24th ABCM International Congress of Mechanical Engineering
December 3-8, 2017, Curitiba, PR, Brazil

COBEM-2017-1227
ANALYSIS OF PARAMETERS THAT INFLUENCE THE PERFORMANCE OF HELIOSTATS IN CENTRAL TOWER TECHNOLOGY

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Abstract. *Solar concentrators solve energy problems within a short time. The central tower technology stands out due to the ability to concentrate many solar rays. These plants have fields of heliostats that reflect the radiation to a receiver. Heliostats make up the bulk of the investment in this system, improving field efficiency promotes cost savings. The purpose of this work is to analyze how some parameters can influence the performance of a solar field located in the city of Natal - RN. Simulations were performed in the Scilab software using a model that calculates the performance of the system due to the movement of the Sun and the various mechanisms of losses. An analysis of the characteristics of the field is made, such as the height of the tower and the distance between the tower and the heliostats, for two types of distribution of the heliostats. For the distribution Model II, an efficiency of approximately 54% and a reflected potency of 95,915 kW was obtained. For Model I, 50% and a production of 92,304 kW were obtained. It can be concluded that with a larger tower height and a smaller tower-heliostat distance the system can achieve better efficiency values.*

Keywords: *Concentrating solar power, Tower Central, Heliostats, Efficiency.*

1. INTRODUCTION

Various forms of energy generation have been studied and implemented since the world is dependent on fossil fuels and this is a finite source of energy, as well as being primarily responsible for climate change. The lack of rain in regions where energy is generated by hydroelectric plants and possible oil crises increase demand for alternative and sustainable energy systems.

In Brazil, wind energy has made strides in its growth, so much so that it has become the fourth nation in the world where this type of energy grows (Gazeta do Povo, 2016). The solar have also advanced. By presenting one of the best conditions in the world for this type of energy generation, Brazil has become one of the most attractive markets.

Among all the renewable technologies currently available for large-scale energy production CSP (Concentrating solar power) is one of those with the greatest potential. This is due to its relatively conventional technology and its large power range in its plants, being able to build power plants that produce from kW to GW with the same technology. Currently there are four types of CSP systems, each in distinct phases of development, which are: parabolic reflectors, central tower systems, Fresnel linear reflectors and parabolic disks.

The system addressed in this work will be the central tower system. This type of system is characterized by using a field of hundreds and even thousands of distributed heliostats that focus and concentrate the reflected radiation on a receiver located at the top of a tower. And because it presents one of the largest investments for the construction of these systems, heliostats have to present their best efficiency in order to reduce the costs of these plants and to make competitive the value of the energy produced. The efficiency is given as a function of the optical losses present in the field due to the cosine effect, the atmospheric attenuation, the shading and blocking, the blurring and the reflectivity. Most of these losses are a consequence of the way heliostats are distributed on the ground.

An example of loss occurs when some of the rays emitted by the Sun can not reach the entire mirror surface. Part of the mirror area does not receive the rays emitted by the Sun due to a heliostat located at the front that is shading the surface of the heliostat that is located behind, preventing that the reflection area is equal to total mirror area. This kind of loss is called shading.

It can be seen that the circumstances that happen to the shading are caused due to the positioning of the mirrors. If there is a good separation between them, possibly the occurrence of shading would be null. However, the further away the heliostats become from each other, the greater will be their distance from the tower where the receiver is located, causing the losses due to atmospheric attenuation to increase. Therefore, it is important to obtain an efficient distribution configuration of the heliostats and the receiver, where each of the losses is the smallest possible and occur in a balanced way, since there is no system that works optimally.

For this work two types of distribution models of the heliostats will be devised and for each one of them will be made variations in two important parameters of the configuration of the field. With this, it will be analyzed how the change of these characteristics influence the final value of the heliostats efficiency.

2. METHODS

For all solar energy systems the basic resource is the Sun. Knowledge of the quality and quantity of energy available in a particular region is of great importance for the study and design of any solar energy system. For this it is necessary to predict the relative position of the Sun for each day and time.

To understand the geometry of the movement of the Sun, one has to know the relation of the axis of rotation of the Earth with the plane of its orbit. The Earth revolves around the Sun every 365.25 days in an elliptical orbit at an average distance of 150 million kilometers. The Earth rotates about its own axis, inclined 23.5º, in a cycle that lasts approximately 24 hours (Kreith e Kreider, 1978).

