Optimal Design of the Reflector in a Concentrator Photovoltaic-Thermal System (CPV-T) for Sweden and Portugal

João Pedro Saraiva Ricardo

Instituto Superior Técnico, Lisbon, Portugal

***Abstract*— With the increasing concern about the effects of climate change and with the need of replacing fossil fuel's energy sources, investment in renewable energy sources is increasing, with emphasis on photovoltaics technologies. Concentrating photovoltaic energy is one solar technology that uses concentrator reflectors to increase the solar radiation incident on the photovoltaic modules. Example of this is the photovoltaic-thermal concentrator PowerCollector^{TM} developed by the company SOLARUS, that has a reflector with a MaReCo^{TM} (Maximum Reflector Concentration^{TM}) geometry, optimized for Sweden. The present work proposes the optimization of this reflector for four countries in different geographic locations (Portugal, Sweden, Mexico and São Tomé and Príncipe) and the comparison of their optimized performances with that of MaReCo$^{TM.}$ For this, an optical-electric model is developed that, given the geometry of the reflector (defined by a polynomial function), the panel inclination, irradiance and solar position, calculates the power received by the photovoltaic cells. With data referring to each country an optimization algorithm, NSGA-II, is used to optimize the panel inclination and the reflector polynomial parameters, to minimize its length and to maximize the energy absorbed by the photovoltaic cells. In sum, the MaReCo^{TM} geometry is the refletctor with smaller dimensions than the optimized solutions. The geometry optimized for Sweden can absorb more energy than the MaReCo^{TM} geometry (+6,7%) after one year.**

***Index Terms*— Concentrating Solar Technology, MaReCo^{TM}, Otimization, Reflector**

I. INTRODUCTION

With the continuous development and growth of human society, leads to an increase of energy demand. The excessive use of non-renewable energy, leading to the consumption of non-renewable resources and, typically to large amount of green-house gas emissions, has been prejudicial to out ambient. One solution to reduce the dependence on these resources use of renewable energy sources to generate electrical energy.

The renewable energy directly related to solar radiation is the photovoltaic/thermal energy. The conversion from solar energy to electricity is done through solar photovoltaic technology that, through photovoltaic cells exposed to light, produce an electric voltage. The technologies of photovoltaic cells have been developed to improve its relationship between energy efficiency and price. Concentrated photovoltaic energy is a variant of photovoltaic energy which concentrate solar radiation in photovoltaic cells using a reflector.

SOLARUS, a Swedish company, relied on concentrated photovoltaic thermal collector technology (CPVT) to develop its PowerCollector^{TM}. Its structure has bilateral symmetry, consisting of a collector with two identical halves, each with a pair of photovoltaic panels, a concentrator and eight channels where the fluid responsible for cooling the cells circulates. This concentrator has a parallelepiped shape with 1054x2444x241 mm of dimensions (width x length x height) and 152 monocrystalline silicon photovoltaic cells. Of these cells 76 are directly arranged for solar, while the remaining 76 are arranged below the previous ones, in order to receive the solar irradiation reflected from the concentrator.

The reflector of the SOLARUS CPVT system has a MaReCo^{TM} (Maximum Reflector Concentration^{TM}) geometry. The MaReCo^{TM} shape can be considered as asymmetrical parabolic trough, where the reflector is an aluminum mirror that concentrates solar radiation of the entire lower photovoltaic panel. As in most of this type of concentration systems, the concentration factor of PoweCollectorTM is relatively low, allowing the concentration of irradiation even in days with high diffuse irradiation [1].

This paper is organized into 5 sections, the first one is the introduction of the reflector PowerCollector^{TM} design by SOLARUS and its reflector MaReCo^{TM}. In the second section the optical-electric model developed to simulate the reflector's geometry performance is explained in detail.

In the third section addresses the optimization algorithm used in this work. The results of the optimizations can be found in section IV. In the fifth of section are shown the conclusions.

II. OPTICAL-ELECTRIC MODEL

The optical-electrical model was programmed in MatLab, to simulate the performance of the panel with a generic concentrator geometry, for a given specific position of the Sun and orientation of the panel. The evaluation of its performance is on the ability of the concentrator to reflect the greatest amount of solar energy to the solar cells, per unit length. The panel consists of photovoltaic cells arranged on the upper and lower surfaces of a collector, the first being directly affected by solar irradiation and the lower being affected by reflected rays from the reflector placed below the collector.

The sun position, the panel inclination (tilt) and the solar irradiance are input variables of the model, defining the direction and intensity of the solar rays. The developed model allows the determination of the reflections of the solar rays in the reflector (red line in **Erro! A origem da referência não foi encontrada.**) and to count the rays that reach the photovoltaic cells (the superior and the inferior ones, separately). If a reflected beam does not reach the solar cells, it may be directed out of the concentrator or reaching another point of the reflector. Thus, the optical-electric model should consider the calculation of multiple reflections of solar rays (**Erro! A origem da referência não foi encontrada.**). Due to the multiple possibilities of reflections and the possibility of the reflected radiation reaching or not the solar cells, a flowchart was constructed that represents all possible paths to the problem (figure 1). It starts by identifying if the randomly generated function for the reflector is valid (it has two zeros and if it has the concavity upwards). If it is valid, *N* solar rays will be generated taking into consideration the inclination of the panel and the solar position. For each ray, an iterative cycle is implemented, which can be described by the following steps: 1) if the reflected ray reaches the solar cells, the energy that the ray has is counted and passes to the next ray, 2) if not, it is verified if it reaches the reflector again and if so, a new reflected ray is defined, 3) this process is repeated until the resulting rays reach the solar cells or leave the concentrator's domain.

