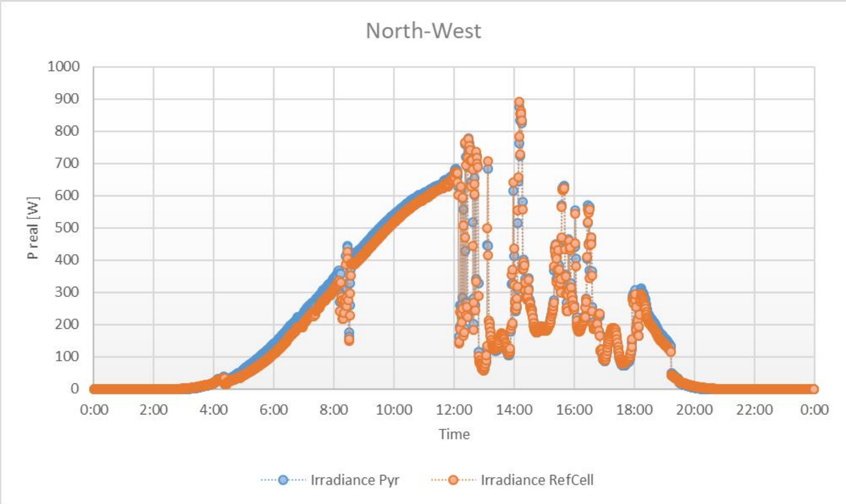

Figure 177. Irradiation received string 7

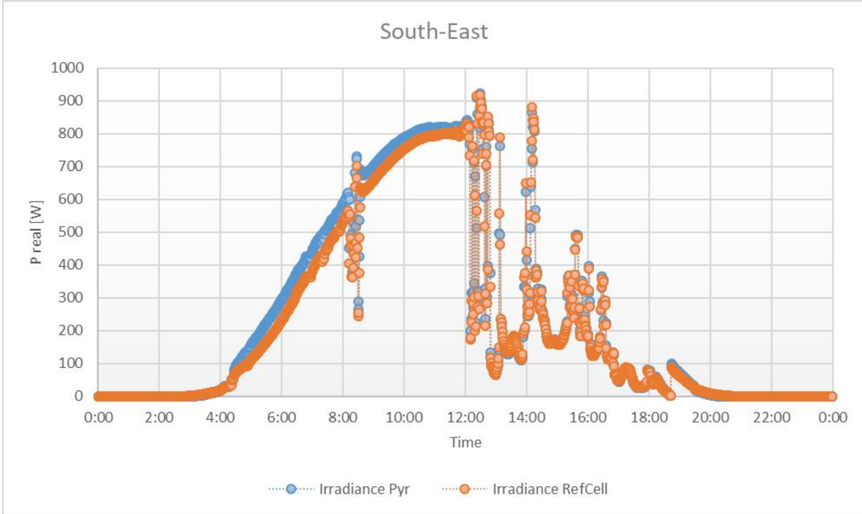

Figure 178. Irradiation received string 8

13th May

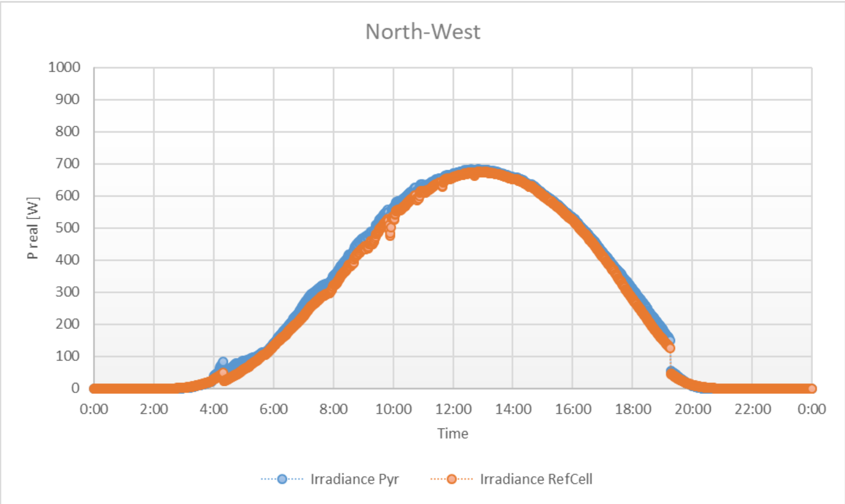

Figure 179. Irradiation received string 7

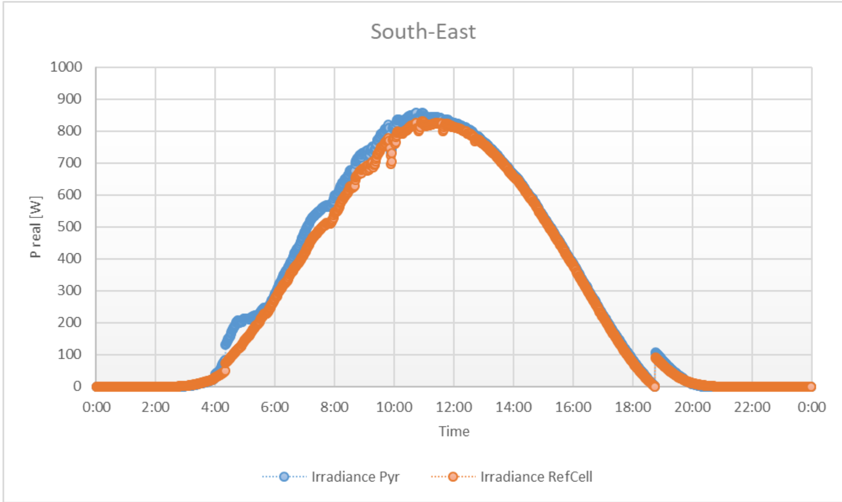

Figure 180. Irradiation received string 8

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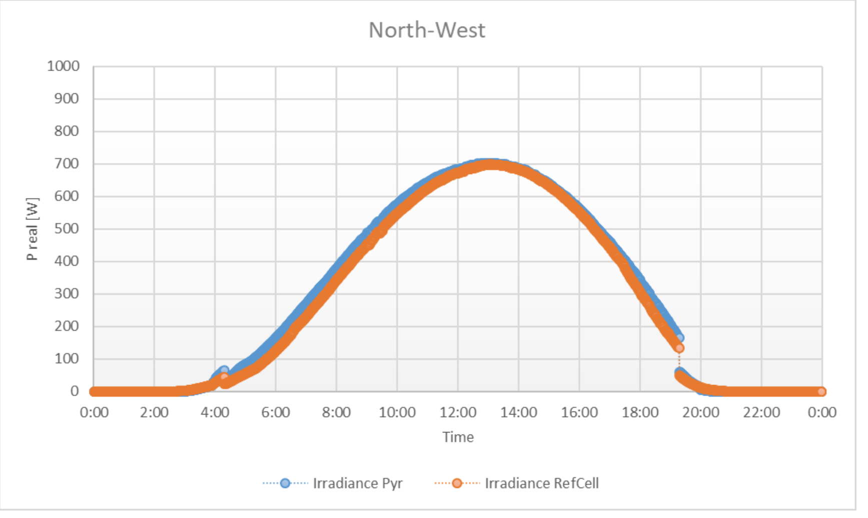

