Influence of an Aluminium Concentrator Corrosion on Solar Cell Parameters

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Abstract

The climate changes observed over the last decades have been altering the energy sector that depended almost entirely on fossil fuels. Renewable energies are a plausible alternative because they can reduce the emission of toxic gases that have been produced in excess by the necessities of men. In the group of renewable energies, solar energy has the biggest potential and growth because it is cheaper and easy to set. These technologies used in this exploration can be equipped with concentrators to increase the efficiency because it reduces the area of the solar cells and, therefore, its price, [2]. However, there are problems that have to be dealt with like the corrosion of the concentrators that induce a premature ageing and costs. In this work, it will be used *Tonatiuh* to trace the solar rays of the concentrator to assess the effect of the defects caused by corrosion due to the ambient circumstances. These studies are complemented with laboratory experiences.
Keywords: Solar Energy, Photovoltaic Cell, Solar Concentrator, Aluminium Corrosion, CPV.

1. Introduction

It is known that renewable energies are a good answer to the increasing demand of energy on modern societies and they are gaining an important momentum in the present time.

Even though we are a long way from replacing completely fossil fuel sources, some alternatives, like solar energy, are generating special interest because it can be extracted from everywhere and has many applications leading to easy set-ups and low prices per kWh.

Nowadays, new ways are being studied in order to increase and improve the way we extract the energy of the sun. In order to enhance the efficiency, new sets of cells, new formats and concentrators are being used.

The main idea behind the use of a concentrator is to direct solar rays from the its surface to a receiver, that may be solar cells or fluids. Concentrators can decrease the number of expensive cells used per area without affecting its performance, leading to a decrease of price kWh generated. On the other hand, problems may arise while using this concentrator-Photovoltaic (CPV) system, mainly due to corrosion, [14].

The objective of this study is to acknowledge the effects that the degradation of concentrators due to corrosion can have in the parameters of silicon solar cells, the most used today. Firstly, a computer simulation is made to analyse how the optical errors of the corrosion in aluminium, that can come in multiple ways [13], [12], concentrators affect the output power of it. Secondly, a laboratory experience is conducted to study the effects of aluminium corrosion on the parameters of the cells.

2. State of Art

2.1. Solar Spectrum

Solar radiation is referred to as the energy emitted by the sun that is transmitted in the form of electromagnetic radiation and is described by frequency, wavelength or photon energy.

With these physical quantities it is possible to create an electromagnetic spectrum and relate them with the irradiance received. These properties are related by the following equations:

$$\begin{aligned} f &= \frac{c}{\lambda} \\ E_f &= fh \end{aligned} \tag{1}$$

After the waves pass through Earths atmosphere its intensity is about 1000 W/m^2, but the value oscillates with the weather. The image 1 shows the solar spectrum distribution out of the atmosphere and the clear sky distribution AM 0 and AM 1.5, respectively, [9].

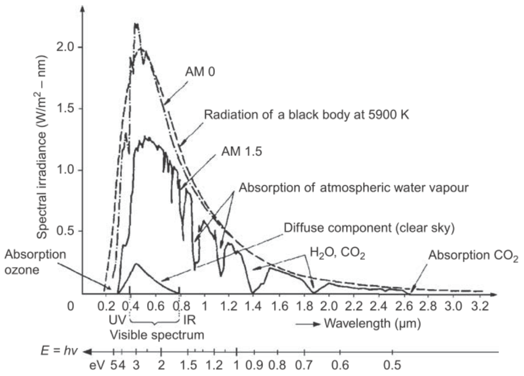

Figure 1: Solar Spectral Distribution of Solar Radiation, [8].

2.2. Solar Cells

Solar cells convert incident light in electricity based on the photoelectric principle. Even though new technologies have been studied to improve the efficiency and adaptability of silicon cells, these are the most used today.

