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FEASIBILITY STUDY OF HYBRID THERMOELECTRIC PLANTS USING CSP TECHNOLOGY AND FOSSIL FUEL: SIMULATION SCENARIOS

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Abstract. *Due to the rapid advance in technology, a new generation of power plants has emerged: the concentrated solar power (CSP). It is a renewable energy system that can be combined with large-scale energy storage systems. CSP holds many promises for the countries with high direct solar radiation, as Brazil. However, there are many problems regarding the viability of these plants in the emerging countries such as high capital costs, lack of national technology and qualified professionals. Hybridization of existing power plants with solar energy could be a possible gateway for the technology deployment. This paper presents the technical and economic feasibility analysis of a steam super-heater plant powered by CSP for electricity production. Such hybridization permits the reduction of* CO_2 *emissions and retrenchment in the long term. In this context, the performances of four different systems of thermoelectric power generation were compared: (i) reheating cycle - superheated steam generated by boiler and it expansion in the first turbine using CSP for reheating second expansion turbine; (ii) saturated cycle - generating saturated steam in a boiler and superheating it using CSP; (iii) supercritical plant - superheated steam production in a boiler and heating at supercritical steam in CSP and (iv) conventional cycle and CSP working in parallel. The direct irradiation data available at the Brazilian solar atlas were analyzed, looking for the best location of power plant installation. In addition to the solar resource data, other criteria as economic, social, environmental and availability of transmission lines were taking into account. The decision matrix with performance indicators helped in the decision-making process of location selection. Comparing to other scenarios the obtained results showed several advantages of scenario (iv) - conventional cycle and CSP working in parallel using solar power towers without thermal storage. Research result as well revealed Santa Maria da Vitória town, Bahia region, as a better place for plant construction using the selected scenario. The total capacity was determined to be 30 MWe in accordance with the incentives offered by 481/2012-ANEEL resolution.*

Keywords: *Concentrated solar power (CSP), Solar irradiation data, Hybrid thermoelectric, Reheating vapor cicle*

1. INTRODUCTION

Brazil faces the dual challenge: the exhaustion of hydroelectricity and the management of the environmental cause. Among the leading candidates to overcome these challenges are the production of electricity based on biomass and production based on solar and wind energy. Biomass could be a substitute for fossil fuels, but the demand for land and water may threat our ability to meet the electricity consumption and to feed the growing world population (Perlack et al., 2005). The use of the wind, despite the great potential, has the limiting of the burst when connected to the grid. Solar energy has enormous potential especially in the area close to Brasilia and, despite suffering with potential change generated throughout the day and year, when associated with other technologies may represent cost savings and significant environmental impacts. The energy that reaches the Earth in one hour is greater than the entire amount consumed by humans in a year (Zhang et al, 2013). In this context, the generation of power in Power Plants by Concentrated Solar Power (Concentrated Solar Power Plant - CSP) is a way to harness this abundant solar resource.

In the case of thermoelectricity generation in small and medium scale, different system configurations can be used: steam cycles, gas, solar. Each technology has different advantages and disadvantages depending on the scenario. The power generation in CSP is a way to reduce dependence on fossil fuels and meets the international goals of reducing CO2 emissions. A promising form of integration between conventional processes is the use of CSP combined with other technologies such as biomass burning to produce steam, can be expanded in appropriate turbines to generate electric power. In order to evaluate the various possible configurations of technologies combination , four scenarios using combining two different technologies simultaneously is studied in this work.

2. ELECTRICITY PRODUCTION USING THERMAL POWER PLANTS

Thermal Power plants are one of the most important process industries for engineering professionals. Over the past decades, the power sector is facing a number of critical issues; however, the most fundamental challenge is meeting the growing power demand in sustainable and efficient ways. Practicing power plant engineers not only look after operation and maintenance of the plant, but, also look after range of activities including research and development, starting from power generation to environmental assessment of power plants (RASUL 2013).

2.1 Concentrated solar power plant

Concentrated solar power is electricity generation concentrating the heat of the sunlight in a small area called receiver. This receiver contains a heat transfer fluid (HTF) expected to transfer heat to a steam power cycle.

