Triangular Shape Geometry in a Solarus AB Concentrating Photovoltaic-Thermal Collector

Luís Marques
luis.caldas.marques@ist.utl.pt
Instituto Superior Técnico, Lisboa, Portugal

***Abstract*—Solar Energy can be used in various ways: there are solar collectors to heat water and air, photovoltaic panels that produce electricity and PVT collectors (Photovoltaic Thermal Collectors), which are basically a hybrid solution. Over recent years, much attention has been focused on an emerging solar technology: solar concentrators, used to reflect and focus radiation on photovoltaic cells and thus improve the power produced. In this work, firstly, it is intended to make a study of photovoltaic cells, analyzing the behavior for different environmental factors: irradiance, temperature and shading. Next, a concencentrating photovoltaic panel is constructed with the aim of testing the concentration ability of triangular reflector. This panel allows the study for different tilts and apertures, which are two factors that influence the power generated by solar cells. For the same dimensions than the panel constructed, an analysis is made using a software intended to simulate solar rays trajectory: SolTrace [1]. This software allows to design and study triangular reflector for different tilts, apertures, latitudes and days and conclude about in which conditions it is collected the highest power in solar cells. Finally, computationally results are compared with the experimental with respect to power generated and collected by solar panel. They show that triangular reflector has potential because, with great simplicity of construction, allows higher powers than parabolic, for certain conditions. Furthermore, it allows the phenomenon of concentrarion on solar cells.**

***Index Terms*—Solar Energy, Photovoltaic Cells, Solar Concentrator, Triangular Concentrator, Reflector**

I. Introduction

Currently, there are several energy sources that are used to realize a wide range of everyday tasks and which are indispensable in our lives. These are fossil fuels like oil, natural gas and coal, and renewable energies, namely biomass, wind, hydro and solar energies, among others.

Fossil fuels are the predominant energy source. Nevertheless, they bring many disadvantages: they have high cost, are non-renewable and cause the increase of greenhouse gases, this in an age where effects of climate changes are becoming increasingly obvious. Hence, it is desirable to find ways to respond to these disadvantages.

In this context, Renewable Energies arise as an excellent alternative to fossil fuels for being inexhaustible at human scale and for having an almost null environmental impact, which is crucial in a sustainable level.

In the case of Solar Energy, it has become increasingly preponderant over the years, being used to produce electricity and heat and having a huge number of applications, since transports until industry, passing through residential and service levels.

The devices used to convert Solar Energy into heat are solar collectors, while photovoltaic panels are used to convert this energy into electricity. More recently, studies have been done about a relatively new solar technology: Concentrating Photovoltaic/Thermal Collector (CPVT collector), which transforms Solar Energy into electricity and heat, being, therefore, a hybrid of solar collector and photovoltaic panel. It is about this new way of utilization of Solar Energy that focuses the current work, more specifically, the evaluation of the electric part of concentrating PVT collectors with triangular shape geometry, which currently require a complex analysis to improve its performance.The structure of the panel under study has as inspiration concentrating PVT collectors of Solarus AB, a swedish small and medium enterprise whose mission is the development, production and marketing of concentrated solar technology to the world market. [2]

A. Problem statement

Solarus AB develops concentrating PVT collectors. The main product of this company is composed by receivers, which have solar cells on the upper and bottom sides [3]. In order to reflect and focus the radiation on the bottom side, a concentrator with a shape very similar to a parable is used. In this work, a different concentrator for this collector is studied: a triangular shape concentrator. It is simpler, easily built and avoids the use of molds, being therefore an economic solution.

Second, solar cells, the main constituents of photovoltaic panels, can convert the available solar energy into electricity. If they had 100% efficiency, Solar Energy would be one of the main energies used, because the energy that is radiated by the sun onto the surface of the Earth exceeds the global consumption of energy in a year [4]. However, solar cell efficiency is well below the desired, where the most common cells - monocrystalline cells - have an efficiency close to 20% [5]. Besides, solar cells, in general, have a relatively high cost, which originates a big investment in photovoltaic panels. Hence, a lot of research and analysis must be done to improve the efficiency and reduce the cost of this technology.

Solar technologies behavior depends largely on the environmental conditions, like temperature and solar irradiance. Power produced by these technologies do not change linearly with these factors, mainly in photovoltaic panels, which makes the optimization analysis very complex [6].

There is another factor that affects solar cells: shading. Shading is the lack of irradiance in some spots of the photovoltaic panel. This phenomenon is a problem because it reduces the power produced by solar cells, at some cases, to zero. Find ways to mitigate its effects and monetize the production are an objective.

Power generated by photovoltaic panels changes, for example, with its tilt and position. Besides, reflectors can be used in this technology, which involves studying solar rays trajectory in order to concentrate the most energy possible into solar cells. Therefore, study solar rays trajectory and the characteristics that optimize the power generated by the panel, like its position and tilt, is important.

In conclusion, studies are being done to potentialize solar technologies and this work pretends to continue that study, which culminates in an inexpensive solution: photovoltaic panel with triangular shape reflector.

B. Solution/Objectives

There are some objectives that must be fulfilled in this work.

The first and main objective concerns the development of an appropriate design of a concentrating photovoltaic thermal collector with a triangular shape reflector. The aim is to optimize the efficiency and, therefore, the power on the receiver (solar cells) without cost penalties to the global system. Due to the complexity of these devices, the focus of current work is the electric analysis, being the thermal one out of the scope of this paper.

To optimize the efficiency and the power collected on the receiver of the panel, it is necessary to analyze photovoltaic cells. The second objective is to study the behavior of solar cells under different environmental conditions: irradiance and temperature.

The third objective consists of analyze the effects of shading on a solar module, which implies to study its impact into different groups of cells and mechanisms that mitigate this phenomenon.

The forth objective includes the implementation of a computational model capable of characterize a solar cell with good approach to reality.

Finally, the fifth and last objective concerns the development of a computer simulation capable of verify the sun′s rays trajectory in the solar panel, allowing to observe its distribution for several conditions: different hours, days, latitudes, apertures and tilts of the panel.

C. Document outline

This document starts with the Background, where the main objective is to give the necessary knowledge to understand this article. Photovoltaic Panels are explored concerning its working principle, constituents (mainly solar cell), characteristics and properties.

Then, Chapter III consists of the main proposal of this thesis: a concentrating photovoltaic panel with a triangular shape reflector, where it is described its design, characteristics, potentialities and materials used in its construction.

