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Potential and impacts of Concentrated Solar Power (CSP) integration in the Brazilian electric power system

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ABSTRACT

This study analyses the Concentrated Solar Power (CSP) potential in Brazil and evaluates the impact caused by a large-scale integration of this alternative into the Brazilian electricity system in the long term (horizon 2040). Four types of CSP plants with parabolic troughs (simple plants, plants with hybridization and plants with thermal energy storage) were simulated at two sites: Bom Jesus da Lapa and Campo Grande. Then, the main parameters obtained for each plant were expanded to other suitable Brazilian sites, as inputs in an optimization model for the expansion of the country's electric power grid. Findings indicate that the least-cost expansion of the Brazilian electricity system should be based on hydroelectric and thermoelectric plants fueled by natural gas and sugarcane bagasse. Hence, in the base scenario CSP plants would not be chosen. However, in an alternative scenario, specific auctions for CSP can be adopted. In this case, the first solar plants would be introduced in 2020 in place of natural gas-fueled thermoelectric plants, and from 2030 on, hydroelectric plants would cease to be installed. This alternative scenario would be about 144 billion dollars dearer than the base.

1. Introduction

The Brazilian electric power system is a hydrothermal one, with thermal power plants operating with, and complementing, hydroelectric power plants to increase the system's firm energy [1]. As of today, hydroelectric power plants account for some 80% of all electricity produced in the country and new hydro plants are still expected to be built in the near and medium terms [2,3]. However, the remaining potential for hydroelectric growth is concentrated in regions that are environmentally sensitive, which has justified investments in run-of-river plants, as well as the greater environmental costs associated with the successive stages of environmental licensing [2]. In the case of thermal power plants, the sector's growth implies an increase in greenhouse gas emissions. In this respect, it is important to analyze the growth potential for alternative sources in Brazil, including the option of solar energy. However, although the direct normal irradiation in several Brazilian states is higher than 6 kWh/m^2/day (or 2000 kWh/m^2/year), described as the minimum recommended for the technical and economic viability of heliothermal plants with solar concentrators (CSP) [4–9], there are no specific studies of the CSP potential for centralized generation in Brazil, whereas there are such studies for the USA [9,10], India [8,11], China [12–14], Chile [15] and United Arab Emirates [16].

Therefore, the objective of this study is to analyze the CSP potential in Brazil and to simulate, based on an optimization model, the impact caused by a large-scale integration of this alternative into the Brazilian electricity system in the long term (horizon 2040).

The CSP plant simulations are made based in the SAM (System Advisor Model) [17] software developed by the National Renewable Energy Laboratory (NREL), managed by The Alliance for Sustainable Energy, LLC for the U.S. Department of Energy (DOE). Four systems of CSP plants with parabolic troughs, with a nominal output of 100 MWe, are simulated in the SAM. There are several studies that analyze the technical CSP potential for a certain place, using as a benchmark a plant size of 100 MWe, such as a study of CSP potential in India [8,18] and China [18], as well as a case study of a CSP plant with hybridization and 12 hours of heat storage in Chile [15]. The plants are simulated at two sites in Brazil: Bom Jesus da Lapa (BJL), in the Northeast, and Campo Grande (CG), in the Midwest.

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Table 1
Comparison between CSP technologies.

Parameters	Unit	Fresnel	Parabolic trough	Concentrating tower	Disc
Typical power	MWe	1–200	10–200	10–200	0.01–0.40
Operating temperature	°C	50–300	50–400	300–2000	150–1500
Peak efficiency	%		20	23	29
Efficiency	%	8–10	11–20	15–30	20–30
Concentration	ratio	25–200	80–200	300–1000	1000–4000
Installed capacity (up to 2010)	MWe	8.4	943.0	38.0	1.5
Energy Storage System		Heat storage	Heat storage	Heat storage	Batteries
Land use	m^2/MWh yr	4–6	6–8	8–12	8–12

Source: [4,8,25,27–33].

This study considers two possible scenarios within the horizon analyzed (2040). The base scenario presents business-as-usual (BAU) characteristics. The alternative scenario (Alternative), on the other hand, incorporates tax incentives and a gradual program of specific auctions exclusively for CSP, with the purpose of facilitating the introduction of solar energy into the national energy matrix.

After the simulation of the CSP plants in the SAM, the main results obtained, such as investment costs for each plant, seasonal fluctuation in electricity output, capacity factor and annual output, are used as inputs in the optimization model MESSAGE (*Model for Energy Supply System Alternatives and their General Environmental impacts*), developed by the UN International Atomic Energy Agency (UN-IAEA) and adapted in this study to the Brazilian energy system.[1] Based on the optimization of the two scenarios, CSP expansion costs and their impacts on the operation of the Brazilian electricity system are identified, as well as the sources to be replaced by solar energy when compared to the base growth scenario.