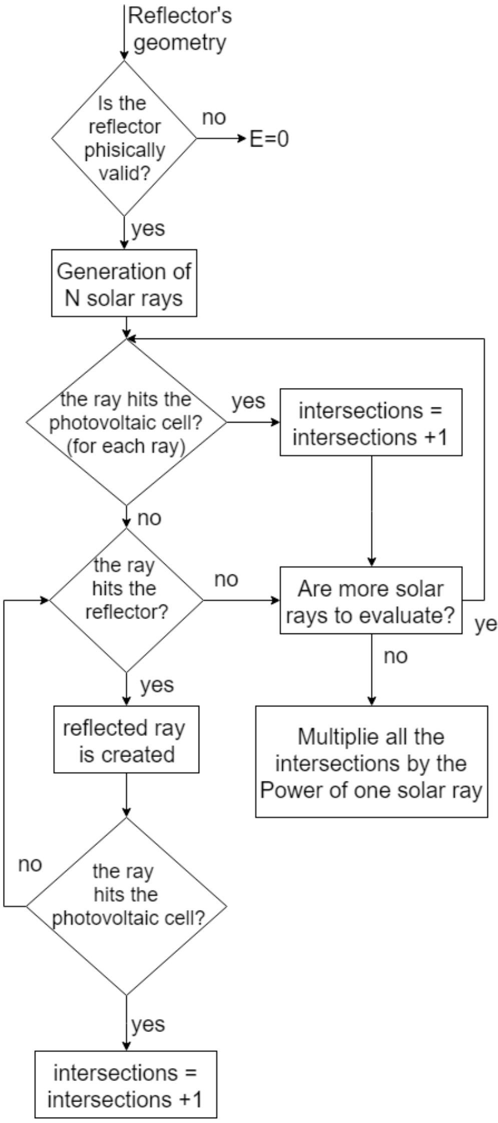

figure 1-flowchart of optical-electric model

A. Reflector

The reflector is defined in a *xz* plane and by a polynomial function of degree 10, *(1)*, where X_0 to X_{10} are the coefficients relative to the degree of each polynomial. This function, which defines the geometry of the reflector, is randomly generated by an optimization program. After the random generation of the function, it will be analyzed from its physical point of view and will only be accepted as reflector geometry if it is validated. For the geometry to be valid, a set of constraints must be considered: it will only be considered valid if it has two zeros, $f(x_{min}) = 0$ and $f(x_{max}) = 0$, and if its concavity is up, $f''(x)>0$, between x_{min} and x_{max}.

$$f(x) = X_{10}.x^{10} + X_9.x^9 + (\dots) + X_2.x^2 + X_1.x + X_0 \qquad (1)$$

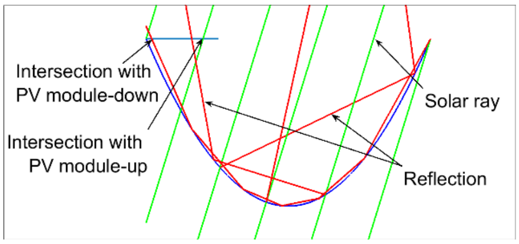

figure 2-General fuction of the model

The reflector has an opening of 1 meter, with the photovoltaic cells occupying 1/4 of this opening and with a reflection factor equal to 1 (figure 3). The reflector aperture and the photovoltaic cell will be at the origin of the *zz* axis. An example of a valid reflector is the MaReCo^{TM} geometry, where all constraints are respected.

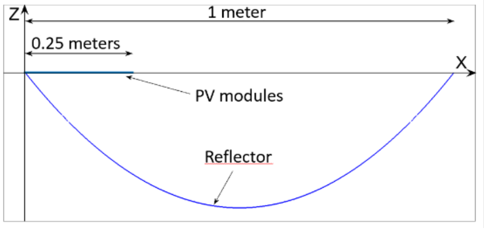

figure 3-reflector and PV modules dimensions

B. Solar Radiation

Irradiance and solar position are directly linked to the final energy absorbed by the photovoltaic cells. The irradiance that reaches the surface of the planet is different during the days of the year and can be described by equation *(2)*. In this, G_r represents the constant solar radiation, per unit area, in a plane perpendicular to the propagation of the radiation outside the atmosphere and its average value is 1000W/m^2, and *n* is the number of the day in the year as for example, the 1st day of February is the 32nd day of the year.

$$G = G_r\left(1 + 0.033\cos\left(\frac{360º \times n}{365}\right)\right) \qquad (2)$$

G is defined as the irradiance that reaches the surface of the Earth in a plane perpendicular to the direction of propagation, without considering the losses in the atmosphere or those by diffusion (all irradiance is considered direct). In order to reduce the computing time of the model, it was considered that each month is represented by its day 21, that is, that the time profile of the irradiation, temperature and solar position of that day is the same for all the rest of that same month. The solar position relative to the reference geometric point is defined by the azimuth, γ, and by the solar altitude, α_s. The azimuth is the angle of the horizontal projection of the Sun on the surface of the Earth, being 0 in the South, and positive to the west. This value varies between -180 and 180 degrees. Solar altitude is the angle between the orientation of solar radiation and the Earth's surface and can take values between 0 and 90 degrees.

