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ANALYSIS OF THE FEASIBILITY OF SOLAR CENTRAL RECEIVER PLANTS IN RIO GRANDE DO NORTE

Cleydson Tiago Ferreira Rufino
Gabriel Ivan Medina Tapia
Universidade Federal do Rio Grande do Norte, Departamento de Engenharia Mecânica, Laboratório de Sistemas Térmicos e Energias Alternativas – LSTEA, Campus Universitário Lagoa Nova, Natal/RN, Brazil
cleydsonrufino@gmail.com, gmedina@ct.ufrn.br

Abstract. *Electricity generation from Concentrated Solar Power (CSP) is growing worldwide, its four technologies are in constant development, but since the 1980s it has been applied commercially. The objective of this work is to make an analysis of the technical and economic feasibility of Central Receiver Systems (CRS) technology in the state of Rio Grande do Norte. CSPs use only Direct Solar Irradiation (DNI) and according to studies the region analyzed receives DNI levels above 2,000 kWh / m² / year and can receive CSP plants. The cities of Caicó and Natal were chosen for the simulations in SAM software, the power of the chosen plants was 20 MW, in the configuration of the plants was incorporated an eight-hour thermal energy storage system and because of the semiarid climate of the region was adopted dry cooling system. Technical parameters such as Solar Multiple, capacity factor, electricity generation and the area occupied by the heliostats were analyzed, and the financial parameters were the levelized cost of electricity (LCOE), Net Present Value, cash flow. According to the results, Caicó has the greatest potential to receive a plant, it presented the best results in all simulations, because Natal receives less DNI and has a wetter climate.*

Keywords: *Concentrated Solar Power, Central Receiver System, Renewable Energy, Economic Viability*

1. INTRODUCTION

Electricity generation from renewable sources in the world grows every year and Concentrated Solar Power (CSP) are clean electric generation technologies, it only needs of high solar radiation in the form of Direct Normal Irradiation (DNI), currently it is in development, implementation and expansion in the market. In 2016, the installed capacity of CSP technology in the world was 4.8 GW and is expected to reach 10 GW in 2022, according to the International Energy Agency (IEA, 2019). CSP technology was first applied in the early twentieth century, but it was not until the 1980s that commercial scale generation began in the US as an alternative for generating electricity because of the oil crisis of the 1970s and only in the 2000s it arrived in Spain, where there were incentive policies.

There are four types of known CSP plants in the world: Central Receiver System (CRS), Parabolic Trough Collector (PTC), Linear Fresnel Reflector (LFR) and Dish Parabolic System (DPS). They may have Energy Storage Systems (TES), these are important because they allow the plant to operate at night and when there is production variability due to fluctuating sunlight during the day (Avapak, 2016).

In this paper only the CRS were cited, they use thousands of individual solar tracking mirrors, called heliostats, to reflect solar energy located on top of a tall tower. The receiver collects heat from the sun in a Heat Transfer Fluid (HTF) that flows through the receiver. (Kalougirou, 2014). HTF goes to the energy block or if there is to the TES, in the energy block there is an energy conversion system that converts the thermal energy into electricity as can be seen in Fig. 1. CSP uses only DNI, these sunbeams do not deviate in their trajectory through the atmosphere to the reflecting mirror. The cooling system can have three modes: dry cooling, wet cooling and hybrid cooling.

CRS plants are growing worldwide, in 2014 CRS contributed only 0.5 GW, currently reaching above 2 GW and by 2021 it is estimated to reach 3.5 GW of installed power, according to data from National Renewable Energy Laboratory (NREL, 2019).

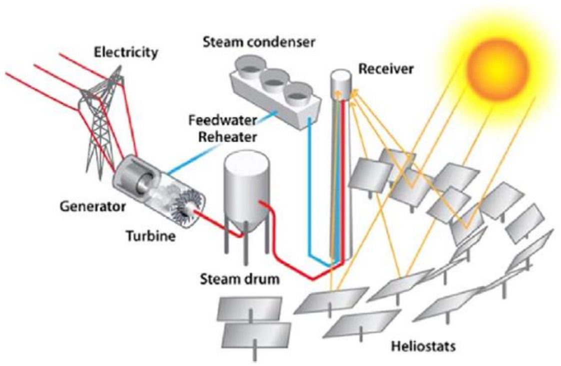

Figure 1. CSP Power Plant Central Receiver System (Source: Purohit and Purohit, 2017).

