ISSN: 2594 - 2905

SUGARCANE ALCOHOL DISTILLATION PROCESS FROM A CIRCULAR ECONOMY PERSPECTIVE

SUGARCANE ALCOHOL DISTILLATION PROCESS FROM A CIRCULAR ECONOMY PERSPECTIVE

Mares Gardea Arturo Ernesto[1]; García Morales Jarniel[2]; Cervantes Bobadilla Marisol[2]; Medina Medina Ivetteh Virginia[2]

https://doi.org/10.61117/ipsumtec.v8i2.398

[1]National Technological Institute of Mexico/ I. T. of Gustavo A. Madero,maresarturoe@gmail.com , https://orcid.org/0009-0004-8430-6628, (2) National Technological Institute of Mexico/ CENIDET,jarniel.gm@cenidet.tecnm.mx , https://orcid.org/0000-0001-7972-6389, (2) National Technological Institute of Mexico/CENIDET,marisol.cb@cenidet.tecnm.mx , https://orcid.org/0000-0002-3166-0584, (2) National Technological Institute of Mexico/CENIDET,d24ce116@cenidet.tecnm.mx , https://orcid.org/0009-0006-8849-0519.

Summary – Talking about the circular economy means decoupling economic growth from the consumption of finite resources, protecting the environment by reducing waste generation, pollution and CO2 emissions, which in turn generates opportunities for economic growth and promotes employment. The circular economy promotes innovation, the optimisation of natural resources, efficiency within organisations and the creation of new business models, which translates into economic and social benefits for all economic agents: society, businesses and consumers.

This research focuses on characterising the systems and/or variables associated with the process of preheating boiler feed water in a sugarcane alcohol distillery from a circular economy perspective and the use of solar collectors to make resource use more efficient. It also identifies specific opportunities within the process related to heat and water consumption. To reduce these indicators, it proposes a strategy to implement a solar collector system to heat the boiler feed water to 70°C, as well as the recovery, storage and recirculation of condensate water that is currently discharged into the drain and discarded. The use of steam condensate follows a circular approach and results in more efficient management of natural resources, greater system efficiency, less fuel needed to heat water, and less use of water from the public supply network, leading to cost reductions, coupled with the optimisation of renewable resources to improve industrial processes.

Keywords: alcohol, solar collectors, thermal energy, circular economy.

Abstract -- Talking about the circular economy means decoupling economic growth from the consumption of finite resources, protecting the environment by reducing waste generation, pollution, and CO2 emissions, which in turn generates opportunities for economic growth and promotes employment. The circular economy encourages innovation, the optimisation of natural resources, efficiency within organisations, and the creation of new business models, which translates into economic and social benefits for all economic agents: society, businesses, and consumers.

This research focuses on the characterisation of the systems and/or variables associated with the process of preheating boiler feed water in a sugarcane alcohol distillery from a circular economy perspective and the use of solar collectors to make resource use more efficient. It also identifies specific niches of opportunity within the process related to heat and water consumption. To reduce these indicators, it proposes a strategy for implementing a solar collector system to heat the boiler feed water to 70°C, as well as the recovery, storage, and recirculation of condensate water that is currently discharged into the drain and discarded. The use of steam condensate follows a circular approach and results in more efficient management of natural resources, greater system efficiency, less fuel needed to heat water, and less use of water from the public supply network, leading to cost reductions, coupled with the optimisation of renewable resources to improve industrial processes.

Keywords – alcohol, solar panels, thermal energy, circular economy.

INTRODUCTION

The industry of producing alcohol from sugar cane is an activity of utmost importance for many regions of the world. However, it faces significant environmental and economic challenges, such as high demand for resources, for example, water and energy

[1]. This is why it is important to consider the circular economy and solar thermal systems to improve the sustainability and efficiency of alcohol distilleries, especially for preheating boiler feed water.
Currently, there is growing concern about the scarcity of natural resources, waste generation and climate change. In this context, distilleries are highly polluting and resource-intensive industries [1] that face critical challenges related to sustainability and efficient resource management, such as high consumption of heat energy and water [2].

