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Energy Integration of an Intensified Biorefinery Scheme from Waste Cooking Oil to Produce Sustainable Aviation Fuel

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ABSTRACT

Sustainable aviation fuel (SAF) is a proven alternative to reduce CO_2 emissions in the aviation sector, supporting sustainable growth. However, SAF processes remain economically uncompetitive with fossil-derived jet fuel, prompting interest in strategies to address these challenges. In 2022, Carrasco-Suárez et al. explored process intensification in the SAF separation zone of a biorefinery using waste cooking oil (WCO), achieving a 3.07% reduction in CO_2 emissions and lower operational costs for steam and cooling water. Despite these gains, the WCO biorefinery remains economically unviable with high energy demands. This work presents the energy integration of the entire WCO biorefinery addressed from the pinch point methodology, combined with separation zones intensification (EI-PI-S), using the principles of sections movement for distillation columns; these energy efficiency strategies were applied on the biorefinery in Aspen Plus V.10.0 in order to improve the scheme. Key indicators—total annual cost (TAC), energy investment per product energy (EI-P), energy investment per main product mass (EI-MP), and CO_2 emissions per main product mass (CO_2-MP)—were used to compare the conventional scheme (CS) and the intensified scheme before energy integration (PI-S). The EI-PI-S scheme achieved the best performance, reducing steam and cooling water requirements by 14.34% and 31.06%, respectively, and CO_2 emissions by 13.85% and 14.13% compared to CS and PI-S. However, TAC for EI-PI-S was 0.89% higher than PI-S. Despite this, the integrated and intensified WCO biorefinery emerges as a feasible option for SAF production, adhering to energy minimisation principles and improving economic performance.

Keywords: WCO biorefinery scheme, SAF, modelling and simulation, energy integration, process intensification

INTRODUCTION

The aviation industry is increasingly under pressure to reduce its carbon footprint while also trying to recover from the crisis caused by the restrictions of the pandemic brought on by the SARS-CoV-2 virus. In this context, using renewable fuels has proven to be a promising and resilient alternative for the sustainable economic recovery of this sector, which faced its worst year in history in 2020 [1]. Currently, the price of renewable aviation fuel is not competitive compared to its fossil counterpart. One of the strategies to achieve its economic feasibility has been using biorefinery schemes based on residual raw materials, such as WCO. In this biorefinery scheme based on WCO, SAF is obtained as the main product [2]. Then, the separation zone was intensified to improve its economic and environmental competitiveness using the Rong-Errico methodology, achieving up to a 66.95 % reduction in reboiler heat duty through the intensified design [3, 4]. To further improve this biorefinery scheme, this study proposes the intensification of the ethanol recovery zone. Additionally, the energy integration of the scheme aims to utilise the energy from process streams while minimising reliance on external energy sources through the application of pinch point methodology [5]. This study seeks to reduce energy consumption in the

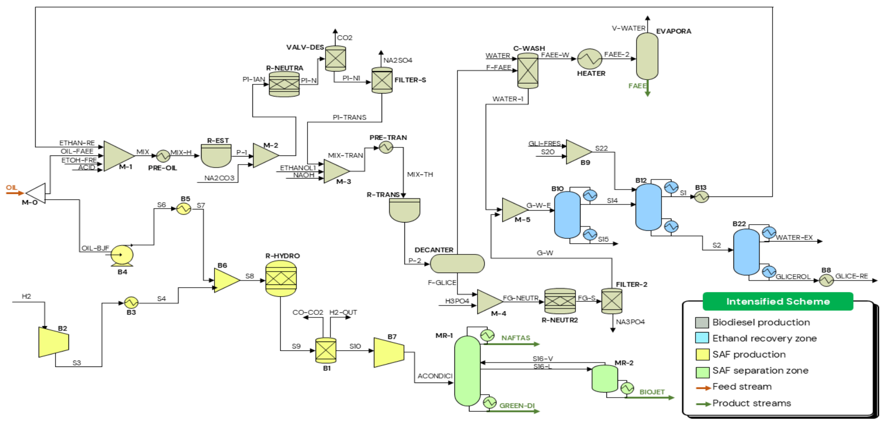

Figure 1. Intensified scheme developed by Carrasco-Suárez et al. 2022 [4].

biorefinery, which will contribute to the overall sustainability of the SAF production process.

