Energy and Exergy Analysis of a Biodiesel Plant

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Abstract:
Despite the current push for full electrification of the transportation sector, the utilization of IC engines (either on their own or hybrid guise) will continue for the foreseeable future. This is even more evident in the freight industry and with construction equipment. Therefore, the use of alternative fuels is a vital stepping stone toward low-carbon transportation. Environmental regulations have been developing enormous interest in biodiesel as an alternating fuel, with the main objective of reducing emissions associated with the transportation sector. Biodiesel is a renewable fuel that is mainly produced from vegetable oils and animal fats. At an industrial scale, its production is an energy-intensive operation that contributes to the overall carbon footprint.
The present paper describes the energy and exergy analysis of an existing biodiesel plant. The facility applies used cooking oils and vegetable oils as raw materials and has an annual consumption of over 1,100 toe (as of 2021). The analysis identified the possibility of using biomass as a primary energy source for heat. Furthermore, the detailed analysis of the plant operation enables the identification of energy conservation measures that can reduce the electricity consumption and the pellet consumption by 29 tons a year.

Keywords:
Biodiesel; Energy; Exergy; Irreversibility; Thermodynamics.

1. Introduction

In recent decades, several concerns have arisen regarding the balance between energy consumption and sustainable, environmentally friendly, economically viable, and socially fair development. In this context, renewable energies started to play a leading role in order to reverse the worrying scenario of the possible depletion of fossil fuels (1). The energy consumption of society has contributed to the reduction of the existing reserves of coal, natural gas, and oil, and the ratio between consumption and production does not allow the continuous replenishment of these reserves, so depletion is inevitable (2). On the other hand, climate change is undoubtedly the greatest socio-environmental concern that the planet is facing today. Although burning fossil fuels is the main problem, it is also true that the increase in the volume of road traffic created by the world's dependence on transportation, particularly in large urban centers, has contributed on a large scale to the increase in pollutant emissions and energy consumption (3). In 2020, the total emissions of pollution gases emitted in Portugal (57.6 Mton CO_2) are estimated that 25% come from national transport, being the sector that consumed the largest amount of energy by year, around 32.6%, followed by industry (31.2%), domestic (19.5%), services (13.4%) and agriculture and fisheries (3.3%) (4).

To comply with the international goals to achieve carbon neutrality by 2050, renewable energy technologies have been at the top of the international discussion and several signs of progress have been conducted in this sector (5). However, no effective solution was implemented regarding the transportation sector and environmental regulations have been developing a huge interest in biodiesel as an alternating fuel, with the main objective of reducing hazardous emissions. In this context, it is believed that the replacement of fossil fuels by biofuels, such as biodiesel, can be a major contributor to the transportation sector (6). Currently, emphasis has been given to the study of bioethanol and biodiesel to replace gasoline and diesel respectively, since to use these biofuels it is not necessary to make major changes in road transportation (7). Biodiesel in particular is a biodegradable, non-toxic energy source synthesized from various raw materials, including man-made waste such as used oils and animal fats, which in contact with nature can cause major environmental

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imbalances (8). According to the international energy agency (IEA) (7) biodiesel production has been gradually increasing, as shown in Figure 1 (a). Although insignificant, this increase tends to remain until 2025 with an estimated world production of 46 billion liters. Regarding the countries that lead the biodiesel production sector, data presented in Figure 1 (b) shows that in 2021, Indonesia was the world's largest producer of biodiesel with a total of 9.5 billion liters, followed by Brazil with 6.9 billion liters of biodiesel produced (6).