Photovoltaic cells have three major parameters: short circuit current, I_{SC}, open circuit voltage, V_{OC} and maximum power, P_{MAX} and these depend mainly on the intensity of incident light, I_L, and the number of cells connected, n. The following mathematical equations describe approximately how the current and voltage vary:

$$\begin{aligned} V &= mV_T \ln\left(\frac{I_L - I}{I_0}\right) \\ I &= I_L - I_0(e^{\frac{V}{mV_T}} - 1) \end{aligned} \tag{2}$$

Where m is the ideality factor of the cells, $V_T = kT/q$, k the Boltzmann constant, T being temperature of the cells and q the charge of an electron. By plotting these we get the following I(V) curve:

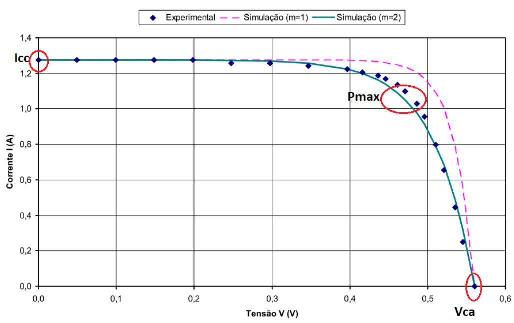

Figure 2: I(V) curve of a Solar Cell, [4].

P_{MAX} is the maximum point of the I(U) curve, and even though it does not depend directly with V_{OC} and I_{SC}, it changes with the parameters altogether. By making some adjustments to 2, we have:

$$\begin{aligned} V_{OC} &= \frac{mkT}{q} \ln\left(\frac{I_L}{I_0} + 1\right) \\ I_{SC} &\approx I_L \end{aligned} \tag{3}$$

By connecting sets of cells in series together, the current stays approximately the same, but the V_{OC} grows by the amount of cells connected, n, [4].

2.3. Solar Concentrators and Their Corrosion Degradation

Solar concentrators are being used in many solar applications to heat fluids, in the case thermal collectors, or to lower prices of PV panels by increasing the area of the system without using more expensive cells, [2].

Generally concentrators are made of aluminium because of its low price and high reflectivity but, despite the fact that it has good corrosion resistance, [1], in certain circumstances their degradation, due to this type of problem, might be troublesome, [6].

Corrosion of aluminium in solar applications come mainly in the form of two types of corrosion: atmospheric and pitting [7]. Atmospheric corrosion on concentrators can quickly affect their reflectivity, that has an impact in the intensity of light that reaches the cell, and pitting leads to errors in the angle of reflection causing non uniformity of light in the receptor that can lead, in extreme cases, that the cell can become shaded or create hot spots.

The use of protective paints to prevent corrosion are known to be a good solution, [11], but the occurrence of corrosion degradation is always unavoidable, [10], mainly because of filiform corrosion, another type of atmospheric corrosion.

The objetive of this study to comprehend how these types of corrosion affect the parameters of solar cells and their power generation.

3. Tonatiuh Simulation

Tonatiuh is a program that uses a ray tracing algorithm and maps the distribution of the irradiance of the concentrator. The code generates randomly - through a Monte Carlo algorithm - rays from the "sun" and simulates those that are reflected by the receiver. The interaction of the system with light is a direct consequence of the optical characteristics of the concentrator.

According to the literature, [3], there are two parameters that are central in the characterization of a reflector:

- Average Reflectivity (R_{avg}): It is related to roughness of the material that directly affects non-specular reflection, 3.a).
- Standard Deviation (σ_{opt}): It intends to define the optical error of the surface, according to a

Gaussian function, from damages in the service time that result in deviations in the angle of the reflected rays, 3.b) e .c).

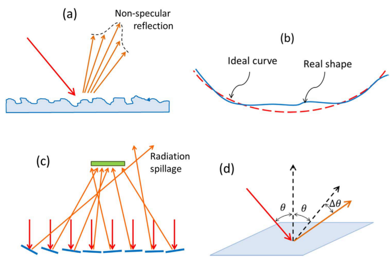

Figure 3: Characteristics Responsible for deviations from the Ideal Reflection, [3].

