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Techno-Economical Evaluation of Parabolic Trough Collectors Systems for Steam Processes in the Chilean Industry

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Abstract. The Chilean industry sector presents an extensive energy consumption which is mainly supplied by fossil fuels. The solar resource available in the country offers an opportunity to supply heat to low and medium temperature processes. The present study evaluates the techno-economical potential of generating solar process heat through a parabolic trough collector arrangement and a steam generator for 5 different processes identified in the food industry. The selected processes require steam, presenting a temperature range of 140 – 200 °C and pressure of 3 – 6 bar. The cost of solar-generated steam is quantified through the levelized cost of heat (LCOH) for the main regions of the Chile and compared with average fossil fuel price. The results show that the temperature of the process affects the LCOH and increasing the outlet temperature of the solar field decreases the LCOH. A geographic analysis of the LCOH for a defined process throughout the country. For most of the regions that presents higher thermal energy consumptions the solar process heat can compete with fossil fuels, considering a solar field installed cost lower than 250 US$/m^2. The sensitivity analysis carried out showed that the parameter that affect most corresponds to the steam production followed by the solar field costs.

INTRODUCTION

Chile presents a large territory, with a complete range of climates due to its vast extension and a huge potential for renewable energy. In particular, the country exhibits a well-known solar energy resource. However, only 10% of the total energy demand is met by renewables (hydro, wind and solar) [1]. In Chile, the industry sector consumes 40% of the total energy consumption, which is mainly supplied by fossil fuels such as petroleum (59%), natural gas (11%) and coal (4%) [1]. This scenario causes high dependence and price volatility towards the fossil fuel producers. A significant amount of heat consumed in the industrial sector corresponds to low (<100 °C) and medium temperature (100 – 400 °C), which is quite promising and suitable for solar thermal technologies [2]. Hence, a part of the Chilean industrial energy demand could be covered with these technologies. However, solar heat for industrial processes (SHIP) is still considered a niche market with 253 solar thermal plants operating over the world by July 2017 [3].

The world largest solar thermal plant for industrial processes is located in Chile, by the copper mining plant Gabriela Mistral. The installation is designed to supply 85% of the total heat demand to refine copper with 39,300 m^2 of flat plate collectors connected to a 4,000 m^3 thermal energy storage [3]. However, other than that reference, very few examples can be found in the Chilean industry. The Appsol project [4] presented an estimation of the energy demand for Chilean industries and an evaluation of the solar thermal potential to cover his demand. According to this research, the major share of the total thermal energy consumption corresponds to the food industry (50%). More than half of this consumption (54%) was in from of steam as heat transfer fluid, in processes such as cooking and heating.

Solar concentrating technologies are able to provide steam for the conditions required for the food industry, either through direct steam generation technologies or through indirect schemes. However, the cost of these systems will

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define if an industry deploys such systems or not. Hence, the key to the development of SHIP systems is the economics, an aspect that has been widely studied.

For example, Schweiger et al. [5] assessed the potential of SHIP for five cities in Spain and Portugal for a temperature range of 60 – 200 °C, for different solar thermal technologies and they concluded that the systems required a funding of about 3/4 of the investment in order to be competitive. An in-depth analysis was carried out by Lauterbach et al. [6], where the authors analyzed and identified the most promising industrial sectors and processes in Germany for the application of solar process heat based on their heat demand below 300 °C and waste heat potential. The authors concluded that for the further development of the solar process heat industry, the focus should be the cost reduction of technologies below 100 °C and the development of cost effective solutions for temperatures up to 200 °C. In general, the results when the assessments are made for a particular industry are not better. In [7], the results for the Tunisian textile industry for hot water and steam generation showed that they were not economically appealing given the significant subsides on fossil fuels. However, a recent study developed by Kurup et al. [8] that, evaluated the market potential for industrial process heat (IPH) for concentrating collectors technologies. They showed that the levelized cost of heat (LCOH) of the solar technologies for many areas in California was lower than the LCOH from natural gas.