Brazil is the largest generator of electricity based on renewable sources in the world in relation to the generation of other countries, but the main source of generation is hydroelectric (69.94%) followed by thermoelectric (19.83%) and wind (7.37%), according to the National Electric System Operator (ONS, 2018). However, hydroelectric plants due to the lack of rain in their dams and rivers are decreasing their production in recent years, increasing the use of thermoelectric plants, increasing the cost of production and polluting the environment with CO_2 emissions. The use of CSP plants is an alternative in the region because of the characteristics of the semiarid climate, characteristic of Rio Grande do Norte. According to Azevedo and Tiba (2013), they must be installed in semi-arid regions with low population density and lands that do not compete for other nobler uses. In Brazil, there are few studies and initiatives to develop CSP plants, it is possible to mention Soria (2011), who analyzed through SAM software technical parameters and the Levelized Cost of Electricity (LCOE) in the city of Campo Grande, Mato Grosso do Sul with the influence of TES and hybridization on a PTC plant, Malagueta (2013), which evaluated alternatives to introduce the technology in Brazil, using SAM software, evaluated several models in a scenario for PTC plants in Bom Jesus da Lapa, Bahia, considering almost all the economic and financial parameters in force, however in other countries there are many studies such as Calamateo and Zhou (2015) who did an analysis of a small CSP plant with industrial application in California, USA, using SAM software, Musi et al. (2017) analyzed CSP plants in terms of LCOE, Meybody and Beath (2017) applied the study in three Australian cities at SAM, commented on some curve adjustments that manufacturers report, stressed the uncertainty of cost and the variability of solar data for the study.

The objective of the study was to analyze the technical and economic viability relating technical parameters such as Capacity Factor (CF), Solar Multiple (SM), base land area occupied by heliostats, power generation and financial parameters such as LCOE, Net Present Value (NPV) and cash flow. After analyzing some nominal costs of the plant, the latter two were made only for the plants chosen to be analyzed from the first results, examining whether it is feasible to use CSP in Rio Grande do Norte, where water resources are scarce and solar radiation and average temperatures are high, so that in the future CSP plants will be incorporated into the National Interconnected System, reducing losses caused by the distance between current plants and consumers and being another source of renewable energy.

According to IRENA (2018), auction results suggest that by 2020 the overall weighted average cost of CSP technology and offshore wind will provide electricity between 0.06 ₡/kWh and 0.10 ₡/kWh by 2020. For projects hydropower the cost is 0.05 ₡/kWh, 0.06 ₡/kWh for onshore wind energy and 0.07 ₡/kWh for bioenergy and geothermal projects and 0.10 ₡/kWh for photovoltaic solar energy in 2017.

For the analysis were chosen two cities of the state of Rio Grande do Norte, Caicó and Natal for the simulations, the cities were chosen for their importance in the state, because of their growth today, according to Furtado et al. (2017), the Natal region consumed 2,653.19 GWh and the Caicó region consumed 220.64 GWh in 2015, 48.1% and 4% respectively of the state consumption.

2. METHODOLOGY

In this work has been used the software SAM (System Advisor Model), version 2018.11.11, developed by NREL, which performs simulations calculating the electrical output of the power system. The sum of these values is the total annual output that the financial model used to calculate projected annual cash flows and financial metrics. For the simulations has been used the financial model of Power Purchase Agreement (PPA), available on software.

Initially two cities were chosen, and the weather data was downloaded from the software itself, according to Purohit and Purohit (2017). Locations with DNI above 1,800 kWh/m²/year up to 2,000 kWh/m²/year can be economically viable with the technology current and attractive financial arrangements and locations with DNI over 2,000 kWh/m²/year can already receive CSP plants, as these locations have comparable irradiation to plants installed in the U.S.A and Spain. As can be seen in Fig. 2. these irradiation levels reach the surface of Rio Grande do Norte.

The simulations have been made for 20 MW power plants for each chosen city. Then some standard software information was changed to get a satisfactory level of comparison with CRS plants in the world. For each simulation some technical data has been adopted according to some CRS plants around the world in operation or under construction, this data is accessible in various documents in the world of government institutions and websites and the changed financial data is from other renewable generation sources in Brazil and its economy, the other data used are software standards.

