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Simultaneous Production of Solar Thermal Heat and Power for Industrial Applications

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Currently most of the energy production is supported by fossil fuels, however, renewable sources contribution on worldwide demand of energy has been in constantly growth. One of the main challenges in the use of solar thermal energy in industrial processes is their cost, especially when is compared to energy generation by fossil fuels. This cost delimits the investment payback time for a thermo-solar installation to be feasible. This fact makes crucial the development of methodologies for the integration of solar energy for large-scale industrial applications. This work deals with the thermo-economic evaluation of the heat and power production through a low-temperature flat-plate solar collector system. Also, strategies were developed to increase energy efficiency by evaluating different process integration scenarios. The proposed strategies for energy efficiency combined with renewable energy were applied to an integrated solar thermal energy system into a 1G and 2G (first and second generation) bioethanol process from sugarcane. It was found that to replace the fully process heat and power with low-temperature solar thermal energy, a heat recovery network ΔT_{min} of 5 °C, a heat duty of 131 kW and a supply temperature of 105 °C are required. All these results lead to a cost of 0.2112 USD/kWh of the integrated system. The power system operates independently by mean an Organic Rankine Cycle and the heating system is supplied by a solar collector network with a cost of 0.0477 USD/kWh$_{ele}$.

1. Introduction

During 2018, worldwide the industrial sector consumed around 28.5 % of the world total energy consumed (IEA, 2020). To achieve the goal of net reduction of greenhouse gas emissions by at least 55 % by 2030 (European Commission, 2021) and also achieve decarbonisation by 2050. It is necessary, among other things, that climate policies be restructured to increase energy efficiency by 32.5 % and encourage the participation of renewable energies by the same amount. This means significantly reduce the use of natural gas and other coal-based fuels. To produce process heat, process steam or electricity more efficiently, and minimise GHG emissions, the integration of renewable energies into industrial processes needs to be a priority. Previously some of these attempts have been studied and implemented based on the Pinch Analysis (Varbanov and Klemeš, 2011). To generate clean power, can be either by a single energy source or a hybrid renewable energy system (HRES), this is, using two or more renewable sources with a minimum fossil fuel backup and storage (Come et al., 2021). Among the possible conformations of HRES are photovoltaic systems: (PV)–wind–hydrogen fuel cell, wind–PV, PV–wind–diesel, hydro–wind–PV, biomass–wind–PV (Sinha and Chandel, 2014). Power can also be generated from low-temperature solar thermal energy systems that can drive conversion systems such as the Organic Rankine Cycle (ORC) (Wang et al., 2013), the Brayton cycle or by a combined heat and power (CHP) system.
The contribution of solar energy to the industrial sector has been growing, but the challenge to widely deploy it is to demonstrate its technical and economic feasibility. Solar process heat integration, both for continuous and batch processes, has the potential to respond to the thermal load supply at some temperature levels (SHC EIA, 2020). Solar plants transfer heat to process fluids, either directly or indirectly, or from a supply system in the form of hot water, air flow, or steam. Storage equipment allows the heat generated to be used at night or on cloudy days. Among the disadvantages of this integration methodology are large surface required and the variability of the solar resource throughout the day and year (Klemeš et al., 2019). However, one of the great advantages of using solar technology is that NO_x, SO_2 and particulate emissions are significantly reduced

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(Patridge and Gamkhar, 2012), advantage that does not exist even when biomass is used, since gas combustion emissions contains ultrafine particles that are extremely harmful to human health (Poláčik et al., 2018). Solar thermal heating can generate temperatures on ranges from ambient to 350 °C. Many representative industrial sectors like as food products, beverages, textiles, tanning and pharmaceuticals, can benefit from solar plants (Ship Plants Database, 2021). The success of integrate solar thermal in industrial process depends directly on the cost of fossil fuel that it will replace (natural gas or other), which varies constantly worldwide. In some countries like Mexico the subsidies of fossil fuels makes harder the solar integration, e. g. parabolic trough collectors, because despite having demonstrated its technical feasibility, operating costs in many cases cannot be competitive with regard the large subsidies of natural gas (Tzuc et al., 2020). Similar economic challenges occur in some regions of Africa with coal (Oosthuizen et al., 2020).
In the present study a new approach is implemented to integrate low-temperature solar thermal energy to a 1G and 2G bioethanol production plant to deliver the whole heat duty and daily required power. Two flat-plate solar collector networks were designed separately: one of them is to supply the whole process heat and the other to feed the power through an Organic Rankine Cycle (ORC). This case study solidifies the technical and economic feasibility of the novel proposal and shows how it could be viable.