CALCULATION OF BOILER FEED WATER, SATURATED STEAM AND RECOVERED CONDENSATE

This research is carried out using a mixed method (quantitative-qualitative) and a correlational approach. The study focuses on a sugarcane alcohol distillery located in Temimilcingo, Morelos, Mexico, which operates by burning wood as its main source of thermal energy to feed a fire-tube boiler for the production of saturated steam. The steam is distributed throughout the different stages of the production process, particularly the feed water preheating stage.

Calculation of feed water and saturated steam flow.

The volumetric flow of a fluid can be determined by taking into account the cross-sectional area of the pipe through which it flows and the velocity of the fluid. The following formulas are used for this purpose [3]:

$$Q = A \times V_P \qquad \text{Eq. (1)}$$

Where:

Q: Volumetric flow (m^3/h)
A: Cross-sectional area of the pipe (m^2) V_P: Fluid velocity (m/s)

The cross-sectional area of the pipe is calculated taking into account the internal diameter of the pipe expressed in metres:

$$A = \pi \left(\frac{d^2}{4}\right) \qquad \text{Ec. (2)}$$

The fluid velocity can be determined based on the pressure over a given time interval using the following linear relationship:

$$V_P = V_0 + k \times (P - P_0) \qquad \text{Eq. (3)}$$

Where:

V_0: Initial velocity at P_0 (m/s)
k: System adjustment value P: Pressure (kg/cm^2)
P_0: Initial or average pressure (kg/cm^2)

Taking the above into account, along with the characteristics of the system, a methodology is established for calculating the feed water flow driven by a centrifugal pump, which operates cyclically, i.e. its start-up and shutdown depend on the boiler's demand.
This methodology is shown below:

1. Record parameters (pump start-up and stop times, feed water gauge pressure, pipe diameter).
2. Calculate the flow for each pump activation cycle ($Q_1, Q_2, Q_3 \ldots Q_n$).
3. Add up the flows for all cycles:

$$Qtotal = Q_1 + Q_2 + Q_3 + \ldots Qn \qquad \text{Ec. (4)}$$

4. Calculate the pump activation cycles per hour (C).
5. Calculate the average flow per hour

$$Q = Q_{total} \times C \qquad \text{Eq. (5)}$$

To determine the volumetric flow of saturated steam generated, follow some of the steps in the above methodology:

1. Record parameters (gauge pressure of saturated steam at the boiler outlet, pipe diameter).
2. Calculate the steam flow for each measurement record ($Q_1, Q_2, Q_3 \ldots Q_n$).
3. Calculate total steam flow.

After establishing the methods for calculating the feed water and saturated steam flow, the prospects and considerations for heat energy recovery are analysed.

In practice, the amount of energy and the proportion of heat energy used in distilleries vary depending on the scale, products, and processes used.
and the efficiency of operations. This energy is present in the preheated water that feeds
the boiler, in the combustion process that occurs in the boiler furnace and accompanies the steam generated, which is used in the diffuser and in the distillation process.

The fermented cane juice is heated with steam to separate and concentrate the alcohol [4]. In some of these plants, the cooling water streams from condensers and fermenters, the vinasses, steam condensates, and hot gases, which are not utilised and contribute to heat dissipation, reducing the energy efficiency of the system [5]. Capturing and utilising these flows can be an important source of thermal energy savings [4].

Specifically, condensate recovery enables savings in thermal energy, as well as in water supply and treatment. Condensate that does not return to the boiler feed system must be compensated for by replacement water, which is cold and must be treated. Condensate recovery will reduce water, chemical and fuel consumption through the recovery of water and heat [4].

