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Thermodynamic Evaluation and Optimization of a Solar-Geothermal Hybrid System in Northern Chile

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Abstract

Chile is developing a national strategy to reduce the external dependence on energy supply sources, for which renewable resources must provide 20% of the electricity generation by 2025. As the northern part of the country exhibits a large arid desert area that has the highest radiation levels in the world and a considerable amount of active geothermal areas, proposing the hybridization of both renewable resources together is deemed advantageous considering the benefits that each resource presents and allows exploring potential synergies between both. A thermodynamic model is developed using the Engineering Equation Solver (EES) software in order to evaluate the performance of a single-flash power plant assisted by a parabolic trough collector system for four different geothermal reservoir conditions. The benefits of delivering the solar thermal energy to the superheating or evaporating processes are analyzed, in order to achieve the maximum 2nd law efficiency for the generation of additional power, or to reduce the geothermal fluid flow consumption. The results in the single-flash hybrid system show that the superheating process generates 0.23 kW of additional power per kW of thermal energy, while enhancing the brine evaporation produces only an additional 0.16 kW of power per kW of solar thermal energy. Hence, the single-flash hybrid power plant is able to produce at least 20% of additional power output and increase at least 3% the exergetic efficiency. This hybrid flash system presents a promising alternative towards the generation of additional power output and extending the lifetime of a geothermal well.

Keywords: *Solar Energy, Geothermal Energy, Hybrid scheme, Thermodynamic analysis*

1. Introduction

Chile is a relatively small country located along the west coast of the southern half of South America, which is endowed with a wide range of natural resources and through the production, addition of value and exportation of such resources it has emerged as a successful economy. However, the country has evinced over the last years several energy issues due to its high dependence on fossil fuels such as crude oil and natural gas, of which more than 90% are imported (CNE, 2013). Currently, the country's primary energy consumption is dominated by fossil fuels, which accounts for 66% of the energy consumed, while renewable energy sources comprising hydroelectricity, wood-based biomass and incipient solar and wind farms, are responsible for the remaining 34% mostly due to the large contribution of hydropower sources (CNE, 2013). This scenario indicates that Chile is a net energy importer and establishes a complex situation due to the difficulties in fulfilling the energy demand growth associated to additional economic and social development. Responding to this situation, the Chilean government has proposed a national strategy based on decreasing the external dependence of the energy supply focusing on promoting the so-called "*Non-Conventional Renewable Energy sources*" (NCRE), defined as small-scale hydro (under 20 MW), biomass, wind, solar, geothermal and tidal energy sources. Large-scale hydropower is considered a renewable source although its already large contribution to the Chile energy mix and its techno-economical maturity does not merit further government

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support for additional development. The government has defined that the existing NCRE quota should grow up to 20% of electricity injected to the interconnected systems by 2025. Currently, NCRE accounts for 9% of the total installed capacity (2,242 MW), whereas 40% corresponds to wind, 23% solar PV, 19% biomass, 16% small scale hydro and 2% biogas (CIFES, 2015). In addition, the government has recently proposed the "*Agenda Energía 2050*", which establishes a schedule to reach the aforementioned goal, along with measures to promote their development (Ministerio de Energía, 2014).

Chile presents a long and narrow territory that extends for 4,330 km, with a wide range of climates due to its vast extension. There is a huge potential for renewable energy, especially at the northern region, which exhibits the most arid desert in the world along with a low presence of clouds and high altitude over the sea level resulting in exceptionally clear skies with low aerosol contents. Recent investigations indicate the existence of a significant solar energy potential in the northern regions, where the annual average of daily global horizontal irradiation (GHI) reaches levels higher than 7.5 kWh/m^2, and whereas the daily average of direct normal irradiation (DNI) present values higher than 9 kWh/m^2 (Escobar et al, 2014, 2015). Furthermore, the Chilean territory is also located in the "*Pacific ring of fire*" accounting over 15% of the world's active volcanoes and more than 300 active geothermal areas through the country, with an estimated resource potential of 16,000 MWe (Hogson, 2013). There are currently more than 20 geothermal areas under exploration in Chile, where the geothermal reservoirs present temperatures over 150ºC and are located no deeper than 3,000 meters (Lahsen et al., 2010). 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, configuring a power plant capable of take advantage of the benefits that each source presents. Solar energy is available during day hours according to the specific climate conditions in a given site; while geothermal energy does not present variations by season. Although, the installation of such systems requires a longer period for deployment than the time needed for solar systems. Considering the high potential of both sources in the northern region of Chile, the present study focuses on the optimization of hybrid schemes that enable the possibility of exploiting these two sources together efficiently.