METHODOLOGY

The methodology adopted in this work centres on minimising energy consumption within the biorefinery framework by incorporating process intensification and energy integration tools. The following sections will discuss these energy efficiency approaches, alongside an evaluation of their effectiveness using economic-environmental indicators.

Biorefinery of WCO

The biorefinery scheme developed after intensifying the SAF separation zone, served as the foundation for this work (Figure 1). It processes 2,004.88 kg/h of waste cooking oil (WCO), which consists of 94% triglycerides and 6% free fatty acids [4]. For more detailed information about the feedstock modelling and the base design of the WCO biorefinery, see [4]. The feed (OIL) is divided into two secondary streams, 50% (by weight) for each processing route; the first (OIL-FAEE) is destined for obtaining biodiesel, and the second (OIL-BJF) is to produce SAF.

Biodiesel is produced through two reactive zones in RBatch modules: esterification (R-EST) and transesterification (R-TRANS). The resulting stream (P-2) enters a decanter (DECANTER), producing two streams: F-FAEE (biodiesel) and F-GLICE (glycerol). The biodiesel is washed with a water stream (50% by weight) in the Extract module (C-WASH) to remove impurities. The washed biodiesel (FAEE-W) is dried in a Heater module (HEATER) and purified in a flash tank (EVAPORA) using the Flash2 module. Secondary products (ethanol, water, glycerol) are separated via a train of three RadFrac columns (B10, B12, and B22), with B12 employing glycerol as an extracting agent for recirculation in the biorefinery. The thermodynamic models used are NRTL and UNIFAC for the reactive zones and NRTL for secondary product recovery.

Regarding SAF production, the WCO enters a Pump module (B4) and a heat exchanger (B5) to condition the feed stream to 380 °C and 30 bar. A hydrogen stream at 10 bar enters a compressor (B2) and then to a heat exchanger (B3) to reach 30 bar and 380 °C. Next, both streams enter the hydrotreatment reactor (R-HYDRO), and its output (S10) is sent to a turbine (Compr module B7) to reduce pressure to 1 bar. The output stream (ACONDICI) containing 28 hydrocarbons is divided into three main products: naphtha (NAFTAS), SAF (BIOJET), and green diesel (GREEN-DI). SAF separation is achieved through a distillation train consisting of two columns (RadFrac modules MR-1 and MR-2), producing 306.12 kg/h of SAF with a recovery rate of 99.62% and representing 16.6% of the total products, with biodiesel being the most abundant at 50.1%. The conditioning and reaction zones use Peng-Robinson for thermodynamics, while the separation zone utilises BK10.

Process Intensification on Separation Zones

Distillation is known for its low thermodynamic efficiency, a significant factor in energy consumption within biorefineries [6]. In this case, distillation accounts for 61.4% of the total energy consumed. This inefficiency requires exploring alternative methods, such as process intensification strategies, to optimise energy use and improve overall performance. Process intensification is a tool in chemical engineering that focuses on designing processes that are more compact, environmentally friendly, safe, and energy-efficient [7]. Using thermally coupled flows instead of traditional heat exchangers in distillation processes has demonstrated a reduction in energy consumption. This improvement enhances heat and mass transfer while meeting recovery and purity goals in distillation sequences [8].

Intensification of the SAF Separation Zone

A systematic methodology developed by Rong and Errico has been implemented to improve the energy efficiency of the SAF, naphtha, and green diesel separation process, as illustrated in Figure 1. This approach reduced the reboiler heat duty by 66.95 % compared to the conventional one, resulting in a 3.07 % reduction in CO_2 emissions. Although the capital cost of the intensified biorefinery is 11.74 % higher than that of the conventional scheme, it offers operating costs that are 2.68 % and 8.13 % lower for steam and cooling water, respectively [4]. These results are promising, indicating that this biorefinery has the potential to meet energy demands sustainably, while significantly reducing emissions and energy requirements. Additionally, the intensification of the ethanol recovery zone could also lead to significant improvements. Thus, both strategies to achieve the complete intensification on the separation zones into the biorefinery scheme could be further improved by using an energy integration tool that utilises process streams and reactive energy zones as energy sources to meet all energy demands in the biorefinery [5].