It is necessary to apply a transformation from spherical coordinates to cartesian ones in order to project the solar rays in this plane. The solar position, in spherical coordinates, is defined by azimuth and solar altitude. The transformation of coordinates for the *xz* plane is represented in the system of equation *(3)*.

$$\begin{cases} z = sin(\alpha_s) \\ x = cos(\alpha_s) \times cos(\gamma) \end{cases} \qquad (3)$$

The solar angle in *xz* plane, α, in degrees is given by equation *(4)*.

$$\alpha = \tan^{-1}\left(\frac{z}{x}\right) \qquad (4)$$

If the panel is tilted with an angle, θ_t it is necessary to adjust the solar radiation model with a rotation along the *yy* axis, resulting in new values of coordinates x' and z'. figure 4 illustrates the adjustment of the solar position due to the inclination of the panel.

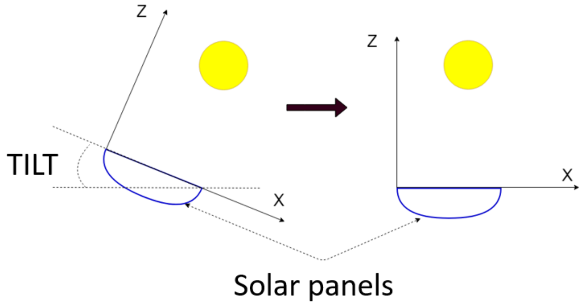

figure 4-Adjustment of solar position

The intensity of the irradiance that reaches the panel, projected under the *xz* plane, G_{panel} depends on the x and z coordinates, as described in equation *(5)*.

$$G_{panel} = G \times \sqrt{x^2 + z^2} \qquad (5)$$

The power per ray, P_{ray}, can be calculated through *(6)* ***Erro! A origem da referência não foi encontrada.***, where α is the solar angle in the *xz* plane and *N* is the number of rays defined in the model for calculating the intersection with solar cells. The number *N* is a parameter of the model, and in this study was considered *N*=100. This number of rays is high enough to obtain quality results, in a sufficiently low computing time.

$$P_{ray} = \frac{Gpanel \times \sin(\alpha)}{N}\ [W/m] \qquad (6)$$

For all solar geometries and angles, the number of rays intersecting on the panel is the same: the first ray intersects the panel at the first zero while the hundredth ray reaches the second zero of the reflector, the remaining rays are evenly spaced. In figure 5 this distribution is exemplified, for *N*=10, to facilitate its visualization.

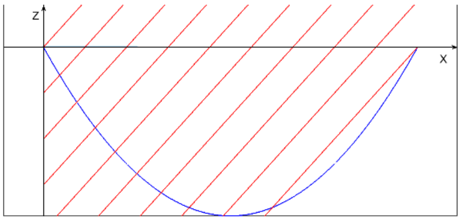

figure 5-Example of solar rays' distribution

After the computation (figure 1) the model will count the number of intersections in the PV modules, N_{hit}, and calculate the power that was absorbed by the PV cells, $P_{absorbed}$.

$$P_{absorvida} = P_{raio} \times N_{hit}\ [W/m] \qquad (7)$$

C. Model Validation

With SolTrace program it was possible to validate the developed model. The verification was made for solar angles between 10 and 80 degrees, comparing the quotient between the number of intersections in lower cells, N_b, and the number of intersections in upper cells, N_s, (8). This ratio, called concentration factor (*CF*), is an important factor in the definition of concentrating photovoltaic panels and it was used to validate the model. As the generation of rays in SolTrace is made through the method of Monte Carlo, implying a high number of rays to ensure a uniform distribution, in order to reduce the random effect of Monte Carlo, the number of rays used in SolTrace was 100,000, being compared with the developed model with 1,000 rays. The geometry chosen for the model validation was a parabola. In table 1 and table 2 are listed the concentration factor values for different solar angles and with variation of the panel inclination, respectively. By analyzing the tables, we can conclude that the model has results very similar to those of SolTrace, with errors lower than 8.2%, thus validating the model developed.

