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SIMULATION OF CSP POWER PLANTS IN THE WESTERN MESOREGION OF THE STATE OF RIO GRANDE DO NORTE – BR

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Abstract. In order to diversify the electricity generation sustainably, through renewable sources, the state of Rio Grande do Norte - RN, Brazil has a high potential to explore the solar resource. Since it is located at low latitudes, the state receives high levels of Direct Normal Irradiance - DNI, ideal scenario for Concentrating Solar Power – CSP exploration, indicating that this technology might be the way to broaden the electricity generation matrix. This work presents simulations results made with the software System Advisor Model - SAM for each one of the four CSP technologies (Parabolic Trough Collector, Linear Fresnel, Central Power Tower and Parabolic Dish) to a location close to the city of Apodi, in order to determine the most viable among them, based on land area requirements, energy output and annual water consumption. The results suggest that for plants with Thermal Energy Storage (TES) systems, the most suitable technology is Linear Fresnel Receiver that presented the greatest generation per unit area in a year, 203.84 GWh/km², and the lowest water consumption per generated power, while the Parabolic Dish turned up to be the best option when not considering TES, since it presented the higher annual generation per land-use among the considered technologies.

Keywords: CSP, Simulation, SAM, Solar thermal power

1. INTRODUCTION

According to the National Agency of Electrical Energy - ANEEL (2018), hydropower is the main source of electrical generation in Brazil, accounting with 1315 hydroelectric plants generating approximately 60.9% of the electricity produced within the country, followed by fossil fuel, representing around 16.1% and, furthermore, it is necessary to import 4.9% from neighbor countries as Paraguay and Argentina. However, as reported by the Energy Information Administration (2017) in the International Energy Outlook 2017, there is a projection that the world energy demand might increase by 28% between the years of 2015 and 2040, indicating that alternative ways of electricity generation, such as wind and solar power, must be explored.

In this context, there have been increasing investments to explore these free and renewable sources by the Brazilian government, especially in the wind power sector which represents 7.5% of the national installed capacity (ANEEL, 2018). The state of Rio Grande do Norte - RN is the leader in electricity generation through wind power and owns 27.8% of the national installed capacity (CCEE, 2018). Analyzing the year of 2015, the state produced 65% more than the internal demand, besides that, 71% of the electricity produced in the state originated from wind energy (Ministério de Minas e Energia, 2016).

Despite that the electric production of the Rio Grande do Norte be predominantly renewable, it is not diversified and is still dependent of fossil fuels. The solar potential of Rio Grande do Norte could be the alternative to generate electricity in a more sustainable way, since the state is located at low latitudes, implicating in high levels of Direct Normal Irradiance – DNI, as illustrated by Fig 1.

Blanc *et al.* (2014) defined DNI as the direct irradiance received on a plane normal to the sun over the total solar spectrum, and it is the component of the global irradiance used by the Concentrating Solar Technologies - CST.

Areas with DNI $\geq$ 2000 kWh/m²/year are considered highly potential to development of CSP power plants. By analyzing Fig. 1, it is safe to conclude that approximately 1/3 of the land area of the Rio Grande do Norte meets this requirement. However, Purohit *et al.* (2013) estimate that in a medium term, locations with DNI between 1600 and 1800 kWh/m²/year became economically viable.
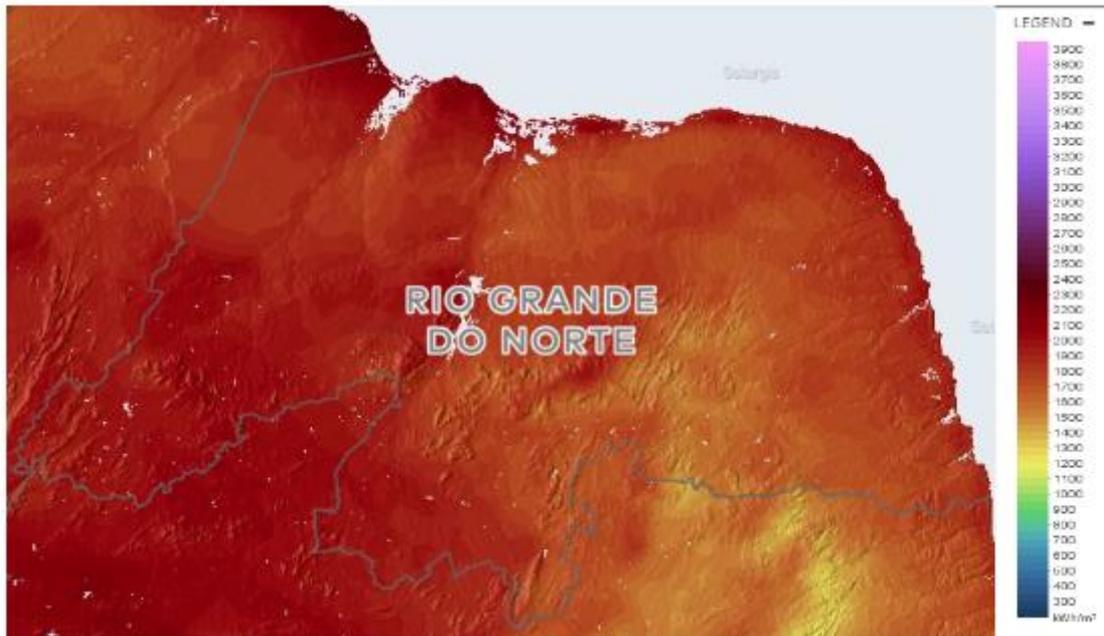
Figure 1. DNI in the state of Rio Grande do Norte (Solargis, 2018).

