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COMPARATIVE STUDY OF SIMULATED SOLAR TOWER POWER PLANT BETWEEN TWO CITIES OF BRAZIL AND THE USA.

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Abstract. *A solar tower CSP power plant with a thermal storage system was simulated for comparison between the cities of Dagget (California/USA) and Petrolina (Pernambuco/Brazil) using solar data files of the Meteonorm software, from the Meteotest swiss company, in the Typical Metrological Year 2 format. The computational programs used for the solar power plant simulation were the EES, SAM and TRNSYS. The EES software was used to write the code of the power block subsystem that outputted its needed parameters, for 41,2% of thermal efficiency, in TRNSYS. The SAM software was used to determine the parameters of the solar field and the thermal storage subsystems, in their most profitable setups, used in TRNSYS simulation, for each city. Finally, the solar tower CSP power plant was simulated in the TRNSYS software outputting the interrelationships between the three subsystems during a typical year. The behaviors of the plant in the solstices and equinox were plotted and the simulated power plant in the city of Petrolina had a solar field with 55.4% more heliostats for an annual energy production and a capacity factor 11.2% and 8,5% lower than Dagget respectively.*

Keywords: *Concentrated Solar Power, Solar Tower Plant, Thermal Storage, Computational Simulations.*

1. INTRODUCTION

The generation of electricity through renewable sources helps to reduce the burning of fossil fuels and thus contributes to a lower emission of greenhouse gases. Resolutions and treaties for the reduction of global warming are due to the consequences of the greenhouse effect, which causes the melting of the ice caps, raises the level of the oceans, changes the thermal profile of the planet, generates natural disasters and creates diverse problems socioeconomic variables (Whitaker et al., 2013).

Thermal energy storage makes energy production more stable. The dispatchability measures how much is produced in relation to the power demanded by the network. In CSP plants with thermal storage the generation takes place in two stages, from solar radiation it is generated heat that is used to power a thermal system of electric energy production, as used in conventional thermoelectric plants. With the CSP 72kg of equivalent carbon per MWh could be achieved, much lower than a plant using combined cycle natural gas, 400kg of equivalent carbon per MWh (Koberle et al., 2015).

State-of-the-art CSP Solar Tower technology, with a molten salt storage above 10h, had a leveled cost of electricity (LCOE) of approximately 13¢/kWh in 2015 in the United States and its development is estimated to cost 6¢/kWh in 2020 (Luo et al., 2016).

The simulation done in this paper tried to reach low costs of energy production. The use of simulation programs calculates the power block, the field of heliostats, the tower and receiver and the thermal storage system. The behavior of the cities of Dagget and Petrolina CSP plants of the Solar Tower type was simulated through the Transient System Simulation Tool (TRNSYS), Fig. 1, version 17.0 with the aid of the following programs: Engineering Equation Solver (ESS), version 10.115 and Systems Model Advisor (SAM), version 2017.1.17.

