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EVALUATION OF THE SOLAR POWER POTENTIAL OF A HYBRID CSP PLANT IN BRAZIL: A CASE-STUDY OF PIRAPORA-MG

Willian Mendes Ferreira*
willianm07@gmail.com

Leonardo de Paula Silva Ferreira*
llferreira_57@hotmail.com

Selson Carias Gomes Jr.*
selson.gomes@gmail.com

Matheus Pereira Porto*
matheusporto@demec.ufmg.br

*Grupo de Energias Renováveis da Escola de Engenharia da UFMG. Laboratório de Termometria - LabTerm. Programa de Pós-Graduação em Engenharia Mecânica - PPGMEC/UFMG.

Abstract. *Generation of electricity in Brazil depends mostly on hydroelectricity, which makes the country vulnerable to severe droughts. To reduce this dependence it is necessary to support the research on other sources of energy, as solar energy. This paper evaluates the generation and distribution of thermal solar power in Brazil. We simulate a hybrid CSP-TES in the North of Minas Gerais. The power output obtained indicates that the CSP is a reliable system and would provide constant power, either for winter, when solar availability is lower, also for the summer when higher variability is present. In a summer clear sky day, a 30 MW CSP plant can generate 545 MW using only solar radiation, producing energy during 6.25 hours with stored energy. We conclude that CSP plants have space for development in Brazil, because the country has a high incidence of solar radiation and CSP's have high dispatchability and potential to integrate with hydroelectric generation.*

Keywords: *renewable energy; solar energy; CSP plant; TES*

1. INTRODUCTION

Numerous policy proposals to encourage the use of renewable energy have been presented by many researchers from around the world. Renewables are essential to promote sustainable development, providing energy security and environmental balance (Martins et al., 2012). In Brazil, there is not a relevant renewable energy policy for solar energy. This occurs because the Brazilian energy matrix is one of the cleanest in the world (Pottmaier et al., 2013), in which 41.0% of the energy produced comes from renewable sources. Such index corresponds to 13.0 % in global average (EPE, 2014). However, such positive scenario is a result of the high dependence on hydropower, accounting for 70.6% of the electricity generated in the country (EPE, 2014). Hydroelectrics find many social and environmental obstacles, mainly due to the people’s displacement and flooding of forests. One of the most instigating questions after the severe droughts in Brazil is: are the hydroelectrics really a sustainable source? Brazil have suffered two severe droughts in the last fifteen years, in 2001 and 2014. In 2001, the drought coupled with infrastructure limitations caused a serious power shortage (Geller et al., 2004). From this experience, the country began to stimulate the construction of power plants based on fossil fuels. In 2014, there were severe price shocks, responsible for causing huge losses to the electricity sector. It is necessary to improve the use of other natural resources abundant in Brazil, investing in solar energy, for example (Geller et al., 2004).

In recent years, some studies have evaluated the potential use of solar resource in Brazil for water heating and mainly for electricity generation, using either photovoltaics (PV) or concentrated solar power (CSP). Much attention has been given to studies about CSP and not only about PV. CSP has some advantages over PV, as dispatchability, when developed with thermal energy storage (TES), and the ability to operate in hybrid configurations (U.S. Department of Energy, 2012).

Martins et al. (2012) defined, from solar maps developed in SWERA (Solar and Wind Energy Resource Assessment) project, that the Northeastern region and the north of the State of Minas Gerais have the greatest potential for CSP projects in Brazil. Malagueta et al. (2013) studied scenarios for the introduction of CSP plants in the Brazilian electric power system. For this purpose, the software System Advisor Model (SAM) was used to simulate the operation of CSP plants in four configurations for two cities: Bom Jesus da Lapa (Northeastern region) and Campo Grande

(Midwestern region). From the results, one of the author's recommendations is to incentive CSP plants with hybridization, because they had the lowest levelized cost of energy (LCOE) and the highest capacity factor among all configurations analyzed.

However, little attention has been paid to analysis of dispatchability aspects of a CSP plant in Brazil. Economic analyses based on the LCOE parameter do not consider an important advantage of CSP plants relative to other renewable technologies of intermittent generation: the ability to adjust the power output according to electricity demand (Brand et al., 2012). Characteristics as intermittency, availability and reliability of renewable sources are not much discussed and should be better evaluated (Trainer, 2013; Lucena et al., 2009).This analysis provides an important tool for local planners and decision-makers assess the potential for integrating of CSP plants to the national grid (Brand et al., 2012).

