Economical and environmental contributions of installing a solar heating system in an industrial process

Contribuições econômicas e ambientais da instalação de um sistema de aquecimento solar em um processo industrial

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ABSTRACT
Aware of the harmful consequences of climate change, several industrial sectors search for alternatives to minimize the environmental impact of their production processes. The use of thermal solar collectors is a promising alternative for the heat supply in industrial processes, contributing to the reduction of fossil fuel consumption for this purpose and, consequently, mitigating the environmental impact caused by greenhouse gas emissions. The present research analyzes the contribution of a Solar Heating for Industrial Processes (SHIP) system in an industry's environmental and economic spheres on the outskirts of Porto Alegre, south Brazil. A solar field of Linear Fresnel concentrating collectors is simulated in SAM software. The field has an aperture area of 352 m² and operates in the supply of saturated steam for a given industrial process. The results indicate that the SHIP system would be able to supply 729 GJ_{th} to the industrial process annually. It means a reduction of greenhouse gas emissions in the magnitude of tens of tons of CO2-equivalent each year, whose value increases as the operation of the conventional steam-generating boiler moves away from ideal (theoretical efficiency of 100%). Two methodologies are

used to calculate LCOH, resulting in 52 and 54 UD/MWh_{th}$ values for the analyzed SHIP system. Compared with the heat supply through burning natural gas and mineral coal, a solar thermal heating system can be evaluated as an environmentally responsible and economically advantageous alternative for the industrial sector that decides on this investment.

Keywords: solar heating for industrial processes, linear fresnel concentrating collectors, solar energy, greenhouse gas emissions.

RESUMO

Cientes das conseqüências prejudiciais da mudança climática, vários setores industriais buscam alternativas para minimizar o impacto ambiental de seus processos de produção. O uso de coletores solares térmicos é uma alternativa promissora para o fornecimento de calor em processos industriais, contribuindo para a redução do consumo de combustíveis fósseis para este fim e, conseqüentemente, mitigando o impacto ambiental causado pelas emissões de gases de efeito estufa. A presente pesquisa analisa a contribuição de um sistema de Aquecimento Solar para Processos Industriais (SHIP) nas esferas ambiental e econômica de uma indústria na periferia de Porto Alegre, no sul do Brasil. Um campo solar de coletores de concentração Linear Fresnel é simulado no software SAM. O campo tem uma área de abertura de 352 m² e opera no fornecimento de vapor saturado para um determinado processo industrial. Os resultados indicam que o sistema SHIP seria capaz de fornecer 729 GJth ao processo industrial anualmente. Isto significa uma redução das emissões de gases de efeito estufa na magnitude de dezenas de toneladas de CO2 equivalente a cada ano, cujo valor aumenta à medida que a operação da caldeira geradora de vapor convencional se afasta do ideal (eficiência teórica de 100%). Duas metodologias são utilizadas para calcular LCOH, resultando em valores de 52 e 54 U$D/MWhth para o sistema SHIP analisado. Em comparação com o fornecimento de calor através da queima de gás natural e carvão mineral, um sistema de aquecimento solar térmico pode ser avaliado como uma alternativa ambientalmente responsável e economicamente vantajosa para o setor industrial que decide sobre este investimento.

Palavras-chave: aquecimento solar para processos industriais, coletores lineares de concentração de fresnel, energia solar, emissões de gases de efeito estufa.

1 INTRODUCTION

The concentration of greenhouse gases, GHG, in the atmosphere has already reached alarming levels, making it urgent to reduce these emissions. The current scenario points to diversifying the energy matrix and introducing clean and renewable energy sources to mitigate the climate crisis. In several industrial sectors, environmental issues have aroused interest in the use of solar thermal energy, as it is an abundant and sustainable source of energy (SEEG, 2020; Reis, 2015; Kalogirou, 2013).