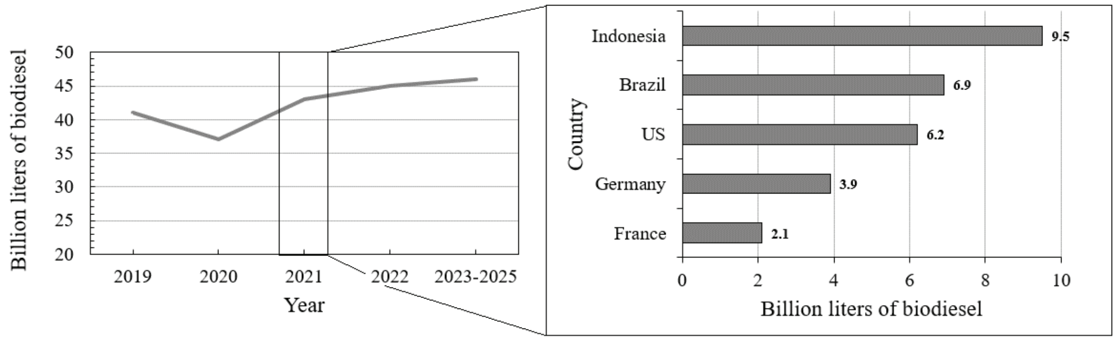

Figure 1. (a) World production of biodiesel; (b) Worldwide leading countries in biodiesel production in 2021.

Although biodiesel is pointed out as a solution for the transportation sector, the increased production worldwide has also led to an increase in the production of vegetable oils, as they are the main raw materials used for biodiesel production on an industrial scale. However, the high cost of biodiesel production, as a consequence of the high price of vegetable oils, is the biggest problem for its implementation and commercialization on a large scale, making biodiesel less economically competitive compared to diesel derived from petroleum [1]. To create alternatives, many methods have been explored to reduce this cost, one of which involves replacing vegetable oil with used cooking oils. Recycling frying oil as a biofuel not only removes a hazardous compound that is most of the time released to the environment but also allows the production of a renewable and less polluting source of energy (8,9).

From an industrial point of view, the biodiesel and conventional diesel production processes have almost equivalent efficiencies, with regard to the conversion of their raw materials into fuels (10). The opportunity to reduce the energy consumption in industrial plants, and therefore decrease the overall energy consumption of the process, allows for an intensification of the integration of biodiesel production on a large scale which could be very important for the dissemination of this fuel worldwide. In this context, this work focuses on an energy analysis carried out on a company in the biofuels sector in Portugal, more precisely, a company dedicated to the industrial production of biodiesel. Since the company is characterized by being an energy-intensive consumer, having consumed throughout 2021, 1120.46 toe, it is important to conduct an energy and exergy analysis of the plant in order to identify energy optimization solutions that can reduce the electrical and thermal energy consumption. Based on the identification of the processes involved in biodiesel production and the related products used for its production, the energy consumed and produced is estimated in this work. This allows to determine the efficiency of the process. However, energy analysis does not provide all the information needed to characterize the performance of the production process. Therefore, exergy analysis is useful to pinpoint the thermodynamic losses and inefficiencies (11). This study presents a methodology to determine energy and exergy efficiencies of biodiesel process production, which include both biodiesel and energy production. Moreover, solutions are presented to increase the energy performance of the biodiesel production process, highlighting the need to conduct a detailed thermodynamic analysis of biodiesel production plants to disseminate the use of this fuel in the transportation sector.

2. Theoretical Background

2.1. Biodiesel

Biodiesel is considered a biofuel, whose composition and properties comply with the European standard EN 14214 or the American standard ASTM D6751. It consists of a mixture of methyl esters of fatty acids formed by transesterification or esterification of vegetable oils (e.g. soybean, rapeseed, sunflower, and palm oils) or animal fats with methanol or ethanol, from various chemical or biological processes (12). From the chemical reaction between these raw materials, two products are obtained, an ester (biodiesel) and glycerol (also known as glycerin), which can be used, for example, by the pharmaceutical industry. The reaction is catalyzed by an acid or a base, depending on the characteristics of the oil and/or fat used. The reaction mechanism can be divided into three stages, where the triglyceride is sequentially converted to diglyceride, monoglyceride, and glycerol, in a sequence of three reversible reactions (12), as shown in Figure 2.

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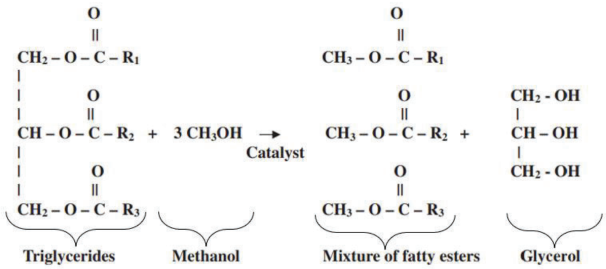

Figure 2. Methanolysis of triglyceride.

