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FEASIBILITY STUDY OF A HELIOTHERMIC PLANT IN THE STATE OF RIO GRANDE DO NORTE

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Abstract. Concentrated Solar Energy (CSP) has been gaining ground in the world's energy matrix, given that it is a source clean, renewable and safe. Considering the potential of the Brazilian Northeast in heliothermic energy generation, this paper presents the main factors for the feasibility study of a CSP plant of central tower in three cities of the state of Rio Grande do Norte: Apodi, Caicó and Mossoró. Using System Advisor Model (SAM) software as the main tool and the Gemasolar plant as a reference to compare, the results showed that Apodi was the most favorable for the plant's implementation of 19.9 MW, with solar multiple of 2.1, generating an optimized Levelized Cost of Electricity of 15.28 ¢/kWh and capacity factor of 61.5 %.

Keywords: Heliothermic energy, central tower, feasibility study.

1. INTRODUCTION

Currently in Brazil there is still a strong dependence on energy from sources that, although renewable, generate considerable impacts to the environment, such as hydroelectric plants. According to the National Energy Balance – 2018 report prepared by the Empresa de Pesquisa Energética (EPE) based on data from 2017, the water source is highlighted with 65.2 % of the internal offer. Although the energy matrix is largely renewable, non-renewable sources still account for 19.6 % of internal offer, according to the report.

Against aggravating environmental, especially climatic, it is essential that alternative sources are increasingly exploited to considerably reduce dependence on non-renewable energy sources such as oil. The state of Rio Grande do Norte, for example, continued to be the leader in oil production in the year 2017, with 33 % of the total onshore (EPE, 2018), in contrast it is highlighted by the potential of renewable energy, especially solar. The written material released in April 2018 by the SEBRAE (Serviço Brasileiro de Apoio às Micro e Pequenas Empresas) shows the state as occupant, in the same period, of the 4th position among the nine states of the Northeast Region in power installed by photovoltaic energy.

An alternative allied to this photovoltaic potential are thermoelectric solar plants operating from Concentrated Solar Power (CSP). According to the International Energy Agency (IEA, 2010), CSP uses renewable solar resources to generate electricity while producing very low levels of greenhouse gas emissions, so it has a strong potential to be a key technology to mitigate changes climatic and in addition to energy security, has the inherent capacity of hybridization when equipped by power generated by fossil fuels, and can continue to generate electricity when clouds block the sun or after sunset. Moreover, due to its green and renewable characteristics, solar energy is one of the most attractive and competitive alternatives among renewable sources (Sun et al, 2015).

Figure 1 illustrates the energy production through technology, showing its attractiveness and potential in the world. South America, for example, is among the most developed regions.

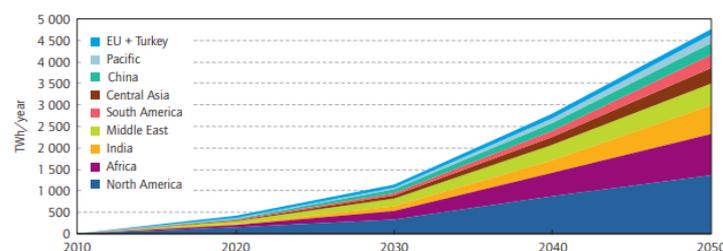


Figure 1. Growth of CSP production by region. Available from: IEA (2010).

2. APPROACH

2.1 CSP Technologies

CSP technologies use optical concentrators to create high levels of solar flux called receivers. In it, the solar radiation is absorbed and converted into heat. The heat is transferred by means of heat transfer which is transported to a thermal energy cycle or a storage system for later use. In the power cycle the heat is converted into electricity that is fed to the grid (Buck et al, 2014).

There are currently four types of CSP technologies: Solar Parabolic-Dish (SPD), Parabolic-Trough Collector (PTC), Solar Power-Tower (SPT) and Linear Fresnel-Reflector (LFR).

In 2014, the capacity of the plants under construction amounted to 1,699 MW, of which 68.1 % are parabolic trough and 18.8 % solar tower. The plants under development had installed capacity of 4,748 MW, of which 22.7 % were parabolic and 74.3 % were solar tower (Oliveira Filho, 2014). It is evident, therefore, the greater domain in the future of the central tower configuration.