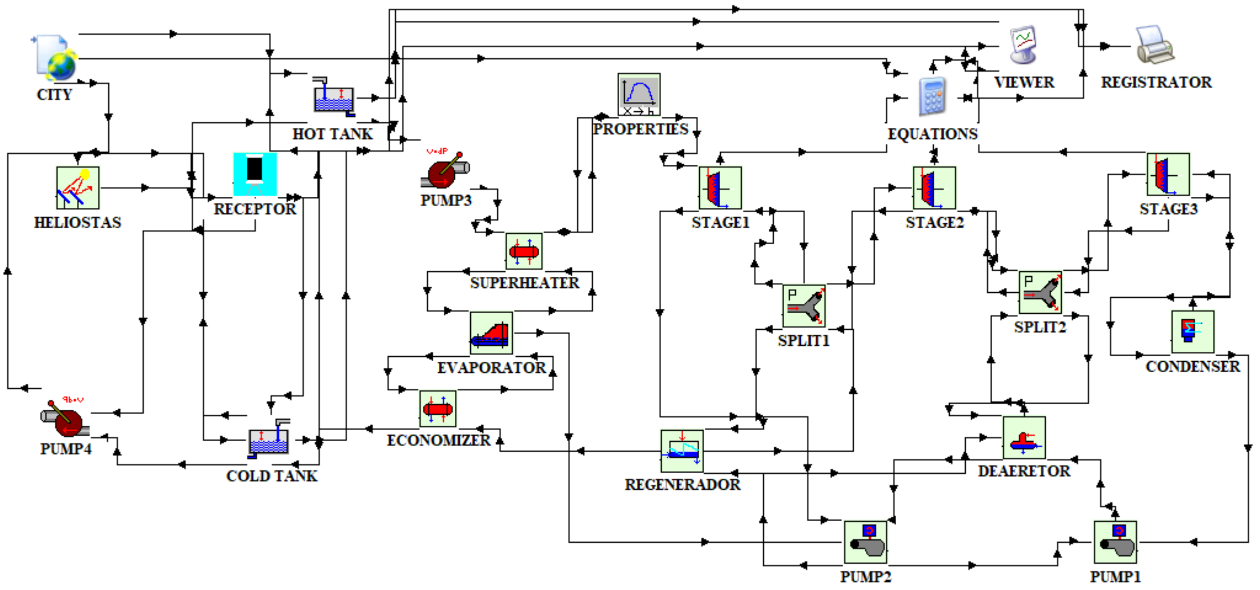


Figure 1. Simulated Power Plant

The dry cooling system for the condenser system of the Rankine power block condenses the steam through forced ventilation, this method consumes energy for the fans and has a lower convective coefficient, which decreases the efficiency of the plant when compared to wet cooling and eleven through (Liqreina and Qoaider, 2014). However, there is a reduction in the water consumption of the plant. To decrease the loss in efficiency, hybrid methods are used. It was used the wet cooling system for the present simulation due to the easiness to write a simple code for the condenser system.

For the thermal energy storage system is was used the direct thermal energy storage. Direct storage systems store the heated HTF in the solar receiver in thermally insulated containers so that it can be supplied at another time to the power block when the solar field fails to produce enough due to cloud passes or night operations (Zaversky et al., 2014).

Solar towers can achieve a higher temperature operation when compared to linear focus systems, such as parabolic troughs and linear Fresnel plants. These higher temperatures produce higher thermoelectric conversion efficiencies in the power block and may result in lower storage costs. The two main concepts of solar tower technology used by developers are defined by the type of HTF in the receiver: steam, molten salt or air. In towers with direct steam generation, heliostats reflect sunlight on a vapor receiver located at the top of a tower. The receiver is similar to a boiler in a conventional Rankine cycle coal mill. The feed water, pumped into the power block, is evaporated and overheated at the receiver to produce steam, which then feeds a turbo generator set to generate electricity. Current steam conditions for direct steam towers range from saturated steam at 250° C to steam overheated to over 550°C.

An analysis can be done among the major technologies comparing the different types of CSP plants, Tab. 1, based on their term economic performance. Through analytical procedures that can be applied in the initial design phase to compare the various options of design parameters and different configurations (Lovegrove and Stein, 2012).

Table 1 – CPS Technologies analysis

	Parabolic Trough	Solar Tower	Linear Fresnel	Parabolic Dish
Relative capital cost	low	high	low	very high
Technological risk	low	medium	medium	medium
Relative land occupation	high	medium	medium	low
Water consumption (m^3/MWh)	3 (Wet cooling) 0,3 (Dry cooling)	2-3 (Wet cooling) 0,25 (Dry cooling)	3(Wet cooling) 0,2(Dry cooling)	0,05-1
Storage Systems	Indirect/Direct (molten salt)	Direct (molten salt)	Direct (Steam)	-

For the simulation in TRNSYS it was used the solar thermal electric components (STEC), version 3.0, created and developed through an initiative of SolarPACES (solar power and chemical energy systems). The library was last updated in November 2007. After that date, due to the large development of commercial solar thermoelectric projects, mainly in the United States and Europe, the progress of the library went from the public research sector to private research of business institutions.