Chapter IV brings the experimental evaluation of the proposal. Here, we state the results and analyse the experiments conducted to study the behavior of solar cells under different environmental conditions, the impacts of shading and the potential of a triangular shape reflector in a photovoltaic panel.

Chapter V consists of the computational evaluation that helps to understand the rays trajectory and power collected by triangular shape photovoltaic panel, for different tilts, days of the year and latitudes. Besides, a comparison is made with another reflector. In the end, the results are compared with experimental results.

Finally, Chapter VI summarizes the main achievements, conclusions and analyses at which point this work can be improved in the future.

II. BACKGROUND

In this chapter, the main objective is to give the necessary knowledge to understand this article. We carefully explore the photovoltaic panel, focusing on its main constituent: the solar cell. It is explained how it works and analysed the several properties.

A. Photovoltaic cell

A photovoltaic cell is a device capable of convert light energy coming from any light source directly into electricity, throughout a process denominated Photovoltaic effect. In other words, a current is generated due to the incidence of photons, which are light beams/packages of electromagnetic radiation or energy that can be absorbed by a solar cell. When the incoming light has a proper wavelength, the energy of photons is transferred to the electrons which jump to a higher level of energy, known as conduction band, and holes are originated and dropped on the valence band, creating electron-hole pairs. In this excited state, electrons are free to move on the material. Since a photovoltaic cell is composed by semiconductor materials of N and P types that form a P-N junction, an electrical field is originated and is due to it that electrons and holes move in opposite directions, being this process that creates an electrical current in the cell. [7]

B. I-V Characteristic of solar cell

The I-V curve provides quick and effective means of accessing the true performance of solar PV modules or strings. In a correctly performing PV system, the shape of the curve should follow the normal profile. To represent I-V curve, we must know that the current that flows through the cell, for the ideal case, is given by:

$$I = I_{PV} - I_S(e^{\frac{V_d}{nV_T}} - 1) \tag{1}$$

Where I_{PV} is the current generated by light energy; I_S is the reverse saturation current; n is diode ideality factor and V_T is the thermal voltage. This means that current generated by solar cell, I, is equivalent to current generated by light, I_{PV}, subtracted by current of diode, I_D. According to equation 1, a chart of current as a function of voltage can be drawn, giving rise to the so-called I-V Characteristic. Besides, multiplying voltage by current, we obtain power and so a P-V Characteristic, that shows the point at which the power is a maximum (P_{MAX}), as can be seen in Fig. 1.

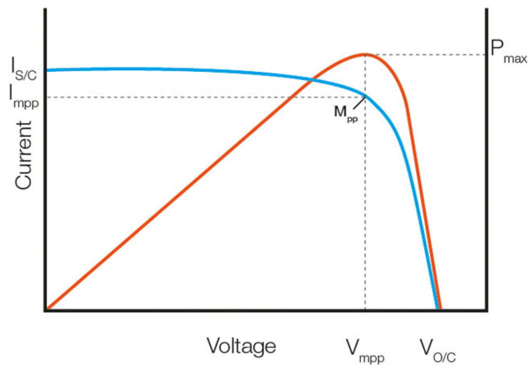

Fig. 1. I-V and P-V characteristics of solar cell [8].

In this figure, there are different parameters that characterize solar cell:

- I_{SC}: Short-ciruit current. It is the greatest value of current generated by the cell. It is produced in short circuit conditions: V = 0;
- V_{OC}: Open circuit voltage. Corresponds to the voltage drop across the cell when the photocurrent I_{PH} (namely I_{PH} = I_{PV}) passes through it and the generated current I is equal to 0;
- I_{MPP}: Current obtained when PV cell is operating at maximum power point. This power corresponds to the maximum power that cell can reach, for certain conditions of irradiance and temperature.
- V_{MPP}: Voltage obtained when PV cell is operating at maximum power point.

There are another important parameters that characterize solar cell. One of those parameters is Fill Factor, which shows how close a I-V characteristic is of a square shape. This parameter is determined by the following expression:

$$FF = \frac{I_{MPP}V_{MPP}}{I_{SC}V_{OC}} \tag{2}$$

This means that if I-V characteristic had a square shape, the FF value would be 1, which is impossible since I-V characteristic always assumes an exponential shape. Another relevant parameter in characterizing the solar cell is efficiency, η . This is determinated in the point of maximum power and it is given by:

$$\eta = \frac{I_{MPP}V_{MPP}}{G * A_C * N} \tag{3}$$

Where G represents solar irradiance (W/m^2), A_C the area of solar cell (m^2) and N the number of cells [9]. These parameters are fundamental for testing, designing, calibrating, maintaining and controlling PV systems.

Theoretically, the I-V characteristic of a solar cell is determined by changing the voltage applied to the cell in progressive steps from zero to infinite resistance. In practice, to obtain this curve are used, at least, 6 distinct methods. These methods consist of using a variable resistor, capacitive load, electronic load, bipolar power amplifier, four-quadrant power supply or a DC to DC converter. A comparison between these 6 methods can be seen in Fig.2.

	Flexibility	**Modularity**	**Fidelity**	**Fast Response**	**Direct Display**	**Cost**
Variable Resistor	Medium	Medium	Medium	Low	No	Low
Capacitive Load	Low	Low	Medium	Low	No	High
Electronic Load	High	High	Medium	Medium	Yes	High
Bipolar Power Amplifier	High	High	High	Medium	Yes	High
4-Quadrant Power Supply	Low	Low	High	High	Yes	High
DC-DC Converter	High	High	High	High	Yes	Low

Fig. 2. Characteristics of different methods used to obtain I-V curve. [10].

C. *Main factors which influence the behavior of solar cells*

1) Variation with temperature: The solar cell behavior depends very much on its temperature. Open circuit voltage decreases with the increase of temperature, while short circuit current is practically the same or has small changes. In relation to maximum power, this reaches greater values for low cell temperatures.

2) Variation with irradiance: Another factor that changes the behaviour of photovoltaic cell is irradiance. If this factor increases, the value of currents also raises and consequently short-circuit current, as shown in Fig.3. In relation to open-circuit voltage, this also increases slightly. Finally, it can be highlighted the increase of maximum power point with irradiance.