2.1.1 Solar Power Tower (SPT)

Figure 2 illustrates a plant with this technology and with thermal storage with molten salt, following the principle of the rankine thermodynamic cycle. It consists of a heliostat field, a receiver that is connected to a tower, a power block and a thermal storage system that depends on the design conditions. The heliostats concentrate the solar radiation in the receiver located at the top of the tower. Heat is transferred to the molten salt which is the heat transfer fluid (HTF), which is then pumped into the power cycle, where the steam generator is located that drives the turbine to produce electricity.

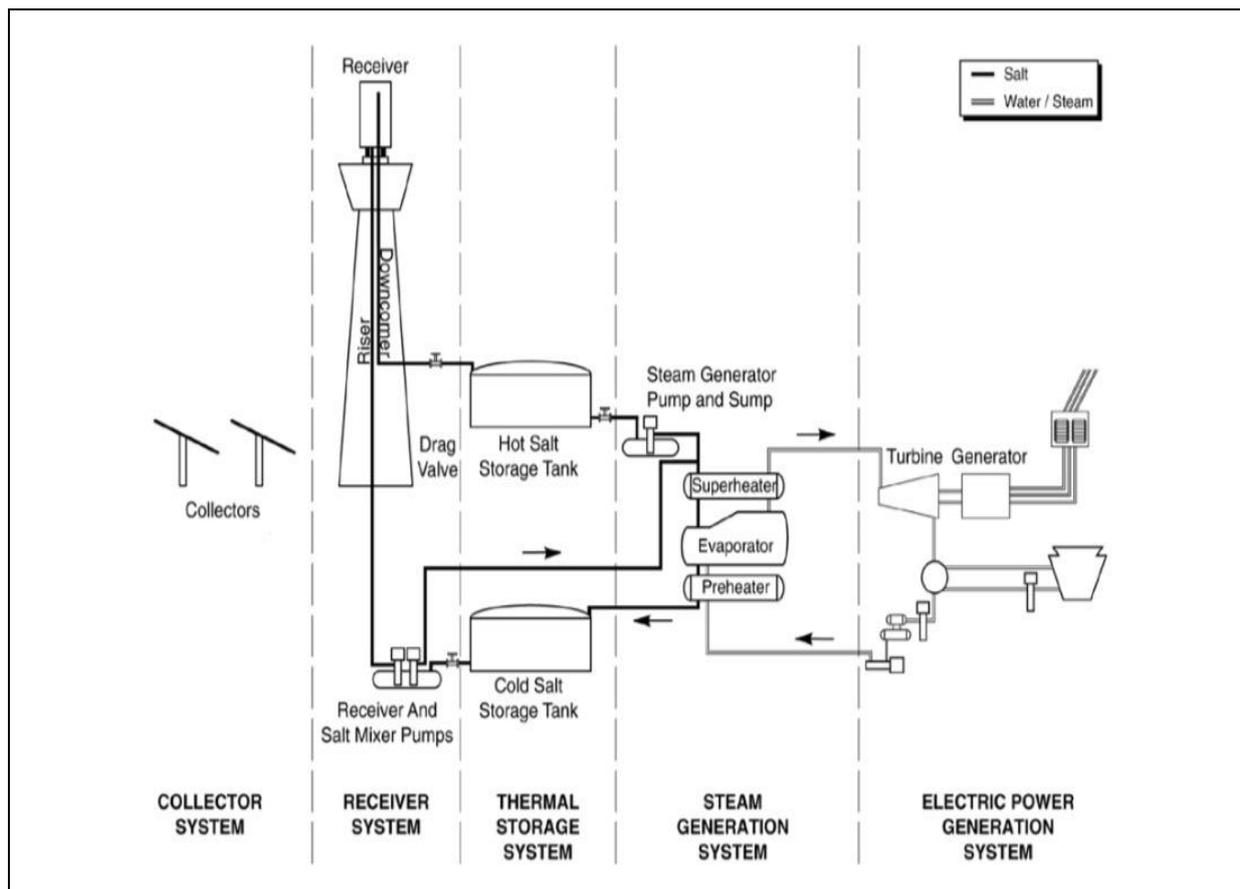


Figure 2. Schematic of a power tower with thermal storage of molten salt. Adapted from: Turchi and Heath (2013).

The choice of this technology for case studies may be based on aspects such as: higher temperatures in the receiver, and consequently in storage; more efficient cycle due to higher process parameters; the course of the more homogeneous annual production, the difference between daily production in summer and winter is less clear and the heliostat field can be built on slightly inclined terrain (Buck et al, 2014).

