Pontifícia Universidade Católica
do Rio de Janeiro

Pedro Bruno de Almeida Barbosa

Estudo do aumento da produção de energia fotovoltaica utilizando rastreamento solar e LCPV

Projeto de Graduação

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Orientador : Sérgio Leal Braga
Co–Orientador: Epifânio Mamani Ticona

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Resumo

Estudo do aumento da produção de energia fotovoltaica utilizando rastreamento solar e LCPV

Seguidores solares e Low concentration photovoltaics (LCPV) são duas técnicas usadas par aumentar a capacidade de produção de paineis solares, atrvés do aumento da quantidade de radiação que os alcança. Para entender os benefícios dessas técnicas, assim como suas viabilidades, esse artigo irá analizar como paineis solares se comportam nessas diferentes condições, e quanto aumento de produção elas podem trazer.

Para poder propriamente avaliar os benefícios dessas técnicas, uma análise teórica será feita para prever o comportamento e os resultados que podem ser alcançados, assim como propor um experimento baseado em um protótipo de pequena escala para testar como eles reagem nas condições intáveis que tem que ser enfrentadas ao aplicá-las.

Para propriamente avaliar os benefícios dessas técnicas, elas serão comparadas com um grupo controle, um painel solar fixo, de modo que suas produções possam ser comparadas com o sistema padrão, mais comumente utilizado.

Os resultados desse estudo podem ser aplicados a instalações solares de pequena escala, podendo também ser expandidos para poderem ser usados em escalas maiores .

Palavras–chave

Fotovoltaico; Low Concentration; LCPV; Espelhos; Seguidor Solar; Comparação.

Abstract

Study of the photovoltaic energy production increase using solar tracking and LCPV

Solar tracking and Low Concentration Photovoltaics (LCPV) are two techniques used to increase the production capacity of solar panels by increasing the amount of irradiance reaching them. To understand the benefits of these techniques, as well as their viability, this paper analyses how the solar panels behave in these different conditions, and how much production increase they can lead to.
To be able to properly assess the benefits of these techniques, a theoretical analysis will be done aiming to predict the behavior and the results these can achieve, as well as propose an experiment based on a small scale prototype to test how they react to the unstable and ever changing conditions that they have to face when applied.
To properly assess the benefits brought by these techniques, they will be compared to a control group, a fixed solar panel, so that their production can be compared to the most standard photovoltaic production method.
The results of this study can be applied to small scale solar production systems, as wells as in powering equipment or charging batteries. However, it can be easily expanded to be put to practice in large scale solar plants.

Keywords

Photovoltaic; Low Concentration; LCPV; Mirrors; Solar Tracking; Comparrison.

Summary

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1
Introduction

Energy production is one of the biggest challenges of our time. The constant increase in demand, coupled with new legislation aiming to reduce our carbon footprint, points us in the direction of renewable energies. However, before renewable energy can become our main source of power, we need to work on optimizing it to harness its full potential, since some of these technologies still present low productivity or efficiency. Despite having come a long way in that sense in the past decades, there is still a long way to go before we can trust in it to sustain us.

Solar energy is one of the most discussed forms of renewable energy. The amount of solar energy that hits the surface of the earth in one hour is enough to supply energy to the whole world for one year [11]. There is a reason why it is on the spotlight, but we still have to find ways to improve the way we use it to produce energy. For decades, and until today, the main line of research in solar energy has been in trying to improve the efficiency and reduce the price of photovoltaic cells, and we have come a long way in that matter, as can be seen in the images below:

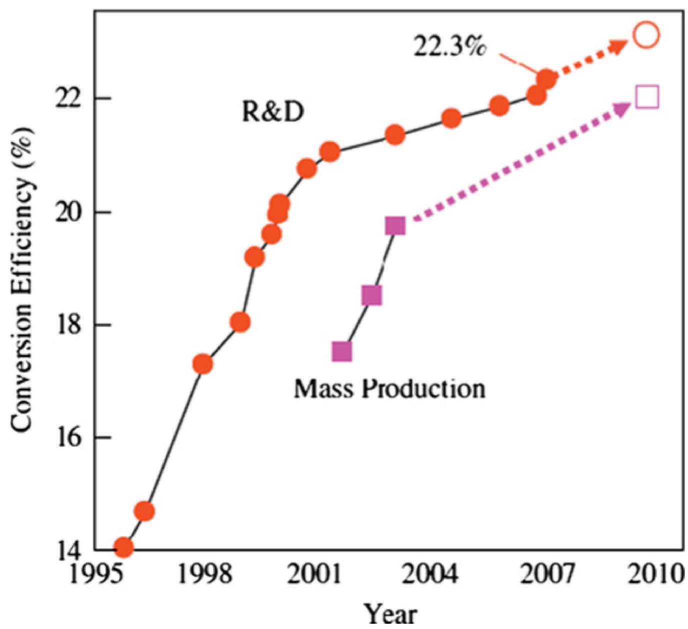

Figura 1.1: Photovoltaic cells conversion efficiency over time [1]

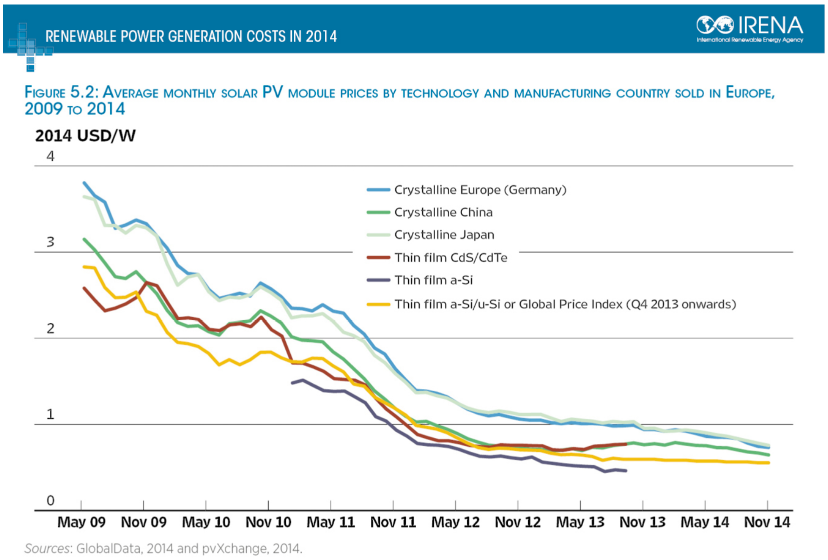

Figura 1.2: Price per watt over time for the different technologies [2]

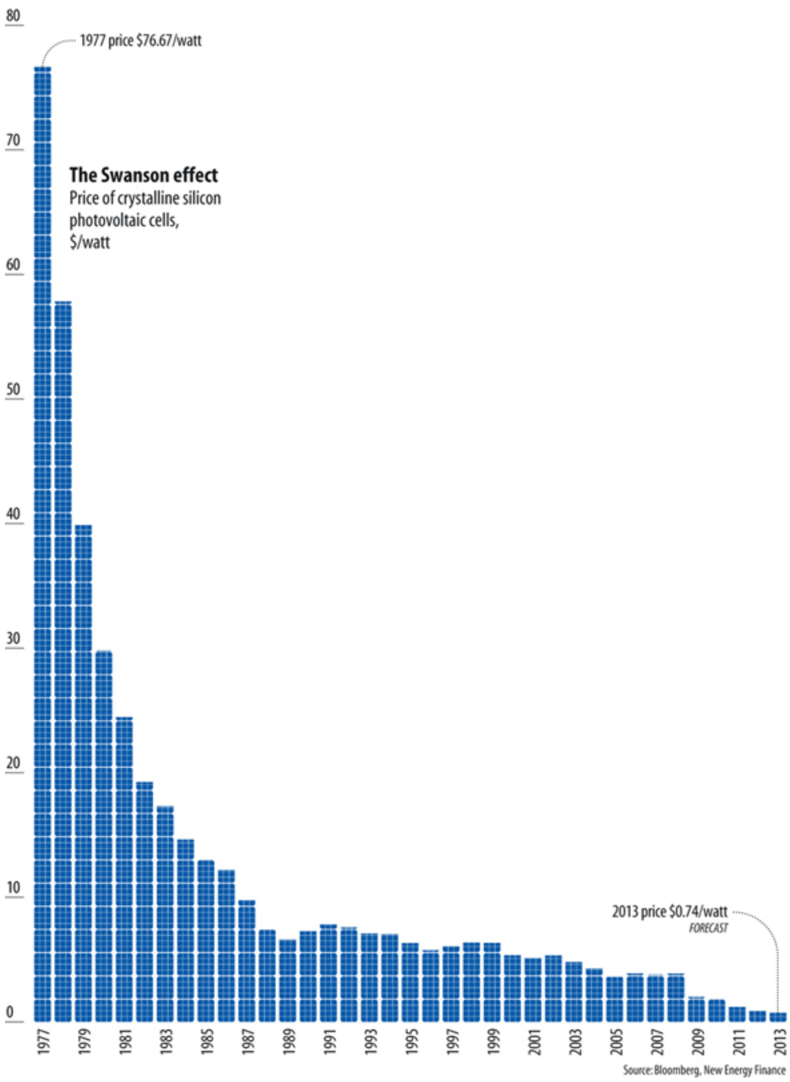

Figura 1.3: Price per watt over time [3]

However, beyond trying to improve the panels, there are many other ways to optimize the energy production of the already existing solar cells increasing its potential.

Energy produced by solar installations is a function of mainly three factors, the installed area of solar panels, their efficiency, and the amount of irradiation reaching these panels, so the aim is to increase them as much as possible. The installed area of solar panels has been increasing every year, and research on efficiency increase of solar cells is going on all around the globe. In terms of increasing the amount of radiation reaching the cells, there are several techniques that can be applied, such as the use of solar tracking, or the use of mirrors to virtually increase the surface area of the panels.

2
Literature Review

2.1
Photovoltaic Cells

With the constant search for new ways to improve the efficiency of photovoltaic (PV) cells, different kinds start being researched with the hope of achieving a higher efficiency then the ones in the market, while also keeping the price as low as possible to be able to compete.

While there are various different types of cells, including some that are still in early stages of development, such as organic and perovskite cells [12][13], the most commonly used are Crystalline silicon (both mono and polycrystalline), with thin film cells also holding a small portion of the market[1].

Crystalline Silicon cells have been on the market for a long time, and due to its high efficiency, compared to the other types, and large-scale production, has the best cost-benefit of the existing cells.

There has been a huge amount of developments in solar cells in the last decade, from the increase of efficiency of existing cells to the creation of brand new technologies that help reduce costs. In order to better understand the evolution of these cells over time, photovoltaic cells are split into three generations.