The Brazilian industrial sector occupies a relevant position in the national energy scenario, accounting for one-third (34%) of final energy consumption in Brazil, according to the survey presented by EPE (2022). Based on this same study, it is estimated that 78%

of Brazil's energy consumed by industrial sectors in 2021 was destined for heat generation, mainly through burning fossil fuels and biomass. Consequently, the Brazilian industrial sector is responsible for the emission of greenhouse gases that correspond to about 100 million tons of carbon dioxide equivalent, $tCO_{2\text{-eq}}$, per year (SEEG, 2020).

The State of Rio Grande do Sul (RS) (NB: there are 26 States in Brazil, plus a Federal District), has a diversified industry, covering the food, chemical, metalworking, textile, and footwear subsectors, among others. The manufacturing industries are predominantly concentrated in the axis of the Metropolitan Region of Porto Alegre and Caxias do Sul. Among the industrial segments operating there, the principal fuels used for heat generation are natural gas, mineral coal and its derivatives, and biomass such as firewood and sugarcane bagasse (EPE, 2021; SPGG RS, 2021).

Industrial processes operate over a wide range of operating temperatures. The heat generation is chosen according to its magnitude. Low (up to 150°C) and medium (between 150 and 400°C) temperature levels are typically met by supplying steam. High-temperature demands (above 400°C) usually employ direct heating. Except for the metallurgical and non-metallic mineral sectors (cement, ceramics), whose operation is concentrated in the temperature range above 400°C, most industrial sectors present between 50 and 100% of the thermal demand within low-temperature or medium ranges. Therefore, they are compatible with solar thermal technology (Saygin et al., 2014; Hahn et al., 2018).

The present study aimed to investigate economical and environmental contributions of installing a heating system using solar thermal energy to reduce greenhouse gas emissions in an industrial process. Therefore, a simulation of a solar field of Linear Fresnel type collectors located in Porto Alegre (RS) was conducted, whose purpose was to supply saturated steam for subsequent heating.

2 SOLAR THERMAL ENERGY

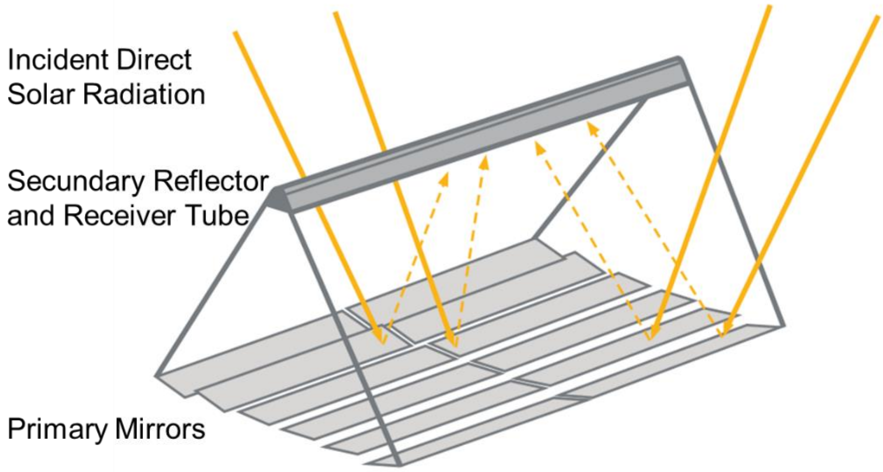
The acronym SHIP, Solar Heat for Industrial Processes, designates the use of solar thermal technology as a supplementary heat source by installing solar collectors and their respective integration with the industrial process. Even not meeting the entire demand of the process due to the intermittent nature of the solar resource, SHIP systems are recognized as an efficient alternative for reducing fossil fuel consumption (Hahn et al., 2018).

The concentrating thermal collectors are characterized by presenting, mainly, a reflective surface (or a set of) and a receiving element. The reflective surface intercepts solar radiation and focuses it toward the receiver. The receiving component absorbs solar radiation and transfers the radiant energy to the working fluid through heat. In some applications, a glass cover may be over the receiver to minimize heat loss to the external environment, but it still allows solar radiation transmission (Kalogirou, 2013).

Linear Fresnel collectors have been gaining notoriety in solar thermal energy applications. They entail lower investment costs and present satisfactory performance compared with the market's most consolidated linear focus collectors, the Parabolic trough collectors (Morin et al., 2012; Farjana et al., 2018; Kalogirou, 2013).

