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CONCENTRATED SOLAR ENERGY AS AN ALTERNATIVE TO REDUCE THE NATURAL GAS CONSUMPTION IN INDUSTRY

Eduardo L K Burin
Federal University of Parana, Palotina-PR
eduardo.burin@ufpr.br

Leandro Rogel da Silva
ICAVI S.A. Engineering and Product Development Department, Pouso Redondo-SC
rogel.engenharia@icavi.ind.br

Edson Bazzo
Federal University of Santa Catarina, Florianópolis-SC
e.bazzo@ufsc.br

Abstract. *This work aimed to evaluate the feasibility of hybrid steam generation in the industry, combining parabolic trough concentrators and a natural gas boiler. Simulations were carried out for the Brazilian cities of Campo Grande, São Paulo, Belo Horizonte, Curitiba, Florianopolis, Recife and Fortaleza, and for Seville (Spain) and Phoenix (USA), covering different levels of Direct Normal Irradiation (DNI) and natural gas prices. The hybrid operation provided a reduction in the natural gas consumption, from 5.7% (Curitiba), to 12.6% (Phoenix). In general, the results indicated the potential of parabolic trough for steam generation in Brazil, a country that has attractive DNI potential, and a high natural gas cost. In this scenario, for the cities of Campo Grande and Belo Horizonte (with DNI around 1800 kWh/m²-year), the hybrid system provided a steam cost similar to the base case. In the cities of Seville and Phoenix, on the other hand, despite having higher levels of DNI, the reduced cost of natural gas was not sufficient to make the hybrid conception feasible. In conclusion, solar energy is an interesting alternative to enable the clean generation of process steam, especially if we consider the prospect of costs reduction for the concentrated solar energy technology.*

Keywords: *hybrid system, natural gas, solar industrial process heat*

1. INTRODUCTION

About 50% of world's energy consumption consists of heat (IEA, 2019). This represents around 40% of global CO_2 emissions. Furthermore, according to this same study, an important share of 50% of heat use occurs in industries.

Regarding energy consumption in the industrial sector alone, about 80% is heat provided mainly by coal (45%) and natural gas (30%) primary energy sources. In terms of heat temperature requirements, about 30% consists of low temperature applications (<150ºC), 22% consists of medium temperature applications (150-400ºC) and 48% consists of high temperature applications (>400ºC) (SOLAR PAYBACK, 2017).

The presented figures turn clear the potential of applying solar thermal energy to partially provide the heat demands of industry. The low temperature applications could be provided by flat-plate or evacuated tube collectors, while medium and high temperature applications would require concentrated solar energy, as linear Fresnel, parabolic trough or central tower (KUMAR; HASANUZZAMAN; RAHIM, 2019).

In Brazil, about 33% of final energy consumption occurs in the industrial sector. This sector is also responsible for the consumption of around 40 million m³/day of natural gas (NG) (FGV, 2019), although the local price of this fuel for industry is one of the highest in the world - reaching 15 US$/MMBtu (EPE, 2019).

In the counterpart, Brazil presents high Direct Normal Irradiation (DNI) incidence levels, reaching 1800 kWh/m²-day in the center-south region, and above 2000 kWh/m²-day in the São Francisco river valley (INPE, 2017). Despite the solar incidence potential, the use of solar thermal energy systems in Brazil is restricted mainly to small installations for hot water production.

In this regard, the objective of this work consists on evaluating the technical and economic feasibility of concentrated solar energy to reduce the natural gas consumption in process steam applications in Brazil. This study contemplates different cities in the national territory, covering different levels of solar incidence and natural gas prices. Furthermore, two cities abroad are also considered to cover higher DNI incidence levels.

2. THE CONCEPT

Under the concept studied in this work (Fig. 1), the saturated steam demand of an industrial process is supplied by a natural gas boiler operated in parallel with a parabolic trough solar field. Heat transfer fluid is heated in the solar field and saturated steam is produced in a thermal oil / water heat exchanger. During the sunny hours, once steam is produced with solar heat, natural gas is economized: the so-called fuel economy operation mode. At night or during overcast hours, the NG boiler load corresponds to the process steam demand.