The first generation cells are mainly based on silicon wafers, and can be split into monocrystalline and polycrystalline cells. They currently dominate the market due to their good performance and high stability. Despite their efficiency having been improved over time, their price per watt is still relatively high since its manufacturing process consumes a lot of energy. [12]

The difference between the cells from the first generation is in the manufacturing process. While the monocrystallines are made of a single silicon crystal, the polycrystallines are made from multiple grains, which can disturb the light flow. This means that the monocrystalline cells have a higher conversion efficiency, but the manufacturing process of the polycrystalline cells consumes less energy, meaning it is cheaper. Thus, both cells are a good option, the choice depending on the proposed use for them. [12]

The second generation is relative to thin film cells. Their focus was on reducing the production price and making cells flexible to allow its installation in places where the geometry is more complex. These cells have a generally

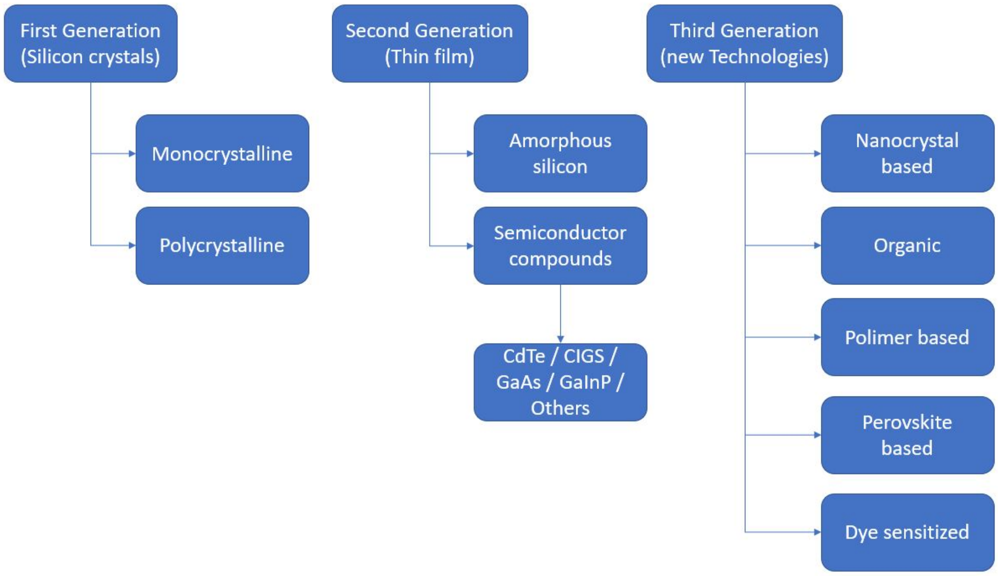

Figura 2.1: Cells by generation

lower conversion efficiency then first generation cells. However, their lower price per watt and the fact that they can be placed in objects where the rigid cells from the first generation can't, make them an attractive option. [12]

The cells from the second generation are either made from amorphous silicon, or from semiconductor compounds. The cells made from the semiconductor compounds had several shortcomings, such as low availability of its elements, as well as the toxicity of some of them, which presented an environmental issue. [12]

Third generation cells are mostly still being researched, not necessarily having common characteristics between them like the previous generations, they are just the cells that are still being designed and assessed. These cells promise higher efficiencies and lower production costs, and have very different approaches amongst them. Figure 2.1 shows some of the existing third generation cells, but there already are more of them, and new technologies are constantly being created.

2.2 The diode curve

To understand the power production behavior of solar cells, it is of utmost importance to understand the diode curve.

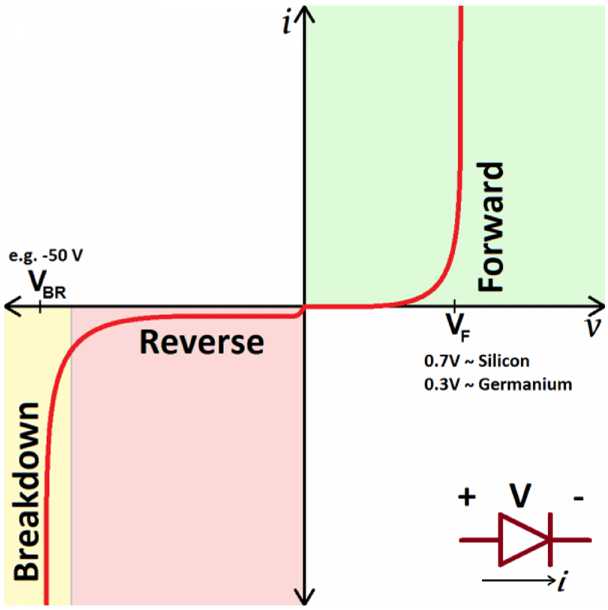

Figura 2.2: Diode IxV curve /cite34

Since the cell's diodes don't work in reverse, it is only necessary to understand the behavior of the forward section. The diode presents an overall non-linear behavior, where it is with its curve being able to be divided between a linear part and an exponential one. [14]

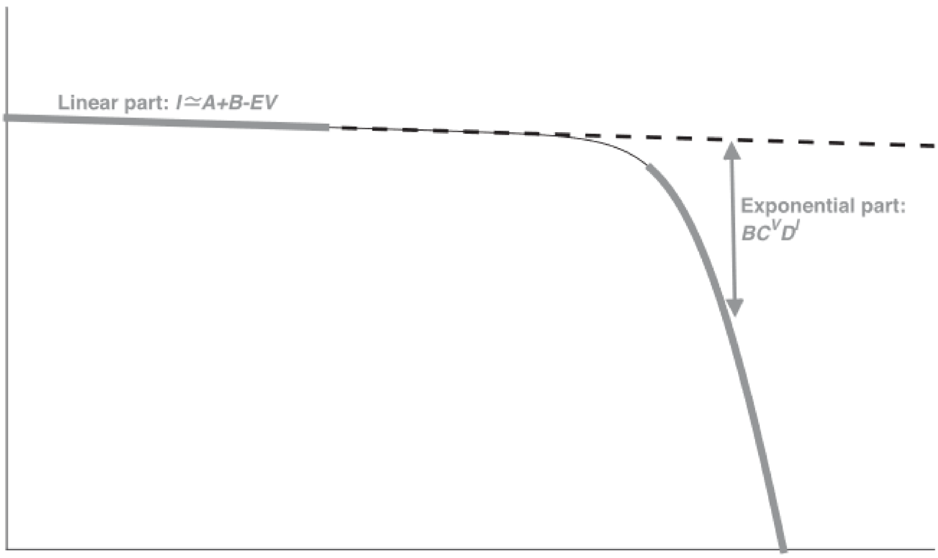

Figura 2.3: Diode IxV curve

The current gradually drops as the voltage increases, until it reaches a threshold where its behavior changes from linear to exponential, with the current rapidly dropping. Since the power produced by the cell can be calculated as the result of P = IV, and the goal is to have the highest possible power output, it is necessary to find the ideal current and voltage pair to achieve that.

2.3 Maximum Power Point Tracking

The objective in solar energy production, as in all power production technologies, is to always get the maximum possible power output in the current operating conditions. Considering a given panel, and that the weather can't be controlled, one of the ways to optimize energy production is through maximum power point tracking (MPPT). This is the technique/technology that aims to find the best operating point in the diode curve, adjusting the behavior of the cell to the changes in the operating conditions.

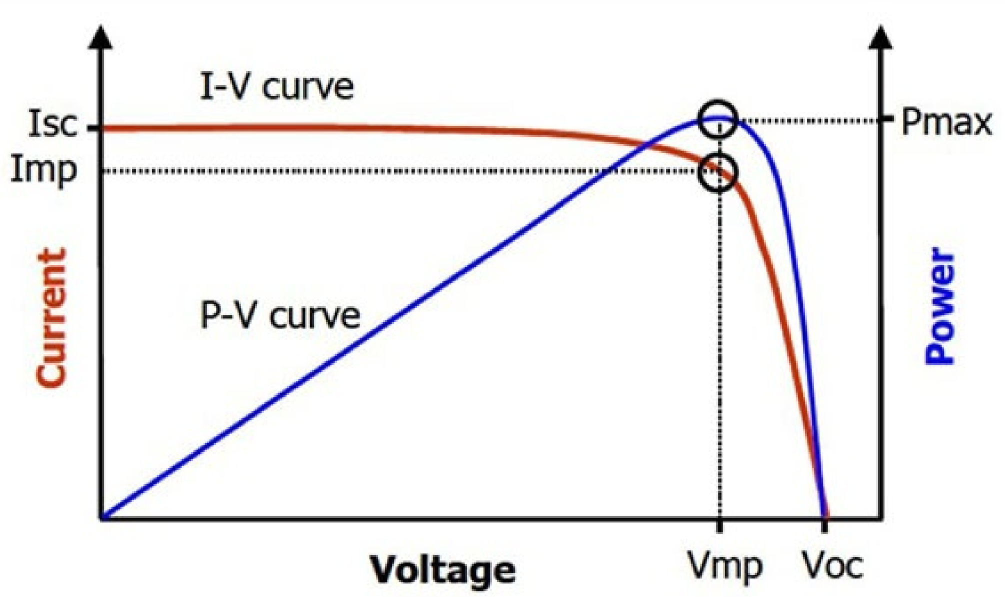

Figura 2.4: Current vs Voltage curve [4]

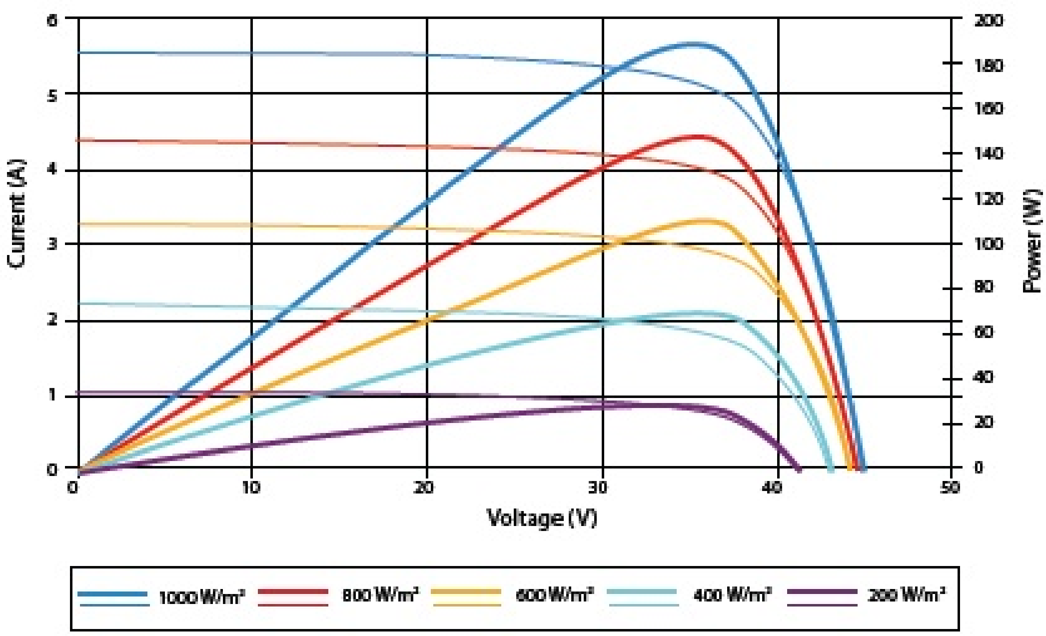

Figura 2.5: Current vs Voltage curves with different power inputs [5]

As shown in the pictures above, for each I(A) vs V(V) curve, there is a specific pair of values that allow for the maximum power production, since power can be given by the product of the voltage and the current. Moreover, environmental conditions, such as the variation in solar radiation arriving at the cell, as well as the temperature of the cell, can change this pair of values, due to the fact that they change the behavior of the cell [15]. That leads to the conclusion that, in order to optimize the power production of a solar installation, constantly looking for and allowing the right conditions to be in the maximum power point is fundamental.