Hybrid solar-geothermal schemes have been proposed in several previous studies that focused on different technologies for exploiting the geothermal resources, such as single-flash (Mir, 2011), double-flash (Lentz and Almarza, 2006, Mir et al., 2011) and binary plants (Greenhut et al., 2010, Astolfi et al., 2011, Zhou et al., 2013, Zhou, 2014, Ruzzenenti et al., 2014) which were commonly combined with parabolic trough system. Lentz and Almarza (2006) proposed a hybrid system to increase the steam quality by integrating a solar field to 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. Later, the authors also evaluated the increase on steam production associated with the liquid-steam mixture by increasing the enthalpy of the geothermal resource. One of the issues presented was the corrosion caused by the geothermal fluid, which limited the performance of the hybrid system. Considering this aspect, Greenhut et al. (2010) assessed the performance of a system by including a heat exchanger between the solar and geothermal fluid, in order to compare the thermodynamic and economic performance of a binary and single-flash system on a steady-state condition. Astolfi et al. (2011) presented a solar concentration plant and a binary geothermal plant based on an organic Rankine cycle (ORC). The study was based on hourly simulations, where the solar resource of two different sites in Italy and the United States were compared by means of the levelized cost of energy associated with the operation of these plants. The research evidenced the attractiveness of incorporating solar energy to low-enthalpy geothermal systems. Later, Mir et al. (2011) developed an evaluation of solar-geothermal systems in order to estimate the effect of increasing the fluid temperature and enhancing the steam generation process, thus achieving higher power production at the geothermal system by adding a solar field of parabolic trough collectors. This allowed quantifying a reduction of geothermal resource consumption up to 10%, considering the same power output than a stand-alone geothermal plant. Recently, Zhou et al. (2013) 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 resource quality. The power output and the economic performance adjusting parameters were analyzed and compared with stand-alone solar and geothermal plants, showing an outstanding potential on these aspects. They also focused on the synergies of the hybrid system to determine the potential for improvement on efficiency and cost reduction. Another recent study 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 and established that the sustainability of the resource relates to the surface of the heat exchanger and the operating conditions of the solar field (Ruzzenenti, 2014).

The aforementioned studies show a growing interest in the efficiency and utilization of the hybrid solar-geothermal systems. However, there are several issues that have not yet been addressed, which are crucial to determine the real potential towards the hybridization of both resources. Most of the studies analyzed the potential for increasing the power output, determining the economic benefits and comparing between all the configurations proposed, taking advantage of the solar energy system for configuring a thermal booster to the geothermal power plant, thus achieving higher thermal efficiencies, energy production and a significant reduction in the cost of electricity. The results agree that there is an improvement opportunity as the hybrid schemes can reduce the high costs associated with the exploitation of renewable energy resources. Nevertheless, there are still some aspects yet to be investigated in order to quantify the real potential from these hybrid systems and benefits on operating the subsystems combined. In this context, the exergetic or 2nd law efficiency of the combined system can be maximized by a proper optimization of the size and the configuration of the hybrid scheme.

Here it is proposed to study the single-flash geothermal technology, with the objective to develop a thermodynamic model of a solar-geothermal hybrid system that can optimize its operation under several resource conditions, maximizing the 2nd law efficiency of using both energy sources with the intent to determine the most effective way to utilize the solar energy captured by the parabolic trough collectors and address the potential benefits such as the reduction on the geothermal fluid extraction rate. To this end, an hourly simulation of a full year of the hybrid solar-geothermal power plant operation was developed in order to evaluate the system performance at one location in the northern region of Chile.

2. System description

Geothermal plants are commonly classified by its capacity: small (under 5 MW), medium (over 5 and under 30 MW) and large scale (over 30 MW) (Bertani, 2010). The small scale plants consider binary and back pressure systems, whereas medium are often associated to flash plants, and finally large scale plants usually refer to dry steam units. In this study, the focus is on medium scale flash geothermal power plants whose hybridization has already been proposed (Lentz and Almarza, 2006a, 2006b, Greenhut, 2010, and Mir, 2011). Regarding the solar technologies, solar thermal energy at medium and high temperature can be supplied by concentration systems of which the parabolic trough collectors are most appropriate for combined use in a geothermal facility due to its modularity and flexibility of installation and operation (Peterseim, 2014).

The single-flash system is one of the most common schemes for geothermal power plants in the world, accounting for 41% of the installed capacity and energy produced (Bertani, 2010). This system is considered the simplest way to convert the geothermal energy into electricity when a steam-liquid mixture composes the geothermal fluid. Fig. 1 corresponds to a single-flash hybrid system integrated to parabolic trough collectors array. The proposed hybrid scheme aims to allow the evaluation of the solar resource impact for superheating and evaporating the geothermal brine. The solar superheating is used to superheat the steam obtained from the separation process in the geothermal flash plant while the solar evaporator is used to increase the evaporation rate.

3. Thermodynamic model

The simulation model for the solar-geothermal hybrid systems proposed was developed using the Engineering Solver Software (Klein, 2015), which is widely used by the scientific community dealing with thermodynamic-related simulations. It allows for the solution of algebraic equations governing the cycles and easily communicates with a thermodynamic properties database based on REFPROP-NIST (Lemmon, 2002).

