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NATURAL GAS AND SOLAR THERMAL ENERGY FOR PROCESS STEAM GENERATION IN THE BRAZILIAN INDUSTRY

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Abstract. *The present study aims to analyze the economic potential of two scenarios: one using only natural gas; and the second using linear Fresnel technology with no thermal storage combined with natural gas boilers to generate industrial process steam, in seven Brazilian cities. The solar field plant was modeled using SAM software. In addition, the cost of the plant's industrial process steam was quantified by LCOH, and the economic evaluation of the project in terms of investment was obtained by the Net Present Value, Internal Rate of Return and capital recovery time criteria. The results indicate that parameters such as the Direct Normal Irradiation, natural gas prices and the cost of the solar field have an impact on the economic viability of the hybrid power plant. Thus, it was observed that for the hybrid operation, the natural gas – solar thermal concept proved to be viable in three cities studied, two in the Northeast region and another in the Southeast. In addition, it was observed that there was fuel savings when integrating the Fresnel concentrators to the natural gas generating units and, consequently, the emission of greenhouse gases is minimized.*

Keywords: *Fresnel concentrators, concentrated solar heat, LCOH, hybrid systems.*

1. INTRODUCTION

The industrial sector consumes a significant portion of the world's primary energy, consuming mainly heat with temperatures below 675 K. The International Energy Agency (IEA, 2021) reported that industrial processes were responsible for consuming 51% of thermal energy (heat) in the world in the year 2021. Furthermore, López (2021) reports that more than three quarters of world demand of heat in industry is due to the consumption of fossil fuels, and that renewable heating systems should grow by 22% in the period from 2019 to 2024.

In the Brazilian industrial sector, in turn, energy consumption related to process heat represents 80% of total energy consumption, while electricity consumption has a 20% share. Furthermore, within the 80% related to the consumption of process heat, 52% is obtained by fossil fuels. In this context, the consumption of fossil fuels used to meet industrial heat demand grew by 33%, from 26.7 megatons of oil equivalent (*Mtoe*) in 1990 to 35.5 *Mtoe* in 2016 (SOLAR PAYBACK, 2019).

Also, according to the National Agency of Petroleum, Natural Gas and Biofuels (ANP), natural gas in Brazil is used mainly in electric generation (thermoelectric plants) and industrial consumption, in the generation of process heat or as a raw material in the petrochemical industry, in which it is used in the manufacture of plastics, paints, synthetic fibers and rubber (Reis, 2018).

Consequently, there is a search for alternatives that can reduce the consumption of fossil fuels in industries, in which solar energy is presented as an option to integrate solar thermal technologies to systems already consolidated in the market, and, in Brazil, an option identified to reduce the consumption of natural gas in the industry consists of the use of thermal solar energy.

López (2021), explains that solar heat for industrial processes (SHIP) has the potential to meet the demand for useful heat, especially in sectors that need heat at low and medium temperatures. Akar et al. (2022) report that solar industrial process heat technologies, via solar energy concentrators, are economically viable to supply steam or heat needs in many industries by providing high temperature heat transfer fluids such as pressurized water, synthetic oil or direct steam.

In this context, it is noted that solar thermal energy, implemented through Concentrated Solar Heat (CSH) plants, or the use of flat plates or evacuated collectors to produce hot water, becomes a promising alternative to supply a portion of industrial processes that use hot water and steam in a temperature range of up to 675 K.

In addition, concentrated solar energy systems for process steam generation can be hybridized with other heat sources already used - fossil or renewable fuels, such as being used separately or added to other energy generation systems, with concentrators as examples, e.g. linear Fresnel, parabolic trough, among others. With this, the industry has the potential to reduce fuel costs and CO₂ generated (Akar et al., 2021), in which solar energy constitutes a real alternative to partially

cover these energy needs (Sepúlveda, 2019). Furthermore, Almeida (2018) points out that when hybridization is implemented with the sharing of common infrastructure, it can enable the reduction of costs generated by the solar field.

Given this scenario, this research proposes alternatives regarding the use of renewable energy, such as concentrated solar energy, to meet the process heat demand of the national industry and reduce the use of natural gas. In this context, the cost of generating process steam from the use of boilers fueled by natural gas is evaluated, as well as this integrated system with Fresnel concentrators technology operated in direct steam generation.

2. METHODOLOGY

Two configurations of plants for the generation of process steam in the industry are evaluated in this work, presenting the following scenarios:

- Scenario A: natural gas steam generating unit;
- Scenario B: hybrid plant characterized by the parallel integration of Fresnel concentrators and a natural gas steam generating unit.