2.2. Mass and Energy Balance

The first law of thermodynamics is the main principle that governs the energy conservation principle of any system. The conservation of energy is closely linked to the mass conservation principle, stated by (13). In a steady state, the mass balance model of the biodiesel production process is expressed by Eq. (1).

$$\dot{m}_{in} = \dot{m}_{out} \tag{1}$$

Analogously, the energy balance results from the difference between the energy produced by a fuel and the energy required to obtain it (14), as expressed in Eq. (2) (15,16):

$$\dot{E}_{in} + \dot{Q} = \dot{E}_{out} \tag{2}$$

Except for the electrical energy, that was measured, the remaining forms of energy were calculated according to Eq. (3), as they do not contain any other form of energy other than the chemical energy of each compound.

$$\dot{E} = \dot{m}\, LHV \tag{3}$$

The heat supplied to the system comes from the burning of pellets, being $\dot{Q}$ expressed by Eq. (4).

$$\dot{Q} = \dot{m}\, LHV \tag{4}$$

2.3. Exergy Balance

While the majority of the chemical industry uses energy analysis to optimize their processes, this does not indicate that the energy is efficiently used (11). To determine if a process is thermodynamically efficient, entropy generation must be analyzed, the higher the entropy generation, the higher energy is degraded (17). This property can be estimated by exergy, which represents the useful amount of work that can be extracted from a system when taken into thermodynamic equilibrium with the environment. Exergy changes account for the irreversibility of a process that depends on entropy production. Consequently, this irreversibility can be obtained by the exergy analysis of the system. In this context, the exergy balance can be expressed in Eq. (5) (10).

$$\dot{\varepsilon}_{in} + \dot{\varepsilon}^{Q} = \dot{\varepsilon}_{out} + \dot{W} + \dot{I} \tag{5}$$

where subscripts *in* and *out* apply the same flows as the ones applied in the energy balance an $\dot{I}$ is the system's irreversibility.

The exergy of a system is composed of several elements, as presented in Eq. (6).

$$\dot{\varepsilon} = \dot{\varepsilon}^{ph} + \dot{\varepsilon}^{0} + \dot{\varepsilon}^{k} + \dot{\varepsilon}^{po} \tag{6}$$

where $\dot{\varepsilon}^{ph}$, $\dot{e}^{0}$ $\dot{\varepsilon}^{k}$ and $\dot{\varepsilon}^{po}$ are the physical, chemical, kinetic, and potential exergy, respectively.

In this study, only fluids with chemical energy (Eq. 7) are considered and all other forms of exergy are therefore neglected.

$$\dot{\varepsilon}^{0} = \dot{m}\, \varphi\, LHV \tag{7}$$

In Eq. (7), φ depends upon the chemical composition of the fuel, being considered approximately equal to 0.975 for liquids and gases and 1.07 for biomass (18,19).

2.4. Efficiency

In this study, two energy efficiencies are considered, the efficiency of the production of biodiesel, presented in Eq. (8), and the total energy efficiency of the process, expressed in Eq. (9).

$$\eta_{Bio} = \frac{\dot{E}_{Bio}}{(\dot{E}_{in} + \dot{P})} \tag{8}$$

$$\eta = \frac{\dot{E}_{Bio} + \dot{E}_{Gly}}{(\dot{E}_{in} + \dot{P})} \tag{9}$$

where $\dot{P}$ represents the pumping power. While the efficiency of biodiesel production, η_{Bio}, is obtained by the ratio between the biodiesel energy and the total energy consumed for its production, the efficiency of the process, η, takes into account the products that are collected from this process, biodiesel, and glycerine.

Regarding the exergetic efficiency, one can consider the rational efficiency for biodiesel production, expressed in Eq. (10), and the rational efficiency of the process, presented in Eq. (11).

$$\psi_{Bio} = \frac{\dot{\varepsilon}_{Bio}}{\dot{\varepsilon}_{in} + \dot{P}} \tag{10}$$

$$\psi = \frac{\dot{\varepsilon}_{Bio} + \dot{\varepsilon}_{Gly}}{(\dot{\varepsilon}_{in} + \dot{P})} \tag{11}$$

The rational efficiency of the production process is a measure of the process performance, being defined by the ratio between useful exergy output and the maximum input exergy. While ψ_{Bio} focuses on the biodiesel production process, ψ considers all the products obtained from this process.