Figure 181. Irradiation received string 7

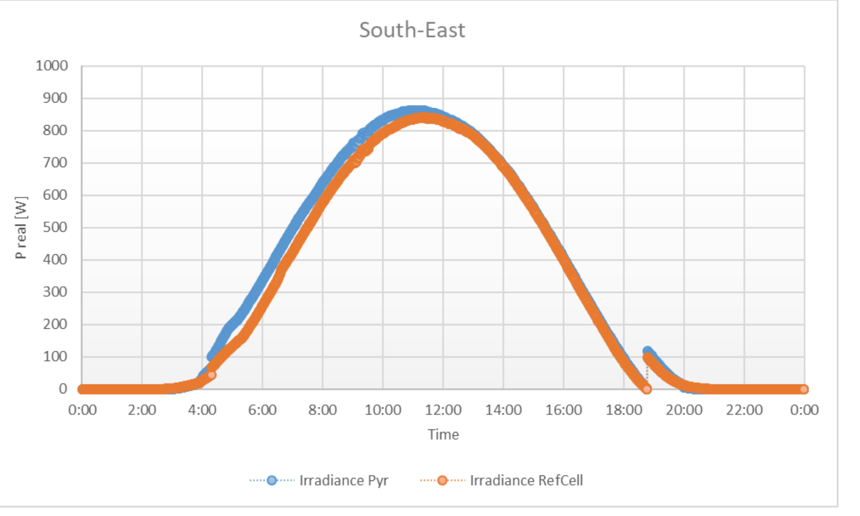

Figure 182. Irradiation received string 8

15th May

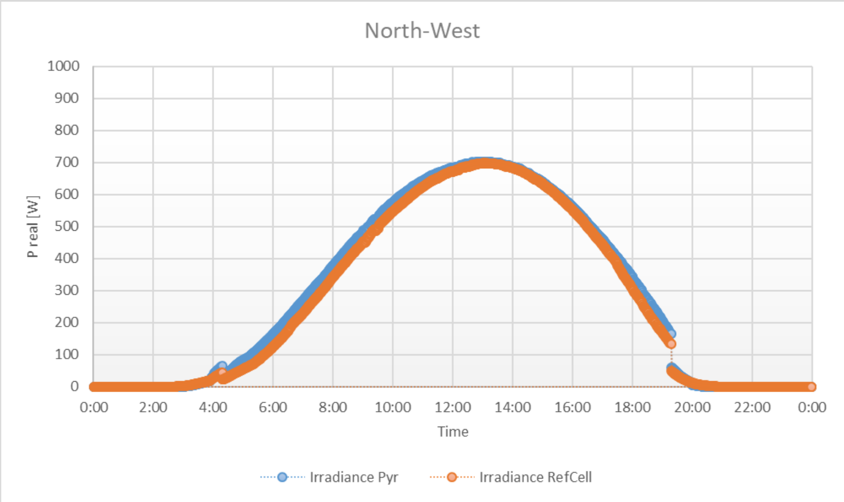

Figure 183. Irradiation received string 7

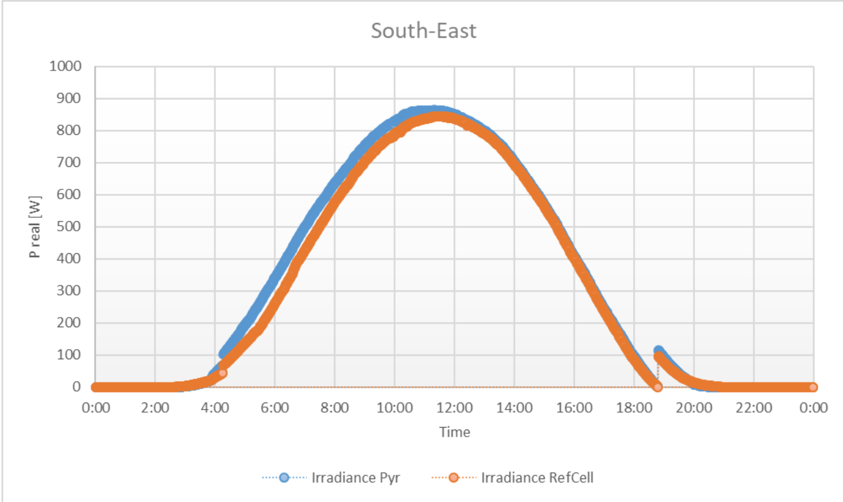

Figure 184. Irradiation received string 8

Appendix VII: Comparison Theoretical and Real Power by measurement device

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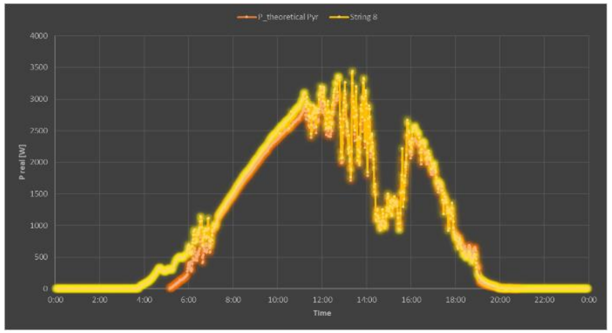

Figure 185. Pyranometer power vs Real Power. String 7.

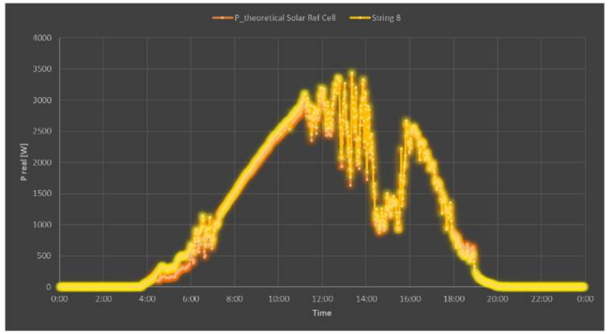

Figure 186. Reference Solar cell power vs Real Power. String 7.

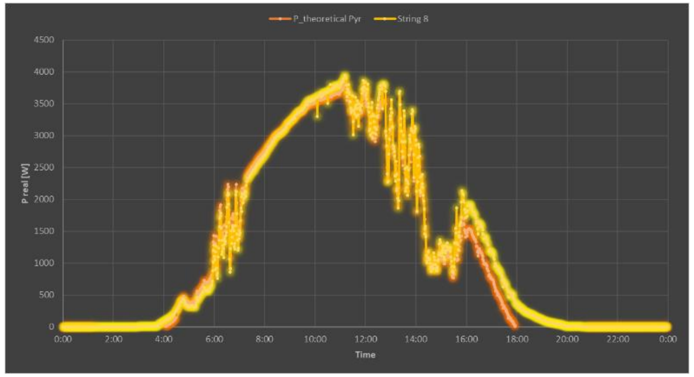

Figure 187. Pyranometer power vs Real Power. String 8.

