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FEASIBILITY STUDY OF CONCENTRATED SOLAR ENERGY INTEGRATION ON A COMBINED CYCLE

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Abstract. *This paper presents a study of concentrated solar power insertion in the Brazilian energy matrix, through integration of the solar energy with Luiz Carlos Prestes Thermoelectric Power Plant (UTE-LCP) in Três Lagoas city. The current situation of the Brazilian electricity sector, which has presented strong growth of thermoelectric dispatch in recent years and the consequent increase in the cost of electricity generation, justifies the development of alternative energy sources. The purpose of this study is to present a model of electricity generation through thermal solar source compatible to technological and economic realities of the energy market. The study is based on evaluation of the linear Fresnel reflector with direct steam generation, because this configuration has investment, operation and maintenance attractive costs. The performance of the solar field is simulated in the System Advisor Model software (SAM) of the National Renewable Energy Laboratory (NREL). The predict performance is used with UTE-LCP operational database to estimate the additional electricity generation. This paper presents the validation analysis of the proposed model performance through of the solar field LFR simulations with existing typical meteorological year (TMY) from Brazilian cities with similar solar availability of Três Lagoas city. Analyzes indicate that it is possible to construct an integrated solar field that increases the power generation of the UTE-LCP at 0.965 MW and the annual additional electric energy production in 1,008.2 MWh with a levelized cost of electricity (LCOE) of USD 90.83 per MWh.*

Keywords: *concentrated solar power, integrated solar combined cycle, linear Fresnel reflector.*

1. INTRODUCTION

The Brazilian electricity matrix historically has presented great participation of renewable energy sources. According to Empresa de Pesquisa Energética - EPE (2014), renewable sources account for 79.3% of the domestic supply of electricity in Brazil. However, it has observed in recent years a substantial increase in thermoelectric power plant dispatch. The electricity generation from non-renewable sources in 2013 represented 20.7% of the total, against 15.5% in 2012 (EPE, 2014).

Several factors are responsible for this greater dependence on thermoelectricity, including the successive periods of low rainfall in the southeast region, environmental restrictions that hinder the construction of hydroelectric plants with large storage capacity, high growth in electricity demand and energy sector planning failure.

The greater participation of thermoelectricity in the electrical system causes substantial macroeconomic impacts such as the cost increase of electricity for industries, commerce and households, the trade balance disequilibrium due to necessity of increase of fuel imports, delay or cancellation of investments because of the unpredictability of electricity costs and energy insecurity.

In this scenario, the share of renewable energy sources such as wind, photovoltaic, biomass and small hydroelectric plants has found space for growth. Brazil has great potential for solar energy utilization throughout the year, as the most part of its territory is located between the tropics. The use of solar energy can bring many benefits to the country such as the viability of development of distant areas and the regulation of energy supply during drought periods.

Therefore, this study aims to propose an alternative to enable the inclusion of solar thermal energy in the Brazilian energy matrix, through the integration of a concentrated solar power (CSP) with a combined cycle power plant.

The Thermoelectric Power Plant Luiz Carlos Prestes (UTE-LCP) was selected as a case study. This plant presents several favorable characteristics, such as wide availability of direct normal irradiation (DNI) in Três Lagoas city (MS), availability of reliable meteorological data from an remote station of the Brazilian national institute of meteorology (INMET), and because of technical and operational aspects of existing equipment.

The chosen CSP technology for this analysis was the linear Fresnel reflector, which presents investment, operation and maintenance competitive costs, in comparison with other solar concentration systems.

2. SOLAR THERMAL ENERGY

Solar thermal technology consists of a series of energy conversions. The solar irradiation collected by mirrors with punctual or linear concentration is transferred as heat to the thermal fluid on a receiver. The absorbed heat is converted into mechanical work through a thermodynamic power cycle, such as Rankine, Brayton, and Stirling and finally into electricity in a generator.

As the solar concentration system does not focus the diffuse radiation, the installation location of a CSP must have high availability of DNI and therefore high average of clear sky days. According to Tolmasquim (2012) it is required a minimum annual DNI around of 1,900 $kWhm^{-2}$ for the technical feasibility of the CSP project.

The CSP can be divided in two distinct systems: solar field and thermoelectric conversion plant. A main advantage of this technology is precisely the similarity of the power block to that used in conventional thermal plants, where chemical energy of fossil fuels is replaced by concentrated solar irradiation (Lopez, 2012).

