Design of solar thermal systems for the mining industry

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Abstract

The design and cost estimation of solar thermal systems for integration to industrial processes require the analysis of multiple alternatives in terms of solar collector technology, configurations, and equipment sizes. This paper presents a practical approach to design and to estimate the costs of the integration of solar thermal energy to the mining industry.

The approach is applied to integrate a solar thermal system to a copper mining process, which is located in Calama, Chile. The proposed solar thermal system consists of a parabolic trough solar field integrating a thermal energy storage to produce hot air for drying copper concentrate. The analysis indicates a capital cost of 3813 USD/kW$_{th}$. The most important investments are the solar field (44%) and the energy storage system (42%). The real (nominal) levelized cost of heat is 5.21 (6.03) cent USD/kW$_{th}$, which is relatively lower than those obtained in Europe.

Keywords: solar mining, solar thermal system, design approach, costs estimation.

1. Introduction

Recent studies reported that the cost of energy represents 20-40% of the total costs of mining operations (COCHILCO, 2019). This is due to the continuous decrease in the grade of ore and the climb in the prices of imported fossil fuels. Low and medium temperature mining processes consume more than 60% of the energy needed by the mining industry (COCHILCO, 2019). In the copper and the iron mining processes electro-wining / electro-refining, concentration, and leaching are the most heat-consuming steps, which generally require temperatures lower than 200°C (Moreno-Leiva et al. 2018).

By analyzing the mining processes, the idea of implanting low-cost solar thermal systems for heat production arises. The development of modeling techniques is a critical phase for the design and the economic evaluation of the integration of solar thermal systems to mining processes.

This paper describes a practical approach for the design and costs estimation of solarized mining processes. A case study on the application of the approach to design a solar thermal system for integration to a copper mining process is presented. The suitable solar thermal system for the selected mining process consists of a parabolic trough solar field integrating thermal energy storage to generate hot air for drying copper concentrate.

2. Methodology

Previous studies have concluded that integrating solar heat is possible at several points of mining processes (Moreno-Leiva et al. 2018). The integration points are on the process level including the transfer of heat to basic operations. Table 1. Illustrates possible integration points for solar heat into the copper mining process.

Table 1. Process operation temperature and suitable solar collectors for integrating solar energy into the copper mining industry.

Cooper process	Pyro-metallurgy					Hydro-metallurgy		
	Drying	Roasting	Smelting	Converting	Electro-refining	Leaching	Solvent extraction	Electro-wining
Operation temperature (°C) (Moreno-Leiva et al. 2018)	180	500-800	1250	1200	60-65	30	30	40-48

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Suitable solar collector	Trough, Fresnel	Tower	Tower, Furnace	Tower, Furnace	FPC, Vacuum tube	FPC, Solar ponds	FPC, Solar ponds	FPC, Solar ponds

Figure 2 illustrates the approach proposed for the appropriate integration of solar thermal energy to the mining industry. The approach consists of three main phases: pre-design, design, and costs analysis.

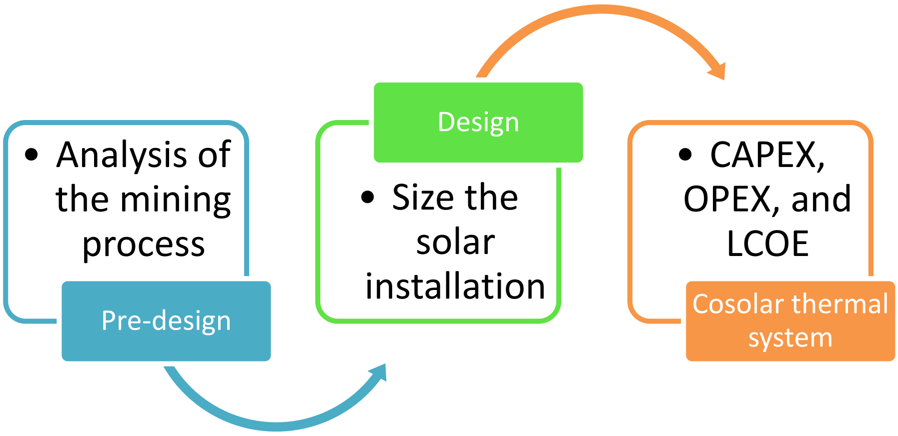

Figure 1. A practical approach for the integration of solar thermal energy to the mining industry

The purpose of the pre-design phase is to analyze the mining process in order to get information about:

- Process temperature,
- Nominal load and load profile,
- Operation schedule,
- Connection between the mining process and the solar thermal system.

