Energy and economic evaluation of a middle-sized CSP parabolic field in an agro-industrial company

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Abstract. The energy assessment carried out in a middle-sized CSP parabolic field of 120 m² is presented; it provides pre-heating water at 70°C to the boilers of the lemon essential oil extraction process in an agro-industrial company located in Piura, at the border of the Sechura desert in Peru. The parabolic cylindrical solar concentrators are made with glass reflectors, an automatic solar tracking system, and collector tubes through which water flows. It was measured that each collector converts solar energy and transfer it as a thermal energy to the water with an average efficiency of 18.1%. Considering this result, theoretically the whole solar field could provide 550.37 GJ/year for water preheating, which is equivalent to saving 28151.8 liters of LPG, and 46.87 tons of CO₂ released to the environment. However, after a year of operation, the solar field provided only 99.59 GJ for water preheating, saving 4,705.26 liters of LPG, equivalent to stop emitting 7.69 tons of CO₂ to the environment. An overall thermal energy efficiency of the CSP solar field in 18.1% was estimated. According to the financial assessment with the actual annual data, the period of recovery of the investment is estimated to be 4.4 years, 3.6 more years than the theoretical projection.

1. Introduction

Concentrated solar power (CSP) technology has been mainly used in electricity generation, with huge solar concentration fields [1] -especially those of the parabolic trough collector and solar power tower type [2] -, in different countries around the world [3]. However, photovoltaic plants for power generation are now a more cost-effective option. In fact, when comparing electricity generation in a parabolic trough CSP plant versus a photovoltaic plant, the former wins in electricity generation (35.7% more) and efficiency (17.12% vs 16.65%) but loses in generation costs (0.1 US$/kWh versus 0.037 US$/kWh) and in payback period (17.5 years versus 4.9 years) [4]. On the other hand, if CSP technology is used to generate heat for different processes in the industrial sector as water heating or steam generation, it is more competitive than photovoltaic and even, depending on international prices and subsidies, fossil fuels [5].

Among the main industrial processes that require thermal energy are heating, drying, sterilizing, washing, pickling, cleaning, blanching, pasteurization, dehydration, cooking, etc., with temperatures ranging from 50 °C to 200 °C. It is estimated that on average 35 % of all energy generated on Earth is used in the industrial sector, which is consumed in the form of electricity (26 %) and heat (74 %); of the latter, 30 % of industries require temperatures below 150 °C in their processes and 70 % require higher temperatures [6]. It is well known that medium-sized parabolic concentrators are best suited to reach temperatures around 150 °C, and in conjunction with a thermal energy storage system, are capable of covering the entire energy demand of the industry [7] in an economically competitive way, also contributing to reduce the carbon footprint [8]. For this reason, the parabolic concentrators are the most used around the world [9].
Despite all the benefits of using concentrated solar power to provide hot water and steam to industry, few countries have yet implemented it, including India, Austria, Germany, the United States, Spain, China, South Africa, Mexico, France and Greece [10]. In Peru there are four medium-sized CSP parabolic fields operating for agro-industrial companies in the regions of Piura, Ica and Arequipa [11], which are the areas with the highest solar irradiance on the northern, central and southern desert coast of Peru [12], respectively.

In this article will be described the results and evaluation obtained from a medium-sized CSP parabolic field of 120 m$^2$ used to preheat to 70 °C the water of the industrial boilers for obtaining lemon essential oil from the agro-industrial Limones Piuranos Co [13]. In the second section the description of the solar field is presented. In the third section the methodology used for the energy and economic evaluation is presented. In the fourth section are presented the theoretical and experimental results and discussion. In the last section the conclusions are presented.

2. CSP parabolic field description

2.1 Solar concentrator

The cylindrical parabolic reflecting mirrors are 9 m$^2$ made of silver nitrate covered by transparent glass, 3 m long and 3 m curved aperture, with a reflectance of around 94%. The mirrors are supported by aluminum and iron structure, and they should be washed with water and detergent at least once a week. The collector pipes are made of 304 stainless steel and are designed to withstand movement, high pressure, and high temperatures. In tests performed, temperatures of 350 °C and pressures of 1.38 MPa (200 psi) have been reached without showing any inconvenience. These tubes should be cleaned once a month. The solar tracking system is based on a programmable logic controller; its function is to pulse energy to the mechanical motion system and analyze the signal from the self-made inclinometer sensor to ensure its accuracy with a maximum error of 0.2 degrees sexagesimal per minute. The mechanical motion consists of a geared motor, sprocket, chains, and a circular rail [14].

2.2 CSP parabolic field

The CSP parabolic field consists in 2 sections of 60 m$^2$ each (20 m long and 3 m curved aperture each section), as shown in figure 1. Both sections are oriented along the North-South direction, which follow the solar movement automatically. This solar field has a safety system that defocuses the mirrors immediately if there is no water flowing through the collector tubes. The CSP field was installed on flat land next to the agro-industrial company, less than 100 m away from its boilers. This company is in Piura (4°55′12″ South, 80°37′33″ West, 60 m above sea level) on the Peruvian northern coast at the border of Sechura which is one of the driest deserts on Earth.