The most common way to achieve that is to equip the panels with a maximum power point tracker, also known as charge controller. A circuit that changes the voltage across the cells so that they produce the maximum amount of power at any given moment. It is a process that happens live and constantly, since any changes to the operating conditions of the solar installations can change the current going through its cells. In experimental conditions, other techniques can be used to find the maximum power point, since the goal in experiments isn't necessarily to produce the maximum power possible, but to discover what the value is. In this case, a couple different approaches can be taken to find this value.

The first option consists on connecting the PV cell to a number of resistances of different values using relays to switch between them, or a potentiometer, and measure the voltage across the resistance [16]. By measuring the voltage and applying it as well as the value of the resistance to Ohm's law, it is possible to find the current for relative to each voltage and resistance pair. Having the voltage and current pairs it is possible to plot the IV curve of the cell relative to the current operating conditions, namely temperature of the cell and irradiance. Having the curve, it is possible to find the maximum power point for these conditions.

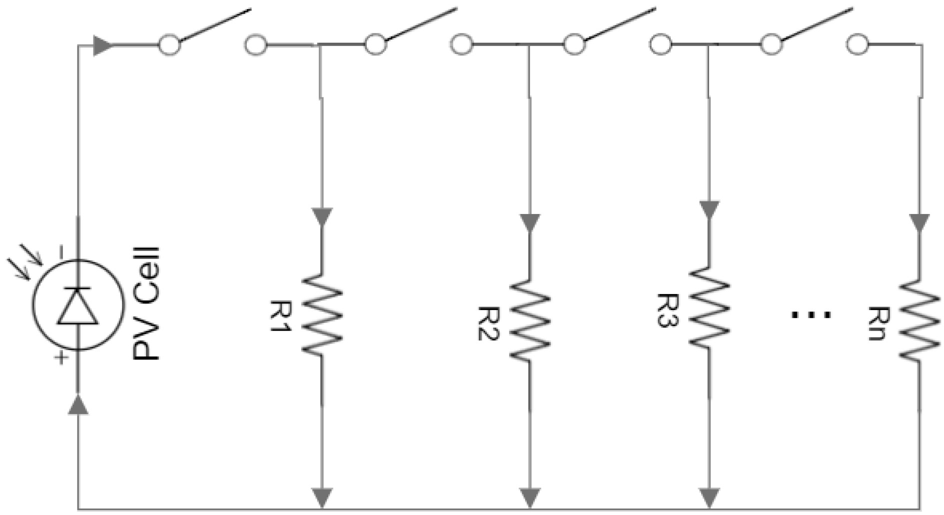

Figura 2.6: Circuit with resistances to approximate the IV curve [6]

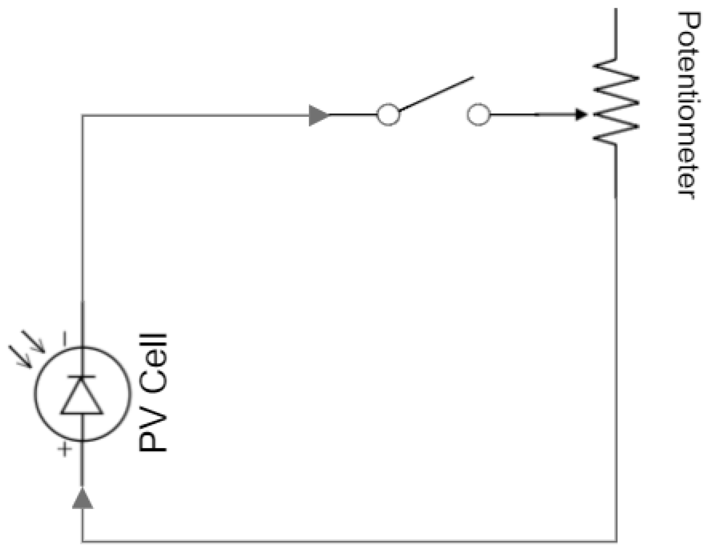

Figura 2.7: Circuit with potentiometer to approximate the IV curve [6]

The other possibility is to connect a resistance, a capacitor and a two of relays to the cell, as shown below. This technique is based on measuring the current and voltage across the capacitor as it charges, and discharges, to gather points to build the IV curve and estimate the maximum possible power production. By closing the capacitor portion of the circuit, and opening the resistance part, the capacitor will rapidly be charged by the power being produced by the cell, once full, the relays can switch, creating a circuit with the capacitor and the resistance, thus discharging the capacitor. [17]

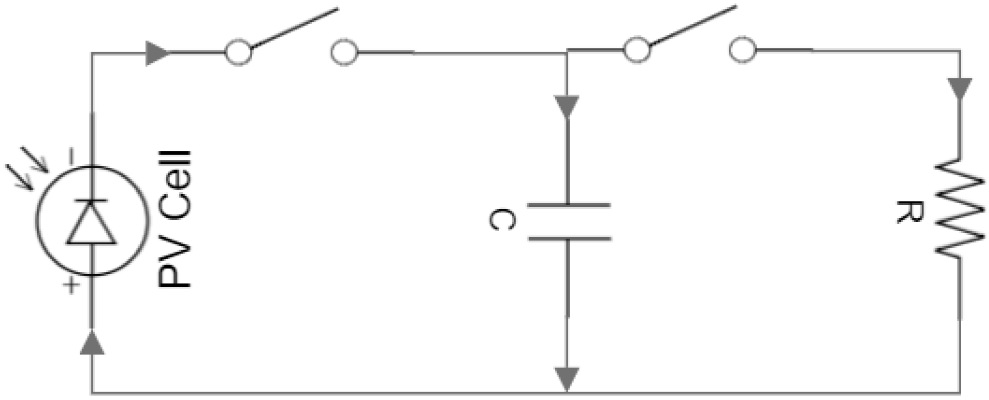

Figura 2.8: Circuit with capacitor and resistance to approximate the IV curve [6]

Both these techniques aim to plot a curve like the one below:

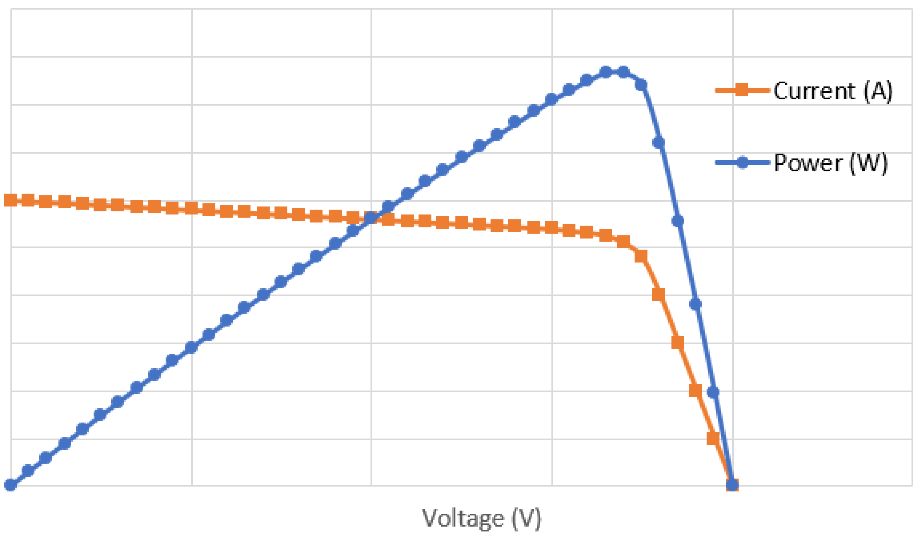

Figura 2.9: IV plot from data points

By creating this plot repeatedly over time, it is possible to identify how the maximum power point is changing, and be able to conclude what the maximum amount of power production during the day is.

2.4 Solar Tracking

Solar tracking is a technology used to increase the average irradiance received by solar panels by making them better aligned with the position of the sun through the day or the year. By changing the angles of the panels to follow the relative position of the sun throughout the day and the year, it is possible to increase the amount of solar radiation reaching it. Solar tracking allows for a production increase in comparison to fixed panels, with this difference is exacerbated during the start and end on the day, since these are the moments when the fixed panels have the worst angle in relation to the sun[18].

Fixed panels are many times placed in the most convenient spot available, such as rooftops of houses, meaning they aren't always optimally placed. However, even when placed in the best position to maximize the power production through the day, they still miss out on a big part of the power for not being aligned to the sun at all times.

The position of the Sun in relation to a given point on the surface of the Earth varies both during the day, due to the Earth's rotation, and during the year, due to the Earth's inclination. To maximize the energy production, it is ideal for the panels to move in two axis to be able to best accompany the trajectory of the sun, so that they receive maximum radiation possible. [15] However, there are many systems that only follow the sun in one axis, normally the one relative to the sun's movement throughout the day. This happens because it is both easier and cheaper to build a one axis solar tracking system, then it is a two axis, moreover, most of the extra production made possible by a solar tracker is relative to the daily movement of the Sun.

Solar trackers can move in many different ways to be able to follow the movement of the sun. This choice is mostly related to the geometry and the purpose of the solar installation. Independently of being a one axis or two axis solar tracker, the system has to know the current position of the sun, as well as the current position its panels are facing, to be able to best align itself over time.

There are two options to make this alignment, the first is to compare the expected position of the sun to the current position of the system, making the changes necessary to align them. The second option relies on having a radiation sensor, with the system constantly making slight changes to face the point of maximum irradiance, it is usually better than the firt, since it adapts better with momentaneous changes to the operating conditions, such as the presence of clouds. For this option, it isn't as important to know where the panels are facing, since they will be constantly realigned to face the maximum irradiance point.