2. CSP POWER PLANTS SIMULATIONS

Fichter et al. 2017, evaluated the CSP technology for hybridization with biomass in the northeastern region of Brazil with a simulation program developed called REMix-CEM-B, which evaluated the technical-economic possibility of the insertion of the technology in Brazil. For competitiveness, it is concluded that it would be necessary to use energy back-up systems with biomass of at least 49% of the nominal power of the CSP plants.

Janjai et al. 2011, simulated three types of CSP plants over a period of eight years for the city of Ubon Ratchathani in Thailand. Solarimetric data derived from satellite images were used. The simulated technologies were the parabolic trough, the solar tower and the parabolic dish, all used in a plant with nominal power of 10MW. The program used was TRNSYS and its STEC 2.0 library. Among the simulated technologies, the parabolic trough was the one with the lowest LCOE, corresponding to 30 ¢ / kWh in dollars. The capacity factor found was 20.5% for this system and the solar-electric efficiency was 18%.

Hussain et al. 2017, simulated solar tower, parabolic trough and linear Fresnel technologies for comparison using hybridization with biomass in regions of Europe, Madrid being the region with the best radiation, between 1600 and 1800 kWh / m² per year. According to the TRNSYS simulation the parabolic trough was the most viable technology for a 3.2MW power plant. The solar field fluid worked at 395°C.

Srilakshmi et al. 2017, simulated the field of heliostats for CSP solar tower type plants with storage and hybridization systems. The receiver used was open and the simulated plants were Spain's Gemasolar, which has a nominal capacity of 20MW, a thermal storage system of 15h and an average annual efficiency of 16%, and Cescent Dunes of the United States, which has a nominal capacity of 110MW, 10h thermal storage system and average annual efficiency of 18.3%. The city of Jodhpur in India was also used for plant simulation after validation of the models. The simulation developed was based on the creation of dimensionless contour conditions related to the size of the tower. The results were validated by comparison with the data collected from the Gemasolar and Crescent Dunes plants.

Abdelhady et al. 2014, simulated a solar thermal plant for an isolated region of Egypt. The region called New Valley of Egypt has one of the highest radiation rates, reaching 3000kWh / m² per year. The simulated technology was the parabolic trough with thermal storage in concrete blocks and the program used was the TRNSYS. The simulation programmed confidentially by the authors generated 180GWh of thermal energy in the year during 3385 hours of operation, converting 33,38% of the normal radiation available. It was evidenced that the TES had a fundamental role in the thermal energy supply for the receiver to work at its operating temperature of 427ºC.

Yamani et al. 2017, evaluate solar-powered CSP technology for the generation of electrical power in the Algerian climate in the cities of Tamanrasset, Hassi R'mel and Algiers. A central tubular open receiver tower with a power block with the Rankine cycle was simulated, and a central volumetric receiver tower with a power block with the Brayton cycle. The STEC 3.0 library was used in the TRNSYS program to simulate the thermal performance of 3MWel production. In the results it was found that the Brayton cycle presented better performance for high radiation rates, but as this cycle works at high temperatures, in the order of 1000ºC, it consumed more fossil fuel during a typical year by using a combustion chamber to regulate the temperature of input to the turbine after the gaseous HTF passes through the solar receiver. The difference in the cost of producing electricity between the two technologies, Rankine and Brayton, was only 3.4% more for Brayton, for the city of Hassi R ' honey. But it was much larger for the other two cities, about 11% in Algiers and 16.4% in Tamanrasset. This was due to the higher DNI and longer duration in Hassi R'mel.

3. SIMULATION MODEL

The thermodynamic cycle of the power block subsystem was written in the EES for a 104MWel plant. The SAM program simulated the solar field subsystems and thermal storage. Templates were created in TRNSYS.