3. Materials and Methods

3.1. Biodiesel Production Line

As previously mentioned, biodiesel is a product resulting from the transesterification of oils with an alcohol in the presence of an acid or alkaline catalyst. The biodiesel production process implemented in the industry where this study was conducted can be summarized in the flowchart shown in Figure 3.

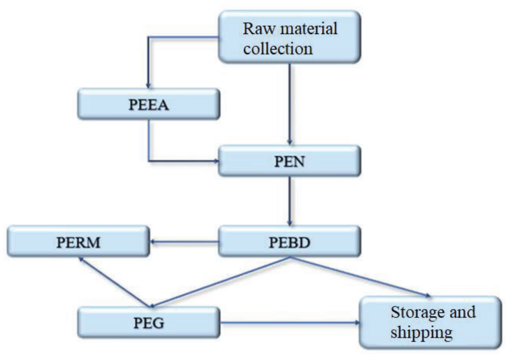

Figure 3. Biodiesel production process.

To ensure that the final product (biodiesel) meets the requirements, several process variables need to be controlled. The biodiesel to be shipped must have the parameters within the specifications, according to the European standard EN 14214. Some of the process parameters to be considered are the acid number (IA) and the percentage of free fatty acids (FFA) in the raw materials, residual raw materials (MPR), the degree of mixing between alcohol and triglycerides in the transesterification process as well as all operating temperatures and pressures.

The process begins with the collection of raw material that consists of waste oils. These oils are mainly wastes from the food industry (restaurants) or resulting from the oil refining industry. The incorporation of this type of waste as a raw material promotes industrial symbiosis and enhances the circular economy. The second stage begins with PEEA (Specific Acid Esterification Production Unit). The raw materials have characteristics that prevent them from being incorporated directly into PEBD (Specific Production of Biodiesel Unit), namely a high acidity index and high content of water, phosphorus, and other contamination. The high-acid MPR (IA > 10 mg/g and FFA > 5%) then need to go through an acid esterification process to be able to be incorporated into the PEN (Specific Neutralization Production Unit). The third phase consists of the pre-treatment of the low-acid MPR (IA < 10 mg/g and FFA < 5%) together with the MPR after the acid esterification process, which occurs in the PEN, to be ready to be incorporated into the PEBD. In the PEBD, biodiesel results from the transesterification of oils with methanol in the presence of a catalyst, sodium methylate. During this process, three reversible reactions take place. From the triglycerides (*TG*) of the oils, two intermediate components are formed, the diglycerides (*DG*) and the monoglycerides (*MG*). The reactions are as follows (12)-(14):

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$$TG + CH_3OH \leftrightarrow DG + R_1COOCH_3 \quad (12)$$

$$DG + CH_3OH \leftrightarrow MG + R_2COOCH_3 \quad (13)$$

$$MG + CH_3OH \leftrightarrow GL + R_3COOCH_3 \quad (14)$$

where $R_{1,2,3}$ are organic radicals.

The global reaction, which characterizes the production of glycerol (*GL*) and biodiesel (*R_3COOCH_3*), is expressed by reaction (15).

$$TG + 3CH_3OH \leftrightarrow GL + 3R_3COOCH_3 \quad (15)$$

The crude glycerine produced in PEBD needs to be treated in order to be able to be exported. PEG is the glycerine treatment process that guarantees a minimum glycerol content of 75-80%. The methanol recovered from the PEBD and PEG (Specific Production of Glycerine Unit) processes needs to be purified (PERM - Specific Production of Methanol Rectification Unit) in order to be used again (> 98 %). Finally, both biodiesel and glycerine are stored in tanks to be later exported.