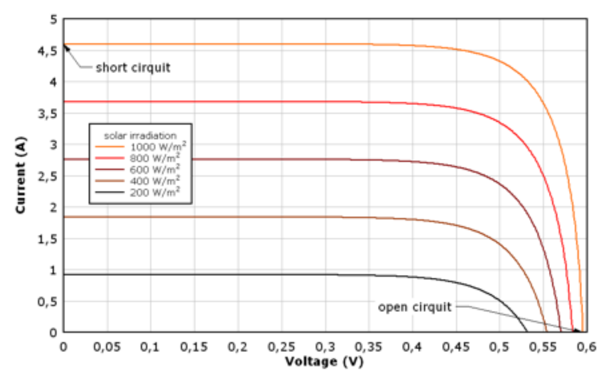

Fig. 3. I-V Characteristics of solar cell, for different irradiances. [11].

D. *Shading*

Shading in a photovoltaic panel consists of the existence of shadows or the absence of light originated by outside objects which impacts the power generated by the panel. Depending on the technology used in the photovoltaic panel, a shadow does not need to cover the totality of the panel to affect all the solar modules, being enough one shaded cell to increase the power losses, reduce to zero the output of photovoltaic panel and also cause damage in the system. The shading sources can be trees, clouds, buildings or dust on the panel. Photovoltaic cells can be associated in series or in parallel. When associated in series, it may happen the case of behave as charge for the rest of the cells, where there is the risk of negative voltage applied at the terminals be higher than the absolute value of breakdown voltage. This leads to a high power dissipated in the cell, giving rise to a warming that can damage it. In the origin of this warming can be the shading. In order to handle and mitigate this problem are used bypass diodes, which are connected in anti-parallel to the terminals of the cells. These diodes, in case of shading, become directly polarized, allowing current to flow through it and shaded cells to not behave as charge for the other cells, as shown in Fig.4.

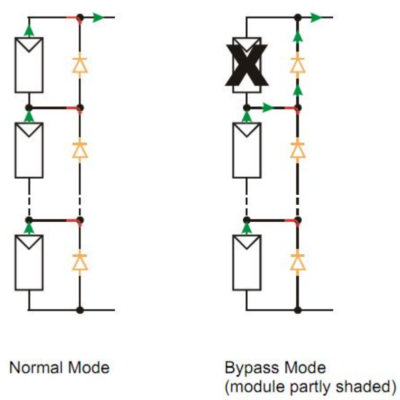

Fig. 4. Diode bypass behavior for normal operation of solar panel and with shading. Current is symbolized by arrows. [12].

E. Concentrating Photovoltaics (CPV)

Concentrating photovoltaics are devices that use lenses or mirrors to reflect and focus solar radiation onto photovoltaic cells. By concentrating sunlight onto a small area, concentrating photovoltaics have huge advantages, namely:

1. Less photovoltaic material required to capture the same sunlight as non-concentrating PV;
2. Replace photovoltaic cells or modules by concentrating optics, which are more economically affordable;
3. Due to smaller space requirements, the use of high-efficiency but expensive multi-junction cells is economically viable. [13]

Concentrating photovoltaics can reach electrical efficiencies higher than 25 %. Triangular shape photovoltaic panel (TSPP) is based on this technology.

III. Triangular Shape Photovoltaic Panel

In this chapter, we describe the proposal of this work: Triangular Shape Geometry in a Photovoltaic Panel. First, we present the main constituent of the proposal: solar cell. Then, we profile the two types of reflectors used to concentrate the radiation on the cells: aluminium and aluminium foil. Moreover, we describe the characteristics of the receiver, like the type of material and number of solar cells. After, we show the stand used for the reflector and, in conclusion, we present the final product.

A. Solar cell

Solar Cells used to implement TSPP have the datasheet shown in Table I. As can be seen in the table, TSPP is constituted by monocrystalline silicon solar cells with a maximum power of 200 mW for standard test conditions (Irradiance = 1000 W/m^2 and temperature of cells = 25^oC).

Voltage at maximum Power:	0.5V
Current at maximum Power:	400mA
Maximum Power:	200mW
Open circuit voltage:	0.59V
Short circuit current:	433mA
Area:	34.96 cm^2
Weight:	9.23g
Operation temperature:	-20 to 80^oC
Cell type:	Monocrystalline silicon
Company:	Conrad Electronic

TABLE I
Datasheet of solar cells used in experiments.

B. Reflector

The reflector used to concentrate the radiation in solar cells is made of two rectangular sections connected in one of the edges, forming a triangle, as shown in Fig.5.

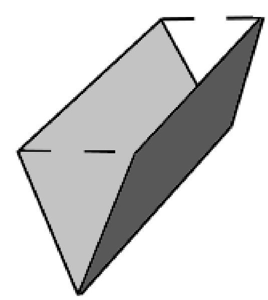

Fig. 5. Reflector with triangular shape geometry.

1) Aluminium foil: Aluminum foil has a high ability to reflect solar radiation. Its reflectance increases with the decrease of surface roughness and increase of the purity and rays wavelength. In visible wavelength range (400-700 nm), the reflectivity has values between 70% and 80%. It has 2 sections, each one with a length of 51cm and width of 27,5cm.

2) Aluminium: Aluminium is affected by the same factors than aluminium foil, like purity and solar rays wavelength. It has a reflectivity between 90 and 92,6% considering the visible spectrum light. Aluminium was chosen because of various reasons, namely its high reflectivity, low-cost, easy cleaning, acceptable durability and lightness.

It has 2 sections, each one with a length of 50 cm and width of 25 cm.

C. Receiver

The receiver is the component where solar cells are positioned. In total, there are eight cells in the receiver: four cells connected in series in the bottom part and four cells in series above. There are also four bypass diodes, with the model 1N4007, each one connected in antiparallel with two cells. The material used is transparent acrylic with length of 10 cm and width of 50 cm. The area occupied by 4 solar cells is 136,5 cm^2, which corresponds to 7,5x18,2cm.

D. Panel stand

Panel stand is used fundamentally to support the reflector, but has another features like:

- Regulate the aperture of the panel;
- Regulate the tilt.

These two factors have great influence in the concentration of energy on solar cells. Panel stand is made essentially of wooden slats and wing nuts to regulate the aperture, and of one iron rod and wing nuts to control the tilt of the panel. This structure can be seen in Fig.6.

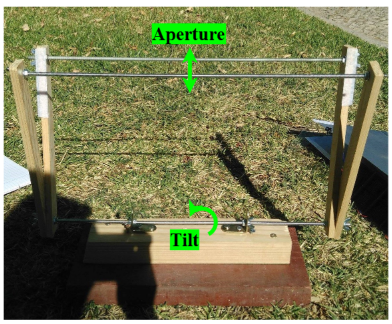

Fig. 6. Panel stand used to change the aperture and tilt of the panel.