The study presented by Dale (2013) compared energy costs of different ways of electricity generation through renewable sources, such as photovoltaic, solar thermal (Concentrating Solar Power - CSP) and wind power, using the parameters of overnight capital cost, operating costs and Levelized Cost of Electricity – LCOE. The work indicated that the most economically viable were: wind power, followed by CSP and then photovoltaics.

Since the wind power potential of the state is already being explored, CSP systems might be the way to diversify the electric generation of the Rio Grande do Norte.

However, to select the most suitable CSP technology, it is indispensable a detailed study of the region, taking in account parameters like the region's economy, geography, meteorology and environmental factors besides the DNI criteria.

To perform this kind of analysis, the System Advisor Model – SAM, simulation software developed by the National and Renewable Energy Laboratory, stands out for being an open source tool capable of performing technical and economic analysis of several energy systems based on renewable sources.

2. OVERVIEW OF CSP TECHNOLOGY

The concentrating solar power technology consists in converting the solar irradiation into thermal energy and finally in electricity. The system uses mirrors to concentrate the DNI on a focus, which can be either linear, or punctual. A Heat Transfer Fluid – HTF flows through the focus, absorbing this energy and increasing its temperature. Following to a heat exchanger, water is heated up by the HTF in order to generate superheated steam, used to drive a steam turbine located in the power block, which is based on thermodynamic cycles as the Rankine, Brayton or a Stirling engine, in the case of the dish systems. Finally, a generator attached to the steam turbine produces electricity.

As an alternative way to the use of synthetic oil or molten salt as HTF, the direct steam generation (DSG) systems use water as working fluid, where steam is generated directly in the heat absorbers tube. The use of this cycle allows the system to reach higher temperatures, once limited by the HTF properties, like the 400°C limit of the synthetic oils, and still dispenses the use of heat exchangers (Guo et al., 2018). In addition, a thermal storage system - TES can be installed, so the plant would generate electricity in cloudy days or after sunset (Baharoon et al., 2015). Figure 2 shows a schematic view of the stages in generating electricity through CSP power plants.
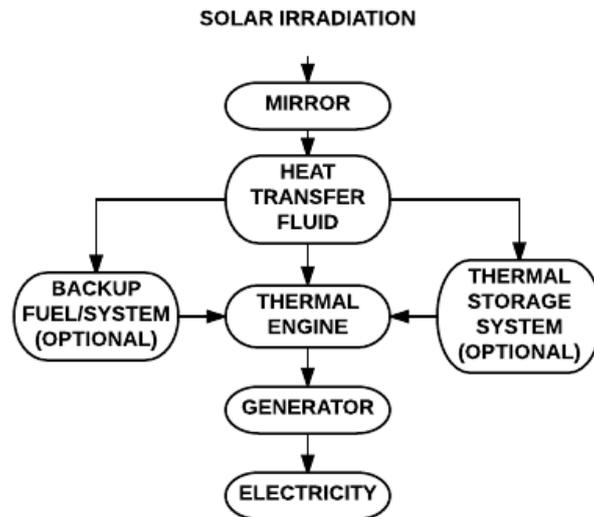
Figure 2. Scheme of a CSP system.

