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Life Cycle Cost Analysis of a Low-Temperature Solar Thermal System Which Delivers Thermal and Electric Energy to a Cotton Dyeing Industrial Process

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Currently, most of the thermal and electrical energy for industrial processes is generated from fossil fuels. Solar thermal energy has unlimited potential to supply thermal and electrical energy for low-temperature industrial processes and has demonstrated the ability to replace the use of fossil fuels partially or totally. The implementation of solar thermal energy systems in industrial processes must be accompanied by a long-range economic analysis that allows evaluation of the benefit obtained during its useful life. The Life Cycle Cost method evaluates the costs associated with the solar thermal system during its operating period and allows for determining the system design that presents the best effective cost. This work presents the Life Cycle Cost analysis (LCCA) of a solar thermal system and an organic Rankine cycle (ORC) driven by solar energy for the supply of thermal and electrical energy to a cotton dyeing process. The LCCA considered the costs of installation, operation, maintenance, services, and basic components, based on the solar fraction supplied to the process by the solar thermal system and the ORC. The results obtained show that the solar fraction that maximizes the effective cost of the thermal system and the ORC powered by solar thermal energy is 1.0. The effective cost of thermal energy reaches 706,413 USD, and for electrical energy, this cost amounts to 1,125,386 USD. The levelized cost of thermal energy, when the best effective cost is presented, is 0.035 USD/kWh$_{th}$, while electric energy presents a levelized cost of 0.103 USD/kWh$_e$.

1. Introduction

In 2021, industrial processes consumed 38 % of the total world energy, which was produced mainly in blast furnaces, generating a large series of environmental problems (IEA, 2022a). In recent years, the world energy sector was responsible for three-quarters of greenhouse gas emissions. Given this situation, the 2050 net zero emissions scenario was proposed, which aims to transition the world energy sector to remove or neutralize carbon emissions to the environment, using technologies with accessible costs and taking into consideration the public policies and conditions of each country (IEA, 2022b). Currently, solar thermal energy is at a point of technological development that allows it to supply a substantial amount of the industrial energy demand in almost any country in an economical and clean way. In addition, efforts continue to be made to reduce the costs of solar thermal systems (IRENA, 2015). The main barriers that arise when implementing solar thermal systems are related to the geographical separation between the resources and the demand side, land use restrictions, and the risk of interruption of the process due to intermittent energy supply (Philibert, 2017). Kalogirou (2003) said low-temperature solar thermal energy (< 120 °C) can integrate successfully into processes of textile industries, carrying out an adequate design based on the available solar resource and an economic analysis that allows evaluating the costs of power generation and carbon emissions. Martínez-Rodríguez et al. (2018a) studied the scope of low-temperature solar thermal systems so that they can be a reliable and flexible option to continuously supply the heat load in industrial processes under variable operating conditions with the maximum target temperature and the smallest absorber area. ORC powered by solar thermal systems is an excellent

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option for the generation of clean electrical energy at a reasonable cost (Loni et al., 2021). Martínez-Rodríguez et al. (2021) carried out a thermo-economic evaluation to produce power through an ORC where the heat load is supplied by a network of flat plate solar collectors with a competitive cost of 0.0477 USD/kWh. The average levelized cost of the production of electrical power from solar thermal energy decreased by 68 % in the period 2010 - 2021, going from 0.358 USD/kWh to 0.114 USD/kWh. For their part, fossil fuels presented a significant increase in their costs. For example, the cost of natural gas increased from USD 0.090/kWh in 2021 to USD 0.145/kWh in 2022. This increase benefits renewable energy systems, given the competition to replace fossil fuels (IRENA, 2022). This variability of the cost of energy in the current global economic scenario makes it imperative to develop long-term economic analyzes that allow evaluation of the feasibility of implementing solar thermal energy systems in industrial processes.

