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Assessment of a Heat Pump Assisted with Solar Thermal Energy for an Industrial Batch Process

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Low-temperature solar thermal facilities face challenges like large storage systems and solar intermittence. This drives the development of novel storage systems that also implies lower costs. This study proposes the coupling of a low-temperature solar storage system that feeds heat of vaporisation to a heat pump; the pump, at the same time, produces higher temperature thermal energy. The heat pump let to supply heat to low and medium temperature industrial processes in a way that volumetric requirements decrease, compared against using a conventional solar thermal storage system. Using the coolant trans-1,3,3,3-tetrafluoroprop-1-ene like working fluid in the heat pump, it is possible to obtain storage volumes up 30 m^3 to supply 4,400 kWh of heat process. This contributes to decrease in 44 % the volume of a conventional storage system. Reducing the installation surface, in turn reduces the costs and the solar thermal systems payback time. These achievements, overall, enable to reach a feasible system that is competitive in front of the fossil fuels costs, reducing or eliminating the environment impact of burning fossil fuels.

1. Introduction

There are challenges to solve when use renewable energies. For industrial applications, the focus is guaranteeing the heat load and the target temperature. The energy production using renewables let to reduce environmental impacts like emissions of greenhouse gases, and an enhanced economic performance (Wang et al., 2020). According to IRENA, renewable energies are replacing fossil fuels as the cheapest way to produce energy (IRENA, 2020). The energy consumed by the industrial sector in 2020 was 156 EJ, this constituted 38 % of the total energy consumed. Data have practical not changed since 2010; although China had the largest increase, more than half of the total increase observed. Solar thermal and geothermal energy rose their consumption in that range of years more than double, and the use of fossil fuels decreased from 73 % to 68 % (IEA, 2020). Solar energy is an abundant renewable source, green, available, and economically accessible. One of its applications is in low-temperature industrial processes, because has shown be more competent than fossil fuels (Koçak et al., 2020). To achieve its widespread use, it is necessary to develop methodologies and technologies that lead to reduce the associated costs of facilities and guarantee the energy supply to industrial processes. A solar facility has two main components, the solar collector network, and the thermal storage system. Due to the availability of sunlight only during the day hours and its intrinsic variability, storage systems guarantee heat load in continuous and batch processes. In the case of batch process, storage increases the supply time of heat load. The storage system installation contributes with 17 % of total solar system cost (Karagiorgas et al., 2001). It is significant to reduce the volume and the installation area of the thermal storage system, to reach this goal, heat pumps gain hot fluid from a low temperature source and give off heat at higher level of temperature.

Heat pumps are closed thermodynamic systems that convert low temperature heat in one of higher level of temperature through work consumed by the compressor. Industrial heat pumps, are also known as high temperature heat pumps (HTHP), these are major used for recycling residual heat of process, which is at low temperatures and convert into useful heat of process close to 160 °C. The HTHP has the potential to performance in chemical, food and paper industry, particularly in processes such as pasteurisation, sterilisation, distillation, and evaporation (Arpagaus et al., 2018). Fan et al., 2021, reported that a combination of solar thermal

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system and heat pumps could increase low efficiencies, operation times and the intermittency of the solar source. Selection of the refrigerant is a relevant aspect in the heat pump design (Arpagaus et al., 2018). The main criteria are based on the thermophysics suitability properties as critical temperature and pressure, environmental compatibility (low ODP and GWP), security (low toxicity and flammability), availability on market, thermodynamic efficiency (COP) and compatibility with the heat pump component materials and lubricating oils. In the current work, the aim is to reduce the cost of the storage system, to reach this, the proposal is to couple a heat pump to a solar thermal facility that feeds a dairy process in the most critical weather conditions in the city of Guanajuato, Mexico, which includes low irradiance levels that exist during all the year. The results showed the storage system volume, for a dairy process, was reduced by 44 % using a heat pump. The thermal fluid used in the heat pump cycle was trans isomer of 1,3,3,3-tetrafluoroprop-1-ene also known as refrigerant R-1234ze(E).