There are four principal concentrating technologies :

- Solar Power Tower (SPT), or Central Receiver System (CRS), is made of a field of reflectors concentrating the sunrays onto a receiver in the top of a tower (Muller Steinhagen and Trieb, 2004). A heat transfer fluid absorbs the heat and transfer it to the heat exchangers of a steam Rankine power cycle.
- Parabolic Trough Collector (PTC): an absorber tube is fixed on the focal line of a one-dimension parabolic shape, made of a group of reflectors. They move in tandem with the sun from sunrise to sunset (Llorente et al, 2011). The absorber tube is a steel tube surrounded by a glass envelope, and vacuum between these two elements.
- Linear Fresnel Reflector (LFR): a linear receiver, fixed on a tower, is surrounded by a field of reflectors, flat or slightly curved mirrors.
- Parabolic Dish Collectors (PDC): the receiver is placed on the focal point of a parabolic dish, concentrating sunrays. There is no need of a HTF, it offers the best efficiency of any CSP system, but this technology remains expensive, and neither high power nor hybridization are possible (Barlev et al, 2011).

Two technologies can enhance the performance of a CSP system:

Thermal Energy Storage system (TES): the heat in excess coming from the solar field can be transferred to a transfer fluid between a cold tank and a hot tank. The heat stored in the hot tank can supply the steam power circuit. Short term thermal storage allows the balance of energy supply throughout the day. Fernandes et al (2012) studied long term thermal storage, throughout the period of the year, and the material that could be used.

Backup System (BS): a fuel backup system aims at regulating the production of energy. CSP plants with a backup system are called hybrid plants. This BS can provide energy to the HTF, to the storage fluid, or to the power circuit. Integrated solar combined cycle plants (ISCC) are integration of a CSP field into a fossil fuel fired power plant, such solar fuel savers have relatively limited investment costs (Zhang et al, 2013).

Parabolic Trough Collector plants are the most developed of all commercially operating plants, but outlook for improvements are limited (Barlev et al, 2011). On the contrary, CRS technology shows promising advances as much as HTF development (IRENA, 2012). Compared with other options, central receiver can provide cheaper electricity and better performances:

- Higher temperatures (up to 1000°C), the large amount of irradiation focused on a receiver (200-1000 kW/m²) simplifies heat transport, minimizes heat losses (Sargent and Lundy Consulting Group, 2003). The whole piping system is concentrated in a central area, which reduces losses, material costs and maintenance.
- Good potential for efficiency improvements (40-65%) (Romero-Alvarez and Zarza, 2007)
- Wide variety of options for integration with fossil fuel plants or hybrid operations (IRENA, 2012)

A typical central receiver system, or solar tower power, is the addition of three subsystems: a heliostat field, a solar receiver and the power conversion system. The heliostat consists of numerous controlled mirrors tracking the sun and reflecting the radiation onto the receiver, fixed on the top of a tower. The performance of the SPT is strongly related to the solar field efficiency: heliostat design, field layout, control system; almost 40% of total energy losses are attributed to the heliostat field (Goswami et all, 2000). The radiation is converted into heat by the circulation of the HTF in the receiver. The upper working temperature can range from 250°C to 1000°C (Pitz-Paal et all, 2005). The heat is transferred to the power circuit, and thermal energy is finally converted into electricity. This conversion can be produced in high efficiency in Rankine cycle, Brayton cycle or combined cycle.

2.2 Steam cycles for electricity production

The Rankine cycle consists of :

- Compressing water to high pressure, over several MPa;
- Boiling and superheating steam, at the focal point or using heat exchanger;
- Expanding the steam in one or several turbines, connected to a generator;
- Finally condensing low pressure steam.

Vapor must be sufficiently superheated before expansion in the turbines in order to avoid blade erosion. According to Lovegrove and Pye (2012), the efficiency is higher and costs are lower if the system is large and run at full load; a larger turbine requires a large field, but implies thermal losses; there is a trade-off against turbine size. Coelho et al. (2012) have reached the same conclusions analyzing several possibilities of hybridizing biomass and CRS receiver power plants, and found a concept reducing biomass consumption by 17% compared with conventional power plant.