2.2 Potential of the Rio Grande do Norte in CSP

Figure 3(a) presents the state of Rio Grande do Norte as an area favorable to this type of energy generation. In this scenario, an important requirement for the implantation of CSP plants is Direct Normal Irradiation (DNI), which from its global distribution can identify the sites of great potential for this type of solar plant (Trieb et al, 2009). According to Buck et al (2014), DNI of 2000 kWh/m²/year is considered as minimum level for economic viability of solar plants. However, the scenario can vary significantly with the irradiation, region, legislation and technology employed. Thus, minimum values of 1800 kWh/m²/year are easily found in research in this area.

From Figure 3(b) it can be observed that the cities located in the west and in the mesoregion of the State are propitious to the implantation of this technology. Cities such as Apodi, Caicó and Mossoró have attractive solar incidence indexes, indicating, therefore, important points for studying the viability of a CSP plant.

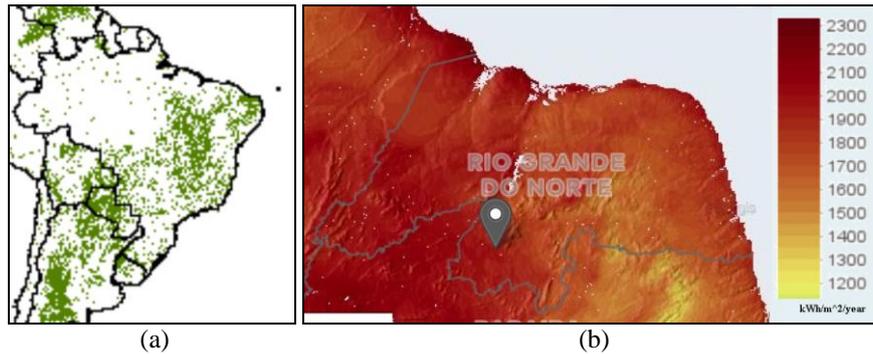


Figure 3. (a) Appropriate locations from the point of view of land suitability for CSP plant construction and (b) distribution of DNI (kWh/m²/year) in the RN. Adapted from: Trieb et al (2009) and SWERA.

3. METHODOLOGY

This work will study the implementation of a thermal storage solar tower with a net generation capacity of 19.9 MW of electricity in the state of Rio Grande do Norte. The determination of important parameters will be based on the case study developed by National Renewable Energy Laboratory (NREL) and values taken from the Gemasolar plant, located in Fuentes de Andalucía, Spain, which is an important solar plant of the same capacity and same configuration that will serve for comparison and consequent validation of the results obtained.

For the simulation, the main tool used in this work is the System Advisor Model (SAM) version 2018.11.11 developed by NREL, Sandia National Laboratories and University of Wisconsin. It is an annual analysis model that greatly contributes to the evaluation of the cost and performance of photovoltaic (PV) and CSP generation. The tool incorporates modules that estimate the performance hours of different PV and CSP systems from project parameters and climatic files that include solar and meteorological data for the selected site (Turchi et al, 2010).

3.1 Data base

Solar resources for renewable energy and meteorological data are automatically downloaded by SAM of the National Solar Radiation Database (NSRDB) database, managed by NREL. Retail electricity prices and fee structures, which compose financial model data, are from the OpenEI U.S. Utility Rate Database, also managed by NREL in partnership with the State University of Illinois, USA. To define the layout of the heliostat field, SAM uses NRE's SolarPILOT™ software to analyze each heliostat based on its generation potential at a given position, allowing more flexibility to mount optimized field models.

3.2 Location

The selected cities, based on their CSP power generation potential, were Apodi, Caicó and Mossoró. Table 1 shows the main parameters provided by the SAM.

Table 1. Climatic data for the three cities. Source: SAM.

City	Latitude	Longitude	DNI (kWh/m ² /year)	Average Temperature (°C)	Average Wind Speed (m/s)
Apodi	-5.67°	-37.78°	2,511.20	27.6	3.6
Caicó	-6.31°	-37.06°	2,430.90	26.8	4.0
Mossoró	-5.19°	-37.34°	2,383.45	27.6	4.7

3.3 Projection of the heliostat field

The position of the heliostat is determined by radial scaling method, where the mirrors are spaced in rows with constant radius (iso-radial lines) and circumferentially spaced along constant azimuth angle lines (iso-azimuthal lines). Physically the heliostats are spaced apart in ΔAz and ΔR as shown in Fig. 4(a).