And the factor that maximizes the cost for the development of a central tower system are heliostats. With this, it is essential that the efficiency of the solar field be as large as possible. The choice of heliostat field layout involves some important variables, such as the location of the heliostats in the terrain and the height of the tower. Together with the choice of these variables the loss mechanisms appear, since these mechanisms depend on the distribution of the heliostats in the field. Because of this, it is extremely important to achieve the best configuration to increase the efficiency of the heliostat field.

2.1 Heliostats

Heliostats can represent up to 36% of the costs of a central tower type plant. Their investment should be as small as possible so that the cost of energy produced becomes competitive in a market with more conventional technologies (Kolb and Jones, 2007). Due to this it is of great importance the study of the losses present in a solar field composed by heliostats.

The reflected area of the heliostats can vary from 1 m² up to 150 m². The advantage of using larger mirrors is that once installed the smaller the number of the segment systems will be and fewer units will need to be maintained. On the other hand, larger heliostats make it difficult to install and maintain mirrors larger (Sattler, 2015).

2.2 Mechanisms of loss of a field of heliostats

The cosine effect is one of the main losses factors of a field of heliostats. The efficiency of the distribution of heliostats is dependent on the position of the Sun and the position of the heliostat relative to the receiver (Eustáquio, 2011). The course of the heliostats is given by means of a tracking mechanism that varies according to the orientation of the azimuth and zenith angles in order to guarantee a precise tracking of the Sun's path throughout the day (Sattler, 2015). This tracking mechanism will position the heliostats so that the normal of their surface divides the angle between the Sun's rays and the direction line to the receiver (Stine, 2001). The reduction of the effectiveness of the heliostat area is proportional to the cosine of the angle of incidence.

The shadowing occurred by a heliostat projects its shadow over another heliostat that is located just behind it, making it impossible for part of the incoming radiation to reach a surface of the second heliostat (Eustáquio, 2011). The blocking happens in a similar way to shadowing, in which case some of the rays reflected by the surface of the heliostat are blocked due to another heliostat being in front of it. This effect can be observed by checking for reflected light on the backs of heliostats. The amount of shadowing and blocking number are defined according to the spacing of the heliostats, a height of the tower and a position of the Sun. Normally, a heliostats organization is made radially so that the types of losses are minimized.

The loss due to the atmospheric attenuation depends on the distances between the position of the heliostat and the tower, because the reflected rays that leave the heliostat surface may not arrive with the same intensity in the receiver. This will be characterized according to the atmospheric conditions of the region where the solar field will be installed, since some gases present in the atmosphere have the capacity to absorb, reflect and spread the reflected solar rays.

Blurring is a source of loss for both receiver and heliostats, since part of the reflected energy that is directed to the receiver may not be absorbed because it does not fit into the absorption area. Typically, the area is large enough to intercept most of the reflected radiation and keep the incident flux at maximum values within the acceptable range. This loss can be avoided by increasing the receiver area, but this change is limited due to convection and radiation losses that are proportional to the absorber area (Stine, 2001). There are several factors that can increase an image reflected by a heliostat: an irregularity of the surface of the mirrors, the error of curvature of each mirror and the errors associated with its point of focus. By associating all these errors, the non-receiver flow profile produces a distribution profile in which 90% of the total flow is concentrated in the center (Stine, 2001).

Many types of materials are used in the composition of the mirrors of heliotates and the efficiency of reflectivity depends on this type of material. But that alone is not enough. Good reflectivity depends not only on the surface quality of the heliostats but also on the degree of degradation of the mirrors and the accumulated dirt due to dust and air pollution. With this, it is important to have a periodicity in cleaning the mirrors to increase their reflectivity.

The most significant losses are due to the cosine effect, even if these are minimized by a good solar field design, even this will be the largest. The second important loss is caused by the reflectivity of the mirrors, when new, the mirrors have reflectivities above 90%, but with the accumulation of dirt and aging, this value reduces rapidly. Because of this, it is important to maintain proper maintenance (Stine, 2001).

The total efficiency of the solar field can be calculated from Eq. (1) and can range from 45% to 85% (Sattler, 2015).

$$\eta_{field} = \eta_{cos} \cdot \eta_{ref} \cdot \eta_{atm} \cdot \eta_{shad} \cdot \eta_{bloc} \cdot \eta_{blur} \tag{1}$$

Since, η_{field} is the total efficiency of the field, η_{cos} the efficiency of the cosine effect, η_{ref} the efficiency of the reflectivity, η_{atm} the efficiency of the atmospheric attenuation, η_{shad} the efficiency of the shadowing, η_{bloc} the efficiency of the blocking e η_{blur} the efficiency of the blur.

