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Solar Thermal Integration With and Without Energy Storage: the Cases of Bioethanol and a Dairy Plant

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This paper looks at the resulting combination of working fluid inlet temperature and heat storage capacity as a means for increasing the solar fraction and the number of hours that renewable energy can be supplied to a background process. The portion of the process heat duty that can effectively be supplied from solar thermal energy, or solar fraction, increases with the inlet temperature of the solar field. The increase of inlet temperature is beneficial since it reduces the size of the solar field. The way to achieve higher inlet temperatures is by means of surplus heat that is stored during sunny hour. For further increasing the period of operation beyond sunny hours, thermal storage must be increased. In this work, two case studies are considered and it is found that the integration of solar thermal plants proves to be a cost-effective alternative in energy conservation and pollution reduction. The payback time reveals that doubling the time where the solar system delivers the required temperature is still profitable.

1. Introduction

There is a significant amount of solar thermal applications in the domestic and service sectors (Evangelisti et al., 2019). In the industrial sector, the application of solar thermal energy is still developing and the challenges associated include the generation of methodologies for the cost-effective solar thermal energy integration into continuous or batch processes. The integration of solar thermal energy could target for the partial or total supply of the process thermal load and must look at the technical, economic, environmental and sustainable aspects.
A considerable amount of work has been done on the solar thermal energy integration in industrial processes. Quijera et al. (2014) reported the case of a canned fish factory where a fraction of 0.115 of the total process duty was supplied with solar energy. Storage was not included in the study, and the collector area was 500 m^2. There are other published works where the heat storage is considered for solar energy integration (Walmsley et al., 2015). The size of the solar collector network has a direct relationship with solar fraction as reported Baniassadi et al. (2015) who developed an algorithm to find the best scenario to integrate thermosolar energy through solar fraction maximisation. This algorithm was applied to an organic distillation plant where heat recovery was first maximised using a ΔT_{min} of 20 ºC, and a field of 1,000 solar collectors was used to supply a solar fraction of 0.051. The payback time of investment was 9 years. Eiholzer et al. (2017) used a time average model (TAM) and time slide model (TSM) to carry out the energy integration of a brewery plant. They achieved a solar fraction of 0.077 with 300 m^2 of evacuated-tube solar collectors area, a storage tank of 17 m^3, and ΔT_{min} of 12 ºC. CO_2 emissions were nearly 38 tons by year and the payback time of investment was of 6.4 years. Allouhi et al. (2017) simulated and optimised a centralised solar heating system for the supply of hot water to four processes. For a dairy process, they concluded that an evacuated-tube solar collector network of 400 m^2, which in turn is connected to a storage tank of 2,000 L, can save 179 kUSD, providing a total annual heat demand of 528.23 MWh. The solar fraction was 41 % and the investment payback time was 12.27 years. The system, can reduce CO_2 emissions by 77.23 t in a year.
It has been identified that between 50 and 70 % of total solar thermal energy costs are related to the capital investment, while the rest includes the costs of installation of the devices and the energy integration (Carbon Trust, 2013). In terms of component costs, the solar collector and its installation constitute 50 %, the pipes 20

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%, the thermal storage and heat exchangers 11 % and the control system 5 % (IRENA, 2015). Walmsley et al. (2018), also reviewed the most important economic parameters that must be considered to calculate the energy/cost rate, including a sustainability evaluation. Constant price increments on energy supply and environmental regulations related to emissions, have compeled the industrial sector to either reduce their energy consumption or substitute the consumption of non-renewable sources. Fortunately, the integration of solar energy offers designers a wealth of possible configurations to achieve different design purposes, as commented by Mangili (2019).

In the present work, the solar thermal integration to industrial processes incorporates the cost of the solar collector network and the associated costs due to thermal storage. Two case studies are analysed, a batch plant and a continuous process. Apart from the economic and environmental aspects, the feasibility of the integration of solar energy into industrial processes is analysed from the operating poit of view.

2. Thermal integration methodology

The design of energy recovery systems and the supply of external utility services have become standard practices in industry due since the introduction of Pinch Analysis design tools (Pedraza, 2017). Pinch Analysis leads the design to target for the minimum heating and cooling external requirements and to achieve an optimal driving force for heat recovery. When solar energy comes into play, its thermal integration poses a set of new challenges, since its low density and intermittency call for considerable plot areas for installation and energy storage for better plant operation.