The design of Linear Fresnel collectors consists of flat primary mirrors arranged in rows to reflect light rays towards the receiver, accumulating incident radiation, as shown in Figure 1. A secondary reflector positioned above the receiver increases the optical efficiency of the receiver collector because it redirects rays that have some deviation from the receiver (Kumar, Hasanuzzaman, and Rahin, 2019; Sun et al., 2020).

Figure 1. Structure and incident direct solar radiation captured in a Linear Fresnel concentrator collector (Hahn et al., 2018)



Due to their lightweight structure and the positioning of the primary mirrors, Linear Fresnel collectors can be installed on rooftops. It is the case of the pilot plant in the RAM Pharma industry in Jordan to generate saturated steam. This installation does not require acquiring land adjacent to the industry to implement the solar field (Sun et al., 2020; Berger et al., 2016).

Integrating the solar field with the industrial process can be carried out at the process or supply levels. The inputs are heated at the process level, while auxiliary systems are fed at the supply level, such as hot water or steam (Schmitt, 2016). Furthermore, the integration is indirect when a fluid without phase change is used in the solar field, and steam generation occurs in separate equipment. When steam generation occurs in the solar field using water as a working fluid, the integration is called direct or referred to by the acronym DSG - Direct Steam Generation (Schenk et al., 2015).

Utility-level steam generation is a promising application for solar thermal energy because integration at the supply level requires less effort than at the process level (Lauterbach et al., 2012). Despite requiring a complex and robust control strategy due to the two-phase flow in the absorber tube, direct steam generation (DSG) is considered an advantageous option. DSG does not use thermal oil as a working fluid and does not require additional heat exchangers, making the installation more economical and safer (Mokhtar et al., 2015).

3 METHODOLOGY

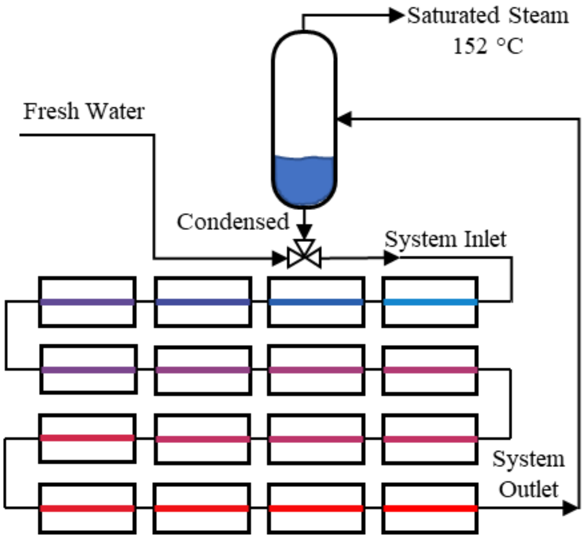
The research consists of performing a computer simulation conducted in the software *System Advisor Model* (SAM 2020.11.29) for a given industrial process, determining the amount of greenhouse gas emissions that can be mitigated by the analyzed system, as well as the estimation of the leveled cost of thermal energy corresponding.

3.1 CASE STUDY AND SIMULATION PARAMETERS

The SAM software developed by the National Renewable Energy Laboratory (NREL) of the US Department of Energy (DoE-US) was chosen to perform the simulation of the analyzed system. It employs weather files in TMY or EPW formats to determine the boundary conditions to which the system is exposed. The climate file used in this research was obtained from the Climate OneBuilding online repository and referred to data from Porto Alegre, RS, between 2004 and 2018.

Figure 2 shows an schematic diagram of the analyzed system, similar to the one presented by Berger et al. (2016), which consists of a set of linear Fresnel solar concentrator collectors arranged in series and equipped with tubular receivers with a glass envelope. The water that feeds the solar field comes from the freshwater supply and the recirculation of the condensate fraction from the steam accumulation vessel (steam drum).