E. Final Form

In conclusion, bringing together all the components, we obtain the triangular shape photovoltaic panel shown in Fig.7, with regulation of tilt and aperture, which allows a complete study of the triangular reflector and power collected on the panel.

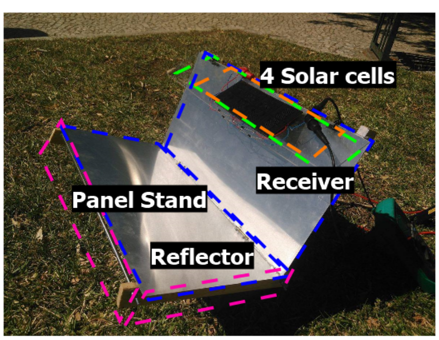

Fig. 7. Triangular shape photovoltaic panel, with regulated aperture and tilt.

IV. Triangular Shape Photovoltaic Panel - Experimental Evaluation

In this chapter, it will be experimentally analysed the potential of our proposal. We start by studying solar cells, individually and associated with another, for different conditions of irradiance and temperature, at laboratory and outside. Then, shading is studied and bypass diodes are used to analyse if it is possible to mitigate the effects of shading. Finally, we test the triangular shape photovoltaic panel explained in chapter III.

A. Behavior of solar cells for different conditions of irradiance, temperature and shading

The objective of this experiment consisted of determine the I-V and P-V characteristics and parameters of solar cells, individually and with four cells in series, as well as to observe its behavior for different conditions of irradiance, temperature and shading.

1) List of Materials:

- 3 multimeters (1 ammeter and 2 voltmeters): Center 120 RS-232;
- 2 solar modules with 4 solar cells in series;
- Temperature sensors: Center 306 Data Logger Thermometer;
- Solar irradiance meter: RS Pro ISM 400;
- 1 incandescent lamp of 60 W;
- 2 variable resistors.

2) Methodology: The method used to determine the I-V and P-V characteristic of solar cells was the one with a variable resistor. According to Fig. 2, it is a simple, faithful and economic way to obtain the desired results. The resistance was varied in steps from small to high values and the corresponding values of current and voltage were measured using, respectively, an ammeter in series and a voltmeter in parallel, to determine the curve from short circuit current to open circuit voltage. In laboratory experiments, the light source was 1 incandescent lamp of 60 W. Fig.8 shows the experimental setup.

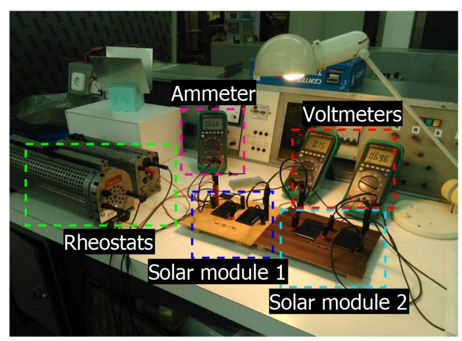

Fig. 8. Experimental setup used for experimental tests.

3) Results for 1 solar cell: The I-V and P-V characteristics of one solar cell were determined for different conditions of irradiance and temperature, as can be seen in Fig. 9. Three tests were made in laboratory, with irradiances of 49, 72 and 128 W/m^2.

It is possible to observe the typical I-V and P-V characteristics of a solar cell with illumination, as shown in Fig.1. We can realise that short circuit current increases with irradiance and open circuit voltage has a slight increase, which agrees with the theoretically expected in Fig. 3. Besides, for higher irradiances, we can observe higher values of maximum powers, as seen by P-V characteristics in Fig. 9. According

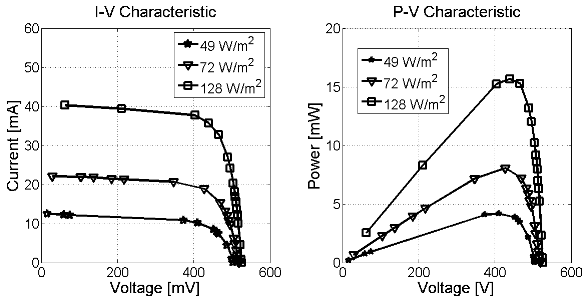

Fig. 9. I-V and P-V characteristics of one solar cell, for three different irradiances.

to Table II, all parameters tend to increase with irradiance, although FF and η had a small increase. For example, the value of maximum power is 4,2 mW for 49 W/m^2 and 15,7 mW for 128 W/m^2. In relation to electrical efficiencies obtained for one cell, they are close to the expected. For standard test conditions and using equation 3, the efficiency is 5,72%, and the values obtained in experiments are lower than 3,5%, for irradiances smaller than 128 W/m^2 (for 1000 W/m^2, the tendency is to obtain an efficiency with a value around 5,8 %). However, these values are far from the electrical efficiency expected of a monocrystalline cell: should be close to 20%.

Irradiance [W/m^2]:	49	72	128
Cell Temperature [^oC] :	27,5	29,1	31,4
I_{SC} [mA]:	12,5	22,3	40,6
V_{OC} [mV]:	504	519	526
I_{MP} [mA]:	10,2	18,9	35,7
V_{MP} [mV]:	410	428	439
P_{MP} [mW]:	4,2	8,1	15,7
FF [%]:	66,4	70,4	72,1
η [%]:	2,4	3,2	3,5

TABLE II
PARAMETERS OBTAINED FOR ONE SOLAR CELL, FOR DIFFERENT IRRADIANCES AND TEMPERATURES. THESE ARE EXPERIMENTAL RESULTS.

In order to compare the results with analytical methods and estimate solar cell parameters for other irradiances without needing to do new experiments, it was used a method called "3 parameters and 1 diode model" [9]. The different parameters of solar cell were calculated for 49, 128 and 987 W/m^2, as shown in Table III.

Irradiance [W/m^2]:	49	128	987
Cell Temperature [^oC] :	27,5	31,4	45
I_{SC} [mA]:	21,2	55,4	427,4
V_{OC} [mV]:	478,8	502,9	547
I_{MP} [mA]:	19,5	51,0	394,7
V_{MP} [mV]:	390,5	412,6	450,7
P_{MP} [mW]:	7,6	21,0	177,9
FF [%]:	74,9	75,5	76,2
η [%]:	4,4	4,7	5,2

TABLE III
PARAMETERS OBTAINED FOR ONE SOLAR CELL, FOR DIFFERENT IRRADIANCES AND TEMPERATURES. THESE ARE OBTAINED WITH "3-PARAMETERS AND 1 DIODE MODEL".