Estimation of the amount of condensate recovered.
The steam generated by the boiler travels along the distribution system pipes to reach the process where the heat will be used. During steam transport, heat is lost through radiation through the pipe wall and condenses. Condensate systems consist of a set of pipes that collect the drains from the steam traps, which discharge into a storage tank equipped with a pump or a pipe system to transport the condensate to the boiler feed water tank [6]. According to the author [7], the amount of condensate recovered in a system can be estimated by taking into account the percentage of steam utilisation by the consumer equipment in the distiller, the diameter and cross-sectional area of the pipes (see equation 2), the feed water flow and saturated steam generated, the temperature and enthalpy of the condensate, among other parameters. In [7], energy balance analysis is used to determine the total amount of condensate recovered in the storage tank in a food industry process. It also considers that the mass flow of feed water is equivalent to the mass flow of steam generated in stable energy systems. A total energy balance takes into account energy transfers across the system boundaries:

$$\sum ment \times hent = \sum msal \times hsal \qquad \text{Eq. (6)}$$

$\sum ment$: Sum of mass flow entering the system (kg/s)
$hent$: Enthalpy of the input fluid (kJ/kg)
$\sum msal$: Sum of mass flow leaving the system (kg/s)
hsal: Enthalpy of the fluid leaving the system (kJ/kg)

On the other hand, [7] and [8] propose the following formulas for calculating the steam flow rate from the secondary flow rate in a heat exchanger.

$$Qv = \frac{Qm}{p} \qquad \text{Ec. (7)}$$

Where:

Qv: Volumetric flow (m^3 /h)
Qm: Mass flow (kg/h)
ρ: Water density (kg/m^3)

$$Ws = \frac{Q \, X \, Cp \, X \, \Delta T}{hfg} \qquad \text{Ec. (8)}$$

Where:

Ws: Steam flow rate (kg/h)
Q: Feed water flow (kg/h)
ρ: Feed water density (kg/m^3) Cp: Specific heat of the fluid (kJ/kg ºC) ΔT: Temperature difference (ºC)
hfg: Enthalpy of steam evaporation (kJ/kg)

This equation allows us to determine the amount of steam currently used in the preheater to increase the temperature of the boiler feed water and compare it with estimates of steam use. It can also serve as a solid basis for evaluating heat energy savings and the potential for implementing a solar thermal energy system.

USE OF SOLAR THERMAL ENERGY

Solar thermal energy is the conversion of solar radiation into heat. Among renewable energy systems, solar thermal is considered the most economical alternative. Typically, systems use solar collectors and concentrators to collect solar radiation, store it, and use it to heat air or water in domestic, commercial, or industrial plants [9]. This type of renewable energy can replace or reduce the use of fossil fuels [10]. Solar water heating accounts for most solar thermal energy applications in both domestic and industrial sectors. Solar thermal energy systems for water heating usually consist of solar collectors and a storage space [11].

The solar thermal collector is the device that transforms solar radiation into thermal energy, which is transferred to a heat transfer fluid, increasing its temperature. It is the main component of the collection system, the heat generator in solar thermal installations. In addition to producing heat efficiently, the collector must be designed to withstand continuous exposure to outdoor conditions (rain, snow, hail, dust, etc.) and to resist the extreme temperatures, both high and low, to which it may be subjected [12].

Flat plate collectors are suitable for low-temperature applications (below 100 °C) and are popular for their light weight, modularity and low cost

[13], which can range from MXN 5,500.00 to MXN 30,000.00 [14]. In this context, it is noteworthy that flat plate collectors (FPC) for heating water are the most widely used and recommended solar thermal technology worldwide in both the domestic and industrial sectors.

Solar energy is transformed into thermal energy by means of a panel composed of a glass cover, which allows solar radiation to pass through and be absorbed by the selective surface of an absorbent plate. Figure 1 shows a cross-section of a CPP, highlighting each of its components. After being intercepted by the plate, the thermal energy is transferred to the interior of the tubes through which the heat transfer fluid circulates, finally passing to a storage system or being used directly [10].

Figure 1. *Parts of a flat plate collector.*

Source: *Carrión-Chamba et al.* (2022).

Determining the number of solar collectors and storage volume for alcohol distiller.