The equations that define each of these types of losses can be found in the recent work of conclusion of course of Medeiros (2016).

2.3 Definition of parameters

The city of Natal, capital of the state of Rio Grande do Norte, was chosen as the location for this study because it is one of the cities with one of the largest numbers of sunny days per year in Brazil. With a high solar radiation index, the state has attracted the interest of international investors to the photovoltaic solar energy sector. In the last two years, the state has been receiving companies that are looking for businesses focused on the implantation of solar panel plants and a second time in the construction of solar plants (SEDEC, 2016).

Local data for the city of Natal are shown in Tab. 1.

Table 1. Local data of the city of Natal – RN

City	Natal – RN - Brazil
Latitude and longitude	05° 47' 42" S, 35° 12' 34" O
Sunrise time	05:20 (INPE)
Sunset time	17:20 (INPE)
Average daily solar irradiation	5,66 kWh/m².day

To begin the characterization of the field of heliostats, some initial parameters were defined. Some of these were adopted with reference to some research already developed for the study of the optical efficiency of a field of heliostats.

The configuration of the solar field in the South was chosen taking into account the location of the city of Natal that is in the Southern Hemisphere, and for a field of heliostats it is preferable that they be placed to the south of the tower. This is due in the southern hemisphere, the diurnal movement of the Sun being seen to the north by the heliostats, and therefore, "facing" the Sun more easily if the heliostats are located south of the tower (UNIDO, 2015).

The average amount of heliostats was defined with reference to the project of a plant located in the city of Caiçara do Rio do Vento - RN, owned by the company Salinova, which contains 75 heliostats.

The initial distribution of the heliostats was made having three definitions, the minimum distance tower-heliostat, the circumference that delimits the space for each heliostat and the dimensions of the mirrors of height and width. Knowing that heliostats are organized circumferentially (Talebizadeh and Mehrabian, 2014) and with the help of Geogebra software, it was possible to create, in a schematic way, possible distributions that heliostats can have. Figure 2 shows one of the distributions, one with a Rmin of 65 m.

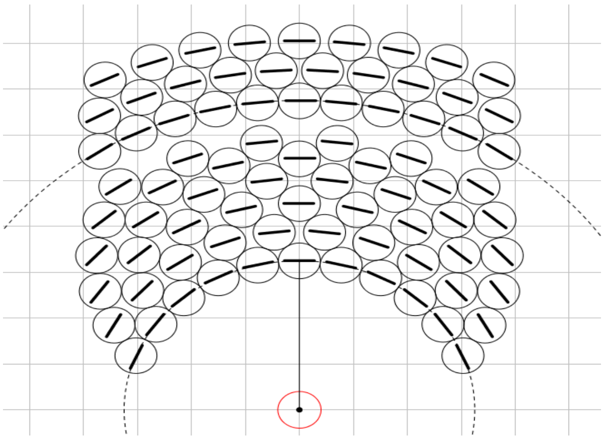

Figure 2. Initial distribution of heliostats on the ground

As observed in Fig. 2, it was necessary to restart a distribution of the heliostats, at a circumference of 170 m, just after a sixth circumference of heliostats. This distribution is restarted due to the voids that begin to form between the heliostats from the third circumference and tend to grow in the consecutive ones. In these void spaces, once the distribution is restarted, they can allocate a larger number of heliostats per circumference as well as a greater amount of energy, in addition to making the field more compact. The initial parameters adopted are presented in Tab. 2.

Table 2. Initial data from the heliostat field simulation

Heliostats	Field configuration	South
	Dimensions of heliostat	11 m x 11 m
	Height of the heliostat stem	3 m
	Reflectivity (Glass with low iron content with a layer of silver)	0,95
	Number of heliostats	81
	Total area	9 801 m²
Receiver	Tower Height	120 m
	Minimum tower distance - heliostat	65 m

With the solar field and its already defined configurations, it used the Scilab program 5.5.2, software with environment used in the development of programs for the resolution of numerical problems, for the realization of optical loss calculations.

For the calculation period, the following criteria were defined: to represent the year of analysis, four days were defined, one for each climatic season, and followed the order in which the first day was started on January 20 and for each the next day a further 90 days were added. This addition value was necessary for the representative months to be the average for each season.

And for the hours of sun of each day, that take place from sunrise to sunset, were chosen according to meteorological data found on the National Institute of Space Research (INPE) website. That is, from 6 o'clock in the morning to 6 o'clock in the afternoon.