Comparing the values obtained experimentally with "3 parameters and 1 diode model" [9] (for irradiances of 49 and 128 W/m^2), we can see that the method used is reasonable. For example, for 128 W/m^2, V_{OC} obtained was 526 mV in experimental tests and 502,9 mV with "3 parameters and 1 diode model"; in relation to efficiency, in the first case was 3,5 % and in the second case 4,7 %. The differences can be a consequence of meteorological conditions and measurements of irradiance and temperature in the experimental activity, which are impossible to determine precisely, whereas "3 parameters and 1 diode model" is an ideal case. However, this method can be applied to have a general idea of the parameters.

4) Results for 4 solar cells connected in series - Effects of shading and bypass diode : In order to study the power generated by 4 solar cells connected in series, as well as the effects of shading, I-V and P-V characteristics and solar parameters were determined for 0%, 25%, 50% and 75% shading, with and without bypass diodes connected to the cells. In tables IV and V, it should be noted the huge decrease from the case where there is not shading to the case with shading. For example, without shading, the short circuit current reaches a value of approximately 380,8 mA against 54 mA of the case with 25% shading and with bypass and 23 mA of the case without bypass. Besides, efficiency is also much bigger without shading (3,26 against 0,25%). From Fig. 10, it is possible to observe that bypass diodes bring advantages to the panel because they enable to obtain higher currents and powers, mainly for small voltages, as expected. However, this does not happen for 75% shading, because a high area of cells is shaded and therefore bypass diodes practically do not have influence. To conclude, efficiency seems to be affected by these devices only for 50% shading.

Shading [%]:	0	25	50	75
Irradiance [W/m^2]:	879,5	850	700	580
Cell Temperature [^oC] :	56	53	47	43
I_{SC} [mA]:	380,8	23	21	12,35
V_{OC} [mV]:	2156	2084	2085	1995
I_{MP} [mA]:	233	19,2	10,94	7,41
V_{MP} [mV]:	1720	1530	1983	1472
P_{MP} [mW]:	400,76	29,38	21,69	10,91
FF [%]:	48,81	61,29	50	44,27
η [%]:	3,26	0,25	0,18	0,13

TABLE IV
PARAMETERS OBTAINED FOR 4 SOLAR CELLS CONNECTED IN SERIES, FOR DIFFERENT SHADING CONDITIONS. THESE TESTS WERE DONE WITHOUT BYPASS DIODES.

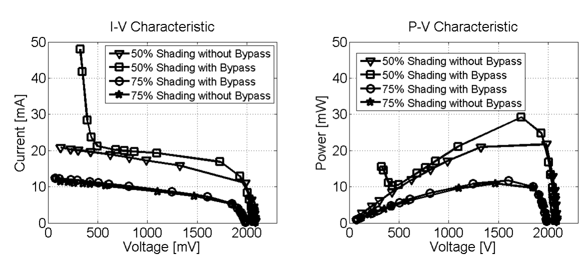

Fig. 10. I-V Characteristic of 4 solar cells in series, for different shading conditions and with and without bypass diodes.

Shading [%]:	25	50	75
Irradiance $[W/m^2]$:	850	700	580
Cell Temperature $[^oC]$:	54	49	47
I_{SC} [mA]:	54	48	12,35
V_{OC} [mV]:	2129	2077	2077
I_{MP} [mA]:	19,4	16,87	7,29
V_{MP} [mV]:	1526	1731	1602
P_{MP} [mW]:	29,60	29,20	11,68
FF [%]:	25,75	29,29	45,49
η [%]:	0,25	0,30	0,14

TABLE V
PARAMETERS OBTAINED FOR 4 SOLAR CELLS CONNECTED IN SERIES, FOR DIFFERENT SHADING CONDITIONS. THESE TESTS WERE DONE WITH BYPASS DIODES.

B. Testing Triangular shape photovoltaic panel

The objective of this experiment consists of study the TSPP proposed in chapter III, determining the I-V and P-V characteristics and the different parameters which characterize solar cells, like efficiency and maximum power. It is intended to analyze the behavior of TSPP with tilt of 30^o and an aperture of the panel equal to 45^o, for a reflector made of aluminium and a experimental setup as shown in Fig.11.

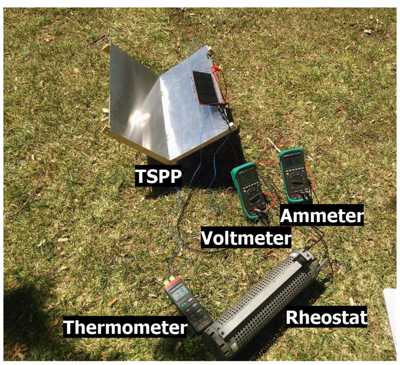

Fig. 11. Experimental setup used for experimental tests.

For that purpose, first, I-V and P-V characteristics and the power generated by the cells were measured throughout the day 26th July, for both upper and bottom parts of the panel. In Fig. 12, we can observe some of those characteristics, namely, for 16h05 and 17h05, which correspond to irradiances of 850 W/m^2 and 738 W/m^2, respectively.

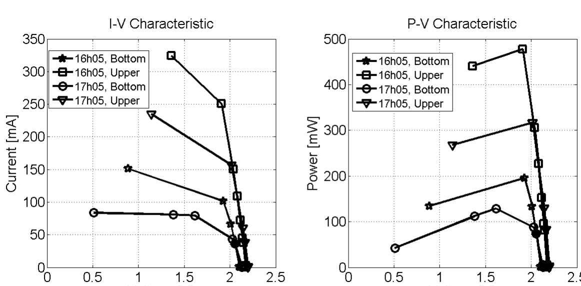

Fig. 12. I-V and P-V Characteristics throughout the day 26th July, for tilt of 30^o and aperture of 45^o.

From tables VI and VII, it is possible to see the differences between upper and bottom parts. We had, for example, a

Hour:	12h05	15h30	16h05	17h05
Irradiance $[W/m^2]$:	980	907	850	738
Cell Temperature $[^oC]$:	39	55	49,5	46,8
V_{OC} [mV]:	2203	2165	2176	2196
I_{MP} [mA]:	309,7	364,3	250,5	157
V_{MP} [mV]:	1800	1478	1907	2017
P_{MP} [mW]:	557,4	538,4	477,7	316,7
η [%]:	4,07	4,25	4,02	3,07

TABLE VI
PARAMETERS OBTAINED FOR MEASUREMENTS MADE AT DIFFERENT HOURS OF THE DAY 26TH JULY AND IN THE UPPER PART OF THE PANEL.