The purpose of this article is to evaluate the generation and dispatchability potential of a hybrid CSP plant with TES in Brazil. For this aim, we performed using the Ebsilon® Professional software the simulation of a CSP plant in the north of Minas Gerais. Considering aspects of the annual climate variability and the intermittency pattern of solar radiation in the chosen locality were obtained characteristic profiles of hourly power generation for the simulated plant. Detailed information about the storage levels and the consumption of fossil fuel of the plant are also presented.

2. METHODS

2.1 Location choice

This study selected the city of Pirapora, located in the northern State of Minas Gerais, for the analysis proposed. The north of Minas Gerais is characterized by physical, social and economic diversity, with great availability of energy resources and low socioeconomic indicators. Initially, three main aspects were considered for the choice of this locality, following the strategy adopted by Martins et al. (2012). First, the high incidence of direct normal irradiance (DNI). In this area, the amount of direct solar irradiation reaches an annual average between 2.2 and 2.4 MWh/m². Many studies indicate that for these values, CSP plants are economically feasible (Malagueta et al., 2013). Second, accessibility to water resources. The Pirapora region is crossed by one of the most important rivers in Brazil, the São Francisco River. Finally, the proximity to transmission lines. Later, other aspects were considered, such as availability of hourly meteorological data, land availability and soft terrain slope (CEMIG, 2013).

An additional factor considered is the possibility of natural gas exploration in the region, which would allow integration with solar thermal generation in a hybrid scheme. Estimates of national oil agency (ANP) indicate a reserve of about 80 trillion cubic feet of natural gas in the São Francisco Basin (ANP, 2013), where is located the city of Pirapora. The exploration of this potential has been evaluated by some companies and stimulated plans for the use of these reserves by the local government for power generation using thermal power plants.

The deployment of hybrid CSP plants in the north of Minas Gerais would mean better use of the energy potential in the region, with the exploration of natural gas reserves and plentiful solar resource. In this configuration, such reserves would be better applied than if they were used only for the supply of thermal plants. Therefore, a hybrid CSP plant in the region is a more efficient and sustainable alternative, also considering that natural gas is cleaner than other fossil fuels such as coal, for example.

2.2 Meteorological Data

Values of solar irradiation are the basis of a solar power plant design. The higher the historical data available, better the design conditions. Pirapora's climate is tropical, with well-defined rainy and dry seasons. Rainfall is concentrated between the months from October to March and the maximum temperature varies between 30 °C and 33 °C.

The National Institute of Meteorology (INMET) has an automatic station on Pirapora region measuring several meteorological variables including temperature, atmospheric pressure, global irradiation, relative humidity, wind speed, among others. The station performs automatic measurements of global irradiation every minute and integrates the values, delivering the results in KJ/m2 for each hour. Therefore, it was necessary to construct an algorithm for the conversion of global to direct irradiation. The formulation proposed by Duffie and Beckman [2006] was used and the results divided by 3600 to find irradiance in W/m2. Figure 1(a) shows the values of DNI throughout the year of 2013 according to INMET data. The amount of energy available varies during the year. These variations are caused mainly by season and cloudiness. Figure 1(b) shows a top view of the surface of annual irradiation, where we can see these variations. The highest amount of energy is available in the summer. However, this season concentrates almost all the rainfall of the year, which causes great variations on the irradiation, as shown in Fig. 1.