Three concentrator shapes were used in the simulation: flat, parabolic and triangular. The last one has twice the area of the flat amd their optical parameters were changed in order to acquire the desired conclusions.

3.1. Reflectance Influence

3.1.1 In Power

On the first experiment, the concentrator parameter for the reflectivity was altered and it is measured in percentage. Tonatiuh makes this calculation by dividing the incident rays by those reflected on the metal. The initial value of the simulation is 100% and drops down to 47%.

A unitary reflection is a value impossible to obtain, since there is no material capable of reflecting all of the incident rays, especially if painted. However, it is an important quantity in the simulation to know the power emitted by the program fictional sun. In the course of the simulation, the value of the reflectivity was lowered by three percent to 47%, a number where it is usual to change the concentrator.

The values obtained in the simulation for the various concentrators were:

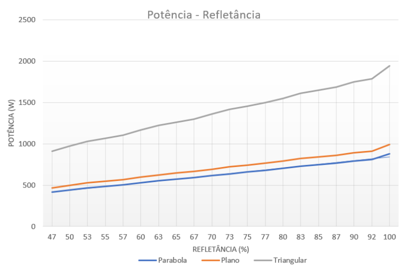

Figure 4: Power-Irradiance Graphic for the Concentrators.

By analysing the graphic one can infer that:

- The reflectance drops linearly with reflectivity independently of the shape of the concentrator
- The power of triangle doubles, when compared with the one of flat, because the area also doubles. There is a linear relationship between the power yielded and the area.

However, it is known that in reality, the loss of reflectivity on a curvilinear concentrator is more pronounced due to the fact that in its manufacturing process the defects generated by bending the metal will give rise to areas prone to the creation of pits and/or difficulties in adhesion of the protective paint. In other words, there is a greater probability of corrosion in a folded metal than on a flat one.

3.1.2 In Flux Distribution

The decrease in irradiance has no relevant influence on the distribution of the flux incident on the receiver. In the following figures it is shown the distributions of the incident flow for the flat concentrator with reflectivities of 92% and 47% with null error of standard deviation.

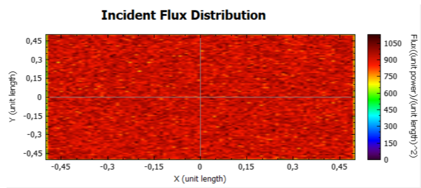

Figure 5: Distribution of Incident Flow at the Receiver from the Flat Concentrator with 92 % Reflectance.

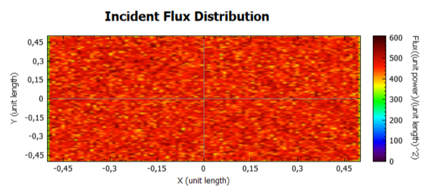

Figure 6: Distribution of Incident Flow at the Receiver from the Flat Concentrator with 47 % Reflectance.

On the right side it is possible to see a coloured scale that varies from purple to brown corresponding to the null and maximum irradiance, respectively. When analysing the image, it is noticeable that the colours are uniform throughout the receiver, indicating that there is no error due to the standard deviation. The reason that 5 has a darker colour than 6 is due to the decrease in power reflected by the concentrator while decreasing the reflectivity.

In the case of the parabolic receiver, the following distributions were obtained:

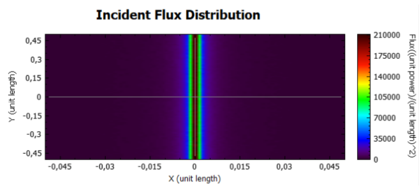

Figure 7: Distribution of Incident Flow in the Receiver from the Parabolic Concentrator with 92 % Reflectance.

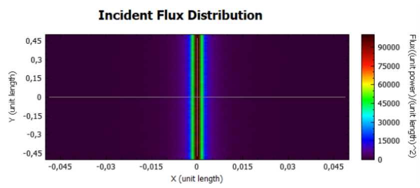

Figure 8: Distribution of Incident Flow in the Receiver from the Parabolic Concentrator with 47 % Reflectance.