![Figure 1. CSP parabolic field installed in Piura, Peru.](image-url)
3. Methodology

3.1 Nomenclature

- $E_{\text{th,CSP}}$: theoretical total solar energy incident on the parabolic solar field during a year [J].
- $E_{\text{exp,CSP}}$: experimental total solar energy incident on the parabolic solar field during a year [J].
- $I_{\text{sol,av}}$: daily average solar irradiance [W/m$^2$/day].
- $n$: number of days used by the parabolic solar field in a year [day].
- $t_{\text{av}}$: total time of sunshine used by the parabolic solar field in a day [s].
- $A_{\text{CSP}}$: total area of the parabolic solar field [m$^2$].
- $Q_{\text{th}}$: theoretical thermal energy [J].
- $m_w$: preheated water mass [kg].
- $C_{\text{e,w}}$: specific heat capacity of water [J/kg.K].
- $\Delta T$: increase in water temperature [K].
- $\delta_w$: density of water [kg/m$^3$].
- $V_{\text{th,w}}$: theoretical volume of preheated water per year [m$^3$].
- $V_{\text{th,LPG}}$: equivalent volume in LPG fuel saved [L].
- $H_{\text{LPG}}$: energy content of LPG [J/L].
- $\eta_{\text{LPG}}$: combustion efficiency of LPG.
- $\eta_{\text{b}}$: boiler efficiency.
- $\eta_{\text{CSP}}$: CSP efficiency.
- $\psi_{\text{LPG}}$: conversion factor of CO$_2$ in kg produced by the combustion of 1 L of LPG.
- $m_{\text{CO2}}$: mass amount of CO$_2$ not emitted to the environment [kg].

3.2 Energy evaluation

The aim of this study is to compare the theoretical versus the actual amount of solar converted into thermal energy in the parabolic solar field which is used to preheat water to its use in the boilers of the agro-industrial company. In this way, the theoretical evaluation was made obtaining the average value of the solar irradiation monthly, based on the measurements made on the horizontal surface during three years by the weather station of the agro-industrial company. From here, it is also possible to know the number of days per year and the number of hours per day that can be used for the proper functioning of the solar field. The theoretical calculation of the incident solar energy on the parabolic solar field was performed with equation (1).

$$E_{\text{th,CSP}} = I_{\text{sol,av}}n t A_{\text{CSP}}$$ (1)

On the other hand, it was possible to estimate theoretically the amount of thermal energy required to increase water temperature in $\Delta T$ degrees, using equation (2).

$$Q_{\text{th}} = m_w C_{\text{e,w}} \Delta T$$ (2)

The theoretical volume of preheated water obtained from the total amount of solar energy in the parabolic solar field in a year is obtained by equating equations (1) and (2). As a result, it is obtained equation (3).

$$E_{\text{th,CSP}} = Q_{\text{th}}$$

$$E_{\text{th,CSP}} = m_w C_{\text{e,w}} \Delta T$$

$$m_w = E_{\text{th,CSP}} (C_{\text{e,w}} \Delta T)^{-1} = \delta_w V_{\text{th,w}}$$

$$V_{\text{th,w}} = E_{\text{th,CSP}} (C_{\text{e,w}} \Delta T \delta_w)^{-1}$$ (3)

On the other hand, the actual evaluation was performed with measurements taken by thermocouples and water meters, and then it was converted the amount of preheated water in its thermal energy...
equivalent. From this value, the equivalent in Liquefied Petroleum Gas (LPG) fuel saved is calculated from equation (4).

\[ V_{th,LPG} = E_{th,CSP}(H_{LPG} \eta_{LPG} \eta_b)^{-1} \]  

(4)

The mass amount of CO\(_2\) not emitted to the environment is evaluated in equation (5).

\[ m_{CO2} = V_{th,LPG} \psi_{LPG} \]  

(5)

3.3 CSP efficiency
Overall efficiency refers to the ratio between the amount of thermal energy used by the company with respect to the thermal energy generated by the parabolic solar field and is calculated with equation (6).

\[ \eta_{CSP} = \frac{E_{exp,CSP}}{E_{th,CSP}} \times 100\% \]  

(6)

3.4 Economic evaluation
The use of solar energy implies savings in the use of LPG fuel to preheat the water in the boilers. This in turn saves money. From this value it is possible to calculate the payback time in which the agro-industrial company will have recovered its investment by adopting CSP technology, including the cost of maintenance and operation. All these aspects are compared between the theoretical projections and the actual situation after a year of operation.

4. Results and discussion
4.1 Available solar energy
Based on 3 years of solar radiation data it was estimated about 250 useful sunny days per year (i.e., more than 650 W/m\(^2\) on average) with a daily average of 728 W/m\(^2\) measured on the horizontal surface within 7 hours per day (from 9:30 a.m. to 16:30 p.m.). Values obtained are shown in figure 2.