Given that the main barrier of solar heat integration in the industry corresponds to the solar field costs, the objective of the present study is a techno-economical evaluation of a solar thermal system for the generation of steam for the Chilean industry. To do so, the first step was to identify the steam processes of the Chilean industry. Then, the yearly production of the solar system (parabolic trough and steam generator) was calculated using TRNSYS [9]. Finally, the economic evaluation was conducted. The evaluation of the LCOH of the selected systems in different locations of Chile was calculated. Additionally, a sensitivity analysis was performed to evaluate the effects of the variability of the considered parameter on the LCOH.

METHODOLOGY

The methodology of the present study initiates with the identification of the steam processes currently used in the Chilean industry. Once the processes were identified, the information was incorporated to the TRNSYS inputs, in the form of process temperature and pressure, along with the other inputs: location and collector. The results delivered from the simulation throughout the year corresponded to: temperatures, flow rates and steam generation, which were used to size the heat exchanger components. Finally, an economic analysis was carried out with the information compiled to estimate the LCOH under different conditions defined by the user.

The industry sector with greater thermal demand was the food industry, with 50% of the total thermal demand [4]. Within this sector, the industrial processes with greater steam demand were identified, as shown in Table 1. Their temperature varies from 140 to 200 °C and their pressure from 3 to 6 bar,

TABLE 1. Main steam processes of the Chilean food industry.

Number	Process name	Inlet temperature (°C)	Outlet temperature (°C)	Pressure (bar)
1	Concentration	140	90	6
2	Cooking	200	96	3
3	Heating	160	100	5.5
4		140	95	6
5	Autoclave LDPE	150	120	6

Once the thermal yields were determined for each process, the simulation of the concentrating solar system was performed using TRNSYS. Fig. 1 presents a simplified schematic of the simulation case. The system is composed by a closed-loop solar field and a steam generator (economizer, evaporator and superheater), whose purpose is to supply steam to the specific process. The module considered for the solar field corresponds to the Type 536, while the Type 637 is used as a steam generator. The model developed in TRNSYS is coupled to a Python code that is in charge of handling the inputs and results of all the studied cases. The variables studied were location, aperture area, collector temperature, pinch temperature, process temperature and pressure. The parabolic trough collector selected was the Polytrough 1800 manufactured by NEP Solar [10], operating with Therminol VP-1 as the heat transfer fluid and a temperature range of 150 – 220 °C.

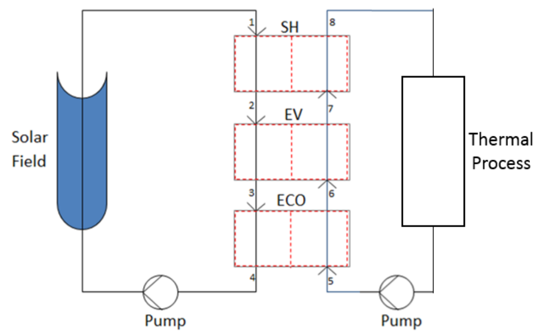

FIGURE 1. Simplified schematic of the simulation case.

Economic Analysis

The economic analysis is carried out to evaluate the potential of integrating solar process heat to meet the demand of the identified processes. The solar field costs was based on the current prices of medium sized parabolic trough according to providers who were contacted. An additional 30% was considered to cover the installation expenses.

The steam generator costs comprises three major components: economizer, evaporator and super heater. From one side of the stream, the heat transfer fluid corresponds to Therminol VP-1 with a temperature range from 140 to 220 °C. From the other side of the stream, the fluid corresponds to water/steam and a temperature range from 100 to 200 °C. The heat exchanger type selected for the economizer and super heater corresponds to a fixed tube sheet and U-tube, while the rising film was selected as evaporator type. Stainless steel was considered as the material. The equations utilized for heat exchanger cost estimations are shown in Table 2 and were obtained from fitting curve exercises according to the literature [11]. The cost for each component was later adjusted using the Chemical Engineering's Plant Cost Index (CEPCI 2016).

TABLE 2. Cost equations and parameters considered for the heat exchanger components.