2.1 Basic considerations

The main issues regarding the integration of solar energy into process plants, whether continuous or semi-continuos, is the way solar energy is availed of to increase the span of time where captured solar energy can be used directly into the process. In this regard, thermal storage is the key issue. Two scenarios can be considered here: a) the supply of solar energy during the period of insolation and, b) extending the operation with solar energy beyond that period. Exteding the operating time brings about larger costs due to energy storage capacity. In this work, both scenarios are analysed.

2.2 Thermal solar storage

To calculate the volumetric thermal storage system capacity, expression Eq(1) (Yang et al., 2014) is employed:

$$C_{STC} = \rho \; C \; \Delta T \tag{1}$$

Where, C_{STC} is the volumetric thermal storage system capacity (kWh/m^3), C is the heat capacity-mass flow rate of heat transfer fluid (kWh/kg ºC), ρ is the density of the heat transfer fluid (kg/m^3) and ΔT is the temperature difference (ºC). The volumetric storage capacity indicates the capacity that a certain volume of a medium has for storage of certain amount of thermal energy as a temperature change takes place. The size of the storage system defines the amount of hours that a process is capable of functioning without additional heat from the solar collector network. To calculate the storage volume, a modified equation, Eq(2), from Yang et al. (2014) is used:

$$\mathrm{V} = \frac{Q_r \; \mathrm{t}}{C_{SCT}} \tag{2}$$

Where, V is the volume of the thermal storage (m^3), Q_r is the heat required by the process where the integration is carried out (kW), t is the operation time of the solar thermal storage system (h), C_{STC} is the volumetric thermal storage system capacity (kWh/m^3). The calculation of the cost of the storage system (C_e) takes into account storage containers, pipes, electricity, installation costs, civil engineering works and labour. According to Yang et al. (2014) the following equation, Eq(3), is used to calculate the cost of the storage tank:

$$Ce = a + bV^c \tag{3}$$

The corresponding values *a, b* and *c* (constants of the cost equation) are taken from Towler and Sinnott (2013), with a cost base for the year 2010. The cost is updated using a plant cost index of 1.18. The given values of the correlations corresponding to Eq(3) are: *a* = 5,800, *b* = 1,600 and *c* = 0.7.

3. Solar thermal plant costs

The cost of the thermal system is analysed under two modes of operation: a) the whole external energy requirement is supplied by the solar thermal plant and no heat recovery within the plant is considered, and b) solar thermal energy is determined after heat recovery within the plant takes place. The total investment costs

now include the heat recovery system, the thermal plant and the heat storage system. The cost difference between these two modes of operation are associated to the solar installation.
Total cost equation after the solar thermal integration is given by the expression:

$$C_{TS} = C_{HRN} + C_{SP} + C_{conv} \quad (4)$$

Where, C_{TS} is the total cost of the integrated system ($), C_{HRN} is the total cost of the heat recovery network ($), C_{SP} is the total cost of the thermosolar installation ($) (Lizárraga-Morazán et al., 2019) and C_{conv} is the energy cost of the conventional energy system ($).The estimated C_{HRN}, developed by Rathjens and Fieg (2020), considers fixed and variable costs that include those of the heat exchanger network as auxiliary services. The C_{TS} also considers fixed costs (equipment, etc.) and variable costs (labour and installation, other services), both for the solar collectors network and for the thermal storage system.

4. Case studies

4.1 Dairy plant

In a dairy products plant, three products are produced from cow's milk: yogurts, cheeses and non-fermented milk drinks. The plant operates in batches and 20,000 L of milk are pasteurised daily. Production takes place from 6:00 to 18:00 h every day, seven days a week for 360 days a year. The plant uses a natural gas boiler, to produce hot water at 95 ºC for the pasteurisation of milk. The energy efficiency of the boiler is estimated at 92 %.
Figure 1 shows the thermal load profile as a function of irradiance at different hours a day, on a surface of 1,000 m^2. Due to the discontinuous nature of the operations and their time lag the hot water tank is a key element to meet the heat demand. Figure 1 shows the schedule of the various energy demands and the availability of the solar heat (7:30 - 17:45 h).