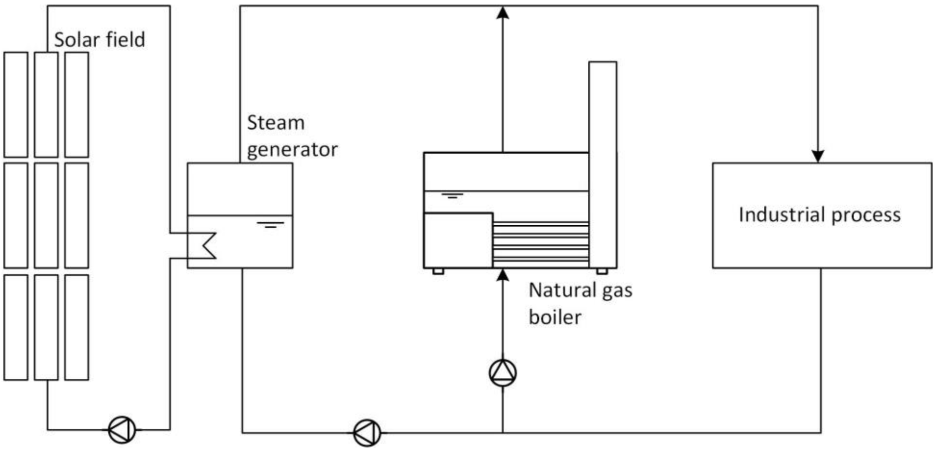


Figure 1. The studied concept.

3. THERMODYNAMIC MODELLING

The solar field simulations were performed using the IPH Trough package of System Advisor Model (SAM®) (version 2020.2.29), by NREL. In this regard, the solar field heat sink was considered as a heat exchanger (see Fig. 1), where the heat transfer fluid (HTF) is cooled and saturated steam is produced. In SAM, simulations are performed for TMY data sets at 1-h time steps. Simulation results include the hourly heat output of solar field, parasitic electricity consumption of plant, solar field thermal efficiency, among others.

After SAM simulations, the hourly fuel consumption was calculated in Excel® by considering that NG boiler produced the steam mass flow necessary to reach the industrial process demand. NG consumption was calculated according to Eq. 1,

$$\eta_{sg} = \frac{\dot{m}_s(h_s - h_{fw})}{\dot{m}_{NG}\, LHV} \tag{1}$$

where η_{sg} [-] represents the steam generator efficiency, $\dot{m}_s$ [kg/h] the steam mass flow, h_s [kJ/kg] the steam enthalpy, h_{fw} [kJ/kg] the feedwater enthalpy, $\dot{m}_{NG}$ [Nm³/h] the NG consumption and LHV [kJ/Nm³] the lower heating value of natural gas.

The economized fuel, EF [Nm³/year], due to the hybrid operation was calculated according to Eq. 2,

$$EF = \sum_{year} (\dot{m}_{NG,b} - \dot{m}_{NG,h}) \tag{2}$$

where the sub-indexes b and h indicate the base case and hybrid plant's NG consumption, respectively.

Finally, the solar fraction, SF [%], which represents the fraction of industry demand provided by solar energy, is calculated according to Eq. 3.

$$SF = 100\% \frac{EF}{\sum_{year} \dot{m}_{b,b}} \tag{3}$$

4. ECONOMIC ANALYSIS

The feasibility of plants was evaluated considering the Levelized Cost of Heat, LCOH [US$/MWh], Eq. (4),

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

where $CAPEX_t$ [US$] is the investment cost, $OPEX_t$ [US$/year] represents the annual operation and maintenance costs, C_t [US$/year] the annual expenditures related to fuel purchasing, H_t [MWh/year] the heat output, r [%] the discount rate, t [years] the time and n [years] the plant lifetime. Quotations and economic assumptions considered in this work are presented at Section 5.1.

5. CASE STUDY

In this section it is presented a case study considering the use of parabolic trough concentrators to produce saturated steam to reduce the natural gas consumption in different sites in Brazil, but also bringing results for USA and Spain, in order to show the influence of DNI incidence on the performance of concept.

5.1 Technical and economic assumptions

The technical assumptions adopted for plant design and simulations are presented at Table 1. As it can be seen, it was considered that the process demanded 10 t/h of saturated steam at 10 bar, 24 hours per day and seven days per week. In addition, solar field was sized to provide 50% of process demand at design point operation. Thus, the NG boiler minimum load was limited to 50% in order not to significantly influence the efficiency (here considered constant) and emissions of this equipment. Regarding the HTF solar field input and output temperatures, they were set to provide saturated steam generation at 10 bar (Tsat=180 ºC) in the thermal oil / water heat exchanger. Finally, additional parameters were defined at SAM by selecting the SkyFuel® trough concentrators, the SCHOTT® PTR 80 receiver and the Therminol® VP1 HTF.