To design a solar water preheating system, it is necessary to know the water capacity of each collector, the temperature at the collector inlet, the temperature required by the process, and the total amount of water that will be used in a day [15]. The location, type of collector, working fluid to determine the necessary storage volume, size of the system, storage volume, and thermal load are other factors that must be considered [11]. In [16], a methodology is proposed to determine the number of solar collectors and the volume of the storage tank required for preheating the feed water of a fire-tube boiler. To do this, the following must be calculated:

1. **Energy demand:**

This is the energy required to raise the temperature of a given volume of water from an initial temperature T_i to a consumption temperature T_f. The following equation is also used by other authors

[7,17,15]

$$Q_{dem} = M \times C_p \times (T_f - T_i) \qquad \text{Ec. (9)}$$

Where:
Q_{dem}: Heat demand or energy demand (kJ/day) M: Feed water flow (kg/day)
C_p: Heat capacity of water (4.18 kJ/kg ºC)
T_f Final or outlet temperature of the collector (°C).
T_i: Initial or inlet temperature of the collector (°C).

2. **Catchment area**

This is the area required to capture enough solar energy to meet energy demand. The area depends on global radiation and the total efficiency of the water heating system.

$$A_{cap} = \frac{Q_{dem}}{Hp\ X\ \eta g} \qquad \text{Ec. (10)}$$

Where:
A_{cap}: Collection area (m^2).
Hp: Average solar radiation (Wh/m^2).
ηg: Overall daily efficiency of the system (%).

3. **Number of collectors**

The number of collectors needed to meet energy demand is determined by the following relationship:

$$Nc = \frac{A_{cap} X\ FS}{Ac} \qquad \text{Ec. (11)}$$

Where:

Nc: Number of collectors.
FS: Safety factor or demand projection factor (1-1.5).
Acap: Catchment area (m^2). Ac:
Area of a collector (m^2).

4. **Tank volume**

This is the total capacity of the hot water storage tank that forms part of the solar thermal system.

$$V_{dep} = 1.15 \times m \qquad \text{Ec. (12)}$$

Where:
V_{dep}: Tank volume (litres) m: Mass of water to be heated (kg)

According to [18], the mass of water to be heated is calculated based on the thermal demand (E) that the system is capable of covering with the given number of collectors. Therefore:

$$E = Nc \times Hp \times Ac \times \eta g \qquad \text{Eq. (13)}$$

$$m = \frac{E}{Cp X\ \Delta T} \qquad \text{Eq. (14)}$$

When positioning the collectors, consideration should be given to optimising the area and storage volumes, seeking the lowest possible cost [19]. The location of any solar energy collection equipment depends on choosing a site that is free of shadows and other equipment [15]. They should be oriented in such a way as to maximise the collection of solar radiation. The minimum distance between collectors must be calculated to prevent the shadow cast by the previous collector from interfering with the optimal operation of the following collectors.

$$d = k \times h \qquad \text{Eq. (15)}$$

Where:
d: Minimum distance between collectors (m)
k: Coefficient that depends on the angle of the collectors with respect to the horizontal plane.
h: Total height of the collector (m)

In the event that there is an obstacle or wall that could cast shadows, the expression for d is transformed taking into account the height (h) of the obstacle as follows:

$$d = 1.732 \times h \qquad \text{Ec. (16)}$$

To determine the total area of the solar field, the available land area, the dimensions of the solar collector, the minimum distances between collectors, the easement space around the collector field on rooftops or enclosed land, and the spacing for connection and maintenance, which is recommended to be at least 20 cm, must also be considered first.

Methodological tools

Distilleries producing alcohol from sugar cane face significant environmental and economic challenges due to the high generation of by-products and high consumption of heat energy and water, leading them to be considered one of the most polluting and resource-intensive industries. The implementation of circular economy strategies and solar thermal technologies is still in its infancy in this sector, despite the fact that they are viable and promising alternatives for improving energy efficiency and resource management, as well as process operation and consumption indicators.