The scheme below illustrates the categories in which solar trackers can be split:

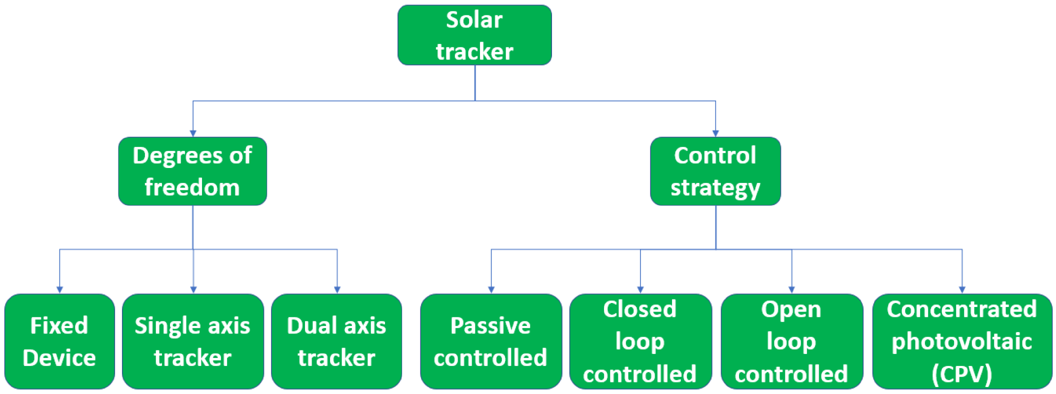

Figura 2.10: Solar tracking possibilities schematic [7]

As with any technique that increases the amount of irradiance reaching the panel, solar tracking doesn't increase the amount of energy production linearly with the amount of radiation. This happens both due to the natural non-linearity of the electrical components of the solar cells, and due to the fact that, the more radiation hits the cells, the higher their temperature will be, consequently reducing their efficiency. [1]

Another fact that has to be considered when adopting this technique is that the apparatus that will be responsible for moving the panels will also be spending energy. This energy can come from the panel itself or from the grid, but either way, it will decrease the total energy gain provided by the solar tracking system.

Some examples of common solar trackers can be seen below:

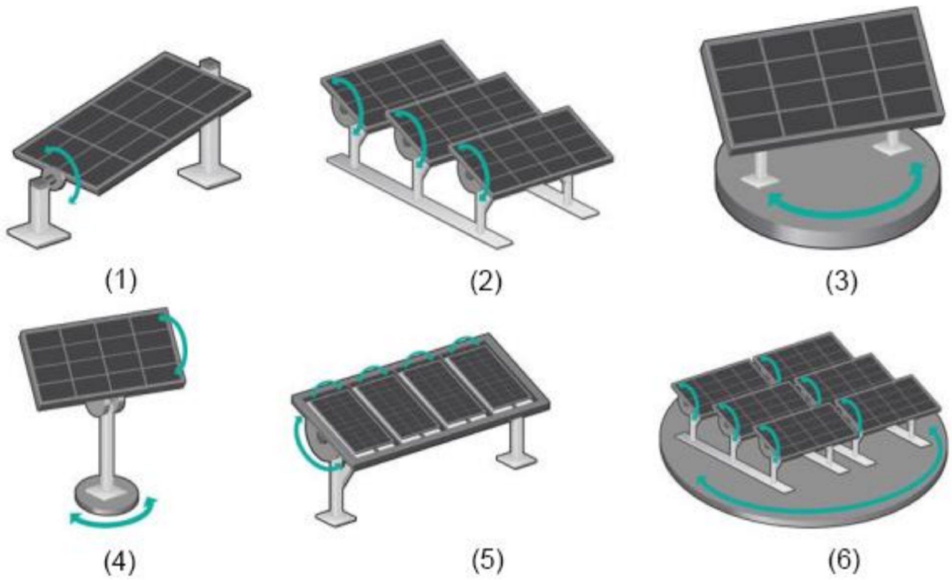

Figura 2.11: Examples of solar tracking systems [8]

This illustrates the difference between one-axis and two-axis solar trackers, being the number of degrees of freedom. While the one-axis solar tracker uses only one movement to best align itself to the sun, the two-axis uses a combination of two movements to track the sun, being able to track the movement of the sun both during the day and the year.

2.5 LCPV

Low concentration photovoltaics (LCPV) is a branch of the more general concentration photovoltaics (CPV), which is a technique based on using reflectors to increase the overall amount of radiation reaching the solar panels, allowing for a higher energy production. The different kinds of CPV are differentiated by the magnitude of suns, which represents the ratio between the energy arriving in the pane with and without the reflectors [16].

- Low concentration (LCPV): between 1 and 40 suns
- Medium concentration (MCPV): between 40 and 300 suns
- High concentration (HCPV): between 300 and 2000 suns

Low concentration photovoltaics works by virtually increasing the surface area of the panel. Since one the most expensive parts of solar installation are the solar panels [19], this technique can increase the cost benefit of solar installations by increasing the production of the same panel, without incurring big costs.

Despite increasing the power production by receiving a higher amount of radiation, there are two important factors to consider when considering LCPV systems. First of all, the increase in the amount of radiation received will lead to an higher temperature for the cell, and since the cells used for this technique are made of a semiconductor material, which has a negative temperature coefficient, meaning its efficiency will decrease with the temperature increase. Another factor that has to be taken into consideration is that for this system to properly function, it has to track the sun. This is necessary since if it was a fixed solar installation, the mirrors would partially or completely shade the panel during most parts of the day, which would go against the purpose of the project. [20]

This technique can be used in small scale for even a single cell, but can also be expanded to be used in even large scale solar power plants. Even though it can be used in small scale it still isn't very common in residences since most solar panels installed in households are fixed, meaning this technique couldn't be applied. Installations for large scale energy production, in addition, are much more prone to already having solar tracking systems to optimize their production, meaning it is easier to adopt this technique.

2.5.1 Concentration Ratio

Concentration ratio (C) is the relation between the area of the mirrors (A_m) and the area of the panel (A_p) they are attached to. It is a way to display how much more radiation the cells will be receiving with the aid of the mirrors. By using the equation C = A_m/A_p [21], we find a dimensionless number that can be seen as a factor by which the amount of radiation the panel would normally receive increases, but it is important to remember that not all the radiation reaching the mirrors will in turn reach the cell, that happens due to the fact that mirrors don't reflect 100 % of the light that hits them, absorbing a fraction. Mirrors commonly used in LCPV installations have around 85 % reflectivity.

Another measure of concentration is called "Suns", and is obtained by comparing the irradiation that is expected to hit the area of the cell using the LCPV technique to the standard peak solar irradiance, which is normally set to 0.1 W/cm^2 or 1000 W/m^2 [21]. The number of suns is the radiation multiplier that using the LCPV technique entails.

In using either of the measures, it is important to emphasize that the radiation coming from the Sun varies through the day, but also due to any disturbances in the way between the sun and the PV cells, such as clouds. However, these values can be used in any of the scenarios, even if a cloud is blocking most of the radiation, these values will still have the same significance, by serving as a multiplier of the radiation that would reach a standard panel, independently of if it is at its peak or at a low point.

2.5.2 Geometry

There is a vast array of possibilities when it comes to the mirror layout for a low concentration photovoltaic system. This choice is very dependent on the whole solar power producing setup characteristics, from the size of the panels, to their proximity to one another, as well as the way the system tracks the sun. Since it is important for the mirrors to evenly distribute the extra radiation on the surface of the panel [21], the shape and size of the mirrors will vary to accommodate that, trying to achieve the highest possible concentration ratio simultaneously.

Below are some of the available geometries that can be used for LCPV:

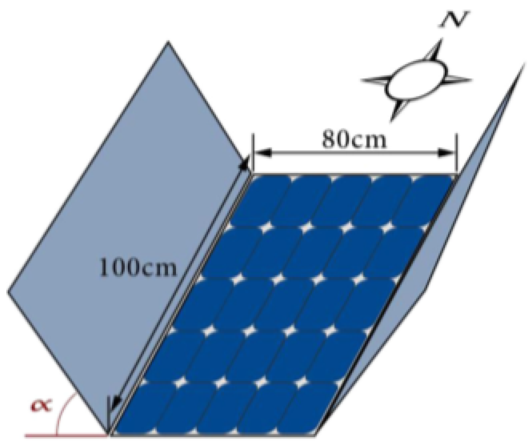

Figura 2.12: Flat concentrator

The flat concentrator geometry is the simplest, done by attaching flat mirrors to the side of the cells, or the panel. It is a good starting point to understand the benefits of using low concentration photovoltaics, since the effect of the flat mirrors in increasing the solar irradiance hitting the cell is very straight forward.

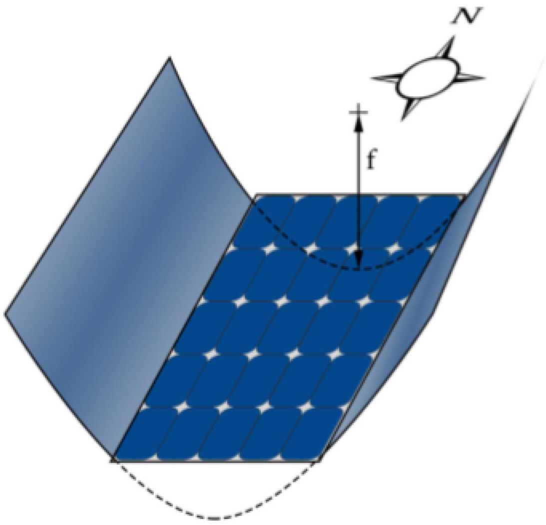

Figura 2.13: Parabolic concentrator

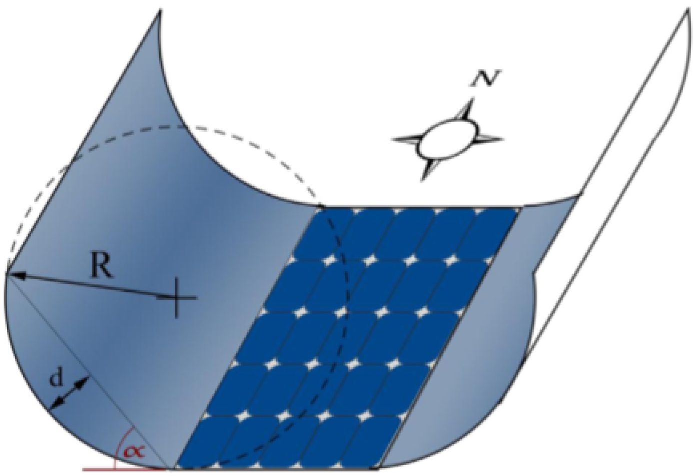

Figura 2.14: Cylindrical concentrator

The parabolic and cylindrical concentrators are more efficient, since their shape allows for a higher amount of reflected radiation within the same usage of space. However, they are more difficult to apply due to the fact that they require curved mirrors to be assembled, and these kinds of mirrors aren't normally as easy to obtain as flat mirrors.