Zoschak and Wu (1975) compared seven options of integrating CRS into a 80MW steam cycle, and they found that the most suitable scheme is using solar heat for both evaporation and superheating.

For maximum efficiency, steam turbine can work at supercritical conditions: steam temperature and pressure exceed the critical point. The phase-change occurs continuously. Studying the effect of thermal conductance and thermal irradiance on the optimal receiver temperature and the efficiency of five Rankine cycles, McGovern and Smith (2012) found that super-critical Rankine cycles are suitable for CRS, and sub-critical cycles for parabolic through power plants.

2.3 Steam superheaters

According Lagemann and HALL (2006) BRAMBILLA (2007), the superheaters are tubular exchangers in the form of coils, in order to create large heat transfer surfaces to increase the degree of vapor superheat. In general, the place where the gas flows is warmer. They consist of two collectors, one for saturated steam and one for superheated steam. In some designs, the superheater can be divided into two or more stages. In this case, between stages is inserted into the intermediate desuperheater. By circulating only inside the steam superheater, its temperature reaches extremely high values and so are designed creep criteria using in their manufacturing, carbon-molybdenum steel or chrome-molybdenum.

When they are located in convection zone, they are named convection superheaters. They have the basic characteristic of increasing steam temperature with increasing boiler load. On the other hand, when they are subjected to radiation, they are named radiation superheaters, and with increasing boiler load there is a decrease of the steam temperature.

Superheater can also be decoupled from the boiler, receiving heat from another independent source. In this case the equipment becomes an accessory to the steam line . It works under high pressure, consequently, it needs to comply with the standards for pressure vessels and undergo frequent testing to certify their safety. Figure 5 represents schematically a Rankine cycle with a solar power cycle feeding the superheater.

3. SCENÁRIOS DEFINITION

The production of electricity through steam is only possible if this is in the superheated state. In this context it was simulated, using specific software, the following variables:

i. Plant location depending on the amount of available solar radiation;
ii. Operational size the plant according to the Brazilian legislation of independent electricity producers;
iii. Type of solar concentrator to be installed;
iv. Technology to be used in this plant:
    a. Reheat to the second steam turbine operating from solar reheating, figure 1;
    b. Saturated steam boiler and a solar superheater, figure 2;
    c. Reheat using supercritical steam in both turbines, figure 3;
    d. CSP parallel to conventional cycle using boiler, figure 4.