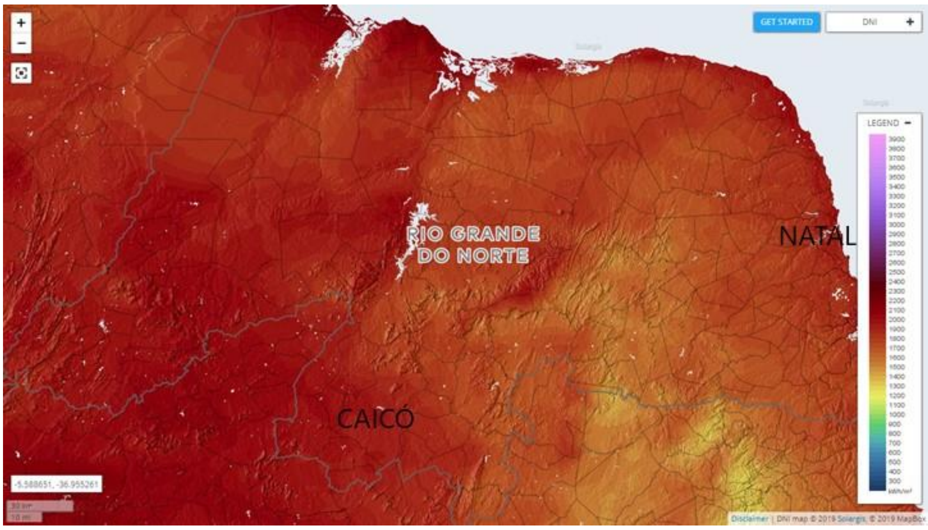

Figure 2. DNI map in the state of Rio Grande do Norte.
Available in: https://globalsolaratlas.info

In Tab. 1, the following is some information that was obtained from the software itself by choosing the option to download locations and resources. The technical-economic parameters have been analyzed separately to observe the behavior of each parameter according to the SM and then analyzed together to choose a satisfactory configuration according to each simulation. So, by choosing these simulations, a little cash flow analysis was done and the NPV of each chosen plant configuration was presented.

Table 1. DNI, latitude and longitude data of the chosen cities. (Source: SAM, 2019).

Cities	Caicó	Natal
DNI (kWh/m²/year)	2,452.80	2,281.25
Latitude	-6.47	-5.79
Longitude	-37.10	-35.22

2.1 Technical parameters

The following technical parameters have been analyzed: the SM which is a dimensionless parameter which is an important indicator because it represents the relationship between solar energy collected at the design point to the amount of solar energy required to generate a gross turbine power, a SM of 1.0 means that the solar field provides exactly the amount of power needed to operate the factory at project exit (Calamateo and Zhou, 2015). The CF is the relation between the actual output of a solar plant in the year and the maximum possible output during a year under optimal conditions (Purohit and Purohit, 2017), and according to Green et al. (2014) typical CF for intermittent renewable energy are between 20% and 40%, but there are projects in the world that offer CF above 50%, this rate was considered satisfactory for the analysis. The base land area occupied by heliostats is the total area where the reflecting mirrors (heliostats) are located, this directly influences the final construction value of the plant, but it depends on the configuration of the heliostats around the tower, this configuration may occupy a larger or smaller area depending on the geography. and local solar irradiation and the expected annual electricity generation from the CSP plant. Tab. 2, shows the technical specifications adopted in the software for all simulations.

The data in Table 2 corresponding to the area of each heliostat is the same as for the 19.9 MW Gemasolar plant and the 20.0 MW PS20 gross power plant, all in Spain. Hot and cold HTF temperatures have been obtained as operating temperatures at the CRS Gemasolar plant in Spain, these data according to NREL (2019). Dry bulb temperatures are different for each city, they depend on climate data from both cities, has been used the maximum temperatures obtained according to the National Institute for Space Research (INPE, 2019).

The simulations have been made for 20 MW power plants, varying the SM from one to three, to observe the behavior of variables such as capacity factor, solar field area and annual electricity production, so the software optimized for each SM its plant configuration by determining several heliostats, tower height and receiver dimensions. All simulations have TES power plant configurations present in all simulations, and it is of the indirect type. The cooling system will be dry type due to the characteristics of the semiarid region.

Table 2. General technical specifications used for all simulations.