Table 1. Technical assumptions adopted for plant design and simulations.

Parameter	Unit	Value
Process steam demand (10 bar / x=1)	t/h	10 (24h/7d)
Natural gas boiler capacity (10 bar / x=1)	t/h	10
Natural gas boiler efficiency	%	90
Natural gas LHV (1)	kJ/Nm³	1247
Peak solar share (design point)	%	50
Solar field capacity (10 bar / x=1)	t/h	5
Solar field inlet and outlet HTF temperatures	ºC	190 / 290
Solar field area (2)	m²	5248

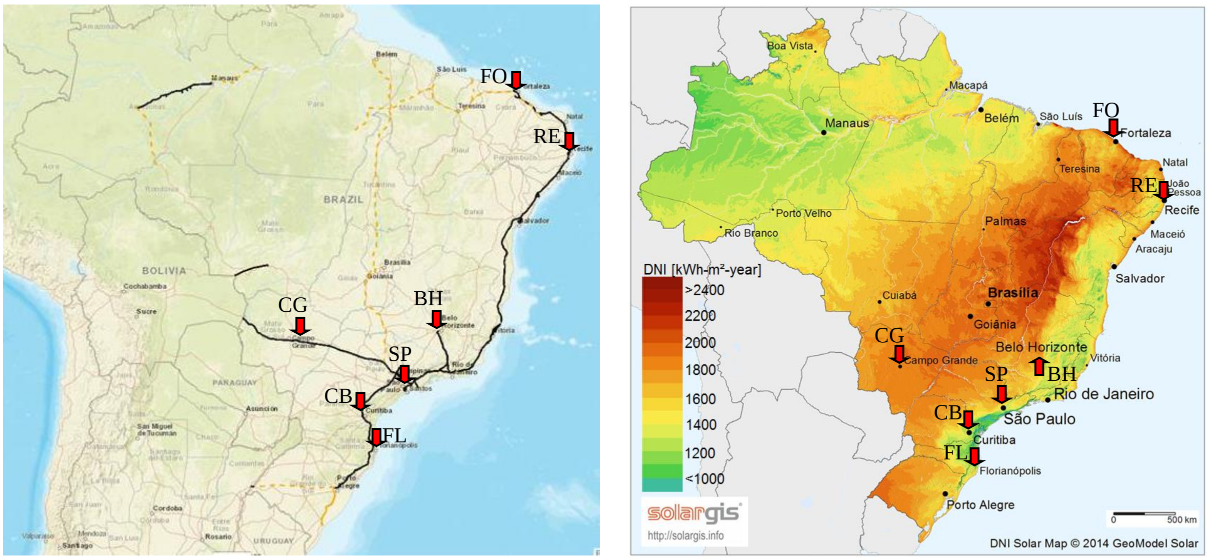
(1) http://www.gasbrasiliano.com.br/media/upload/manual.pdf; (2) Solar field: 2 loops x 4 SCA's SkyFuel®, SCHOTT® PTR 80 receivers and Therminol® VP1 heat transfer fluid.

In Table 2 are listed the cities analyzed in this article, the references for NG costs, and the DNI incidence values. In case of Brazil, natural gas prices are those charged for industrial use by the concessionaires in each region. In Fig. 2 are shown the gas distribution network and DNI incidence maps for Brazil.

Table 2. Studied sites.

City, State	Natural gas cost references	DNI [kWh/m²-year](1)
Curitiba (CB), PR	COMGAS	1223
Florianopolis (FL), SC	SCGAS	1424
Campo Grande (CG), MS	MSGAS	1785
São Paulo (SP), SP	COMPAGAS	1247
Belo Horizonte (BH), MG	GASMIG	1854
Recife (RE), PB	COPERGAS	1518
Fortaleza (FO), CE	CEGAS	1595
Seville (SE), AN, Spain	(STATISTA, 2020)	2091
Phoenix (PH), AZ, USA	(IEA, 2020)	2679

(1)TMY data sets downloaded at https://energyplus.net/weather



(a) (b)

Figure 2. (a) gas distribution network and (b) DNI incidence maps for Brazil

Finally, in Tables 3 and 4 are listed the assumptions adopted for the calculation of CAPEX and OPEX of solar field and base case NG steam generator, respectively. To calculate the LCOH, the interest rate and plant lifetime were set as 8% and 25 years, respectively.