The main factors that affect the efficiency of CSP are the optical losses in the concentrator, heat losses in the receiver, transportation and energy storage and, energy losses in the electricity conversion system, according to the representation of Fig. 1 (Lovegrove and Stein, 2012).

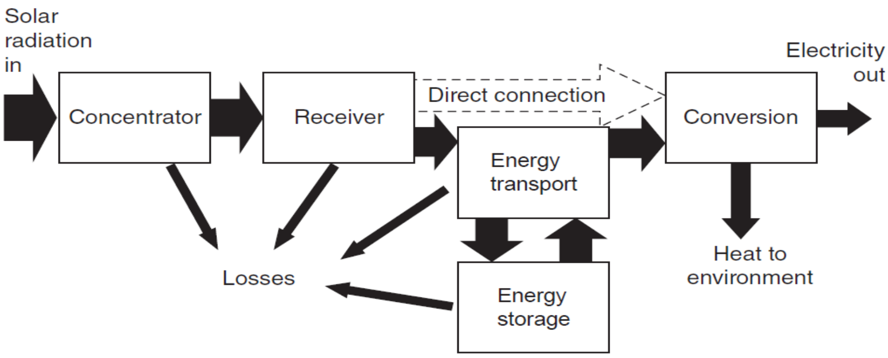

Figure 1. Diagram the main components of a CSP plant.

The radiative losses in the receiver include loss of radiation emitted by the absorber due its temperature and reflection of concentrated solar radiation (Lovegrove and Stein, 2012). Therefore, it is desirable that the surface of the absorber has high absorptivity in the solar radiation spectrum and low emissivity for long waves, thus avoiding losses by radiation heat transfer (Macagnan, 2010). Materials with these characteristics are known as selective surfaces and consist of high absorptivity covering application on low emissivity substrates.

Convection losses come from the air motion over the surface of the absorber, either naturally or due to wind. To minimize these losses, the receiver can use glass coverings or evacuated tubes.

Conduction losses occur through the thermal insulation covers on the absorber tubes or any other heat path between the hot surface of the receiver and the environment.

2.1 Concentrating solar power technologies

The core of CSP plant is the mechanism of concentration of solar radiation, which provides operation with high temperature fluid. The existing solar concentration technologies are parabolic trough, parabolic dish, central tower and linear Fresnel.

Table 1 presents, according to Kalogirou (2011), a comparison of performance data of CSP technologies, where can be observed that the parabolic trough systems, central tower and linear Fresnel have greater power generation capacity. The main cause of this generation capacity is the use of these concentration systems with Rankine cycles.

Table 1. Performance characteristics of CSP technologies.

Technology	Capacity range, MW	Concentration ratio	Peak solar efficiency, %	Solar-electric efficiency, %
Parabolic trough	10-200	70-80	21	10-15
Fresnel reflector	10-200	25-100	20	9-11
Power tower	10-150	300-1000	20	8-10
Parabolic Dish	0.01-0.4	1000-3000	29	16-18

The solar-electric efficiency of a CSP, defined as the ratio between net power generation and incident beam radiation, is lower than in conventional power plants because it include the conversion of solar energy to heat in the solar field and the conversion of the heat in electricity in the power block (Kalogirou, 2011). The linear Fresnel reflector was the solar concentration system selected for this study. The main characteristics that drive the choice are presented in the next section.

2.2 Linear Fresnel

The LFR system uses an array of parallel reflecting mirrors to direct the solar radiation to a fixed linear receiver located above the plane of mirrors, as shown in Fig. 2. Thus, the LFR consists of three main components: mirrors field, receiver and tracking system (Lin *et al*., 2013).