Figure 4(b) illustrates how a heliostat can influence a later heliostat. Each mirror needs to reflect the solar rays at the center line of the receiver in the region closest to it. However, simulations go much further, assessing the optical efficiency of each and include the cosine effect, attenuation, intercept factor, reflectance, dirt and blocking effects. In this way, the heliostats that have the worst performances are removed from the plant.

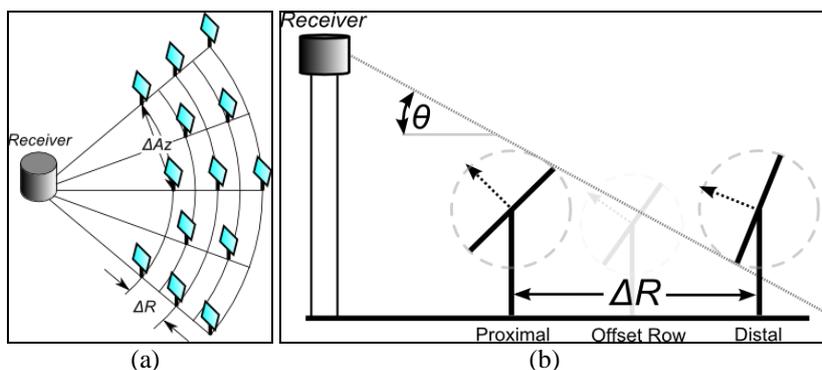


Figure 4. Distribution of heliostats in radial and azimuthal lines. Adapted from: SAM.

According to the authors Montes et al. (2009), Lodi (2011) and Soria (2011), the size of this field depends basically on the solar multiple (SM) adopted for the plant. The SM represents the ratio between the size of the heliostat field and the field required to reach the power capacity of the plant at the instant of the nominal irradiation stipulated in the project and is an important variable to be analyzed, since it is an indicator of plant performance and viability of the project. In addition, the solar field represents the major part of the capital investment, being in a range of 33 and 39 % of the installed power cost. For this reason, the simulation proposes the use of an SM that generates lower costs for the production of energy in the plant for the owner.

The cost for power generation can be measured from different methods and each method has its own meaning within accounting (IRENA, 2018). One such method is based on the Levelized Cost of Electricity (LCOE).

LCOE is an indicator of the price of electricity needed for a project where revenues would equal costs, including return of invested capital equal to the discount rate. An electricity price above this would yield a higher return on capital, while a price below it would produce a lower return on capital, or even a loss. LCOE from renewable sources varies according to technology and design, based on resources, capital, operating costs and technology performance (IRENA, 2018).

The SAM calculates the LCOE by the definition of Eq. (1). Where TCC is the cost of capital (\$), FOC is the fixed annual operating cost (\$), VOC is the variable operating cost (\$/kWh), FCR is the fixed charge rate and AEP is the annual electricity production (kWh).

$$LCOE = (FCR \times TCC + FOC) / AEP + VOC \quad (1)$$

3.4 Cost system

The costs are organized into three categories and their values are filled with reasonable values for the typical project in the US. Analyzes on this scale are still little developed in Brazil, so the default values based on the North American market will be adopted for prior estimation.

In the category of direct capital costs are the expenses with purchases of equipment and installation of labor applied in the year zero of the cash flow. In the indirect costs of capital are framed the expenses with licensing, engineering and territory. Finally, there are the costs of operation and maintenance of labor and equipment. SAM then calculates the total installed cost as the sum of direct and indirect costs.

3.5 Financial model

PPA projects provide electricity at a wholesale rate in order to meet internal rate-of-return requirements through an power purchase agreement. As PPA financial models are more appropriate for large scale models, this will be adopted for the development of this study. In addition, the model will fall into the "single owner" category. The adoption of this category has the advantage of not having to allocate cash and tax benefits to different partners.

The financial model is based on the Power Purchase Agreement (PPA) and the Internal Rate of Return (IRR). The analyst solution module determines whether SAM should calculate the PPA price required to achieve a designer-specified IRR or calculate the IRR based on a PPA also determined by the designer. For the simulation proposed in this work will be specified the IRR and the program will use the algorithm to find the PPA price.