Figure 2: Analyzed solar field configuration diagram



The design conditions defined for the simulation, shown in Table 1, were based on the technical data of the respective commercial models [1] of the Linear Fresnel collector, LF-11, from the manufacturer Industrial Solar, and the tubular receiver, PTR70, from the manufacturer Schott Solar.

Table 1. Simulation Input Parameters

ENVIRONMENTAL PARAMETERS [a]	
Average DNI	750 W/m²
Average DBT	20 °C
Local	Porto Alegre (-29.994 ; -51.171)
OPERATING PARAMETERS	
Pressure	500 kPa (5 bar)
Inlet water temperature	30 °C
Outlet steam quality (ϕ)	0.75
SOLAR FIELD	
Number of Collector Modules per String	16
Number of Strings	1
Aperture Area (Aa)	352 m² (22 m² per module) [b]
Collector Surface Reflectivity (ρ)	0.95 [b]
Incidence Angle Modifier (IAM) Coefficients [b]	
Transversal	[1.0350; -0.0082; 5E-4; -1E-5; 5E-8]
Longitudinal	[0.9998; -0.0071; 1E-4; -6E-6; 5E-8]
RECEIVER [c]	
Glass Envelope Transmissivity (τ)	0.963
Receptor Tube Absorptivity (□)	0.96
Receiving Tube Thermal Emissivity (□)	≤ 0.09 for temperatures up to 200 °C

[a] From climate file (Climate OneBuilding, 2019); [b] Collector's datasheet (Industrial Solar, 2020); [c] Receiver's datasheet (Schott Solar, 2020)

[1] No commercial use intended. Reference for specifications only.

The software calculated the energy balance in the receiver. It determined the flow of the working fluid that circulates in the solar field that meets the desired operating conditions, using the parameters presented and the data from the climate file.

The useful heat, *Q*, in kJ, is delivered to the industrial process in the form of saturated steam,

$$Q = m.\phi.\Delta h \quad (1)$$

where: *m* is the sum of the mass that flows in the control volume over the operating time interval, in kg; ϕ is the quality of the saturated steam that is delivered to the phase separation vessel, dimensionless; and Δh is the working fluid vaporization enthalpy, in kJ/kg, under pressure and temperature conditions corresponding to the operation of the SHIP system.

For this study, only those days in which the SHIP system delivered saturated steam during a minimum period of three consecutive one-hour intervals in the simulation results were counted as valid days of operation. The simulation data corresponding to sparse periods of operation was disregarded in the total amount of saturated steam supplied calculations. Thus, a conservative approach was adopted in interpreting the results, considering that a SHIP system, which operates in real situations, needs a startup period for the effective supply of steam to exist.

3.2 QUANTIFICATION OF GREENHOUSE GAS EMISSIONS

This research uses the Brazilian GHG Protocol Program tool (PBGHG 2021.0.1), developed and made available by Fundação Getúlio Vargas at the Center for Sustainability Studies (FGVces, 2016), to quantify the GHG emissions resulting from the generation of steam in the industry through the burning of fuels. This tool uses the approach proposed by the International Panel on Climate Change (IPCC, 2006) that establishes emission factors for each fuel type.

The GHG emission factor covers carbon dioxide emissions based on the amount of carbon in the fuel composition and other gases such as methane and nitrous oxide. They are converted into $CO_{2\text{-eq}}$ units through their respective Global Warming Potential, GWP, values, as shown in Table 2.

Table 2: Equivalence of Greenhouse Gases (IPCC, 2006)

GHG mass	GHG mass in $CO_{2\text{-eq}}$
1 kg CO_2	1 kg $CO_{2\text{-eq}}$
1 kg CH_4	21 kg $CO_{2\text{-eq}}$
1 kg N_2O	298 kg $CO_{2\text{-eq}}$

The amount of GHG released into the atmosphere, E_{GHG}, in kg $CO_{2\text{-eq}}$, is determined by

$$E_{GHG} = EF.\ \frac{Q}{\eta} \quad (2)$$

where *EF* is the emission factor, in kg $CO_{2\text{-eq}}$/GJ, corresponding to the analyzed fuel, the amount of thermal energy consumed is *Q*, in GJ, and the boiler efficiency is η, dimensionless.