Intensification of the Ethanol Recovery Zone

The distillation train illustrated in blue in Figure 1 is designed to recover ethanol with a purity of 99.89%. This high-purity ethanol can subsequently be recirculated back into the biodiesel production process. This part of the biorefinery accounts for 57.7% of the total energy requirements. Thus, implementing energy-saving methodologies is essential for cost reduction, as decreased energy consumption significantly lowers operational expenses and enhances profit margins. Furthermore, such measures mitigate environmental impact by reducing greenhouse gas emissions. This approach is vital for establishing a long-term, viable, and resilient SAF production process, particularly as energy resources become increasingly scarce and expensive.

The conceptual principles of the Rong-Errico methodology were taken as the basis for reducing energy consumption in the ethanol recovery distillation process [3]. It is specifically designed for traditional distillation columns with a single condenser and reboiler, intended for non-azeotropic mixtures. Due to the formation of an azeotrope between ethanol and water, extractive distillation is necessary, utilising glycerol as the extracting agent. Therefore, the distillation train used to recover ethanol, as shown in Figure 1, falls outside the scope of the Rong-Errico approach; however, in order to address this challenge, the conceptual principles of the Rong-Errico methodology were used to enable the creation of intensified configurations.

In this case, a singular simple column configuration (D-SC) exists. The intensification process for this configuration commences with the generation of all possible original thermally coupled configurations (OTC) by substituting the heat exchangers linked to the submixtures S14 and S2 with thermal coupling streams, resulting in three distinct OTCs. These OTCs are the foundation for deriving thermodynamically equivalent structures (TES) by manipulating movable sections. Regarding OTC-2, section 5 cannot be relocated to column B12, as it is not a transport side column. In contrast, TES-1 and TES-3 incorporate a single-section transport side column (B12), while columns B10 and B22 maintain a simple column design. Consequently, ISC-1 and ISC-3 can be generated by omitting column B12 from the configurations.

The modifications to the original methodology for generating the seven intensified configurations involved using the feed stream S14 to define the rectifying and stripping sections in column B12. Additionally, to achieve the desired purity of the products, the feed stage location for stream S22 was modified, along with adjustments to operational parameters such as reflux ratio and mass flux of the thermal coupling streams. The D-SC achieves purities of 99.89% for ethanol, 85.83% for water, and 99.99% for glycerol. Among these configurations, OTC-2 is the only option that meets these requirements, while the other ones present convergence troubles. OTC-2 achieved the required purity specifications by adding glycerol to the top of column B12 to break the azeotrope and introducing thermally coupled flows at the bottom of the column for effective separation. In contrast, in other configurations, the thermally coupled flows in column B10 disrupted the separation process by mixing ethanol, water, and glycerol in the feed with the glycerol needed for column B12. This factor and heat duty savings in the condenser and reboiler were considered when determining the configuration to replace the conventional train. Consequently, OTC-2 was coupled into the biorefinery (Figure 2), which reduced heat duty by 8.17% for the condenser and 5.56% for the reboiler, compared to D-SC.

In the PI-S (Figure 2), designed after intensifying both distillation sequences, the energy requirements for heating and cooling were reduced by 3.10% and 11.81%, respectively, compared to the conventional scheme (CS). CO_2 emissions increased by 0.33%. This rise is attributed to the high heat duties in column B22, which has only four stages. Introducing thermal coupling streams (S2-V and S2-L) has negatively affected the column's energy efficiency and performance. With just four stages, the column requires a higher reflux ratio to achieve the necessary purity for glycerol and water. This, in turn, increases the heat duty of the reboiler by 2.76%, meaning the column must work harder to achieve effective separation.