Life Cycle (LC) methodologies seek to describe the performance of a system throughout its useful life; among these, the Life Cycle Cost (LCC) analysis is presented as an economic evaluation method that allows selecting the design with the best effective cost in a particular period, taking into consideration the construction, maintenance, operation, equipment replacement and residual costs of a system (Sesana and Salvalai, 2013). Naves et al. (2018) carried out a review of 258 documents published in the last 50 y in which the use of the LCC method is described as an auxiliary tool in the design of solar systems. The reported bibliography shows many studies of photovoltaic and thermal systems applied to residential units. More recent studies show that LCC has been used as a tool for the financial evaluation of various solar thermal systems, mainly in concentration systems, such is the case of the study carried out by Ko et al. (2018), who analyzed the environment, economic and social impact of a central tower solar concentration system for the production of 101 MW of electrical energy, the economic analysis developed used the LCC to evaluate the economic behavior of the system considering the construction, operation, and maintenance costs of the system in a period of 30 y of useful life. On the other hand, Backes et al. (2021) carried out a sustainability analysis of a Stirling cycle powered by a concentrator disc solar thermal system for the production of 500 MW of power, using the LCC to evaluate the economic behavior of the system during its useful life; the following factors were considered for the study: installation costs, transportation, maintenance, components, and a weather station to assess the financial impact of the project. However, among all the studies analyzed, there is none that mentions the use of this method in the design of low-temperature solar thermal systems with applications in industrial processes.

Until now, the authors do not have knowledge that the analysis of LCC has been reported in an industrial process where low-temperature solar thermal energy is used. From the economic point of view, the cost of a solar thermal installation must consider, in addition to the cost of the solar thermal installation and the storage system, the costs associated with operation, maintenance, equipment, government incentives and sale after the useful life. In this work, the analysis of LCC was carried out when integrating a solar thermal installation to an industrial process. The minimum total cost is 706,413 USD for a fraction of f = 1, with an energy cost of 0.035 USD/kWh$_{th}$ and a payback time of 5.05 y. Based on the results obtained, the analysis of the LCC allows reaching the cost of energy that makes the construction of the solar thermal installation feasible.

2. Life Cycle Cost Analysis (LCCA) for industrial applications

The most important contribution of the LCC analysis, LCCA, is the monetization of the impact that a solar thermal plant causes when it is built and installed on a land surface. The impacts of the industrial facility are environmental, social and ecological. The effects of the change in land use are more easily quantifiable economically. These costs include installation, operation, maintenance, equipment, government incentives, and after-life sales expenses.

In the environmental part, greenhouse gas emissions (GHG) that are no longer emitted were calculated. To now, a global legal-economic framework has not been applied in a standardized manner to economically weigh the total or partial elimination of GHG during the production processes. With respect to the social part, in the same way, as with the environmental, an economic value is not applied to the industry that carries out actions in favor of avoiding greater effects on health due to the pollutants of the industry, in addition to other social factors, as important as the affectations to the cultural part of his life in general.

This work focuses on the economic evaluation of solar thermal installation for industrial applications and how the total cost, applying the LCCA, is related to the solar fraction. The LCC evaluates the relationship of the total cost with respect to the supply of solar thermal energy of a facility during its useful life, which allows for selecting the installation that presents the lowest total cost. During the application of LCCA, it is possible to identify 3 key stages (Toniolo et al., 2020).

a) Definition of the objective and scope: given the information available for the process, it is established the purpose for which the LCC is carried out, and the degree of detail that can be achieved.

b) Inventory: this step implies the collection of information for the estimates obtained directly from the process or from reliable sources such as technical reports or scientific literature.

c) Calculation of the LCC and results: at this point, the total cost of the selected system is calculated with the information collected and through an analysis are determined the factors that affect the total cost of the system in greater proportion. LCCA will be applied to a facility to produce solar thermal energy and power, using a low temperature ORC. LCC can be expressed in a general way as shown in Eq(1) (Yang et al., 2020).