2. Design of solar thermal facility

The heat pumps have used as a viable alternative to electric heaters and boilers in domestic hot water applications or climatisation (Kutlu et al., 2020). The drying of agricultural products is a method to preserving foods, this process prevents the products deterioration by moisture reduction using heat. Alishah et al. (2018), designed and evaluated a solar assisted heat pump dryer to dehydrate coriander, their results showed a decrease in drying time in comparison of a dryer without a heat pump, and COP value of 2.33 was achieved. Hasan-Ismaeel and Yumrutaş, 2020, proposed a solar assisted heat pump wheat drying system using thermal energy storage tank to heat supply in evaporator, 200 m^3 of volume storage, 70 m^2 of solar collector area and COP values until 5 were achieved.
However, the current work aims to use industrial heat pumps to reduce the size of solar thermal facilities in an industrial process. The heat load is delivered to the evaporator of the heat pump by means a solar thermal facility. Both main components of the solar thermal installation, low temperature solar collector network (54 % of total cost) and the heat storage system (17 % of total cost), have significant contribution on the total cost. In this study the size of the storage system is decreased, which impacts on its cost and the installation area. The designed system has a solar thermal installation coupled to a heat pump. Low temperature solar collector network delivers hot water at 50 °C. This hot water is mixed with storage water at 100 °C, produced by heat pump. Figure 1 shows the main components of the facility, which are solar collector network, storage system, photovoltaic network, and heat pump. The power required by the compressor is supplied by photovoltaic cells. R-1234ze(E) or trans-1,3,3,3-tetrafluoroprop-1-ene is the working fluid ($\dot{m}_{ref}$) of the heat pump, and water for solar thermal installation.

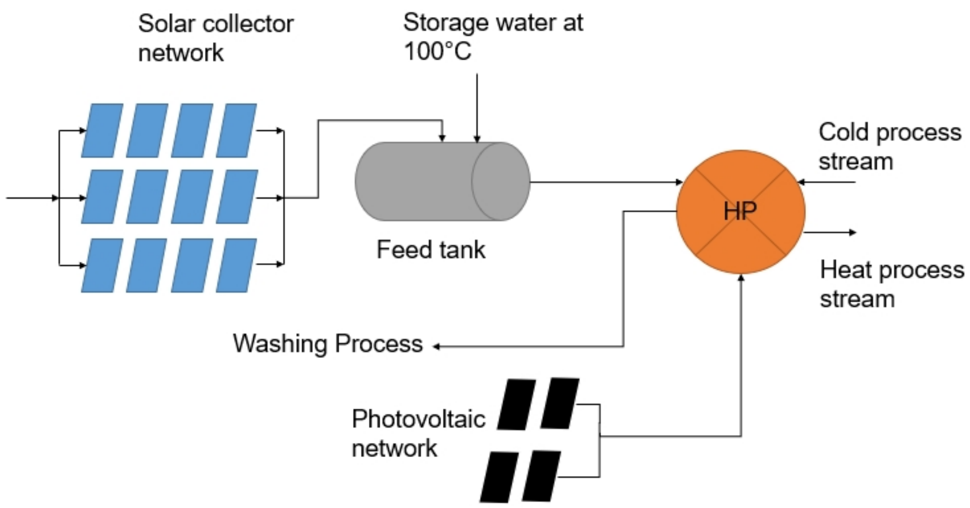

Figure 1: Solar thermal supply system proposed.

Design of the low temperature solar collector network (158 W/m^2), was carried out to guarantee the heat requirement during all year, including days with low irradiance and those with higher irradiance as Martínez-Rodríguez et al., (2019) detail.
Water is feeding at 19 °C to the flat-plate solar collector network. Heat pump produces additional hot water that is stored at higher temperature (100 °C) in a tank. Storage water is mixed with the water that comes out of the solar collector network to supply the heat load (746 kW) at target temperature to evaporator (70 °C). The

temperature difference between hot water and refrigerant is 10 °C, in both the evaporator and the condenser. In a dairy process the pasteurisation is achieved at 85 °C, and the temperature of the hot water must be 95 °C and 105 °C for the refrigerant.