3.2. Specific Production of Biodiesel Unit

The biodiesel production unit is schematically represented in Figure 4. The process begins with the heating of neutral oils from the PEN (D-03) together with virgin vegetable oils from the D-05 by a plate heat exchanger and a tubular heat exchanger to a desired temperature. Then the raw material is mixed with methanol and sodium methylate, the catalyst. The mixture enters the R-3001 reactor (cavitation reactor) and the reaction takes place up to a percentage of methyl esters close to 85%. The products resulting from this reaction (biodiesel and glycerine) are sent to the D-06 decanter, where the glycerine is decanted and separated, going to the D-08. To simplify this operation, recirculation of the glycerine is conducted, i.e., part of the glycerine that leaves the D-06 goes back in to maintain the temperature and help with its separation (the greater the amount of glycerine, the greater the tendency for deposition). Biodiesel (light phase of D-06) is mixed again with the reagents and passes through the cavitation reactor R-3002 where the formation of esters is completed. The products go to the D-07 and the glycerine is decanted into the D-09 accumulator.

In the production of biodiesel, using an alkaline catalyst, some amount of soap is always produced. Thus, once the transesterification reaction is completed, the excess catalyst and soap tend to be concentrated in the glycerine phase. However, there is always some amount of these constituents that remain in the biodiesel stage. This fact can cause problems in the follow-up of the process: the soaps remain in the process and can cause the clogging of the resins. To solve the problem, when the mixture reaches the D-10 accumulator, phosphoric acid is added keeping the pH controlled (close to neutral). Acidification aims to create conditions less favorable to the formation of soaps and to end the transesterification reaction. This is followed by Flash 1 at approximately 75 ºC and a pressure of 130 mbar, the methanol in the biodiesel is dried to 5000 ppm. Methanol is recovered to D-11 while biodiesel goes to D-15. In the resin basins (R-3003 and R-3004) occurs the final adsorption of glycerine which has sodium, methanol, and some impurities. Biodiesel leaves the resins for Flash 2 where, under more severe conditions of pressure and temperature, methanol drops to values within the European standard, EN 14214, below 2000 ppm. After physical filtration, the biodiesel goes to D-01/D-02. Subsequently, an antioxidant is added to the biodiesel, and this is transferred to the shipping tanks.

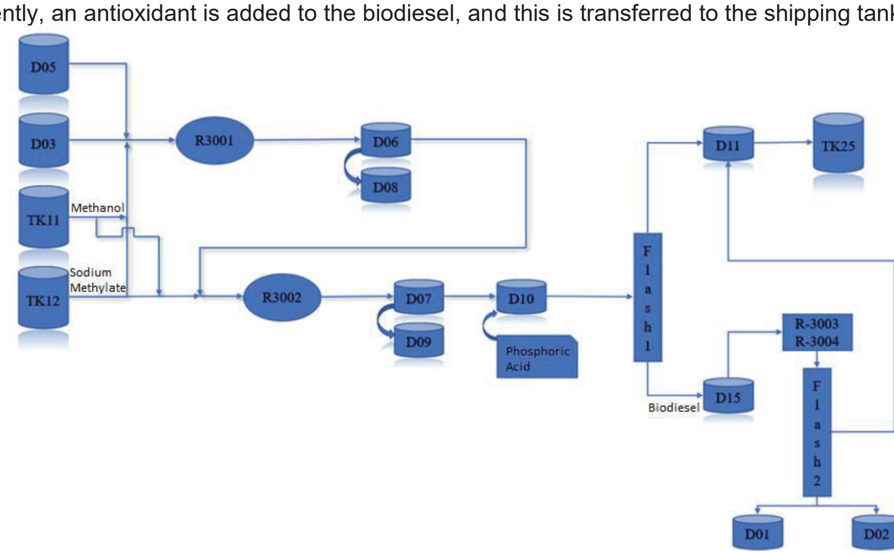

Figure 4. Scheme of the Specific Production of Biodiesel Unit.

4. Results and Discussion

4.1. Energy consumption and biodiesel production

Because of fluctuations in biodiesel production, energy consumption is not constant throughout the year. However, since biofuel production requires temperature control, the highest energy consumption is due to the heating and cooling operations. To better understand the energy needs in biodiesel production, it is essential to carry out an analysis of the history of energy consumption of the processes, which is divided into electricity consumption (electric motors for the pumps and chiller) and consumption of pellets (boiler). For this, the data referring to the year 2021 were used, as presented in Table 1.