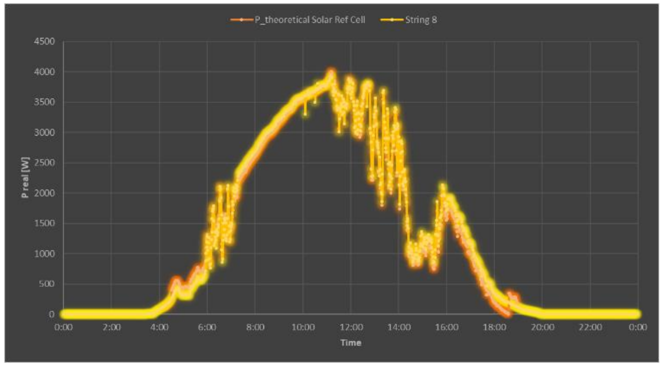

Figure 188. Reference Solar cell power vs Real Power. String 8.

10th May

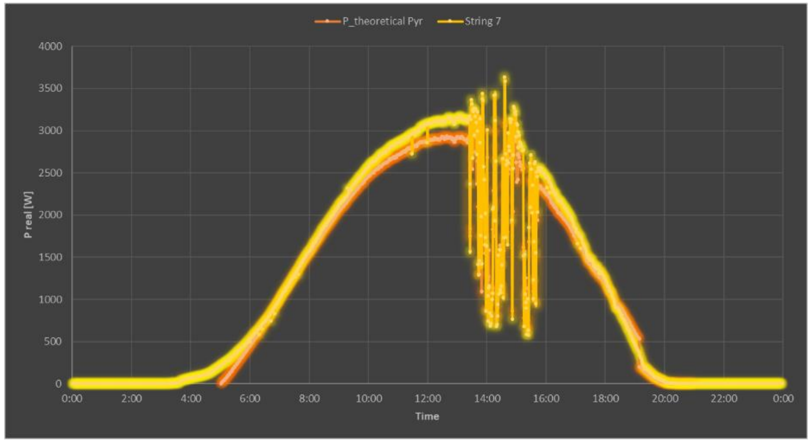

Figure 189. Pyranometer power vs Real Power. String 7.

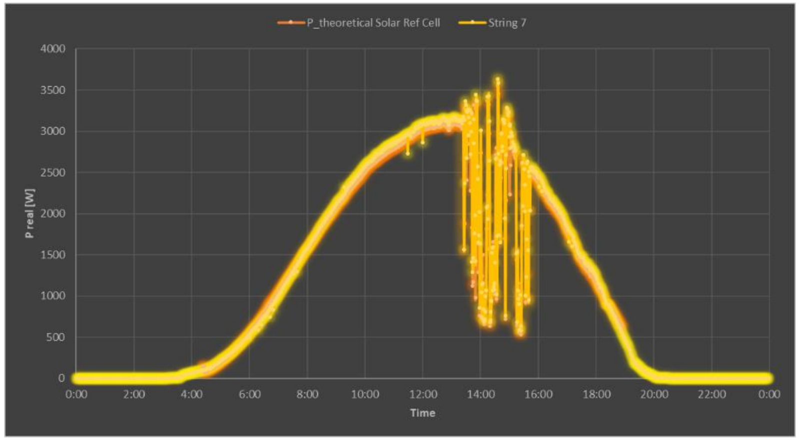

Figure 190. Reference Solar cell power vs Real Power. String 7.

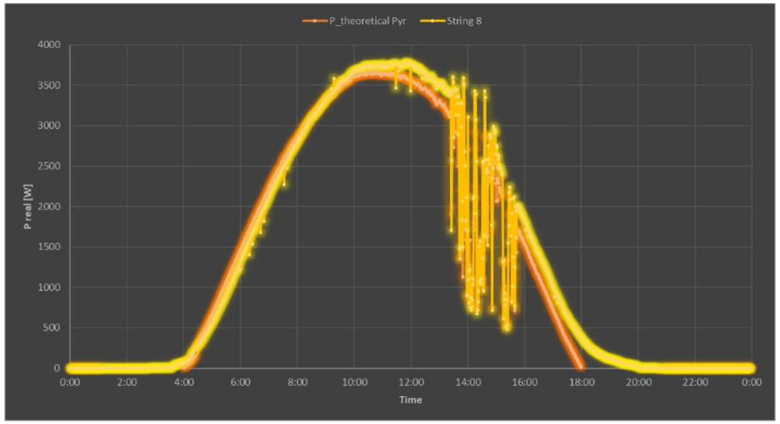

Figure 191. Pyranometer power vs Real Power. String 8.

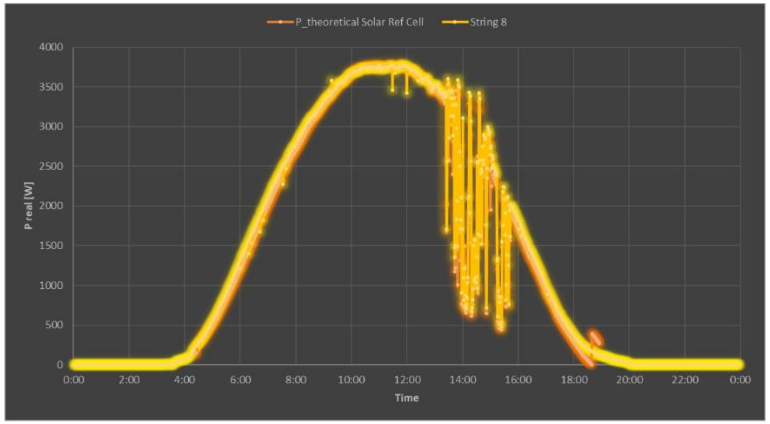

Figure 192. Reference Solar cell power vs Real Power. String 8.

11th May

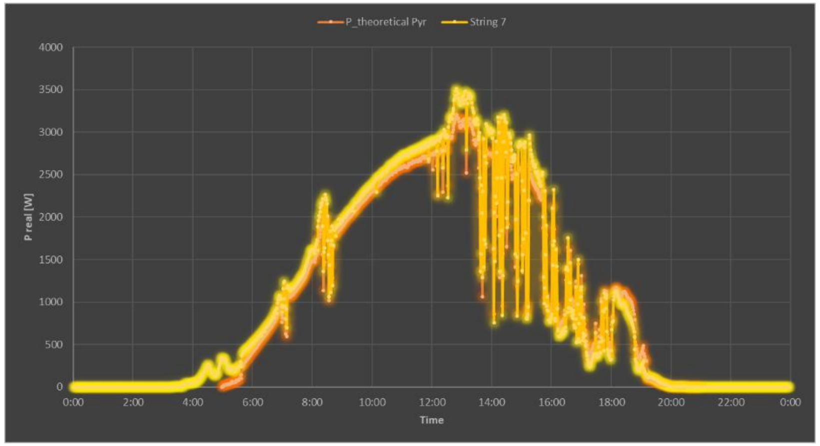

Figure 193. Pyranometer power vs Real Power. String 7.