$$LCC = IC + OC + DC \tag{1}$$

Where IC is the initial investment cost, OC is the operating cost and DC is the discarding cost of the system. The initial investment cost for the solar thermal system includes the cost of solar collectors, storage tanks, installation land, and control and pumping systems. The operating cost includes the costs associated with the periodic maintenance of the system, the cost of fuel to feed the auxiliary system, and the working fluid. The discarding cost for this system is considered as a cash return flow from the sale of equipment as recycling material at the end of its useful life. In ORC, the sum of the costs of the main equipment (turbine, evaporator, condenser, and pump) is considered the investment cost, and the operation and discarding costs are estimated in a similar way to the solar thermal system. The evaluation of costs in the period of useful life is made from the future cost shown in Eq(2).

$$FC = PV(1 + i)^n \tag{2}$$

Where FC is the future cost of solar system components; PV is the present value of the energy system components; i, is the annual fixed interest rate for financing the equipment or components, with a value of 8.0 % (Sethi and Dwivedi, 2014); and, n, is the 5 y financing period for the solar energy system, considering a useful life of the plant of 30 y. The future cost of fuel for the auxiliary system is calculated from Eq(2); where PV is the current cost of fuel in the market; i, is the annual fuel cost escalation rate, taken at 1.46 % (NIST Escalation Rate Calculator, 2022). The operation and maintenance cost can be calculated with this same equation considering this cost is affected only by inflation, projected at 2.25 % in 10 y (Trading Economics, 2023). The base cost of the main equipment (solar collectors, storage tank, and pumping system) was calculated based on the cost model proposed by Ferreira and Silva (2020). The following costs were taken estimating the cost of the energy system; the costs for operation and maintenance are equivalent to 1 % of the cost of the equipment (Ayompe et al., 2011), the control system represents 5 % of the initial cost of the equipment (Franco, 2020), the installation cost represents 30 % of the initial cost of the equipment (Hang et al., 2012), the cost of the land for the installation is 81 USD/m^2 (Richford, 2020), the cost of natural gas for the auxiliary system is 43.57 USD/GJ (Natural gas prices around the world, 2022). The government contribution is fixed, which is 30 % of the cost of equipment and installation (Energy Star, 2022) and the return due to the sale of equipment is equivalent to 10 % of its original cost. In the LCCA of the organic power cycle, these considerations were carried out using the cost equation system reported by Roumpedakis et al. (2020) to calculate the base cost of the pump, turbine, evaporator, and condenser. The electricity cost for this analysis is assumed to be 0.193 USD/kWh_e (Electricity prices around the world, 2022), and the annual electricity scaling rate is 1.47 % (NIST Escalation Rate Calculator, 2022).

3. Case study: industrial cotton dyeing process

The LCCA was applied to a cotton dyeing industrial process, described by Espejo-Mamani and Gomez-Ramos (2017). It has a processing capacity of 407.35 kg of cotton per batch in an operation period of 2.75 h. Figure 1 shows a simplified diagram where the 6 main stages of the process are represented: pre-bleach (35 min/90 °C), rinsed (10 min/40 to 80 °C), neutralized (10 min/50 °C), dyeing (10 min/60 °C), soaping (20 min/80 °C), fixed and smoothed (25 min/40 °C). Water consumption in most of them is 1.55 m^3, except for rinsing and pre-bleaching, which consume 4.65 and 2.5 m^3. There seeks to integrate a low-temperature solar thermal energy system to produce the heat load and the power demanded by the process (f= 1). The process consumes 18.4 m^3 of hot water, which must be supplied at various temperature levels in the range of 40 to 90 °C. Currently, this heat load is produced in a natural gas boiler that generates a heat flow of 1,600.5 kWh, while the electrical consumption is 288 kW and is supplied from the national electricity supply network. Production of thermal and power energy operates with two networks of independent solar collectors. Design of the solar thermal systems shown in Figure 1 was carried out with methodology proposed by Martínez-Rodríguez et al. (2018b), considering the average annual irradiance conditions for the city of Guanajuato, Mexico (Lat. 21.01° N, Lon. 101.25 O).