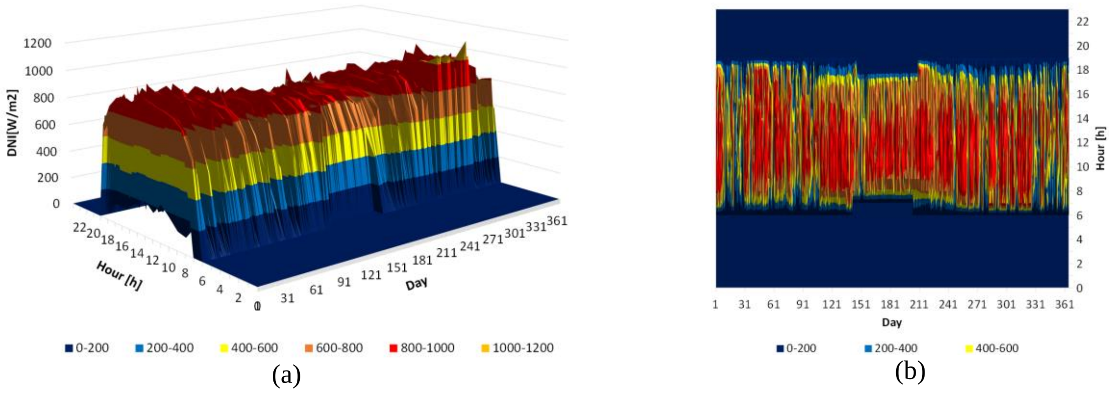


Figure 1. (a) INMET Data and (b) Top view of the irradiation

The historical data of the last seven years have been used to determine the design irradiance. However, only the values of the year 2013 were used for the simulations presented in section 3. In this section, two scenarios were simulated: typical days of each season and days with different cloudiness. These days are repeated over the years, so the use of only the 2013 data is justifiable.

2.3 CSP Plant Model

In this step, we modeled a hybrid CSP plant with TES for the city of Pirapora. The model was elaborated using the software EBSILON® Professional. EBSILON® consists of a mass and energy balance simulation program, used for planning of thermal power plants processes (Mason, 2011). This software is a tool developed by Evonik Industries in collaboration with DLR (German Aerospace Center) in Germany.

The modeled configuration has technical and economic advantages because it is able to improve the dispatchability and increase the capacity factor of the plant. The combined use of TES and hybrid systems allows the plant to control the power output and produce energy in periods of insufficient solar radiation, i.e., at night, on cloudy days or at peak times. The simplified plant model, shown in Fig. 2, is formed by four subsystems: power block, solar field, TES and hybridization system. Each subsystem will be presented in the next sections.

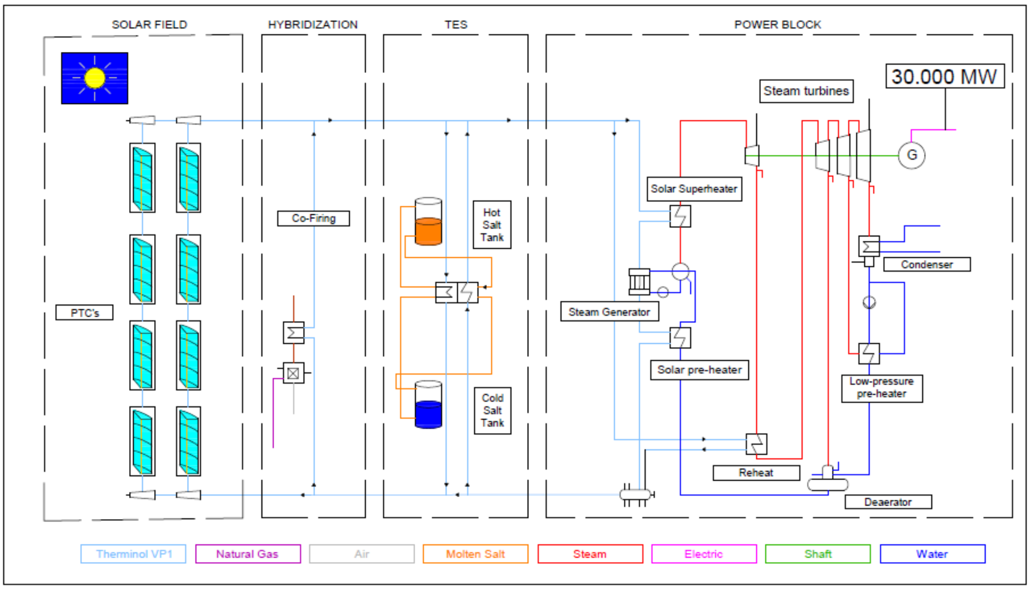


Figure 2. Simplified Plant Model

2.3.1 Power Block and Solar Field

Power block consists of a Rankine cycle with regeneration and reheat for a nominal power output of 30 MW. The choice of power was determined by the availability of specific incentives in Brazil for small plants of renewable energy up to 30 MW (ANEEL, 2010). Moreover, this value is compatible with the configuration of most CSP plants in the world, operating for a power of 50 MW. The main parameters defined in the power block design are shown in Tab. 1.