$$CF = \frac{N_b}{N_s} \qquad (8)$$

table 1-Validation of the model with solar angle variation

	Soltrace			Modelo			Relative error [%]
α [º]	N_b	N_s	CF	N_b	N_s	CF	
10	19770	6616	2,988	749	250	2,996	0,3
20	10418	10662	0,977	244	250	0,976	0,1
30	46	13319	0,003	0	250	0	-
40	51	15534	0,003	0	250	0	-
50	8473	17473	0,484	119	250	0,476	1,7
60	17532	19346	0,906	208	250	0,832	8,2
70	30071	25030	1,201	293	250	1,172	2,4
80	36597	25173	1,453	367	250	1,468	1,0

table 2-Validation of the model with tilt variation

	Soltrace			Modelo			Relative error [%]
$Tilt$ [º]	N_b	N_s	CF	N_b	N_s	CF	
15	12951	18425	0,703	173	250	0,692	1,6
25	42	14485	0,003	0	250	0	-
35	3817	16509	0,231	56	250	0,224	1,6
45	4530	11999	0,378	93	250	0,372	1,6
55	21288	20030	1,063	257	250	1,028	3,3

III. OPTIMIZATION ALGORITHM

The objective of this work is to optimize the geometry of a concentrator solar panel reflector to maximize the energy received by the photovoltaic cell and minimize its length. As described in the previous section, in the developed model the reflector is defined by a polynomial degree 10. The purpose of the optimization algorithm is to find the best coefficients of this polynomial, leading to the maximization of the energy received per unit length. The NSGA-II (Non-dominated Sorting Genetic Algorithm II) [2] algorithm was used due to the experience of the supervisor group with this algorithm. It starts by generating a population of elements that are individually characterized by an individual genetic code, represented by the value of the decision variables. After analyzing the objective functions, the algorithm uses an elitism process to select the best solutions and through genetic operations, such as *cross-over* and *mutation*, generates a new generation of individuals from the selected individuals of the previous generation. The *cross-over* process consists on using the genetic code of two individuals, called "parent individuals", and generating two new "child individuals" with a genetic code similar to the two "parents". This process is done randomly. The mutation process makes small changes to the values of the genetic code with a certain probability and in a random way. The best elements of each generation are combined with each other and with those of the next generation so that the best characteristics are always preserved. Figure 20 shows the flowchart of the optimization algorithm. The "developed model" block represents the optical-electric model that allows to calculate the objective functions of each geometric solution.

The decision variables are the polynomial coefficients that define the reflector and the inclination of the panel, in total there are 12 decision variables. The limits of the decision variables were calibrated through tests to calibrate the model, Table 3.

table 3-Decision variables and their limits

Decision Variables	Tilt	Reflector		
		X_0	X_1 e X_2	X_3 a X_{11}
minimum	0	-100	-10	-1
maximum	60	100	10	1

After simulating the electric-optimal model with the reflector specifications and inclination of the panel, the objective functions are analyzed. The first objective function is the maximization of the energy received by the photovoltaic cells.

The energy received is calculated by the power absorbed *(7)* in each hour, $\Delta t = 1h$. The second objective function is to maximize the form factor, which normalizes the length of the reflector in relation to its opening, causing its value to vary between 0 and 1. The higher the value of the form factor, the smaller the length of the reflector (figure 8). The maximization of uniformity was also analyzed in a case-study. This represents the relation between the amount of irradiation in two halves of the photovoltaic cells. In *(9)* it is possible to observe the equation of uniformity, where M1 represents the number of intersections in the first half of the cell and M2 represents the number of intersections in the second half of the cell. The uniformity value varies between 0 and 1, the higher its value the more uniform the irradiation along the cells will be. figure 7 shows an example of the calculation of uniformity. In *(10)* and *(11)* the objective functions used in the course of this work are defined. The number of generations and populations used in the optimizations were 100 and 120, respectively.

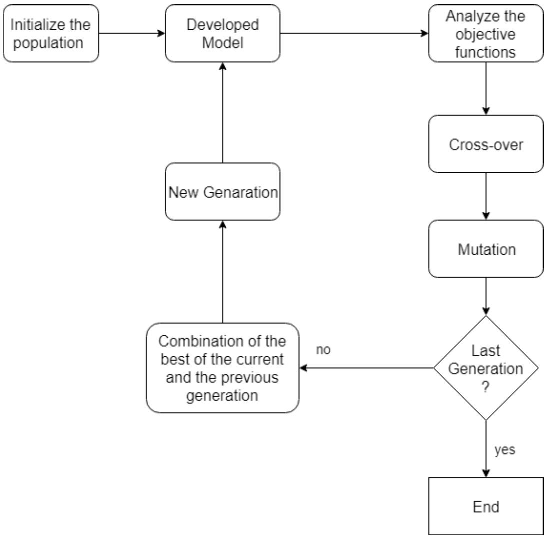

figure 6-flowchart of the optimization algorithm

$$uniformidade = \frac{min\{M1, M2\}}{max\{M1, M2\}} \qquad (9)$$

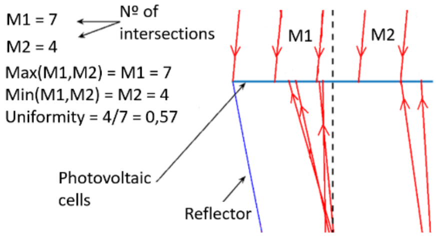

figure 7- Example of uniformity

$$f_1 = \begin{cases} máx\left\{E = \sum_{i=1}^{24} P\,.\,\Delta t\right\} \\ máx\left\{Fator\ de\ Forma = \dfrac{abertura}{comprimento}\right\} \end{cases} \qquad (10)$$

$$f_2 = \begin{cases} E = \sum_{i=1}^{24} P\,.\,\Delta t \\ máx\left\{Fator\ de\ Forma = \dfrac{abertura}{comprimento}\right\} \\ max\{uniformidade\} \end{cases} \qquad (11)$$