Table 1. Typical energy consumption and biodiesel production in a year (2021).

Month	Pellets (ton)	Electricity (kWh)	Production of biodiesel (ton)
January	131.90	155,882.00	1,252.60
February	125.56	108,908.00	876.00
March	154.84	183,094.00	1,787.70
April	135.44	157,979.00	1,491.20
May	160.86	177,861.00	2,104.40
June	132.98	168,588.00	1,740.90
July	127.20	154,309.00	1,572.60
August	100.98	134,481.00	1,227.70
September	160.92	192,194.00	2,064.70
October	157.58	173,891.00	1,706.40
November	157.04	174,555.00	1,780.40
December	106.02	127,698.00	899.40
Total	**1,651.32**	**1,909,440.00**	**18,504.00**

To determine the energy consumption per ton of biodiesel produced, the consumption values are converted into toe to obtain a reference value in toe /ton of biodiesel, taking into account the thermodynamic and electrical conversion factors (1 toe = 41,868 MJ and 1 kWh = 215 $\times 10^{-6}$ toe) presented in Dispatch nº 17313/2008 (20). For calculation purposes, the lower heat value (LHV) of the pellets is considered equal to 18.0 MJ/kg. To determine the consumption of pellets in toe, Eq. (16) is used. On the other hand, the conversion of electrical energy consumption into toe is given by Eq. (17).

$$E_{\mathrm{toe}} = \frac{m.\,\mathrm{LHV}}{41.868} \tag{16}$$

$$E_{\mathrm{toe}} = ec\,.\,215 \times 10^{-6} \tag{17}$$

where *m* is the mass in ton, the LHV is in MJ/kg and the *ec* corresponds to the electric consumption in kWh.

Regarding the energy consumption and using the values for 2021, it appears that the company is covered by the SGCIE (Portuguese Management System of Intensive Energy Consumption), since the total energy consumption exceeds 500 toe – 1120.46 toe (0.06 toe / ton biodiesel) – the company is considered an Intensive Energy Consumer (CIE).

Through the plot presented in Figure 5 (a), it is possible to observe the evolution of energy consumption throughout 2021. For the period under analysis, a significant variation in energy consumption over time is observed. Throughout January and February, the average flow rate of biodiesel produced was 2.7 tons/h, a value lower than the average flow rate seen in the rest of the year (3.5 tons/h). On the other hand, in February a stoppage of about 2 weeks due to a fire occurred. During the summer months, the company was once again stopped, for 3 weeks for the vacation period and in December the average flow rate of biodiesel produced was 2.4 ton/h due to a limitation in a pump. For these reasons, it is possible to perceive the existing variations in energy consumption and biodiesel production, Figure 5 (b), since energy consumption is directly related to biodiesel production. Moreover, an analysis was conducted to determine the major contributors to energy consumption. These contributors were divided into two groups, the boiler, which is responsible for heating the thermal oil that feeds the heat exchangers in the factory, and electrical equipment which includes all the electric motors that power the pumps, lighting, office equipment as well as other less relevant equipment. It should be noted that the Chiller is also included in electrical equipment, which further demonstrates that energy consumption related to utilities (production of heat and cold) is much higher than the energy consumption of

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other equipment directly associated with the biodiesel production process. The plot depicted in Figure 6 (a) shows the difference between the weight of energy consumption between the boiler and the electric motors, being responsible for 63.4 % and 36.6 % of the consumption of the total energy consumed by the company, respectively. To provide more information regarding the energy consumption throughout 2021, the monthly specific energy consumption was plotted and presented in Figure 6 (b). The data show that although January, February, and December are the months with lower biodiesel production, 2.7 ton/h for the first two months and 2.4 ton/h for the last one, the specific energy consumption is much higher. On the other hand, this parameter in the coldest months (October to April) is higher than in the remaining months of the year due to the lower operating temperatures used in the production process, requiring a greater amount of thermal energy.