The useful life of both the solar field and the power block is 30 years and 25 years assumed for the storage system (Viebahn et al, 2011), so the analysis period adopted for this study will be 30 years.

Based on the financial values presented by Soria (2014), Oliveira Filho (2014) and Turchi and Heath (2013), Tab. 2 presents the values of the financial and cost parameters assumed in this simulation. For the other values not shown, the program's own standards were used.

Table 2. Values of financial parameters and costs.

Costs	Heliostat field	180 \$/m ²
	Power cycle	1,200 \$/kW _e
	Storage	27 \$/kWh _t
	Land	10,000 \$/acre
	Site improvement	25 \$/m ²
	EPC and owner cost	11 % of direct cost
	Contingency	20 %
Financing	IRR target minimum	15 % year
	Inflation rate	0 %
	Real discount	10 %
	Federal income tax rate	34 %
	Insurance rate	0,5 % of total direct cost
	Salvage value	0 % of total direct cost
	Tenor	16 years
	Interest rate	7,4 % year
	Debt percent	70 %

3.6 System design

Table 3 presents the values of the other input parameters based on the Gemasolar central tower, located in Fuentes de Andalusia (Seville, Spain), which will be used for further comparison and validation of the results. The values were obtained from the case study of NREL and Burgaleta et al (2014).

Table 3. System design values.

Field	Variable	Gemasolar	Simulation
System design	Design turbine gross output	19,9 MW _e	19,9 MW _e
	Turbine efficiency	0.875	0.875
	Thermal cycle efficiency	-	0.412
Heliostat Field	Solar multiple	2.5	2.5
	Multiple field area	1.4	1.4
	Dimensions of heliostats	10.9 m x 10.9 m	10.9 m x 10.9 m
Receiver	HTF hot temperature	565 °C	565 °C
	HTF cold temperature	290 °C	290 °C
Thermal Storage	HFT	Molten salt ¹	Molten salt ¹

	Tank height	10.5 m	10.5 m
	Tank diameter	23 m	22.8 m
	Full load hours	15 h	15 h
	Piping loss coefficient	8,000 W _t /m	8,000 W _t /m

⁽¹⁾ 60 % NaNO₃ 40 % KNO₃

The values in Tab. 4 referring to receiver and tower geometry were determined by optimization performed by the SAM algorithm. Parameters of this nature depend on the conditions and solar resource of the locality and therefore cannot be fixed.

Table 4. Tower and Receiver dimensions.

Field	Variable	Gemasolar	Apodi	Caicó	Mossoró
Tower and Receiver	Receiver height (m)	14.22	8.57	8.57	8.23
	Receiver diameter (m)	8.89	7.16	7.16	7.37
	Tower height (m)	140	97.29	92.11	93.10

4. RESULTS

Figure 5 shows the graph resulting from the optimization of the LCOE as a function of the solar multiple from the values indicated previously. It is possible to observe that in all SM interval Caicó and Mossoró presented close values when compared to Apodi. The latter in turn proved to be the most economically viable location.