Taking into account the shape of the parabola, the reflected rays will be in the central part of the receiver thereby obtaining a mostly dark flux throughout the image. The blue and green zones are transition zones, where there may be a shadow in the concentrator due to the receiver's rectangular shape. Due to the reasons given for the flat concentrator, by evaluating the images, a decrease in the red's intensity in the center is observed as the reflectance decreases without the colours spreading to the rest of the receiver.

3.2. Standard Deviation Influence

3.2.1 In Power

In this subsection the influence of the standard deviation on output power is evaluated. The errors in this study were 0, 10 and 30 mrad for being representative and sufficient to obtain the necessary conclusions. The values obtained for the power can be related from the graphs for the different concentrators:

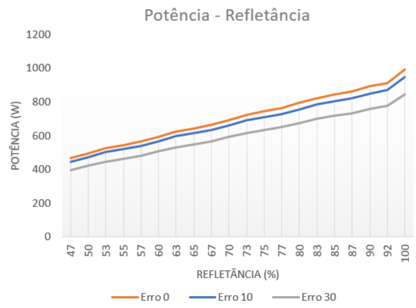

Figure 9: Variation of the Power in Relation to the Reflectivity of the Flat Concentrator for the Different Errors..

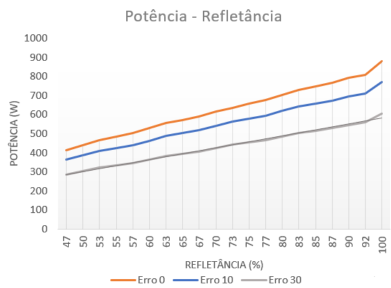

Figure 10: Variation of the Power in Relation to the Reflectivity of the Parabolic Concentrator for the Different Errors.

When analyzing the figures 9 and 10 it is verified that the power decreases when the error of the standard deviation is greater. However, for the parabolic concentrator this effect is more evident because it has a smaller receiver. In addition, a rectangular receiver has always been used in this simulation, but in the case of the parabolic concentrator it is not the appropriate format.

However, it can be seen in both cases that as the error increases, more reflected rays fail the receiver resulting in a lower received power.

3.2.2 In Flux Distribution

The variation of this parameter in the distribution can be verified in the following figures:

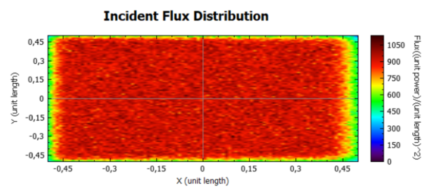

Figure 11: Incident Flux Distribution for an error of 10 (Flat Concentrator; Refletance of 92%).

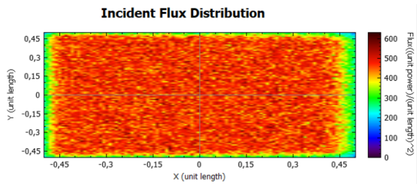

Figure 12: Incident Flux Distribution for an error of 10 (Flat Concentrator; Reflectance of 47%).

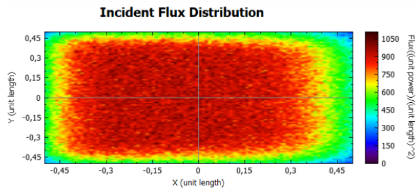

Figure 13: Incident Flux Distribution for an error of 30 (Flat Concentrator; Reflectance of 92%).

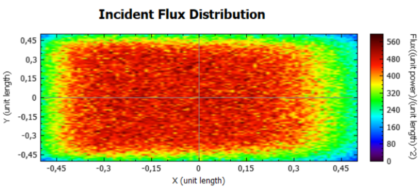

Figure 14: Incident Flux Distribution for an error of 30 (Flat Concentrator; Reflectance of 47%).