The units of analysis are the fire-tube boilers used in sugarcane alcohol distilleries or similar industries to generate saturated steam for their processes.

The distillery under study is located in Temimilcingo, Morelos, and is dedicated to producing alcohol from sugar cane. It has an ECOVIS 350HP biomass fire-tube boiler, which It uses bagasse and wood chips as fuel to generate saturated steam at 7 kg/cm^2 and 165°C. This steam passes through a common header and is then distributed to the diffusion, distillation and feed water preheating processes in different proportions. It should be noted that the company is relatively new and does not have a robust metrological system, as the instrumentation installed only covers the fundamental parameters for alcohol production and does not focus on monitoring the performance of the boiler or other equipment. Therefore, it was necessary to use water vapour property tables, as well as methodologies for estimating certain parameters such as feed water flow, saturated steam generated and condensate recovery.

Taking into account the cross-sectional area of the pipe through which the water that must enter the boiler circulates, the pressure and velocity of the fluid, as well as the operating parameters of the centrifugal pump that sucks the water, the feed water flow is calculated using equations 1 and 5, resulting in a flow of 1.10 m^3 /h.

On the other hand, the saturated steam pressure at the boiler outlet was recorded during a working day and, based on the pipe diameter, it was determined (equation 4) that the steam flow is 1.07 m^3/h. The relationship between the amount of water entering the boiler and the steam flow generated indicates that losses are minimal, so the system is considered stable. Considering a 9.5-hour working day according to the operating conditions in force at the time of data collection, the feed water consumption is 10,450 litres/day and the steam generation and consumption is 10,165 litres/day.

Likewise, in the analysis of steam use by different equipment, it is estimated that the diffuser, distillation tower and preheater consume approximately 2,927.52 litres, 5,204.48 litres and 2,022.83 litres of steam per day, respectively, representing 28.8%, 51.3% and 19.9% of the total steam produced by the boiler. Currently, only the steam condensate from the preheater is recovered, which is added to the water flow used in the diffuser to extract the cane juice.
Taking into account an effective steam condensate recovery of 85% for each piece of equipment [7], it can be estimated that the amount of condensate obtained in the distillation tower is 4,423.8 litres/day, in the diffuser it is 2,488.3 litres/day, in the preheater it is 1,719.4 litres/day and in the boiler, as a result of purges and losses, it is 242.25 litres/day (0.03%).

To determine the volume of condensate that can be recovered, the appropriate system conditions (accessories, condensate tank, measuring instruments) and apply equation 6 for energy balance in the condensate tank, for a temperature of 80°C, as shown below:

$$\sum m_{ent} \times h_{ent} = \sum m_{sal} \times h_{sal}$$
$$m_{dif} \times h_{cond} + m_{td} \times h_{cond} + m_{cald} \times h_{cond} = m_{cond} \times h_{cond}$$
$$m_{cond} = \frac{h_{cond}(m_{dif} + m_{td} + m_{cald})}{h_{cond}}$$

$$m_{cond} = \frac{0.734171 \text{ kWh/kg } (7{,}154.35 \, litros/día)}{0.734171 \text{ kWh/kg}}$$

$$mcond = 7{,}154.35 \, litros/día.$$

7,154.35 litres of condensed hot water per day that was previously discarded would now be reused and recirculated back into the process, representing a recovery rate of 69%. This translates into an improvement in overall system efficiency, a reduction in fuel consumption to bring the water to boiling point, and a reduction in water consumption from the supply network, thereby lowering associated costs. Equation 7 is used to calculate the steam flow required to raise the boiler feed water temperature from 28°C to 70°C in the preheater. First, the units of measurement are converted from volumetric flow to mass flow, taking into account the density of the feed water. This is shown as follows:

$$Qm = Qv \times \rho$$
$$Qm = 1.10 m^{(3)} /h \times 1{,}000 kg/m^{(3)}$$
$$Qm = 1.100 kg/h$$

The steam flow rate is then calculated using Eq. 8:

$$Ws = \frac{1{,}100 \text{ kg/h} \times 4.19 \text{ kJ/kg°C} \times 42\text{°C}}{2{,}762.79 \times 9.5 \text{ h/day}}$$

$$Ws = 7.37 kg/día$$

DISCUSSION AND ANALYSIS OF RESULTS

Solar energy is widely used to generate electricity and heat, through photovoltaic panels and solar thermal systems, respectively [21]. Considerable efforts are being made to gradually introduce renewable energy sources to meet future energy needs, which play an essential role in the circular economy.