The design phase describes the complete configuration of the solar thermal system taking into account the operation schedule and the load profile of the mining process.

- Identify a suitable solar collector type,
- Design the heat exchangers (if needed),
- Design the thermal energy storage (if needed),
- Design the solar field.

The last phase is the costs analysis, in which the investment costs, O&M costs, and Levelized Cost of Heat (LCOH) are determined.

3. Application of the approach

A copper concentrate process located in the north of Chile (Calama), at 2,850 m above sea level is selected as a case study. As illustrated in Figure 3, typical copper concentrate process entails crushing, grinding, flotation, and dehydration. In crushing and grinding steps, the ore is reduced to an optimum grind size to liberate the copper mineral grains from the non-copper mineral grains. After that, it is mixed with water and chemical agents to separate the copper-mineral from non-copper mineral grains to produce wet copper concentrate. The latter is then dehydrated and dried by the dryer, and high-grade copper concentrate powder is obtained.

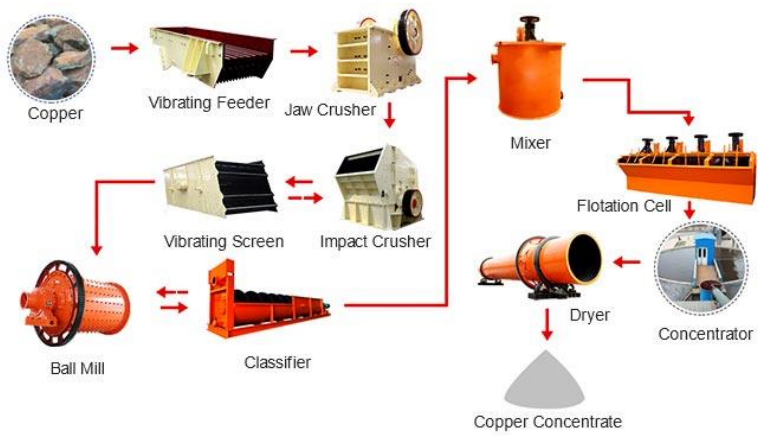

Figure 2. Typical copper concentrate process (FTM, 2019)

The idea of the integration of solar energy to the copper mining process at the level of the dryer aims to reduce the humidity of the copper concentrate prior to export and to reduce conventional energy needs in the existed conventional dryer. This increases the solar energy share and reduces the need for fossil fuels in the copper mining industry since 45% of produced copper in Chile is exported as copper concentrate. The solar-fossil hybrid configuration is possible after a slight modification in the existing drying process. The approach highlighted above is applied to evaluate the integration of solar energy to the cited copper process.

3.1. Pre-design

The pre-design consists of the analysis of the drying process. Table 2 summarizes the results of the pre-design phase.

Table 2. Main technical data of copper concentrate drying process

Parameter	**Value**
Process temperature	180 °C
Nominal load	50 ton/h
Load profile	Constant
Operation schedule	24h a day, 340 days a year
Connection	In-direct integration via a heat exchanger

3.2. Design

The first step in the design phase is to select appropriate climate and radiometric parameters for the design of the solar thermal system. After the analysis of the yearly data, a Direct Normal Irradiance of 950W/m2, ambient temperature of 15°C, wind speed of 30km/s and relative humidity of 45% are selected. The type of solar collector is chosen with respect to the operating temperatures of the mining process and the thermal energy storage. As shown in Figure 3, the selected solar thermal system consists of a parabolic trough solar field with oil-HTF, two-tanks molten salt storage system, and a heat exchanger for hot air production. Oil-HTF at 270°C is pumped through the solar field to be heated up to reach 390°C. The HTF then flows to the air/oil heat exchanger where ambient air heated up to 180°C. During high solar irradiance, the surplus in the solar heat is stored into the hot tank to be used during the night or when solar energy is not enough to meet the demand.