Natural gas and mineral coal are the fuels most used in the generation of process heat in the industrial segments operating in Rio Grande do Sul. The first one typically accounts for 20 to 35% of energy consumption in the textile and chemical sectors. The second and their derivatives represent 40 to 70% of energy consumption in the metalworking and cement sectors (EPE, 2021; SPGG RS, 2021). The emission factors associated with these fuels are shown in Table 3.

Table 3: Fossil Fuel Emission Factors (PBGHG 2021.0.1)

Fuel	EF
Natural gas	56.15
Mineral coal [a]	96.54

[a] Coal Specification: Higher Heating Value 5200 kal/kg

3.3 LEVELED COST OF HEAT (LCOH)

Leveled cost indicators allow for comparing energy acquisition by different technologies. This research uses this indicator to compare thermal energy obtained between the SHIP and conventional fuel-burning systems. It computes the total cost of the project’s life cycle. It divides it by the thermal energy supplied by it in the same period, correcting both terms of the calculation to present value through an interest rate. Thus, it is possible to obtain a metric of the cost associated with each unit of energy supplied by the system (Short, Packey, Holt, 1995; Yang et al., 2021).

Two approaches are used to calculate the LCOH. The first refers to the traditionally used calculation method, in which the initial investment cost, *I*, the acquisition cost of fossil fuels, *C*, maintenance costs, *M*, and the thermal performance of the system as supplied heat, *Q*, are considered constant over the period of analysis, i.e.,

$$LCOH_{general} = \frac{I + \sum_{t=1}^{20} \frac{C + M}{(1+j)^t}}{\sum_{t=1}^{20} \frac{Q}{(1+j)^t}} \quad (3)$$

The second, in turn, corresponds to a modification of this method, proposed by López (2021)

$$LCOH_{modified,\ fuel} = \frac{\sum_{t=1}^{20} \frac{C(1+i)^t + M}{(1+j)^t}}{\sum_{t=1}^{20} \frac{Q}{(1+j)^t}} \quad (4)$$

And

$$LCOH_{modified,\ solar} = \frac{I + \sum_{t=1}^{20} \frac{M}{(1+j)^t}}{\sum_{t=1}^{20} \frac{Q.(1-d)^t}{(1+j)^t}} \quad (5)$$

which adds an inflation term, *i*, to the fuel acquisition cost and another degradation term, *d*, to the performance of the solar thermal system. For both approaches, the analysis period, *t*, is considered 20 years, and an interest rate, *j*, of 9 % p.a.

The initial investment cost of the solar field, *I*, is proportional to the collector aperture area, Aa, and results from the acquisition costs of collector and receiver modules, additional installation costs, instrumentation and hydraulic connections, and auxiliary equipment costs. The value used as a reference for the initial investment cost of the solar field was 250 USD/m² (Khajepour, Ameri, 2020; López, 2021). The investment cost of steam generation boilers fueled by fossil fuels is not included in the LCOH calculation because this equipment is already installed.

The terms *C* and *M* of the equations compute the costs of the steam generation system. For systems powered by fossil fuels, these costs include the acquisition costs of fuel and the boiler's maintenance. The costs of the solar field throughout its life cycle correspond to the operation and maintenance costs, estimated as a percentage of the initial investment cost, whose value can vary between 0.3% and 1% per year (SHC, 2020; López, 2021).

Table 4: LCOH Parameters

GENERAL	
Analysis Period (t)	20 years
Interest rate (j)	9 % p.a.
SOLAR FIELD	
Investment (I) [a,c]	250 USD/m²
Maintenance (M) [b,c]	2.50 USD/m².year (1% of the investment)
Degradation rate (d) [c]	0.5 % p.a.
FUEL: Natural gas	
Acquisition Cost (C) [d]	720 USD/t
Inflation rate (i) [c]	5 % p.a.
Maintenance (M) [e]	1,40 USD/GJ_{th}
Boiler Efficiency (η) [e]	0.85
FUEL: Mineral coal (Spec. 5200 kcal/kg)	
Acquisition Cost (C) [d]	150 USD/t
Inflation rate (i) [c]	5 % p.a.
Maintenance (M) [e]	4,20 USD/GJ_{th}
Boiler Efficiency (η) [e]	0.75