For its part, [22] designs a solar thermal system for preheating the feed water of a 600 HP boiler, in which it considers it necessary to collect operational and consumption data from the boiler, as well as to determine the appropriate type of collector and the installation area for the system.

According to [23], 60% of the total industrial heat used in Mexico usually requires a temperature below 150°C, which determines the type of solar device to be used, such as flat plate and evacuated tube collectors. These technologies are commonly used for various applications, including the preheating of boiler feed water, which is corroborated by the research analysed to date. That is why thermal energy in the alcohol distillation process in industry plays an important role in the circular economy. To structure the improvement proposal, three methodological phases were followed: (i) characterisation of the current system, (ii) design of the complementary solar thermal system, and (iii) proposal for integration with condensate recovery.

The distillery in question has a fire-tube biomass boiler, which uses bagasse and wood chips as fuel to generate saturated steam at 7 $^{kg/cm^2}$and 165°C. This steam passes to a common header and is then distributed to the diffusion, distillation, and feed water preheating processes in different proportions.

A mass flow rate of 7.37 kg/day of steam is required, equivalent to 2 m³/day or 2,000 litres/day, which coincides with estimates made on steam usage. These results can serve as a solid basis for evaluating the heat energy savings if, instead of preheating the feed water with steam, a solar thermal energy system is used for this purpose. Next, the appropriate solar collector is selected and the solar thermal system is sized.

Selecting the ideal solar collector for a solar thermal system in an industrial setting is a significant step and must be approached carefully, as it is very important to maintain and supply the temperature required for the

process. Similarly, the space required for the installation of these systems is an essential factor at
consider. Based on the information gathered and the analysis of the data collected, it was determined that flat-plate solar collectors are best suited for preheating the feed water for the boiler of the distillery under study. For this reason, a commercial flat-plate solar collector for industrial use produced by the Mexican company Módulo Solar, model MAXOL Hipertinox, was selected. To determine the number of these solar collectors and the volume of the storage tank required to preheat 10,450 litres/day of boiler feed water, the methodology proposed by [16] was developed, and the results obtained are summarised in Table 1:

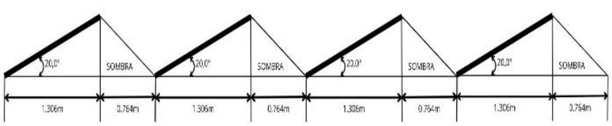
Table 1. *Variables calculated for the sizing of a solar collector system.*

Variables calculadas	Símbolo	Resultados	Unidad de Medida	Observaciones
Demanda energética	Q_{dem}	1,834,602	kJ/día	Para aumentar la temperatura del agua de alimentación en 42°C.
Radiación promedio solar	H_p	6.018	kWh/m²/día	Se promedia la radiación solar incidente en Temimilcingo, Morelos, en los meses de zafra (noviembre - mayo)
Área de captación	A_{cap}	121.49	m²	Se tiene en cuenta la demanda energética, la radiación promedio solar y una eficiencia del colector solar de 69.7 %.
Número de colectores	N_c	61	Adimensional	Se tiene en cuenta un Factor de seguridad FS igual a 1, según el tipo de proceso.
Volumen del depósito	V_{dep}	12,067.55	litros	Volumen máximo para almacenar el agua caliente proveniente de los colectores.

Source: *Own elaboration*.