The previous figures show the deviation in the parameter change for the highest and lowest reflections considered. With non-uniformity of colours it is observed that there is a diffusion of the incident power by increasing the standard deviation. In these images it is evident the deviation of the expected angle of incidence, portrayed in the figure 3.d). When comparing these images with 5 and 6 we can observe a dispersion of the flux leading to a decreasing power reflected. To conclude, we present the effect of this parameter on the distribution of the incident flux in the receiver from a parabolic concentrator and, in an analogous way, the conclusions are similar.

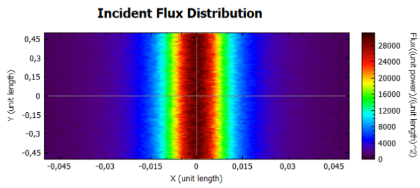

Figure 15: Incident Flux Distribution for an Error of 10 (Parabolic Concentrator; Reflectance of 92%).

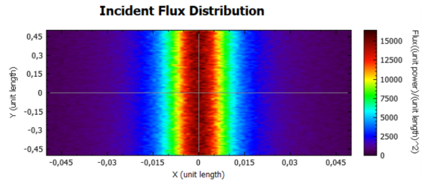

Figure 16: Incident Flux Distribution for an Error of 10 (Parabolic Concentator; Reflectance of 47%).

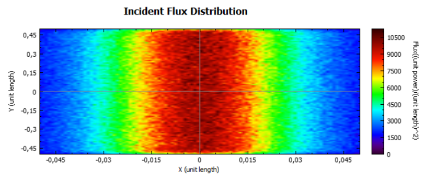

Figure 17: Incident Flux Distribution for an Error of 30 (Parabolic Concentrator; Reflectance of 92%).

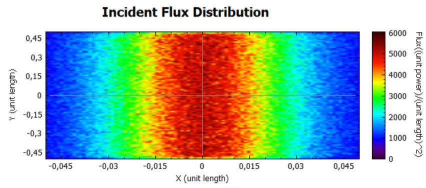

Figure 18: Incident Flux Distribution for an Error of 30 (Parabolic Concentrador; Reflectance of 47%).

This simulation served to intuitively demonstrate what might happen physically in a solar concentrator and to see how errors in the material can change the illuminated zones and decrease the incident power at the receiver. In the scope of this work the receiver are solar cells and its parameters may vary depending on the errors of the concentrator.

Previously, the concepts of short-circuit current, I_{SC}, and open circuit voltage, V_{OC}, were introduced and with these simulations it is possible to make a connection to the theoretical and physical domains.

Knowing that V_{OC} depends directly on the number of cells connected, it is trivial to think that by varying the distribution of the flux more (or less) cells can be illuminated by changing the measured value of the voltage. On the other hand, the degradation of the reflectivity changes the intensity with which the photons occur in the cells culminating in a lower illumination current and consequent decrease of the I_{SC}.

Although the flow distribution and the loss of reflectance are intrinsically linked in the corrosion process, it is possible to approximately separate their effects into each of the parameters.

4. Laboratory Experience

It was tested in the laboratory the behaviour of the aluminium sheets when submerged in salted water, [5], and how this accelerated corrosion process is going to affect the solar cell parameters.

In the scope of the experiment were used 4 aluminium plates with characteristics presented in the following table:

Number	Colour	Aluminium
1	Red	No treatment
2	Green	No treatment
3	Blue	Polished
4	Light Blue	Painted

Table 1: Material Used Summary Table.

4.1. First Measurement

In the first measurement it was possible to verify the differences in the reflectances of the different types of aluminium. When measuring the output current and voltage of the photovoltaic cells, the corresponding power was calculated, and it was conjectured on which aluminium plate had the highest reflectance value. The following table and images show the results obtained for the maximum power point, short current and open circuit voltage for each plate:

Number	I_{SC} (A)	V_{OC} (V)	P_{MAX} (W)
1	0.110	4.3	0.3744
2	0.110	4.3	0.3744
3	0.090	4.2	0.3072
4	0.086	4.3	0.3040

Table 2: I_{SC}, V_{OC} and P_{max} in the first measurement.