In order to start the optical loss algorithm of a field of heliostats, first the positioning of the center of each heliostat was calculated, taking as reference the minimum tower-heliostat distance and the delimitation of the space required for each heliostat, thus continuing for the other circumferences following the design shown in Fig.1.

3. RESULTS AND DISCUSSION

In order to analyze the field of heliostats and to know the importance of each some variables and how the change of them affects the efficiency, modifications were made in some important parameters of the configuration.

3.1 Analysis for the Distribution Model I

As already mentioned in this work, the way heliostats are distributed in the field directly affect the amount of optical losses that are in a solar field. To do this analysis, two types of distribution models were made. The first Model, with 81 heliostats, shown in Fig. 3, has as main characteristic the resumption of the distribution of the heliostats to the seventh circumference. Being the difference between the radius of the first circumference and that of the seventh of 105 m.

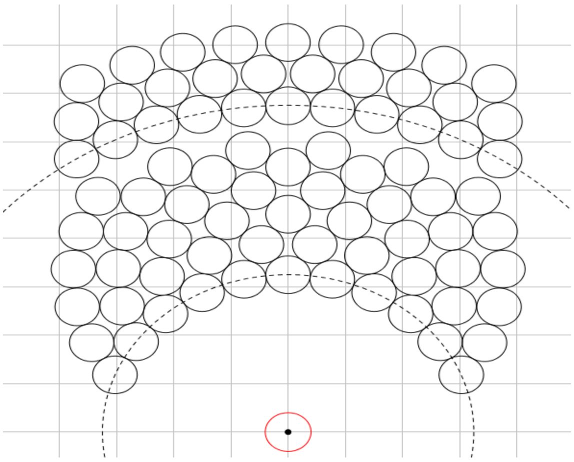

Figure 3. Distribution Model I

Two parameters of the solar field will be the variants for this Model I, keeping constant the positioning configuration of the heliostats and the day of analysis, which will be October 17. The parameters were, the minimum tower - heliostat distance (Rmin) and the height of the tower. Figure 4 graphically demonstrates how the optical efficiency varies according to the change of the minimum distance between the tower and the first heliostat circle of the field having the tower a constant height of 120 m.

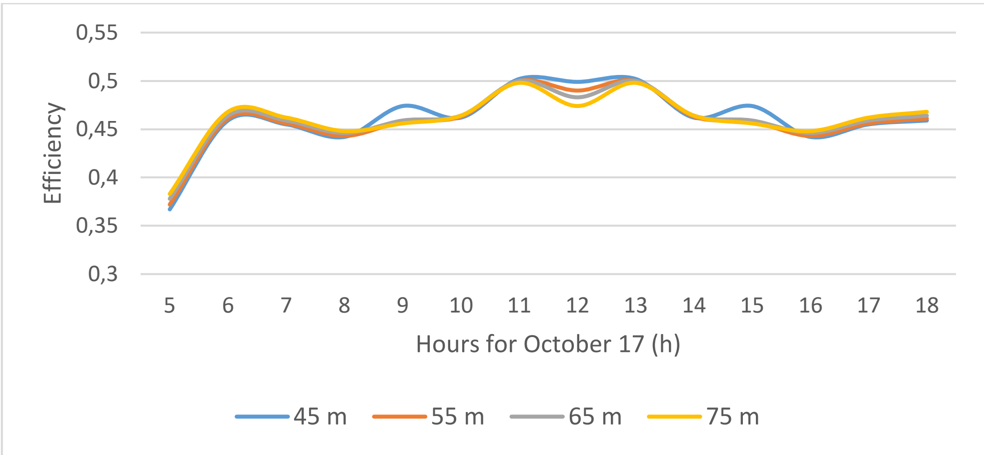

Figure 4. Efficiency of the solar field for Model I by varying the minimum distance

It can be observed that in the initial and final hours of the day, the efficiency variation is small compared to the difference of the analyzed distances. However, for values close to 12 hours, which is one of the best hours to obtain DNI values, this variation shows the behavior in that the higher the minimum distance the smaller the efficiency.

For the value of 45 m the efficiencies remain almost constant, between 11 and 13 hours, which does not occur with the other distances, where vales represent a decrease in efficiency. Therefore, among the minimum distances analyzed, the one that obtained a greater performance was the one of 45 m.

Table 3 shows the mean values of the optical losses used to define the efficiencies shown in Fig. 4. Note that the cosine effect, the atmospheric attenuation and the blocking are the types of losses that more present changes in their values with the increase of the distance, since these losses are direct functions of the analyzed distances.