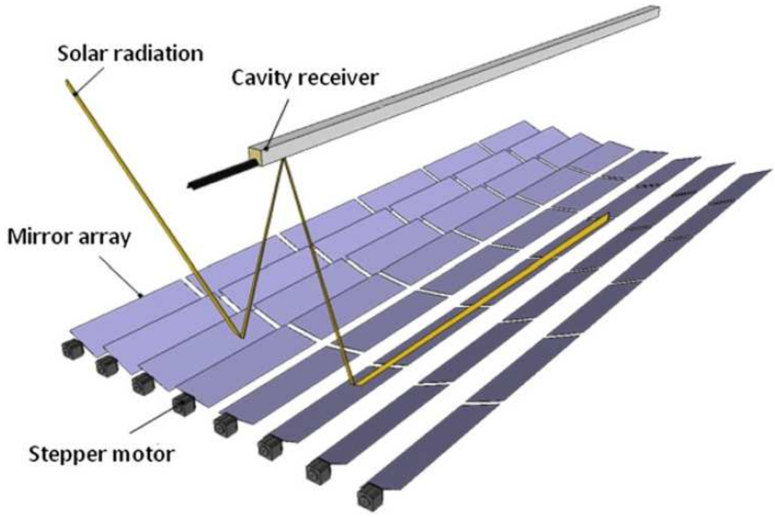

Figure 2. Diagram of linear Fresnel reflector.

The arrangement of mirrors can be understood as a segmentation of a parabolic trough concentrator in long parallel rows of flat mirrors where each line has its own tracking system to reflect solar radiation and focus collectively on an elevated long linear receiver that runs parallel to the rotational axis of the reflector (Mills, 2004).

The main difference of a LFR system is its manufacture, operation and low maintenance costs when compared with the parabolic trough, due to the use of flat glass mirrors, fixed absorber tube and less robust support structure, thus simplifying the assembly process.

The geometry of the LFR provides low aerodynamic drag, so the concentrator construction is simpler than parabolic trough systems. This feature results in a better structural stability, thereby reducing optical losses and mirror breakage.

However, the Fresnel linear concentration technology has lower optical efficiency than the parabolic trough, mainly due to solar radiation shading and blockage by adjacent segments of mirrors. This problem can be avoided through the raise of the absorber tubes or through the increase of the space between the mirrors, which leads to a higher land use in relation to the collector area (Mills and Morrison, 2000).

Several geometries of receivers for LFR concentrators were studied and tested. The receiver design can be divided into two groups: multi-tube and single tube (Montes *et al.*, 2014). The most conventional multi-tube design consists of a series of parallel tubes arranged horizontally in a cavity with a trapezoidal cross-section without secondary concentrator. The single tube design is based on a single pipe located inside a cavity with compound parabolic collector (CPC).

The existing LFR power plants use direct steam generation (DSG), where steam is generated directly in the solar field without any heat transfer fluid (HTF) between the solar field and power block, such as thermal oil or molten salt (Montes *et al*., 2014). The DSG systems can work with saturated or superheated steam.

According to Günther (2011), the main parameters in the design of Fresnel collectors are: width of the complete collector, width and the quantity of parallel mirrors, height of the absorber tube above the primary mirror plane, space between the mirrors and the curvature of the mirrors.

The different effects of the incidence angle in transversal and longitudinal direction are important for determining the solar field orientation. Theoretically, it is possible to align the Fresnel solar field in any direction. However, existing plants have adopted the north-south orientation of LFR field due to their higher annual energy efficiency.

LRF systems that use DSG are able to produce superheated steam with temperatures reaching 500 °C because they use vacuum absorber tubes, which have lower thermal losses. The solar field can be divided into two sections: vaporization and superheating, as shown in Fig. 3. The vaporization section has a larger area because the process of vaporization of water requires more energy.

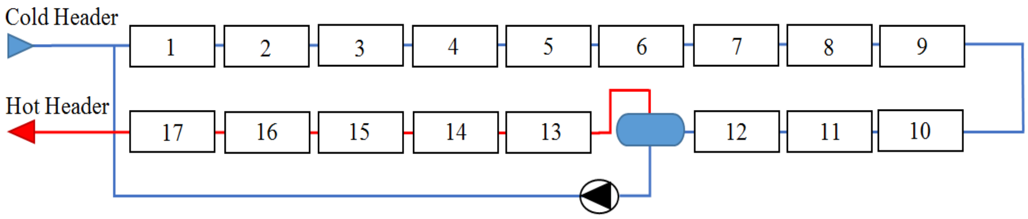

Figure 3. Diagram of solar field loop with direct steam generation.

The solar field with DSG can be classified into two types: with recirculation, as Fig. 3, or once through. To control the quality and avoid the passage of liquid to the superheating section, the recirculating system uses a separator drum with level control. The excess of saturated liquid in this drum is transferred to the beginning of the vaporization section.