3.1 Power Block

The EES program was used to calculate, through a set of equations, the parameters: specific heats and densities of molten salt and water at certain temperatures; the condenser, evaporator, economizer, regenerator and superheater thermal capacitances; the mass flow of the system and its ramifications for the extractions in the stages of the turbine; the output pressures of the steam in the turbine stages and the pressure variations in the pumps and the mass flow rate and the cooling water temperature. The vapor generator system was simulated according equation 1 (Bergman et al.,2011).

$$\dot{Q}_{SIST} = \dot{m}_{H2O} \cdot \left(i_{H2O,out} - i_{H2O,in}\right) = \dot{m}_{HTF} \cdot cp_{HTF} \cdot \left(T_{HTF,in} - T_{HTF,out}\right) \quad (1)$$

Where $\dot{Q}_{SIST}$ is the thermal transfer rate that occurs in the steam generator system, $\dot{m}_{H2O}$ mass vapor flow, $i_{H2O,out}$ the enthalpy of the vapor at the output of the steam generator, $i_{H2O,in}$ the enthalpy of the vapor in cp_{HTF} the specific heat of the HTF, $T_{HTF,in}$ the temperature of the HTF at the entrance of the solar field and $T_{HTF,out}$ the temperature of the HTF the system output.

3.2 Solar Field

The SAM program was used to determine the amount of heliostats and the dimensional data of the solar field for the solarimetric data of the Dagget and Petrolina locations, through a parametric study with used the equation 2 [18].

$$V_{HTF} = \frac{\dot{W}_{TURB,NOM} \cdot t_{STR}}{\rho_{HTF} \cdot cp_{HTF} \cdot \left(T_{H,HTF} - T_{C,HTF}\right) \cdot \varepsilon_{RANKINE}} \quad (2)$$

Where $\dot{W}_{TURB,NOM}$ is the nominal power of the turbine, $t_{STR}$the storage time, $\rho_{HTF}$the density of the HTF, $cp_{HTF}$the specific heat of the HTF, $T_{H,HTF}$the temperature of the HTF in the state "hot", $T_{C,HTF}$ the temperature of the HTF in the "cold" state and $\varepsilon_{RANKINE}$ the efficiency of the Rankine cycle.

The TRNSYS program was used to obtain the dynamic behavior of the plants through solarimetric data and the interconnections of the power block (PB), solar field (SF) and thermal storage (TES) subsystems.

For the Modeling of the cycle the Tab. 2 boundary conditions (Parameters) were adopted.

Table 2 – Solar Tower boundary conditions

HTF hot	574°C
HTF cold	290°C
Receiver Design Thermal Flow	1000kW/m²
Gross Turbine Power	115MW
Gross Power to Net Conversion	0,9

For the simulation of the storage system and solar field the SAM program was used, which relates the dimensional parameters, such as the number of heliostats, dimensions of the tanks and receiver, among others, with financial parameters.

By analyzing the accumulated percentage of the solarimetric data, Fig. 2, it is possible to know for how long of the year the flow will be above the DNI. In Dagget, 30% to 40% of the data are less than 500W / m² in Petrolina the amount of solarimetric data with the DNI below 500W / m² is approximately 60%.