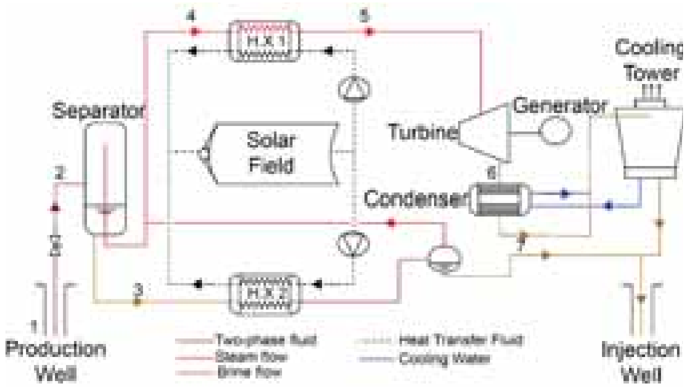

Fig. 1: Single-flash hybrid power plant scheme

The energy analysis is based on the 1st law of thermodynamics, neglecting kinetic and potential energy variations:

$$\dot{Q} - \dot{W} = \sum \dot{m}_{out} h_{out} - \sum \dot{m}_{in} h_{in} \quad \text{(eq. 1)}$$

where $\dot{Q}$ denotes the heat transfer rate, $\dot{W}$ the work transfer from the system, $\dot{m}$ the mass flow rate, h are the specific enthalpies and the subscripts in and out denote the inlet or outlet of the system, respectively.

The exergetic analysis is based on the 2nd law of thermodynamics, using the following exergy balance expression:

$$\dot{X}_{heat} - \dot{W} = \sum \dot{X}_{out} - \sum \dot{X}_{in} + \dot{X}_D \quad \text{(eq. 2)}$$

where $\dot{X}_{heat}$ is the exergy transfer by heat, $\dot{X}_{out}$ the exergy outlet, $\dot{X}_{in}$ the exergy inlet and $\dot{X}_D$ the exergy destruction.

The exergy transfer by heat ($\dot{X}_{heat}$) can be obtained using the following expression:

$$\dot{X}_{heat} = \left(1 - \frac{T_0}{T}\right) \dot{Q} \quad \text{(eq. 3)}$$

where T_0 is the environmental temperature, and T the temperature of the heat source.

The exergy flow in each component is expressed as follows:

$$\dot{X}_i = \dot{m}_i [(h_i - h_0) - T_0 (s_i - s_0)] \quad \text{(eq. 4)}$$

where $\dot{m}_i$, h_i and h_0 represents the flow rate, specific enthalpy at the state i and environmental state, respectively; s_i and s_0 the specific entropy at the same states. Hence, in order to evaluate the performance of the hybrid system, the 2nd law efficiency is used according to the following expression:

$$\eta_{II} = \frac{\dot{W}}{\dot{X}_{geo} + \dot{X}_{HTF}} \quad \text{(eq. 5)}$$

where $\dot{W}$ indicates the net power delivered by the hybrid system, $\dot{X}_{HTF}$ and $\dot{X}_{geo}$ are the exergies delivered by the heat transfer fluid from the solar field and geothermal field, respectively. The solar exergy is considered as the provided by the heat transfer fluid (HTF) and expressed as follows:

$$\dot{X}_{HTF} = \dot{m}_{HTF} \left[(h_{HTF,out} - h_{HTF,in}) - T_0 (s_{HTF,out} - s_{HTF,in}) \right] \quad \text{(eq. 6)}$$

where state HTF, out and HTF, in corresponds to the solar field outlet and inlet, respectively.

On the other hand, the exergy from the geothermal resource is defined as (Kanoglu, 2012):

$$\dot{X}_{geo} = \dot{m}_{geo} [(h_1 - h_0) - T_0 (s_1 - s_0)] \quad \text{(eq. 7)}$$

where the state 1 represents the geothermal reservoir. The exergy of the geothermal resource only considers the reservoir conditions, since the brine generated at the separation process is considered an exergy loss, according to the established technical literature (Agung, 2014, Jalilinasrabady 2012).

3.1 Geothermal resource

For the purpose of this study, four geothermal reservoir characteristics were examined: two considering compressed liquid (cases 1 and 3) and two considering saturated water-steam mixture (cases 2 and 4), as shown in Table 1 (Ocampo, 1998, Anderson, 2014). Therefore, the brine production on the geothermal field is assumed to follow the choked well flow proposed in DiPippo (2008), where the relation between the total mass flow of geothermal fluid is function of the wellhead pressure, as expressed by the following equation:

$$\dot{m}_{geo} = 99.663 - 2.6287P_2 + 0.5802{P_2}^2 - 0.04212{P_2}^3 \qquad \text{(eq. 8)}$$

where $\dot{m}_{geo}$ is the mass flow rate extracted from the well and P_2 is the pressure at which the separator operates. The flashing process in the well between the states 1 and 2 is considered as isenthalpic, neglecting any change in the kinetic or potential energy according to previous studies (DiPippo 2008 and 2013). Other operating conditions for the system considered herein are summarized in Table 2.