The study is carried out through the schematic representation of the system that includes the Fresnel field, without storage, operating in parallel with the steam generating unit, shown in Figure 1.

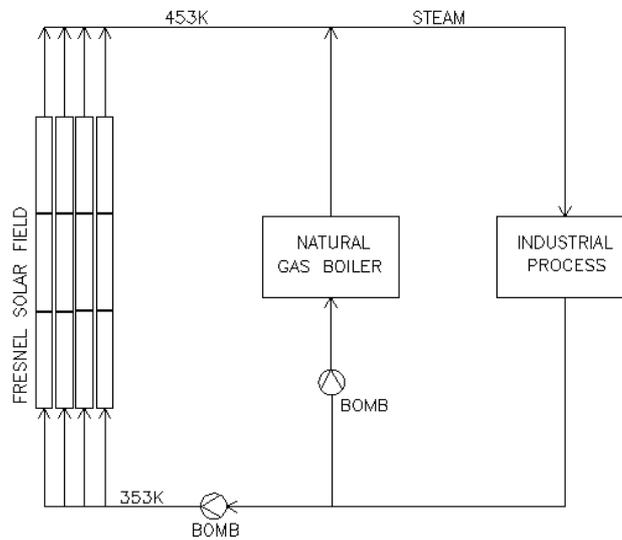


Figure 1. Model of the studied hybrid system.

The solar field simulations were carried out using the Linear Fresnel Direct Steam/IPH Linear module of the System Advisor Model software (SAM, version 2020.2.29), developed by the National Renewable Energy Laboratory (NREL), based on data of the LF-11 Fresnel Collector module provided by the equipment manufacturer (Industrial Solar, 2021), according to data adapted from Industrial solar (Table 1).

Table 1. General data of the basic module (Fresnel Collector LF-11)

Description	Unit	Value
Width	<i>m</i>	7.5
Length	<i>m</i>	4.06
Area of primary reflectors	<i>m</i> ²	23
Terrain area (a single module)	<i>m</i> ²	30.45
Primary reflector height above ground level	<i>m</i>	4.5
Minimum space between parallel rows	<i>m</i>	0.2
Maximum operating wind speed	<i>m/s</i>	27.78

For modeling the steam generating unit, hourly fuel consumption was calculated using the Excel® tool, considering that the natural gas boiler (scenarios A and B); must produce the necessary steam flow to meet the steam demand of the industrial process at all times. In this context, Eq. (1) was used,

$$\eta_{gv,gn} = \frac{\dot{m}_v(h_v - h_c)}{Q_{gn} PCI_{gn}} \quad (1)$$

Where: $\eta_{gv,gn}$ [-] represents the thermal efficiency of the natural gas steam generating unit; \dot{m}_v [kg/h] the flow of saturated steam generated by the unit; h_v [kJ/kg] the enthalpy of saturated steam; h_c [kJ/kg] the enthalpy of the unit's feed water (condensate); Q_{gn} [Nm³/h] the consumption of natural gas; PCI_{gn} [kJ/Nm³] is the lower calorific value of natural gas.

The amount of fuel (natural gas) saved per year in the hybrid operation, in turn, was calculated by Eq. 2,

$$EF_{gn} = \sum_{year} (Q_{gn.b} - Q_{gn.h}) \quad (2)$$

Where: EF_{gn} [m³/year] represents fuel economy (natural gas); $Q_{gn.b}$ [m³/h] consumption of natural gas, where *b* and *h* are the sub-indices that indicate the consumption of the conventional system and the hybrid plant, respectively.

Finally, the thermal efficiency of hybrid steam generation systems was calculated according to Srinivas and Reddy (2014), Eq. 3,

$$\eta_s = \frac{QT}{Q_{gn} PCI_{gn} + DNI_T \times A_{cs}} \quad (3)$$

Where: QT [kWh/year] represents the useful energy generated by the boiler and the solar field; DNI_T [kWh/m² year] represents annual direct normal radiation; and A_{cs} [m²] is the mirror area.

In the case of conventional (non-hybrid) units, the terms DNI_T and A_{csc} are equal to zero and the efficiencies correspond to the efficiencies of gas boilers.

To obtain the cost of industrial process steam for each plant, it was calculated the Levelized Cost of Heat (LCOH), presented in Eq. 4,

$$LCOH = \frac{\sum_{t=0}^n (CAPEX_t - OPEX_t + C_t) (1+r)^{-t}}{\sum_{t=0}^n (H_t) (1+r)^{-t}} \quad (4)$$

Where: $CAPEX_t$ [US\$] is the investment, and $OPEX_t$ [US\$/year] the operation and maintenance annual costs; C_t [US\$/year] annual expenses related to the purchase of fuel; t [years] is the lifetime of the plant; H_t [MWh] is the thermal energy produced, r [%] is the discount rate.