DNI Dagget **DNI Petrolina**

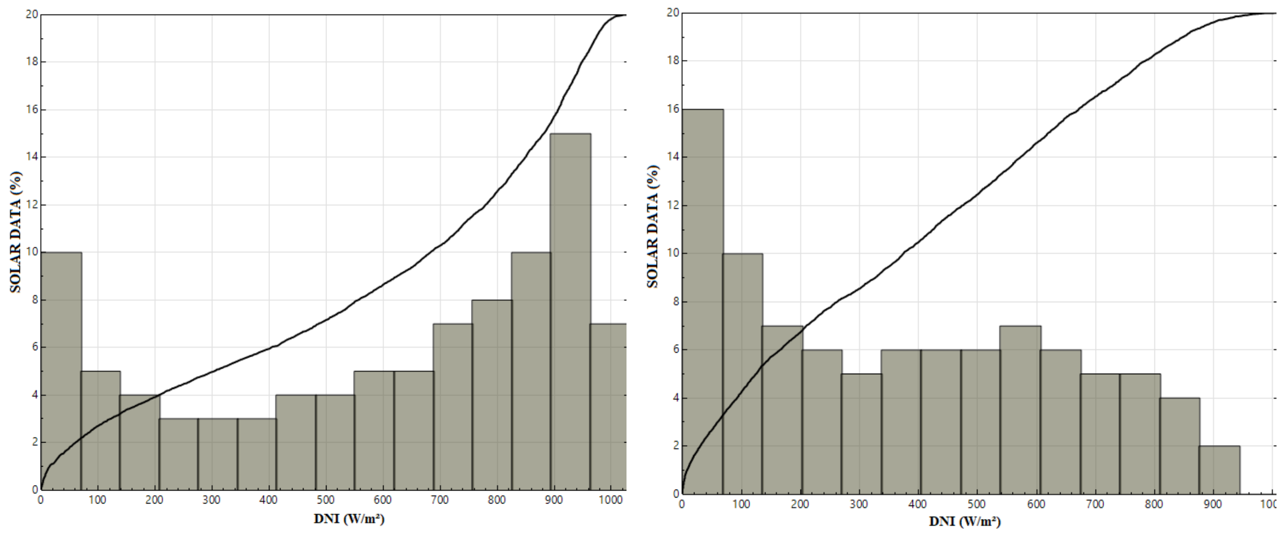


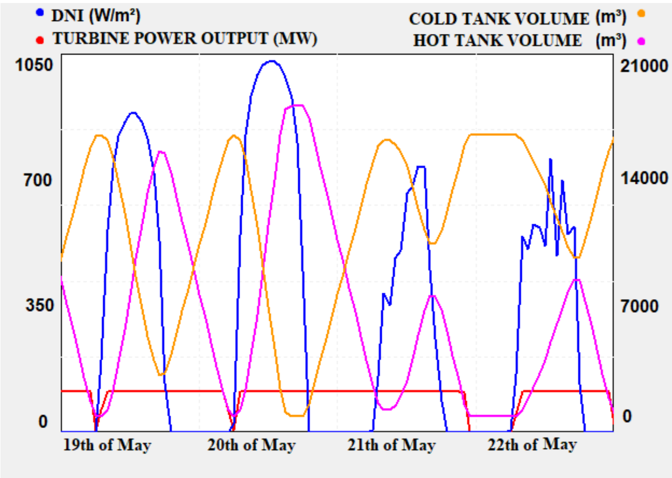
Figure 2. Direct Normal Irradiation

The axis of the left ordinates in figure 2 is that of the solar data, which contains information such as DNI, ambient temperature, wind speed, etc. for each hour of a typical year. The DNI is represented on the abscissa axis, the vertical bars are related to the left-hand axis and it is possible to see that 14% of the data has values between 900 and 960W/m² for Dagget. For Petrolina only 2% of the data has a DNI between 900 and 942W/m², which is the maximum registered DNI for this city, and for Dagget the DNI of 1025W/m². The amount of DNI data between 0 and 75W/m² is 10% for Dagget and 16% for Petrolina.