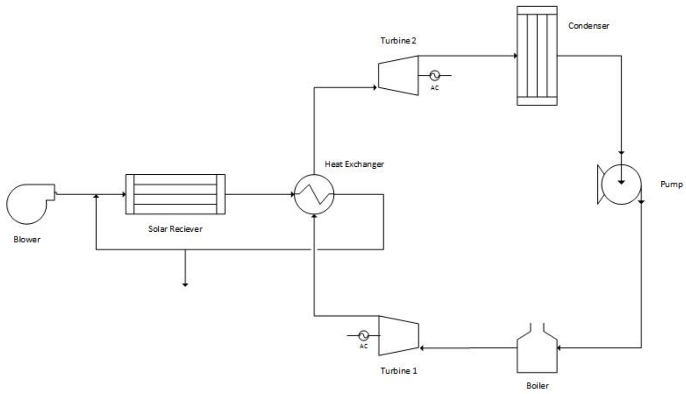


Figure 1. solar reheating

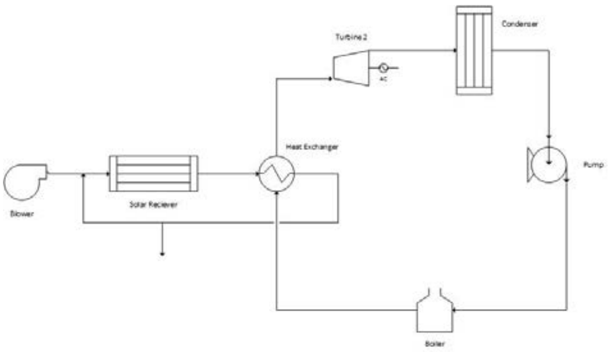


Figure 2. solar superheater

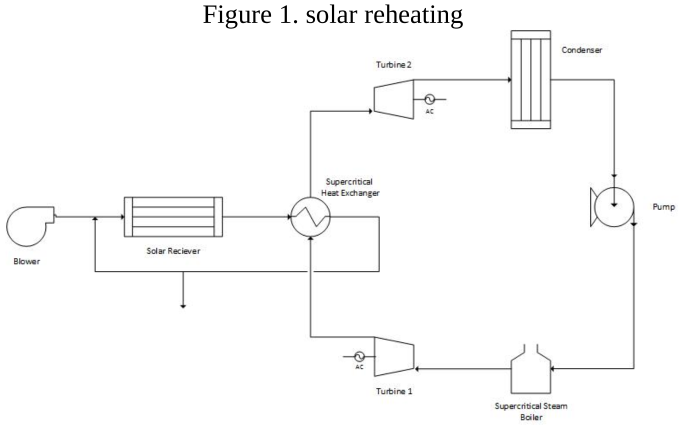


Figure 3. supercritical steam in both turbines

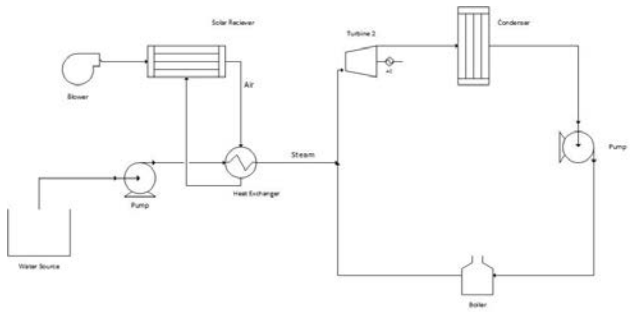


Figure 4. CSP parallel to conventional cycle using boiler

4. MATERIALS AND METHODS

For the best site selection the NASA solar irradiation data from the last 5 years is used. From the choice of locality, the data collected in the region were inserted into the RETScreen 4 software for first technical and economic feasibility analysis.

With solar radiation data and economic feasibility study, the thermodynamic cycle using software CyclePad v2 is configured in order to determine the operating conditions of the plant equipment. After the first definitions, the data are inputted into system advisor model (SAM) version 2015.1.30 to refine the simulations and collect data for final analysis and discussions.

The data used for economical simulations are presented in table 1 below. For site selection is used a hybrid plant with same operational configuration and layout like the one shown in figure 4.

Table 1. Input values used for the SAM simulation

Inputs	Values	Inputs	Values
Period of analysis	30 years	IRR target year	10 years
Inflation	0%	Contingency	10%
Real discount rate	10%	Land cost	5000 $/per acre
Federal tax	34%	Turbine gross output	30MWe
State tax	7%	Cycle efficiency	41.2%
Sale rate	5% of installed cost	Turbine inlet pressure	103.4bar
Insurance	0,5% of installed cost	High outlet pressure	20bar
Debt percent	70% of installed cost	Boiler LHV efficiency	90%
Interest rate	7,40%	Condenser type	Evaporative
Amortization time	16 years	Ambient temperature	$30^{o}C$
IRR target	15%	Fossil dispatch mode	Suplemental operation

4.1 Economic simulation and analysis

The economic viability of a power plant is a key component in deciding whether or not such a plant would be a feasible source of power. A simple Levelized Cost of Electricity (LCOE) economic model was also developed and integrated with the Hybrid CSP model in order to assess the potential economic viability of a 30 MW power plant.

Levelized cost of electricity (LCOE) is the per-kilowatt hour cost (in real dollars) of building and operating a generating plant over an assumed financial life and duty cycle. Key inputs to calculating LCOE include capital costs, fuel costs, fixed and variable operations and maintenance (O&M) costs, financing costs, and an assumed utilization rate for each plant type. The equation 1 below describes how to calculate it.

$$\mathrm{LCOE} = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+\mathrm{r})^t}}{\sum_{k=0}^{n} \frac{E_t}{(1+\mathrm{r})^t}} \tag{1}$$

Where: LCOE - the average lifetime levelized cost of electricity generation; I_t = investment expenditures in the year t; M_t = operations and maintenance expenditures in the year t; Ft = fuel expenditures in the year t; Et= electricity generation in the year t; r = discount rate; and n = life of the system.