Component	Cost Equations	Global Heat Transfer Coefficient [12]
Economizer	$PEC(2004) = exp\{-0.0062log(A)^4 + 0.0472log(A)^3 - 0.0328log(A)^2 + 0.3631log(A) + 3.2021\}$ $F_p = 0.0444log(P)^2 + 0.1078\,log(P) + 0.8534$	$U_{eco} = 675\ \frac{W}{m^2K}$
	$F_{BM}^{\alpha} = 1.3125(F_p \cdot F_M) + 1.6875$	
Super heater	$F_M = 3$ $CBM = F_{BM}^{\alpha} \cdot PEC(2004)\ \cdot \frac{CEPCI(2016)}{CEPCI(2004)}$	$U_{sh} = 1150\ \frac{W}{m^2K}$
Evaporator	$PEC(2004) = exp\{0.8674log(A) + 2.8154\}$ $F_p = 0.1433log(P)^3 - 0.6387log(P)^2 + 1.2141log(P) + 0.2795$ $F_{BM}^{\alpha} = 6.2$ $CBM = F_{BM} \cdot F_P \cdot PEC(2004)\ \cdot \frac{CEPCI(2016)}{CEPCI(2004)}$	$U_{ev} = 45\ \frac{W}{m^2K}$

where $PEC(2004)$ the purchased equipment cost, A the area, F_p the pressure factor, P the pressure, F_{BM}^{α} the factor correction of the bare module, F_M the material factor, U the global heat transfer coefficient and $CEPCI(2016)$ the chemical engineering plant cost corresponding to the year 2016.

The selected economic methodology to assess the integration of solar heat into industrial processes was the levelized cost of heat (LCOH), according to the following equation:

$$LCOH = \frac{I_0 + \sum_{t=1}^{T} \frac{C_t}{(1+r)^t}}{\sum_{t=1}^{T} \frac{E_t}{(1+r)^t}}$$

where I_0 corresponds to initial investment, C_t operation and maintenance costs (year t), E_t energy saved and r discount rate. The parameters for the over mentioned cost analysis are shown in Table 3.

TABLE 3. Parameters for economic analysis.

Parameters	Value
Solar field	250 \$US/m^2
O&M Cost	2% of Investment
Discount rate	10%
Lifetime of the systems	20 years

Additionally, to assess the effect of the variation of the parameters considered in the LCOH equation a sensitivity analysis was performed. This analysis compares the variation of the LCOH value when some parameters are varied ±1%. The selected parameters for this analysis were the energy production, the solar field and steam generator costs, the discount rate and the O&M costs.

RESULTS AND DISCUSSION

As previously mentioned, the Chilean industry presents a wide range of steam processes, defined by their operating temperature and pressure. Fig. 2 shows the influence of the solar field outlet temperature on the LCOH for the different processes (for a specific location and under the same collector field characteristics). The selected location is Santiago, where 26% of the food industry thermal energy consumption is located.

The solar field outlet temperature produced differences on the LCOH up to 20% approximately, depending on the process characteristics. The solar field temperature difference affected the LCOH depending on the outlet temperature of the process. Hence, the results in Figure 2 are grouped in three main lines. The effect on process 1 and 4 were very similar, given the similarity of the processes characteristics. Process 2 was evaluated only for solar field outlet temperatures between 210-240 °C due to the required steam temperature (200 °C), although it behaved similar as Process 3 in this range. The outlet temperature of the process defined the flowrate of steam generated by a given ΔT defined at the solar field. Therefore, the LCOH was also affected by this solar field ΔT.