Table 3. Average of the optical losses for the variation of the minimum distance I

	Cosine	Attenuation	Blocking	Shadowing	Reflectivity	Blur
45 m	0,871	0,981	0,669	0,728	0,95	0,9
55 m	0,865	0,98	0,668	0,725	0,95	0,9
65 m	0,858	0,979	0,672	0,727	0,95	0,9
75 m	0,853	0,978	0,676	0,726	0,95	0,9

For the effects of the variation of the height of the tower where the receiver is located, Fig. 5 shows how the efficiency behaves along the hours of the day, being the minimum tower - heliostat distance of 45 m. It is possible to notice that the efficiency increases as the height of the tower increases. This is due to the facts of the block being the type of loss that has the height of the tower as its main characteristic and the cosine effect also depends on the positioning of the receiver.

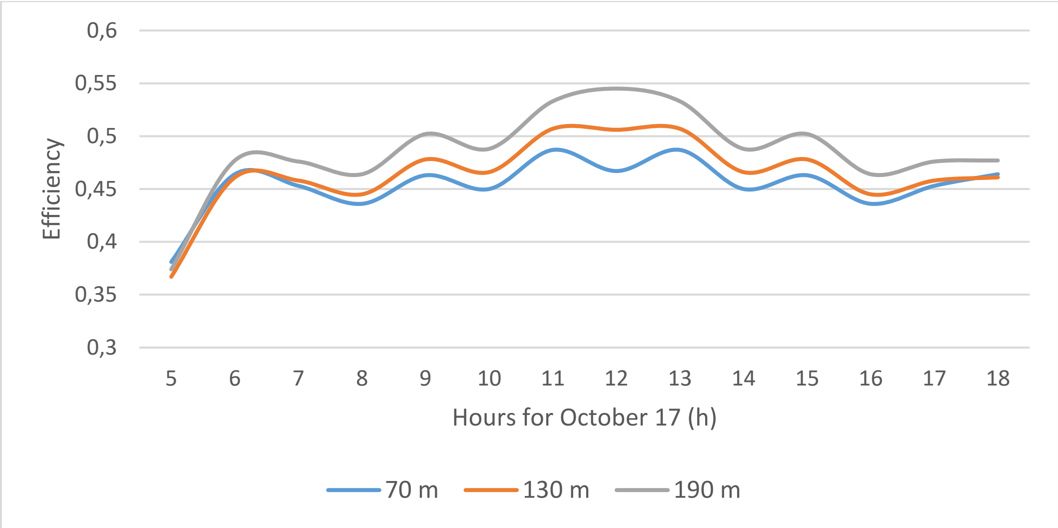

Figure 5. Efficiency of the solar field for Model I varying the height of the tower

Table 4 shows the mean values of the optical losses obtained with the tower height variation. Note that the cosine effect is the one that exhibits more variations, which may have motivated the difference in the efficiencies between the changes of the height of the receiver.

Table 4. Average of the optical losses with the change of the height of the tower I

	Cosine	Attenuation	Blocking	Shadowing	Reflectivity	Blur
70 m	0,834	0,918	0,678	0,728	0,95	0,9
130 m	0,876	0,918	0,675	0,728	0,95	0,9
190 m	0,889	0,918	0,718	0,728	0,95	0,9

Thus, for Model I, the height of 190 meters gives the heliostats field a greater efficiency during all hours of the day. While the heights of 70 and 130 m presented lower values.

For these conditions, according to the analyzed variables, the minimum distance of 45 m and the height of the tower of 190 m presented better values of efficiency for the Model of distribution I. These values will be used later to estimate how much potency can be produced with these field settings.

3.2 Analysis for the Distribution Model II

The heliostats distribution Model II is shown in Fig. 6. In it can be seen that, unlike Model I, there are two circumferences where the distribution is restarted. The difference between the radius of the first circle and the seventh is 85 m. And contains 84 heliostats, three more than the previous model.

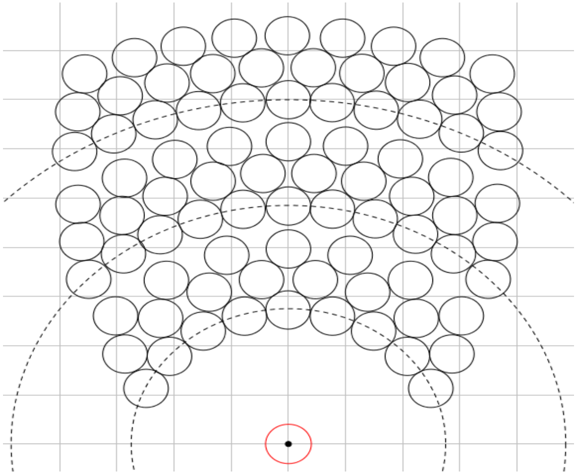

Figure 6. Distribution Model II

The same conditions of variations presented in Section 3.1 will be analyzed for this model.