Table 1. Design-point conditions for the power block.

Power output	30 MW
Cooling system	Evaporative
HTF inlet temperature	393 °C
HTF outlet temperature	300 °C
Steam temperature at turbine inlet	373 °C
Steam pressure at turbine inlet	100 bar
Condenser pressure	0.1 bar
Turbine isentropic efficiencies (all)	0.88
Pump isentropic efficiencies (all)	0.80
Generator efficiency	0.986
Power cycle efficiency	0.384

The solar field is the location where the energy is absorbed. Several technologies enable the capture of solar energy and its conversion into thermal energy. Among these technologies, we chose the parabolic trough technology, which is the most consolidated in the world. The parabolic trough collectors (PTCs) are installed in parallel and the heat transfer fluid (HTF) circulates among the receivers, installed in the focal area of the collectors, made up of concave mirrors (DGS, 2005). The main technical data about the solar field are shown in Tab. 2.

Table 2. Design-point conditions for the solar field.

CSP technology	Parabolic Through
PTC	Eurothrough 2012
Net aperture area of collector	817.43 m²
Peak optical efficiency	0.75
Irradiance at design	900 W/m²
Ambient temperature at design	25 °C
Solar multiple (SM)	1.81
Number of collectors per loop	4
Number of loops	68
Total aperture reflective area	222,341 m²
HTF	Therminol VP1

2.3.2 TES

An important advantage of CSP technology is the possibility to storage heat during the sun hours by incorporating TES systems (U.S. Department of Energy, 2012). Such systems enable the plant to continue producing electricity when the solar radiation is not enough and are still much cheaper than storing energy in batteries (Kalogirou, 2009). Currently, the most common TES configuration is the use of molten salt in a two-tank system. The hot tank storages useful heat while the cold tank holds the exhausted cold fluid (NREL, 2011). The parameters adopted in the TES system model are shown in Tab. 3.

Table 3. Design-point conditions for TES.

Storage Fluid	Molten salt
Full load hours of TES	6 h
Maximum level	16,000 t
Minimum level	815 t
Hot tank temperature	384 °C
Cold tank temperature	292 °C

2.3.3 Hybridization

The hybridization or backup system of the plant consists, essentially, of a burner and a heat exchanger. In the burner occurs the reaction between the fuel and air. The fluid resulting from the combustion, at high temperature, is then routed to the heat exchanger, providing heat to the HTF. Hybridization is used alternatively to the storage system, i.e., only for the situation in which the TES can no longer provide heat to the power cycle. The basic parameters defined for the plant's backup are presented in Tab. 4.

Table 4. Design-point conditions for the backup system.

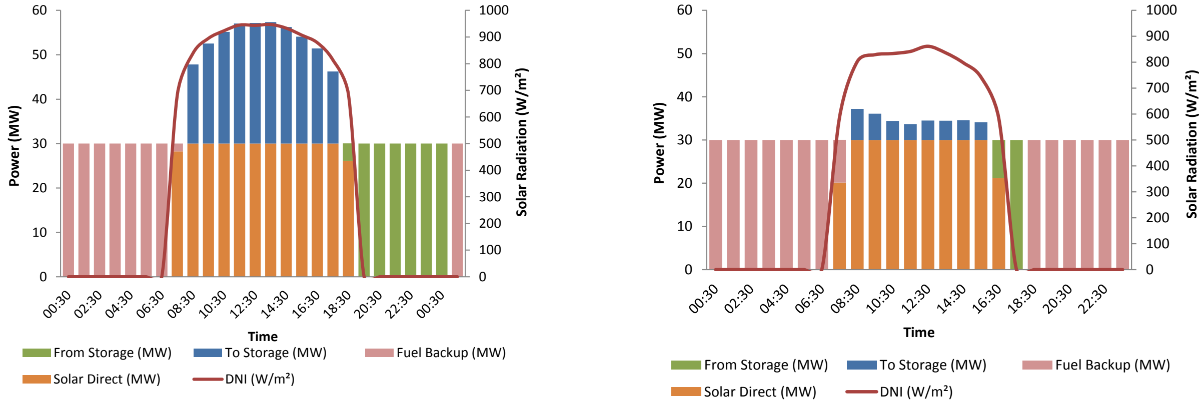
Back-up fuel	Natural gas
Composition	Methane (CH_4)
Specified net calorific value at 0° C	50,015 kJ/kg
Density	0.614 kg/m³
HTF outlet temperature	393 °C
Back-up fuel	Natural gas