This first data suggests that pure aluminium has a higher reflectance, followed by plate 3 and 4. Plate 2 has a value equal to 1 because it has not been subjected to any immersion, both being of the same material and without treatment.

When analyzing I_{SC} and V_{OC}, it is possible to infer that the value of current has a greater variation than the open circuit voltage. This is because the current varies directly with the incident illumination current, 3.

Although the ranges in the measurement of the parameters are not the same, with the value of I_{SC} being much more accurate, it is expected that V_{OC} remains constant throughout the experiment. In the equation 3, it is predicted that the voltage value will vary markedly with the number of cells connected in series and not with the illumination current, I_L.

4.2. Evolution of the Cell Parameters

In order to follow the development of the corrosion process some measurements were made. To confirm that the corrosion progress is different for the plates, the solar cell power was measured and its decrease was observed for 15 days and a linear regression was performed. The results were as follows:

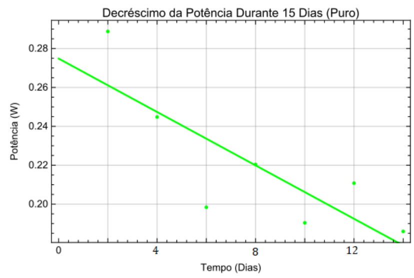

Figure 19: Measured Power on Pure Aluminium Sheet for 15 Days and Respective Linear Regression.

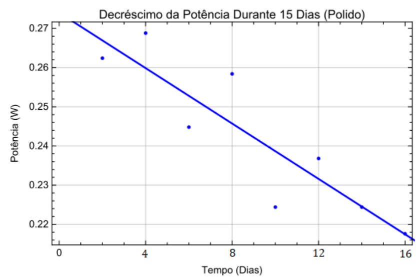

Figure 20: Measured Power on Polished Aluminium Sheet for 15 Days and Respective Linear Regression.

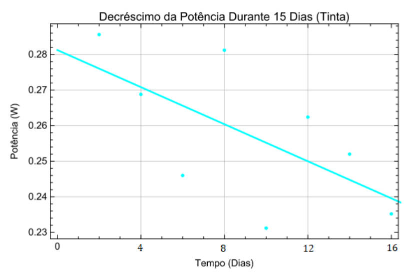

Figure 21: Measured Power on Painted Aluminium Sheet for 15 Days and Respective Linear Regression.

Number	Linear Regression (x = days)
2	0.275 - 0.0137x
3	0.274 - 0.0071x
4	0.281 - 0.0052x

Table 3: Linear Regression Data.

By analyzing these data it is again confirmed by the slope of the line that the rapidity of progression of corrosion is higher in pure sheet of aluminium than in the others, being approximately doubled. It should be noted that the value of the ordinate at the origin is approximately equal for all plates to make these measurements with similar power values.

As it was mentioned, it is estimated that the power decrease presented depends mainly on the measured current in the circuit. However, it is important to note that the value of V_{OC} fluctuated throughout the measurements, and although it has shown a downward trend that may be significant, due to the range used and the variations associated with the error in its measurement no concrete conclusions can be drawn.

During this time interval the variation of the parameters is summarised in the following tables:

Day	P_{max} (W)	V_{OC} (V)	I_{SC} (A)
1	0.3744	4.4	0.110
15	0.2888	4.4	0.084
30	0.1860	4.3	0.066

Table 4: Parameter Variation for Pure Aluminium Sheet.

Day	P_{max} (W)	V_{OC} (V)	I_{SC} (A)
1	0.3072	4.4	0.090
15	0.2368	4.4	0.076
30	0.2112	4.0	0.072

Table 5: Parameter Variation for the Polished Aluminium Sheet.

Day	P_{max} (W)	V_{OC} (V)	I_{SC} (A)
1	0.3040	4.3	0.086
15	0.2624	4.4	0.086
30	0.2184	4.0	0.078

Table 6: Parameter Variation for the Painted Aluminium Sheet.