3. Case study

The present research proposal is applied in a dairy batch process. Its operation is for 300 d and 5 h every day (8:00 h – 13:00 h). The required heat load for milk pasteurisation is 4,400 kWh (15.840 GJ). Case study consists of supply 880 kW to the process, which is removed from the condenser of the heat pump. Design starts on the condenser to guarantee the heat duty to dairy process. For this study, the heat pump works on isothermal of 60 °C for evaporation and 100 °C for condenser. The evaporator was designed to have a degree of overheating of 5 °C, condenser has the same degree of overcooling. A compressor isentropic efficiency of 85 % was considered. Figure 2 shows a P-h diagram of refrigerant used, with the main operating conditions.

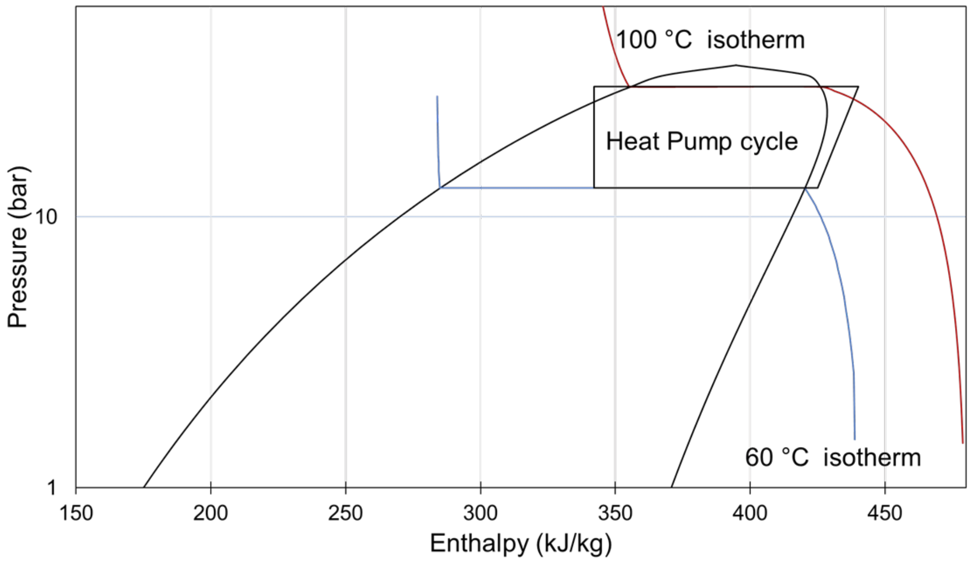

Figure 2: P-h Diagram for heat pump.

Considering an isentropic compression on the line of $1.7 kJ/kg$, it has a temperature of $105\ °C$ $(h_1 = 440\ kJ/kg)$ while condensation occurs up to $5\ °C$ below the condensation temperature and corresponds to $95\ °C$ $(h_2 = 342\ kJ/kg)$, thus the mass flow can be calculated from the Eq(1).

$$\dot{Q}_{cond} = \dot{m}_{\text{ref}} \Delta h_{cond} \tag{1}$$

Refrigerant mass flow rate is used to calculate compressor power and evaporator heat load. Compressor power is calculated with Eq(2).

$$\dot{W}_{comp} = \dot{m}_{ref} \Delta h_{real} = \frac{\dot{m}_{ref} \Delta h_{isoent}}{\eta_{isoent}} \tag{2}$$

Where the efficiency of isentropic compressor is calculated from Eq(3), which considers the enthalpy difference if the process were isentropic with respect to the actual or real enthalpy difference.