3. RESULTS AND DISCUSSION

3.1 Simulations throughout the year

Aiming to evaluate the plant dispatchability throughout the year, it was proposed the analysis of a representative day for each season. Thus, four days that marks the beginning and end of the seasons were selected: summer and winter solstice and spring and autumn equinox. If any of these days present cloud cover, it was decided to choose the nearest clear sky day. The largest amount of radiation occurs in summer and lower in the winter. The values recorded for fall and spring are between these two, and ones for December are moved an hour because of the summer time.

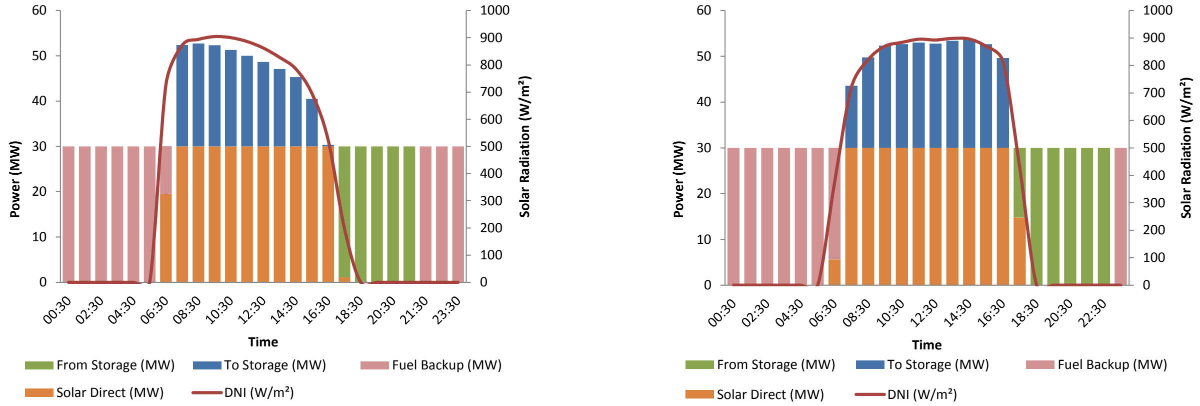
As a project definition, it was stipulated that in the absence of solar radiation, the energy stored in the molten salts would be used before the hybridization system be activated. Initially comparing the summer months with the winter in Fig. 3, we can see that generation is very different in these stations. On a typical summer day, solar radiation can supply the plant all day and still provide stored energy until 01:15. The rest of the demand is supplied by hybridization system. On the other hand, on a winter day, the solar radiation is barely capable to maintain the plant in full operation.



(a) (b)

Figure 3. Generation profile at summer (a) and winter (b)

In the autumn and spring seasons (Fig. 4), the operation of the plant is closer to the summer. However, solar radiation is able to meet the demand for fewer hours and less energy is stored for use at night, ending at 23:24 and 21:21, respectively.

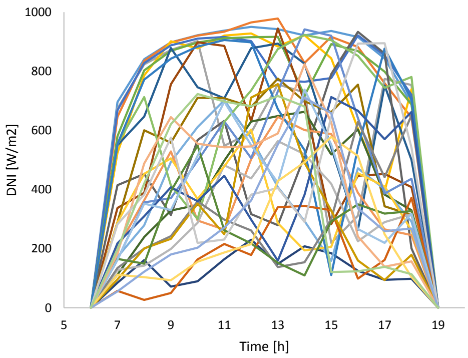


(a) (b)

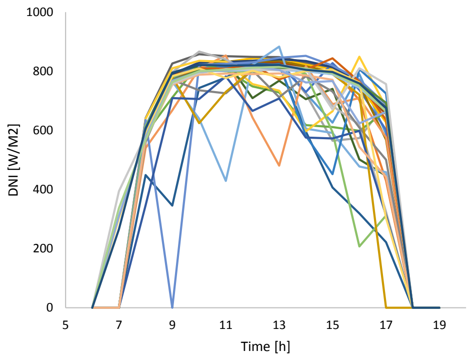
Figure 4. Generation profile at spring (a) and autumn (b)