Tab. 1: Geothermal reservoir characteristics

Resource	Temperature	Enthalpy	Pressure	References
Case 1	240 ºC	1038 kJ/kg	100 bar	(Ocampo, 1998)
Case 2	235 ºC	1351 kJ/kg	31 bar	(Anderson et al., 2014)
Case 3	210 ºC	900 kJ/kg	35 bar	(Anderson et al., 2014)
Case 4	205 ºC	1146 kJ/kg	17 bar	(Anderson et al., 2014)

Tab. 2: Hybrid solar-geothermal reference conditions

Parameters	Value
Ambient temperature	15 ºC
Ambient pressure	0.8 bar
Heat exchanger effectiveness	70%
Solar irradiance	1000 W/m^2
Maximum solar HTF temperature	391 ºC
Condensing temperature	50 ºC

3.2 Solar field model

For the purpose of this study, the solar field is considered as an arrangement of parabolic trough collectors using Therminol VP-1 as heat transfer fluid. The performance of the system is determined by using the model developed by Duffie & Beckman (2006), later adapted by Wendel (2010). The amount of solar thermal energy output rate ($\dot{Q}_{solar}$) is calculated by accounting the relation between the collector performance and the loss factors related to the utilization of direct normal irradiation ($\dot{G}_{b,T}$), as follows:

$$\dot{Q}_{solar} = A\left[f_{shadow} f_{corner} \dot{G}_{b,T}(a_1 + a_2\Delta T) f_{dirt} IAM - b_1\Delta T - b_2\Delta T^2\right] \qquad \text{(eq. 9)}$$

where the parameters included in this equation are: A the solar field collection area, ΔT the temperature difference between the average temperature of the HTF and ambient temperature, IAM the incident angle modifier, f_{shadow} the losses factor due to shadowing, and f_{corner} the loss factor due to the collectors corner. Finally, the optical coefficients a_1 and a_2, the thermal coefficients b_1 and b_2; and the dirtiness coefficient f_{dirt} in (eq. 9), are given by the collector properties according to the manufacturer data (Hublitz and Spinnler, 2003, Lüpfert et al., 2001). The EuroTrough collector is used for a variety of application such as industrial process heat and electricity generation, and it was selected for the solar-geothermal hybrid system because of the low specific investment cost.

3.3 Turbine model

Geothermal turbines generally operate at wet steam conditions and therefore its isentropic efficiency is affected by the amount of moisture present in the steam during the expansion process. As the moisture increases, the turbine reduces its efficiency. This effect can be quantified by using Baumann's rule (DiPippo, 2008), which proposes that a 1% average extra moisture causes roughly a 1% drop in the turbine efficiency.

Hence, the isentropic efficiency is defined as:

$$\eta_T = \eta_{TD}\left(\frac{x_{in}+x_{out}}{2}\right) \qquad \text{(eq. 10)}$$

where η_{TD} represents the turbine efficiency at dry steam conditions, x_{in} is the inlet dryness fraction and x_{out} the outlet dryness fraction.

The variation in the inlet turbine temperature is given by the solar resource availability and the pressure drop at the inlet nozzle of the turbine, which limits the mass flow admitted by the device. Chaibakhsh (2008) developed a relationship between the mass flow, temperature and pressure drop over the steam turbine as follows:

$$\dot{m}_{in} = \frac{K}{\sqrt{T_{in}}}\sqrt{P_{in}^2 - P_{out}^2} \qquad \text{(eq. 12)}$$

where $\dot{m}_{in}$ represents the inlet mass flow rate, K the mass flow coefficient, T_{in} the inlet temperature, P_{in} the inlet pressure and P_{out} the outlet pressure.

The heat exchanger considered in this work to deliver the solar thermal energy towards the steam was modeled using the effectiveness-NTU method (Nellis and Klein, 2009).

4. Results and discussion

4.1 Stand-alone power plant results

The optimization methodology for the single-flash plant and each geothermal reservoir was developed by varying the separation pressure in order to achieve the highest power output possible. The separation pressure optimizes the amount of geothermal fluid through the system and the steam generation at the separator. The maximum amount of power output possible as a function of the separation pressure is shown in Fig. 2. The amount of power output generated by each reservoir is highly related to the thermodynamic state of the geothermal fluid, where the two cases with higher power production correspond to those with higher enthalpy. Case 1 presents higher resource temperature, yet it is not enough to generate a similar power production as in cases 2 and 4.