Table 3. Economic assumptions for solar field.

Parameter	Unit	Value
CAPEX	MUS$	2.527
Solar field cost(1)	US$	1.943
Evaporator(2)	US$	163,090
EPC(2)	US$	421,258
OPEX(3)	US$/year	8 US$/kW$_{th}$ + 0.001US$/kWh$_{th}$ + 0.08US$/kWh$_e$

(1)Quoted cost; (2) https://iea-etsap.org/E-TechDS/PDF/I01-ind_boilers-GS-AD-gct.pdf; (3) 2% of CAPEX/year + 1 operator per shift (excluding NG costs)

Table 4. Economic assumptions for natural gas system.

Parameter	Unit	Value
CAPEX	US$	337,500
NG boiler cost(1)	US$	150,000
BOP(2)	US$	75,000
Installation(2)	US$	112,500
OPEX(3)	US$/year	45,150

1 Quoted cost; 2 https://iea-etsap.org/E-TechDS/PDF/I01-ind_boilers-GS-AD-gct.pdf; 3 2% of CAPEX/year + 1 operator per shift (excluding NG costs)

5.2 Results and discussion

In Table 5 are shown the results regarding the base case scenario. In all cities, the annual natural gas consumption was 6.478 MNm³ / year, once boiler efficiency and NG LHV parameters were set constant. Results regarding the NG specific cost and system's LCOH for the different sites are also presented. As it can be seen, Brazil has a high natural gas cost in comparison with Spain and USA, as well as in comparison with other places in the world (STATISTA, 2020), what's one motivation for the development of this work.

Table 5. Base case plants (no solar) results.

Country	Brazil							Spain	USA
City	CB	FL	CG	SP	BH	FO	SE	SE	PH
NG expenses(1), MUS$/year	3.374	2.505	3.003	3.021	3.211	3.070	2.710	2.190	0.893
NG specific cost, US$/MBtu	14	10	12	12	13	12	11	9	4
NG specific cost, US$/MWh	47	35	41	42	44	42	37	30	12
LCOH, US$/MWh	58	43	52	52	55	53	47	38	16

(1)NG consumption in all cases equal to 6.478 MNm³ / year.

Results regarding the thermodynamic analysis of hybridized plants are presented in Table 6. In case of Brazil, the best results in terms of NG economy and solar fraction were obtained for Belo Horizonte (1854 kWh/m²-year). Once DNI is increased, fuel economy and the solar fraction are also increased (see the results for Seville and Phoenix). It might be noticed, in addition, that solar fraction could be increased by implementing thermal storage. In this regard, Silva et al (2014) proposed the process steam generation for a vegetables preservation industry in a parabolic trough solar field equipped with a stratified thermal storage system, reaching a solar fraction above 30% in the southern Spain.

Table 6. Hybrid plants thermodynamic results.

Country	Brazil							Spain	USA
City	CB	FL	CG	SP	BH	FO	SE	SE	PH
Solar field net energy output, MWh/year	3,410	3,992	5,206	3,622	5,338	5,006	4,784	5,730	7,497
NG consumption, MNm³/year	6.107	6.043	5.911	6.084	5.897	5.933	5.957	5.854	5.661
Economized NG, MNm³/year	0.371	0.435	0.567	0.394	0.581	0.545	0.521	0.624	0.817
Solar Fraction	5.7%	6.7%	8.8%	6.1%	9.0%	8.4%	8.0%	9.6%	12.6%
Annual parasitic electricity load, MWh/year	15.4	17.3	21.6	15.7	22.2	20.6	19.5	24.8	32.9

In Table 7 are presented the economic results of hybrid plants for the different sites studied in this work. In this regard, an important analysis to be done consists on the comparison of the solar steam LCOH with the cost of steam generated with NG. In case of Brazil, even considering the high PTC solar field cost of 370 US$/m², the breakeven is reached in the cities of Campo Grande (CG, 1785 kWh/m²-year) and Belo Horizonte (BH, 1854 kWh/m²-year) – see in Table 7 that the hybrid plant combined LCOH is equal or higher than the solar steam LCOH. For Seville and Phoenix, the solar steam LCOH was lower in comparison with the Brazilian scenarios, but breakeven with NG was not reached due to the lower gas prices in that countries – specially in USA.