Figure 7 graphically demonstrates the efficiency behavior with the change of the minimum distance between the tower and the heliostat. It is possible to observe that, regardless of distance values, the values are higher than those analyzed for Model I. Although there is a voucher in the hours close to noon, the efficiency is close to 0.5, which is also characteristic of the distribution analyzed above. However in this analysis there are large peaks in the 10 and 14 hour hours, which raises the values to more than 0.55 thus increasing potency production. The position change of the heliostats decreased the losses by cosine, blocking, attenuation and even shading. As already described, losses depend on the positioning of field elements.

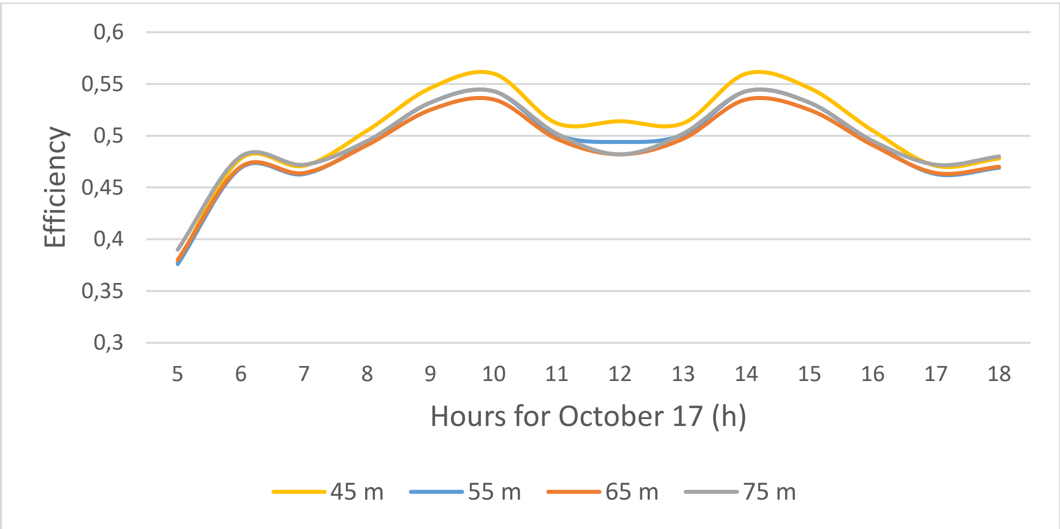

Figure 7. Efficiency of the solar field for the Model II varying the minimum distance

Table 5 shows the average values of the losses obtained during the hours of the analyzed day. Similar to Tab. 3, the values that present the most noticeable variations refer to the cosine effect, the atmospheric attenuation and the blocking. The distance of 45 m also stands out for this model having one of the best performances most of the time of day.

Table 5. Mean of the optical losses for the variation of the minimum distance II

	Cosine	Attenuation	Blocking	Shadowing	Reflectivity	Blur
45 m	0,871	0,982	0,699	0,734	0,95	0,9
55 m	0,865	0,980	0,669	0,739	0,95	0,9
65 m	0,859	0,979	0,701	0,743	0,95	0,9
75 m	0,855	0,978	0,706	0,746	0,95	0,9

For the tower height change the efficiency behavior is analogous to the minimum distance for the Model II, as shown in Fig. 8. Different from the analysis of this variable for Model I, the values for the height of 130 m were very close to 190 m.