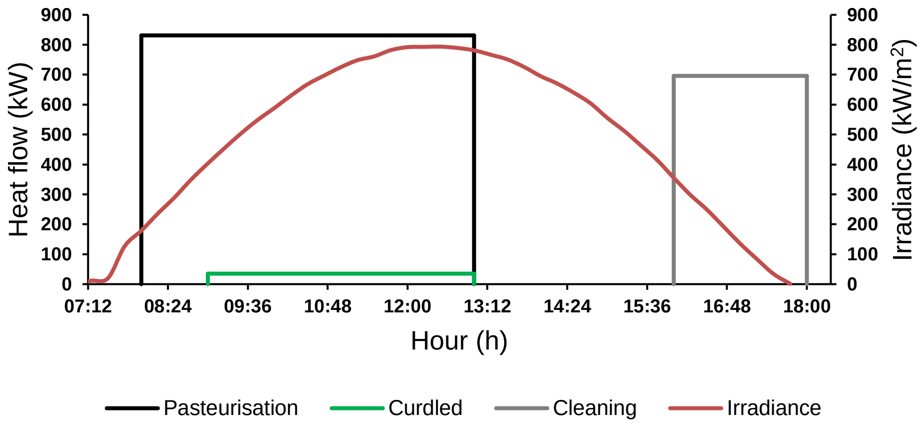

Figure 1: Thermal load profile and process requirements as a function of irradiance on a 1,000 m^2 surface at different hours a day

External heating services provide a heat flow of 880.20 kW for 5 hours. This is done by supplying a continuous volumetric flow of 180 L/min of water at a temperature of 95 ºC for 5 h (this consideres a minimum ΔT of 10 °C for heat transfer). Throughout this time, the total thermal load produced by the boiler is 4,401.01 kWh, which, in principle, can be provided with low temperature solar energy. Pasteurisation requires a temperature of 85 °C between 8:00 and 13:00 h. The curdling stage requires a temperature of 40 °C for 4.5 h and the cleaning process requires a temperature of 62.4 °C from 16:00 to 18:00 h.
In the operation mode where no heat recovery is considered, a solar field is designed to meet the 95 °C delivery temperature. This can be achieved through a 34 x 28 (parallel-series) collector network (Martínez-Rodríguez et al., 2019). The system reaches a temperature of 95 °C only between 11:00 and 13:00 h. This means that solar energy can only be supplied for two hours. However, if energy is stored so that the supply temperature to the network of collectors can be increased to 60 °C, the solar system wil be able to supply the required 95 °C during the 5 hour-period. The solar collector field for this operation contains a total of 1,682 units with a total surface

area of 3,263.08 m², in a 58 x 29 (parallel-series) arrangement and a storage tank of 47.0 m³. The total cost of the systems is $ 1,451,563.23 of which, 4 % correspond to the storage tank.
In the second mode of operation, heat recovery within the plant is maximised first and the external heating and cooling utilities determined. The optimal ΔT_{min} is determined, which is approximately 10 ºC, as shown in Figure 2. The heat recovery network operates with 18 exchangers and the external heating service is 294.78 kW with a total investment cost of $ 834,504.70. If this heating utility is supplied using solar energy, the solar thermal installation would require 20 x 29 collector network design with a total cost of $ 474,079.48.
Table 1 shows a comparison of results for the two scenarios of a dairy plant. When no Heat Integration is considered, two options are analised, with and without storage tank. It can be seen that the fraction of thermal needs that can be met by solar energy increases if energy storage is involved in the process. This means that the operation time using solar energy also increases. The size of the solar collector network when energy storage is considered is larger compared to the scenario with no storage. In scenario two, the required hot utility is reduced after maximising heat recovery. Greenhouse gas emissions are calculated for both cases.