Table 7. Hybrid plants economic results.

Country	Brazil							Spain	USA
City	CB	FL	CG	SP	BH	FO	SE	SE	PH
Solar field OPEX, US$/year	32,406	33,139	34,697	32,641	34,876	34,411	34,103	35,476	37,892
NG expenses, MUS$/year	3.183	2.341	2.744	2.847	2.962	2.814	2.493	1.979	0.780
Annual economy, 10³US$/year	159	130	224	141	214	222	183	175	75
Solar steam LCOH, US$/MWh	79	68	52	74	51	54	57	48	37
Hybrid plant combined LCOH, US$/MWh	59	45	52	54	56	53	48	39	19

Once the feasibility of proposed system is dependent on the solar field and natural gas costs, a sensitivity analysis is presented below. In this regard, in Fig. 3, the solar steam LCOH for the different studied cities in Brazil and for different solar field costs is compared with the LCOH of a natural gas boiler (NG @ 12 US$/MMBtu - average NG cost in Brazil). As it can be seen, once DNI is lower, solar field cost might be also lower to reach breakeven. For example, in case of Curitiba, the solar field specific cost should be reduced by -43% against the reference (370 US$/m²) in order the solar steam cost breakeven with steam produced burning natural gas.

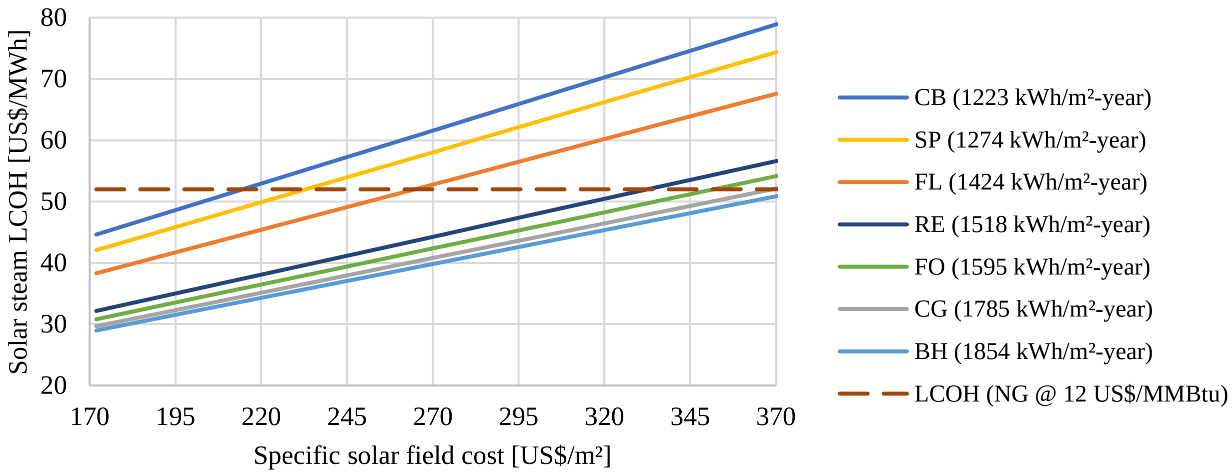


Figure 3. Solar steam LCOH versus solar field specific cost for different sites.

In Fig. 4, in the other hand, are presented the NG costs that would turn the solar steam feasible in comparison with steam generated with NG, as a function of DNI and for different solar field specific costs. To make the graph clearer, only the cities in Brazil with the higher and lower DNI levels are plotted. As it can be seen, the higher the DNI, the lower the NG cost to reach breakeven. In case of Phoenix, for example, due to the high DNI, reduced gas prices would already turn the CSP technology feasible. Currently, however, even if solar field cost would be reduced by -50% (185 US$/m²) against the reference (370 US$/m²), the NG cost to reach breakeven would be yet above the today's practiced 4 US$/MMBtu. Anyway, the presented results are important for the identification of niches for the concentrated solar technology, considering the frequent fluctuation in the price of gas, as well as the prospect of reducing the cost of CSP.