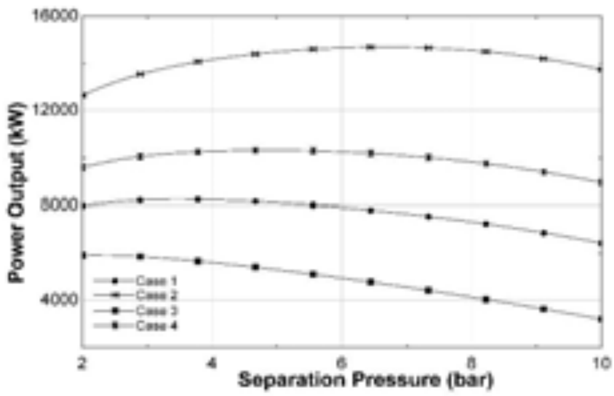

Fig. 2: Power output of the reservoir as function of separation pressure

4.2 Single-flash hybrid power plant

4.2.1 Additional power generation

The solar thermal energy in the single-flash hybrid scheme is added in two heat exchangers (HX) as shown in Fig. 1. The first HX is used for superheating the steam, while the second HX generates additional steam in the separator system. The additional power produced by both devices, when there is solar thermal energy available, was evaluated considering the reservoir case 2 as shown in Fig. 3. The HX 1 generates a higher amount of additional energy per kW of solar power delivered. For every kW of thermal energy the superheating process generates 0.23 kW of additional power output. Delivering the solar thermal power to the superheating process increases the steam quality at the turbine discharge, which improves the turbine efficiency. On the other hand, the HX 2 generates only 0.16 kW of additional power per kW of solar thermal power. Nevertheless, it has to be considered that the first HX can only superheat the steam flow until it reaches 320 ºC due to the HX effectiveness limitation.

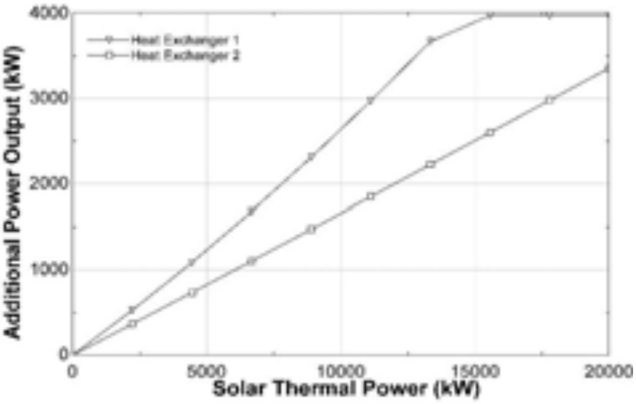

Fig. 3: Additional power output as function of solar thermal power

This situation is observed in Fig. 4, where the superheated steam temperature and additional steam generation as function of the solar thermal power is shown. Each additional kW of solar thermal power causes an increase of 0.012 ºC in the steam temperature and/or generates 0.00035 kg/s of additional steam. The optimization of the integration of both energy resources is developed by varying the separation pressure and solar thermal power in order to achieve the maximum 2nd law efficiency.

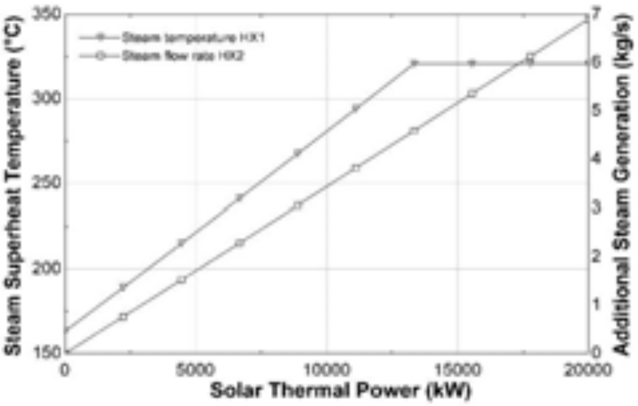

Fig. 4: Superheated steam temperature and additional steam generation as function of solar thermal power

The exergetic efficiency increases whenever solar thermal energy is supply to the superheating process. In contrast, using the solar energy to generate additional steam produces a lower rate of power, which is reflected in a reduction of the 2nd law efficiency. Fig. 5 shows the effect of the solar thermal power addition in the 2nd law efficiency for the four cases. The exergetic efficiency increases on the four cases proposed until it reaches a maximum and then it decreases. As the solar power is added, the amount required for each case is defined by the flow rate and temperature of the steam. The geothermal reservoirs with high enthalpy allow the separator to produce a higher amount of steam and at a higher pressure. This causes the hybrid single-flash plant to require a higher amount of thermal power as the enthalpy of the resource increases to achieve the maximum 2nd law efficiency. The maximum exergetic efficiency for the hybrid system proposed is achieved once the superheat steam reaches a temperature of approximately 320 ºC. Increasing the solar field aperture area to deliver additional thermal power to the HX 2 decreases the power production as shown in Fig. 3. This effect causes the reduction of the exergetic efficiency. The results of the geothermal only and single-flash hybrid power plants are shown in Table 3. The optimization routine indicates that the hybrid scheme increase slightly the separation pressure to achieve the maximum 2nd law efficiency. This benefits the system because a higher separation pressure reduces the flow rate and increases the steam temperature, which requires a lower amount of thermal power to achieve the maximum 2nd law efficiency. In the four cases analyzed for the single-flash power plant, the efficiency and power output increase as long as thermal power is delivered towards the superheating process. The power output for the single-flash hybrid presents at least 20% of additional power output and the 2nd law efficiency increase by more than 2.9%, for each reservoir case.