Due to temperature limitations of the materials used in solar field and due to the high temperature protections systems in the steam turbines, the superheating section is provided with a steam output temperature control. Two methods are used for steam desuperheating: condensate injection and defocusing of the superheat section mirrors.

2.3 Power block

The system used in CSP to convert thermal energy into electricity, also known as power block, is similar to conventional power plants, but the major difference is the heat source. In some hybrid solar plant designs, the solar field operates in conjunction with a conventional boiler or with a combined cycle.

Thermal analysis of solar power plants is similar to those used in power plants that operate with Rankine cycle. According to Çengel (2013), the ideal Rankine cycle does not consider any internal irreversibility and consists of the following four processes: isentropic compression in a pump, heat supply at constant pressure, isentropic expansion in a turbine and heat rejection at constant pressure in a condenser.

The water in the saturated liquid state is compressed isentropically in a pump up to the boiler operation pressure. During compression, the water temperature rises slightly due to decrease of the specific volume.

In the boiler, the water receives heat and raises its temperature up to the superheating state. The pressure inside the boiler is considered practically constant. The superheated steam is directed to the turbine, where an isentropic expansion occurs, moving the blades and consequently moving the turbine shaft, thus producing work. The turbine shaft is coupled to an electric generator, which converts mechanical energy into electrical energy.

The steam reduces its temperature and pressure in the expansion process. The steam is directed to the condenser after exiting the turbine. The condenser is a heat exchanger that transfers the fluid latent heat to a cold source, which can be the atmosphere, even a river or the sea.

The simple Rankine cycle has much lower efficiency than the efficiency of the corresponding Carnot cycle, due to the irreversibilities associated with the heat transfer to and from the working fluid. In order to increase the efficiency of the cycle, some projects predict boilers with more than one pressure level or the inclusion of regenerators. The average temperature at which the heat is transferred to the fluid in the boiler and the temperature at which the heat is transferred from the fluid in the condenser affect the efficiency of Rankine cycle (Çengel, 2013).

3. METHODOLOGY

This chapter describes the steps of the study, which starts checking the availability of direct solar radiation in the region of the solar field installation, the description of Luiz Carlos Prestes Thermoelectric Power Plant, the solar field analysis, the costs of CSP installation and the presentation of the software of the concentrated solar power simulation.

3.1 Direct normal irradiation in Brazil

According to the International Energy Agency (IEA, 2014) Brazil has semiarid regions with daily DNI around 6 kWhm^{-2}. The greatest potential is located in the São Francisco Basin in the northeast region. This region has important features such as proximity to the equator line, available land, water availability, low annual rainfall and low population density.

The Brazilian Atlas of Solar Energy (Pereira et al., 2006) indicates that the average annual DNI in Três Lagoas city is about 2,181 kWhm^{-2}. This information encourages the feasibility analysis of the installation of concentrated solar power with UTE-LCP because, as the bibliography cited previously, CSP projects can be technical feasibility in regions with availability of annual DNI greater than 1,900 kWhm^{-2}.

To carry out the performance of simulations of the solar field and to compare the results, other two Brazilian cities with existing TMY and solar availability to that of Três Lagoas were selected. The selection of these cities was based on data of bright sunshine duration and maps of the average annual DNI. Therefore, the cities selected for this analysis were Petrolina in Pernambuco State and Campo Grande in Mato Grosso do Sul State. The typical meteorological year

(TMY) of these cities were taken from SWERA (Solar and Wind Energy Resource Assessment) project and the TMY of Três Lagoas was from Meteonorm software of Meteotest Company.

3.2 Luiz Carlos Prestes Thermoelectric Power Plant

The Luiz Carlos Prestes Thermoelectric Power Plant has the exclusive purpose to produce electricity and its generating units are divided in two independent blocks. Each block consists of two gas turbines, two heat recovery steam generators (HRSG) and one steam turbine.

The four gas turbines (GT) are the PG6101 6FA of General Electric, rated 71 MW at ISO conditions (15 °C temperature, atmospheric pressure of 101.3 kPa). However, due to fuel characteristics, weather and local conditions, the nominal power of gas turbine is 65.25 MW.

The steam turbines (Siemens) are simple flow and total condensation, with nominal power of 62.545 MW. The nominal pressure of the inlet steam is 69 bar and the temperature is 500 °C.