In a first approach is presented the variation of the parameters for the different types of aluminium. It is noteworthy to verify the linearity with which the maximum power decreases throughout the corrosion process of 4 and 6. Every 15 days, the power decrease for pure aluminium decreases by approximately $0.10W$ and for painted aluminium $0.5W$. However, in 5 the degradation seems to have been faster at an early stage. This may be because the product used in the polished aluminium has catalyzed the oxidation reactions.

In the case of the current there is a decline in all materials, but in the 6, this does not manifested in the first two lines where the value of day 15 was expected to be lower. Once again, 5 shows an acceleration of its corrosion at an early stage.

As already noted above, the V_{OC} is susceptible to high errors due to the scale used but the values obtained in the rows of the tables may mean that this is a significant variation. This doubt remains due to the fact that the voltage obtained for 4 has remained approximately constant.

The figures presented below, are intended to illustrate the differences between the curves obtained between measurements.

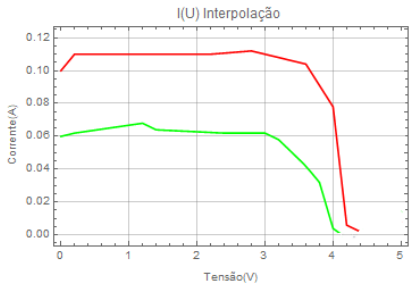

Figure 22: I(U) Curves Comparison for the First And Last Measurements (Pure Aluminium).

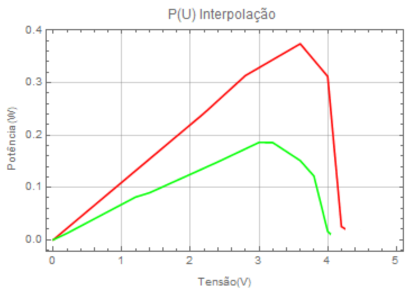

Figure 23: P(U) Curves Comparison for the First And Last Measurements (Pure Aluminium).

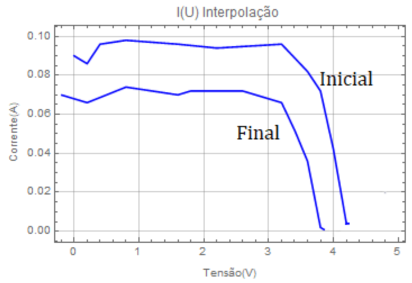

Figure 24: I(U) Curves Comparison for the First And Last Measurements (Polished Aluminium).

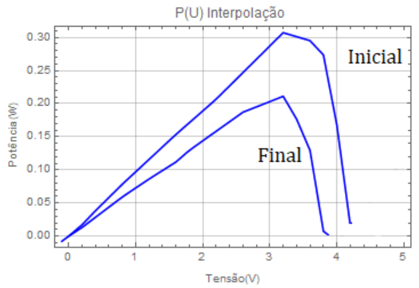

Figure 25: IPU) Curves Comparison for the First And Last Measurements (Polished Aluminium).

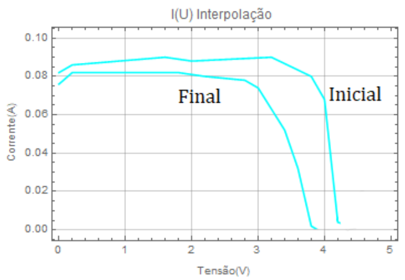

Figure 26: I(U) Curves Comparison for the First And Last Measurements (Painted Aluminium).

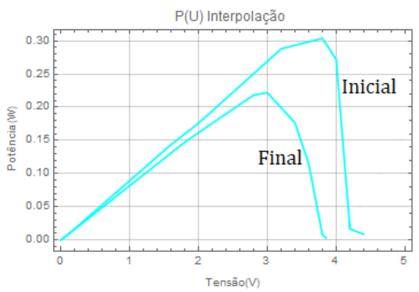

Figure 27: P(U) Curves Comparison for the First And Last Measurements (Painted Aluminium).

In the curves I (U) and P (U), there is a sharp decrease in the current and maximum power that are in agreement with the one presented in the tables 4, 5 and 6.