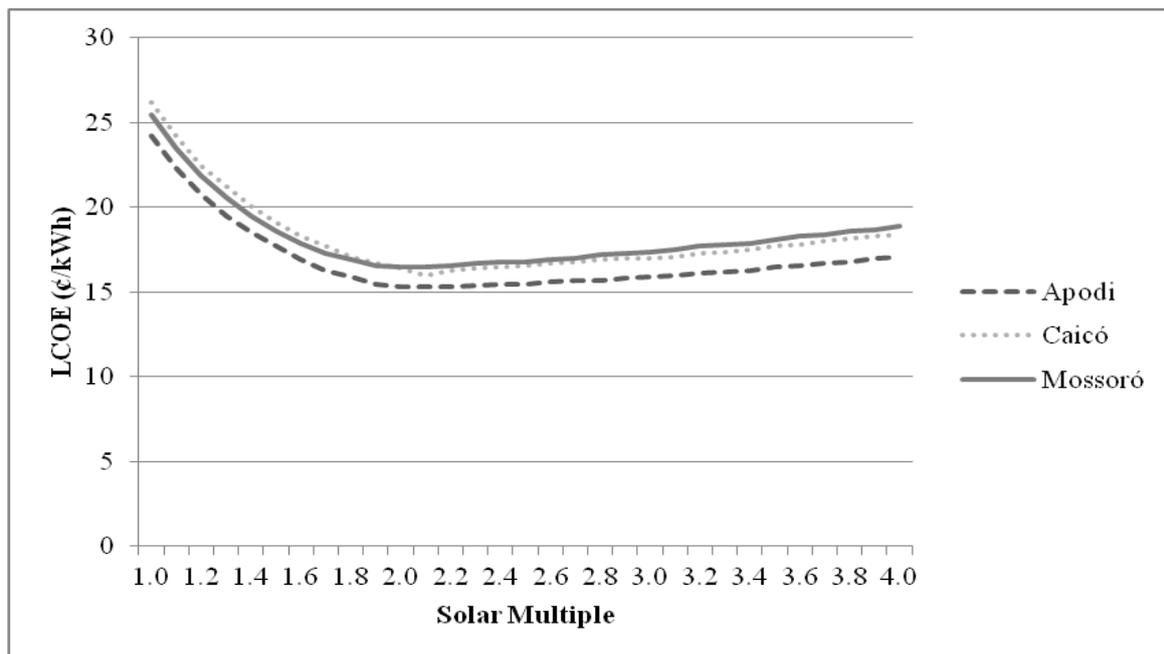


Figure 5. LCOE x SM optimization graph.

It is important to note that Apodi at the same time that presented LCOE lower, is the city, of the three chosen, that presents greater DNI. It is expected that it is also the city with the lowest number of heliostats, because the greater the availability of the solar resource, the smaller the number of collectors (disregarding much of the variables) needed to generate the same capacity (in this case with SM of 2.5 and power of 19.9 MW). In fact, for the same conditions, according to the SAM, 1,903 heliostats are needed for Apodi, 1,928 heliostats for Caicó and 1,923 heliostats for Mossoró.

The values used for the generation of the graph of Fig. 5 showed that for the city of Apodi the most suitable SM is 2.1, reducing the LCOE (with solar multiple of 2.5) from 15.53 ¢/kWh to 15.28 ¢/kWh. For Caicó, the most adequate SM was 2.1, reducing the LCOE from 16.58 ¢/kWh to 16.29 ¢/kWh. For Mossoró, the SM was the lowest, with a value of 2.0, reducing from 16.85 ¢/kWh to 16.46 ¢/kWh.

Table 5 presents the results of the plant in two cases for each city compared to Gemasolar. The first case with SM of 2.5 and the second case with MS with which the lowest LCOE was obtained.

Table 5. Results of the simulations.

Parameters	Gemasolar	Apodi		Caicó		Mossoró	
Solar Multiple	2.5	2.5	2.1	2.5	2.1	2.5	2.0
Annual Energy (kWh)	110,000,000	92,368,824	93,864,168	86,554,888	88,117,600	85,023,184	87,088,456
LCOE (¢/kWh)	-	15.53	15.28	16.58	16.29	16.85	16.46
Capacity Factor (%)	74	60.6	61.5	56.7	57.8	55.7	57.1
Annual Water Usage (m ³)	-	16,768	16,878	16,459	16,574	16,309	16,461

IRENA (2012), in a specific scenario, studied the sensitivity of the LCOE with the discount rate for 2015. The study showed that lowering the discount rate from 10 % to 5.5 % reduces LCOE by 30 % to 32 %. Increasing the discount rate to 12.8 %, the LCOE is raised from 21 % to 22 %, increasing the discount rate to 14.5 %, LCOE increased between 32 % and 35 %.

Observing Tab. 5, the range of LCOE variation was 15.28 ¢/kWh at 16.85 ¢/kWh. IRENA (2012) found an interval for LCOE values of 15 ¢/kWh and 20 ¢/kWh, approximately. This study shows that the LCOE found by the SAM represents a reliable estimate for the proposed project. On the other hand, it is common to find much higher values, but each case presents its peculiarities, because there is a range of factors that are strongly related and that directly influence the LCOE values.

The capacity factor (CF) represents the ratio of the energy actually produced in the year by the energy produced if the plant operated at nominal capacity in the same period, this increases as thermal and fossil storage grows. This value is as important as LCOE and can be seen as a kind of plant efficiency. Apodi presented the best values because even with SM close to the other cities presented lower LCOE (15.28 ¢/kWh), higher annual energy production (about 94 GWh) and consequent higher CF (61.5 %). According to the NREL case study, Gemasolar has 15 % of reserve fossil fuel, which raises its CF when compared to the results of this simulation.