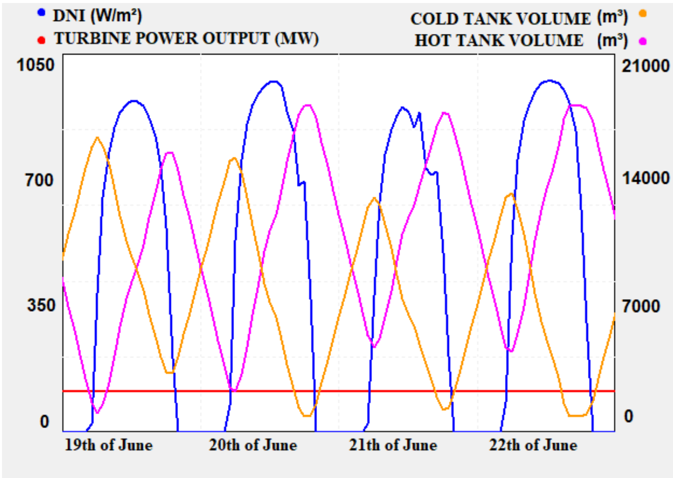
4. RESULTS

The days analyzed were the spring and autumn equinoxes and the summer and winter solstices, due to the position of the sun on these dates, Fig. 3. In relation to the Equator the spring and autumn equinoxes provide an equal declination angle of the earth to 0°, which reduces the losses in the radiation absorbed by the plant. The summer and winter solstices correspond to the possible dates of higher and lower incidence of radiation in the tropics, which occur between June 20 and 21 and December 20 and 21, respectively, for the northern hemisphere. For the southern hemisphere the winter solstice is between 20 and 21 June and the summer between 20 and 21 December.

Spring Dagget



Summer Dagget



Autumn Dagget

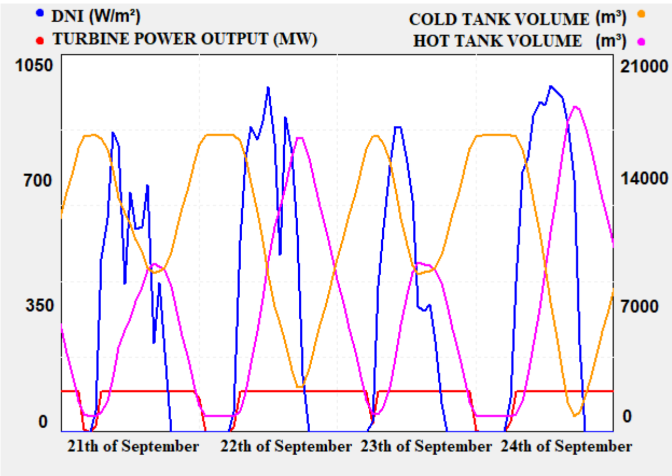


Figure Winter Dagget

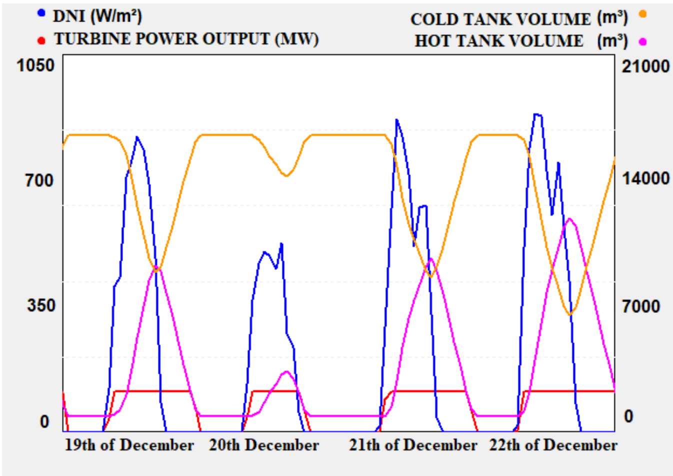


Figure 3. Dagget Power Plant Behavior

In spring, in only three moments the PB lost power, ending up for a longer period between March 21 and 22. The day 20 radiation was excellent, which allowed the plant to run uninterrupted at maximum power for two days in a row.

The summer behavior of Dagget represents the ideal behavior of a CSP power plant, as it produces the energy demanded during the day and during the night. The solar source is harnessed to the maximum during the day and the amount of heat stored in the hot tank supplies the PB overnight and until the sun is providing the radiation necessary for the operation of the plant without the use of the storage system.