3.2 Influence of cloudiness

Another important condition to be analyzed is the influence of cloudiness on the operation of the CSP. The climate of Pirapora is tropical, with the rainy and dry seasons well defined. The annual rainfall is about 1200 mm and most of it occurs between November and March, with peaks in December and January. Figure 5 shows the influence of cloudiness on the curves of daily irradiance. Figure 5(a) shows the irradiance for all days of January, as Fig. 5(b) shows irradiance for July. Despite the month of January has the highest values of peak irradiance, most days has some cloudiness. On the other hand, in July the irradiance is considerably lower, but few days have clouds that could disrupt power generation.



(a)



(b)

Figure 5. Irradiance values for: (a) January of 2013 and (b) July of 2013

Thus, three days with different cloud levels were selected in January: a day with few clouds, called a good day; a day with intermediate cloudiness, called intermediate; and a day with lots of cloudiness, called a cloudy day. A clear sky day was used to serve as a basis of comparison. Figure 6 shows the curves of solar irradiance for the selected days.

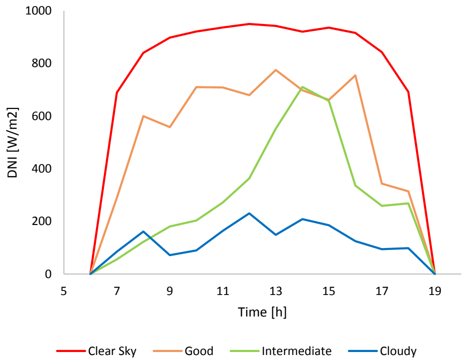
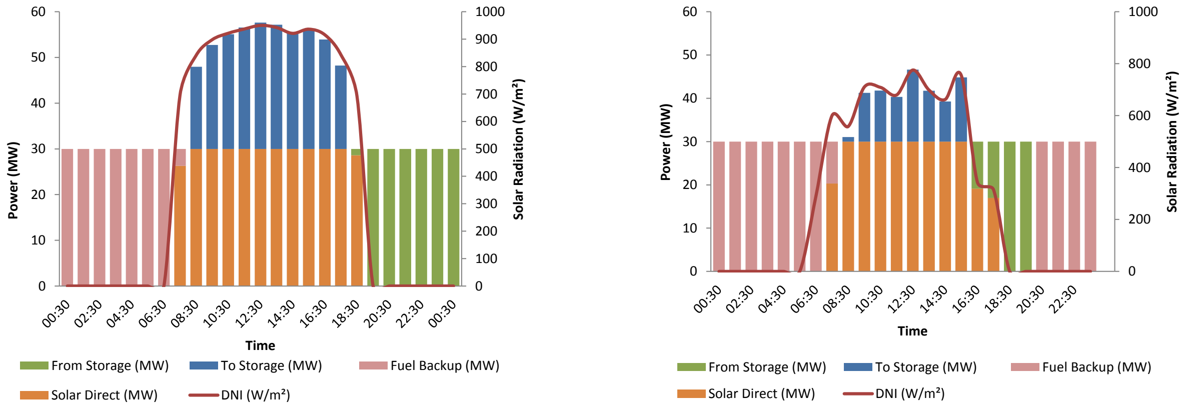


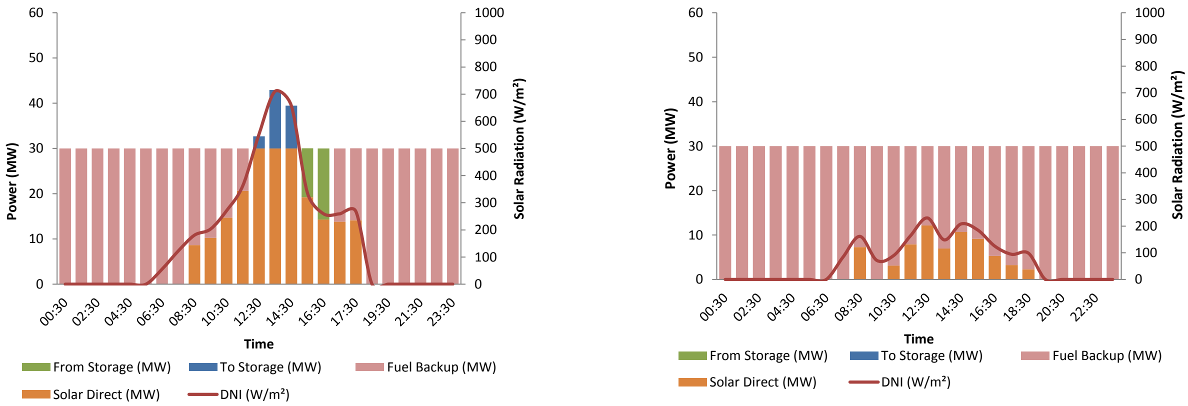
Figure 6. Selected days for evaluate the cloudiness impact