The exhaust gases of the gas turbine can be forwarded directly to the by-pass stack (single cycle) or to the respective HRSG (combined cycle). CBC Heavy Industries manufactured the four HRSG that work with superheated steam with nominal pressure of 69.43 bar, outlet temperature of 502 °C and nominal mass flow rate of 30 kgs^{-1}.

The installed capacity of UTE-LCP is 386 MW and the consumption of natural gas at base load is approximately 1.9 x 10^6 m^3day^{-1}. The plant has been operated commercially since January 2004.

3.3 Proposal for solar thermal integration

The selection of solar concentration technology used in this study and the solar field integration method with the UTE-LCP were the subjects of extensive bibliographic analyses. According to Zhu *et al.* (2013), nowadays two companies produce commercial systems of linear Fresnel reflectors, Novatec Solar and Areva Solar. Both systems utilize direct superheated steam generation with temperature between 480 °C and 520 °C. Novatec Solar provided relevant information that helped to define the solar thermal integration system.

The proposed system is a solar field LFR with DSG without thermal storage, which will run in parallel with the HRSG of the UTE-LCP, feeding its steam turbine, as shown in Fig. 4.

The power of the solar system was determined so that the sum of the steam flows from HRSG and the solar field does not exceed the operating limit of the steam turbine.

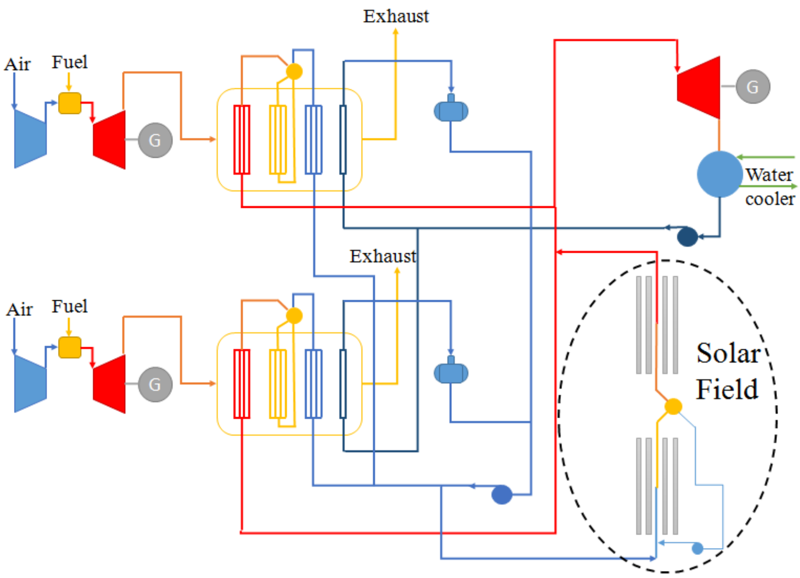

Figure 4. Schematic diagram of solar thermal integration with the UTE-LCP.

The German company Novatec Solar produces the LFR system selected. According to the manufacturer's information, Novatec is a worldwide leading technology provider of low cost and efficient concentrated solar power. According to Novatec (2014), the Supernova technology enables the production of superheated steam at temperatures up to 550 °C, with the following features:

a) Automatic cleaning system with low water consumption;
b) Highly efficient land use;
c) Direct steam generation, without using thermal oil;
d) High availability factor.

The solar field with this technology is modular and the main components of a control unit are foundations, support structure, primary reflectors, receiver and tracking system. A control unit consists of 128 primary mirror units with a reflective surface area of 513.6 m². The control unit can be arranged in longitudinal direction in rows of 5 to 22 units. Consequently, the rows can be settled to form solar fields of different sizes.

3.4 Cost of the linear Fresnel reflector system installation

LFR is a relatively new technology, with few units in operation and limited number of market suppliers and the cost data of the solar concentration system installation are not available enough.

According to the International Renewable Energy Agency (IRENA, 2013), the cost of a CSP plant with parabolic trough technology or linear Fresnel without energy storage in non-OECD countries such as Brazil, ranged between USD 3,100 and USD 4,050 per kW of installed capacity, due to low cost of products and local supply and renewable energy promotion mechanisms. According to IRENA (2015), 66% of the installation cost refers to the solar field and support structure while the other 34% of the cost refers to the generation block and heat transfer system.