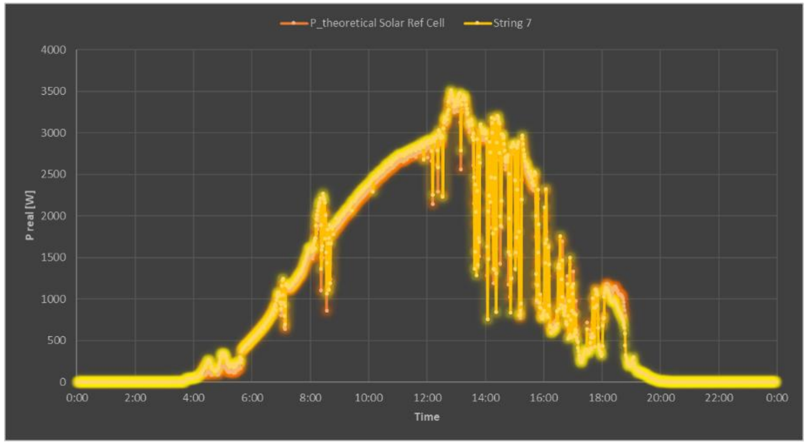

Figure 194. Reference Solar cell power vs Real Power. String 7.

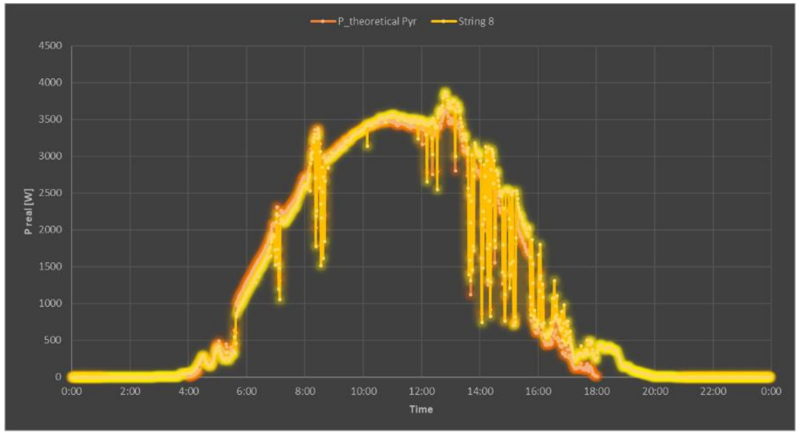

Figure 195. Pyranometer power vs Real Power. String 8.

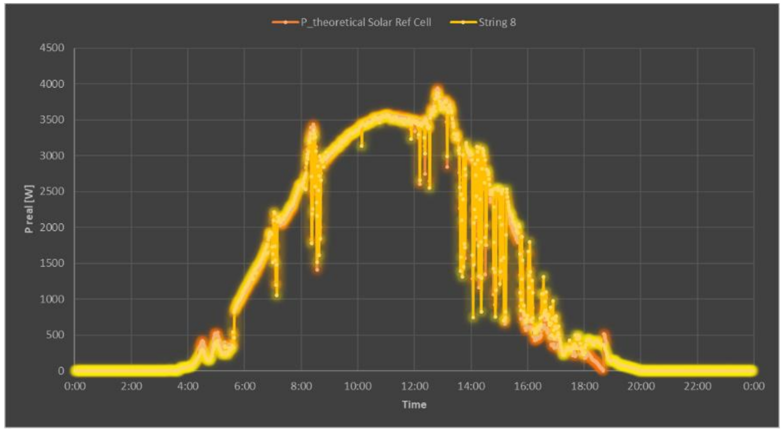

Figure 196. Reference Solar cell power vs Real Power. String 8.

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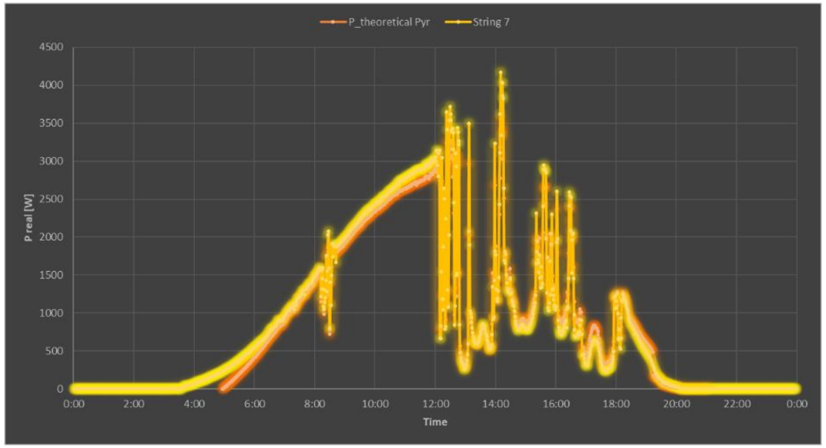

Figure 197. Pyranometer power vs Real Power. String 7.

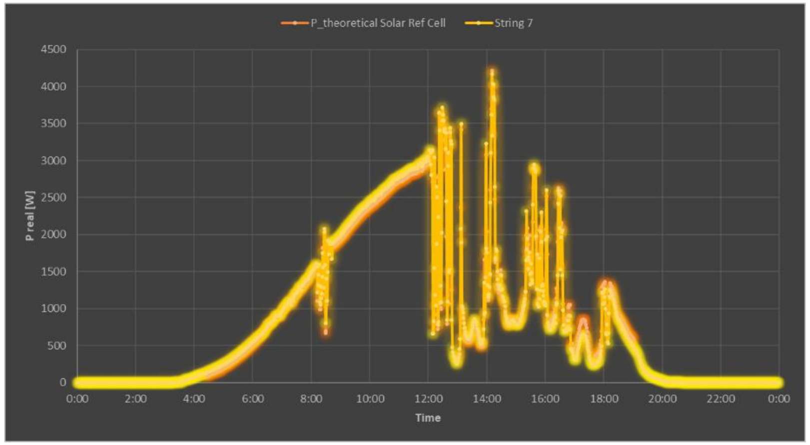

Figure 198. Reference Solar cell power vs Real Power. String 7.

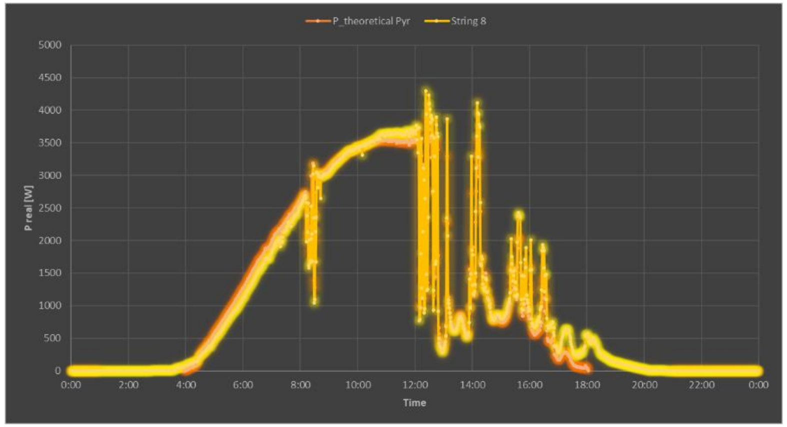

Figure 199. Pyranometer power vs Real Power. String 8.