Technical specifications	Caicó	Natal
Single heliostat area (m²)	120.009	
Heat Transfer Fluid	Molten salt, 60% $NaNO_3$ and 40% KNO_3	
HTF hot temperature (°C)	565	
HTF cold temperature (°C)	290	
Cycle thermal efficiency	0.412	
Boiler operating pressure (bar)	100	
Full load hours of storage (h)	8.0	
Dry bulb temperature (°C)	34.0	30.0

2.2 Financial parameters

The LCOE is the main financial parameter, it is the relation between lifetime costs and lifetime electricity generation, both of which are discounted back to an ordinary year using a discount rate that reflects the average cost of capital (IRENA, 2018), as seen in Eq. (1), where I_t is the investment in year t, $O\&M_t$ is the operating and maintenance expense in year t, F_t is the fuel expense in year t, E_t is the electricity generation in year t, r is the discount rate and n is the lifetime of the system.

$$LCOE = \frac{\sum_{t=1}^{n} \frac{I_t + O\&M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \tag{1}$$

To calculate the cost of electricity generated, the software lists various costs (direct and indirect installation, operation and maintenance, taxes, Internal Rate of Return (IRR), incentives and depreciation). However, as CSP technology is non-existent on commercial scale in Brazil, it is necessary a market study, tax regulation of Regulatory Agencies and administrative agencies to reach accurate values, which is not the objective of this work, so the data that are software standard for CSP technology, there have only been changes to known data in the Brazilian economy as well as some fees that were found in use at CRS plants or federal and state government application fees at another renewable source, for example photovoltaic solar energy generation.

Regarding the contingency percentage value, the software default value is 7%, Malagueta (2013) considered 20% in his work, a conservative value because the country has not established development for all areas of the plant implementation. In this paper, the contingency value of 15% was admitted, also a conservative value, but lower due to the advancement of technology in the world, according to Leite (2001), contingent is what is uncertain or not, regardless of knowledge and relative probability value.

The inflation rate applied in this paper was the average of the accumulated inflation of the year between 2016 and 2018 of Brazil. Regarding federal and state government taxes, the same tax rate for photovoltaic modules was generally applied, with the tax reduction policies for technology promotion in the country, according to the final report of the photovoltaic solar working group of Ministry of Industry, Foreign Trade and Services, the photovoltaic module has a federal tax rate of 12%, this percentage is the import tax, there is exemption from PIS and COFINS because it was considered the Special Incentive Regime for Infrastructure Development (REIDI), intended for centralized generation in photovoltaic plants, for state governments that include taxes such as IPI and ICMS, there is exemption for IPI, but ICMS has aliquot of 18% rate applied to the amount (BRASIL, 2018). Photovoltaic modules are also exempt from ICMS because Rio Grande do Norte has adhered to the CONFAZ 16/2015 Agreement, but this agreement is for micro and mini generation, considering a generating plant up to 5 MW of installed power, according to ANEEL (2019) exemption is not presented for CSP of this work either. All other financial values are software standards. In Table 3 below are some important financial data for this study.

After the simulations, will be presented for the first plants that presented the capacity factor greater than 50%, some other technical data of these followed by a financial analysis, with NPV, cash flow and operating costs, administrative and economic costs of the plants chosen. The NPV of a project is the sum of the present values of each cash flow, positive and negative, that occur over the life of a project, if NPV is positive, it indicates an economically viable project, if negative, the project is not viable (Urtado et al., 2009). Cash flow is an accounting statement whose purpose is to highlight the impact of the company's activities on cash behavior (Spadin, 2008). Importantly, these values do not include fees and taxes that are only used to calculate the actual LCOE, which is the value used in this work, only the values that are inherent to the activities of each plant. Depreciation was as per software standard.

Table 3. Financial specifications used for all simulations.

Financial specifications		
Direct costs	Heliostat field cost (US$/m²)	140.00
	Tower cost fixed (US$)	3,000,000.00
	Receiver reference cost (US$)	103,000,000.00
	Thermal energy storage cost (US$/kWht)	22.00
	Power cycle cost (US$/kWe)	290.00
	Contingency cost (%)	15
Operation and Maintenance	Fixed cost by capacity (US$/kW-yr)	66.00
	Variable cost by generation (US$/MWh)	3.50
Financial parameters	IRR target (%)	11
	Analysis period (yr)	25
	Inflation rate (%/yr)	4.33
	Federal income tax rate (%/yr)	12
	State income tax rate (%/yr)	18
	Sales tax (% of total direct cost)	5

3. RESULTS

3.1 Solar Multiple *x* LCOE

According to Fig. 3, the best LCOE results for the whole range of MS were in Caicó, the lowest value found in the SM was 2.6 when the LCOE was 10.66 ₵/kWh. The lowest value in Natal was in the SM equal to 2.8 when the LCOE was 11.55 ₵/kWh. Between the two cities, there was a difference of less than 1.0 ₵/kWh between the SM equal to 2.5 and 3.0, and the smallest difference was in the SM equal to 2.7 when the LCOE was equal to 0.82 ₵/kWh.

From the SM equal to 2.3 in Caicó, the LCOE was below 11.0 ₵/kWh, being the only city to reach this value. With these results for the adopted conditions, Caicó obtained better LCOE values than Natal for having higher DNI, presenting the most competitive prices.