Energy Integration of an Intensified Biorefinery Scheme

Energy integration is a systematic approach designed to improve the energy efficiency of processes by

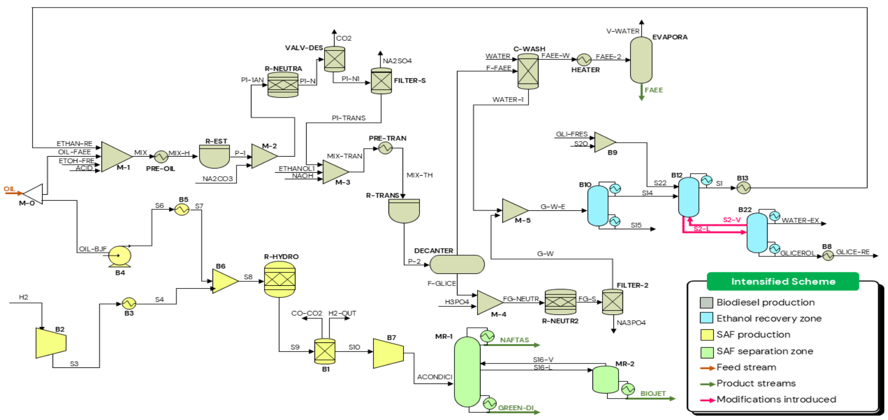

Figure 2. Intensified WCO biorefinery scheme

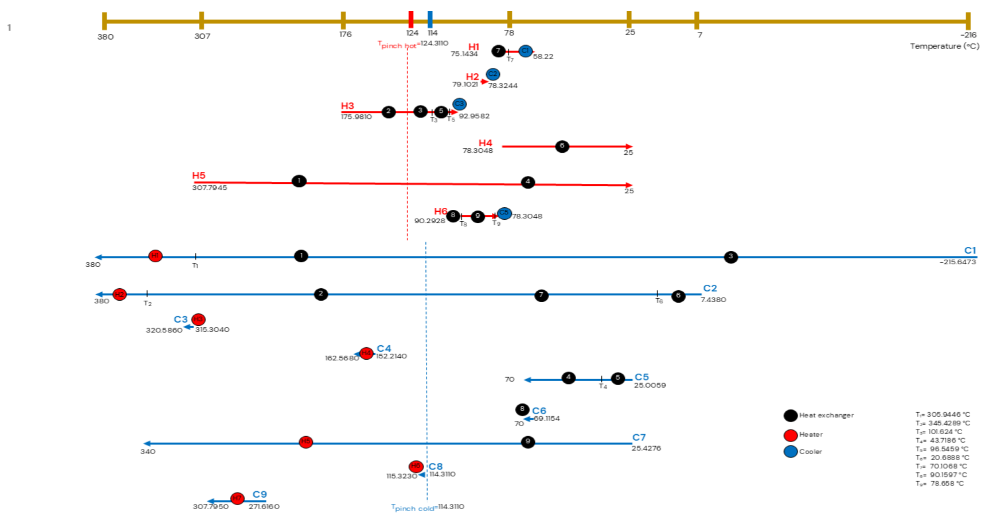

Figure 3. HEN designed for the intensified scheme

optimising energy use and recovery within a system. A key technique is pinch point analysis, which minimises energy requirements across the entire biorefinery process[9].

This technique was applied for energy integration of the PI-S, beginning with the collection of data on the energy requirements for both hot and cold process streams, including their temperatures and flow rates, from Aspen Plus V.10.0. This information was then visualised on a temperature-enthalpy (T-H) diagram, where a temperature difference (ΔT) of 10 °C was applied to adjust the temperatures of the hot streams. A heat cascade was employed to identify the pinch point, which was the optimal location for heat recovery, marked by the minimal temperature difference between the hot and cold streams. A heat exchanger network (HEN) was designed to maximise heat transfer around this pinch point while considering thermal constraints. This network aimed to significantly reduce energy consumption, resulting in cost savings and a lower environmental impact [10].

Biorefinery assessment

The EI-PI-S was evaluated and compared with the CS and PI-S using economic-environmental indicators, defined from the energy and mass requirements of the process. These results quantify the energy performance and the CO_2 emissions from the process, as well as its profitability and efficiency. The indicators determined in this work are shown in Table 1.

RESULTS

In this section are presented the results of energy integration and process intensification, energy efficiency strategies, applied on the WCO biorefinery. Based on the pinch point analysis, the pinch point temperature for hot streams was identified at 124.31 °C, while for cold streams, it was 114.31 °C, using a temperature difference (ΔT) of 10 °C. The calculated minimum heating and cooling requirements, determined through heat cascade analysis are 1126.40 kW and 441.02 kW, respectively.

Table 1: Economic-environmental assessment indicators.