There are four CSP technologies available nowadays: Parabolic Through Collector (PTC), Linear Fresnel (LF), Parabolic Dish (PD) and Central Power Tower (CPT or Central Receiver System, CRS), Fig. 3 illustrates the technologies according to its focus configuration. Each of these technologies has the same basic elements: mirrors, HTF, thermal engine and generator.

Despite having the same basic structure, each configuration differs in some aspect, for example: reflector shape, working temperature, efficiency, cost, thermal engine, thermal storage system and hybridization possibility.
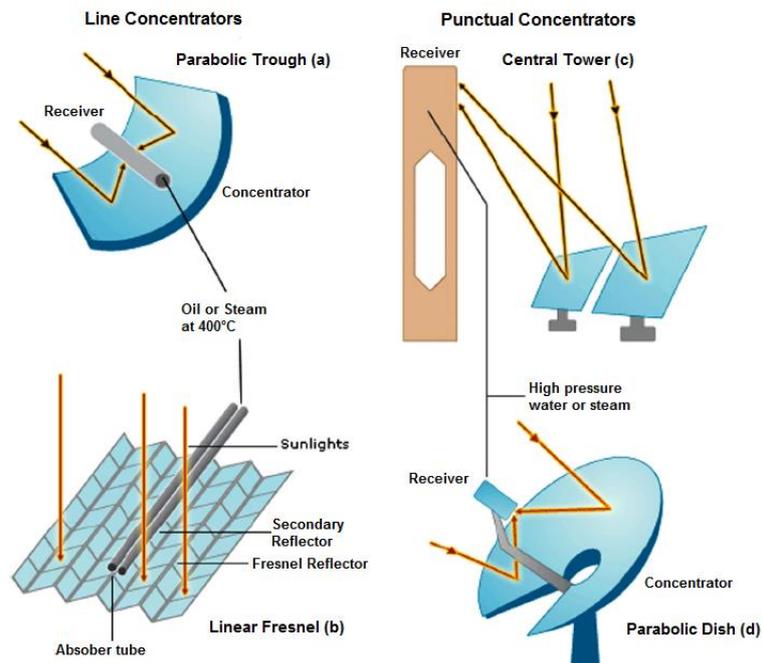

Figure 3. CSP technologies (Adapted from Purohit and Purohit (2013))

2.1 Parabolic Trough Collector (PTC)

The Parabolic Trough Collector technology is the most common among the operational CSP power plants, according to Tab. 1, it represents approximately 85.4% of the installed capacity.

In PTC systems, solar collectors (mirrors) shaped based on a parabola are used to concentrate the solar radiation on the absorber tubes located at the linear focus, as illustrated by Fig. 3a. The HTF flows in the receivers, which move simultaneously with the mirrors, due to a single-axis tracking system used to orient both toward the sun (IRENA, 2012), allowing the system to absorb more energy.

Depending on the HTF, the system can achieve 400°C when using synthetic thermal oil, 550°C with molten salt and 500°C in case of pressurized water (DSG) (Baharoon *et al.*, 2015).

2.2 Linear Fresnel (LF)

There are two types of Fresnel collectors: the Linear Fresnel Reflector (LFR) and the Fresnel Lens Collector (FLC). LFRs have taken place in the field of concentrating solar systems and have been widely investigated for its simplicity in manufacturing, operation and maintenance (Purohit and Purohit, 2017). The LFR field can be imagined as a broken-up parabolic trough reflector, where receiver and mirrors are disassociated (Chu and Maisen, 2011).

The LFC technology consists in using strips of mirrors to concentrate the DNI onto the receivers, where the HTF flows. Differently from the PTC, the reflectors move independent of the collector, not requiring the use of flexible connections for the piping system, once the focus does not move.

According to Baharoon *et al.* (2015), the use of water as working fluid can make it possible to generate saturated steam with pressures 50 times the atmospheric at 250℃.

Chu and Maisen (2011) point out as main advantage of this system the use of flat or elastically curved mirrors which are cheaper compared to parabolic glass reflectors. Furthermore, these are mounted close to the ground, minimizing wind effects and consequently, structural requirements. As disadvantage, LFRs have lower efficiencies and present more difficulty to incorporate storage capacity.