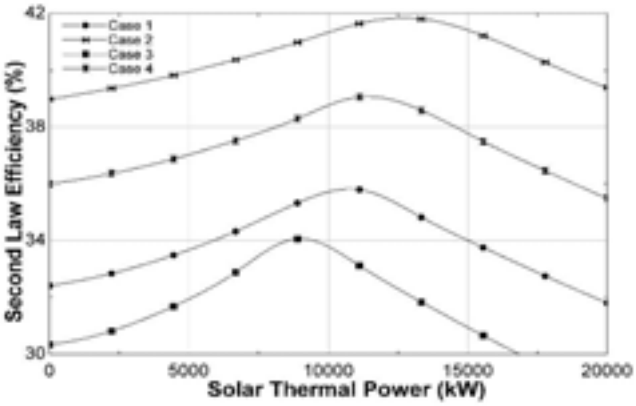

Fig. 5: 2nd law efficiency of the reservoir as function of solar thermal power

4.2.1 Geothermal flow rate reduction

The single-flash hybrid power plant can be used for a second purpose, which is reducing the geothermal fluid consumption thus allowing an extended geothermal well lifetime. This is carried out considering the power output of a single-flash only power plant fixed. Thereby, whenever there is solar energy available, the hybrid system is able to reduce the geothermal flow and compensates with the superheating of the steam or enhancing the steam generation until it reaches the fixed power output. The geothermal flow rate reduction is achieved by increasing the separation from the choked well flow considered in (eq. 8). The superheating process was used for this case due to the higher power production rate as it is integrated with the solar thermal energy. The effect of adding solar thermal power to the geothermal flow rate is studied for the proposed cases, as shown in Fig. 6. The higher enthalpy resources present a higher pressure, which enhances the reduction of the geothermal fluid given the geothermal well choked-flow conditions. The amount of geothermal flow reduction is directly related to the separation pressure and amount of steam that can be superheated. Cases 2 and 4 present higher steam rates, which is reflected in a considerable reduction of the geothermal fluid flow. This reduction achieves a stable point when the steam reaches it maximum superheat temperature given by the steam characteristics at the inlet of the HX.

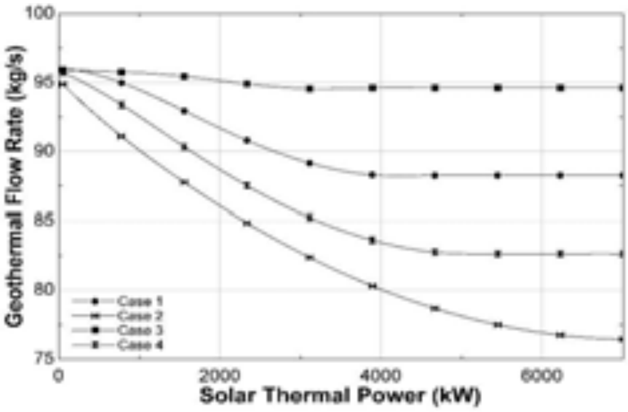

Fig. 6: Geothermal flow rate as function of the solar thermal power.

The high enthalpy resources present an increase of the 2nd law efficiency as long as the geothermal flow rate is reduced, as shown in Fig. 7. Cases 2 and 4 present a considerably increase in the 2nd law efficiency caused by the pressure and steam through the system. Once the superheat process reaches the maximum capacity the efficiency starts decreasing. Case 1 presents a geothermal flow reduction, which is still unable to produce a considerable increase in the 2nd law efficiency. As mentioned, the pressure at which each separator operates according to each reservoir conditions contributes to the reduction in the geothermal fluid flow. Case 3 presents no improvement in the 2nd law efficiency due to the low pressure at which the separator operates, which is determine by the lower enthalpy from the reservoir.

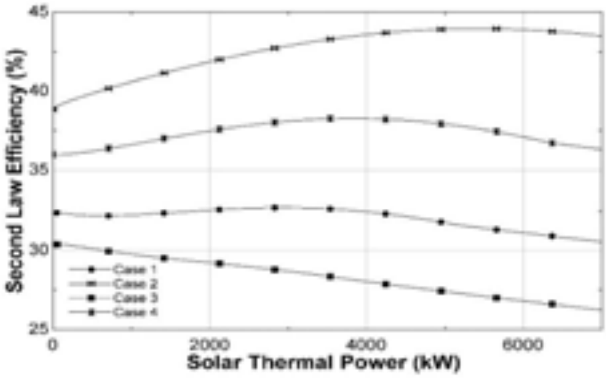

Fig. 7: 2nd law efficiency as function of solar thermal power for reducing the geothermal flow rate

The optimum results from the single-flash hybrid for geothermal flow reduction purpose are shown in Table 3. Case 3 does not present any difference because the integration presents a decrease in the 2nd law efficiency. As on the other cases, it can be seen how the geothermal flow is reduced while the 2nd law efficiency is increased. The geothermal flow rate can be reduced up to 16% depending on the reservoir conditions.