In the period of high solar radiation, the TES, which was being discharged overnight, returns to store heat. This process can be visualized following the displacement of the pink and orange lines throughout the days. The upward movement of these lines represent the filling of the respective tank and the downward movement of its discharge. About half of the sun's period the tanks volumes even, in a process of hot tank loading and cold tank discharge.

During the autumn in the city of Dagget the days presented great variations in the tendencies of the curves of DNI, in which momentary falls were shown before, during and after the point of zenith. From dawn to the point of zenith, DNI presented slight variations. At dusk, abrupt variations can be explained by records of rainfall, clouds or other events that hampered the incidence of DNI in the solar field during the typical year analyzed.

Between September 22 and 23, the heliothermic plant loses power due to the depletion of the storage system and lack of solar radiation, but does not stop to function, as it happens between the other represented days. The solar radiation before the zenith point was good enough for the production to increase the power before the plant shutdown.

The worst time represented for Dagget was the winter solstice, in which the plant had to be shut down completely during intervals in every day analyzed. On the days of 19 and 21 December, the MWel production after the DNI incidence was still good, due to the filling of the hot salt tank at volumes close to its halves, as represented in the pink and yellow lines. By December 20 the hot salt tank stored heat only for the operation of the plant for a few hours after the end of the day's DNI.