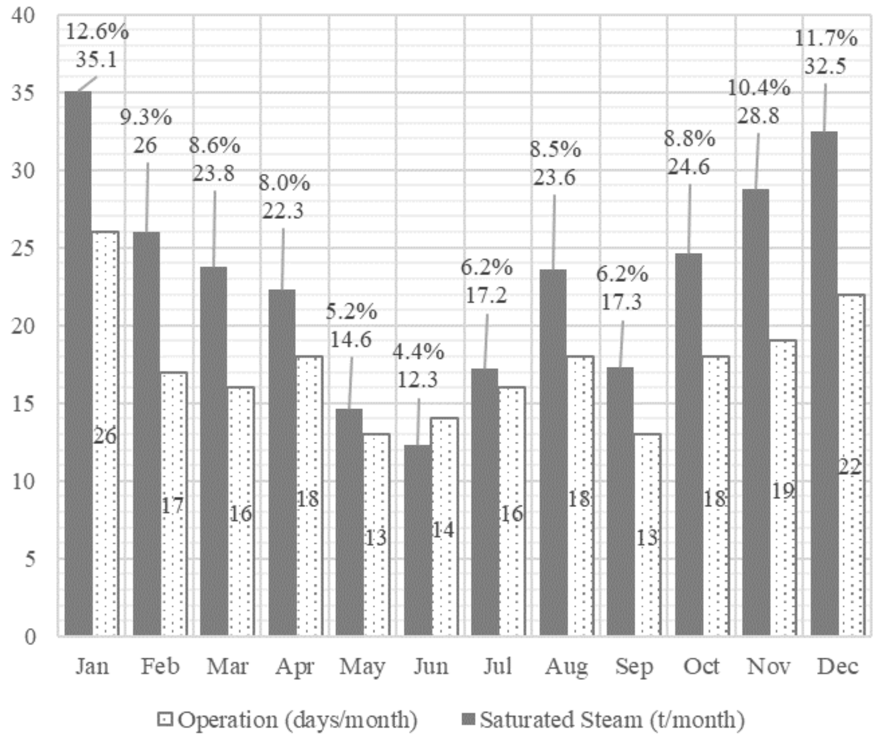
[a] (Khajepour, Ameri, 2020); [b] (SHC, 2020); [c] (López, 2021); [d] (EPE, 2020); [e] (Tolmasquim, 2016).

4 RESULTS AND DISCUSSION

The present study brings results obtained through simulations using the SAM software. They quantify the capacity of the SHIP system to supply saturated steam to the industrial process and, thus, promote the reduction of greenhouse gas emissions. The supply of saturated steam (5 bar, 152°C) by the analyzed SHIP system corresponds, in terms of useful heat, to 729.61 GJ_{th} annually, of which 61% were observed between October to March.

The supply of steam over one year is shown in Figure 3. The respective amounts of saturated steam supplied each month relate to the number of operating days required to achieve this supply. It is possible to observe that the system presents better performance between November and February. Both months showed a supply of saturated steam to the process greater than 25 tons per month each.