Hour:	12h10	15h25	16h10	17h10
Irradiance $[W/m^2]$:	980	907	850	738
Cell Temperature $[^oC]$:	39,5	48	52,2	46,8
V_{OC} [mV]:	2159	2151	2107	2129
I_{MP} [mA]:	186,6	134,6	101,3	79,5
V_{MP} [mV]:	1920	1962	1926	1615
P_{MP} [mW]:	358,3	264,1	195,1	128,4
η [%]:	2,61	2,08	1,64	1,24

TABLE VII
PARAMETERS OBTAINED FOR MEASUREMENTS MADE AT DIFFERENT HOURS OF THE DAY 26TH JULY AND IN THE BOTTOM PART OF THE PANEL.

maximum power of 477,7 mW in the upper part and 195,1 mW in the bottom part, for an irradiance of 850 W/m^2. The efficiency was 4,02% in the first case and 1,64% in the second, which corresponds to a ratio of 2,45 between upper and bottom parts. This is a lower value comparing, for example, with a reflector made of aluminium paper (it was obtained a minimum ratio of 3,88).

V. TRIANGULAR SHAPE PHOTOVOLTAIC PANEL - COMPUTATIONAL EVALUATION

In this chapter, we make an evaluation of the potential of Triangular Shape Photovoltaic Panel. The main objectives are the following:

- Simulate the trajectory of solar rays inside the TSPP, for different hours and days of the year, latitudes, tilts and apertures;
- Determine the power in the receiver, either in top and bottom sides, for the same factors stated before;
- Compare the power collected with another reflectors;
- Make a comparison with experimental results.

A. SolTrace

The computational evaluation of the trajectory of solar rays and power received on the panel was done with the help of SolTrace. SolTrace is a software tool developed at the National Renewable Energy Laboratory (NREL) to model concentrating solar power optical systems and analyze their performance. The code utilizes a ray-tracing methodology (Spencer and Murty, 1962). The user selects a given number of rays to be traced. Each ray is traced through the system while encountering various optical interactions. Some of these interactions are probabilistic in nature, while others are deterministic. The handling of reflection and refraction at surface interfaces is calculated using the well-known Fresnel equations [1].

B. Panel Design

TSPP was designed in SolTrace with maximum similarity to reality, not only in geometry, but also in optical properties and dimensions.

First, the two parties of the reflector were designed with 25cm width and 50cm length: the same dimensions than TSPP built for the experimental tests. These two rectangles were arranged in a way that originates a union between two edges (one of each part of the reflector), forming an angle of 45^o with the perpendicular to surface.

Second, the receiver. The area considered for this component corresponds to the area of solar cells (7,5x18,2cm), because it is the area where it is generated energy. The TSPP designed in SolTrace can be seen in Fig.13.

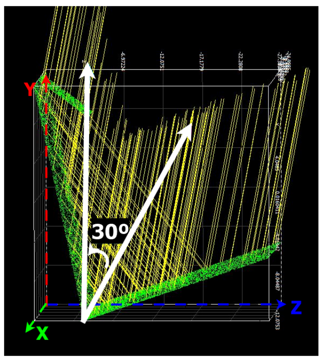

Fig. 13. Triangular reflector designed in SolTrace, with tilt of 30^o and aperture of 45^o.

Third, we have also interest in changing the tilt of the panel, because the power generated depends on this factor. To do so, it is necessary to appeal to Aim Point coordinates, which will allow to define the tilt of the panel according to the following relation:

$$z = -y \cdot tg\theta \tag{4}$$

Next, concerning the optical properties of materials, we considered a reflectivity and transmissivity of 0 to the receiver and 0,90 and 0 to the reflector, because the last one is made of aluminium, as previously seen.

Finally, with SolTrace, it is possible to change parameters related to sun positioning and with big influence on the power collected, like latitude, the day of the year, solar hour, Sun Shape Profile and DNI (direct normal irradiance). These parameters are variable and will be used to do tests with different conditions. Irradiance changes according to the place, day and hour. It was neglected the existence of meteorological aspects.

C. Results

In order to test the triangular shape photovoltaic panel in SolTrace, upper, bottom and total powers on the receiver have been calculated, for the following conditions and situations:

- Different tilts of the panel;
- Different months and same tilt;
- Different latitudes and same tilt;
- Comparison with a different reflector;
- Comparison with experimental results.

1) Different tilts of the panel: Tests began with the calculation of the power for different tilts of the panel, keeping the local hour of the day in twelve p.m., choosing summer and winter solstices, an aperture of 45^o and the latitudes of Lisbon (IST) and Gavle (Solarus).

We could observe that in the summer solstice the optimal tilt is around 40^o in Lisbon and 50^o in Gavle. In relation to winter months, the biggest values of power are obtained both for 90^o. We could also note that there are tilts in the panel where the power of the bottom part of the receiver is bigger than the upper part.

2) Different months and same tilt: In this test, it was calculated the power for different months. The process was repeated once every 30 days, beginning in twentieth day of the year and keeping the optimal tilts of 40^o for Lisbon and 50^o for Gavle. The local hour of the day was kept in twelve p.m. In Fig.14, it is possible to observe that the power collected in Lisbon is higher than Gavle, during the whole year.

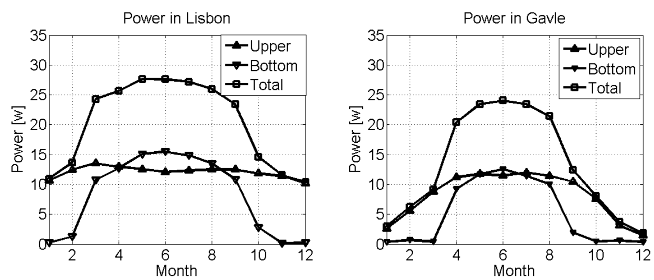

Fig. 14. Power collected on the receiver, for different months and same tilt.