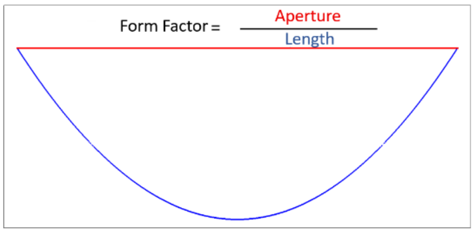

figure 8- Form factor

IV. OPTIMIZATION RESULTS

The results of the concentrator optimization were obtained for Portugal, Sweden, Mexico and São Tomé and Príncipe. The choice of these sites is due to their different geographical zones. Portugal and Sweden are in the northern temperate zone. Mexico and Sao Tome and Principe are respectively in the tropical zone and in the equator. All optimizations are for a period of a year.

All optimized reflector solutions are compared with the MaReCoTM geometry, which was designed to operate in Sweden.

The results were based on the solar position information available on the SunCalc platform. In order to reduce the calculation time of the model, each month was represented only by its twenty-first day, to coincide with the summer and winter solstices. For the 21st of each month, the solar altitude and azimuth values were recorded for each local time. The data were taken from the year 2018.

A. Portugal

In order to understand the optimal characteristics of the reflector for winter and summer, separate optimizations were made for a typical winter and summer day in Portugal. figure 9 shows the Pareto curves obtained for the maximization of the energy received by the solar cells and the minimization of their form factor. Being the main objective, the maximization of the energy received by the photovoltaic cells, the structure of the reflector is analyzed for the case of higher energy received. The points of higher energy correspond to an energy absorbed of about 6300Wh/m, for the winter, and 7190Wh/m, for the summer. The value of the form factor of the optimized geometry is 0.654 and 0.678 for winter and summer respectively. With similar shape factors, the reflector length is similar in winter and summer.

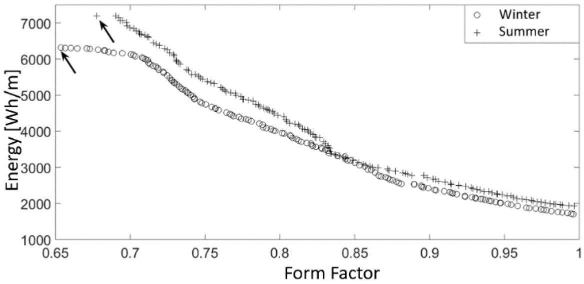

figure 9-Pareto curve for Summer and Winter in Portugal

figure 10 shows the Pareto curve for the maximization of the annually absorbed energy. Some optimization results present incoherent data, such as high energy values, but with a very reduced form factor, this means the length of the reflectors is much greater than the aperture of the panel. Therefore, the reflector indicated in the figure was chosen as the optimal point. This solution presents an annually absorbed energy value of 1,725MWh/m, for a form factor of 0,65 and with the panel inclined at 29º. The maximum energy absorbed by MaReCo^{TM} during the whole year in Portugal is 1,555 MWh/m, with the panel inclined at 5,0º. The optimized geometry for Portugal shows an increase of 10.9% in absorbed energy, when compared to the MaReCo^{TM}.

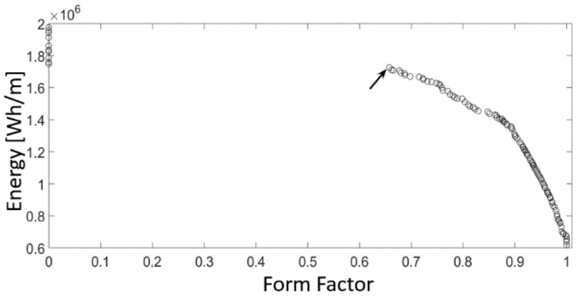

figure 10-Pareto curve of the optimization for Portugal

Another important aspect, besides the energy received and the form factor, is the uniformity of the radiation incident on solar cells. Uniformity is an important factor due to the influence of temperature on the electrical efficiency of solar cells and the creation of hot spots that can damage the cells. Zones with higher solar concentration will have higher temperature values and, consequently, lower electrical yield values. Therefore, an optimization was performed, now with an additional objective function: maximization of the uniformity of the solar irradiation in the cell. The results of the optimization, now with three objective functions, are presented in figure 11. These now form a Pareto plane. In figure 12 and figure 13 are presented two-dimensional views of the results, to facilitate their understanding. It is verified that it is possible to obtain the same energy with different uniformity values. For example, for the 1.7MWh/m, the uniformity varies between values close to 0.3 with a form factor close to 0.7, but for an energy of 1.6MWh/m the uniformity can reach values close to 0.8 with form factors slightly higher. In the analysis of a possible reflector solution it is important to take into consideration all the objective functions presented: energy, form factor and uniformity.