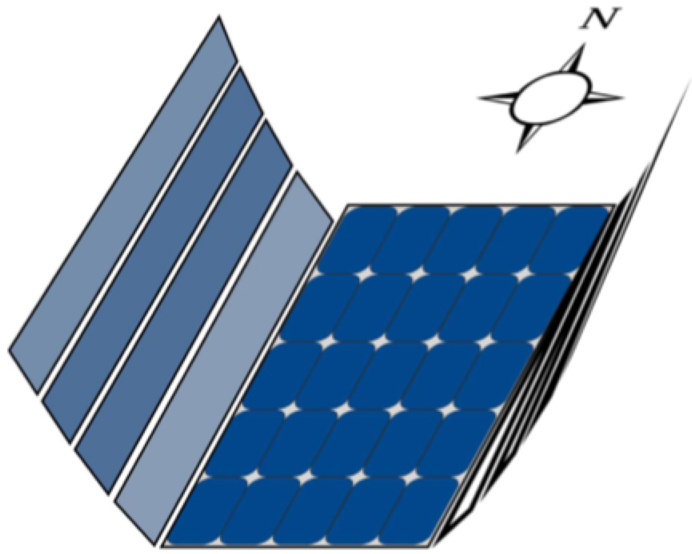

Figura 2.15: Linear Fresnel concentrator

The linear Fresnel concentrator is the solution to be between the flat concentrator and the ones with curved mirrors. It mimics the effect of the parabolic concentrator by placing strips of flat mirrors and varying angles. By doing this, it achieves high concentration ratios, while still using flat mirrors.

Another fact that has to be taken into consideration is that each of these geometries have their own variations that occur by changing the parameters shown in the figures. In the case of the flat concentrator, depending on the angle of choice, the length of the mirror will change to maintain even lighting on the cell, while also making sure the mirror isn't overly long for no reason [20]. However, these parameters can't be chosen at random. For example, by considering the concentration ratio theory, the largest possible mirrors would be best, but these large mirrors, related to the biggest angles in relation to the horizontal line (α), present a couple of challenges. Not only do they make the whole structure heavier, creating the need for a stronger solar tracking engine and reinforced structure, but most importantly, it requires a more precise solar tracking, since even the slightest deviation to the correct angle could lead these big mirrors to completely shade the cells. With that in mind, the choices of all the characteristics for the LCPV system, will vary depending on the purpose of the installation, as well as its limitations, such as structural strength, engine power and solar tracking precision.

There are also many other possible geometries for low concentration photovoltaics, depending on the constraints of the installation, as well as its objectives, and the kind of cells at use.

3
Proposed experiment

To test the effectiveness of low concentration photovoltaics, a small scale prototype can be built to allow the power production from different setups to be compared. Since low concentration photovoltaic has to be accompanied by solar tracking, this experiment will be able to analyze the advantages of both solar tracking and LCPV. The goal is to compare a standard fixed-mount cell to a solar tracking cell, and finally to a LCPV cell.

Since there are many different approaches to using these techniques, this project will narrow them down to better focus on analyzing the increase in productivity that the techniques themselves can bring, and not on how each different form of that technique performs compared to the others. The propositions are to use a single axis tilted tracker, following the sun during the day, and flat mirrors as the concentrators, aiming to analyze the simplest version of these technologies.

To be able to analyze the difference that they can bring to the amount of energy being produced, there will be three solar cells with different set ups. The first cell will be the simplest possible, just the cell at a fixed position, facing the estimated optimal position for power production during the year. This will be the control cell, to which the others can be compared. The other 2 cells will be set up in a solar tracking structure. There will be only one structure for the two cells to assure the fairest possible comparison. The first of these two cells will still have no mirrors, having the solar tracker as the only difference to the control cell, while the second will be equipped with mirrors.

3.1
The cell

The suggested cell for this experiment is be the Maxeon C60, which is a Crystalline silicon cell, since it has already been used in CPV projects, meaning it is capable of handling the harsher conditions caused by the use of concentrators. Since this is a small scale experiment, only one cell will be used for each case being assessed. Not only does this diminish the cost of buying more solar cells, but it also simplifies the construction of the solar tracking apparatus, since the cell and the mirrors on it will be both smaller and lighter.

3.2 Maximum power

To be able to properly compare the power producing performance of each of the setups, the maximum power that could be produce by them at any point in time will be estimated using the procedure explained in 2.6. By using this procedure in each of the 3 cells, it will be possible to find and compare their maximum power during the day, allowing for a simple analysis of the benefits of each technique. This is a good method for this experimental scenario, but can't be used for a real life scenario, since it doesn't actually produce useful power, so for an actual power producing installation the application of an actual maximum power point tracker is necessary.

3.3 Geometry

The benefit of the LCPV technique will be assessed using flat concentrators, with two mirrors, to increase the irradiance reaching the cell. As seen in the image below, it is then necessary to determine the angle α as well as the length L of the mirrors, to find the concentration factor that will be applied to the cell.

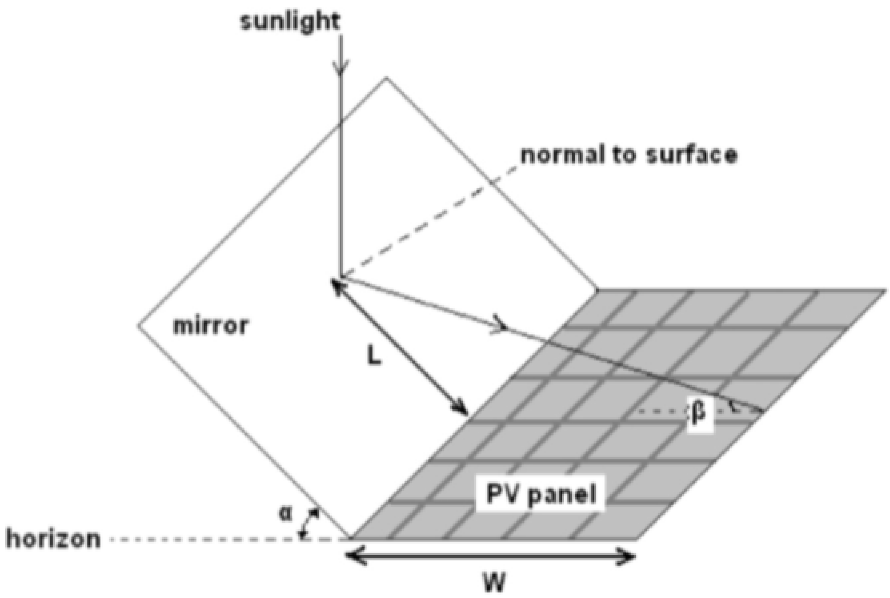

Figura 3.1: Flat concentrator Parameters

The first choice to be made is the angle α, since the length depends on it. Despite the fact that it would be ideal to use the steepest angle possible, the solar tracking system that will be used won't have enough precision to accommodate that, so it is necessary to make a compromise and use a smaller angle to make sure the mirrors won't be shading the cell. Considering the suggested set of angles from [21] seen below, α will be equal to 60 degrees. The panel from the article has a width of 80 cm, and the suggested cell for this experiment is a square with 12.5 cm sides, meaning that the length L that the table suggests should be divided by a factor of 6,4 to find the actual length of the mirror that should be used.

The calculated values of useful length (L) and concentration ratio (C) in flat concentrators (W=80 cm).

α (degree)	L (cm)	C
50	22	1.35
60	80	2
70	180	2.53
80	433	2.89

Figura 3.2: Flat concentrator parameters table

Based on these values and the factor of 6,4, the length L of the mirror should be 12,5 cm, which is equal to the width of the cell. By using these parameters, the system will have a concentration factor of 2. However, it is important to remember that the concentration factor doesn't take optical losses into consideration, such as the fact that the reflectivity of mirrors isn't 100 %, meaning the actual multiplier will be lower than that.

3.4 Solar Tracking

The solar tracking structure will be a single axis tracker on a tilted axis, like the one illustrated below:

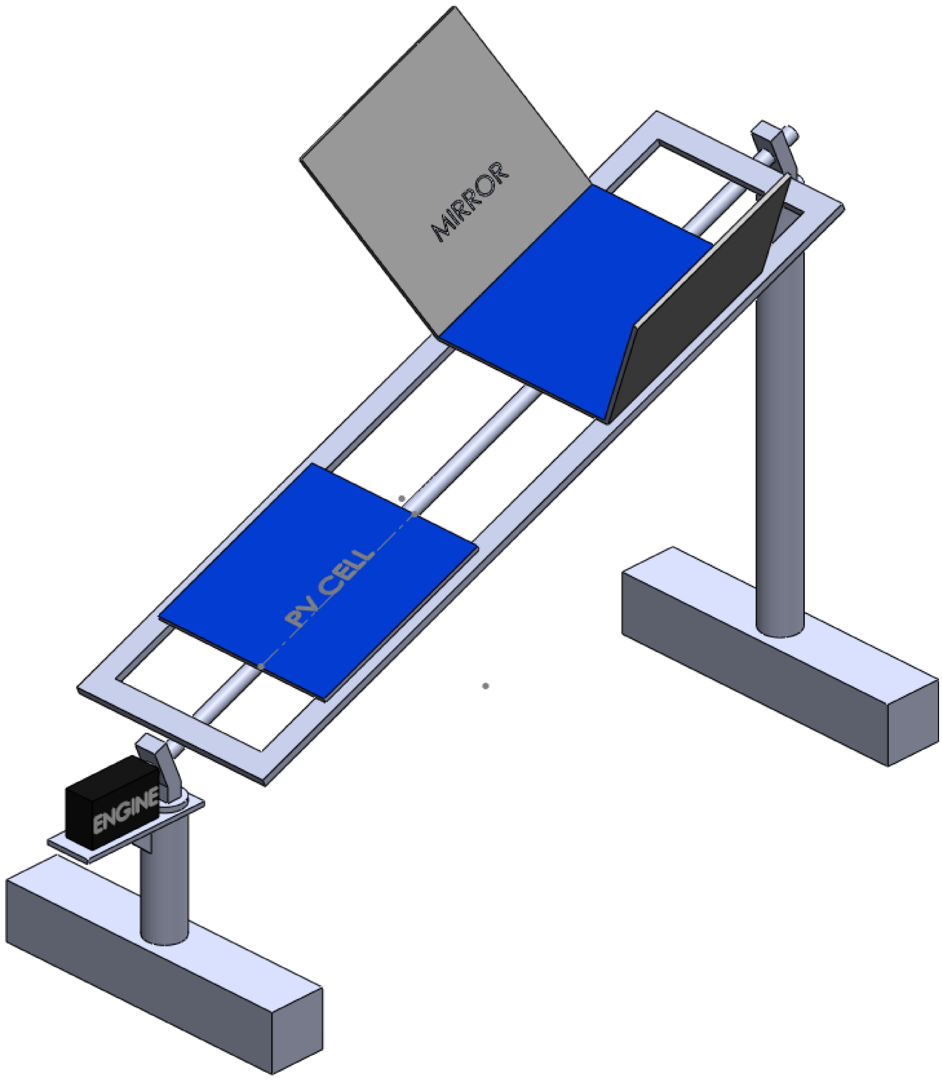

Figura 3.3: Solar tracker

In terms of the tilt angle, there are two possible options, the first is to adjust it to be the best angle to ensure maximum total production during the year, which in Rio de Janeiro, where the experiment will happen, is 22 degrees, and it will follow the movement of the sun from east to west during the day. The second one is to actually make one of the legs have variable length, allowing for its tilt angle to be changed through the year to maximize the total production. This way, it will behave similarly to a two axis tracker, following the sun both during the day and the year.