According to the results obtained, 61 MAXOL Hipertinox flat-plate solar collectors are needed to cover a collection area of 121.49 m² for preheating 10,450 litres of water per day to 70°C. Similarly, a storage tank with a maximum capacity of 12,067.55 litres is required to hold the entire volume of hot water. For the installation of the system, the minimum distance between collectors is calculated to prevent the shadow cast by the previous collector from interfering with the optimal operation of the following collectors. The length, width and height of the scissor base and the selected solar collector are taken into account, as well as the coefficient k=1, in accordance with the collector's angle of inclination recommended by the manufacturer (20°). Equation 15 determines that the minimum distance between collectors should be 0.764 m, as shown in the following figure:

Figure 2. *Minimum distance between flat-plate solar collectors*.



Source: *Own elaboration*.

The layout also includes a spacing of 20 cm for connection and maintenance, and it is taken into account that the distribution of collectors should not exceed 10 per row or column of the system. Based on the above data, it is determined that a total area of 122.26 m²is required for the location of the collectors.

On the other hand, it is suggested that the solar collector system be located as close as possible to the chemical water treatment plant (PTQA), from where the water is sucked up to pass through the collector system for preheating, stored in the storage tank and then enter the boiler area.

CONCLUSIONS

The integration of renewable energy technologies using solar collectors is presented as a viable and promising alternative for improving the operating and consumption indicators of the feed water preheating process and the distiller in general.

This methodology will reduce the consumption of heat energy from the boiler and steam for conventional water preheating. For its part, the recovery and reuse of condensed steam promotes a circular economy approach and improved management of natural resources in the process. The recovery of 69% of the condensates generated translates into an improvement in the overall efficiency of the system, a reduction in fuel consumption to bring the water to its boiling temperature, and a reduction in water consumption from the supply network, thus lowering associated costs. The adoption of these practices enhances the company's reputation by demonstrating its commitment to sustainability and environmental responsibility.

It is estimated that the simulation of the proposed system will continue using tools such as MATLAB and TRNSYS, which are extremely useful for validating the energy and economic impact of the research. This strategy represents a firm step towards energy transition and the sustainable modernisation of the sector.

As part of future work and lines of research, it is considered appropriate to equip the plant to take real-time measurements of key variables (temperatures, flow rates, pressures and radiation) in order to experimentally evaluate the results obtained, as well as to quantify the effect of solar intermittency on effective heating time, evaluate the sizing of the collectors and apply uncertainty and sensitivity analysis with an appropriate experimental design.

A second line of research will focus on deepening the circular economy of the process by identifying and valorising by-products currently considered waste, and on evaluating advanced control and optimisation strategies (e.g., predictive control and multi-objective optimisation) to maximise the use of solar energy and other by-products that could be reused with the aim of increasing the overall efficiency of the system and optimally reintegrating these by-products optimally into the relevant stages, contributing to the closure of material and water cycles.

BIBLIOGRAPHY

[1] Mikucka, W., & Zielińska, M. (2020). Distillery stillage: characteristics, treatment, and valorisation. Applied Biochemistry and Biotechnology, 192, 770-793.

[2] Ones, O. P., Yeney, L. G., de Cárdenas, L. Z., & Cabrera, Z. R. (2018). Analysis of the distillation section of a cane spirit distillery using a commercial simulator. Science and Technology, 11(2), 47-56.

[3] Yauce Milian, A. B. (2015). Technical, economic, and financial study on the implementation of flat-plate solar collectors to heat feed water for the Apin fire-tube boiler, reducing the consumption costs of industrial oil No. 6 at the Alicorp SAA–Trujillo company.

[4] Stuckrath, C., & Worrell, E. (2022). Energy Efficiency and Cost Saving Opportunities for Distilleries United States Environmental Protection Agency An ENERGY STAR® Guide for Energy and Plant Managers.

[5] Ones, O. P., León, O. G., & de Cárdenas, L. Z. (2012). Modelling, simulation and analysis for energy purposes in hydrated ethanol distilleries Editorial Universitaria.

[6] Borroto, A., & Rubio, A. (2010). Combustion and steam generation. Editorial Universo Sur, 1-117.