4. Results

In this section, the results for the supply of the heat load and the power required by the process are presented. Table 1 shows the results for different solar fractions during thermal energy production. For each solar fraction, the surface occupied by the solar thermal installation, the generated solar thermal energy, the total cost, the levelized cost of energy (LCOE), the solar payback, and the total annual greenhouse gas emissions generated (GHG) are determined (CO_2, CH_4 and N_2O) (EPA, 2023).

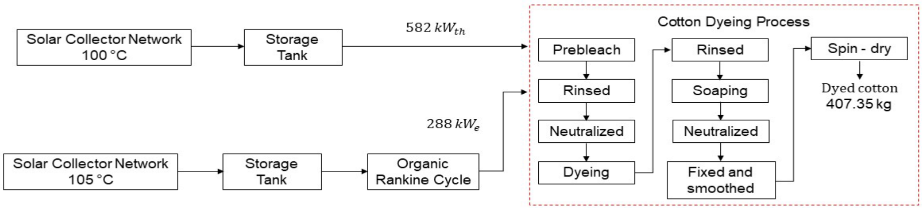

Figure 1: Simplified diagram of the cotton dyeing process

Table 1: Characteristics of the solar collector network based on the solar fraction of the process

Solar fraction	Surface (m^2)	Annual generated energy (GJ)	Cost of fuel (USD)	Total cost LCC (USD)	LCOE$_{SOLAR}$ (USD/kWh)	Solar Payback (y)	Emissions (t/y)	LCOE$_{TOTAL}$ (USD/kWh)
0.00	0	0	4,906,943	4,906,943	0	-	121.74	0
0.05	114	350	4,197,227	4,333,291	0.047	7.12	104.13	1.485
0.20	438	857	2,861,768	3,105,145	0.029	4.05	59.54	0.369
0.30	687	1,337	2,196,721	2,504,656	0.028	3.85	54.50	0.225
0.40	876	1,366	1,677,838	2,047,379	0.028	3.88	33.90	0.154
0.60	1,313	1,665	961,852	1,448,683	0.030	4.22	18.90	0.089
0.80	1,751	1,876	480,382	1,078,992	0.033	4.69	8.25	0.059
1.00	2,189	2,040	0	706,413	0.035	5.05	0.00	0.035

For a solar fraction of one (f = 1), the cost of the land surface occupied by the installation is 22.3 % of the total cost. The cost of solar thermal installation represents 19.6 %, and the costs for operation and maintenance are 18.6 %. These costs are the ones that contribute the most to the total cost for all solar fractions. For solar fractions less than 0.3, what contributes the most to the total cost are operation and maintenance with 20 %.
Figure 2 shows the behavior of the total cost of the thermal energy system based on the solar fraction. The total cost of fuel behaves in an exponentially decreasing manner, and from solar fractions of 0.8 the total cost remains practically constant, presenting an asymptotic behavior. For the solar fraction of 1.0, with the lowest total cost (706,413 USD) the surface occupied by the solar thermal installation is 4,378 m^2. The savings from burning fuel is 140,017 USD/y and presents a simple solar payback of 5.05 y. The cost of energy for this system is 0.035 USD/kWh$_{th}$.