A modular modeling technique is to design the solar thermal system. The technique consists of modeling each component of the system separately and then links several components together according to the desired configuration. Matlab software was used for this purpose. The solar field modeling includes a single collector model (Behar et al., 2015), a collector loop model, and a piping layout model (Behar, 2018). The heat exchanger model is based on the NTU method. Table 3 shows the estimated design data of the solar thermal system.

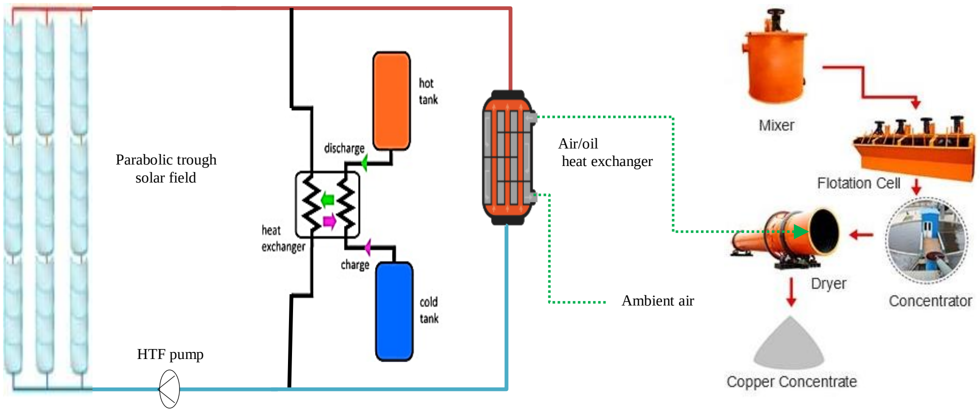

Figure 3. Configuration of the solarized copper mining process

Table 3. Size of the main components of the solar thermal system

Parameter	**Value**
Collector type	Parabolic trough collector
Heat exchanger capacity	1780 kW_{th}
Storage capacity	37, 597 kWh_{th} (16h)
Solar field reflective surface	12, 505 m^2

3.3. Costs

The method used in the cost analysis is based on a yearly discounted cash flow. The investment costs, O&M costs, the LCOH, and the capital cost per capacity is the key economic indicators. Table 4 summarizes the input data for the economic analysis. The O&M costs are supposed inflating at an inflation rate of 2.4%. The year “zero” is the construction start year. Straight-line model is considered for depreciation of the investment costs.

Table 4. Input data for the economic analysis (reference: 2015 USD)

Parameters	**Value**	**Note**
Inflation rate	2.4	% per year
Real discount rate	8.4	%
Construction period	2	Years
Depreciation period	10	Years
Operation lifetime	25	Years
Site improvements	30(1)	USD/m^2
Solar field	170(1)	USD/m^2
HTF system	70(1)	USD/m^2
Storage	75(1)	USD/kWh_{th}
Heat exchanger	217.12 (2)	USD/kW_{th}
O&M fixed costs by installed capacity	23.76(3)	USD/kW_{th}
O&M variable costs by generated heat	0.18(4)	USD/MWh_{th}

(1)Taken from (Parthiv Kurup and Craig S. Turchi, 2015); (2)Taken from (C. Perera et al., 1998), case of counter flow heat exchanger; (3)Derived from (Parthiv Kurup and Craig S. Turchi, 2015) based on thermal-to-electric efficiency of 36%; (4)Derived from (A. Aly et al. 2019) based on thermal-to-electric efficiency of 36%

The LCOH is calculated using the expression proposed by the International Renewable Energy Agency (IRENA, 2012).

$$LCOH = \left(\frac{\sum_{n=1}^{N} \frac{I_n + OM_n}{(1+d)^n}}{\sum_{n=1}^{N} \frac{Q_n}{(1+d)^n}} \right) \quad \text{(eq. 1)}$$

Where: N is the lifetime of the solar thermal system, I_n is the investment costs in the year n, OM_n is the operations and maintenance costs in the year n, Q_n is the heat generation in the year n, and d is the discount rate.