2.3 Central Power Tower (CPT)

Central Power Tower systems have a large number of computer-controlled mirrors, called heliostats, arranged in an area around a tower, called solar field. The incoming DNI is redirected by the heliostats to a single point at the top of the tower, where the receiver is located and the HTF is heated. As all heliostats concentrate the energy in a small area, the temperatures obtained are higher than in the PTC and LF systems (Tapia and Sousa, 2017): 567℃ using DSG and 565 ℃ using molten salts (Islam *et al.*, 2018) This allows the annual solar-to-electric efficiency to range from 20% to 35% (Müller-Steinhagen, Trieb and Trieb, 2004)(Brakmann, Aringhoff and Geyer, 2005).

However, the land requirement, water usage and installations costs are considerable, representing a challenge for CPT development. Alternatives are being implemented to overcome these difficulties such as hybridization with other energy sources (natural gas, oil and PV) to reduce the energy production and storage costs, solar field optimization to reduce the number of heliostats and increase the field performance and air cooled heat exchangers, to reduce the amount of water required.

According to (Tapia and Sousa, 2017), the current CPT commercial market has 8 operational plants, 6 under construction plants and 15 projects under development, totaling, 602,9 MW, 631 MW and 4.085 MW, respectively.

2.4 Parabolic Dish Stirling (PDS)

Although it is one of the oldest solar technologies (Abbas *et al.*, 2011), solar dish-engine systems convert the energy from the sun into electricity at a very high efficiency. Commonly, Parabolic Dish Systems use Stirling engines to convert thermal into mechanical energy, therefore these systems are called Dish-Stirling technology. This technology shown in Fig.3(d) use mirrored dishes to focus and concentrate sunlight onto a solar receiver located at the focal point of the dish. The receiver is designed to transfer the absorbed solar energy to the working fluid in the Stirling engine. As working fluid can be used air, helium, nitrogen (Kongtragool and Wongwises, 2003), but hydrogen is applied in the most cases (Abbas *et al.*, 2011).

PDS are modular systems, that is, each system is a self-contained power generator. A single system produces relatively small amounts of electricity compared to other CSP technologies - typically in the range of 3-25 kW. However, they can be assembled into plants ranging in the size from one kilowatt to 10 MW. Kongtragool and Wongwises (2003) points that for solar electric generation in the range of 1-100 kW, the Dish-Stirling technology was considered to be cheapest. In terms of efficiency, according to Barbee (2015), a Ripasso Energy system being tested in the Kalahari Desert in South Africa showed 34% efficiency.

Table 1. World's CSP capacity (NREL, 2018)

CSP technology	Operational capacity (MW)	Under construction capacity (MW)	Under development capacity (MW)	Non – operational capacity (MW)
Parabolic Trough	4453.6	580.0	1074	48.8
Linear Fresnel	157.4	24.0	200	8
Central Power Tower	606.5	815.0	1922	8
Parabolic Dish	-	-	-	3

3. OBJECTIVES

To simulate different CSP technologies systems in the western mesoregion of the state of Rio Grande do Norte, using the System Advisor Model – SAM, analyzing, among the simulated configurations, which is the most viable to the RN.

Through the simulation results, it will be possible to determine the installation requirements for each solar power plant technology (land area, energy output and water consumption) and compare them with the data from similar operational CSP plants.

4. METHODOLOGY

The design and installation of CSP plants require that a series of parameters be analyzed. Besides a strong solar resource, other factors such as land availability, relief conditions, water availability and infrastructure must also be considered. Selective criteria to choose areas with potential to install a CSP power plant, based on the ones used by Purohit *et al.* (2013), Salvi (2013) and Soria (2011), were applied to the western mesoregion of the Rio Grande do Norte in order to point a suitable area where a CSP power plant will be simulated.

In order to compare the suitability of each power plant, it is important to understand the definition of capacity factor, defined as the ratio of the system's annual net energy production to the nameplate output, which is the quantity of energy the system would generate if operating at its installed capacity for every hour of the year.

4.1 Solar resource

The solar resource is the key factor for the effective feasibility assessment of large-scale CSP projects. However, the long-term ground DNI data availability is a barrier towards deployment of new CSP systems. There are three forms for measuring the DNI over a location: a) by measurements stations (using pyrheliometers), b) Albedo of the earth's surface (estimations through measurements of reflected radiation), and c) statistical approach (in which DNI incidence is determined through interpolations of ground and satellite data sets).