2. Method for integrating solar thermal energy into an industrial process to production of heat and power

In the integration of solar thermal energy using the Pinch Analysis, the minimum hot and cold utilities are determined from the information of the process streams, and in most cases a ΔT_{min} is selected based on the minimum total cost. However, there are other variables that must be considered, like environmental impact, minimum absorbing area and use of clean resources — solar thermal energy. The evaluation of these variables will define the feasibility of integrating not only the process thermal energy but also the power used by the same industrial process. The feasibility is based on the evaluation of different scenarios varying the ΔT_{min}, the corresponding minimum temperature difference between hot and cold utilities in the heat recovery network.
The Grand Composite Curve (GCC) allows to establish other temperature levels at which the process services could be supplied. Using this tool, it can set a ΔT_{min} in which is possible integrate low-temperature solar thermal energy (around 100 °C) and determine the possibility of cover all the process requirement by solar energy (solar fraction of one) that could reduce the size of the solar collector network.
Once the hot utility is defined, it is possible to design the solar thermal system, which includes the solar collector network, thermal storage, and control system, with different configurations according to the process needs and operation. Thermal storage system must provide certainty and stability to the industrial process. The design was carried out with the critical conditions that exist during the winter in Mexico. The model used to evaluate and design the flat-plate solar collector network and storage system is the one proposed by Martínez-Rodríguez et al. (2019). Two solar collector networks were designed, one to supply the necessary heat duty by the process and one more to be used in the Organic Rankine Cycle to produce the total process power requirements.
An analysis of the thermodynamic variables and parameters was carried out on the power produced and the cycle performance by Eq(1) and Eq(2).

$$W_{ORC} = W_T - W_P \quad (1)$$

$$\eta_{ORC} = \frac{W_{ORC}}{Q_{EVA}} \quad (2)$$

where η_{ORC} is the thermal efficiency of the Organic Rankine Cycle Cycle, W_{ORC} is the power produced by the power Organic Rankine Cycle (kW), W_T is the power generated by the turbine (kW) and W_P is the power used for pumping (kW). Q_{EVA} is the thermal load of evaporator (kW).

2.1 Costs calculations for solar thermal heat system and solar thermal power system

The cost associated with the solar thermal system and the heat recovery network are based on different models reported in literature. The cost of the solar collector network from Lizárraga-Morazán et al. (2020), cost of the storage system and the cost related to the heat recovery network from Towler and Sinnott (2013), and the auxiliary heating and cooling services costs considered were 0.0116 USD/kWh for the heating water and 0.0018 USD/kWh for the chilled water (Trisha et al., 2021).
The cost of the power system using solar thermal energy includes the cost of the solar thermal system and the cost of the power Organic Rankine Cycle. The cost of the ORC considers the capital cost (evaporator, turbine-generator, condenser, and pump) and other costs related with civil infrastructure and architecture, service installation, construction supervision, manpower and contingencies (Mohammadi et al., 2019).

Finally, an economic analysis was carried out to determine the feasibility and the viability of solar thermal integration. The costs of the solar thermal kWh ($C_{kWh_{th}}$) and the integrated system kWh (kWh is) were levelised at 30 y life span. The plant operates 24 h/d for 365 d (Valderrama et al., 2020). In the economic evaluation, an interest rate of 5 % was considered (Smith, 2005). The $C_{kWh_{th}}$ is calculated with Eq(3).