For the structure to follow the movement of the sun there will be an engine attached to one of the ends of the structure, and there will be a potentiometer attached to the other end, used to measure the current angle of the panels. The output of the potentiometer will then be translated to an angle by an arduino system, which will, in turn, compare it to the expected position, if there is a difference of over 0.5 % between the two, the arduino system will send a command to the engine to slightly change the angle of the system until the real angle is within this margin of error of the expected angle.

Another important measurement that has to be done in respect to the solar tracking system is to account for all energy expenditure, both of the engine and of the data acquisition system. This way, it can be taken into consideration when comparing the cost benefit of the different systems.

3.5 Costs

To make this experiment from scratch, the costs below have to be taken into consideration:

- 3 Solar cells - R$100,00
- Solar tracking equipment - R$200,00
- Mirrors - R$ 50,00
- Arduino system - R$200,00
- Electrical circuit and equipment - R$100,00

Amounting for a total cost of around R$650,00 for the experimental setup.

4
Theoretical analysis

In order to understand the benefits and viability of the LCPV technique, a theoretical analysis can be done to approximate the power production for different photovoltaic setups. To predict the behavior of a solar cell, the main factors that have to be taken into consideration are:

- The irradiance, as well as its variation through the day and year
- The ambient temperature
- The conversion efficiency of the PV cells
- The temperature coefficient of the PV cells
- The area of the cell/panel

4.1
Irradiance

The analysis will be based on information from Rio de Janeiro in Brazil. The information about the irradiance can be found in The Photovoltaic Geographical Information System [22], which makes available the irradiance and the clear sky irradiance using both a fixed panel and solar tracking panel as references. This is fundamental, since it makes possible to better compare the behavior of fixed, solar tracking and LCPV panels.

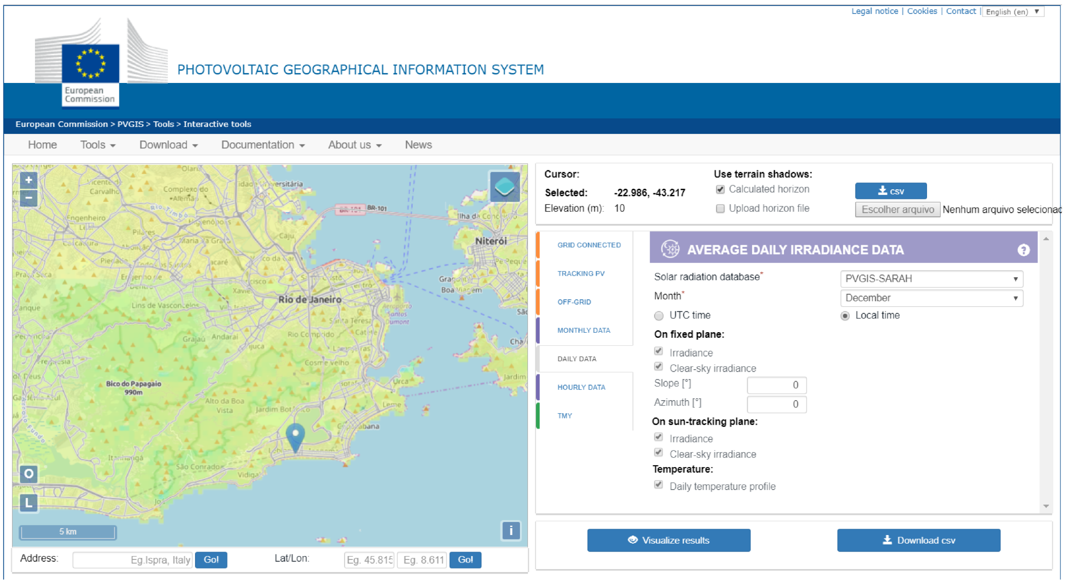

Figura 4.1: Photovoltaic Geographical Information System

This application displays the variation of these parameters during the day. It shows the average value for each time slot during the selected month, allowing for and understanding of the daily behavior of the radiation for each month.

To make the most accurate prediction possible, it is best to use the irradiance, since it takes into consideration the disturbances in the path of the radiation, such as clouds, making it more realistic than clear sky irradiance.

Time, Local Time	Global irradiance on a fixed plane (W/m^2)	Global irradiance on 2-axis tracking plane (W/m^2)
06:00	63	223
07:00	211	444
08:00	376	582
09:00	544	691
10:00	684	772
11:00	763	794
12:00	805	813
13:00	786	815
14:00	692	779
15:00	541	701
16:00	298	404
17:00	118	148
18:00	23	37

Figura 4.2: Irradiance during the day

To analyze the behavior of the panels though the year, so that the total yearly power production can be calculated, the information for each month will be used so that the variation of radiation through the year can be taken into consideration.

4.2 Cell temperature

The temperature of the cell directly affects their conversion efficiency, the higher the temperature, lower the efficiency. The base for comparison is the standard temperature at which PV cells are tested (25°C), and the data sheets for PV cells inform how much the efficiency loss is per temperature increase.

The cell taken into consideration in this study is the Maxeon C60 from Sunpower [23], which has a power loss of 0.32%/°C. This means that after calculating the power by multiplying the current irradiance by the area of the cell, it is necessary to decrease it by the percentage given by the number of °C over 25 times 0.32.

To make these calculations, it is necessary to find and approximation for the temperature of the cell. There are several formulas to estimate the temperature of the cell, using ambient temperature, wind speed and irradiance, as can be seen below:

Model	Empirical Models
Ross (1976) [14]	$T_c = T_a + kG_T$ where $k = \Delta(T_c - T_a)/\Delta G_T$
Rauschenbach (1980) [15]	$T_c = T_a + (G_T/G_{T,NOCT})(T_{c,NOCT} - T_{c,NOCT})(1 - n_m/\gamma)$
Risser & Fuentes (1983) [16]	$T_c = 3.81 + 0.0282 \times G_T 1.31 \times T_a - 165V_w$
Schott (1985) [17]	$T_c = T_a + 0.028 \times G_T - 1$
Ross & Smokler (1986) [14]	$T_c = T_a + 0.035 \times G_T$
Mondol et al. (2005, 2007)	$T_c = T_a + 0.031G_T$ $T_c = T_a + 0.031G_T - 0.058$
Lasnier & Ang (1990) [5]	$T_c = 30.006 + 0.0175(G_T - 300) + 1.14(T_a - 25)$
Servant (1985)	$T_c = T_a + \alpha G_T(1 + \beta Ta)(1 - \gamma V_w)\ \ 1 - 1.053n_{m,ref}$
Duffie & Beckman [3]	$T_c = T_a + (G_T/G_{NOCT})(9.5/5.7 \times 3.8V_w)(T_{NOCT} - T_{a,NOCT})(1 - n_m)$
Koehl (2011) [6]	$T_c = T_a + G_T/(U_0 + U_1 \times V_w)$
Kurtz S (2009) [7]	$T_c = T_a + G_T \times e^{-3.473 - 0.0594 \times V_w}$
Skoplaki (2009) [8]	$T_c = T_a + (G_T/G_{NOCT}) \times (T_{NOCT} - T_{a,NOCT}) \times h_{w,NOCT}/h_w$ $\times [1 - \eta_{STC}/\tau \times \alpha(-\beta_{STC}T_{STC})]$

Figura 4.3: Formulas to estimate cell temperature [9]

Comparing the equations with known variables and with cell temperature equal to ambient temperature at zero irradiance, the plot below can be created.

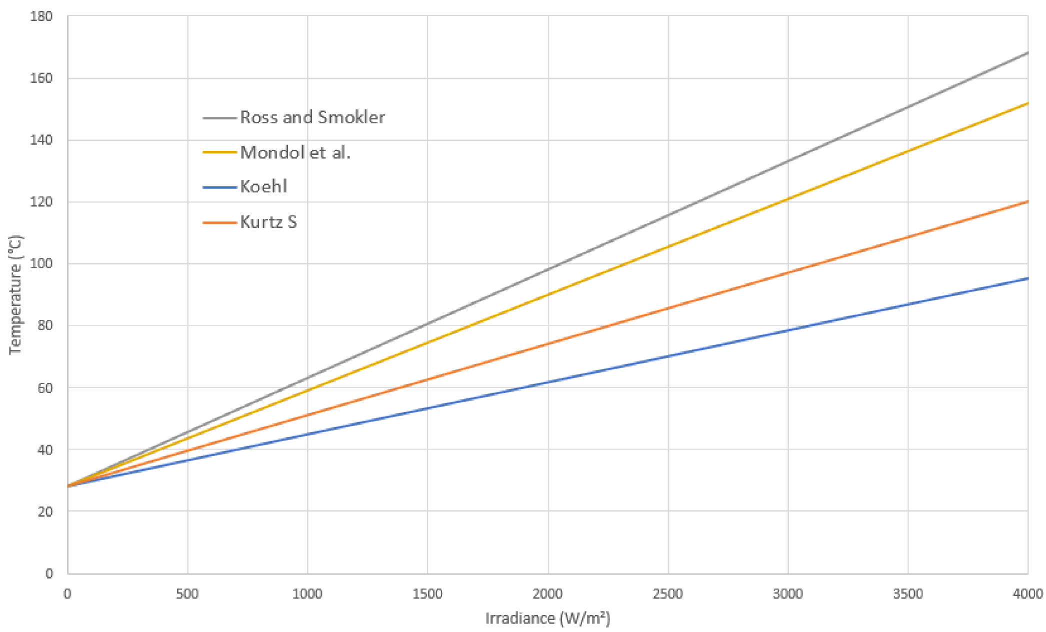

Figura 4.4: Temperature comparison of different approximations

As seen above, they present similar behaviors, with Ross and Smokler being the most conservative one. The analysis will use this approximation to make sure not to overestimate the gains from the different techniques.

As it can be observed in the plot, at high irradiances, which are common when applying the LCPV technique, the temperatures the cell can reach are very high, so in order to diminish these temperatures, increasing the efficiency, as well as decreasing the risk of degrading the cells due to the high temperatures, using aluminum fins on the back of the cell is a viable option.