This paper assumed a minimum value for the annual Direct Normal Irradiance (DNI) of 1800 kWh/m²year as excluding parameter when choosing the place to be simulated.

4.2 Land assessment

Site selection is a crucial activity associated with the planning and designing of any large-scale solar power project. The terrain must be relatively flat, unoccupied, and suitable for development, environmental protection zones (ZPAs) and urban areas should be excluded from the analysis, as well as the regions with a declivity percentage over 3% (Salvi, 2013). Also, areas smaller than 1 km² were not considered, according Purohit *et al.,* (2013), these sites are not economically viable. Finally, it should be evaluated the infrastructure conditions for connectivity (proximity to roads and cities), water availability and electrical grid (proximity to substations of the national integrated substations).

However, due to lack of geo-processed data, this step was not taken to choose the precise location of the power plants simulated in the present work.

5. Simulation

Finally, it will be simulated on SAM different CSP technologies to the chosen area in order to determine the most suitable and if it will attend to the previous criteria. It was assumed a installed capacity of 19.9 MW to all simulations, the same parameter used in a case study provided by NREL (2013) to simulate Gemasolar, a power plant located in Spain. The only exception to this assumption was the Parabolic Dish plant simulation, that consisted in 800 individual collectors of 25 kW, totalizing 20 MW.

The area used in the simulations is located near the city of Apodi, -5.63 °N -37.78 °E, the weather data downloaded through SAM used the National Solar Radiation Database (NSRDB), which indicated an annual DNI of 2500 kWh/m²year, which is above the minimum value stablished in subsection 4.1.

The inputs assumed to simulate the Parabolic Trough power plant were based on the work of Bishoyi and Sudhakar (2017a) and Bishoyi and Sudhakar (2017b), the case study provided by NREL where a simulation of Andasol -1 was performed using SAM. The parameters used in the simulation are listed on Tab. 2, the remaining ones were used SAM's default values.

Table 2. Parameters of the PTC and LFR simulations

Technical parameter	Unit	PTC	LFR
Capacity	MW	19.9	19.9
Solar multiple	-	2	2
Full load hours of thermal storage	h	0 – 7.5	0 – 7.5
Heat transfer fluid	-	Therminol VP-1	Hitec Solar Salt
Target loop outlet temperature	°C	398	590
Number of SCA per loop	-	4	-
Collector model	-	SkyFuel SkyTrough (80mm OD)	-
Absorber tube model	-	Schott PTR80	Evacuated tube
Design gross output	MWe	22.11	22.11
Gross to net factor	-	0.9	0.9
Cooling system	-	Dry	Dry

The technical parameters considered for CPT system simulations are given in Tab 3. The following specifications are based on Amadei *et al.* (2013), where GEMASOLAR simulations are performed. In this work, two configurations are simulated: a CPT without thermal storage and a CPT with 15 hours of storage. The non-specified parameters are SAM's default value.

Table 3. Parameters of the CPT simulation

Parameter	Unit	Assumed	Amadei *et al.* (2013)
Capacity	MW	19.9	19.9
Solar multiple	-	2 – 3	2
Thermal energy storage	h	0 – 15	0 – 7.5
Heat transfer fluid	-	Molten salt (60% KNO3/40% NaNO3)	-
Heliostat Area	m²	115	120
Number of heliostats	-	1679 - 2546	2650
Receiver height	m	14.22	14.22
Receiver diameter	m	8.89	8.89
Design gross output	MWe	22.11	22.11
Gross to net factor	-	0.9	0.9
Cycle conversion efficiency	-	0.412	0.375
Cooling system	-	Dry	Dry

The PDS plant simulated values are based in the work of Abbas *et al.* (2011), differing only in the solar field layout, total number of individual units and installed capacity, Table 4. The remaining variables used SAM's default value.

Table 4. Parameters of the PDS simulation

Parameter	Unit	Assumed	Abbas *et al.* (2011)
Number of Collectors, North-South	-	20	50
Number of Collectors, East-West	-	40	80
Total Solar Field Area	km²	0.18	0.9
Total Capacity	MW	20	100

After running the simulations, the results are expected to be within the range of the data obtained by Purohit *et al.*, (2013) for net energy, capacity factor and water consumption, illustrated by Tab. 5.