To compare the competiveness of the different renewable generation technologies normally is used the levelized cost of electricity (LCOE), that represents the cost of building and operating a generating plant over an assumed financial life. According to U.S. Energy Information Administration (EIA, 2014), the LCOE of the solar concentrated power in the United States of America range from USD 176.8 to USD 388.0 per MWh.

3.5 Simulation software

In consequence of the lack of experimental data to predict the annual energy produced by the solar concentration system, this work uses the System Advisor Model (SAM) simulation software, developed by the National Renewable Energy Laboratory (NREL). The SAM is a software with a graphical interface, able to simulate the operation of various renewable technologies, including CSP (Wagner and Zhu, 2012).

The software combines an extensive performance model and economic analysis tools. It allows the user to retrieve data from hourly and totalized generation, thermal performance, efficiency, levelized cost of electricity and, capital, operation and maintenance costs. The model of the SAM systems is supported in the Transient System Simulation Tool (TRNSYS) software, developed at the University of Wisconsin, USA.

The linear Fresnel model SAM provides the performance of a plant with direct superheated steam generation, which can adjust the temperature and the working pressure. The model also allows specifying whether the solar field uses recirculation system or once-through (NREL, 2014).

The SAM uses hourly time basis to perform the simulations such as the TMY file. Thus, the results of the processed variables can be visualized for the year 8760 hours. The SAM program begins with the choice of weather data file from a particular location. After, the solar field and power block are configured. The parameterization of the solar field in the software was carried out with the help of Novatec Solar Company.

The data provided by Novatec Solar are supported in a previous work done by the company with NREL to simulate the performance and to validate the model implemented in the linear Fresnel model SAM (Wagner and Zhu, 2012).

4. RESULTS

The analysis of operational database collected from the control system of the UTE-LCP, identifies that the maximum power generation of steam turbine (ST) occurs for low ambient temperature conditions, usually in the early morning hours, mainly in the winter.

The decrease of the ambient temperature provides a greater inlet air mass flow in the axial compressor of the gas turbine (GT) and, therefore, it causes the elevation of the compressor discharge pressure and the elevation of the pressure ratio, increasing the efficiency of the Brayton cycle. Additionally, the high pressure air provides a greater cooling capacity of the combustion chambers and the blades of the first stage of the gas turbine, allowing the increase of the fuel flow and consequently the increase of the GT power.

With the increase of power and mass flow from the GT exhaust gases there is an increase of speed and available heat in the gases to the HRSG, allowing an increase of the superheated steam production and thus it results in an increase of the ST power.

In the operational database analyzed, the maximum observed output power of the ST is 61.58 MW. As mentioned previously in this article the rated power of the ST is 62.54 MW, so the unit has minimum availability of 0,965 MW for additional power generation.

The steam turbine average efficiency in base load was determined with the help of the Engineering Equation Solver software (EES). The inlet steam enthalpy was predicted through the pressure, temperature and mass flow rate from the ST operational data. The electricity produced by the ST was used to determine the overall performance. Thus, the ST average efficiency in base load is 29.6% with a standard deviation of ±0.5%.

With these data, the simulations on the SAM to check the performance of the solar field in the three Brazilian cities were carried out. Figure 5 presents a comparison of the solar system performance for these cities through a monthly base comparative performance of the additional net electric energy produced for the integrated solar field. It was observed that the energy pruduced decreased at the end of the wet period and in early winter, when the incidente irradiation is smaller than the other periods of the year.