The LCOE depends primarily on capital costs and the local solar resource (IRENA, 2011). In Brazil there is no any real data for the CSP technology cost. Moreover, until the auction for CSP technology is done in Brazil, we will not know the price for electricity. However, based on the values proposed in the work of Biancchinni (2013), we were able to simulate the economic viability for three cities using SAM, where scenario for CSP power tower direct steam PPA partnership flip with debt (utility) is selected.

PPA projects are usually utility-scale projects and sell electricity at a price negotiated through a power purchase agreement (PPA) to meet a set of equity returns requirements, and may involve one or two parties.

SAM provides options for calculating a power purchase price given a target internal rate of return, or for calculating the rate of return given a power purchase price. Based on the values proposed in the work of Biancchinni (2013), we used 15% as a given target internal rate of return.

5. RESULTS AND DISCUSSIONS

For installation design is a Solar Thermal Plant of 30 MW connected to the Brazilian distribution network. The system will have hybrid operation, using burning biomass boiler and complementary heliothermic cycle. The power plant was set in obedience to Brazilian legislation brings tax relief for electricity production plants with capacity below 30 MW.

5.1 Site selection

The location of the plant to take into account mainly the amount of solar radiation that receives location. For the present study were evaluated three locations: Santa Maria da Vitoria – BA, Porto Nacional – TO and Brasília – DF. The figure 5 below compares mean direct irradiation over these cities during a year.

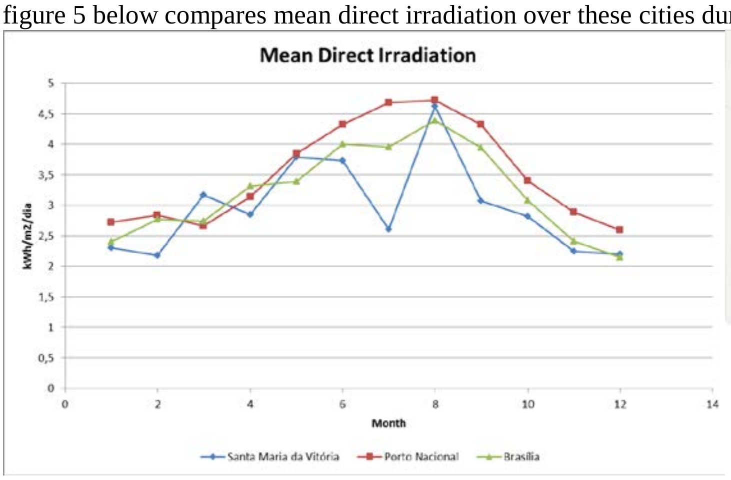


Figure 5. Mean irradiation in the cities
Source: NASA (2013)

Figure 6. Transmission lines in Brazil
Source: Aneel 2014

The distance to transmission lines are shown in figure 6, as well as the position of cities. These three metrics – distance to transmission lines, availability of water and direct solar radiation, are used to choice the better city to install the hybrid plant. Additionally, SAM software is used with the operational data listed in table 1. Simulations for economic and operational conditions for each plant are performed, the result is shown in table 2 below.

Table 2. The results of simulation for three selected cities in Brazil
Simulation using SAM software, 2015

Metric	Santa Maria da Vitória	Brasilia	Porto Nacional
Annual energy	57,592,840 kWh	41,207,464 kWh	40,677,192 kWh
Capacity factor	24.4%	17.4%	17.2%
Levelized PPA price (nominal)	60.42 ¢kWh	83.85 ¢kWh	86.57 ¢kWh
Levelized cost (nominal)	38.10 ¢/kWh	53.74 ¢/kWh	54.51 ¢/kWh
Investor IRR (after-tax)	15.73 %	15.64 %	15.73 %
Investor NPV (after-tax)	$18,365,788	$24,560,474	$18,631,806
Developer NPV (after-tax)	$106,255,512	$109,735,616	$107,836,768
Initial cost	$205,580,992	$202,100,656	$208,702,880
Equity	$74,507,424	$73,244,696	$75,599,424
Debt	$131,073,576	$128,855,952	$133,103,456
Minimum DSCR	2.23	2.16	2.23

The results presented in the table 2 from the three scenario simulation reveal Santa Maria da Vitória as the most attractive region as LCOE reaches only 0.38 USD/kWh. However, it requires the larger initial investment around $205 million and investor net present value (NPV) around $18 million.