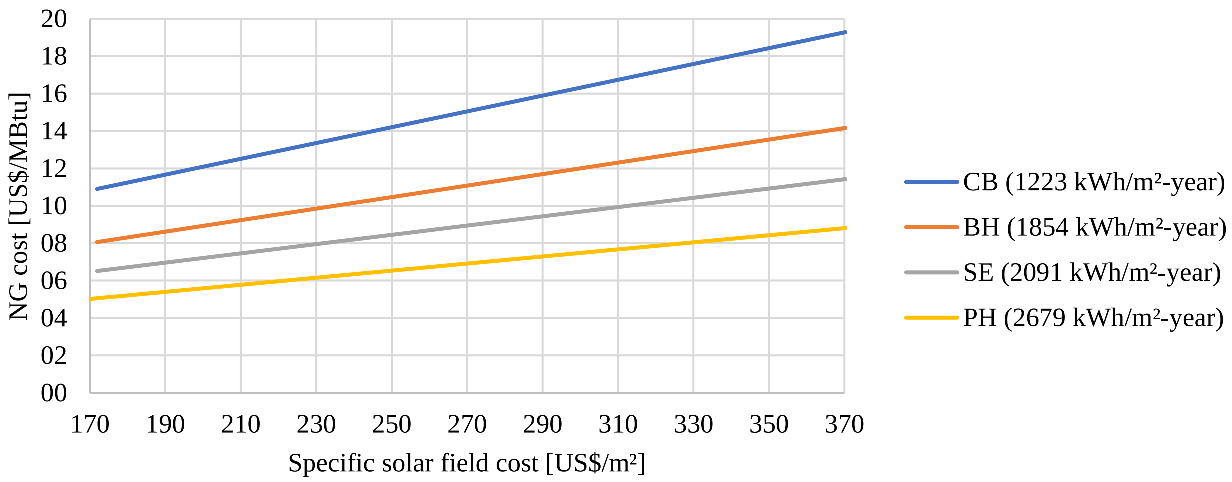


Figure 4. NG cost that turns the solar steam feasible as a function of solar field cost for different locations.

Similar results are presented in the literature, but in fact, the feasibility of solar thermal energy for process steam generation depends on which technology is considered, plant configuration, steam pressure/temperature, among other aspects. For example, Cortés et al (2018) present the LCOH for solar steam at different pressure levels in different regions of Chile. Gabbrielli et al (2014), suggests that linear Fresnel LCOH (process steam at 200°C) would breakeven the NG steam LCOH of 50 €/MWh in sites where DNI is 1900 kWh/m²-year for a solar field specific cost at 280 €/m². Marín et al (2019) studied the integration of a Fresnel solar field in a cogeneration plant designed to provide the electricity and thermal demands of a textile industry in Santa Catarina / Brazil, suggesting that solar field specific cost should be 170 US$/m² for the hybrid plant present the same economic feasibility in comparison with the base case.

The figures here presented are preliminary and further analyses will be generated in the context of the ongoing project, considering different steam temperatures, solar field technologies, and the hybridization of CSP with biomass. These preliminary results turn clear the potential of CSP in Brazil for process steam generation due to the high natural gas costs and important DNI incidence levels. It is shown that solar thermal energy can significantly contribute to reducing CO2 emissions and industrial operating costs with energy.

6. CONCLUSION

In this work, the feasibility of applying parabolic trough concentrators to generate process steam in the industry was evaluated in order to reduce the consumption of natural gas. The study was carried out considering different cities in Brazil, as well as two cities outside the country, covering different levels of DNI and natural gas prices.

The price of natural gas for industry in Brazil is especially high, reaching up to 15 US$/MMBtu. In this regard, for the cities of Campo Grande and Belo Horizonte with DNI close to 1800 kWh/m²-year, the cost of steam generated by the hybrid system was similar to the cost of steam generated by the base system, demonstrating the feasibility of the proposed system. For the cities of Seville and Phoenix, also studied in this work, despite having a higher incidence of DNI compared to Brazilian cities, concentrated solar technology was not feasible, since the cost of natural gas in these locations is lower.

In summary, the results presented here demonstrate the potential of concentrated solar energy technology for generating process steam and reducing greenhouse gas emissions, especially if we consider the prospect of reducing the implementation and O&M costs of this technology still in the consolidation phase in the world.

7. ACKNOWLEDGEMENTS

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