With regard to the hybrid plant, in turn, an analysis of the feasibility of integrating the solar field with the conventional plant (hybridization process) was carried out, considering that the investment in the solar field must be paid for by the revenue arising from the fuel savings. In these cases, the Net Present Value indicators (NPV, Eq. 5), the Internal Rate of Return (IRR, Eq. 6), and the discounted return on investment (payback) were also calculated.

$$NPV = \sum_{t=0}^n CF (1 + MARR)^{-t} \quad (5)$$

$$0 = NPV = \sum_{t=0}^c \frac{CF}{(1+IRR)^t} \quad (6)$$

Where: CF [US\$] is the cash flow at present value; t [year] is the *n*th period in time; n [years] represents the number of periods, $MARR$ is the minimum attractive rate of return of the investment; IRR is the discount rate of return that zeroes out the NPV, and the IRR must be greater than the $MARR$ so that the project can be considered economically viable.

The study considers the discounted payback, which represents the time required for the benefits generated by the project to offset the investment made. Finally, verify the return on investment and the costs of the studied fuels, in order to present an alternative that will reduce the consumption of fossil fuel within the studied scenario.

3. CASE STUDY

The research was developed considering the installation of the industrial plant in some cities where natural gas is supplied, namely: Campo Grande, São Paulo, Belo Horizonte, Curitiba, Florianópolis, Recife and Fortaleza. The simulations were carried out considering series of TMY data (typical meteorological years) obtained from the Solar and Wind Energy Resource Assessment (SWERA) platform. Prices for natural gas for industrial use vary according to the concessionaires in each region (Table 2).

Still, the study considers reducing the consumption of natural gas for the production of saturated steam in the Brazilian industrial sector. To this end, the indicators adopted to prepare the analysis of natural gas consumption had as a reference the value of the cubic meter consumed (January 2022) which is applied in the distributors of each region studied.

Table 2. Average DNI and NG concessionaire, by studied city

City, State	DNI ($kWh/m^2 \cdot year$)	NG cost reference
Curitiba, PR	1347.4	Compagas
Florianopolis, SC	1424.0	Segas
Campo Grande, MS	1879.0	Msgas
São Paulo, SP	1464.5	Comgas
Belo Horizonte, MG	1742.2	Gasmig
Recife, PB	1735.6	Gasbrasiliano
Fortaleza, CE	1986.4	Cegas

3.1 Technical and economic premises

The technical premises adopted for the design and simulations of the plant are for the process steam demand in the industry: 10 t/h of saturated steam ($x=1$) at 1 MPa absolute ((outlet water temperature: 453 K), 24h/day, seven days a week and 365 days per year; with thermal efficiency of the natural gas steam generator unit of 90%, model A3P-10 (Alfa Laval, 2022); and Lower Calorific Value (PCI) of natural gas equal to 8364 $kJ/N.m^3$ (Gasbrasiliano, [201-]);

Table 3, in turn, shows the assumptions adopted for dimensioning the solar field. As can be seen, the solar field was dimensioned to supply 3.4 MW_{th} (equivalent to 5 t/h of saturated steam). In this condition, the solar field supplies 50% of the mass flow of steam demanded by the industry, a condition established considering that the minimum operating load of the boilers must be limited to 50%, thus avoiding operational problems, gas emissions above the established in legislation, as well as a significant reduction in its thermal efficiency.

Table 3. Parameters added in SAM for System Design and Solar Field

Parameter	Unit	Value
Water temperature at the entrance to the solar field (condensate)	K	353
DNI ⁽¹⁾ in design condition	W/m^2	900
Solar field capacity	MW_{th}	3.4
Ambient temperature in design condition	K	303
Solar multiplier	-	20% (MS=1.2)

⁽¹⁾ *Adapted from Industrial Solar (2021)

Also, it is important to pay attention to the solar multiple (MS) of the concentrator field, defined at 1.2. That is, it has an area 20% larger than that defined in the design condition, aiming to increase the number of hours in the year in which the system can supply the design thermal load of 3.4 MW_{th} (a value typically used for systems without thermal storage).

The assumptions adopted in relation to the Capital Expenditure (CAPEX) and Operational Expenditure (OPEX) of the solar field and boiler are shown in Table 4. The minimum attractive rate of return was set at 10% (establishes a limit for investors), OPEX of 1% of the investment cost.