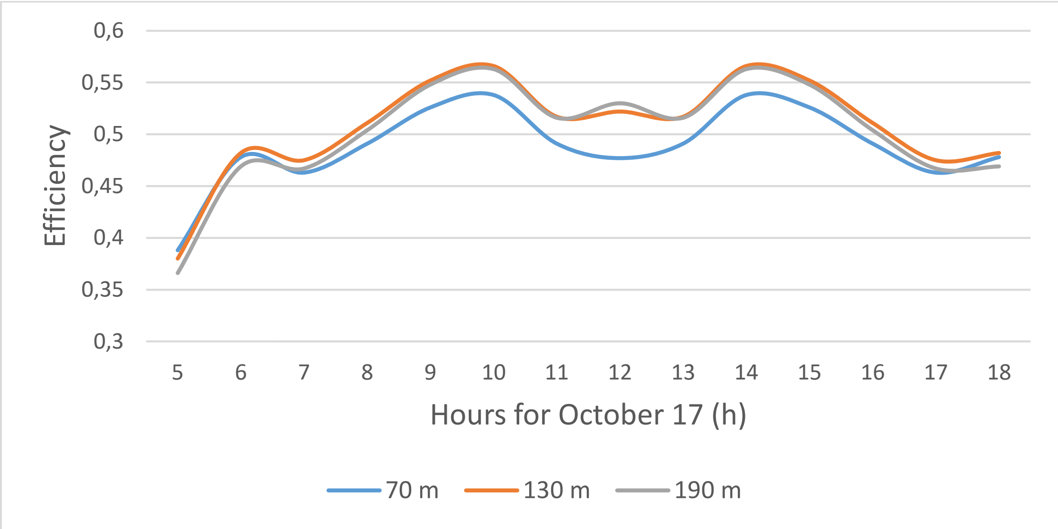

Figure 8. Efficiency of the solar field for the Model II varying the height of the tower

Table 6 shows how the position change of the heliostats and the variation of the height of the tower decreased the losses. As the curves for 130 m and 190 m were very close, it can be analyzed by the values in the table that losses to 190 m were smaller when compared with the values of 130 m. It is also observed that the values for the height of 190 m, when compared with those of Tab. 4, increased considerably, since the only change at that point is the distribution of the heliostats.

Table 6. Average of the optical losses with the change of the height of the tower II

	Cosine	Attenuation	Blocking	Shadowing	Reflectivity	Blur
70 m	0,838	0,982	0,723	0,734	0,95	0,9
130 m	0,876	0,982	0,702	0,734	0,95	0,9
190 m	0,892	0,982	0,735	0,734	0,95	0,9

Thus, for the distribution Model II, the values of the analyzed variables that had the best performance in the solar field were 45 m for the minimum tower - heliostat distance and 190 m for the tower height.

3.3 Analysis of energy reflected by heliostats

With the defined values of the variables analyzed for each model, it was possible to analyze the potency produced by each one during the representative days chosen for the year. Actual DNI data for the city of Natal - RN were provided by the company CTGÁS-ER and used for this analysis. These data were averaged for each hour using every day of the months analyzed in this work. This was done trying to soften the values of DNI when there were possibly hours when the sky was cloudy or there were rains.

Figure 9 shows the amount of potency reflected for distribution Model I. It is noted that the month that contains the largest area below the curve, and consequently the highest amount of potency produced, is October. Between 9 and 14 hours of the day the values remain close to 3,000 kW. While for the other months the values are very varied during the hours of the day, with January having the lowest potency reflected among all.

A total of 81 heliostats, a total area of 9,801 m² and considering all the losses discussed in this study and having only four representative days of the year, total reflected potency for the receiver was 92,304 kW and the annual efficiency of the solar field was 49.5% . A near efficiency when compared values of some plants already in operation. As is the case with PS20 in Spain, which is 61%.