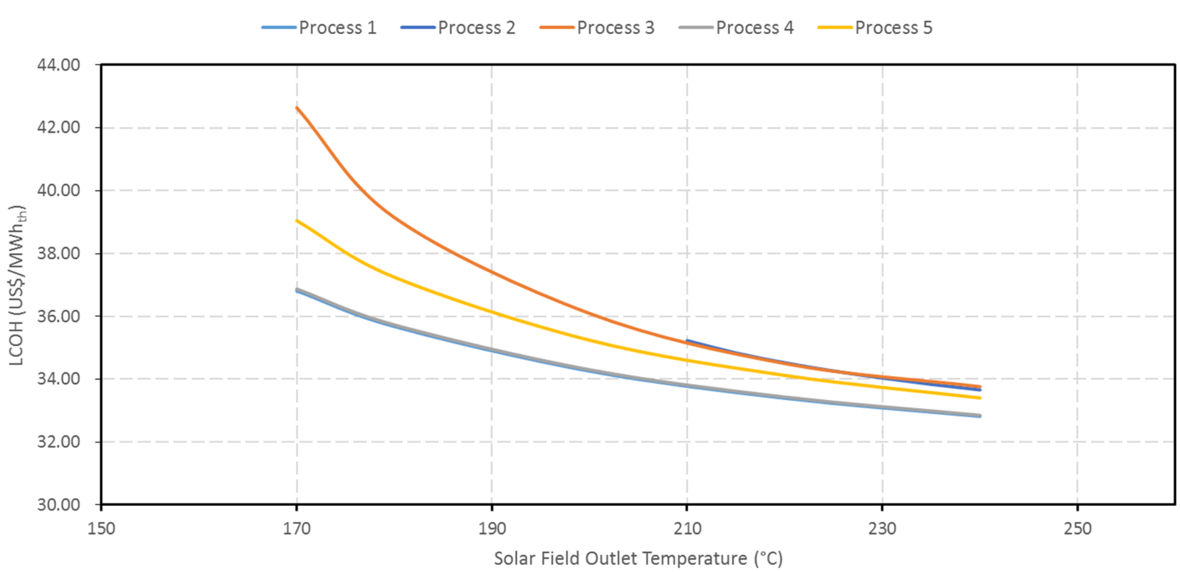

FIGURE 2. Influence of solar field outlet temperature on the LCOH of each process in Santiago.

The process of concentration (Process 1) was selected to evaluate the LCOH throughout the country, as shown in Figure 3. The north region exhibited the most remarkable results with a minimum value of 19.19 US$/MWh$_{th}$ (in Atacama region) and an average of 21.84 US$/MWh$_{th}$, from Arica to Atacama Region. Moreover, if the difficult access to fossil fuel is considered, the results in this area were particularly favorable for the development of solar industrial processes, although the demand of the region for food industries is smaller than southern regions. The central regions of Chile, Valparaiso and Metropolitana which hold approximately 40% of thermal energy demand of the food industry, presented a LCOH of below 33 US$/MWh$_{th}$ which could compete with fossil fuel depending on the fuel cost for each specific industry. The remaining share of the thermal energy demand of the food industry was at the south region, mainly in Bio-Bio region. The results for this area showed an average LCOH of 36 US$/MWh$_{th}$ which is slightly higher than the natural gas average price. Moreover, the south region of Chile is distinguished by the abundance of biomass at a low cost which ends up reducing the attraction of using solar thermal technologies for industrial processes.