The results of the analysis are given in Table 5. The investment costs are 6.788 million USD, which results in a capital cost per capacity of 3813 USD/kW$_{th}$. As Figure 4 demonstrates, the most important investments are the solar field (44%) and the storage system (42%). The O&M costs represent 25% of the total costs of the solar thermal system. The real LCOH, which excludes the inflation is 5.21 cent USD/kWth while the nominal LCOH (includes inflation) is 6.3 cent USD/kWth. These values are relatively lower than those obtained in Europe (IREA, 2015).

The LCOH from the solar thermal system is slightly higher than that from natural gas (the most used fuel in industrial applications). The LCOH from natural gas depends on the global market and usefully varies from 3 to 5 €/kWh (Gabbrielli, 2014), which is equivalent to 3.3 to 5.5 USD/kWh. Therefore, the integration of solar thermal energy to mining processes, particularly those located in arid regions, could be more competitive than the use of fossil fuels, because in the arid regions, the transport of natural gas is very expensive and Diesel fuel is commonly used. The latter is more expensive than natural gas, which results in a LCOH higher than 5.5 USD/kWh.

Table 5. Main economic indicators of the solar thermal system (reference: 2015 USD)

Economic indicators	Value	Unit
Investment costs	6.788	USD million
O&M costs	2.290	USD million
Real LCOH	5.21	Cent USD/kWh$_{th}$
Nominal LCOH	6.03	Cent USD/kWh$_{th}$
Capital cost per capacity	3813	USD/kW$_{th}$

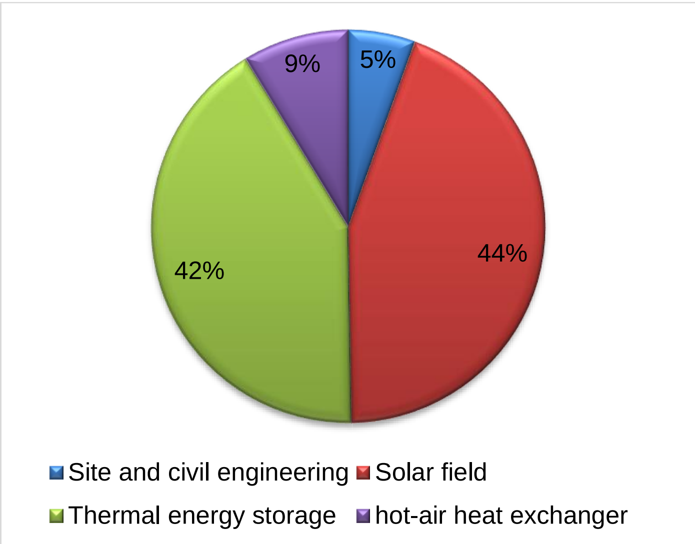

Figure 4. Costs breakdown of the solar thermal system.

4. Conclusion

A practical approach to the design and costs estimation of the solarized mining process is presented. It consists of three phases: pre-design (to analysis the mining process), design (to size the components), and costs analysis (to determine the key economic indicators).

The proposed approach has been used to design a solar thermal system for a copper mining process located at Calama, Chile. Based on the pre-design phase, the type of the collector is selected and the configuration of the solar thermal system is defined. The sizing of the solar thermal system is then carried out based on a modular modeling technique. Results show that the specific heat per solar field reflective area is about $7m^2/kW_{th}$. The cost analysis indicates a capital cost per capacity of 3813 USD/kWth. The real (nominal) levelized cost of heat is 5.21 (6.03) cent USD/kWth, which is relatively lower than those obtained in Europe. These values are slightly higher than that obtained using natural gas, which varies from 3.3 to 5.5 USD/kWh. Nowadays, Diesel fuel is usually used for heating purpose and it is more expensive than natural gas, which results in a LCOH higher than 5.5 USD/kWh. Therefore, the integration of a solar thermal process might an economical option, particularly for arid mining processes.

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