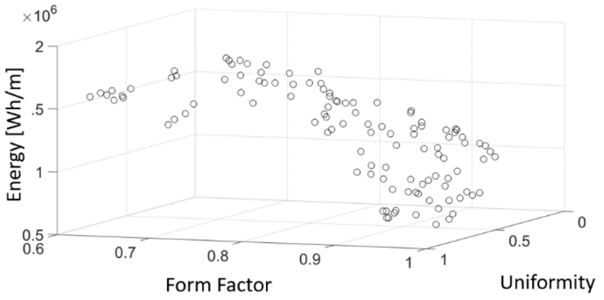

figure 11-Pareto plane of the optimization of the uniformity

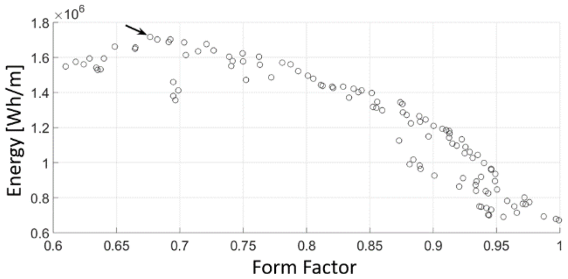

figure 12-2D view from Pareto plane (Energy and Form Factor)

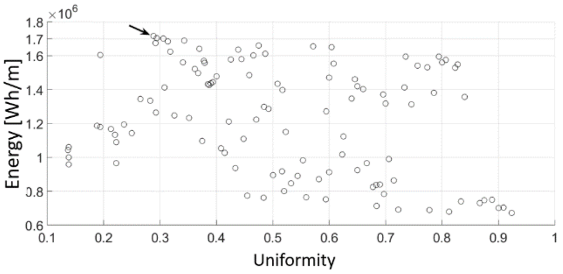

figure 13-2D view from Pareto plane (Energy and Uniformity)

In table 4 it is possible to verify the optimized parameters for two geometries originated by the optimization. Geometry 1 absorbs +10.4% of annual energy than the MaReCo^{TM} geometry but is 13.1% longer in length and its solar radiation uniformity in the cells is -11.9%. Geometry 2 absorbs +2.6% that MaReCo^{TM} geometry and radiation uniformity is 142.8% better. However, its length is 19.2% longer. You can understand when you want to absorb more energy the length and uniformity worsen its values, the same happens with the other 2 parameters.

table 4-Comparasion between two given geometrys by the optimization

	MaReCo^{TM}	Geometry1	Geometry 2
Energy [MWh/m]	1,555	1,716 (+10,4%)	1,595 (+2,6%)
Form Factor	0,778	0,676 (-13,1%)	0,629 (-19,2%)
Uniformity	0,327	0,288 (-11,9%)	0,7941 (+142,8%)

Taking into consideration the main objective of maximizing the energy received by the photovoltaic cells, the reflector indicated in figure 12 and figure 13 was chosen with an absorbed energy of 1.716MWh/m, a form factor of 0.676 and a uniformity of 0.288, with inclination of the panel at 27º. table 5 shows the values of absorbed energy, form factor and uniformity for the different geometries.

All the chosen reflectors are represented in figure 14. It can be observed that all geometries have similar shapes. The smallest reflector is MaReCo^{TM} with 0,778 form factor and the reflector with greater length is the one optimized for a full year without uniformity with 0,657 of form factor.

table 5-Values of the geometries optimized for a year in Portugal and MaReCo^{TM}

	MaReCo^{TM}	Geometry optimized for a year	Geometry with uniformity optimized
Tilt [º]	5,0º	29,0º	27,0º
Energy [MWh/m]	1,555	1,725(+10,9%)	1,716(+10,4%)
Form Factor	0,778	0,657(-15,6%)	0,676(-13,1%)
Uniformity	0,327	0,224(-31,5%)	0,288(-11,9%)

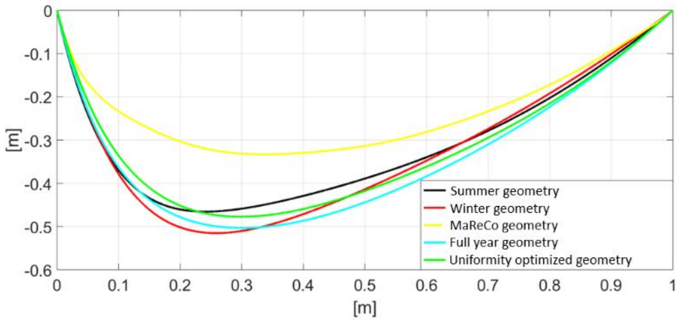

figure 14-Optimized geometries for Portugal and MaReCo geometry

B. Sweden

figure 15 shows the Pareto curve resulting from the optimization of the energy received by the photovoltaic cells and the minimization of the reflector size, the maximization of the form factor, for a typical summer and winter day in Sweden. In the curves the desired reflectors are identified, which maximize the energy absorbed by the panel. As can be seen, the values of energy absorbed in summer and winter are similar (around 4,700Wh/m), and lower than those found for Portugal (7,194Wh/m and 6,319Wh/m, respectively).