2. Identification of technologies

The first commercial CSP (Concentrated Solar Power) plant in the world was installed in New Mexico in 1979 by the Sandia National Laboratory [19]. Since then, the countries that have invested the most in R&D related to CSP plants are the USA and Spain [20–22], which have most of the world's installed electric power using this technology (515 and 1002 MWe respectively) [23,24]. There are four main CSP technologies: disc, parabolic trough, Fresnel and concentrating tower [6,25–27]. Table 1 presents a comparison among the four technologies in the CSP family.

The parabolic trough collector (PTC) technology is the most mature, and therefore the most widely used [4,32–35]. Indirect steam generation circuits constitute the state of the art, while direct steam generation (DSG) remains under study [35]. The heat transfer fluids most often used in the solar field are the Therminol VP-1® and DowTherm A® synthetic oils, which operate in the liquid phase between 12 °C and 400 °C [4,27,35,37]. The state of the art in relation to the components of PTC CSP plants is shown in the latest large plants built. For example, the 64 MWe Nevada Solar One (NSO) plant, in the USA, used Solargenix SGX-2 collectors, a blend of Schott PTR70 and Solel UVAC receivers, and Flabbeg mirrors [29,38]. The Andasol I and II plants use 624 SKAL-ET150/AS1 collectors, Schott PTR70 receivers and Flabbeg mirrors [29,39].

This study evaluated the following types of CSP plants with PTC for two typical Brazilian locations: simple plants, plants with hybridization and plants with thermal energy storage (TES).

2.1. Simple plant

This plant operates with solar energy alone, without the TES system or hybridization [9]. An example of this type of plant is the 1 MWe APS Saguaro, which uses a Rankine ORC cycle with evaporative cooling and Xceltherm 600® synthetic oil, which can operate between −20 and 416 °C [40]. The simple plant modeled in this study has an indirect steam generating system, using VP1 synthetic oil and operating with a simple Rankine cycle.

2.2. Plant with Thermal Energy Storage (TES)

This plant has a TES system, whereby the solar heat collected during the day is stored for a certain number of hours in thermal systems, which use materials such as molten salts, concrete, ceramics, steam or PCM,[2] to be used later for generating electricity during periods of lower irradiation, at night, or at times of peak demand [4,27,41]. The latest plants built in Spain and the USA have a two-tank indirect TES system, with capacities of 6.0–7.5 h, using synthetic oil in the solar field and molten salts (60% $NaNO_3$ and 40% KNO_3) as a storage medium, thus achieving capacity factors of around 36–41% [4,27]. An example of this technology are the Andasol (I, II and III) plants, installed in Spain [42]. Expectations are concentrated on the development of two-tank direct TES systems with molten salts, which will enable higher operating temperatures (500–600 °C) to be reached, with the resulting efficiency gains in the thermodynamic cycle [41]. The 5 MWe *Archimede* ISCC (Integrated Solar Combined Cycle) project in Italy, in operation since 2010, is the first PTC plant to use molten salts in a two-tank direct TES system [39]. If this project solves the problem of the relatively high freezing point of molten salts (120–220 °C), the new CSP plants, especially those with a concentrating tower, may be designed for 12–15 h of TES, with capacity factors greater than 60%, depending on the Direct Normal Irradiation (DNI) of the place in question [4].

There are two plants with storage modeled in this study: 1) a plant with an indirect 6-h TES system, using VP-1 synthetic oil in the solar field and molten salts in the heat storage tanks; and 2) a plant named "advanced", with a 12-h direct TES system using molten salts. The concept of this "advanced" plant is based on Refs. [4,5,43].

2.3. Hybrid plant

Hybridization enables the generation of electric power partly by using a back-up fuel [9]) usually natural gas [15], solid biomass or biogas [4]. Hybridization has different purposes: in medium and large quantities, it aims at generating electricity during night hours, peak hours during the day, and cloudy days, and in addition, adjusting the amount of power supplied according to the system's "instantaneous" demand [6,9,29]; in small quantities, it aims at maintaining the minimum temperature in the thermal system, thus preventing the HTF (heat transfer fluid) from freezing during the night and on cold days [6,9,15,29]. Hybridization improves the CSP plant's dispatchability properties by raising its capacity factor [4,29].

[1] This is in fact the tenth Brazilian version of the MESSAGE model implemented since [36].

[2] PCM: "*phase-change material*", which is a substance with a high fusion heat, capable of storing and releasing large quantities of energy when the material changes from solid to liquid state and vice versa.