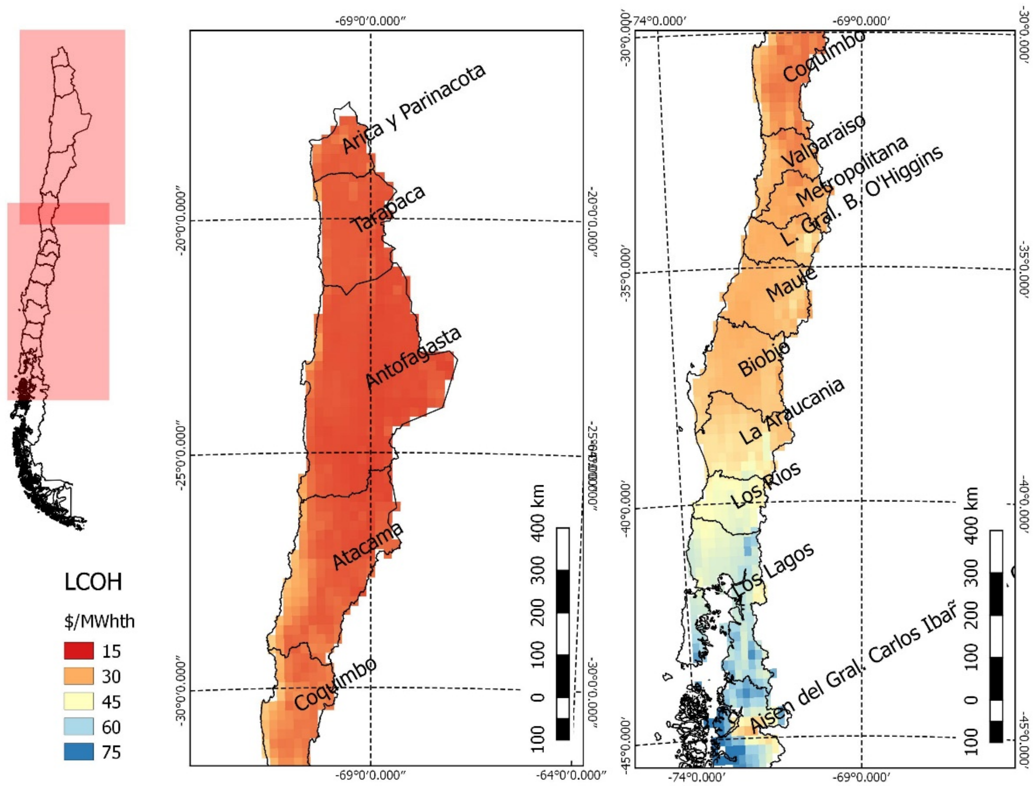

FIGURE 3. LCOH Map of Chile for the process of concentration using a defined model of parabolic trough collectors.

The sensitivity analysis was carried out for the concentrating process (Process 1) for the location of Santiago, and the results are shown in Figure 4. The variation of the parameter that affected the LCOH the most was the steam production, followed by the solar field cost and the discount rate. For the reference value of 32.35 US$/MWh$_{th}$, an increase of 1% of the steam production generated a reduction of 0.3 $/MWh$_{th}$. The energy production throughout the year is most likely to be high, due to the high solar resource available in most of the region of the country. Meanwhile, the increase of the rest of the parameters generated an increase on the LCOH. In relation to the investment costs, the solar field cost was considerably more important than the steam generator. Nevertheless, the solar field cost is a parameter complicated to estimate given the limited number of solar concentrating installations in the country. Hence, the cost of the collector is a key point when evaluating the viability and the potential development of this kind of technology in the country.

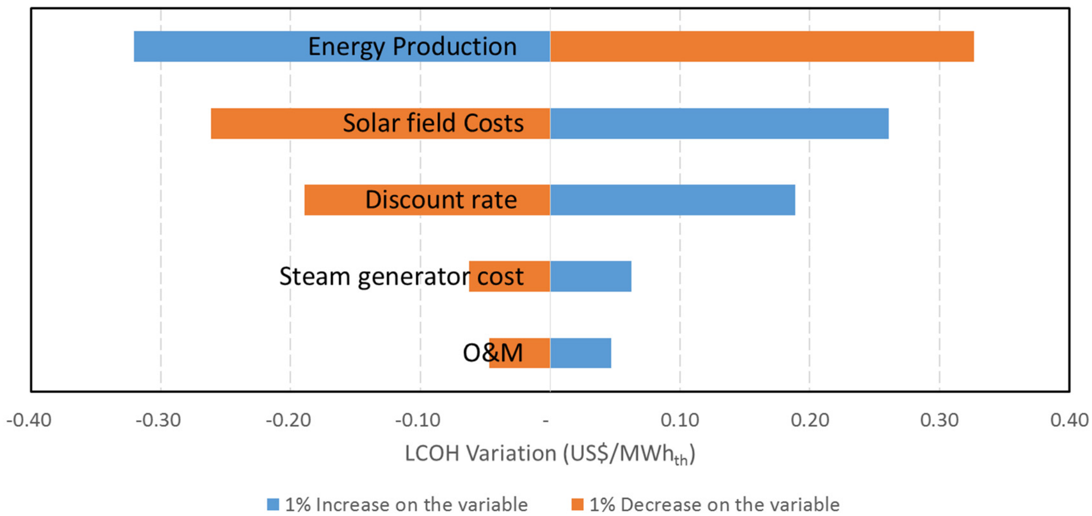

FIGURE 4. Sensitivity analysis for the concentrating process in Santiago, Chile.