However, none of the formulas in the image above take the possibility of fins into consideration. So the equation to rule the temperature of the cells with aluminum fins will be based on the equation and parameters from an article from PVeducation [10]. The general formula for the temperature is:

$$Tc = Tair + \frac{NOCT - 20}{80} G_T \tag{4-1}$$

Where the air temperature will be considered as the average ambient temperature during the day in each month, and NOCT is the nominal operating temperature of the cell, which is the temperature of the cell under the conditions:

1. Irradiance = 800 W/m^2
2. Air temperature = 20°C
3. Wind velocity = 1 m/s

The value from the NOCT can change based on the back of the cell, with the standard being an open back side (NOCT = 48°C), and the best case being an aluminum finned substrate (NOCT = 33°C)

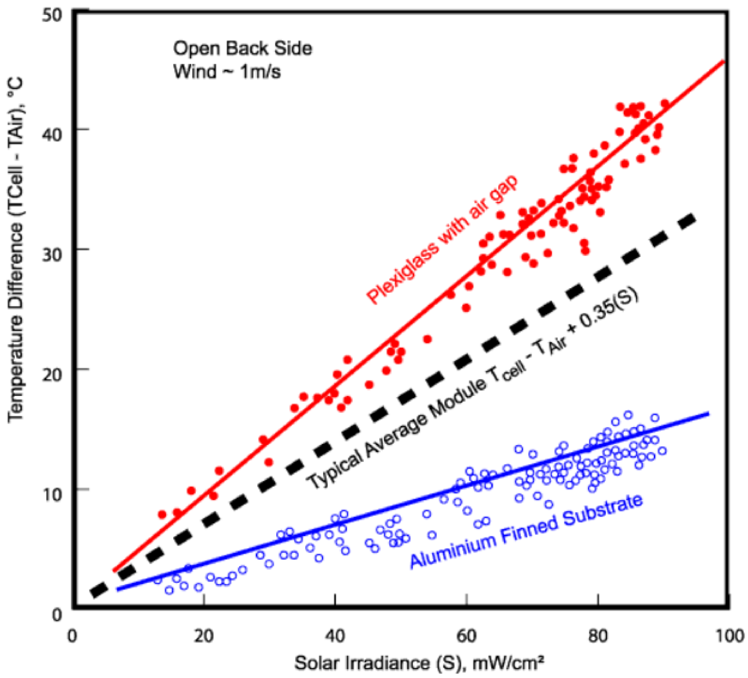

Figura 4.5: Temperature comparison based on the back of the cell [10]

This means that the irradiance multiplier $\frac{NOCT-20}{80}$ can be considered as 0.35 fro the standard cell, and as 0.1625 for the finned cell. However, this would be the multiplier using irradiance in mW$/cm^2$, and since the standard unit is W$/m^2$, the values used will be 0.035, which matches the conservative approach of Ross and Smokler, and 0.01625 respectively.

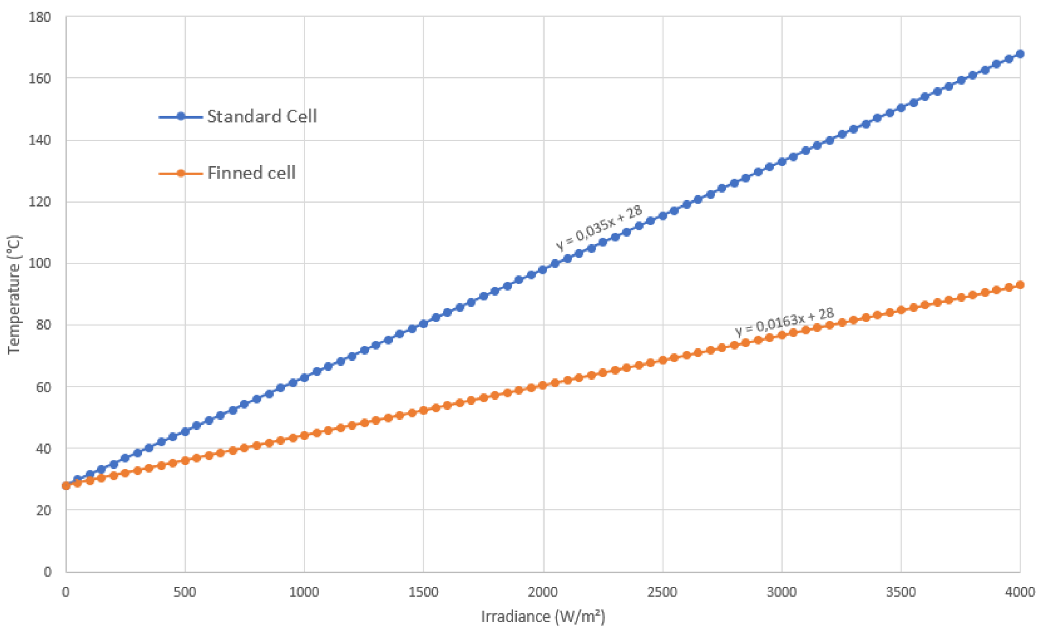

Figura 4.6: Variation of the temperature with irradiance

It is necessary to analyze the temperature at very high irradiances due to the presence of the concentrators. As can be observed, the temperature of cells without aluminum fins can reach very high values, demonstrating the importance of the fins, not only for the efficiency of the cell, but also for its integrity.

4.3
Power production

To estimate the power production (P) for a cell/panel, it is necessary to have:

1. Temperature of the cell (T_C)
2. Irradiance (G_T)
3. Conversion efficiency of the cell (η)
4. Temperature coefficient of the cell (α)
5. Area of the cell/panel (A_C)
6. Standard testing temperature (T_S)

With these information in hand the following equation can be applied to find the expected power production:

$$P = G_T A_C \eta (1 - \alpha(T_C - T_S)) \tag{4-2}$$

For the Maxeon C60 cell, η = 22%, α = 0.32%/W, T_S = 25°C and the area for one cell A_C = 0,015625 m^2. The temperature of the cell depending on if it has fins or not, on the irradiance reaching the cell, which is increased in the cells with the concentrators, and on the ambient temperature.

The plots below display the comparison between the power production behavior of the different setups, using the irradiance information from the Photovoltaic Geographical Information System for Rio de Janeiro. The LCPV system is being studied as having a concentration factor of 2, meaning the concentrator have twice the area of the cell.

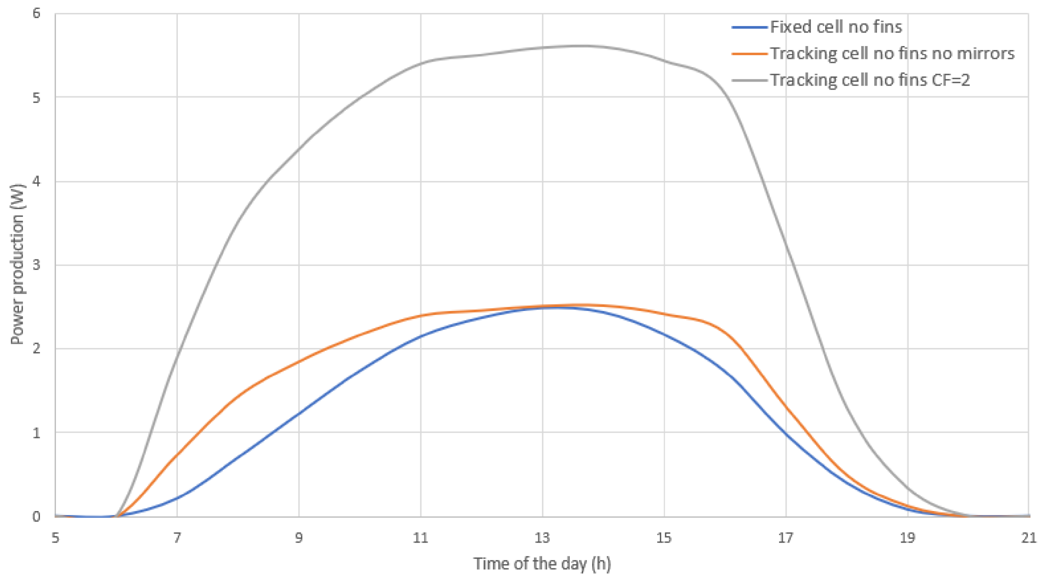

Figura 4.7: Power production comparison of the different setups with no fins

The plot above shows the benefits in energy production that both solar tracking and the use of the LCPV technique bring. As expected, the difference between the fixed and solar tracking setups comes from the higher power production from the tracking system in times where the irradiance isn't at peak, such as early morning and late afternoon, with the production in the middle of the day, when irradiance hitting the cells is at its peak, being very similar.

In terms of the LCPV, it is possible to see that it brings a lot of extra production through the whole day, even with the big temperature increase, producing almost triple the amount of the solar tracking setup with no mirrors.

