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Thermodynamic evaluation of solar-geothermal hybrid power plants in northern Chile

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ABSTRACT

A thermodynamic model was developed using Engineering Equation Solver (EES) to evaluate the performance of single and double-flash geothermal power plants assisted by a parabolic trough solar concentrating collector field, considering four different geothermal reservoir conditions. The benefits of delivering solar thermal energy for either the superheating or evaporating processes were analyzed in order to achieve the maximum 2^{nd} law efficiency for the hybrid schemes and reduce the geothermal resource consumption for a constant power production. The results of the hybrid single-flash demonstrate that the superheating process generates additional 0.23 kWe/kWth, while supplying solar heat to evaporate the geothermal brine only delivers 0.16 kWe/kWth. The double-flash hybrid plant simulation results allow obtaining 0.29 kWe/kWth and 0.17 kW/kWth by integrating solar energy at the superheater and evaporator, respectively. In this context, the hybrid single-flash power plant is able to produce at least 20% additional power output, depending on the characteristics of the geothermal resource. Moreover, all of the cases analyzed herein increased the exergy efficiency of the process by at least 3%. The developed model also allowed assessing the reduction on the consumption of the geothermal fluid from the reservoir when the plant power output stays constant, up to 16% for the hybrid single-flash, and 19% for the hybrid double-flash. Based on the results obtained in this study, the solar-geothermal hybrid scheme increases the power generation compared with geothermal-only power plants, being an attractive solution for improved management of the geothermal reservoir depletion rates. The study shows evidence of existing optimum configurations for the hybrid systems. A relative performance map was developed in order to determine the best operation approaches according to the reservoir conditions and solar field size.

1. Introduction

Chile presents a huge potential for renewable energy, especially in its northern region. The low presence of clouds and high altitude over sea level in the Atacama Desert result in exceptionally clear skies with low aerosol contents and high levels of global and direct irradiation throughout the year. Recent investigations indicate the existence of a significant solar energy potential in the northern regions, where the annual average daily global horizontal irradiation (GHI) reaches levels higher than 7.5 kWh/m^2 and the daily average direct normal irradiation (DNI) presents values higher than 9 kWh/m^2 [1,2]. Furthermore, the Chilean territory is also located in the so-called "*Pacific ring of fire*" region which accounts for over 15% of the world's active volcanoes; related to this there are more than 300 active geothermal areas throughout the country, with an estimated resource potential of 16,000 MWe [3]. More than 20 geothermal areas are currently under exploration in Chile, where the geothermal reservoirs present temperatures over 150 °C and are located no deeper than 3000 m [4]. According to this, the northern region of the country accounts for at least six already explored geothermal areas and more than 25 other sites with potential for geothermal generation.

The present study proposes to assess the use of these two renewable resources combined in a hybrid scheme, thus configuring a power plant capable of taking advantage of the benefits that each source presents. Solar energy is available during the day according to the specific climate conditions in a given site, while geothermal energy does not present variations by season. However, the installation of geothermal power plants in general

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requires a longer period for deployment than for CSP plants. Considering the high potential of development for both sources in the northern region of Chile, the present study focuses on the optimization of hybrid schemes that enable exploiting these two sources together efficiently.

Hybrid solar-geothermal schemes have been proposed in several studies [5–13], which focused on different technologies for exploiting geothermal resources, such as single flash [7,9], double flash [5,6,9] and binary plants [7,8,10–12], commonly combined with parabolic trough solar collector fields. In 2006, Lentz and Almanza [5] proposed a hybrid system to increase the steam quality by integrating a solar field into a geothermal flash plant located at Cerro Prieto, Mexico. This work also analyzed two different alignments for the solar collectors: N-S and E-W. The authors showed the feasibility of increasing the steam quality by 10%, thus increasing the steam generation. Later, Lentz and Almanza [6] also evaluated the increase in steam production associated with the liquid-steam mixture by increasing the enthalpy of the geothermal resource. One of the issues presented in their investigation was the corrosion caused by the geothermal fluid, which limited the performance of the hybrid systems. The authors showed that the flow enthalpy from the geothermal reservoir increased with the integration of a parabolic trough solar field. Furthermore, the steam intensification allowed presenting a better geothermal reservoir classification, thus increasing the capacity factor of the plant. Considering this aspect, in 2010, Greenhut et al. [7] assessed the performance of the system by including a heat exchanger between the solar and geothermal fluid to compare the thermodynamic and economic performance of a binary and single flash system on a steady-state condition. This last system was selected to examine the transient performance using historic solar and temperature data from Nevada, United States, where the solar generation fraction varies from 8% in winter to about 20% during summer.