The simulations of these days are shown in Figs. 7 and 8. The result for the reference day is consistent with that obtained for the summer day, in section 3.1. There is energy storage throughout the day, and it is used during the earlier hours of the night. When the stored energy ends, the gas complement system comes into operation. For the day considered good, the operation is similar, but the storage system should complement the energy of the plant at times of day when the radiation drops sharply. Furthermore, because there is less energy, the volume stored in the hot tank is depleted more rapidly and the complement by gas must come sooner. In days of intermediary cloudiness, energy storage only occurs at some moments and hybridization system must be activated during the morning and earlier at night. In the completely cloudy day, solar radiation can supply only a small portion of the demand, and the hybridization system must supply almost all power generation.



(a) (b)

Figure 7. Clear sky (a) and good day (b)



(a) (b)

Figure 8. Intermediate (a) and cloudy (b) days

3.3 Dispatchability

The plant power generation is strongly influenced by the season and cloud cover, as shown in sections 3.1 and 3.2. The Brazilian electric system is based on hydroelectric generation, and the diversification of the matrix through solar energy can bring benefits. A power system composed mainly of hydro plants implies a structural instability, becoming the country more susceptible to energy crises in periods of droughts. This scenario requires efforts for greater integration of renewable sources, preventing damage resulting from adverse climatic situation. Thus, it is necessary to invest in complementary sources to the hydropower as wind and solar, for example. In the case of the CSP plants, the complementarity is more evident, since the availability of solar radiation is greater when there is a lack of rain.

In rainy seasons, the loss of power generation at solar plant can be compensated by an increase in the generation of hydroelectric plants. In times of drought, the reservoirs can be saved with energy produced in the solar plant. Even with lower radiation levels in the winter, the plant may have a higher capacity factor due to the lower level of cloudiness. As suggestion for future works, this dispatchability evaluation may be accomplished by simulations of a longer period of time such as a week, a month or even a year.

4. CONCLUSIONS

In this study, we designed a hybrid CSP plant with TES for the city of Pirapora, in the north of Minas Gerais. The main objective of the present paper was to assess the dispatchability potential of the solar thermal power systems in Brazil. For this purpose, we performed a detailed evaluation of the climate characteristics of the chosen locality. From this analysis, it was possible to simulate the operation of the CSP plant modeled for a large number of weather conditions and establish the power generation profile of the plant during representative days of the year.

The results of this paper show that CSP plants in Brazil are able to offer high dispatchability and reliability to the Brazilian electrical system. On days of high incidence of solar radiation, prevailing in the most part of the year, the solar resource is sufficient for the plant provides electricity during the daylight hours, and part of the energy absorbed by the solar collectors is stored to supply the demand up to six hours at night. In typical summer day, about 75% of the power generated (assuming full operation) is derived from solar radiation.

In winter, the plant is not capable of storing energy to produce electricity at night. However, during the hours of sunshine, the plant is almost self-sufficient, since approximately 90% of the generated power is produced from solar radiation. In rainy summer days, with low and unstable solar radiation or when the storage system is not enough, the hybridization system is able to balance the electricity supply of the plant. These characteristics represent an important differential in comparison to other renewable technologies of intermittent generation and can create a large space of development for the CSP technology in the country. This technology would bring two major benefits to Brazil: the use of renewable energy sources and the diversification of the Brazilian energy matrix.

The results obtained can be also applied to many other regions in the country of similar characteristics to Pirapora. In the Northeast, for example, there are localities with equivalent climate profiles and levels of direct solar irradiation higher than in Pirapora. In these places, hybrid plants could still be constructed using other back-up fuels.

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