$$\eta_{isoent} = \frac{\Delta h_{isoent}}{\Delta h_{real}} \tag{3}$$

The expansion process in the heat pump is carried out at constant enthalpy $(h_3 = 342\ kJ/kg)$, while at the exit of the evaporator, $h_4 = 425\ kJ/kg$ to reach the isentropic line with temperature of 65 °C; the Eq(4) allows to calculate the heat flow in the evaporator.

$$\dot{Q}_{evap} = \dot{m}_{ref} \Delta h_{evap} \tag{4}$$

Heat pump COP is an important parameter to conduct the thermodynamic analysis. Heating COP is the rate between condensation heat and the power consumed by the compressor, how it is showing in Eq(5).

$$COP = \frac{\dot{Q}_{cond}}{\dot{W}_{comp}} \tag{5}$$

The total heat at the evaporator defines hot water mass required. The required heat load on the evaporator of heat pump comes from hot water of solar collector network at 50 °C mixed with storage water at 100 °C, to get hot water at 70 °C. Considering a specific heat capacity of water of $C_{p_{H_2O}} = 4.182\ kJ/kg\ K$, the hot water mass is calculated with Eq(6).

$$Q_{stor} = \dot{Q}_{cond} t_{proc} = m_{H_2O} C_{p_{H_2O}} \Delta T \tag{6}$$

Where $\dot{Q}_{cond}$ is the heat flow on the condenser, t_{proc} is the operation time process, m_{H_2O} is total mass water required by the process, ΔT, is the temperature difference between storage temperature (T_{stg}) and the average annual water temperature ($T_{ave} = 19\ °C$). The operation time is 5 h, hot water mass flow required by the process is calculating with Eq(7).

$$\dot{m}_{H_2O} = \frac{m_{H_2O}}{t_{proc}} \tag{7}$$

Storage tank volume is calculating with Eq(8) (Yang et al., 2014), and density of water is taken as an average between 19 °C and 100 °C $\left(\rho_{H_2O} = 977\ kg/m^3\right)$.

$$V = \frac{Q_{stor}}{\rho_{H_2O} C_{p_{H_2O}} \Delta T} \tag{8}$$

The total hot water required without heat pump is 46 m^3 at 100 °C to meet the heat demand (4,440 kWh or 880 kW). By coupling the solar thermal system to assist the heat pump, the total hot water required by dairy process is reduced from 46 m^3 to 29.2 m^3. This represents a reduction of 44 % on volume of hot water. The estimation considers the most critical irradiance values during the year, ensuring the supply of the heat load at a target temperature of 95 °C for milk pasteurisation**.**

4. Cost analysis

The cost of storage tank, C_{STA}, can be determined by Eq(9) (Towler and Sinnott, 2013), which depends on the storage volume; the constant parameters (a, b and c) are related to the type of tank used. Costs for installation, maintenance, insulation, among other, are included.

$$C_{STA} = a + bV^c \tag{9}$$

The solar collector network cost is determined by Eq(10) (Lizárraga-Morazán et al., 2020), this equation depends on geometrical characteristics and build materials of the collector, fluid properties, total number of collectors and mass flow rate, among others.

$$C_{SN} = N_c\left[\gamma_0 + \frac{A_t N_t}{\pi}\left(\gamma_1 d + \gamma_2 + \frac{\gamma_3}{d}\right) + WL\gamma_4 + \gamma_{10}\frac{\dot{m}L\mu}{\pi\rho d^4}\right] + \gamma_5\left(\frac{\dot{m}H_b}{e_{ff}}\right) \tag{10}$$

According to Zhang et al., 2016, the installation cost of an industrial heat pump by vapor compression with maximum temperature lift of 80 °C and maximum sink temperature of 120 °C, is 1,250 $yuan/kW_{heat\ output}$, equivalent to 200 $dollar/kW_{heat\ output}$.