$$C_{kWh_{th}} = \frac{C_{TA\,SOLAR}}{P_{TA}} \tag{3}$$

where $C_{TA\,SOLAR}$ is the cost of the total annualised investment at 30 y (USD) of the solar thermal network and P_{TA} is the total thermal load in the same period (kWh_{th}). The fossil fuels savings in a year, A_{comb}, are used to calculate the simple payback time ($Payback_{SOLAR}$) with Eq(4). The emissions are calculated taking the natural gas parameters, that are published for a typical fixed combustion equipment (EIA, 2016).

$$Payback_{SOLAR} = \frac{C_{TA\,SOLAR}}{A_{comb}} \tag{4}$$

3. Case study: bioethanol production from sugarcane, first (1G) and second generation (2G)

The necessary unit operations of sugar and bioethanol production process are presented in Figure 1. The production of 1G and 2G bioethanol from sugarcane is 120 L/t. The facility process 38 t/h of sugarcane, the total bagasse generated is 12,564.5 kg/h of which 60 % is used to generate electricity and steam. The generated power is approximately 3.2 GW that is used to supply energy for the process, mainly for milling sugarcane.

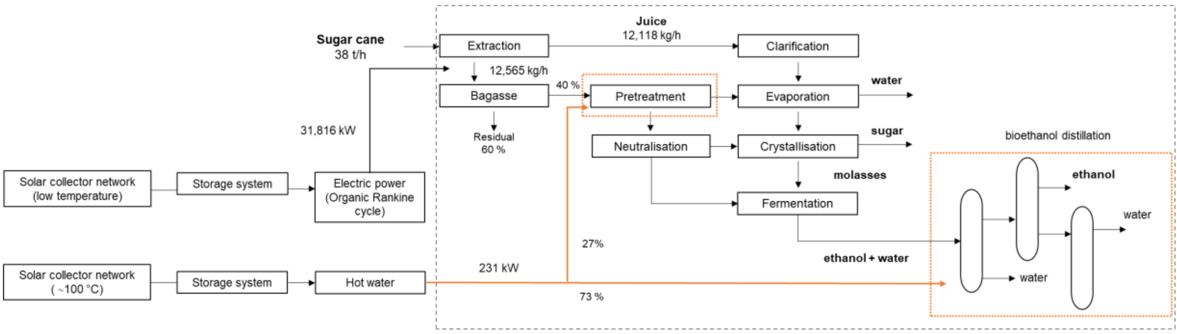

Figure 1: Flow diagram of the main stages of the 1G and 2G bioethanol production process and the solar thermal energy integration to supply heat and power requirements

The efficiency of the boiler is 64 % (Valderrama et al., 2020). Thermal energy is consumed in the bagasse pre-treatment and in the bioethanol purification section, which are highlighted with orange dotted line. The novel proposal includes replacement of the cogeneration system by two solar collector networks to produce the process heat and power.

To determine the minimum utilities for heating and cooling, the Pinch Analysis was applied, using information from the process streams. The operation conditions of the bioethanol process streams are shown in Table 1. The convective coefficient (h) of the working flow was considered 3 kW/(m^2 °C).

Table 1: Data from the main process streams

Streams	Description	T_i (°C)	T_o (°C)	CP (kW/°C)
H1	Neutralisation 1	167	50	22.19
H2	Neutralisation 2	52	25	7.63
H3	Neutralisation 3	52	30	44.65
H4	Distillation 1	98	32	48.36
H5	Distillation 2	150	25	5.43
C1	Extraction juice	25	90	14.40
C2	Clarification 1	34	85	40.34
C3	Clarification 2	84	100	50.03
C4	Separation 1	38	50	80.14
C5	Separation 2	93	150	27.97

To integrate the solar thermal energy in the bioethanol process, the Grand Composite Curves were used varying the ΔT_{min}. Figure 2a shows when a ΔT_{min}= 5 °C in the heat recovery network, in this case it is possible to supply the entire thermal load with low temperature solar collectors. Figure 2b shows the process when ΔT_{min}= 10 °C, in this case it is necessary to use fossil fuels to supply auxiliary services of heating. By increasing ΔT_{min}, the solar fraction diminishes because the temperature of the required process hot utility cannot be reached with low-temperature solar collector networks.