Table 4. Assumptions adopted for analyzing the economic viability of the systems

	Parameter	Unit	Value
Solar field	CAPEX ⁽²⁾	US\$	2,899,880.00
	OPEX	US\$/years	1% of CAPEX
	MARR ⁽³⁾	%	10
Economic assumptions	Service life ⁽⁴⁾	Years	25

⁽²⁾ Quotation; ⁽³⁾ Siqueira Neto (2018); ⁽⁴⁾ Industrial Solar (2021)

The cost of the Fresnel system was quoted at 2.5 million Euros. To determine the CAPEX in dollars, the average value of the Euro and the dollar for the month of October 2021 was considered (BCB, 2021). For the OPEX of the scenario studied, operating costs and annual preventive and corrective maintenance of equipment were included, such as the natural gas boiler and the solar field.

4. RESULTS AND DISCUSSIONS

This section describes the results achieved after simulating the conventional system (natural gas boilers), as well as the hybridization of this system with Fresnel technology over a typical meteorological year, operated for direct generation of process steam.

4.1 Conventional Plant

The results referring to the generation of process steam using natural gas as fuel (scenario A) for the different cities studied are presented in Table 5.

Worldwide there is a variation in the price of natural gas that serves the industrial sector. Brazil has a high LCOH of NG compared to the United States (10.86 *US\$/MWh*) and Canada (9.87 *US\$/MWh*). However, it has values close to those of some European countries, such as Switzerland and Ireland, being 64.94 *US\$/MWh* and 43.38 *US\$/MWh* of natural gas, respectively (STATISTA, 2023).

In addition, the Brazilian industry monitoring bulletin, from the Ministry of Mines and Energy (MME), points out that, during the year 2021, natural gas presented variations in the average price, resulting in an increase in the monthly expenses of industries. In addition, the Federation of Industries of the State of Santa Catarina (FIESC, 2022) reported that the natural gas tariff for the industry of Santa Catarina had a readjustment of 41.05% in July 2022. The price of natural gas can be considered a factor that can increase monthly costs for industrial steam production in Brazil.

Table 5. Results related to the study of NG consumption

Cities	Recife	Fortaleza	Campo Grande	São Paulo	Belo Horizonte	Curitiba	Florianopolis
NG Consumption (10^6 Nm ³ /year)	6.78	6.78	6.78	6.78	6.78	6.78	6.78
Costs related to the purchase of NG (10^6 US\$/year) ⁽⁵⁾	33.76	40.77	38.08	50.36	34.36	42.10	40.03
NG specific average cost (US\$/Nm ³) ⁽⁵⁾	0.55	0.66	0.62	0.82	0.56	0.68	0.65
LCOH (US\$/MWh _{th}) ⁽⁵⁾	45.61	55.09	51.45	68.05	46.43	56.89	54.09

⁽⁵⁾ Dollar: average for the month of October 2021 (BCB, 2021)

4.2 Hybrid Plant

In this topic, the performance results of the proposed scenario B, over a typical meteorological year of operation, are presented. The hybrid scenario corresponds to the generation of saturated process steam at an absolute pressure of 1 MPa in order to reduce the boiler's fossil fuel consumption.

4.2.1 Thermodynamic analysis of the scenarios studied

The results regarding the design point condition of the solar field are shown in Table 6. The area of the solar field was dimensioned at 7084 m². The thermal capacity of the solar field already considering the adopted solar multiple (20%) was 4.08 *MW_{th}*. It is important to note that, despite the capacity of the solar field being 4.08 *MW_{th}*, steam generation was limited to a capacity of 3.4 *MW_{th}*, as a way to prevent the boilers from operating below a 50% load.

Table 6. Data on solar field dimensions and loop efficiency in the design condition

Description	Unit	All cities studied
Receiver target thermal power	<i>MW_{th}</i>	4.08
Full loop conversion efficiency	-	0.65
Effective area of mirrors	m ²	5842
Solar field area	m ²	7084
Total land area needed to install the solar field	m ²	8500

Due to Brazil having different climatic characteristics for each region, the solar field installed in each studied city presented a distinct annual solar fraction. Note that Fortaleza, Recife and Belo Horizonte have the highest values of solar fraction and, consequently, greater fuel economy. In addition, there is the possibility that all cities have a reduction in greenhouse gas emissions, meeting the global goals to minimize the amount of CO₂ emissions (Table 7).