Astolfi et al. [8] presented a research in which a solar concentration and a binary geothermal plant based on an organic Rankine cycle (ORC) were combined. The study considered hourly simulation, where solar resources of two different sites from Italy and the United States were compared by quantifying the levelized cost of energy associated with the operation of these plants. The authors showed the possibility of increasing the energy production about 15–28% depending on the site, through the integration of a solar field arrangement. Moreover, the results showed an energy cost reduction of 54–60% for the hybrid system when compared to stand-alone solar thermal plant. The research displayed the attractiveness of incorporating solar energy into low-enthalpy geothermal systems.

Later, Mir et al. [9] developed an evaluation model for hybrid solar-geothermal systems in order to estimate the effect of increasing the fluid temperature and enhancing the steam generation process, achieving higher power production at the geothermal system by adding a solar field of parabolic trough collectors. The author was also able to quantify a reduction in geothermal resource consumption of up to 10%, considering the same power output as with a stand-alone geothermal plant. The energy generation increased by 12% when compared to a geothermal-only power plant, following the daily peaks of solar radiation.

Recently, Zhou et al. [10] proposed a binary geothermal system with solar boosting to investigate the effects on the hybrid system performance of parameters such as ambient temperature, solar irradiance, geographical location and geothermal resource quality. Power output and economic performance adjusting parameters were analyzed and compared to stand-alone solar and geothermal plants, showing an outstanding potential on these aspects. The results showed an increased between 22% and 78% on the power output, depending on solar field size where an increase on the solar field area resulted in a reduction on the LCOE from 225 $/MWh (geothermal-only) to 165 $/MWh. Zhou [11] continued the research on this aspect, focusing on the synergies and conditions from his previous investigation seeking to determine the potential for improving efficiency and reducing costs. The study proposed a supercritical and subcritical ORC, combining solar and geothermal sources to compare the performance of each system. This analysis identified the conditions under which the hybrid solar-geothermal systems are feasible, which in the best case can supply between 4 and 17% more power output than the subcritical cycle using supercritical ORC. The supercritical hybrid configuration presented 51% of additional power by the addition of the solar field, with an annual power production of 13,258 MWh.

Ruzzenenti et al. [12] evaluated a hypothetical ORC plant employing different working fluids. The effect of the fluid used within the power block on the life cycle assessment and exergy utilization from the geothermal resource was estimated, establishing that the sustainability of the resource is related to the heat exchanger surface and the operating conditions of the solar field. One of the most recent studies was developed by Turchi et al. [13], in which the authors evaluated the use of geothermal resource to provide feed water heating in a CSP plant. The authors examined the performance of the proposed system in terms of design, efficiency and power generation. The geothermal energy allowed the hybrid plant to increase by 8.5% the power output and an increase in the system efficiency compared to a CSP – only plant. In this context, the geothermal energy represented 11.4% of the annual thermal energy input to the hybrid scheme. Additionally, the authors highlighted the economic benefits of the hybrid design due to the elimination of the geothermal power block and the potential of the reduction of the brine flow rate that allows extending the geothermal reservoir life.

Recent studies evidence the potential of solar-geothermal facilities for poligeneration purposes such as electricity, heating, cooling and even fresh water production [14–16]. In this aspect, Tempesti et al. [14], proposed two different micro CHP systems driven by geothermal and solar energy. The first configuration considered a binary geothermal power plant and an evacuated solar collector arrangement. The second configuration considered only heating a portion of the working fluid through a parabolic trough collectors arrangement. This work considered different working fluids and the results were evaluated in terms of the conversion efficiencies and the production of heat and electricity. The results showed that a single stage arrangement could satisfy the space heating demand for 30 apartments. In a similar approach, Al-Ali and Dincer [15] proposed a large scale system for producing power, cooling, space heating and heat for industrial use, by the incorporation of a PTC arrangement to a high enthalpy geothermal plant. A parametric study was conducted to evaluate the performance of the system and compare the benefits of the polygeneration scheme. The exergy efficiencies for single-generation and multigeneration systems were 26.2% and 36.6%, respectively. The authors justify the importance of the exergy analysis to correctly analyze systems for multiple purposes. One of the most recently studies in this matter corresponds to Calise et al. [16], whom developed a model of a solar-geothermal polygeneration system. The system proposed was based on an organic Rankine cycle, driven by a medium-enthalpy geothermal source and a parabolic trough collector field, the geothermal residual heat was deployed to power up a multi-effect distillation unit. A 2^{nd} law analysis was developed to identify the main issues affecting the performance of the system. The highest exergy destruction were identify in the ORC module, secondary heat exchanger and parabolic trough collectors.

The aforementioned studies show a growing interest in hybrid solar-geothermal power generation systems. However, several crucial issues have not yet been addressed in order to determine the