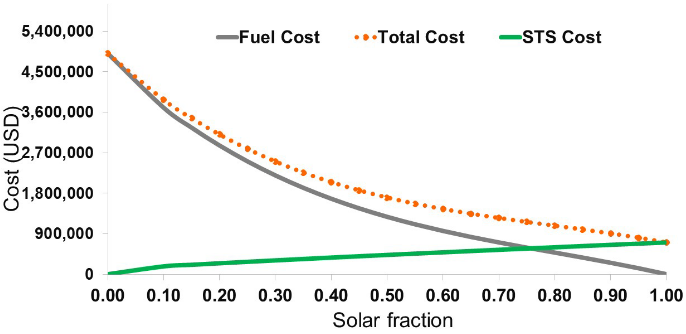

Figure 2: Total cost of the thermal energy system related with solar fraction

The ORC was designed considering an evaporator temperature of 105 °C supplied by an independent solar thermal installation; the selected working fluid is R600a due to its low environmental impact, the maximum working pressure is 16 bar and the minimum is 5 bar. The turbine has an isentropic efficiency of 0.9 and the pump 0.85. The thermal efficiency of this cycle is 15.87 %, the refrigerant flow is 4.48 kg/s and the heat load on the evaporator is 1,751.8 kW. Table 2 shows some results of the cost analysis, which are complemented by Figure 3. In Figure 3, the cost of the solar thermal system (STS Cost) presents a constant increase and tends to be asymptotic for a solar fraction of 1.0. In solar fractions less than 0.10, the costs related to operation and maintenance in small systems present very high costs compared to the cost of equipment.
On the other hand, the cost of electricity produced by fossil fuels presents a decreasing linear behavior. The lowest total cost of the power production system is reached when the solar fraction is 1.0, the surface area occupied by the solar thermal installation is 15,386 m^2.

Table 2: Characteristics of the solar collector network based on the solar fraction of the process

Solar fraction	Surface (m^2)	Annual generated energy (kWh)	Cost of electricity (USD)	Total cost LCC (USD)	$LCOE_{SOLAR}$ (USD/kWh)	Solar Payback (y)	Emissions (t/y)	$LCOE_{TOTAL}$ (USD/kWh)
0.00	0	0	3,311,823	3,311,823	0	0	665.28	0
0.10	769	36,414	2,980,641	3,273,233	0.268	227.46	598.75	2.996
0.20	1,539	72,828	2,649,458	3,065,116	0.190	50.54	532.22	1.403
0.30	2,308	109,242	2,318,276	2,842,711	0.160	33.54	465.69	0.867
0.40	3,077	145,656	1,987,094	2,611,436	0.143	26.74	399.17	0.598
0.60	4,616	218,484	1,324,729	2,131,101	0.123	20.49	266.11	0.325
0.80	6,155	291,312	662,365	1,634,215	0.111	17.38	133.06	0.187
1.00	7,693	364,140	0	1,125,386	0.103	15.44	0.00	0.103

The total cost of the system for power production is 1,125,386 USD, this cost represents a saving of 72,881 USD/y. The cost of electrical energy produced by the ORC is 0.103 USD/kWh_e, and the solar payback is 15.44 y. The savings for energy consumption of the electrical network is 2,186,437 USD.

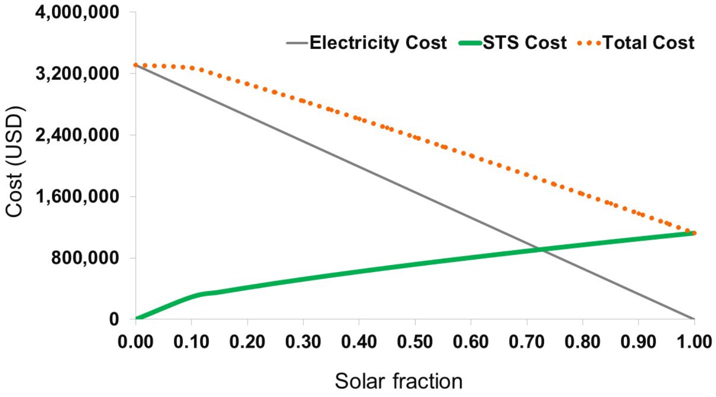

Figure 3: Total cost of power system related to solar fraction

5. Conclusions

By applying the Life Cycle Cost analysis it is possible to supply all the thermal energy and power required by an industrial cotton dyeing process. Through an analysis of the Life Cycle Cost, the generation of greenhouse gases to produce heat and power was eliminated with a total saving for the burning of fossil fuels of 4,200,530 USD and 2,186,437 USD. The costs of thermal energy (0.035 USD/kWh_{th}) and electricity generated (0.103 USD/kWh_e) are economically competitive with currently used fossil fuel-based power generation systems.

The study presents several options that can be used depending on the needs of the industrialist. Based on the results obtained, the most convenient scenario can be selected according to the available surface, required investment recovery time or tons of greenhouse gases that need to be stopped from being emitted into the air.

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