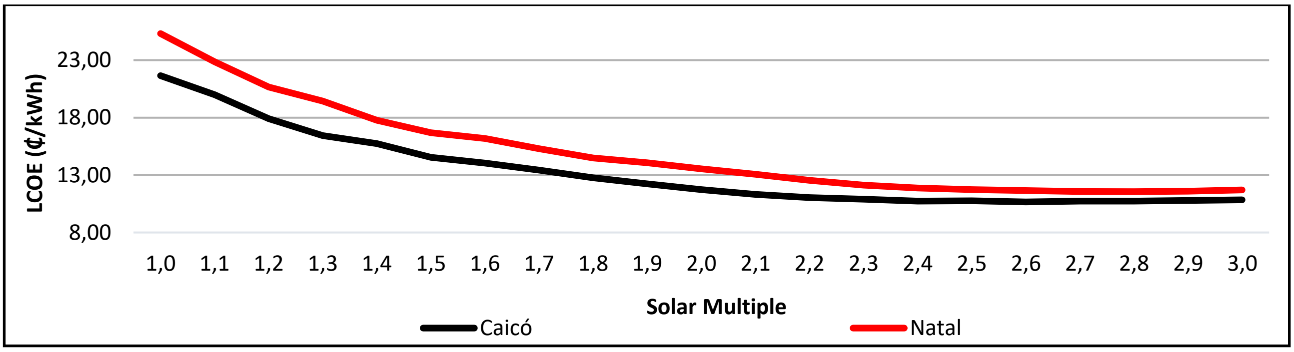

Figura 3 – Relation between SM and LCOE to Caicó and Natal plants.

3.2 Solar Multiple *x* Capacity factor

In Fig. 4 presented that the capacity factor for Caicó is the highest for all interval. All plants had their lowest capacity factor in SM equal to 1.0, Caicó with 18.91% and Natal with 16.12% and its largest in SM equal to 3.0 when Caicó is 58.77% and Natal is 54.23%.

For the MS near 3.0, the growth rate of all decreased, the growth rate was not greater than 2% for Caicó after the SM equal to 2.3 and Natal after the SM equal to 2.4.

It has been considered a good capacity factor above 50% and this rate was first exceeded by Caicó in the SM equal to 2.3, when it obtained 51.89% and Natal only in the SM equal to 2.6 reached 50.86%.

The largest difference presented between the rates was in the SM equal to 2.0, when Caicó had a rate of 45.25% and Natal had a rate of 38.64%, being the difference equal to 6.61% and the smallest difference was in the SM equal to 1.1, also among the same plants when Caicó presented a rate of 21.14% and Natal of 18.41%.

In the relation of the SM with the capacity factor, the superiority of the Caicó simulation is explained by the high DNI and the semiarid climate of the region.

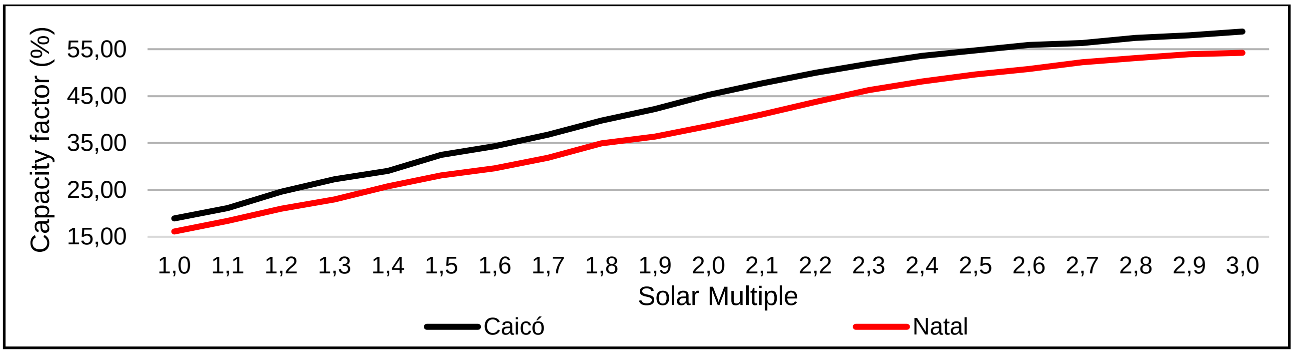

Figure 4 – Relation between SM and Capacity factor to Caicó and Natal plants.