[7] Yauce Milian, A. B. (2015). Technical, economic and financial study of the implementation of flat solar collectors to heat the feed water of the Apin fire-tube boiler, reducing the costs of industrial oil No. 6 consumption at the Alicorp SAA–Trujillo company.

[8] Matteini, M. (2014). Training manual on industrial steam system optimisation (OSV). In: Vienna: United Nations Industrial Development Organisation.

[9] Rodríguez, J. C. S. (2008). Renewable energies and energy efficiency. Canary Islands Institute of Technology. https://books.google.com.mx/books?id=6FEOkgAACA AJ

[10] Carrión-Chamba, W., Murillo-Torres, W., & Montero-Izquierdo, A. (2022). A review of the state-of-the-art of solar thermal collectors applied in industry. Ingenius. Science and Technology Journal (27), 59–73.

[11] Mekhilef, S. (2018). Circular economy and renewable energy through industrial applications. Constructing a Green Circular Society, 24, 121.

[12] ASIT, A. S. l. I. T. (2021). Solar thermal energy in industrial processes. IndustriAmbiente: environmental and energy management (34), 56-60.

[13] Gil, J. D., Topa, A., Álvarez, J., Torres, J., & Pérez, M. (2022). A review from design to control of solar systems for supplying heat in industrial process applications. Renewable and Sustainable Energy Reviews, 163, 112461.

[14] ModuloSolar. (2024). Catalogue of flat plate solar collectors. Retrieved 10 April from https://tienda.modulosolar.com/

[15] Quezada González, M. A. (2016). Proposal for the use of solar energy as part of water preheating in the boilers of the San Juan de Dios General Hospital, University of San Carlos de Guatemala].

[16] Jiménez Borges, R., Madrigal Monzón, J. A., & Cabello Eras, J. J. (2019). Selection of a solar collector to increase the temperature of the feed water to the steam generator at the University of Cienfuegos. Revista Universidad y Sociedad, 7(2), 64-71.

[17] Vega Melo, Y. J. (2017). Influence of preheating feed water using solar energy on the efficiency of a fire-tube boiler at the Industrial University of Santander. Peru.

[18] Vásquez, S. (2003). Design of a solar water heating system.

[19] Arcos Adame, J. G. (2018). Sizing of water preheating systems for boilers using solar energy and thermal storage. Cenidet. Mexico.

[20] Puigventós, Francesc; Riera, Melcior; Delibes, Carla; Peñaranda, María; De la Fuente, Laura; Boronat, Assumpció. (2002). Studies on adherence to antiretroviral drugs: a systematic review. Med Clin (Barc). Jun;119(4):130-7.

[21] Dos Santos, M. R., de Brito, J. L. R., & Shibao, F. Y. (2022). Circular economy in photovoltaic solar energy. COLÓQUIO-Revista do Desenvolvimento Regional, 19(1, Jan/Mar), 293-311.

[22] Dardón Contreras, J. D. (2021). Research design for increasing the energy efficiency of a boiler through the use of solar energy as part of water preheating in a soap industry. University of San Carlos of Guatemala.

[23] CANAINCA. (2020). Solar heat for industrial processes: Study of potential in the food canning industry in Mexico.

Contribution Role Table

Role	Author(s)
Conceptualisation	Arturo Ernesto Mares Gardea
Data curation	Marisol Cervantes Bobadilla
Methodology	Jarniel García Morales
Project management	Arturo Ernesto Mares Gardea Ivetteh Virginia Medina Medina (equal contribution)
Resources	Marisol Cervantes Bobadilla
Software	Jarniel García Morales
Supervision	Arturo Ernesto Mares Gardea
Validation	Ivetteh Virginia Medina Medina
Visualisation	Marisol Cervantes Bobadilla
Writing	Arturo Ernesto Mares Gardea
Editorial	Jarniel García Morales

Receipt: 05/08/2025 | Acceptance: 13/09/2025 | Publication: 30/10/2025