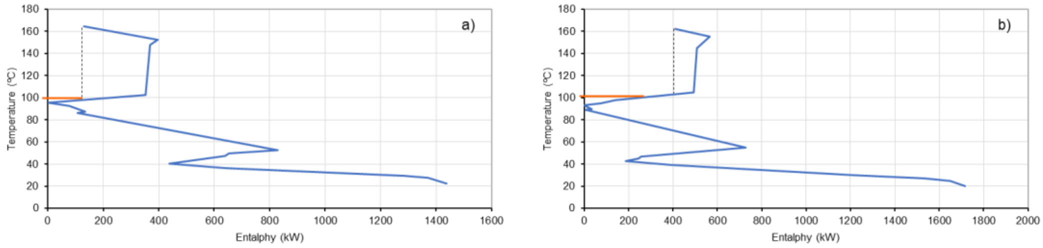

Figure 2: Grand Composite Curve of bioethanol process plant from sugarcane: a) ΔT_{min}= 5 °C, b) ΔT_{min}= 10 °C

Table 2 shows the results using the proposed approach to integrate the solar thermal energy to industrial process. The scenarios considered in this study were those whose ΔT_{min} fell between 5 °C and 10 °C, with solar fractions between 1.0 and 0.6. The size of the solar collector network is directly related to the solar fraction. There are three scenarios with solar fraction equal to one. Comparing the first scenario (ΔT_{min}= 5 °C) against the third scenario (ΔT_{min}= 7 °C), the cost varies significantly by 42.5 %, and the absorbing area by 43.7 %.

Table 2: Relationship of ΔT_{min} with the solar thermal integration to industrial process parameters

ΔT_{min} (°C)	Q_h (kW)	f	Array of the solar collector network	C_{RRC} (USD)	A_C (m²)	V_{TA} (m³)	$C_{T\ sd}$ (USD)	$C_{T\ is}$ (USD)
5	131	1.00	40x29	2,392,562	2,123	32	651,570	3,044,132
6	181	1.00	56x29	2,254,598	2,972	45	900,496	3,155,094
7	231	1.00	71x29	2,137,619	3,768	58	1,132,957	3,270,575
8	281	0.96	82x29	2,036,856	4,352	66	1,303,016	3,339,872
9	346	0.74	78x29	1,968,149	4,139	63	1,241,212	3,209,360
10	410	0.59	74x29	1,875,677	3,927	60	1,179,368	3,044,132

The results for the power Organic Rankine Cycle driven by solar thermal system are shown in Table 3. In this case, for each ΔT_{min} it is supplied the whole power demanded by the process. The fuel savings vary with the minimum hot utility and solar fraction. In the three first scenarios the cost of solar thermal kWh (kWh_{th}) remains constant, while the total cost of kWh from the integrated system (kWh_{is}) decreases. In general, is considered natural gas use to produce heat for industrial processes. The average cost in the first quarter of 2021 of natural gas in Mexico is 0.0216 USD/kWh and the CO_2 emission factor of natural gas is 0.1850 kg/kWh according to (EIA, 2016).

Table 3: Economic and emissions analysis for the bioethanol heat

ΔT_{min} (°C)	Fuel savings (USD/y)	Solar System Payback (y)	CO_2 emissions by burning natural gas (t/y)	kWh_{th} cost of solar thermal system (USD/kWh)	kWh_{is} total cost of integrated system (USD/kWh)
5	24,752	26.3	0	0.0369	0.2112
6	34,202	26.3	0	0.0369	0.1571
7	43,653	26.0	0	0.0364	0.1267
8	50,767	25.7	22	0.0360	0.1127
9	48,204	25.7	161	0.0361	0.1279
10	45,640	25.8	299	0.0362	0.1440

3.1 Power production

To supply the total process power, an independent low-temperature solar thermal system was designed to provide the thermal load to the evaporator of a power Organic Rankine Cycle (R123), the efficiency of the turbine and the generator was considered 87 % and 85 %. The thermal load of the evaporator is 31,816 kW that is supplied with a network of solar collectors. The cost of the solar system was approximately $145,076,193 USD and the cost of the ORC was $5,494,480 USD. The avoided of CO_2 emissions by using the ORC for power generation are 56,578 t/y and the solar LCOE is 0.0477 USD/kWh.