The solar field cost can vary greatly due to the low amount of installations and technology providers in Chile. To assess the effects of this variability on the potential of development of these technologies, the LCOH was calculated for a solar field cost varying from 50 to 350 US$/m^2, as shown in Figure 5, for six locations. The selected locations corresponded to the capital of the six regions with more demand. When considering a solar field cost lower than 250 US$/m^2 [5, 7, 8] the LCOH of steam produced by solar thermal technologies could compete with fossil fuel prices, for the major locations where the industry is developed. The development in Puerto Montt presented the most adverse case, due to its lower solar resources (3.88 kWh/m^{2}day). The best locations was Copiapó, located in the Atacama Desert, with an average annual irradiation value of 8.18 kWh/m^{2}day.

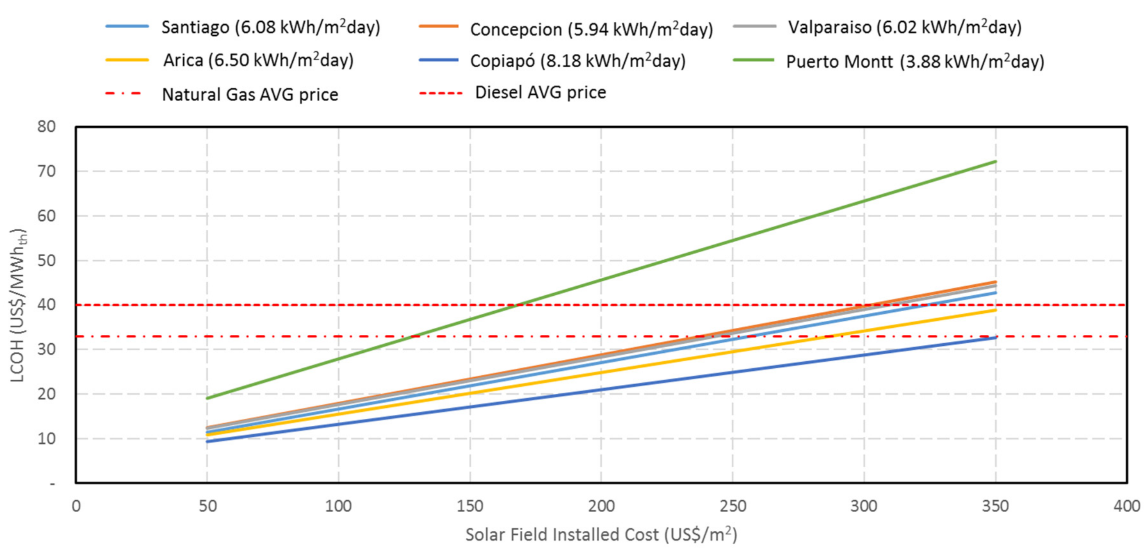

FIGURE 5. Influence of solar field installed cost in the LCOH for Process 1 for the locations with major presence in the food industry.

CONCLUSIONS

This works focused on the techno-economical evaluation of integration of parabolic trough collector systems into industrial thermal processes existing in the Chilean industry. The industry analyzed, the food industry, presents the biggest thermal demand in Chile and a wide range of processes, which perfectly engage with the solar process heat.

The economic evaluation was carried out through the levelized cost of heat, which allowed the determination of the cost of using solar thermal technologies for steam generation.

The results showed that two critical parameters affected the LCOH: the outlet temperature of the process and the ΔT of the solar field. For a specific project, these two parameters require to be further analyzed to obtain the most attractive cost of heat. Through the geographic analysis the most promising zones for the solar steam generation were identified. The country presented a good potential from the north until the Region of Bio-Bio. The lowest LCOH was reached in the Region of Atacama, at 19.19 US$/$MWh_{th}$.

The variability of the steam production and the cost of the solar field were the parameters that more affected the value of the LCOH. The increase of 1% of the steam production could generate a reduction of up to 0.3 $/$MWh_{th.}$ For most of the locations with high food industry presence the solar steam generation could compete with fossil fuel when the cost of the solar field was under 250 US$/$m^2$.

The economic results of the present study shows that Chile presents favorable conditions for the integration of solar process heat into industrial processes. The solar field cost was a key effect on the LCOH. For the further development of the solar process heat industry in Chile it is necessary to reduce prices of the collectors for these working conditions and moderate the uncertainty of the installations costs.

ACKNOWLEDGMENTS

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