To visualize the sensitivity of the CF with the variation of the SM, the graph of Fig. 6 was assembled. The values generated by the SAM showed that the same SM that generates the lowest LCOE is the same that provides higher CF. In addition, Apodi also showed a more attractive scenario compared to other locations. Throughout the interval, the generation capacity was higher. Caicó and Mossoró continued to present close values.

In view of these analyzes it is possible to conclude that Apodi would be the most suitable place to build the plant of 19.9 MW. However, just like any engineering project, one cannot fail to study the natural resources in the region necessary for the execution of the work.

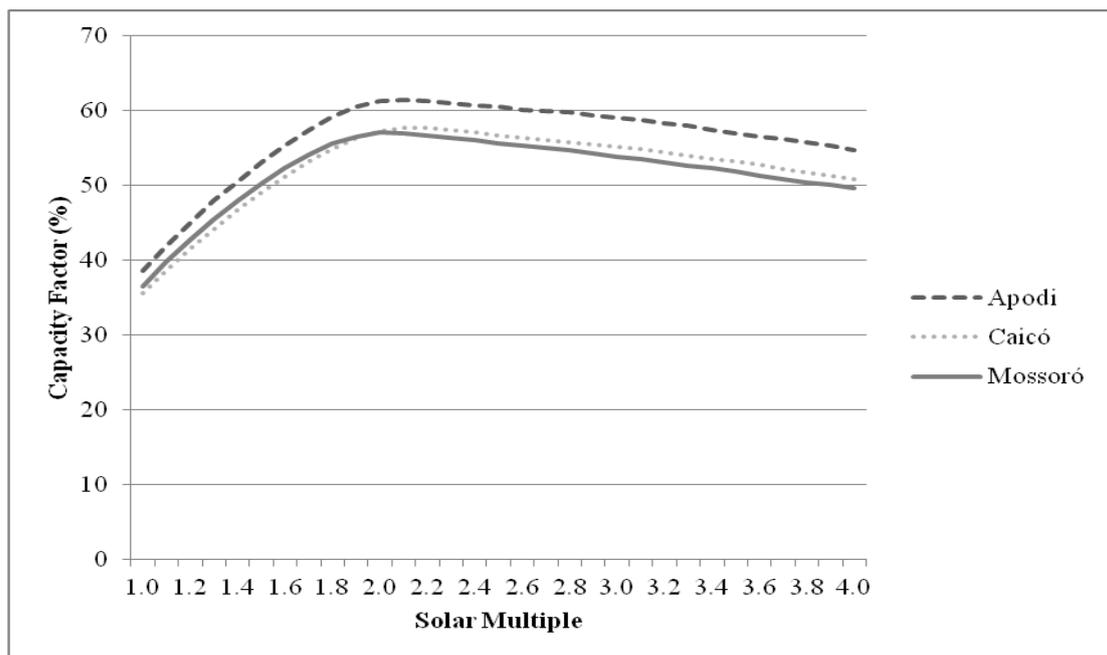


Figure 6. Variation CF x SM.

In relation to water resources, both cases have strong dependence on water, since they operate in the rankine cycle. The municipality of Caicó is located in the areas of the Piranhas-Açu basin and is bathed by the sub-basin of Rio Seridó. In addition, small ponds and small to large reservoirs can be found, such as Itans (81,750,000 m³), Mundo Novo (3,600,000 m³) and Palma (100,000 m³) (Beltrão et al, 2005). For Apodi and Mossoró there is the Apodi/Mossoró Hydrographic Basin, the largest Potiguar basin, where 618 dams were registered, totaling a volume of accumulation of 469,714,600 m³ of water. This corresponds, respectively, to 27.4 % and 10.7 % of the state's accumulated dams and volumes, according to the Instituto de Gestão das Águas do Rio Grande do Norte (IGARN).

Figure 7 shows the distribution of the 1,903 heliostats along 103 hectare, with 162 hectares being the total field area computed heliostat field, tower, power plant, pipeline, storage tanks, buildings, etc. Gemasolar, for example, has 2,650 and occupies an area of 185 hectare.