4. Analysis of the results

The achieved results in Table 3 show that the simultaneous production of heat and power from solar thermal energy is feasible for a 1G and 2G bioethanol process with simple payback time around 26 y. Some of the scenarios makes possible to supply all the thermal energy and power using only solar energy. The selected ΔT_{min} was of 5 °C with: zero emissions to the atmosphere (Table 3), the smallest solar collectors' area (Table 2), the lowest value for integrated cost and solar (Table 2). The whole integrated system is 100 % renewable.
For higher ΔT_{min} values the cost of the solar thermal device decreases because it is not possible to reach the temperature levels needed by the process with low-temperature solar collectors and only a fraction of the total load can be supplied. The cost of ancillary services with fractions less than one increases. All the scenarios, including those with solar fraction less than one, maintain a simple payback time approximately of 26 y. The lowest total cost of kWh for integrated system (kWh is) was with ΔT_{min}= 7 °C, because the cost of the heat recovery network has the lowest value, and the solar fraction is equal to one.
It is important to clarify that the study was carried out in conditions of less irradiance in the year.
The related emitted GHG (metric t) by year grow significantly when the solar fraction is less than one reaching values up to 299 t/y. To provide the total process heat duty by a solar system the process should be operate to a ΔT_{min} between 5 - 7 °C. The average cost of the solar thermal kWh_{th} is 0.0368 USD. The average total cost of the thermal kWh_{th} of the integrated system is 0.1650 USD. The burning bagasse to generate heat and power could be replaced using solar thermal energy.

5. Conclusions

The integration of solar thermal energy was feasible based in the result reached. There are three scenarios with zero emissions but, the scenario with ΔT_{min}= 7 °C presents the lowest kWh_{th} cost for the solar system and for the integrated system cost. The absorbing area in this scenario is 77 % bigger compared with the scenario with ΔT_{min}= 5 °C. The total power demanded by the process could be supplied with the Organic Rankine Cycle fed by a network of low-temperature solar collectors. It is important to highlight that payback time is directly related to natural gas cost and this fact impacts it significantly. The payback time could be adjusted by reducing the solar fraction for a constant hot utility. Regarding GHG emissions, the analysed scenarios focused on those where emissions are completely avoided. For the specific case of the bioethanol industry, the comparison between two renewable sources (solar energy and biomass) is attractive since the residuals (bagasse) are burned to generate power and heat to be used in the process, and because the costs of kWh for heat and power are competitive.

Nomenclature

A_C – Solar absorbing area, m^2
CP – Heat capacity flowrate, kW/°C
C_{RRC} – Cost of heat recovery network, USD
$C_{TA\ is}$ – Cost of integrated system, USD/y
$C_{T\ sd}$ – Cost of solar thermal system, USD
ΔT_{min}– Minimum temperature difference, °C
f – Solar fraction
GCC – Grand Composite Curve
GHG – Greenhouse Gases
h – heat transfer coefficient, kW / (m^2 °C)
kWh is – Thermal kWh for integrated system
kWh_{ele} – Electric kWh
LCOE – Levelised Cost of Energy
ORC – Organic Rankine Cycle
Q_h – Heating thermal load, kW
Q_{EVA}- Thermal load of evaporator, kW
T_i – Inlet temperature of the fluid, °C
T_o – Outlet temperature of the fluid, °C
t – Metric t
V_{TA} – Storage tank volume, m^3
η_{ORC} - thermal efficiency of the Organic Rankine Cycle Cycle

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References

Authin E.A., Liew P.Y., Klemeš J.J., Ho W.S., Che Jusoh N.W., Mohammad Rozali N.E., 2021. Integration of Combined Heat and Power Energy Systems with Gas Turbine in Locally Integrated Energy Sectors. Chemical Engineering Transactions, 83, 37-42.

Brunner C., 2020. SHC IEA: Solar Heat Integrations in Industrial Processes, Technology Position Paper, <iea-shc.org>, accessed 31.03.2021.