5. Results

The results were obtained based on thermal requirements of dairy process, it means 880 kW in a period of 5 hours. The refrigerant mass flow rate was 9 kg/s and the heat pump operating conditions were: the evaporator works on a constant pressure of 12.77 bar between 60 °C and 65 °C, the compressor increases the pressure to 30.26 bar and temperature to 105 °C; the condenser also operates on constant pressure of 30.26 bar and temperatures of 105 °C and 95 °C, finally expansion valve decreases temperature and pressure to 60 °C and 12.77 bar. The calculus of enthalpy and pressure was achieving with the equation of state reported by Thol and

Lemmon, 2016, by which the saturation curves and the working isotherms, were graphing. Following the same procedure, the heat flow required at the evaporator was 746 kW for the refrigerant mass flow rate.
The objective is to calculate the water mass and the mass flow rate to supply 746 kW on evaporator. Table 1 shows the obtained results of a sweep for different temperature operation values on this device. Considering an isentropic efficiency of 85 %, a compressor power of 158.5 kW, and a heat pump COP of 5.55.
A previous study was conducted on the dairy process for the same energy supply of 4,400 kWh. Forty-six (46) m^3 of hot water at 100 °C were required.

Table 1: Mass and mass flow rate of hot water for different mix temperatures.

T_{stg} (°C)	m_{H_2O} (kg)	$\dot{m}_{H_2O}$ (kg/s)
60	78,242	4.35
65	69,737	3.87
70	62,900	3.49
75	52,284	3.18
80	52,589	2.92
85	48,605	2.7
90	45,182	2.51

Different scenarios were analysed to verify the impacts of the temperature of storage tank. In one of these scenarios the storage temperature could reduce 10 °C, therefore the hot water temperature is 90 °C. In this case the volume is reduced in 30 %, with an output temperature of 50 °C from the solar collector network. Another scenario could be based on the critical solar irradiance of 158 W/m^2. The outlet temperature of the solar collector network with this level of irradiance is 58 °C. The reduction of the volume at 100 °C is 47 % maintaining the hot water storage at 90 °C.
Table 2 shows the required volume of hot water to supply the heat duty to the evaporator at different target temperatures. This work considers a target temperature of 70 °C in the evaporator to reduce the hot water storage required for the dairy process. The required volume to the evaporator increases exponentially when the target temperature decreases. The difference between the volume at 80 °C with respect to the volume at 60 °C is 32 %.

Table 2: Hot water volume for different solar collector outlet temperatures.

T_{stg} (°C)	V_{tank} (m^3)
60	80.0
65	71.4
70	64.4
75	58.6
80	54.0
85	50.0
90	46.3

Taking the highest natural gas price reported during 2021, which was 0.201 USD/kWh (GlobalPetrolPrices, 2021) and estimating the cost of fuel to supply the total heat load to the process, an expense of $884/d or $265,380/y, was calculated. The cost of the proposed industrial heat pump to supply the heat load is $880,000 (including the cost of equipment and installation).

6. Conclusions

The selection of R-1234ze(E) refrigerant as working fluid in the heat pump complies with the strictest environmental criteria (ODP=0 and GWP=0), in addition, the critical temperature and pressure of the refrigerant reach optimal operating conditions of proposed energy system.
It is feasible to couple a heat pump to a solar thermal installation made up of a network of low-temperature solar collectors and a storage system. Under this scheme the volume of the storage system can reduce by 44 %.
The proposal guarantees the supply of the thermal load to the dairy process throughout the year by means a 100 % renewable energy system.
Simple payback of the heat pump was 3.4 years, making the proposal competitive regarding conventional fossil fuel systems.

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References

Alishah A., Valizadeh-Kiamahalleh M., Yousefi F., Emami A., Valizadeh-Kiamahalleh M., 2018, Solar-assisted heat pump drying of coriander: An experimental investigation, International Journal of Air-Conditioning and Refrigeration, 26, 4, 1-13.

Arpagaus C., Bless F., Uhlmann M., Schiffmann J., Bertsch S. S., 2018, High temperature heat pumps: market overview, state of the art, research status, refrigerants, and application potentials, Energy, 142, 985-1010.