5.2 Social and environmental analyses

Solar energy plant impacts positively and negatively environmental conditions at the selected territory. It requires a large amount of groundwater use and wastewater treatment. Moreover, as any technology, it impacts the bio system around the plant, as for example there are many birds, attracted to the light at the tower, die because of the high temperature. Nevertheless, the plant brings a large saving of CO2 emissions. The 30 MW plant will save around 86000 tCO2 that equivalent to 37 million liters of non-consumed fuel.

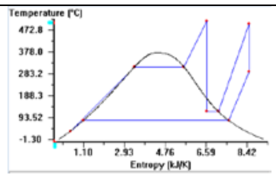
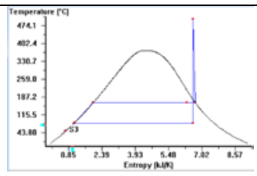
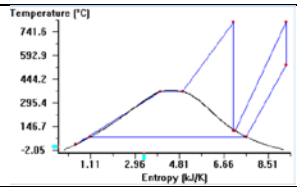
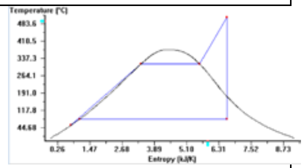
Accordingly to the World Bank report based on the case in Morocco, more than 200 workers will be employed during the construction of the plant and around 50 workers during the operation phase. Even though the direct impact on local employment is not as significant as during the construction phase, there is an opportunity for greater dissemination of skills into the local workforce. It will promote tourism and create the new image for the city as the foreign knowledge (ACWA Power, 2015)

5.3 Simulation of thermodynamic cycle

For all scenarios, the same configuration set is used: turbine gross output near to 30MWe, turbines working with inlet pressure $P_{in}$and outlet pressure P_{out} except in scenario using supercritical steam. The main calculated metrics are steam mass flow $\dot{m}$, heat flux in $\dot{Q}$, power out $\dot{W}out$, net power $\dot{W}net$.

Table 3. The results of simulation scenarios
Simulation using CyclePad software, 2015

	Fig.1 solar reheating	Fig.2 solar super-heater	Fig. 3 supercritical steam	Fig. 4 CSP parallel
η_t	≤ 59.91%	≤ 41.82%	≤ 71.9%	≥34.5%
T_{max}	510°C	510°C	800°C	510°C
P_{in}	10342kPa	10342kPa	20000kPa	10342kPa
P_{out}	50kPa	50kPa	400kPa / 50kPa	50kPa

$\dot{m}$	16kg/s	38kg/s	11kg/s	27.5kg/s
$\dot{Q}in$	62.2MW	84.4MW	53.9MW	≤97.3MW
$\dot{W}out$	31.3MW	30.4MW	30.9MW	30.2MW
$\dot{W}net$	28.8MW	26.2MW	29.2MW	29.9MW
Diagram				

According table 3 above, the best scenario is where thermodynamic cycle works with supercritical steam in a reheating cycle like shown in figure 3. However these arrange is very expensive and technologically challenging. Solar reheating showed in figure 1 is an attractive scenario when yield may reach 59.9% using small machines, the steam mass flux is only 16kg/s, but to use, heat storage construction will be required.

Due the flexibility of operation, the parallel mode shown in figure 4 is the most economical. Work using solar power tower with air at 1100^{o}C exchange heat to rankine cycle. All of sun irradiation variation is compensated by a boiler, while all produced steam is accumulated in a tube, to be expanded in the turbine following.

6. CONCLUSIONS

In view of the presented, it is recommended to build a hybrid power plant with biomass burning and the use of solar thermal solar energy in the area of the municipality of Santa Maria da Vitória BA, with power of 30 MWe dispatching directly to the Brazilian distribution system. The solar system to be used is solar power tower in parallel to conventional rankine cycle using boiler.

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