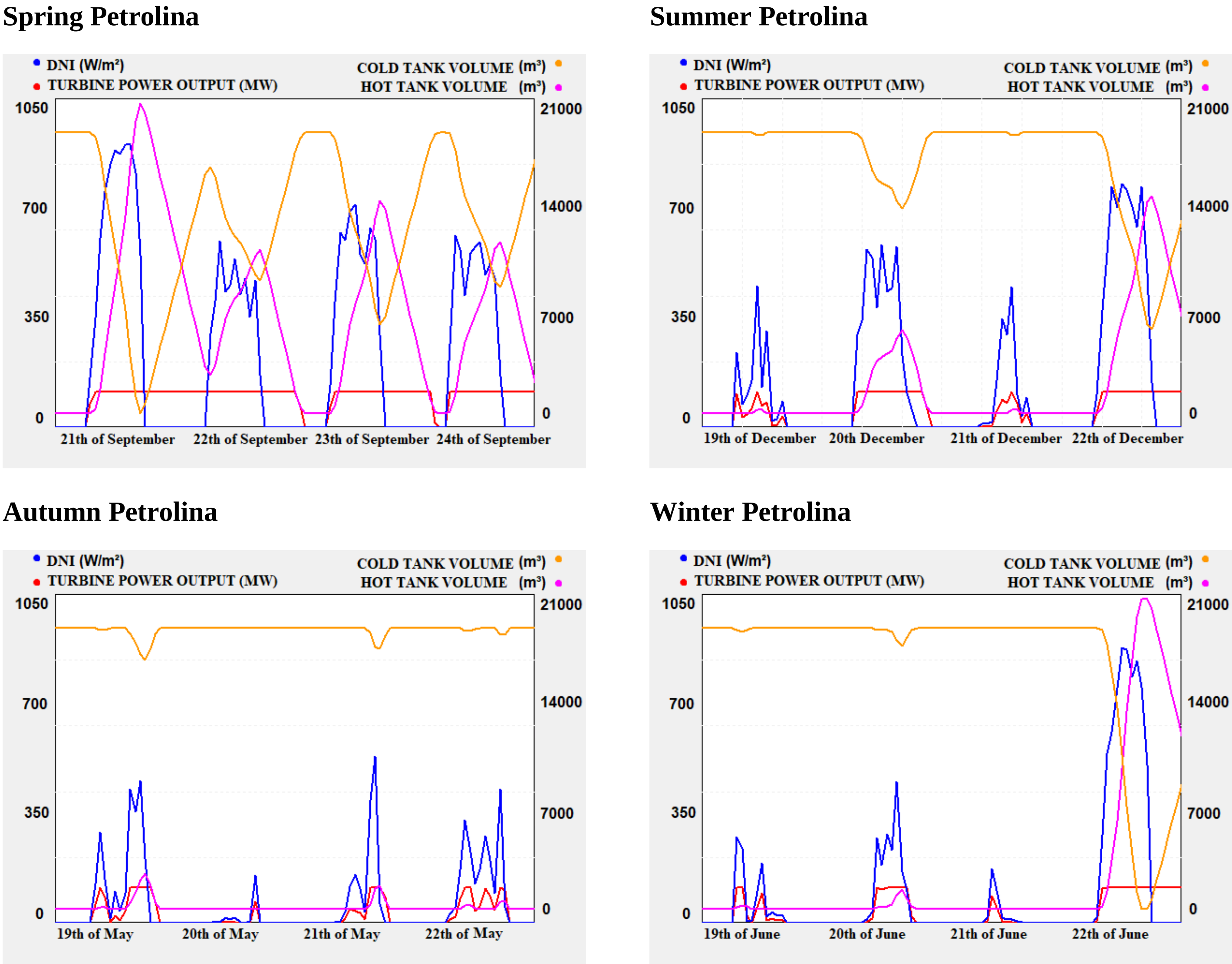


Figure 4. Petrolina Power Plant Behavior

The solar field of the plant located in Petrolina has a larger solar multiple, with a value of 3.8 for a thermal storage of 16h. In the case of Dagget, a solar field with a solar multiple of 2.9 was enough to allow a thermal storage of 14 hours in the best cost-benefit of the plant. The explanation of the high increase in the solar multiple for the little gain in storage hours is due to the lower and more intermittent DNI in Petrolina.

The spring represented the best performance of the Petrolina CSP plant. Because it has a large solar field, the plant can produce its nominal power for 24 hours without incident radiation reaching high values. The plant was designed for a design DNI of 850W/m², because as the radiation is lower than in Dagget it was necessary a plant that worked satisfactorily in these worst conditions.

The days of September 22, 23 and 24 made possible the operation of the storage system from 50 to 70% of its capacity.

On December 19, 20 and 21, the plant's thermal storage system was practically unused. Only on the 20th that the plant produced a few hours beyond the period of incidence of radiation and on days 19 and 21, in addition to not working at its nominal power the plant did not use the storage system. The most dispatched day was December 22.

The sizing of the solar field and the storage system considered the DNI at all times of the year. The SAM program simulated the configuration chosen for these subsystems considering these bad days demonstrated in Fig. 56. One way to reduce the size of the solar field and its storage system would be the use of fossil fuels or biomass to heat the HTF after the receiver tower. The more robust the auxiliary heating system, the smaller the heliostat field. If solar radiation were not used to provide the heat needed for PB, the plant would be a conventional thermoelectric plant.

In the analyzed days of autumn and winter, where the autumn equinox and the winter solstice respectively are shown, the Petrolina heliothermic plant does not produce electricity at its rated power for a long time. Of the days, only July 22 has a good incidence of solar radiation.

The results obtained for Petrolina help to understand the largest number of heliostats in its solar field. Each day of the year when the plant is not produced, its capacity factor decreases, this makes it necessary to increase the reflecting area so that the radiation is better used in lower values to compensate for the days lost.

5. CONCLUSION

The factors with the greatest influence on the economic aspect of the plants were the solar field dimension data, in which the Petrolina plant presented 5954 heliostats more than the simulated plant in Dagget. This led to an increase in the cost of the solar field subsystem by approximately 70% for Petrolina compared to Dagget. The increase in the number of heliostats was due to the need to maintain a nominal power output of 104MW for both plants during an annual period in which plant capacity factors were not reduced to the point of causing a large increase in the values of each LCOE. Petrolina, which had a lower incidence of normal direct radiation DNI, worked with a design flow of 850W/m², 100W/m² less than in Dagget.

6. ACKNOWLEDGEMENTS

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