3) Different latitudes and same tilt: In this test, power was calculated for different latitudes. Day, hour, longitude, tilt and aperture remained constant. We could observe in Fig.15 that, in summer solstice, for a tilt equal to 40^o, the power collected in the bottom part of the receiver is bigger than the upper part for latitudes of 30, 40 and 50^o, and the reverse happens for the remaining latitudes. The maximum total power is 25,4 mW and is reached for a latitude of 40^o. By observing the power for a tilt of 10^o, we can see a very similar variation of power with latitude than the case of 40^o. However, the maximum power was achieved in a different latitude: 10^o. We can therefore conclude that, when we change the tilt of reflector, there is a shift in the curve of power-latitude. Besides, for a certain value of tilt, the maximum total power is achieved for a latitude with the same value, in summer solstice. In December, to obtain the optimal tilt we must add 50^o to the value of latitude.

4) Comparison with a different reflector: In order to know the potentialities of triangular reflector, it is also necessary to compare its performance with other types. Therefore, a parabolic concentrator was simulated in SolTrace with the same dimensions of receiver and half of the area of reflector. In Fig.16, we can see a comparison for different months, using the best tilts of parabolic (10^o) and triangular reflector (40^o). We can conclude that the total power generated by triangular reflector is higher than parabolic reflector between March and September, basically, in Spring and Summer. For the same area

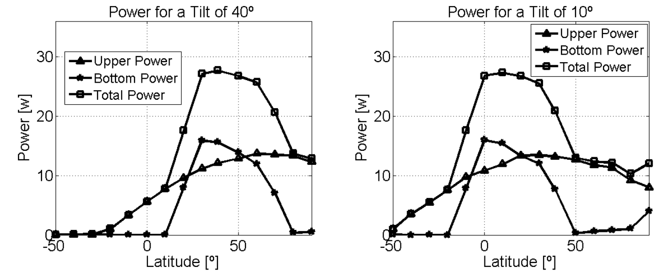

Fig. 15. Power collected on the receiver, for different latitudes. Day: 173; Local Time: 12h; Longitude: $-9,14^o$; Tilt: 40^o; Aperture: 45^o.

of aluminium, total power collected by triangular reflector is greater than parabolic during 4 months of the year, according to tests conducted.

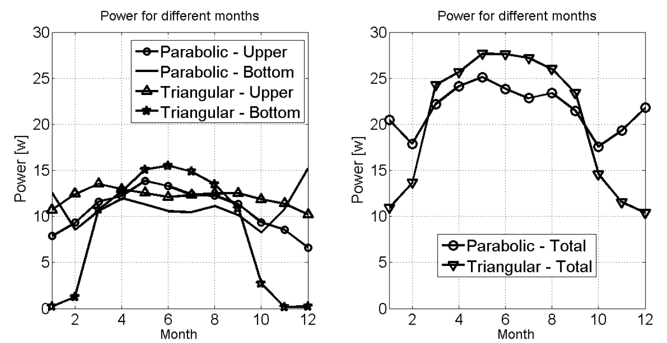

Fig. 16. Power collected on the receiver, for triangular and parabolic reflectors, in Lisbon, for different months.

5) Comparison with experimental results: Next, it was intended to do a comparison between experimental results and SolTrace. Therefore, experimental maximum power for each hour was compared with the power collected obtained with SolTrace, in same conditions (tilt = 30^o; aperture = 45^o; 26th July; day 207; Lisbon: longitude = -9.13^o and latitude = 38.72^o). The area considered for the receiver to make experimental and SolTrace tests was the same and it was equal to 139,84 cm^2, that corresponds to the area of 4 solar cells connected in series.

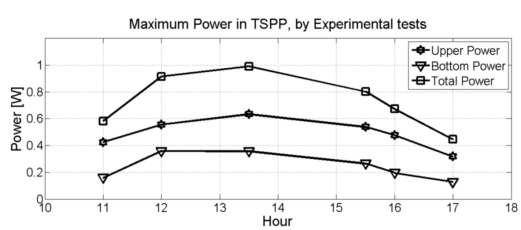

Fig. 17. Maximum Power in TSPP, by Experimental tests.

From Fig.17 and Fig.18, we could observe that power has different values between SolTrace and experimental tests. This is because powers are not the same: first one corresponds to the power collected on the receiver and the second to the electric power generated by solar cells. Second, it is possible to see that upper power curves are almost equal in the two cases, having a maximum power around 13h30. These results

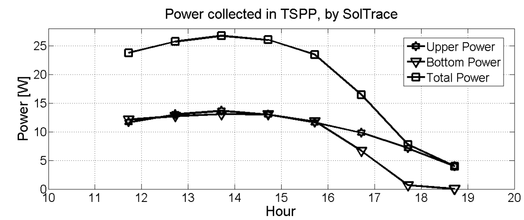

Fig. 18. Power collected in TSPP, by SolTrace.

give some credibility to the methodology used in SolTrace and experimental tests. In relation to the power in the bottom part of the receiver, the situation is different: experimentally, it should be higher and closer to upper power between 12 and 16 hours. This difference happens mainly due to the ideal case of Soltrace, by contrast with experimental tests. In Soltrace, weather conditions are not considered. Besides, a slight shading and a non-uniform distribution of solar radiation originated by reflector may have occurred, experimentally, on the bottom part of the receiver, which causes a reduction of power generated. To conclude, the ratios between experimental and Soltrace powers were estimated, as seen in Table VIII.

Normal Hour:	12h10	15h30	16h05	17h05
Exp. Upper Power [mW]:	557	538	478	317
Exp. Bottom Power [mW]:	358	264	195	128
SolTrace Upper Power [W]:	12,0	11,6	11,0	9,5
SolTrace Bottom Power [W]:	12,1	11,8	10,5	6,6
Upper ratio [%]:	4,64	4,64	4,34	3,33
Bottom ratio [%]:	2,96	2,24	1,86	1,95

TABLE VIII
RATIOS BETWEEN EXPERIMENTAL AND SOLTRACE POWERS.

It is interesting to note that the ratios obtained are very similar to the efficiencies stated in tables VI and VII. For example, in the bottom part of the panel, for 16h10, the efficiency achieved is equal to 1,64% using equation 3 and 1,86% dividing experimental bottom power by SolTrace bottom power, as seen in Table VIII. In fact, this makes sense because efficiency of the panel is equal to the electric power generated by solar cells (experimental upper power) divided by the power collected in the receiver (Soltrace upper power). Therefore, we have another method to obtain efficiency of solar cells.

VI. CONCLUSION

Solar cells were studied, step by step, until obtain triangular shape photovoltaic panel. Therefore, overall conclusions were achieved not only about the main proposal but also before its construction. First, the method used to obtain I-V and P-V characteristics consisted of using a variable resistor, which is simple, economic and reliable. For small irradiances, this method worked very well and it was possible to determine I-V and P-V characteristics like expected theoretically. For greater values, it is necessary to use several rheostats in parallel to support higher values of current.