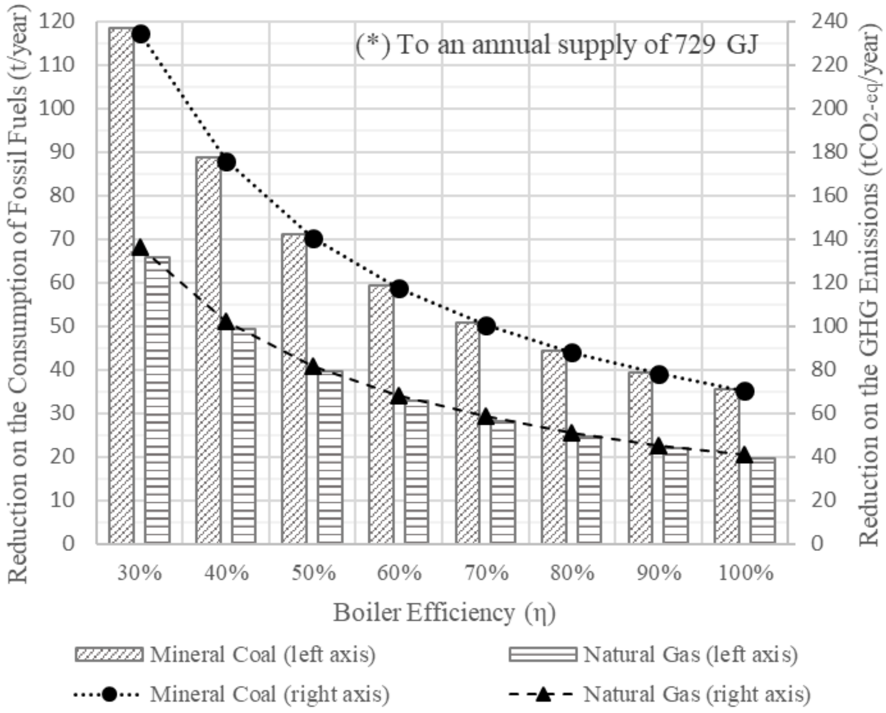
Figure 3: Annual performance of the solar thermal system for supplying saturated steam



The performance of the SHIP system in January stands out for achieving the highest monthly supply, with about 35 tons of saturated steam over 26 days of operation. Also noteworthy was the 33 tons of saturated steam corresponding to the month of December, which, although slightly smaller than January, took only 22 days of operation of the SHIP system to reach it. On the other hand, the month's climatic conditions close to the winter solstice harm the system's performance, as can be seen. The sum of the supply corresponding to the months of May, June, and July corresponds to only 15.9% of the system's annual saturated steam generation capacity.

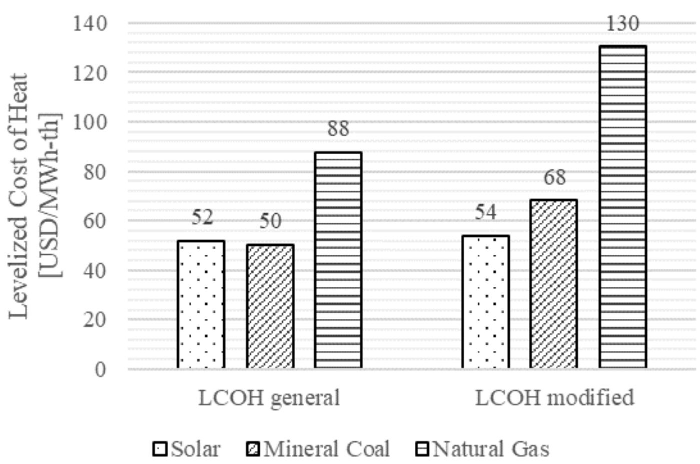
The SHIP system's contribution to reducing greenhouse gas emissions is indicated in Figure 4, according to the type of fossil fuel saved and the efficiency of the boiler in which it would be consumed, based on the supply of 729 GJ in the form of thermal energy. To exemplify the graph interpretation, in Figure 4, consider an industry that currently uses the burning of natural gas in a boiler with an efficiency of 80% to meet its process heat demand. In a year, this industry could save 24.74 tons of Natural Gas, corresponding to about 17.8 thousand USD, and avoid the release of 51 tons of $CO_{2\text{-eq}}$ in the atmosphere using the SHIP system.

Figure 4: Possibility of reducing fuel consumption and GHG emissions through the implementation of the SHIP system analyzed, comparing different efficiency ranges of the conventional boiler



A more detailed analysis of Figure 4 shows that the amount of GHG whose emission can be avoided by applying the analyzed SHIP system is directly proportional to the irreversibilities of the conventional steam generation process. The lower the boiler's efficiency, the greater the fuel burned to meet the exact demand for thermal energy. Thus, investing in environmentally responsible projects in the industrial sphere is also an economic advantage. It makes production costs less susceptible to changes in fossil fuel prices in the national and international markets. The LCOH comparison between fossil fuels and the proposed SHIP system can be performed based on Figure 5.