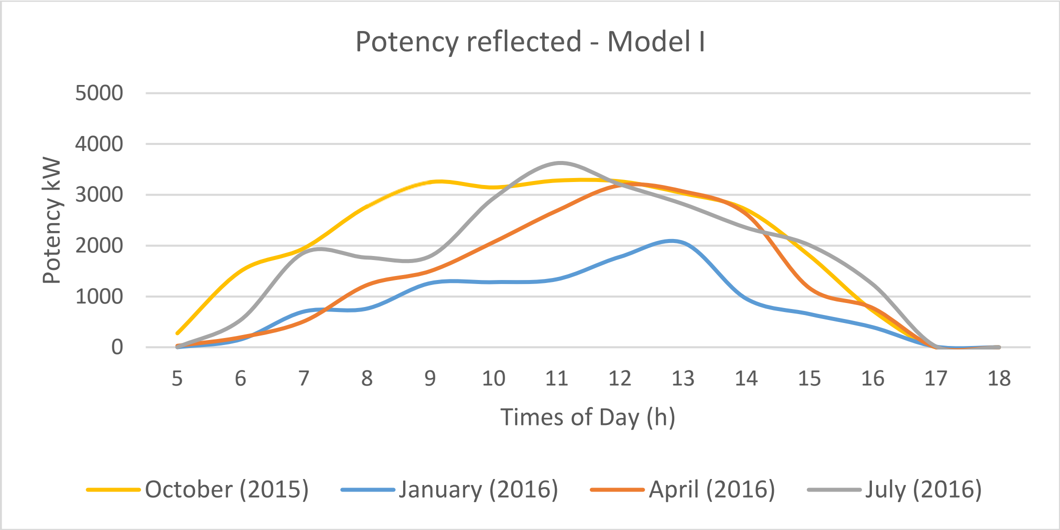

Figure 9. Potency reflected by heliostat field for Model I

For the same DNI values and the conditions imposed by the previous tower height distance analyzes, the reflected potency was analyzed for distribution Model II, Fig. 10.

As expected, there was an increase in potency values over the hours of the days chosen. October, again, had an area below the chart larger than the other months. Being the potency produced of 95,915 kW and a heliostats field efficiency of 53.9%. Values slightly higher than Model I, but with an efficiency closer to the reference value.

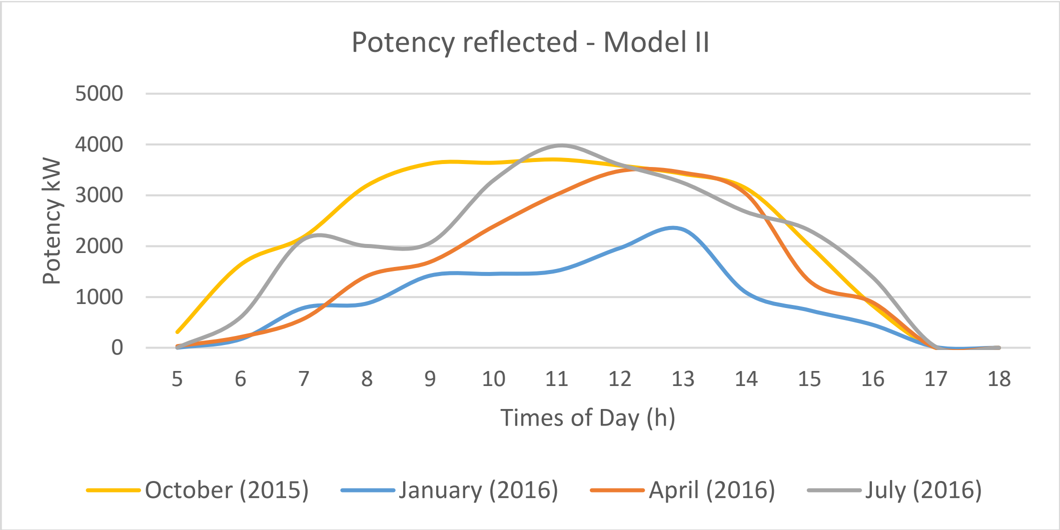

Figure 10. Potency reflected by heliostat field for Model I

4. CONCLUSIONS

The analysis performed allows a better understanding of the characteristics of a solar field composed of heliostats, which is used in CSP technology of the central tower type. Since this field presents approximately 40% of its total cost, it is important to study how the optical efficiency of this system behaves with the change of some field parameters.

The simulations developed allowed to prove that, although the two models are organized circulating part of the tower, the distribution of heliostats in the field is an important factor to reduce the optical losses. The distribution Model II was the one that presented the best efficiencies and consequently greater potential to reflect the solar rays to the receiver.

In addition, the resulting efficiencies may have been somewhat below the reference value, 61%, since the field may be oversized or the positioning of the heliostats may have been misleading, since the equations used in this work are used only in preliminary project studies. And to determine how they will be organized, there are specific programs that configure the positioning of heliostats through a complex mathematical code that already considers the various mechanisms of losses. Even so, the efficiencies were within the expected range between 45% and 85%.

The height of the tower and the minimum tower-heliostat distance were just two of the many variables involved in the configuration of a field of heliostats. The change of these two parameters showed that for a field containing on average 83 mirrors with 121 m² each, a smaller minimum distance and a larger tower height helps to improve efficiency. However, there are other factors that may interfere in the definition of these parameters, since besides efficiency, cost and maintenance are also taken into account in the final decisions of the project.

Another point to draw attention to is that, according to research data, the cosine effect is the main cause of losses in a solar field. However, shading and blocking, according to the results, obtained an efficiency around 70% and values close to 90% were expected. This again shows that the organization of heliostats may have interfered with these results, or the equations used to quantify these types of losses are inadequate. Since, those that were applied were in function of distances and the ideal form is using the reflected area and the total.

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