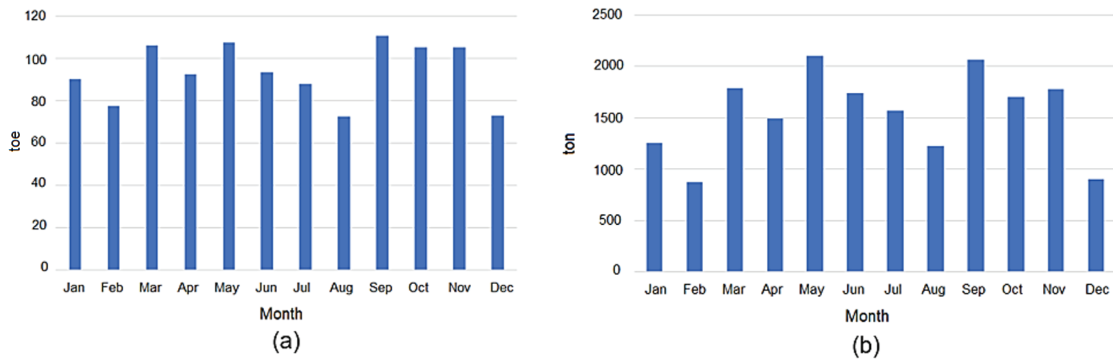

Figure 5. (a) Evolution of energy consumption throughout 2021; (b) Variation in biodiesel production throughout the year (2021).

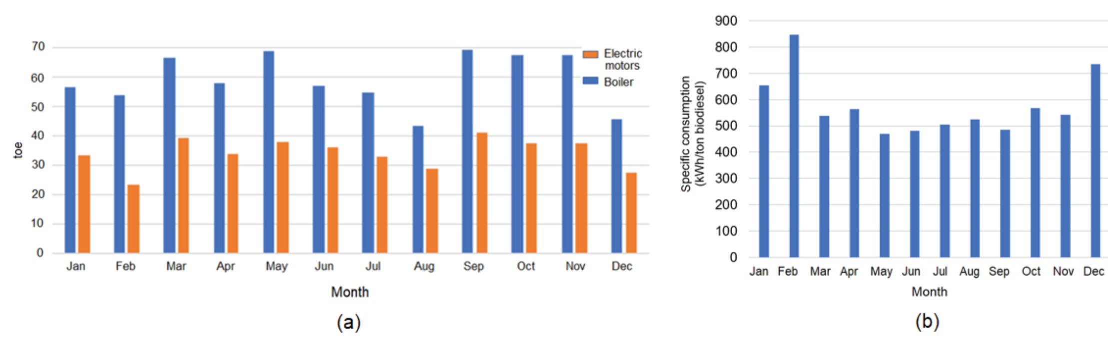

Figure 6. (a) Energy consumption by the boiler and electric motors; (b) Specific energy consumption.

4.2. Mass balance

As previously mentioned, the biodiesel is produced by a chemical reaction between triglycerides, which in this case are composed of virgin oils (VO) and used oils (UO), methanol (CH_3OH), and catalysts, in this case, the phosphoric acid (H_3PO_4) and the sodium methylate (CH_3NaO). In this unit, recovered biodiesel is also introduced into the process. From these inlet components, biodiesel, glycerine, and methanol are produced, as expressed in Figure 7.

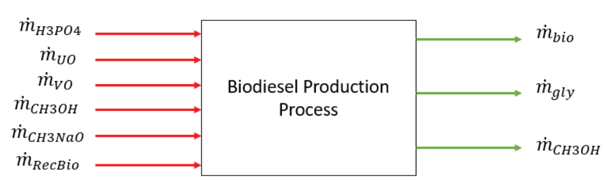

Figure 7. Mass balance of the biodiesel production process.

Regarding the scheme presented in Figure 7, the mass balance of the PEBD unit can be written as follows:

$$\dot{m}_{in} = \dot{m}_{H3PO4} + \dot{m}_{UO} + \dot{m}_{VO} + \dot{m}_{CH3OH} + \dot{m}_{CH3NaO} + \dot{m}_{RecBio} \quad (18)$$

$$\dot{m}_{out} = \dot{m}_{bio} + \dot{m}_{gly} + \dot{m}_{CH3OH} \quad (19)$$

$$\dot{m}_{gly} = \dot{m}_{in} - (\dot{m}_{bio} + \dot{m}_{CH3OH}) \quad (20)$$

where $\dot{m}_{in}$ and $\dot{m}_{out}$ are the inlet and outlet mass flow rates, respectively. In this study, all the mass flow rates were measured, except for the case of the glycerine which was obtained by difference.