3.3 Solar Multiple *x* Annual energy

Fig. 5 presents the expected electricity generation for each simulation according to the adopted conditions, but the hourly demand situation of the region was not considered. The Caicó plant obtained better results than for Natal for the whole interval, both obtaining the lowest generation for SM equal to 1.0 when Caicó has expected generation at 29,821,300 kWh and Natal obtained 25,420,500 kWh and the largest generation. in SM equal to 3.0 when Caicó obtained a generation of 92,660,900 kWh and Natal obtained 82,510,500 kWh.

The largest growth from one SM to another for Caicó was in the SM equal to 1.4 to 1.5, when the generation increased by 5,293,000 kWh and for Natal it was in the SM equal to 1.7 to 1.8 when the increase was 4,807,700 kWh. The biggest difference in generation between them was in SM equal to 2.1, when Caicó generated 10,427,800 kWh more than Natal.

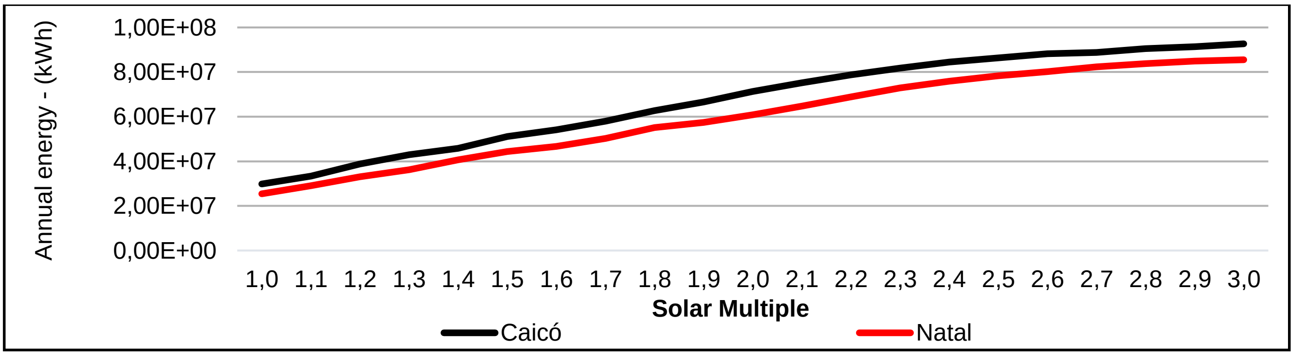

Figure 5 - Relation between SM and Annual energy to Caicó and Natal plants.

3.4 Solar Multiple *x* Base land area occupied by heliostats

Fig. 6 presents the base land area occupied by heliostats of each simulated CRS plant, the plants alternate in the best results, where Caicó was twelve times better than Natal and this was nine times better than Caicó.

Caicó had the smallest base land in the SM equal to 1.1 when it had 0.717 km², which is the smallest base land found, and Natal in the SM equal to 1.0 when its base land obtained an area of 0.776 km². And Caicó obtained its largest base land in the MS equal to 3.0 with an area of 2.097 km², which is the largest base land found in the simulations, and Natal in the SM equal to 2.8 obtained its largest base land with an area of 1.847 km².

In the SM equal to 1.6, there were the largest base land reductions compared to the previous SM, and in the SM equal to 3.0 there was the largest difference between the base land, when the Caicó plant was larger than that of Natal in 0.281 km² in area, but in the SM equal to 2.3, Caicó was less than Natal about 0.221 km².

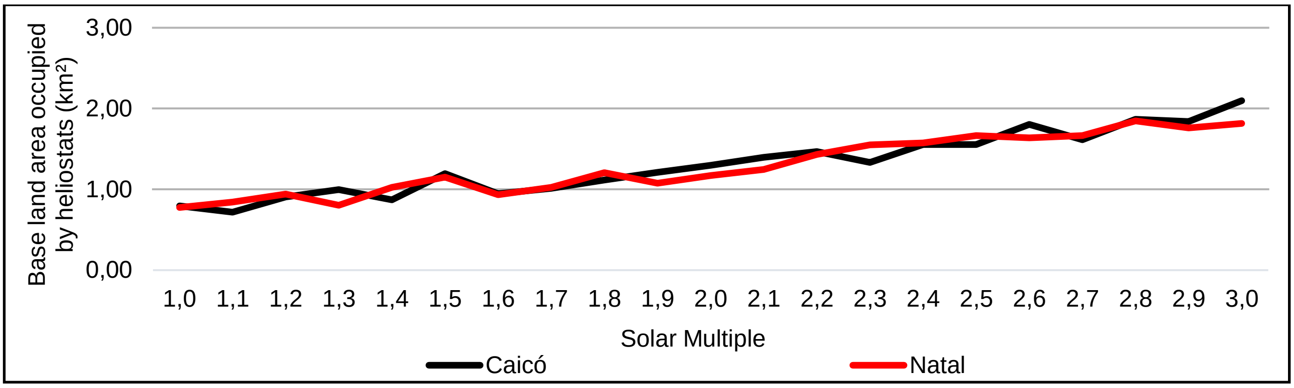

Figure 6 – Relation between SM and Base land area occupied by heliostats to Caicó and Natal plants.