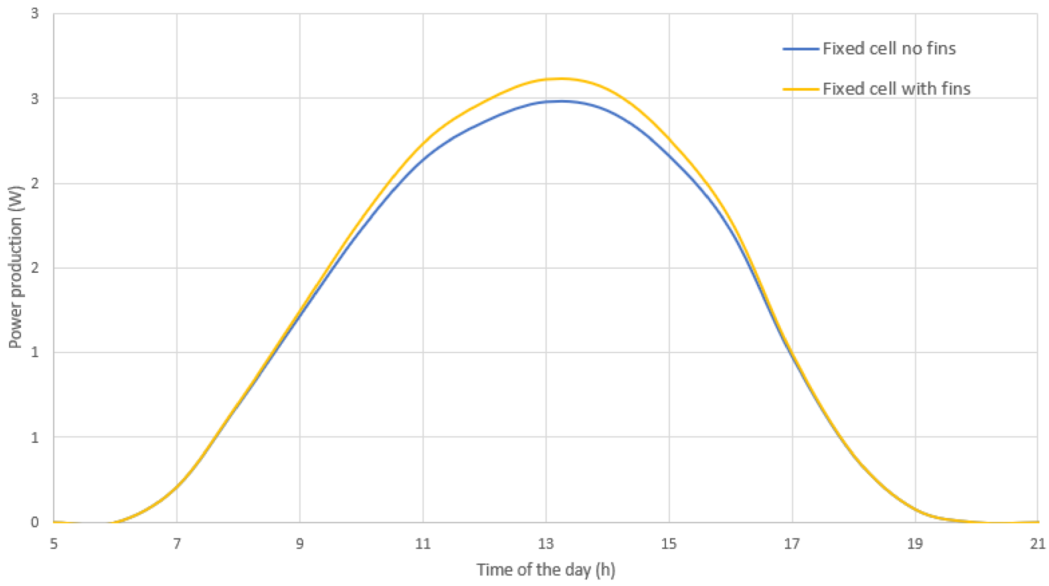

Figura 4.8: Power production comparison for fixed cells with and without fins

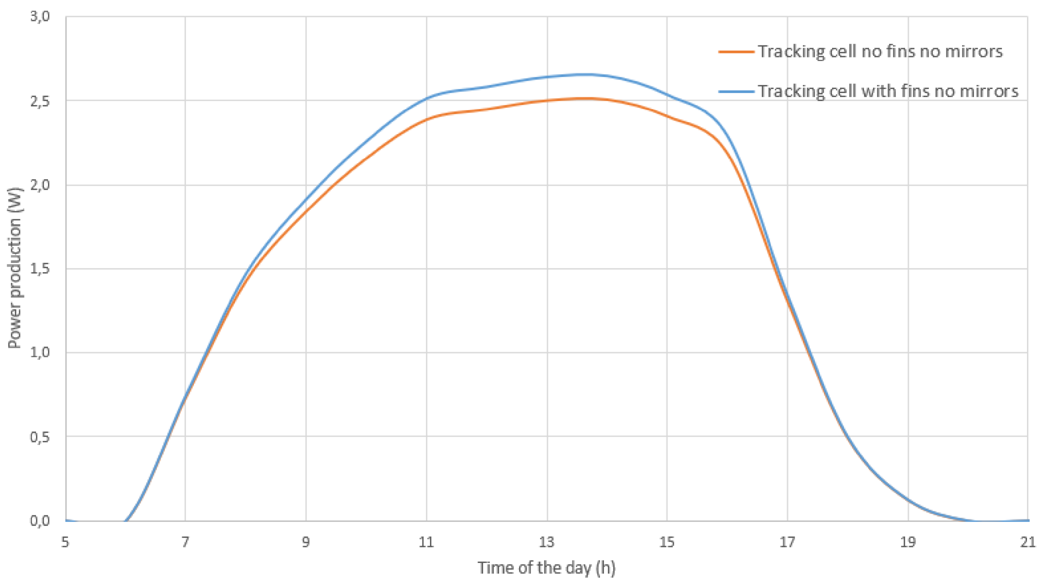

Figura 4.9: Power production comparison for tracking cells with and without fins

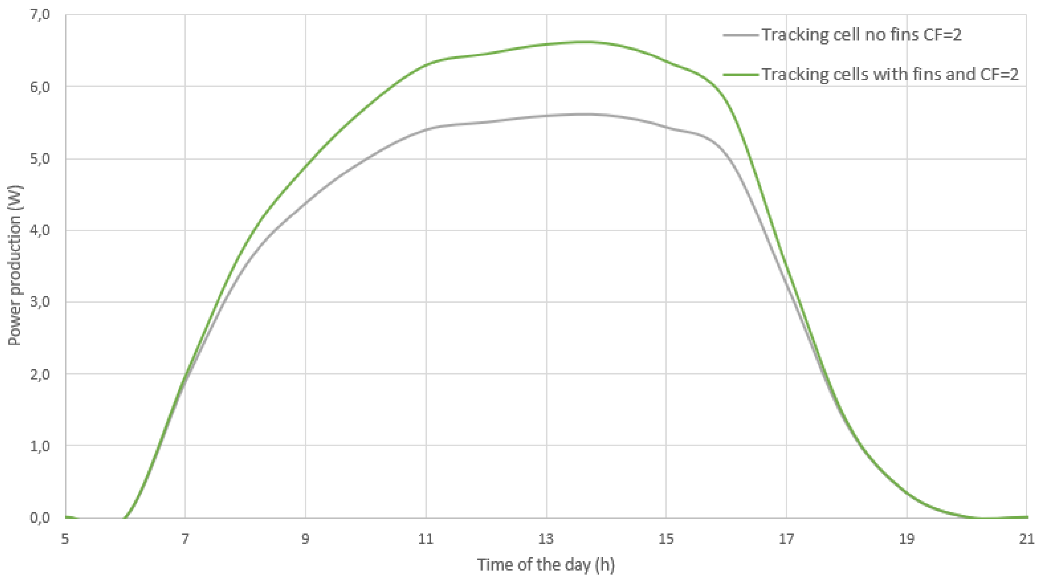

Figura 4.10: Power production comparison for tracking cells with CF=2 with and without fins

The effectiveness of the fins can be observed in the plots above, with benefits to all three of the different setups. However, it is clear that the benefits it brings to the system with mirrors are much higher, which is expected since it achieves the highest temperatures, with the extra convective heat exchange made possible by the fins having a greater impact.

It is however important to note that in case the option to install fins is available, it brings positive benefits to all of the systems, always being a good addition, especially due to its low costs.

4.4 Economic analysis

To understand what techniques should be applied to a solar installation, an economic analysis must be made, so that it is possible to better visualize what setup will bring the most profit, or savings. This can be accomplished by comparing the expected kWh production over time, generally the amount produced in one year, to the installation costs and upkeep.

When considering the solar panel installation of a household for example, some costs will be there independently, such as the solar panel itself, a maximum power point tracker, an inverter, and the battery. Since they are part of all the different setups, this constitutes the control group, being composed by the minimum requirements of a regular solar installation. By comparing the amount of money saved/gained with the energy produced by this basic setup with its costs, it is possible to estimate the payback time for this installation.

From this point on, the viability of any equipment added to the system can be assessed by comparing the new production to the new costs and finding its payback time. As a general rule, if the payback time is shorter than the one relative to the control group, the technique is worth investing on. However, there can be exceptions in certain cases, and the availability of capital also must be taken into consideration due to the higher investments.

This analysis will take into consideration the use of:

- Aluminum fins
- Solar tracker system
- Mirrors used as concentrators

It will take one panel, composed of 100 Maxeon C60 cells, forming a 330W PV panel, with a 1.5625 m^2 of area. The economic analysis will take into consideration six different systems, based on this same panel, to be able to compare the effects of each variant.

1. Fixed solar panel
2. Fixed solar panel with aluminum fins
3. Solar tracking panel
4. Solar tracking panel with aluminum fins
5. Solar tracking panel with concentrators
6. Solar tracking panel with concentrators and aluminum fins

It is necessary to evaluate the benefits of the aluminum fins in each scenario, since their effectiveness depends on the temperature of the panel, which varies highly in these different scenarios due to the difference in irradiance reaching the panels.

Another important consideration is that since different solar trackers may require different mirror arrangements, instead of classifying the concentrators by mirror layouts, they will be classified by concentrator factor, since the same concentration factor can be achieved with several different setups and geometries.

As far as the costs go [24], it is necessary to estimate them for each of the different setups. For the control setup:

- Solar panels 300 W - R$1200,00
- Maximum power point tracker 40 A - R$800,00
- Inverter 1000 W - R$600,00
- Battery 105 AH - R$700,00

Arriving at a total R$3300,00, which will be the base cost for all the setups, to which the price of the extra equipment can be added to. In terms of the price of the extra equipment:

- Aluminum fins - R$100,00
- Solar tracker - R$1500,00
- Mirrors (5 m^2) - R$100,00

The yearly kWh production for each of these setups has been calculated by summing the values for each month.

Tabela 4.1: Yearly power production comparison between the different setups

System	Production (kWh per year)
1	560,40
2	580,75
3	749,68
4	782,49
5	1742,98
6	1982,19

However, before comparing the costs with these productions it is necessary to subtract any energy expenditure. In this case, the only equipment using energy is the solar tracker, both the engine and the controller, which consumes an approximate 100 Wh per day [25], equivalent to 36.5 kWh per year, which will be subtracted from systems 3 to 6. With these values, as well as the estimated power output of each setup, it is possible to compare their costs with their production and obtain the payback time for each system.

Tabela 4.2: Economic comparison between the different setups

System	Costs (R$)	Production (R$ per year)	Pay back time (years)
1	3300,00	560,40	5,89
2	3400,00	580,75	5,85
3	4800,00	713,18	6,73
4	4900,00	745,99	6,57
5	4900,00	1706,48	2,87
6	5000,00	1945,69	2,57

The first observation that can be made is that the aluminum fins decreased the pay back time for all the different setups, showing that it is a cheap solution that can benefit the power production even in the case of the fixed panel, which doesn't have a lot of temperature increase.

Looking at the comparison between the solar tracking and fixed systems, we can see that the payback time for the solar tracking system is higher, but its energy production is higher, meaning that, although it would take longer to pay for itself, it will allow for more profits/savings over time.

When it comes to the LCPV system, it has a much smaller payback time than all the other systems, proving that it is a viable technique that can increase the production of solar power plants, specially if coupled with a cooling system, such as the aluminum fins.

With that in mind, the techniques applied to a solar installation are very dependent on the objective of the stakeholders. While the fixed system is the cheapest one, making it more accessible, it will produce less daily energy, and will in the long term be less economically beneficial then either of the other options. Despite making the project more expensive, solar tracking will allow for a higher production, as well as making the use of LCPV possible, which is shown to, apart from initial costs, be financially better the other options.

These results also show that, if an installation is already equipped with solar trackers, it is highly beneficial to apply the LCPV technique to it, since it has low cost and can increase the power production of the panels.

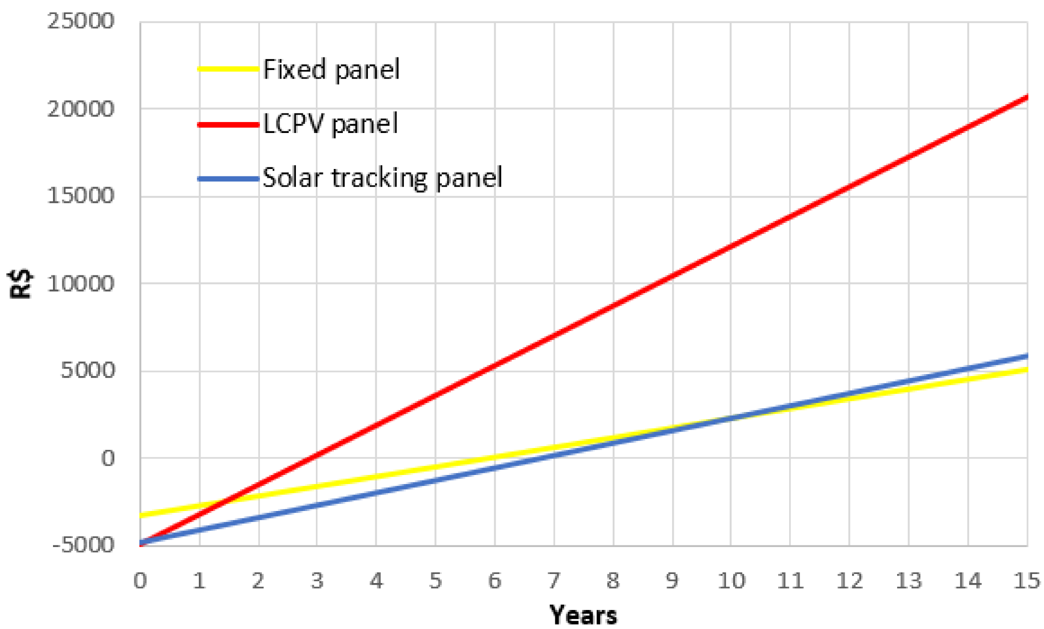

Figura 4.11: Economic comparison over time

5
Conclusion

This paper has shown through theoretical analysis that the use of the LCPV technique is highly advantageous for solar installations, both in terms of power production and payback time, having as only downfall in relation to fixed mount panels the fact that it has a higher initial investment. Beyond that, it has shown that the application of cooling techniques, namely aluminum fins, on solar panels is very cost effective, since it increases the power production in all setups, as well as having a small cost.

Despite having been shown through the calculations, a more precise analysis can be made by building the proposed experiment and making the measurements so that the approximations made on the theoretical analysis can be put to test, and to allow for a better idea of the actual gains that these techniques can bring to solar installations.

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