In order to complement this chapter, the performance of the different materials was compared. In 7, we observe the variation between the parameters and, as expected, it is concluded that the paint gave better protection than the others. Another important detail is related to the 40 % variation that existed in material 2, where the susceptibility of corrosion propagation in aluminium is confirmed.

Nmero	$\Delta\ I_{SC}$ (%)	$\Delta\ P_{max}$ (%)
2	40.00	50.32
3	20.00	31.25
4	13.33	28.15

Table 7: Variation of I_{SC} e P_{max} Between the First and First Measurement.

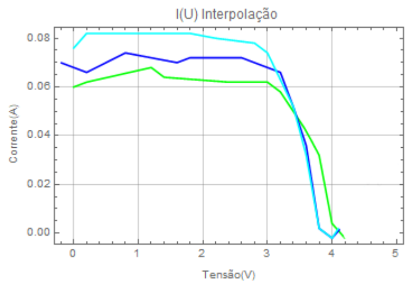

Figure 28: Comparison of I(U) Curves Obtained for the Last Measurement.

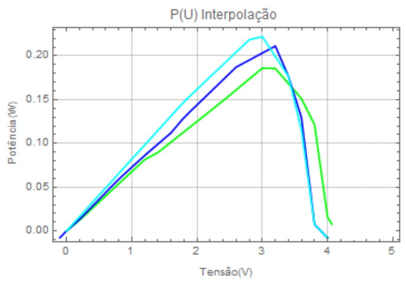

Figure 29: Comparison of P(U) Curves Obtained for the Last Measurement.

The latest images are illustrative of the necessity to provide a form of aluminium protection. Even though we know that in the first phase the protections lowered the parameters significantly, at the end of the measurements, they were able to maintain a better long-term performance since they exceeded the pure aluminium in all the parameters.

5. Conclusions

In the present dissertation it was possible to observe how the corrosion of aluminium affected the parameters of the silicon solar cells, including their power. To perform this study, we used simulation models and laboratory experiments.

In the first simulation, we used the *Tonatiuh* program that allows the variation of the optical parameters of a previously built concentrator with the necessary geometry. It was determined that the most important parameters in the definition of the optical error are the reflectance and the standard deviation. The variation of these influences the incident power on the cells and the distribution of power flow. During the experiment, it was possible to obtain the following conclusions:

- The decrease in reflectance has a proportional influence on the incident power at the receiver and the flow distribution does not vary significantly;
- The standard deviation modestly modifies the power incident on the receiver and causes a significant change in the power flow distribution.

In a second simulation, a bridge was formed between the solar cell parameters and aluminium corrosion. It has been clarified that the short-circuit current of the solar cells is directly influenced by the incident light and that the open-circuit voltage varies proportionally with the number of illuminated cells.

In the laboratory experiment it was possible to test in a physical system the influence of the corrosion in a concentrator system-solar cells.

The degradation of the concentrator affects the parameters V_{OC} and I_{SC} of the cells and in the degradation of the aluminium simultaneously occur several types of corrosion, it being not possible to totally divide the decrease of these two parameters.

For one month, three different aluminium sheets (untreated, polished and painted) were corroded in containers with salt water and the variation of the cell parameters was observed.

During the experimental period, the most important points were:

- In the first measurement, the aluminium with the highest maximum power was the plate with no treatment, followed by the polished and then painted. I_{SC} and V_{OC} had the same behaviour;
- During the experiment the plate without treatment had a greater corrosion speed, unlike what happened with the painted plate;
- At the end of the experiment, the values for the power of the painted plate were those that had a smaller variation; the short-circuit current and maximum power are greater in this plate than in the others. In the case of untreated aluminium, its variation was the largest and its values are the lowest.

In the course of this work, it was possible to observe how the parameters of the solar cells change with the corrosion of the concentrators. The analysis aims to survey the optical interactions between a concentrator system and solar cells and thereby promote a development of this interesting technology in terms of cost and efficiency, at a time when it is important to promote and improve renewable energy.

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