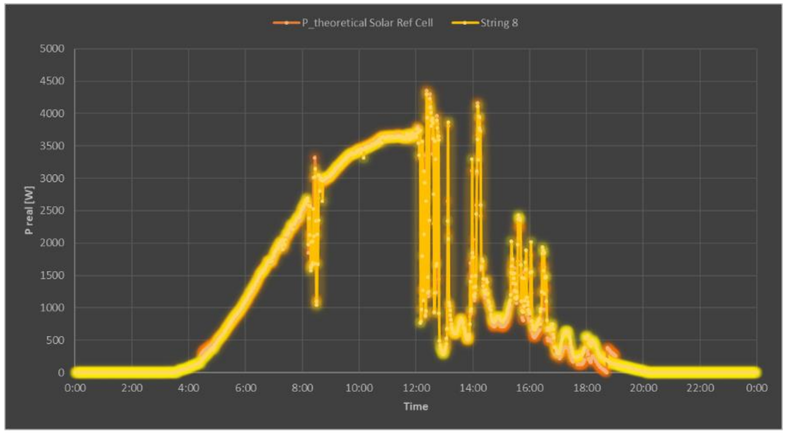

Figure 200. Reference Solar cell power vs Real Power. String 8.

13th May

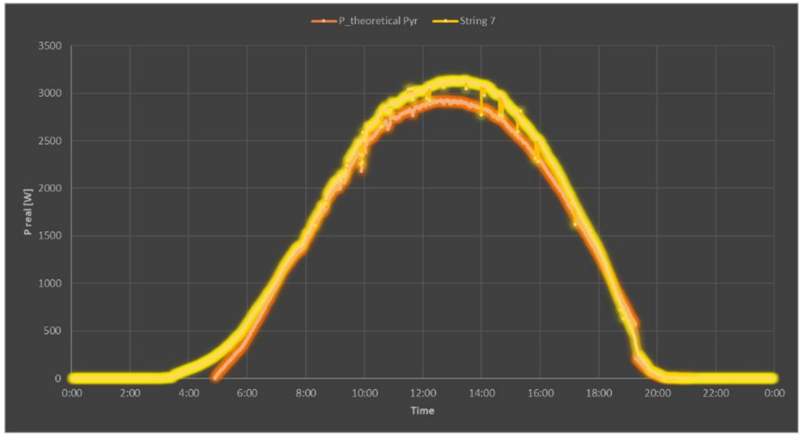

Figure 201. Pyranometer power vs Real Power. String 7.

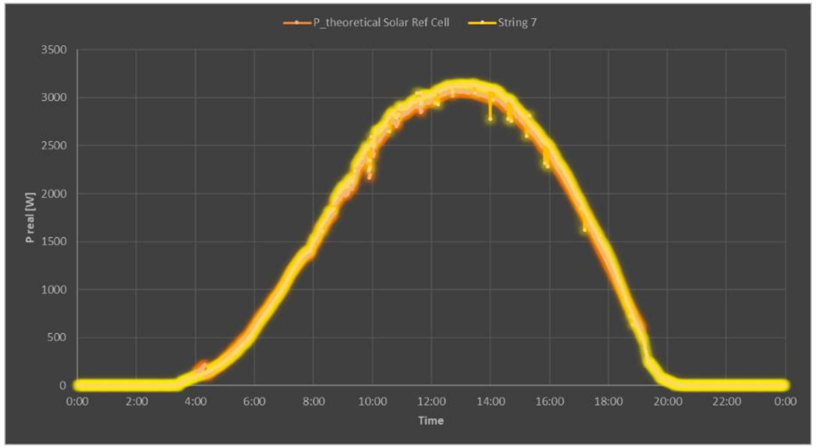

Figure 202. Reference Solar cell power vs Real Power. String 7.

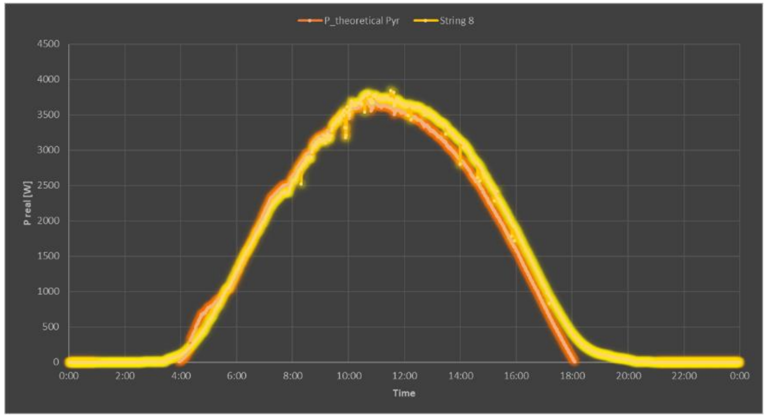

Figure 203. Pyranometer power vs Real Power. String 8.

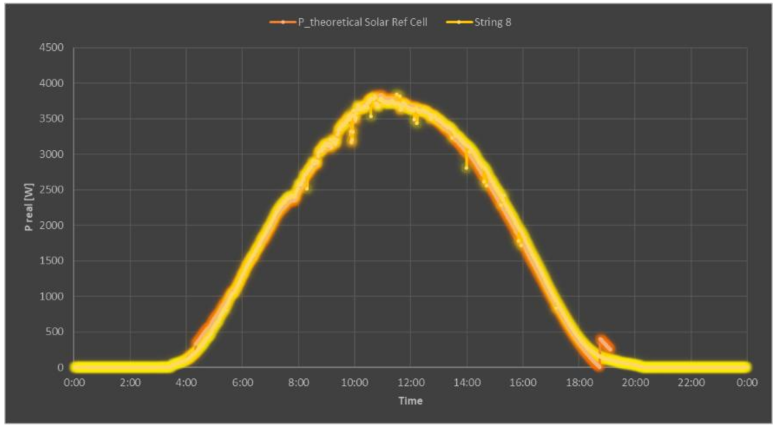

Figure 204. Reference Solar cell power vs Real Power. String 8.

14th May

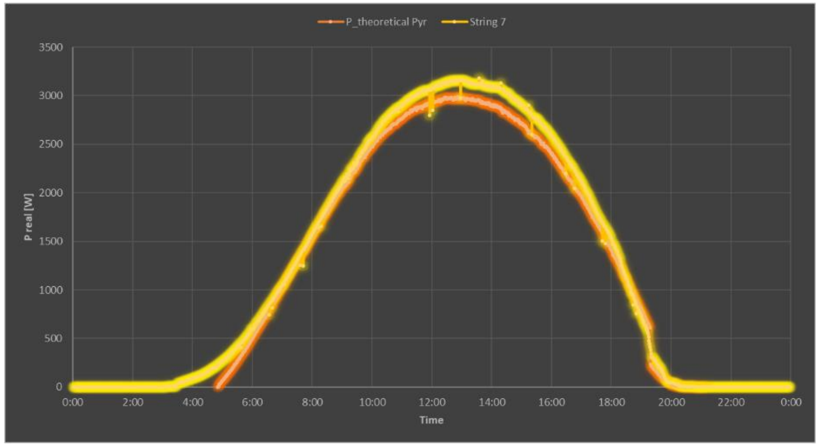

Figure 205. Pyranometer power vs Real Power. String 7.