Come Zebra E. I., van der Windt H. J., Nhumaio G., Faaij A. P. C, 2021. A review of hybrid renewable energy systems in mini-grids for off-grid electrification in developing countries. Renewable and Sustainable Energy Reviews, 144, 111036.

European Commission, 2021. 2030 Climate & energy framework, <ec.europa.eu/clima/policies/strategies/2030_es>, accessed 31.03.2021.

IEA, 2020. World Energy Balances Highlights, <iea.org/data-and-statistics/data-product/world-energy-balances>, accessed 31.03.2021.

EIA, 2016. Carbon Dioxide Emissions Coefficients. US Energy Information Administration, <eia.gov/environment/emissions/co2_vol_mass.php>, accessed 29.06.2021.

Klemeš J. J., Varbanov P. S., Oclón P., Chin H. H., 2019. Towards Efficient and Clean Process Integration: Utilisation of Renewable Resources and Energy-Saving Technologies. Energies, 12, 4092.

Lizárraga-Morazán J.R., Martínez-Rodríguez G., Fuentes-Silva A.L., Picón-Núñez M., 2020. Selection of solar collector network design for industrial applications subject to economic and operation criteria. Energy & Environment, doi:10.1177/0958305X20927375.

Martínez-Rodríguez G., Fuentes-Silva A. L., Lizárraga-Morazán J. R., Picón-Núñez M., 2019. Incorporating the Concept of Flexible Operation in the Design of Solar Collector Fields for Industrial Applications. Energies, 12, 570.

Mohammadi K., McGowan J. G., 2019. Thermoeconomic analysis of multi-stage recuperative Brayton cycles: Part II – Waste energy recovery using CO_2 and organic Rankine power cycles. Energy Conversion and Management, 185,920-934.

Oosthuizen D., Jurgens Goosen N., Hess S., 2020. Solar thermal process heat in fishmeal production: Prospects for two South African fishmeal factories. Journal of Cleaner Production, 253, 119818.

Partridge I., Gamkhar S., 2012. A methodology for estimating health benefits of electricity generation using renewable technologies. Environment International, 39, 103–110.

Poláčik J., Šnajdárek L., Špiláček M., Pospíšil J., Sitek T., 2018. Particulate Matter Produced by Micro-Scale Biomass Combustion in an Oxygen-Lean Atmosphere. Energies, 11, 3359.

Ship Plants Database, 2021. 2013-2021 Database for applications of solar heat integration in industrial processes, AEE INTEC, <ship-plants.info/>, accessed 31.03.2021.

Sinha S., Chandel S. S., 2014. Review of software tools for hybrid renewable energy systems. Renewable and Sustainable Energy Reviews, 32, 192-205.

Smith R., 2005. Chemical Process Design and Integration. John Wiley & Sons, Ltd., Chichester, UK.

Towler G., Sinnott R., 2013. Chemical Engineering Design: Principles, Practice and Economics of Plant and Process Design. Butterworth-Heinemann, Oxford, UK.

Trisha V., Koh K. S., Ng L. Y., Chok V. S., 2021. Heat Exchanger Network Retrofit of an Oleochemical Plant through a Cost and Energy Efficiency Approach. ChemEngineering, 5, 17.

Tzuc O.M., Bassam A., Ricalde L.J., Jaramillo O.A., Flota-Bañuelos M., Escalante Soberanis M.A., 2020. Environmental-economic optimization for implementation of parabolic collectors in the industrial process heat generation: Case study of Mexico. Journal of Cleaner Production, 242, 118538.

Varbanov P.S., Klemeš J.J., 2011. Integration and management of renewables into Total Sites with variable supply and demand. Computers & Chemical Engineering, 35, 1815-1826.

Valderrama C., Quintero V., Kafarov V., 2020. Energy and water optimization of an integrated bioethanol production process from molasses and sugarcane bagasse: a Colombian case. Fuel, 260, 116314.

Wang M., Wang J., Zhao Y., Zhao P., Dai Y., 2013. Thermodynamic analysis and optimization of a solar-driven regenerative organic Rankine cycle (ORC) based on flat-plate solar collectors. Applied Thermal Engineering, 50, 816-825.