Figure 5: LCOH values for each methodology



In the general LCOH analysis, the solar source was approximately economically equivalent to coal, with 52 and 50 USD/MWh_{-th} values, respectively. It is because mineral coal, a fuel with lower calorific value and the disadvantage of generating ash during burning, has a meager acquisition cost. On the other hand, the general LCOH already shows the competitive advantage of the solar source concerning natural gas, with values of 52 and 88 U$D/$MWh_{-th}$, respectively. Although natural gas is a cleaner-burning fuel with lower maintenance costs, it also has a higher acquisition cost.

However, the general LCOH does not contemplate some crucial aspects regarding comparing fossil fuels and solar thermal sources. While the performance of the solar field is gradually reduced over the years of its useful life due to the degradation of its components, the acquisition price of fossil fuels shows a tendency to increase during the investment analysis period. For this reason, the modified LCOH methodology is closer to the costs experienced in practical situations. When observing the results for the modified LCOH, the competitive advantage of the process heat supply model through the use of the solar resource becomes more expressive against both analyzed fuels.

5 CONCLUSIONS

The productive sectors have, at the same time, the challenge and the opportunity to become more sustainable to stop climate change from worsening. The implementation of an alternative system to the use of fossil fuels in the generation of process heat represents, therefore, the possibility of reducing the environmental impacts caused by the emission of greenhouse gases and of making the industrial sector less susceptible to the variability of the acquisition flues price.

The present study quantifies, through simulation, the environmental and economic advantages that can be promoted by using a SHIP system in the auxiliary supply of saturated steam in an industrial process. The simulation was performed in the SAM software (v. 2020.11.29), using the climate file corresponding to Porto Alegre and the technical data of the Linear Fresnel LF-11 collector (Industrial Solar) and the tubular receiver PTR70 (Schott Solar).

The results indicate that a solar field of Linear Fresnel collectors with an opening area of 352 m² could contribute to savings of 20 to 66 tons of natural gas or 35 to 118 tons of coal per year, meeting a 729GJ_{th} share of the process heat demand annually. Consequently, the SHIP system operation would reduce GHG emissions by between 41 and 235 tons of CO_{2}-$_{eq}$ annually, depending on the boiler technology and the fossil fuel used in conventional steam generation. LCOH analysis points to a competitive advantage in using the SHIP system, with values of 52 to 54 USD/MWh-$_{th}$, depending on the approach used.

Thus, it can be affirmed that the SHIP system's implementation for heat supply is beneficial in comparison with production processes served only by fossil fuels. It leads to financial savings concerning the amount of fuel purchased and promotes an improvement in environmental indices by reducing greenhouse gas emissions. The implementation of the SHIP system for the supply of saturated steam, under the conditions analyzed in this research, is particularly interesting for application in the textile, food, and chemical industries, as these are production processes whose largest share of heat demand concentrates in the temperature range up to 150°C.

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ANEXOS

ABBREVIATIONS AND NOMENCLATURE

Aa	Aperture Area, m^2
C	Costs for the current fossil fuel, USD/kg
d	Degradation rate, % *per annum*
DBT	Dry Bulb Temperature, °C
DNI	Direct Normal Irradiance, W/m^2
EF	Emission Factor, kg $CO_{2\text{-}eq}$ /GJ
E_{GHG}	Emission of Greenhouse Gas, kg $CO_{2\text{-}eq}$
i	Inflation rate, % *per annum*
I	Investment Cost, USD
j	Interest rate, % *per annum*
LCOH	Levelized Cost of Heat, USD/MWh_{th}
m	Mass of the working fluid, kg
M	Maintenance Costs, USD *per annum*
Qu	Useful Thermal Energy, kJ
r	Interest Rate, % *per annum*

Δh	Vaporization Enthalpy, kJ/kg
α	Absorptance
ε	Emittance
η	Boiler Efficiency
ρ	reflectivity
ϕ	Steam Quality
τ	Transmittance

Subscripts

eq	equivalent
in	inlet
out	outlet
th	thermal