3.5 Net Present Value and cash flow analyzed

The Caicó plant in the SM of 2.3 and the Natal plant in the SM of 2.6 were chosen for analysis in this topic because they reached a level of CF greater than 50% first among them, so some data are presented in Tab. 4 below shows other technical characteristics such as tower height, number of heliostats, amount of water used in the plants and the NPV of each plant as a financial characteristic to better illustrate each configuration.

Table 4 – Technical and financial parameters of the plants chosen for financial analysis

Parameters	Caicó	Natal
SM	2.3	2.6
LCOE (₵/kWh)	10.89	11.64
CF (%)	51.89	50.81
Annual Energy (kWh)	81,814,880	80,120,736
Base land area occupied by heliostats (km²)	1,332	1,638
Tower height (m)	100,57	96,89
Number of heliostats	1,670	1,933
Water used annually (m³)	14,965	16,281
Net Present Value ($)	3,514,354	3,733,616

As the NPV of the chosen plants is positive, they are viable for the adopted conditions. Below in Fig. 7 is presented the cash flow in the first 25 years of life of each plant. In the first year there is the largest cost due to the initial expenses with the works and commissioning to put the plant into operation, around US$ 70.3 million to Caicó and US$ 74.4 million for Natal, but in the second year with the start of operation of the plants was a good recovery of both with US$ 48.4 million to Caicó and US$ 51.2 million to Natal. Between year 2 and year 16, there was an average cash flow of US$ 2.44 million to Caicó and US$ 2.58 million for Natal, in year 17 there was a slight loss of both, about US$ 151,000 to Caicó and US$ 160,000 to Natal, and between 18 and 25 the average cash flow to Caicó was US$ 7.20 million and US$ 7.65 million to Natal.

This cash flow is calculated to various segments of the plant's accounting, including operating, management and development costs, financing, etc. Fig. 8 below shows the operation costs of each plant in 25 years, the values below are nominal, not including inflation. Caicó's plant had an average operating cost of US$ 7.89 million per year and Natal had a higher average of about US$ 8.36 million, after 25 years the Caicó plant had a total operating cost of US$ 197.32 million and Natal of US$ 209.06 million. So, the Caicó's plant obtained the lowest LCOE values, achieved a capacity factor for a lower SM than Natal, has the highest expected electricity generation for a smaller base land area occupied by heliostats than Natal and even obtained the lowest operating costs.

The simulated total cost is divided by the invested software, which was about 46.5% of the total invested, the remainder is similar to a financed amount and this financing for both factories is completed in year 18 and has an average annual cost of US$ 4.49 million and total cost of US$ 80.84 million to Caicó and annual average cost of US$ 4.75 million and total cost of US$ 85.43 million to Natal.