Second, solar cells parameters changed as expected theoretically. In general, all parameters increased with irradiance. In relation to electrical efficiencies obtained for solar cells, they are close to the expected, but far from the electrical efficiency of a monocrystalline silicon cell: should be close to 20%.

Third, it was observed the shading effects on solar cells. For example, for the case of 4 solar cells in series there was a big reduction of values of current and voltage from 0 to 25% shading, then, the values were almost constant to 50% of shading, having again a big reduction to 75% shading. This is explained by the partial and total shading of solar cells.

Fourth, we could observe the advantages of bypass diodes in case of shading. When solar cells are not shaded, bypass diode is off, but when some cells have shading, the voltage across the diode is positive, this device is on and the current can run through. This resulted in higher currents in the case with bypass diode, mainly for small values of voltage, and it was observed a step in the graph, which agrees with the expected theoretically. It was also seen that efficiency and maximum power are affected by bypass diodes only for 50% shading. For values of shading of 75%, these devices practically do not have influence in the power generated because the shaded area is too high.

Fifth, we could confirm that a triangular reflector made in aluminium is a fair concentrator of radiation because the ratio between upper and bottom powers of the receiver is around 2,45, in other words, the powers are not so different. To improve reflectivity and consequently the power collected in the bottom part of the receiver, it could be used another material with better reflectivity like tinplate. However, aluminium was chosen because it has high reflectivity, reduced cost, acceptable durability, is lightweight and easily cleaned.

Sixth, we could conclude that some meteorological and geographical factors affect the power collected by solar cells: irradiance, latitude, day and hour. Irradiance is the power of the radiation incident on the surface; latitude, day and hour are related with the position of the sun and consequently with the ray's trajectory. Besides, there are two factors of the panel which influence the power collected: tilt and aperture of the reflector. Therefore, it was constructed the main proposal of this thesis: triangular shape photovoltaic panel (TSPP). With this panel, it was possible to change freely the tilt and aperture and compare with SolTrace results.

Seventh, some conclusions about TSPP were made using SolTrace. Power collected by TSPP during the year is higher in Lisbon than Gavle, this considering an aperture of 45^o and tilt for maximum power in summer solstice, which is 40^o in Lisbon and 50^o in Gavle. Next, in respect to latitude, we can conclude that triangular shape photovoltaic panel reaches its maximum value of power for a tilt equal to the value of latitude, in summer solstice. In December, to obtain the optimal tilt we must add 50^o to the value of latitude. Moreover, comparing triangular reflector with a parabolic reflector, in Lisbon, it is possible to conclude that the first one reaches higher values of power than the second one for certain months of the year. This shows the potential of triangular reflector because, with great simplicity, it allows to obtain higher powers than the parabolic, which is more complex.

Finally, experimental tests validate SolTrace results. Upper powers for different hours of the day have similar curves. Bottom powers are different, which happens mainly due to the ideal case of SolTrace, by contrast with experimental tests. In SolTrace, weather conditions are not considered. Besides, a slight shading and a non-uniform distribution of solar radiation originated by reflector may have occurred, experimentally, on the bottom part of the receiver, which causes a reduction of power generated. To finish, ratios between experimental and SolTrace powers have shown an agreement with electrical efficiencies. In fact, this makes sense because efficiency is equal to the electric power generated by solar cells (Experimental power) divided by the power collected on the receiver (Soltrace power).

A. *Future work*

In the future, it would be interesting to study triangular shape photovoltaic panel with respect to the following topics:

- Analyse another materials to reflect and collect solar energy, like tinplate and silver, in order to improve the power generated by the panel;
- Compare triangular reflector with another reflectors apart from parabolic, like MaReCo of Solarus, with respect to the power collected for different tilts and months;
- Analyse triangular reflector not only to generate electricity but also to heat water, transforming it in a PVT collector;
- Expand the triangular shape photovoltaic panel, concerning the dimensions of reflector and number of cells, and determine the generated power;

References

[1] T.Wendelin, A.Lewandowski, and A.Dobos, "Soltrace," 2012. National Renewable Energy Laboratory (NREL).

[2] Solarus, "Solarus," 2017. URL http://www.solarus.com/. Last checked: Oct 2017.

[3] J.Fernandes, J.Torres, P.Branco, and C.Fernandes, "Analysis of a concentrating photovoltaic and thermal hybrid collector (c-pvt): Laboratory number 4 and 5," tech. rep., Instituto Superior Técnico, 2017. Last checked: Oct 2017.

[4] Doityourself, "6 ways to improve solar cell efficiency," 2017. URL http://www.doityourself.com/stry/6-ways-to-improve-solar-cell-efficiency. Last checked: June 2017.

[5] RenewableEnergyWorld, "Solar cell efficiency round-up: Thin film closing the gap with silicon," 2013. Last checked: June 2017.

[6] S. K. Nashih, "Stationary solar concentrating photovoltaic thermal collector cell string layout," tech. rep., Instituto Superior Técnico, 2015. Last checked: May 2017.

[7] Electrical4u, "P-n junction theory behind p-n junction," 2016. URL https://www.electrical4u.com/p-n-junction-theory-behind-p-n-junction/. Last checked: June 2017.

[8] Seawardsolar, "Curve tracing faqs," 2017. URL http://www.seawardsolar.com/userfiles/curve-tracing.php. Last checked: June 2017.

[9] R. Castro, *Uma Introdução às Energias Renováveis: Eólica, Fotovoltaica e Minihídrica*. IST Press, 2nd ed., 2013.

[10] E. Duran, M. Piliougine, M. Cardona, J. Galan, and J. M. Andujar, "Different methods to obtain the i-v curve of pv modules: A review," *Conf. Rec. IEEE Photovolt. Spec. Conf.*, 2008.

[11] D.Lenardic, "Solar cells characteristics," 2015. URL http://www.pvresources.com/en/solarcells/solarcells.php. Last checked: June 2017.

[12] L.A.Hecktheuer and A.Krenzinger, "Uso de díodos de bypass e de bloqueio na proteção de sistemas fotovoltaicos," tech. rep., Universidade Federal do Rio Grande do Sul, 2015. Last checked: May 2017.

[13] G. R. Energy, "Concentrating photovoltaics (cpv)," 2013. URL http://www.greenrhinoenergy.com/. Last checked: June 2017.