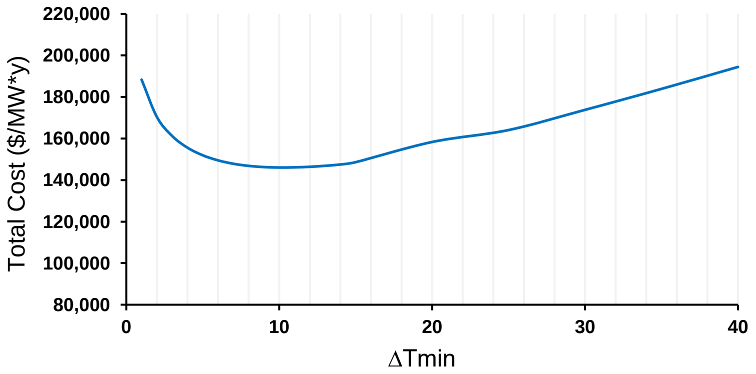

Figure 2: Total operating costs vs ΔT_{min} for the dairy plant processes

Table 1: Cost analysis for the dairy plant

Parameter	Scenario 1 No heat recovery no storage tank	No heat recovery with storage tank	Scenario 2 With heat recovery and storage tank
Boiler heat load (kWh/d)	4,401.01	4,401.01	4,401.01
Boiler operation time (d/y)	350	350	350
Minimum hot utility (kWh/d)	0	0	1,470
Solar plant supply temperature (°C)	95	105	105
Total cost of Heat recovery network (USD)	0	0	834,504.70
Solar heat load (kWh/d)	1,760.40	4,401.01	1,473.90
Array and size of the collector network	34 x 28	58 x 29	20 x 29
Total cost of solar collector network (USD)	695,965.97	1,451,563.23	474,079.48
Storage tank volume (m³)	0	47.0	16.2
Total cost of thermal storage (USD)	0	56,513.45	30,991.49
Solar fraction	0.4	1	1
Supply time of solar installation (h)	2	5	5
[a]Final emissions of CO_2 (t/y)	187.62	0	0
Energy saved (USD/y)	221,178.96	552,947.41	185,182.31
Payback time (y)	3.15	2.73	2.72
Levelised cost (USD/kWh)	0.045	0.039	0.038

[a](Emission factors, 2019)

4.2 Bioethanol production

The purification section of a bioethanol plant is shown in Figure 3. The feed enters the process at a concentration lower than 10 %. The product purity required is 99.5 %. This process operates 24 hours a day for 350 days a year. Steam produced at a boiler at 204 °C is supplied to meet the thermal load of 97,914.4 kWh.

For the continuous production of anhydrous bioethanol the optimum $\Delta T_{min\ opt}$ is 10 °C. The resulting heat recovery network operates with 14 exchangers. A solar thermal plant supplies 727.22 kW of heat at a temperature of 105 °C. The field of solar collectors is made up of a total 1,102 units in an arrangement with 38 lines of collectors in parallel and each line with 29 collectors in series. This corresponds to a total solar collection area of approximately 2,138.88 m^2 and a total costs of $ 951,024.18.
The results presented in Table 2 show the effect of increasing solar storage capacity. This is evidenced by a larger solar fraction. The direct benefits of increasing energy supply from the solar source is the reduction of CO_2 emissions; however, as more renewable energy is used, the levelised energy cost decreases. In all cases, the pay back is around 3 years. This pay back time could be maximised in the same way the supply time of solar thermal installation.

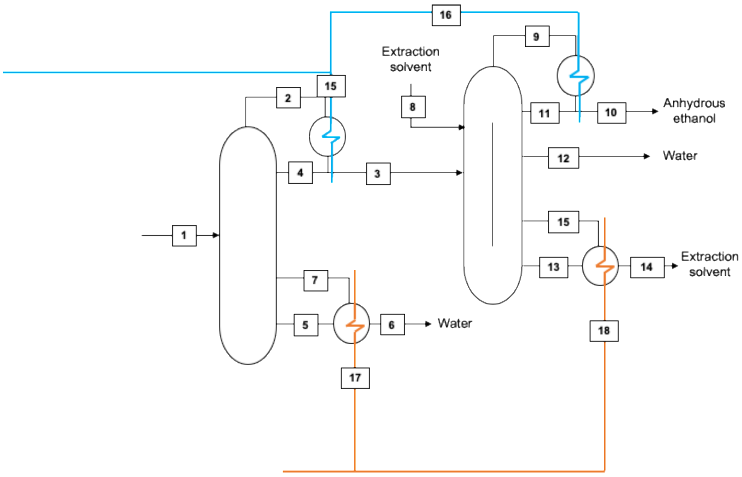

Figure 3: Purifying section of a bioethanol production plant

Table 2: Cost analysis for the bioethanol plant

Process / Parameter	Scenario 1 No heat recovery No storage tank	No heat recovery With storage tank	Scenario 2 With heat recovery and storage tank
Boiler heat load (kWh/d)	97,914.40	97,914.40	97,914.40
Boiler operation time (d/y)	350	350	350
Minimum hot utility (kWh/d)	0	0	22,856.88
Solar plant supply temperature (°C)	105	105	105
Total cost of HRN (USD)	0	0	1,519,077.32
Solar heat load (kWh/day)	2,857.11	5,714.22	5,714.22
Array and size of solar collector network	38 x 29	75 x 29	75 x 29
Total cost of solar collector network (USD)	951,024.18	1,521,795.14	1,521,795.14
Storage tank volume (m^3)	0	60	60
Total cost of thermal storage (USD)	0.00	68,069.07	68,069.07
Solar fraction	0.030	0.060	0.25
Supply time of solar installation (h)	3	6	6
[a]Final emissions of CO_2 (t/y)	6,735.78	6,532.78	1,218.00
Energy saved (USD/y)	358,970.23	717,940.46	717,940.46
Payback time (y)	2.65	2.21	2.21
Levelised cost (USD/kWh)	0.038	0.032	0.032

[a](Emission factors, 2019)

5. Conclusions

The sizing of a network of solar collectors must be understood from the point of view of the plant operation strategy. A plant might be looking at the supply of solar heating within the hours where the required temperature is achieved by a single network. In this case, there is only a limited number of hours when solar energy is available to supply the temperature required by the process. However, if the strategy consists in increasing the operating hours using solar energy, then energy storage has to be considered. Under these conditions, a larger solar network is needed to provide the energy that must be stored for the network to operate with a higher feed temperature. From the results obtained, the use of thermal storage to increase the operating hours using renewable energy is economically feasible, with payback times below three years. In the case of semicontinuous proceeses that operate only during the day, as in the dairy plant, the solar fraction can reach a value of 1. In continuous processes the solar fraction is generally lower than 1.