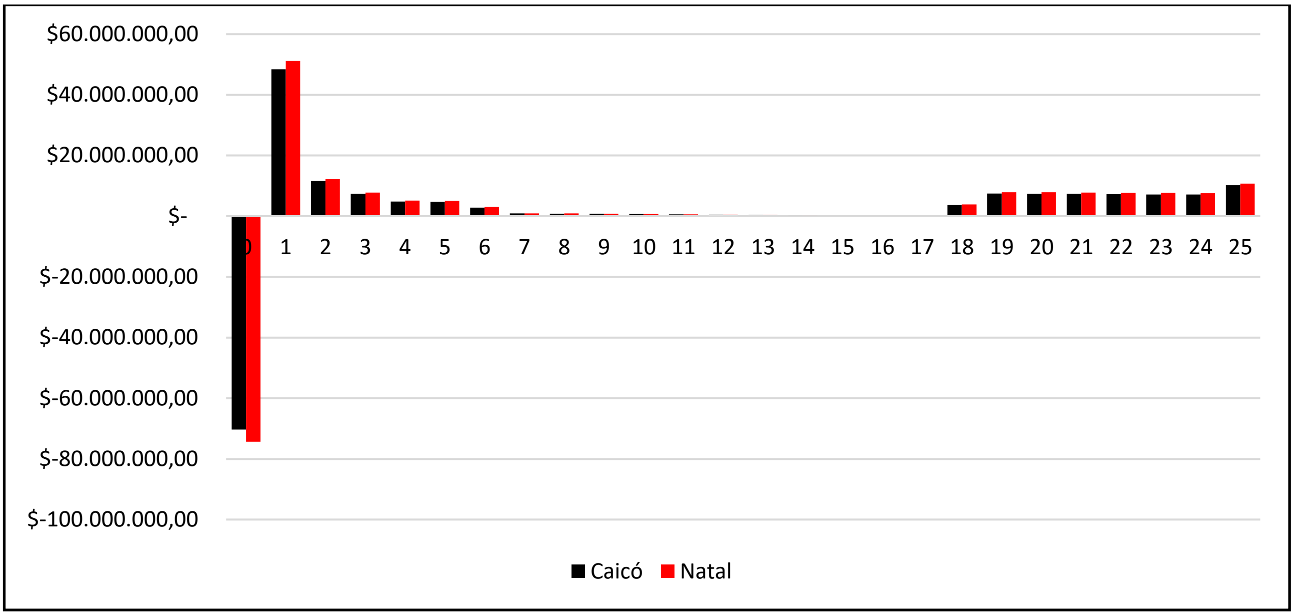

Figure 7 – Cash flow from Caicó and Natal plants.

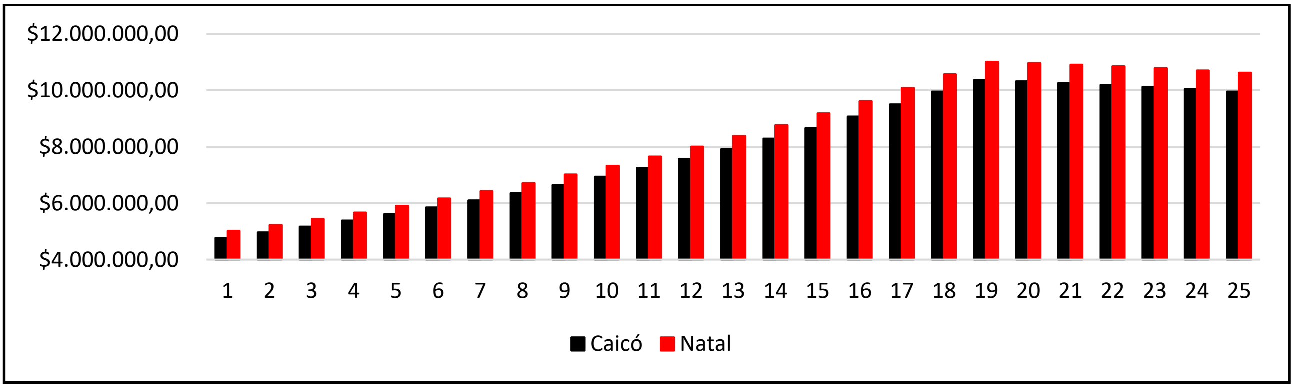

Figure 8 – Operating costs from Caicó and Natal plants.

4. CONCLUSION

With the predominantly semi-arid climate, the state of Rio Grande do Norte may be an option for renewable energy, especially concentrated solar energy, the results showed that Caicó has good potential to receive this technology, Natal is a coastal city and has a climate wetter compared to Caicó, showed worse results. Caicó, in the SM equal to 2.3, the simulation had expected electric generation approximately 371 times that consumed by the city in 2015, but this plant of only 20 MW could supply electricity to the entire southern and northern regions of the state of Paraíba, because Caicó is border of the two states. The 20 MW plant for Natal, simulated in the SM of 2.6, generated approximately 30 times the electricity consumed in the city in 2015 because it is the state capital, has the largest population, industry, commerce is also high, the demand for energy is also higher.

More detailed consumption and site geography studies are needed to determine an accurate nominal LCOE value, capacity factor, base land area occupied by heliostats, expected electricity generation and to know how public and private investments and financing will be made in the future to get at a value of real LCOE, NPV, real cash flow with fees and taxes inherent to operating and economic and financial activities, to include this technology in ANEEL's energy auctions, for a differentiated option of renewable energy generation because the TES as well as offering job creation, regional development and a possible lower cost of electricity, due to the lower use of thermoelectric plants, thus also reducing CO_2 emissions into the atmosphere.

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