Indicator	Equation and description
Total annual cost (TAC)	$$TAC\ \left(\frac{USD}{year}\right) = \frac{CC+0.18CC+0.61CC}{n} + OC \quad (1)$$ This includes estimating capital (CC) by Aspen Plus and adjusting by CEPCI, as well as the operating costs (OC) and a period of recovery from the investment (5 years) [12,13].
Energy indicator per total energy products (EI-P)	$$EI-P\ = \frac{Invested\ energy\ for\ heating}{Energy\ provided\ by\ total\ products} \quad (2)$$ It indicates the overall energy efficiency of the biorefinery.
Energy indicator per total products (EI-MP)	$$EI-MP = \frac{Invested\ energy\ for\ heating}{Mass\ of\ main\ product} \quad (3)$$ Similarly to EI-P, this indicator measures how effectively the energy input is converted into SAF, reducing reliance on external energy sources.
CO_2 emissions indicator per total products (CO_2-MP)	$$CO_2-MP\ \left(\frac{ton\ CO_2}{kg}\right) = \frac{Total\ CO_2\ equivalent\ emissions}{Mass\ of\ main\ product} \quad (4)$$ This metric provides insights into the environmental impact and quantifies the emissions relative to the total SAF mass, helping assess the carbon footprint.

Table 2: Estimated indicators

Scheme	% TAC savings	EI-P (kW/kW)	EI-MP (kW/kg)	CO_2-MP (ton CO_2/kg)
CS	-	4.2919	12.5465	9.2918
PI-S	-25.77 %	4.1394	12.1580	9.3226
EI-PI-S	-26.90 %	4.0245	11.8202	8.0051

The designed HEN, shown Figure 3, uses the fewest heat exchangers to maximise savings in steam and cooling water consumption, as well as equipment costs. The energy savings achieved are 14.34% for heating and 31.06% for cooling, compared to the CS. The steam requirement for the EI-PI-S system was 0.67% higher than that of the CS and 0.13% higher than the PI-S. Similar to the PI-S, the ethanol recovery process is responsible for a 2.5% increase in emissions from column B10 in EI-PI-S. This increase occurs because column B10 handles the bulk of the three compounds from the feed, concentrating them into the liquid phase. As a result, higher reboiling energy is needed to generate the vapour phase required for separation, particularly for ethanol and water, which form an azeotrope and thus require additional energy for phase change. Conversely, the amount of cooling water used in the EI-PI-S scheme was reduced by 35.51% compared to the CS and by 8.53% compared to the PI-S.

The results from Table 2 indicate that implementing these methodologies contributed to energy savings and environmental benefits. By combining process intensification and energy integration strategies, the total energy invested is reduced, with the EI-P-S decreasing by 6.23% and the EI-MP decreasing by 5.79% compared to the CS.

Although the amount of vapour required in the EI-PI-S increased, the overall efficiency gains from energy integration led to a reduction in CO_2-MP by 13.85% when compared to the CS. The EI-PI-S demonstrates a 26.90% increase in TAC compared to the CS and a 0.89% increase compared to the PI-S.

This suggests that although the EI-PI-S reduces energy consumption and emissions, making it a promising alternative for sustainable biorefineries in the production of SAF, the costs of the equipment and raw materials outweigh the economic benefits gained from energy savings. This presents a challenge to the economic feasibility of the EI-PI-S scheme, and achieving financial profitability remains a hurdle [11].

CONCLUSION

In this work, the implementation of the pinch point analysis methodology in an intensified WCO biorefinery scheme to produce SAF was presented, achieving savings of 14.34 % and 31.06 % in heating and cooling requirements, respectively, compared to the conventional scheme. This energy-integrated scheme (EI-PI-S) was evaluated and compared with the conventional (CS) and intensified (PI-S) schemes, reporting savings across the proposed energy-environmental indicators. Thus, the production of SAF in this energetically integrated-intensified biorefinery scheme from WCO represents a promising alternative. Strategies are essential to tackle the challenge of cost competitiveness in biorefineries. Government initiatives and incentives, such as tax credits, grants, and subsidies, can significantly help reduce the capital and operational costs associated with biorefinery investments. Furthermore, promoting stakeholder collaboration is crucial for successfully deploying biorefineries.

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