The winter reflector absorbs 4,773 Wh/m of energy with the panel tilted at 43° and has a form factor of 0.908. The summer-optimized reflector absorbs 4,763 Wh/m, with zero panel tilt (0°) and has a form factor of 0.905. The MaReCo^{TM} geometry, for a typical winter day in Sweden, absorbs 4.658 Wh/m of energy, with the panel tilted at 60° and a form factor of 0.778, while for a typical summer day it absorbs 5468 Wh/m with the panel tilted at 20°.

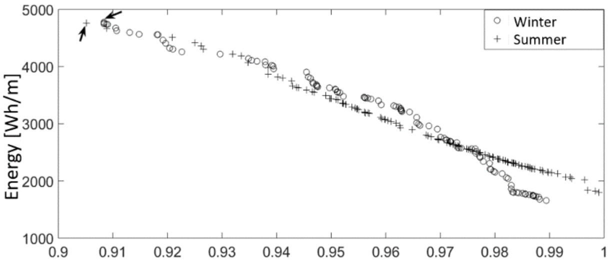

figure 15- Pareto curve of Summer and Winter in Sweden

figure 16 shows the Pareto curve resulting from the optimization of the maximization of the energy absorbed by the panel in Sweden for a year. Several sections of the curve are observed, with different behaviors, but without unusual values of very high energy and a much smaller form factor. As the main objective is to maximize the energy received by the panel, the reflector chosen is the one with the highest energy, indicated in figure 16. This reflector absorbs 1,633MWh/m, with the panel inclined at 36° and a form factor of 0,727. Figure 36 shows the geometry of the reflector chosen for the annual optimization, as well as the geometries previously optimized for Sweden, and the MaReCo^{TM} geometry, which in this case absorbs an energy of 1,530 MWh/m, with the panel inclined at 25° and with a form factor of 0,778. These data are shown in table 6.

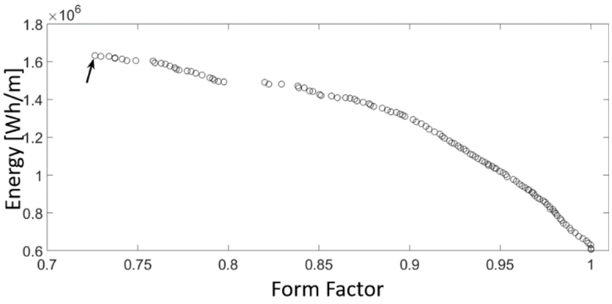

figure 16-Pareto curve of full year optimization for Sweden

table 6- Values of the geometries optimized for a year in Sweden and MaReCo^{TM}

	MaReCo^{TM}	Geometry optimized for a year
Tilt [°]	25,0°	36,0°
Energy[MWh/m]	1,530	1,633 (+6,7%)
Form Factor	0,778	0,727 (-6,6%)

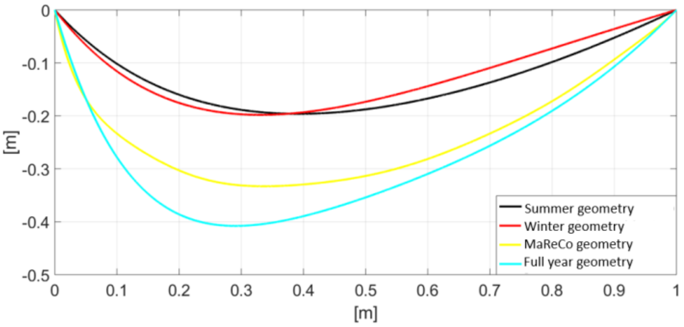

figure 17- Optimized geometries for Portugal and MaReCo geometry

C. Mexico and São Tomé and Príncipe

figure 18 shows the Pareto curve resulting from the optimization for Mexico for full year. There are several sections in the Pareto curve, but there also are several points that represent reflectors with large values of absorbed energy and very low values of form factor (approximately 10^{-16}). Form factor values of these magnitudes are unsustainable to project in real size. Therefore, the choice of the reflector (shown in figure 18) is based on the reflector that absorbs the highest energy and has a sustainable form factor value.

The chosen reflector can absorb 1,714 MWh/m after one year with the panel inclined at 15°. The form factor is 0,646, where the MaReCo^{TM} geometry of SOLARUS in Mexico can absorb 1,459MW/h per year with the panel at 0°. It can also be seen that the optimized geometry has a smaller factor than the MaReCo^{TM}, so it has a longer length.

The Pareto curve that results from the optimization of the maximization of the energy received by the solar cells and minimization of its size for the whole year is shown in figure 19. Based on the figure we can see that the chosen reflector, indicated in figure 19, maximizes the energy received by the cell, without its length being something unsustainable in physical terms. The geometry, for a panel inclination of 0°, absorbs an energy of 1,704 MWh/m per year. The MaReCo^{TM} solution is capable of absorbing 1,261 MWh/m during the same period.