Tab. 3: Single-flash hybrid power plant results

	Single-flash power plant				Additional power generation				Geothermal flow rate reduction			
Parameters	Case 1	Case 2	Case 3	Case 4	Case 1	Case 2	Case 3	Case 4	Case 1	Case 2	Case 3	Case 4
Separation temperature (ºC)	138.8	163	123.7	150.6	139.3	167.6	129.2	158.5	179.7	188.7	123.7	185
Separation pressure (bar)	3.49	6.67	2.22	4.82	3.54	7.47	2.63	5.95	9.95	12.19	2.22	11.22
Power output (kW)	8237	14689	5915	10308	10818	18434	7900	13050	8237	14689	5915	10308
Steam flow rate (kg/s)	20.24	30.49	16.71	23.18	20.15	29.6	15.75	21.86	-	-	-	-
Geothermal flow rate (kg/s)	95.77	95.44	96.22	95.76	-	-	-	-	89.44	77.53	96.18	83.71
2nd law efficiency (%)	32.41	38.83	30.33	35.99	35.84	41.78	33.95	38.88	32.71	43.95	30.33	38.27
Solar collection area (m^2)	-	-	-	-	15000	19600	12200	15000	4300	7900	-	5500

5. Transient simulation of hybrid power plant

The transient simulations consider hourly meteorological data from a selected location in Chile, Crucero, which displays excellent solar resource while being relatively close to existing geothermal prospection sites (Escobar et al, 2015). This region is well known for the large number of clear days throughout the year, while a few cloudy periods are present during February due to the “altiplanic winter” effects and in proper wintertime, in this case during the months of June to August. Total direct normal irradiance (DNI) in Crucero amounts to over 3500 kWh/m^2-year, possibly the highest in the world. The geothermal flow presents a high thermal inertia because of minimum variation of the reservoir conditions throughout the year. There is no thermal energy storage considered partly due to the higher additional costs involved and partially since the power dispatchability (understood as power production able to supply expected electricity grid demand as requested with minimum variability) is achieved by the combination of the solar-geothermal hybrid system able to produce baseload conditions. The analysis presented in the previous sections evaluated the optimum conditions for the operation of the hybrid systems, in which the 2nd law efficiency is maximized. Case 2 was selected to evaluate the performance of the single-flash hybrid system under the design conditions considering the common variation of the solar resource along a year. The transient simulations for the single-flash hybrid system are developed with the objective to maximize the power output or minimize the geothermal flow consumption throughout the year by integrating the hourly simulation results.

5.1 Additional power generation

The performance of the hybrid single-flash for two representative days with clear and cloudy skies are shown in Fig. 8, for which as a reference the hybrid scheme generates 14.68 MW when there is no DNI available.

During a clear day, there are hours with DNI higher than the rating conditions, causing the system to reach its maximum capacity of 18.43 MW. The alternative of using HX 2 for periods with high DNI does not compensate the investment costs, due to the low additional power generated. As in the northern region of Chile there are only a small number of cloudy days, the hybrid scheme is still able to generate during low levels of DNI. For example, as observed in Fig. 8, at a DNI of 400 W/m^2 the hybrid scheme can produce 6.7% of additional power output.

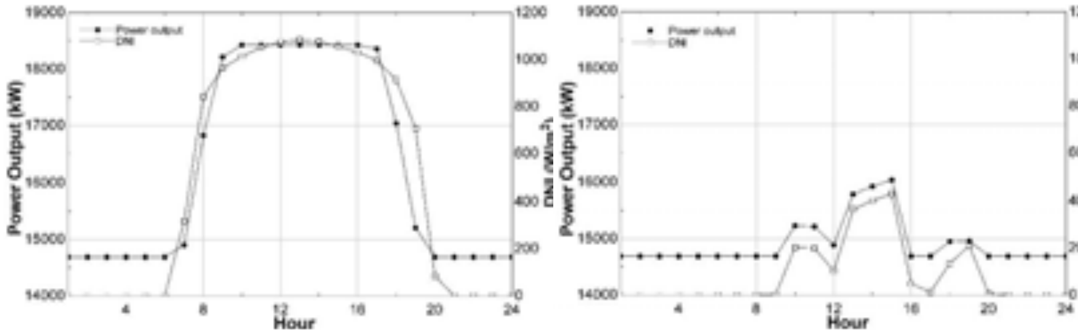

Fig. 8: Single-flash hybrid power plant daily performance

The results from the hourly simulations during a full year are shown in Fig. 9. The dark blue zones represent the base power production of the single-flash geothermal-only power plant, which corresponds to 14.68 MW, while the color code corresponds to the extra power derived by integrating the solar collector arrangement. As mentioned, the altiplanic winter effects during February reduce the production to the levels of the geothermal-only power plant. During spring, the higher average of power output is produced, reaching 17.53 MW when solar energy is available, while autumn presents a lower performance with an average power production of 16.71 MW. The performance of the hybrid single-flash system during the year presents an average power output 7% higher than the single-flash geothermal-only plant. Higher radiation values during summertime do not translate directly into additional power generation as the solar field is dimensioned with a design DNI of 1000 W/m^2, where higher DNI values only result in collector defocusing.