4.2 Previously thermal energy evaluation
Based on experimental data obtained during two months from 100 m\(^2\) CSP parabolic field installed previously in Ica (another sunny place in Peru) it is known that for an average incident solar irradiance of 767.15 W/m\(^2\), the amount of thermal power transferred to the water averaged 357.3 W/m\(^2\). This represents an average efficiency of only 46.6\%, as shown in figure 3. This efficiency corresponds to the
useful energy collected and transferred to the water and is explained by the thermal losses due to convection and radiation in the far infrared, which increase with the increase of the surface temperature of the pipes and the wind speed; and, by the reflection of the infrared radiation on the mirror of about 97.9% [15], as well as the absorption of this radiation by the pipes that transport the water.

4.3 Theoretical calculations

Theoretically, from equation (1) the total thermal energy obtained in the CSP parabolic field considering $I_{sol,av} = 728 \text{ W/m}^2$, $A_{CSP} = 120 \text{ m}^2$, $n = 250$ days and $t = 25200 \text{ s}$, is $E_{th,CSP} = 550.368 \text{ GJ/year}$. Also, from equation (3), considering $C_c = 4184 \text{ J/kg.K}$, $\Delta T = 50 \text{ K}$ and $\delta_w = 1000 \text{ kg/m}^3$, the theoretical amount of preheated water is $V_{th,w} = 2630.822 \text{ m}^3/\text{year}$.

From equation (4), considering $H_{LPG} = 25 \text{ MJ/L}$ [16], $\eta_{LPG} = 0.92$ and $\eta_b = 0.85$, the equivalent in LPG fuel saved in a year is $V_{th,LPG} = 28151.8 \text{ L/yr}$. It is also important to highlight that the amount of CO$_2$ not emitted to the environment is equivalent to $m_{CO2} = 46.87 \text{ tons/yr}$. This amount is obtained from equation (5) considering $\psi_{LPG} = 1.665 \text{ kg CO}_2/\text{L of GLP}$.

The cost of this amount of fuel corresponds to a payback period of investment of 0.8 years.

4.4 Experimental results after one year

After one year of operation, the company did not use all the preheated water generated by the parabolic solar field because the sunny days did not necessarily coincide with high lemon production seasons, weekends, and holidays. The amount of preheated water actually used by the company was equivalent to $E_{exp,CSP} = 99.59 \text{ GJ}$ of thermal energy. The company also reported saving of $4705.26 \text{ L}$ of LPG in its boilers for the entire year, as shown in figure 4.
These results imply that the CSP parabolic field operated with an overall energy efficiency of \( \eta_{\text{CSP}} = 18.1\% \) obtained from equation (6). This efficiency is almost the same as the 14 – 16\% efficiency reported for CSP parabolic fields to power generation. However, it is much lower than the around 70\% efficiency theoretically simulated for a plant dedicated to thermal generation [17]. Finally, the amount of LPG is equivalent to no more emitting 7.69 tons of \( \text{CO}_2 \) to the environment.

Most of the low efficiency is explained by heat losses to the environment during the transfer of preheated water from the solar concentrators to the boilers inside the agro-industrial company, especially because it is an area where there are strong winds. However, some aspects must also be considered. For example, the agro-industrial company underutilized the CSP parabolic field because during 6 months of the year it only used 50\% of its essential oil production capacity. Another example concerns the construction of a nearby roof that reduced two hours of direct sunlight to the solar parabolic field. Finally, there were only 217 days of direct radiation during the year, 13\% less than those considered in the theoretical calculations.

The actual money saved after a year by the agro-industrial company represents only 20.6\% of the total amount for the acquisition of the CSP parabolic field. This means that the real payback time of the investment is extended to 4.4 years, i.e., 3.6 years longer than theoretically planned.

### 4.5 Comparative summary

Table 1 shows a summary of the estimated theoretical values and the actual results obtained after one year of operation.

| Description          | Theoretical | Results after a year |
|----------------------|-------------|----------------------|
| Thermal energy       | 550.37 GJ   | 99.59 GJ             |
| LPG savings          | 28151.8 L   | 4705.26 L            |
| \( \text{CO}_2 \) not emitted | 46.87 tons | 7.69 tons            |
| Payback period       | 0.8 years   | 4.4 years            |

These results have allowed correcting the theoretical calculations to have a better projection of the sizing of future CSP parabolic fields.

### 5. Conclusions

It was installed a 120 m\(^2\) middle-sized CSP parabolic field at the Northern arid coast of Peru to preheat water used in the boilers of an agro-industrial company of lemons. Theoretically, it was projected to obtain 550.37 GJ per year, but after a year of operation it was only used 99.59 GJ of thermal energy by the agro-industrial company. In a previous experience the parabolic solar concentrator has an efficiency of 46.6\% transferring thermal energy to preheat water. However, also considering weather conditions, heat loss pipes, amount of water used by the company, among others, results in an overall efficiency of 18.1\%. Also, it was projected savings of 28151.8 liters of LPG per year, but it was only saved 4705.26 liters. In the same way, the theoretical payback period was calculated in 0.8 years, but after a year of operation it was increased to 4.4 years.

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