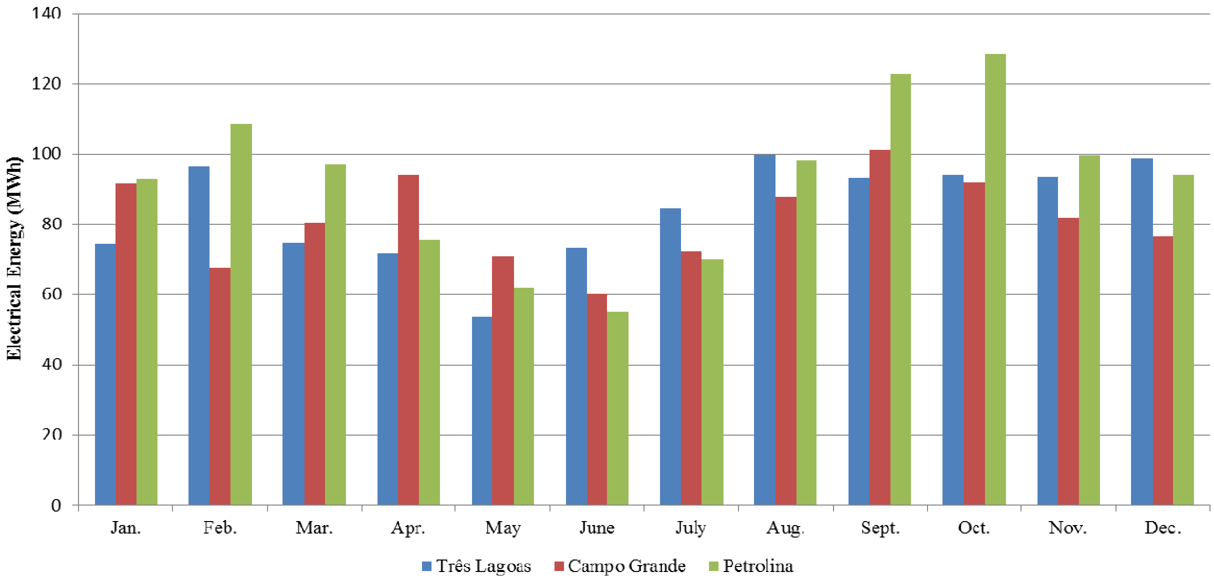

Figure 5. Performance comparison of the solar systems in the three Brazilian cities.

The analisis show that Petrolina has higher power generation throughout the year than Três Lagoas and Campo Grande. This is due to some key factors, especially due to the greater availability of beam irradiance, the greater number of operating hours of the solar system and the highest duration of bright sunshine over the year, as it can be seen in Tab. 2.

Table 2. Performance comparation

Annual Data	Petrolina	Campo Grande	Três Lagoas
Bright sunshine duration, h	2,860.6	2,576.1	2,601.7
DNI incident in the solar field, MWh	10,359.4	10,084.8	10,075.8
Solar system operating time, h	2,221	2,071	1,913
Field thermal energy produced, MWh	3,902.1	3,471.2	3,577.8
Additional net electric energy output, MWh	1,104.2	976.6	1,008.2
Capacity Factor	0.142	0.126	0.130

It is verified that the annual additional eletric energy produced by the integrated sistem with UTE-LCP in Três Lagoas is about 1,008.2 MWh with capacity factor of 0.13. The solar-eletricity efficiency of this system is 10%, which meets with the data of Kalogirou (2011).

The proposed solar field is formed by 11 control units, where 8 are in the vaporization section and 3 are in the superheating section, summing up 5649.6 m² of the mirror surface. According to Novatec data, the installation cost of this solar field is about 1,129,920.00 USD.

Following the analyses methodology of EIA (2014) that considers the cost recovery period of 30 years and weighted average cost of capital of 6.5%, the levelized cost of electricity is USD 90.83 MWh^{-1}, that is 48,5% lesser than the minimum value of LCOE of a solar thermal plant in the EIA (2014). This reduction in the LCOE is mainly caused by the use of LFR without thermal storage and there is no need to use investments in the power block.

5. CONCLUSIONS

Due to the presented analyses, it can be said that the proposed solar energy integration with an existing thermoelectric power plant has some competitive advantages. The main one is the use of direct steam generation in the solar field, which prevents exergetic losses because of to successive thermal exchanges between different working fluids and eliminates the use of the thermal energy storage system that presents technical difficulties. Other advantages are the reduced time and energy consumption for the heating of the CSP system at startup, the cost of investment is low and use the structure of an existing plant.

The integration methodology presented in this study may enable the insertion of concentrated solar energy in the Brazilian electricity matrix, enabling the development of the CSP market and the improvement of the technical staff in the area.

Through the simulations performed in the present work it was found that the solar LFR field performance model available in SAM can be used for the project installation feasibility analysis of solar thermal integration with the combined cycle of Luiz Carlos Prestes Thermoelectric Power Plant.

It was verified the competitiveness of the proposed integrated solar combined cycle, which presents LCOE lower than the data presented in the U.S. Energy Information Administration (EIA, 2014).

6. ACKNOWLEDGEMENTS

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8. RESPONSIBILITY NOTICE

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