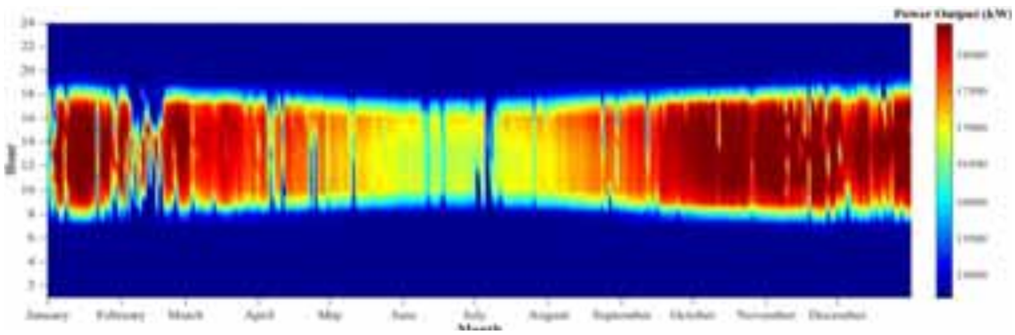

Fig. 9: Single-flash hybrid power plant year performance

5.2 Geothermal flow rate reduction

The hybrid single-flash power plant performance is able to reduce the geothermal fluid flow consumption during the year as shown in Fig. 10. The geothermal-only power plant operates with a geothermal flow rate of 95.43 kg/s, which is represented with the red layer. The lower amount of geothermal fluid flow that the hybrid system can achieve by integrating the solar thermal power is 76.84 kg/s considering the same base power output of 14.68 MW. The best performance in terms of geothermal fluid flow reduction is achieved during the spring with an average of 80.5 kg/s, while the worst operational results are observed during autumn where the solar system reduces the flow rate to only 82.9 kg/s. The average geothermal fluid flow is reduced during the year to 89.19 kg/s. Similar to what was presented in section 5.1, higher radiation values during summertime do not translate directly into additional geothermal fluid flow reductions, as the solar field is dimensioned with a design DNI of 1000 W/m^2, where higher DNI values only result in collector defocusing.

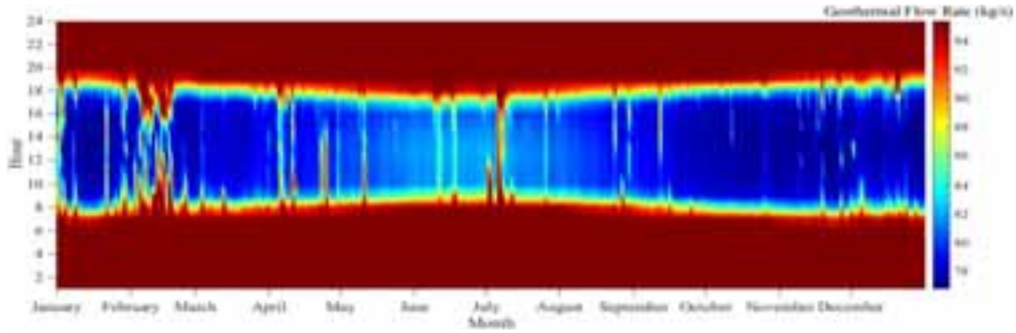

Fig. 10: Single-flash hybrid power plant year performance

6. Conclusions

An evaluation for a solar-geothermal hybrid power plant was developed in order to estimate their performance over a year. The optimization of the thermal power provided by the solar field showed that the superheating and evaporating process are able to increase the power generation, with the superheating process presenting higher rates (0.23 kW) of additional power output per kW of thermal power integrated to the single-flash hybrid plants. Delivering solar thermal energy in order to increase the steam temperature increases the 2nd law efficiency and allows the turbine to operate in a region of increased efficiency. Considering the hybridization of these two renewable resources, utilization of high-enthalpy geothermal resources shows greater promise given that the higher steam flow rates allow a better performance for the superheating process resulting in additional power generation and higher exergetic efficiencies. The solar field aperture area that maximizes the 2nd law efficiency of the flashing hybrid power plant is directly related to the steam flow conditions. The geothermal resources with higher enthalpy presented a larger reduction on the geothermal flow rate consumption due to the separation pressure at which they operate. Considering the reduction rate of the geothermal fluid produced by the solar energy, a 20-year useful life of a production well can be extended in at least 1 ½ years generating approximately 4.5 GWh of additional power output during. The benefits from the hybridization of these renewable sources are evident in terms of the power production increase during peak hours and the useful life extension for the production well. Furthermore, the hybrid scheme is a simple design considering the implementation of components that are common in a stand-alone geothermal power plants and concentrated solar power plants. For the Chilean energy market, the solar-geothermal power system presents an interesting yet still undeveloped alternative that can help fulfill the renewable energy utilization targets. These hybrid systems constitute an additional opportunity to diversify the energy resources utilization, with environmentally friendly base load energy using the large renewable potentials existing in the country.

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