Table 5. Expected outputs for the simulations (adapted from Purohit *et al.*, 2013)

Parameters	Unit	CSP technology			
		PTC	LF	CPT	PD
Net energy range	GWh/MW	1.34 – 2.19	1.24 – 2.21	1.21 – 2.13	0.96 – 1.79
Capacity factor	%	15.4 – 27.1	14.16 – 25.23	13.80 – 24.28	10.96 – 20.32
Water consumption	m^3/MWh	3 (Wet cooling)	3 (Wet cooling)	2 – 3 (Wet cooling)	0.05 – 0.1 (For mirror washing)
		0.3 (Dry cooling)	0.2 (Dry cooling)	0.25 (Dry cooling)	

6. RESULTS AND DISCUSSIONS

The results obtained after the simulations are presented in Tab. 6, for plants without TES and Tab. 7 for plants with TES. The values of net energy and capacity factor of all technologies are slightly higher, when compared with the expected range in Tab. 5. This can be explained, due to the weather data provided by NSRDB, which are slightly overestimated. According to resource data used in simulations, the DNI annual average value is 6.85 kWh/m²day, which annual values represents 2500 kWh/m²year. The weather data from software Meteonorm, which according to Purohit and Purohit (2013) has higher accuracy as it derives higher resolution satellite and ground data, reported annual DNI value close to 2050 kWh/m²year, a difference of 22%.

For systems without thermal storage, the simulations have indicated that the Central Power Tower presented the highest annual generation for same installed power and, consequently, the largest capacity factor followed by Parabolic Trough. However, LFR and PDS technologies showed the lowest land requirements, being that Parabolic dishes have produced more energy per unit area. The authors understand that the most viable technology is the one that produces more energy with less area, so according to this analysis, the most suitable CSP system for power generation is Parabolic Dish. However, for a technical suitability indication is required a study of financial parameters and system costs, especially about the LCOE (Levelized Cost of Electricity) for each system.

Table 6. Simulation results without TES

Parameters	Unit	CSP technology			
		PTC	LF	CPT	PD
Net generation	GWh/MW	2.47	2.37	2.51	1.84
Capacity factor	%	28.2	27.1	29.1	21
Water consumption	m^3/MWh	0.29	0.092	5.58	-
Total area	km^2	0.67	0.31	1.13	0.18
Annual generation per land-use	GWh/km^2	73.36	152.52	44.28	204.44

Figure 4 shows the comparison between the energy generation per installed capacity and per land-use area over a year, making it possible to note that a high capacity factor do not implicate in the best exploitation of the area's solar potential.
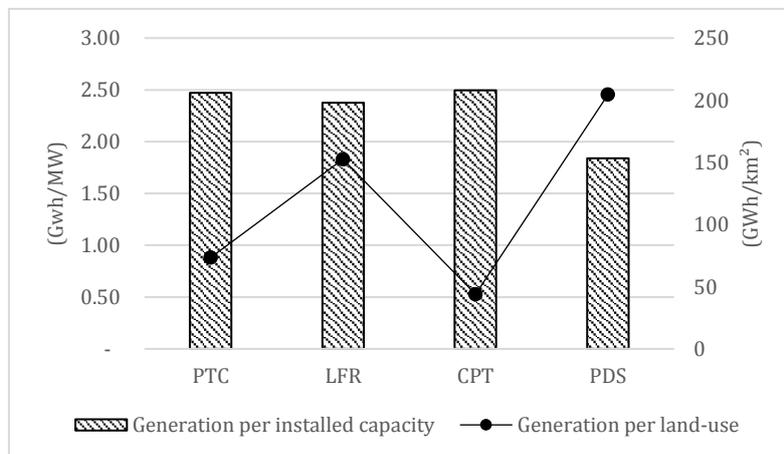

Figure 4. Comparison of the annual energy generation per installed capacity and per land-use area

The results shown in Tab. 7, obtained for the capacity factor by the simulations considering a thermal storage of 7.5h for PTC and 15h for CPT shown to be close to the ones presented by NREL in the case studies performed for Gemasolar (74%) and Andasol-1 (41.5%), a Central Power Tower and a Parabolic Trough Collector power plant. In addition, the LFR technology presented the best annual energy per land-use, and the CPT system even with the higher capacity factor, presented the lowest annual generation per land use.