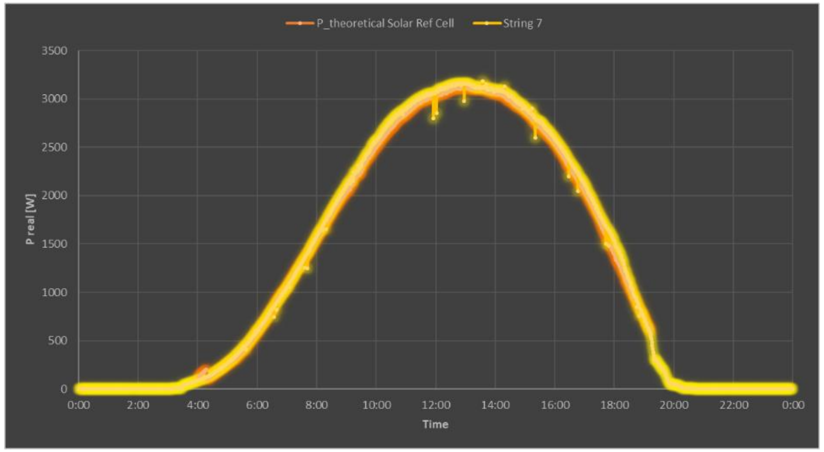

Figure 206. Reference Solar cell power vs Real Power. String 7.

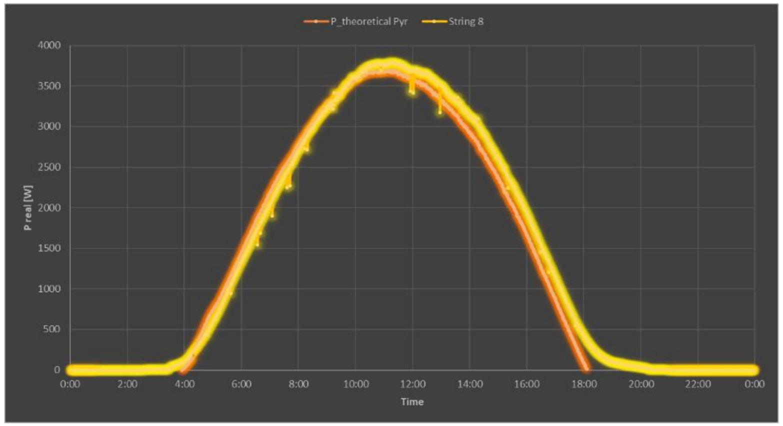

Figure 207. Pyranometer power vs Real Power. String 8.

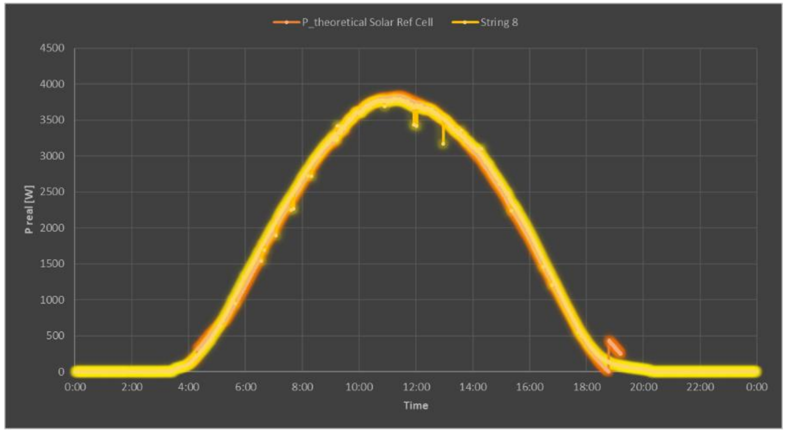

Figure 208. Reference Solar cell power vs Real Power. String 8.

15th May

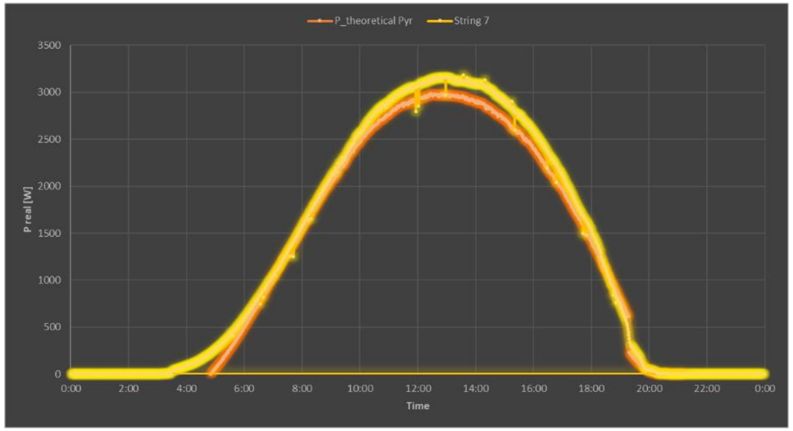

Figure 209. Pyranometer power vs Real Power. String 7.

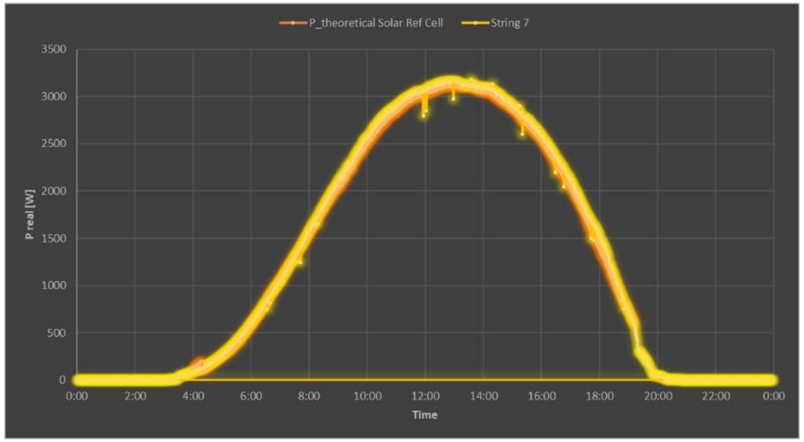

Figure 210. Reference Solar cell power vs Real Power. String 7.

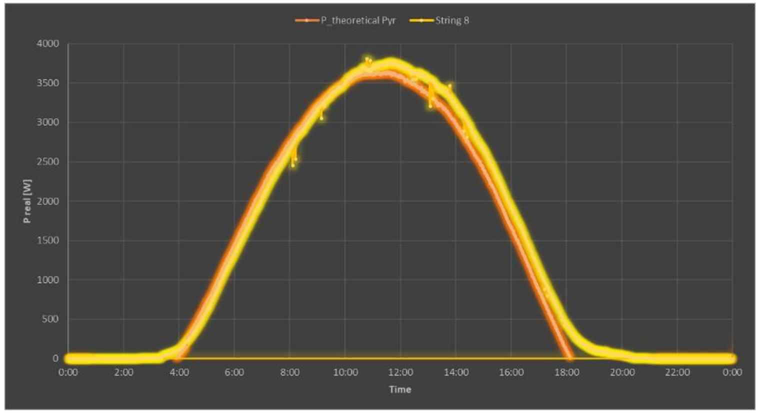

Figure 211. Pyranometer power vs Real Power. String 8.