Table 7. Solar fraction per studied city

City	Annual Solar Fraction (%)
Recife - PE	11.27
Fortaleza - CE	11.92
Campo Grande - MS	8.67
São Paulo - SP	7.21
Belo Horizonte - MG	11.51
Curitiba - PR	4.82
Florianopolis - SC	5.60

The results of the thermodynamic analysis for the natural gas hybrid plant are presented in Table 08 (Scenario B), which shows the saved amount of natural gas, in thousands of m³/year. The cities located in the Northeast region of Brazil stand out in terms of fuel economy. As an example, Recife stands out for saving 11.04% in fossil fuel consumption. The cities of Curitiba and Florianopolis, in turn, did not show a significant value in terms of NG savings over a year.

Table 08. Results for scenario B (NG – Solar thermal)

Cities	Recife	Fortaleza	Campo Grande	São Paulo	Belo Horizonte	Curitiba	Florianopolis
NG consumption (10 ⁶ Nm ³ /year)	6.02	5.97	6.19	6.29	6.00	6.46	6.40
NG saved (10 ³ Nm ³ /year)	764.34	808.34	588.31	489.13	780.39	327.11	380.00
Energy related to steam generation (MWh _{th} /year)	81,528.06	81,528.06	81,528.06	81,528.06	81,528.06	81,528.06	81,528.06

4.2.2 Economic Analysis

Table 9 shows natural gas savings in US\$/year. If the value of the hybrid LCOH is greater than the LCOH of the conventional system (only NG), the result found is reflected in the payback period of the investment, making it high. The result for LCOH ranges from 44.78 US\$/MWh_{th} to 67.41 US\$/MWh_{th}, in which the city of São Paulo stands out for having a high cost, which occurs due to the specific average price of NG being the highest among the cities studied. In addition, the table presents the values corresponding to the NPV, IRR and discounted payback for the evaluated scenarios. Knowing that if the IRR has an attractiveness rate below 10%, the benefits of integrating the Fresnel concentrators with the natural gas boiler are not positive, as well as the NPV. Thus, the return on capital will not occur over the useful life of the plant. This was verified for the cities of Curitiba and Florianopolis.

5. FINAL CONSIDERATIONS

The present work had as objective to evaluate the alternative regarding the reduction of the consumption of natural gas. The economic analysis was carried out by calculating the leveled cost of heat, allowing the determination of the cost of industrial process steam in US\$/MWh_{th} generated, using the natural gas plant, as well as for the hybrid design.

For scenario B, there was fuel savings by integrating the Fresnel concentrators to the natural gas steam generating unit in all the cities tested. To this end, the integration of Fresnel systems with natural gas boilers in saturated steam generation processes in those installed mainly in the cities of Fortaleza, Belo Horizonte and Recife is promising. In these regions, Brazil stands out for having relevant levels of solar radiation, especially in the Northeast region. Thus, the DNI is one of the parameters to be considered for the cost of generating saturated steam, in which the installation location of the industry must be observed.

Furthermore, although the solar field capacity was considered constant in this work, the system can be expanded due to its modular design. Thus, the greater the area of the solar field, the greater the solar generation of the unit. However, it is important to observe if a minimum partial load that the natural gas boiler can operate in order not to promote a significant drop in its efficiency or provide a reduction in gas emissions into the atmosphere, remaining above what is established in the legislation.

Finally, the results of the economic feasibility analysis of the present study show that cities located in regions with DNI above 1700 kWh/m²-year, and with annual solar fraction reception greater than 10%, conditions presented for the integration of heat from direct solar process in the industrial segments. However, in Brazil it is still necessary to reduce the prices of Fresnel concentrators, so that the investment is lower, thus making its installation increasingly advantageous.

Table 9. Economic results of the hybrid plant (NG - Solar thermal)

Cities	Recife	Fortaleza	Campo Grande	São Paulo	Belo Horizonte	Curitiba	Florianopolis
Annual savings (10³ US\$/year)	416.98	507.82	357.18	399.81	435.24	220.00	241.69
LCOH combined hybrid plant (US\$/MWh_{th})	44.78	53.14	51.35	67.41	45.37	58.44	55.40
IRR (%)	15.09	19.75	12.07	14.22	16.02	4.83	6.05
NPV (10³ US\$)	911.85	1,736.43	369.00	755.94	1,077.57	-876.16	-679.27
Payback	11 years and 10 months	9 years and 8 months	16 years and 1 month	13 years and 1 month	10 years and 10 months	> 25 years	> 25 years

Dollar: average for the month of October 2021 (BCB, 2021).

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