Chaturvedi S.K., Abdel-Salam T.M., Sreedharan S.S., Gorozabel F.B., 2009, Two-stage direct expansion solar-assisted heat pump for high temperature applications, Applied Thermal Engineering, 29, 2093-2099.

Fan Y., Zhao X., Han Z., Li J., Badiei A., Akhlaghi Y.G., Liu Z., 2021, Scientific and technological progress and future perspectives of the solar assisted heat pump (SAHP) system, Energy, 229, 1-12.

GlobalPetrolPrices.com. 2021, https://es.globalpetrolprices.com/Mexico/natural_gas_prices/#:~:text=M%C3%A9xico %2C%20septiembre%202021%3A,es%200.066%20USD%20por%20kWh. Date: 04/14/2022.

Hasan-Ismaeel H., Yumrutaş R., 2020, Investigation of a solar assisted heat pump wheat drying system with underground thermal energy storage tank, Solar Energy, 199, 538-551.

IEA Tracking Industry 2021 Report, 2021, International Energy Agency, < https://www.iea.org/reports/tracking-industry-2021> accessed 01.04.2022.

IRENA Renewable Power Generation Cost in 2020, 2020, International Renewable Energy Agency <https://www.irena.org/publications/2021/Jun/Renewable-Power-Costs-in-2020> accessed 01.04.2022

Karagiorgas M., Botzios A., Tsoutsos T, 2001, Industrial solar thermal applications in Greece Economic evaluation, quality requirements and case studies, Renewable and Sustainable Energy Reviews, 5, 157-173

Koçak B., Fernandez A.I., Paksoy H., 2020, Review on sensible thermal energy storage for industrial solar applications and sustainability aspects, Solar Energy, 209, 135-169.

Koşan M., Aktaş M., 2021, Experimental investigation of a novel thermal energy storage unit in the heat pump system, Journal of Cleaner Production, 311, 1-13.

Kutlu C., Zhang Y., Elmer T., Su Y., Riffat S., 2020, A simulation study on performance improvement of solar assisted heat pump hot water system by novel controllable crystallization of supercooled PCMs, Renewable Energy, 152, 601-612.

Lizárraga-Morazán J.R., Martínez-Rodríguez G., Fuentes-Silva A.L., Picón-Nuñez M., 2020, Selection of solar collector network design for industrial applications subject to economic and operation criteria, Energy & Environment, 0, 1-20

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. doi:10.3390/en12030570

Thol E., Lemmon E.W., 2016, Equation of state for the Thermodynamics Properties of trans-1,3,3,3-tetrafluoropropane [R-1234ze(E)], International Journal of Thermophysics, 37, 1-16

Towler G., Sinnott R., 2013, Chemical Engineering Design, Second Ed. Retrieved from https://www.academia.edu/25282800/Chemical_Engineering_Design_Principles_Practice_and_Economics_of_Plant_and_Process_Design_Second_Edition accessed 12.04.2022

Trading Economics Natural gas, 2022, <https://tradingeconomics.com/commodity/natural-gas> accessed 12.04.2022

U.S. Department of Energy Industrial Heat Pumps for Stem and Fuel Savings, 2003, <https://www.energy.gov/eere/amo/downloads/industrial-heat-pumps-steam-and-fuel-savings> accessed 12.04.2022

Wang J., Han Z., Guan Z., 2020, Hybrid solar-assisted combined cooling, heating, and power systems: A review, Renewable and Sustainable Energy Reviews, 113, 1-26.

Wu D., Hu B., Wang R.Z., Fan H., Wang R., 2020, The performance comparison of high temperature heat pump among R718 and other refrigerants, Renewable Energy, 154, 715-722

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

Zhang J, Zhang H., He Y., Tao W., 2016, A comprehensive review on advances and applications of industrial heat pumps based on the practices in China, Applied Energy, 18, 800-825