The simulation also shows that the total area required is the same for PTC and LF systems, with or without TES. For CT plants the results indicate that the area required by the one with TES is 53% larger than the one without TES, due to need of higher solar multiple, achieved using a larger solar field.

Moreover, the water consumption per MWh generated is reduced for all simulated technologies with TES, indicating that these plants are more suitable to the selected region environment, since the water resources there are scarce.

Table 7. Simulation results with TES

Parameters	Unit	CSP technology		
		PTC	LF	CT
Net generation	GWh/MW	3.93	3.18	6.52
Capacity factor	%	44.9	36.3	75.6
Water consumption	m^3/MWh	0.22	0.086	0.17
Total area	km^2	0.67	0.31	1.73
Annual generation per land-use	GWh/km^2	116.76	203.84	75.06

Figure 5 compares the use of a thermal storage system influence in the annual energy generation per installed capacity of the power plant for each CSP technology. It can be seen that the presence of TES increases the net energy generation and the capacity factor, behavior explained by the plant additional worked hours during poor solar conditions and after sunset using the same installed capacity.

However, despite the better performance of CSP plants with TES on the considered parameters, it is recommended a financial analysis, like the one suggested for plants without TES, as opting for TES increases installation, operation and maintenance costs.
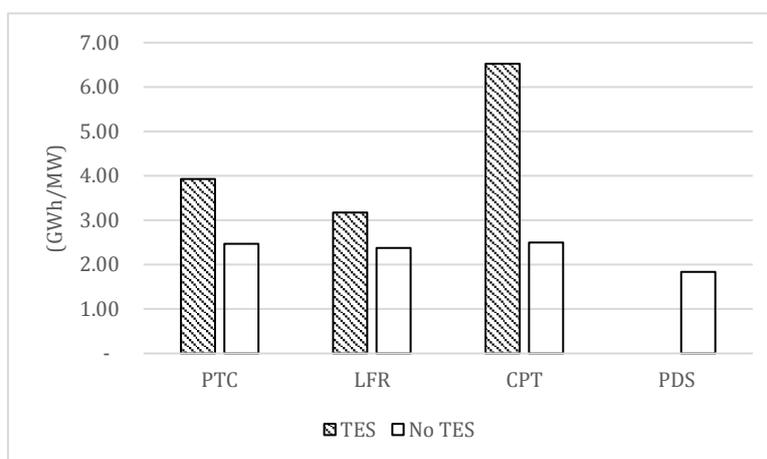

Figure 5. Influence of the TES in the power plant's generation

7. CONCLUSION

This study analyzed the CSP potential in the western mesoregion of the state of Rio Grande do Norte through CSP power plants simulations performed to a location with high-rated DNI resources using the software NREL System Advisor Model - SAM. The weather data used to perform the study are referring to a location close to the city of Apodi.

As expected, the simulations results indicated that the western mesoregion of Rio Grande do Norte has a good solar potential to be explored, independently of the CSP technology.

Considering the parameters of net energy, capacity factor, water consumption and total area resulted from the simulations, the recommended CSP configuration without TES is Parabolic Dish, since it presented the highest annual generation per land-use, 204.44 GWh/km², and is expected to use the minimum amount of water, according to Tab. 5.

It is important to mention that PD systems do not use TES, meaning that to produce electricity after the sunset or during rainy or cloudy days it is necessary to use a backup generating source, such as natural gas, PV panels, coal, oil, etc.

Regarding simulations performed considering TES, it can be highlighted the similarity between the results found in this study and the reference values from selected power plants (Andasol-1 e Gemasolar) reported by NREL (2013). The simulations have pointed out a difference of 1.6% for CPT (Gemasolar) and 3.4% for PTC (Andasol-1) in the capacity factors. Among the power plants with TES, the most suitable technology is Linear Fresnel Receiver that has presented the greatest generation per unit area in a year, 203.84 GWh/km², and the lowest water consumption per generated power. Nevertheless, it is important to emphasize the high capacity factor of simulated CPT system that ensures a stable generation of power even after the sunset.

Once the simulations performed in the present work did not take in account an economic analysis for each power plant to determine its real viability, the authors consider important that a more complete study of the initial capital investments involved as well as incentives, depreciation, maintenance costs, in order to determine the Levelized Cost of Energy (LCOE), which determines how much money must be made per unit of energy.

8. ACKNOWLEDGMENTS

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