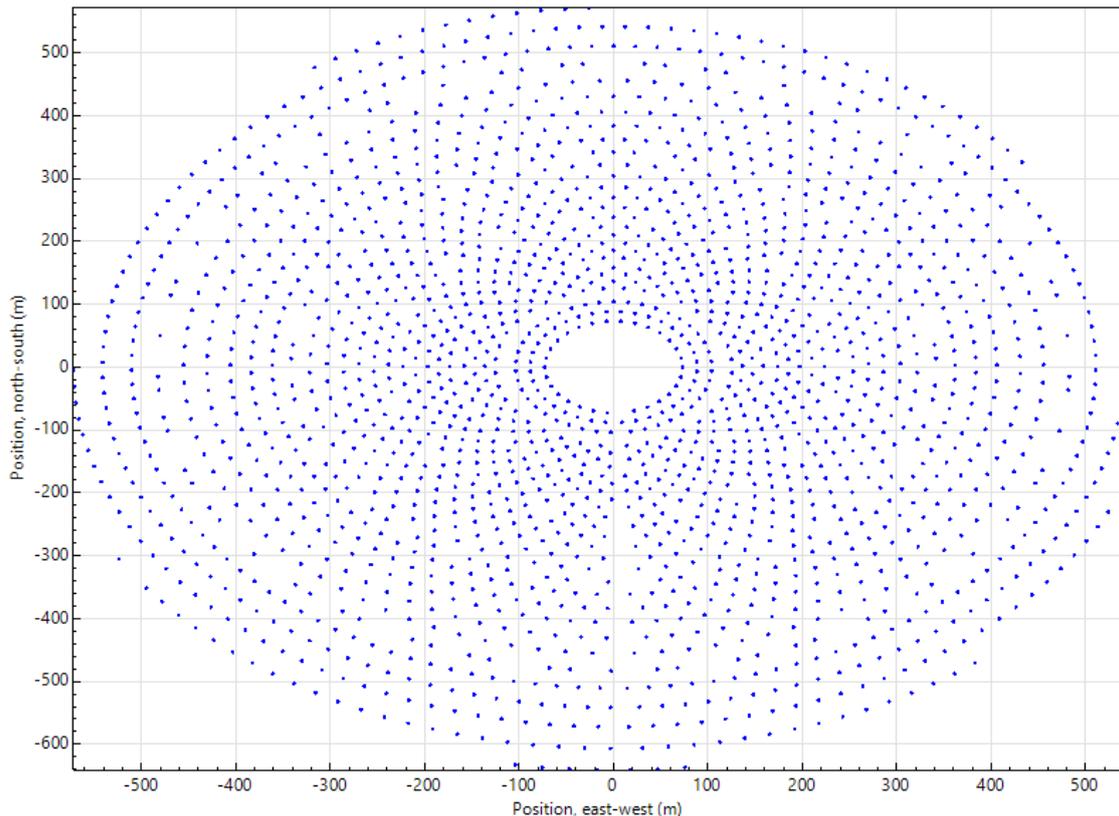


Figure 7. Distribution of heliostats in Apodi for SM de 2.5. Source: SAM.

5. CONCLUSION

CSP plants are alternatives for more sustainable energy production in view of the countries' strong dependence on fossil sources. Considering its importance, this study proposed the feasibility analysis of a plant with the capacity to generate 19.9 MW of electricity. For this, an initial proposal of a solar multiple of 2.5 is in Gemasolar so the cities are for the best value. As simulations for this purpose, do not contemplate less LCOE for design and information saving purposes. Thus, the solar multiple of 2.1 has an optimum LCOE of 15.28 ¢/kWh and 16.29 ¢/kWh for the cities of Apodi and Caicó respectively. For Mossoró the most suitable SM was 2.0, providing an LCOE of 16.46 ¢/kWh.

In general, analyzing only the most important values, such as annual energy production and capacity factor, it is concluded that the city of Apodi was the most favorable for the plant's implementation. It is important to note that the values presented and calculated here serve only as an estimate to guide a project of this scale. Therefore, the values are not entirely true to reality, but serve as an important guide for the study.

Lastly, because Rio Grande do Norte presents high CSP generation potential, this resource should be further explored in view of the environmental need for the reduction of carbon monoxide and carbon dioxide emissions. Further study will provide more and more risk reductions associated with such projects. The dissemination of knowledge in the area still not very encouraged in Brazil is an important means to make the State even more attractive to investments to build power plants in this branch, generating employment and income. New levels can be achieved, keeping Rio Grande do Norte among the largest producers of renewable energy in Brazil.

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