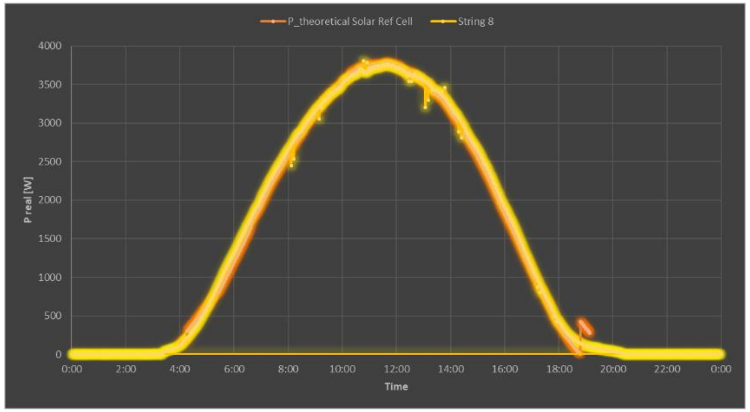

Figure 212. Reference Solar cell power vs Real Power. String 8.

Appendix VIII: Visual Basics Code

Step 1

Module 1

```
Sub Datos()
UserForm1.Show
End Sub
```

UseForm 1

```
Private Sub Label1_Click()
End Sub
Private Sub Label14_Click()
End Sub
Private Sub Label2_Click()
End Sub
Private Sub Label4_Click()
End Sub
Private Sub Label9_Click()
End Sub
Private Sub TextBox1_Change()
Dim TextBox1 As Single
End Sub
Private Sub TextBox2_Change()
Dim TextBox2 As Single
End Sub
Private Sub TextBox3_Change()
Dim TextBox3 As Single
End Sub
Private Sub TextBox5_Change()
Dim TextBox5 As Single
End Sub
```

```
Private Sub TextBox6_Change()
Dim TextBox6 As Single
End Sub
Private Sub TextBox7_Change()
Dim TextBox7 As Single
End Sub
Private Sub TextBox8_Change()
Dim TextBox8 As Single
End Sub
Sub CommandButton1_Click()
    Cells(5, 3) = Val(TextBox1)
    Cells(11, 3) = Val(TextBox2)
    Cells(12, 3) = Val(TextBox3)
    Cells(7, 3) = Val(TextBox5)
    Cells(8, 3) = Val(TextBox6)
    Cells(9, 3) = Val(TextBox7)
    Cells(10, 3) = Val(TextBox8)

    Dim mes As Single
    Dim dia As Single

    mes = Cells(12, 3)
    dia = Cells(11, 3)

    If mes = 1 Then
      dia = Cells(11, 3)
    End If
    If mes = 2 Then
      dia = Cells(11, 3) + 31
    End If
    If mes = 3 Then
```

```
    dia = Cells(11, 3) + 31 + 28
End If
If mes = 4 Then
    dia = Cells(11, 3) + 31 + 28 + 31
End If
If mes = 5 Then
    dia = Cells(11, 3) + 31 + 28 + 31 + 30
End If
If mes = 6 Then
    dia = Cells(11, 3) + 31 + 28 + 31 + 30 + 31
End If
If mes = 7 Then
    dia = Cells(11, 3) + 31 + 28 + 31 + 30 + 31 + 30
End If
If mes = 8 Then
    dia = Cells(11, 3) + 31 + 28 + 31 + 30 + 31 + 30 + 31
End If
If mes = 9 Then
    dia = Cells(11, 3) + 31 + 28 + 31 + 30 + 31 + 30 + 31 + 31
End If
If mes = 10 Then
    dia = Cells(11, 3) + 31 + 28 + 31 + 30 + 31 + 30 + 31 + 31 + 30
End If
If mes = 11 Then
    dia = Cells(11, 3) + 31 + 28 + 31 + 30 + 31 + 30 + 31 + 31 + 30 + 31
End If
If mes = 12 Then
    dia = Cells(11, 3) + 31 + 28 + 31 + 30 + 31 + 30 + 31 + 31 + 30 + 31 + 30
End If
Cells(6, 3) = dia
```

```
    UserForm1.Hide
End Sub
Private Sub UserForm_Click()
End Sub
```

Step 2

Módulo 2

```
Sub Constantes()
UserForm2.Show
End Sub
```

UseForm2

```
Private Sub Label1_Click()
End Sub
Private Sub TabStrip1_Change()
End Sub
Private Sub Label10_Click()
End Sub
Private Sub Label20_Click()
End Sub
Private Sub TextBox1_Change()
End Sub
Private Sub TextBox6_Change()
End Sub
Private Sub TextBox10_Change()
End Sub
Private Sub TextBox2_Change()
End Sub
Private Sub TextBox3_Change()
End Sub
Private Sub TextBox4_Change()
End Sub

Private Sub TextBox5_Change()
```

```
End Sub
Private Sub TextBox7_Change()
End Sub
Private Sub TextBox8_Change()
End Sub
Private Sub TextBox9_Change()
End Sub
Private Sub TextBox11_Change()
End Sub
Private Sub CommandButton1_Click()
    Cells(20, 3) = Val(TextBox1)
    Cells(20, 4) = Val(TextBox2)
    Cells(20, 5) = Val(TextBox3)
    Cells(20, 6) = Val(TextBox4)
    Cells(23, 3) = Val(TextBox5)
    Cells(23, 4) = Val(TextBox11)
    Cells(26, 3) = Val(TextBox6)
    Cells(26, 4) = Val(TextBox7)
    Cells(26, 5) = Val(TextBox8)
    Cells(26, 6) = Val(TextBox10)
    Cells(29, 3) = Val(TextBox9)
    UserForm2.Hide
End Sub
Private Sub UserForm_Click()
End Sub
```