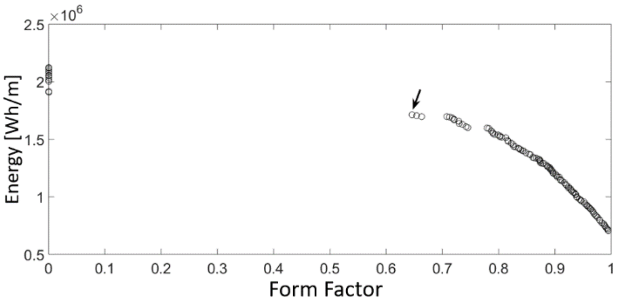

figure 18- Pareto curve of full year optimization for Mexico

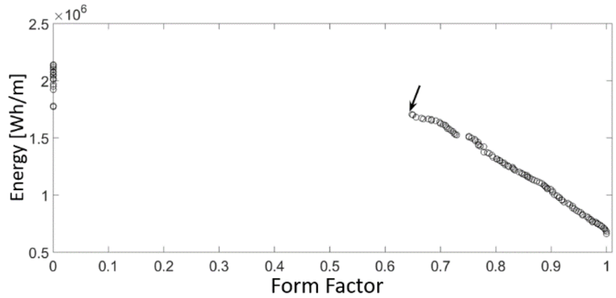

figure 19- Pareto curve of full year optimization for São Tomé and Príncipe

In table 7 the data from the two optimized geometry is shown. The relative differences are related for the values of MaReCo^{TM} in the two locations.

table 7-Values of the geometries optimized for a year in Mexico and São Tome and Príncipe

	Optimized geometry for Mexico	Optimized geometry for São Tomé and Príncipe
Tilt [º]	15,0º	0,0º
Energy [MWh/m]	1,714 (+17,5%)	1,704 (+35,1%)
Form Factor	0,646 (-17,0%)	0,648 (-16,7%)

All the yearly optimized geometries can be found in figure 20 and it can be observed that MaReCo^{TM} geometry has the smallest length. On the other hand, the reflector optimized for Mexico is the largest with more 17% than the geometry MaReCo^{TM}. It is pretty clear that all the reflectors have the same shape.

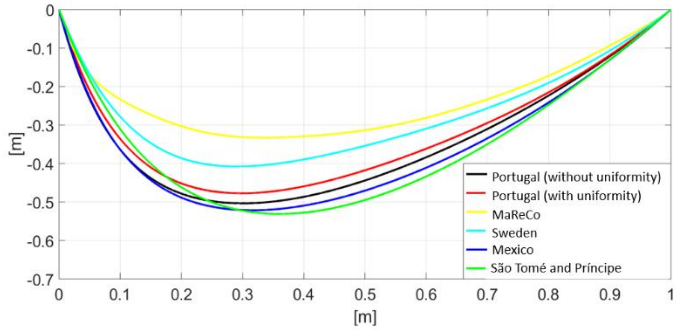

figure 20-Reflectores optimized and MaReCo^{TM}

V. CONCLUSIONS

The main objective of this work is to optimize the reflector of a concentrator solar panel for different climatic zones of the planet and compare it with the MaReCo^{TM} geometry of SOLARUS. A 2D optical-electric model was developed which, given the geometry of the reflector, calculates the amount of energy absorbed by the photovoltaic cells, coming from direct irradiation and reflected by the reflector. The geometry of the reflectors is defined by a polynomial function that is randomly generated by an optimization program. With the help of the NSGA-II optimization algorithm, the reflector structure was optimized for four different countries (Portugal, Sweden, Mexico and São Tomé and Príncipe) to maximize the energy absorbed by the cells and to minimize its size.

The optimization results show that the optimal formats for each geographic location are similar and the longer the length of the reflector, the greater the energy received by the cells, and it is necessary to pay attention to the length of the panel so that it can be applied experimentally.

The optimized geometry for Portugal, without the optimization of uniformity, provides a 10.9% increase in absorbed energy, 1.725MWh, in Portugal, compared to the MaReCo^{TM} geometry. Considering also the optimization of the uniformity of the solar concentration, it is possible to obtain the same energy absorbed by the photovoltaic cells for different uniformities. The chosen solution, considering the optimization of uniformity, absorbs 10.4% more energy and has 11.9% less uniformity than the MaReCo^{TM} geometry. Regarding the length of the reflector, the two optimized solutions have longer lengths, plus 15.6% and 13.1% for cases with and without optimized uniformity, respectively.

SOLARUS' MaReCo^{TM} reflector was manufactured for Sweden, but the optimized solution obtained for the same country presents higher absorbed energy values, about 6.7% compared to the concentrator of the Swedish company, with an increase of 6.6% in the reflector length.

For Mexico and São Tomé and Príncipe, the optimized solutions show values of absorbed energy much higher than the MaReCo^{TM}, 17.5% and 35.1%, respectively. On the other hand, its length is also considerably higher than the MaReCo^{TM} geometry, 17.0% and 16.7%, respectively. From these results, the conclusion is drawn that for the same length increase there is a much greater gain in energy absorbed in relation to the MaReCo^{TM} geometry, which for Mexico absorbs 1.459 MWh/m of energy after one year and for São Tomé and Príncipe 1.261 MWh/m.

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