References

Allouhi A., Agrouaz Y., Benzakour-Amine M., Rehman S., Buker M.S., Kousksoub T., Jamila T., Benbassoua A., 2017, Design optimization of a multi-temperature solar thermal heating system for an industrial process. Applied Energy, 206, 382 - 392.

Baniassadi A., Momen M., Amidpour M., 2015, A new method for optimization of Solar Heat Integration and solar fraction targeting in low temperature process industries. Energy, 90, 1674 - 1681.

Carbon Trust, 2013, Small-scale concentrated solar power: a review of current activity and potential to accelerate deployment, Department of Energy and Climate Change or the Department for International Development. <www.gov. uk/government/uploads/system/uploads/attachment_data/file/191058/small_scale_concentrated_solar_power_carbon_trust.pdf. > accessed 01.01.2020.

Eiholzer T., Olsen D., Hoffmann S., Sturm B., Wellig B., 2017, Integration of a solar thermal system in a medium-sized brewery using Pinch Analysis: Methodology and case study. Applied Thermal Engineering, 113, 1558 - 1568.

Emission factors (In Spanish), 2019, Carbon footprint registry, compensation and carbon dioxide absorption projects Version 12, Ministry of ecological transition, Government of Spain. <www.miteco.gob.es/es/cambio-climatico/temas/mitigacion-politicas-y-medidas/factores_emision_tcm30-479095.pdf> accessed 01.01.2020.

Evangelisti L., De Lieto V. R., Asdrubali F., 2019, Latest advances on solar thermal collectors: A comprehensive review. Renewable and Sustainable Energy Reviews, 114, 1093 -1101.

IRENA, 2015, Solar heat for industrial processes technology brief <irena.org/publications/2015/Jan/Solar- Heat-for-Industrial-Processes> accesed 01.01.2020.

Lizárraga-Morazán J. R., Martínez-Rodríguez G., Fuentes-Silva A. L., Picón-Núñez M., 2019, Multi-objective optimisation of flat plate solar collector-networks. Chemical Engineering Transactions, 76, 961 - 966.

Mangili V.D.M., 2019, Improvement of the butyl acetate process though Heat Integration: A sustainability-based assessment. Chemical Engineering and Processingn – Process Intensification, 135, 93 - 107.

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.

Pedraza A. L., 2017, Application of Pinch technology for the extractive distillation process for the propane-propylene mixture (In Spanish), Bachelor Thesis, National Polytechnic Institute, Higher School of Chemical Engineering and Extractive Industries, Mexico City, MX.

Quijera J. A., González-Alriols M., Labidi J., 2014, Integration of a solar thermal system in canned fish factory. Applied Thermal Engineering, 70, 1062 - 1072.

Rathjens, M., Fieg, G., 2020, A novel hybrid strategy for cost-optimal heat exchanger network synthesis suited for large-scale problems. Applied Thermal Engineering, 167, 114771.

Towler G., Sinnott R., 2013, Chemical Engineering Design (Second Ed.), Butterworth-Heinemann/Elservier, Oxford, UK. <www. academia.edu/25282800/Chemical_Engineering_Design_Principles_Practice_and_Economics_of_Plant_and_Process_Design_Second_Edition > accessed 01.01.2020.

Walmsley T. G., Walmsley M. R. W., Tarighaleslami A. H., Atkins M. J., Neale J. R., 2015, Integration options for solar thermal with low temperature industrial heat recovery loops. Energy, 90,113 - 121.

Walmsley T. G., Walmsley M. R. W., Varbanov P. S., Klemeš J. J., 2018, Energy Ratio analysis and accounting for renewable and non-renewable electricity generation: A review. Renewable and Sustainable Energy Reviews, 98, 328 - 345.

Yang P., Liu L. L., Du J., Li J. L., Meng Q. W., 2014, Heat exchanger network synthesis for batch processes by involving heat storages with cost targets. Applied Thermal Engineering, 70, 1276 - 1282.