Step 3

Módulo 1

```
Sub Potencia()
x = 2
y = 2
While Sheets("Current").Cells(y, x) <> ""
    While Sheets("Current").Cells(y, x) <> ""
```

```
            Sheets("Power").Cells(y,x)=Sheets("Voltage").Cells(y,x) *
Sheets("Current").Cells(y, x)

            x = x + 1

        Wend

        y = y + 1

        x = 2

Wend


I = 2

        While Sheets("Irradiance").Cells(I, 3) <> ""

            If (Sheets("Irradiance").Cells(I, 3) < 0) Then

                Sheets("Irradiance").Cells(I, 4) = 0

            ElseIf (Sheets("Irradiance").Cells(I, 7) < 0) Or (Sheets("Irradiance").Cells(I,
6) < 0.25) Then

                Sheets("Irradiance").Cells(I, 4) = Sheets("Irradiance").Cells(I, 3) * 1000 /
Sheets("Main Program").Cells(23, 3)

            Else

                Sheets("Irradiance").Cells(I, 4) = (Sheets("Irradiance").Cells(I, 3) * 1000
/ Sheets("Main Program").Cells(23, 3)) * (Sheets("Irradiance").Cells(I, 7) /
Sheets("Irradiance").Cells(I, 6))

            End If

                I = I + 1

        Wend

h = 2

        While Sheets("Irradiance").Cells(h, 2) <> ""

            If (Sheets("Irradiance").Cells(h, 2) < 0) Then

                Sheets("Irradiance").Cells(h, 5) = 0

            ElseIf (Sheets("Irradiance").Cells(h, 7) < 0) Or
(Sheets("Irradiance").Cells(h, 6) < 0.25) Then

                Sheets("Irradiance").Cells(h, 5) = Sheets("Irradiance").Cells(h, 2) * 1.02
* 1000 / Sheets("Main Program").Cells(20, 4)

            Else
```

```
            Sheets("Irradiance").Cells(h, 5) = (Sheets("Irradiance").Cells(h, 2) * 1.02 * 1000 / Sheets("Main Program").Cells(20, 4)) * (Sheets("Irradiance").Cells(h, 7) / Sheets("Irradiance").Cells(h, 6))

            End If

              h = h + 1

        Wend

T = 2

        While Sheets("T_module").Cells(T, 2) <> ""

            Sheets("T_module").Cells(T, 5) = ((Sheets("Main Program").Cells(20, 3) - (1000 * Sheets("T_module").Cells(T, 2))) / Sheets("Main Program").Cells(20, 5)) + Sheets("Main Program").Cells(20, 6)

            T = T + 1

        Wend

p = 2

        While Sheets("T_module").Cells(p, 3) <> ""

            Sheets("T_module").Cells(p, 4) = Sheets("T_module").Cells(p, 3) + (Sheets("Irradiance").Cells(p, 4) / Sheets("Main Program").Cells(23, 4))

            p = p + 1

        Wend

r = 6

e = 2

        While Sheets("Calculate solar angles").Cells(r, 14) <> ""

            Sheets("Angle incidence correction").Cells(e, 2) = 1 - Sheets("Main Program").Cells(29, 3) * ((1 / Sheets("Calculate solar angles").Cells(r, 14)) - 1)

            r = r + 1

            e = e + 1

        Wend

End Sub
```

Step 4

Módulo 3

```
Sub PowerTotal()

Dim B As Single
```

```
x = 2
y = 2
B = 0
A = 0
Maxim = 0
While Sheets("Power").Cells(y, x) <> ""
   While Sheets("Power").Cells(y, x) <> ""
      A = Sheets("Power").Cells(y, x)
      B = B + A
      x = x + 1
   Wend
   x = 2
   Sheets("Totalpower").Cells(y, x) = B
   If B > Maxim Then
      Maxim = B
   End If
   y = y + 1
   A = 0
   B = 0
   'KW'
   Sheets("Totalpower").Cells(3, 4) = Maxim / 1000
Wend
I = 2
   While Sheets("Irradiance").Cells(I, 4) <> ""
      If (Sheets("Angle incidence correction").Cells(I, 2) < 0) Or (Sheets("Angle
incidence correction").Cells(I, 2) > 1.5) Then
       Sheets("PTheoric").Cells(I, 2) = ""
      Else
         Sheets("PTheoric").Cells(I, 2) = 0.95 * Sheets("Main Program").Cells(26, 6)
* Sheets("Main Program").Cells(26, 3) * (Sheets("Angle incidence
correction").Cells(I, 2) * Sheets("Irradiance").Cells(I, 4)) * (1 +
```

```
((Sheets("T_module").Cells(l, 4) - Sheets("Main Program").Cells(20, 6)) *
(Sheets("Main Program").Cells(26, 5) / 100))) / 1000

        End If

            l = l + 1

    Wend

p = 2

        While Sheets("Irradiance").Cells(p, 5) <> ""

        If (Sheets("T_module").Cells(p, 5) > 60) Then

          Sheets("PTheoric").Cells(p, 3) = ""

        Else

            Sheets("PTheoric").Cells(p, 3) = 0.95 * Sheets("Main Program").Cells(26,
6) * Sheets("Main Program").Cells(26, 3) * Sheets("Irradiance").Cells(p, 5) * (1 +
((Sheets("T_module").Cells(p, 5) - Sheets("Main Program").Cells(20, 6)) *
(Sheets("Main Program").Cells(26, 5) / 100))) / 1000

        End If

            p = p + 1

        Wend


j = 2

k = 2

While Sheets("Power").Cells(k, j) <> ""

        While Sheets("Power").Cells(k, j) <> ""

            If (Sheets("Irradiance").Cells(k, 4) = 0) Then

                    Sheets("Ppeak_Pyr").Cells(k, j) = 0

            Else

                Sheets("Ppeak_Pyr").Cells(k, j) = Sheets("Power").Cells(k, j) /
Sheets("Irradiance").Cells(k, 4)

            End If

            j = j + 1

        Wend

        k = k + 1

        j = 2
```

```
Wend

m = 2
n = 2
While Sheets("Power").Cells(n, m) <> ""
    While Sheets("Power").Cells(n, m) <> ""
      If (Sheets("Irradiance").Cells(n, 5) = 0) Then
            Sheets("Ppeak_RefCell").Cells(n, m) = 0
      Else
        Sheets("Ppeak_RefCell").Cells(n, m) = Sheets("Power").Cells(n, m) / Sheets("Irradiance").Cells(n, 5)
      End If
      m = m + 1
    Wend
    n = n + 1
    m = 2
Wend
End Sub
```

Step 5

Module 4

```
Sub Pnominal()
j = 2
k = 2
While Sheets("Power").Cells(k, j) <> ""
    While Sheets("Power").Cells(k, j) <> ""
      If (Sheets("Power").Cells(k, j) = 0) Or (Sheets("Angle incidence correction").Cells(k, 2) < 0.22) Or (Sheets("Angle incidence correction").Cells(k, 2) > 1.5) Then
        Sheets("Pnom_Pyr").Cells(k, j) = ""
      Else
```

```
            Sheets("Pnom_Pyr").Cells(k, j) = Sheets("Power").Cells(k, j) / (Sheets("Angle incidence correction").Cells(k, 2) * (1 + ((Sheets("T_module").Cells(k, 4) - Sheets("Main Program").Cells(20, 6)) * (Sheets("Main Program").Cells(26, 5) / 100))))
        End If
        j = j + 1
    Wend
    k = k + 1
    j = 2
Wend


m = 2
n = 2
While Sheets("Power").Cells(n, m) <> ""
    While Sheets("Power").Cells(n, m) <> ""
        If (Sheets("Irradiance").Cells(n, 5) = 0) Or (Sheets("T_module").Cells(n, 5) > 65) Then
            Sheets("Pnom_RefCell").Cells(n, m) = ""
        Else
            Sheets("Pnom_RefCell").Cells(n, m) = Sheets("Power").Cells(n, m) / (1 + ((Sheets("T_module").Cells(n, 5) - Sheets("Main Program").Cells(20, 6)) * (Sheets("Main Program").Cells(26, 5) / 100)))
        End If
        m = m + 1
    Wend
    n = n + 1
    m = 2
Wend
End Sub
```