For the mass balance, in-site mass flow rate measurements were conducted in the PEBD Unit. The mass flow rate of each pump was recorded directly from the control room except for the following pumps: P-3005 and P-3007 in the Flash 31 and P-3010 Evaporator and P-3022 in the Flash 32 evaporator. To determine the mass flow of these 4 pumps it was necessary to take samples at strategic points, as presented in Figure 8. In Flash 31 (Evaporator Fe-31, Figure 8), 2 samples were collected: one before the evaporator (sample 1, Figure 8) and another later (sample 2, Figure 8). The analysis of these samples allowed to determine the methanol percentage in biodiesel upstream and downstream of the evaporator and, consequently, the evaporated methanol flow rate. This process was repeated for the Flash 32 evaporator.

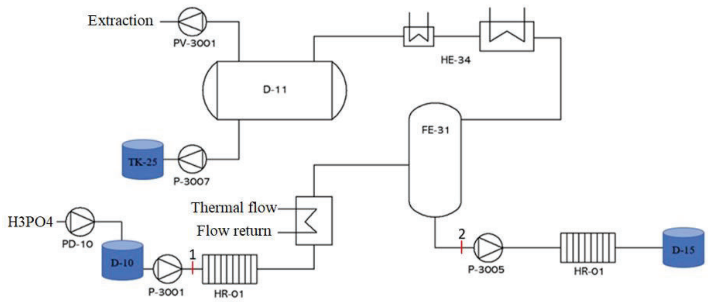

Figure 8. Schematic of sample collection in Flash 1.

According to the data presented in Table 1, it was possible to determine the working time of the PEBD for each month, based on the monthly production of biodiesel and the mass flow rate measured for each product that integrates the biodiesel production process is expressed in Table 2. The results are expressed in Figure 9 and represent the percentage of the products consumed (inlet) and produced (outlet) in 2021.

Table 2. Measured mass flow rates.

Process	Products	Mass flow rate (kg/h)
Output	Biodiesel	3404.32
	CH_3OH	195.68
	Glycerine	631.64
Input	H_3PO_4	3.15
	UO	2244.2
	VO	875
	CH_3OH	588
	CH_3NaO	140.49
	Rec. Biodiesel	380.8

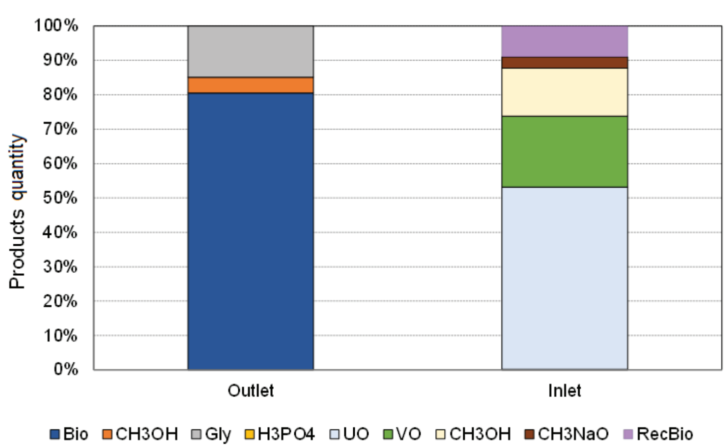

Figure 9. Products consumed (inlet) and produced (outlet) by the PEBD Unit in 2021.

As it can be observed in Figure 9, used cooking oils represent the major consumption (53 %), followed by virgin oils (21 %) and methanol (14 %). The recovered biodiesel introduced into the process is approximately

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10 % while the catalysts are residual. Regarding the final products obtained from the PEBD Unit, the analysis shows that biodiesel represented 80 % of the products, followed by 15 % of glycerine and approximately 5 % of methanol.

4.3. Energy balance

The energy balance of the PEBD Unit is presented in Figure 10. As previously stated, the outflow energy from the production of the biodiesel process is equal to the energy inflow plus the thermal energy provided by the boiler. This initial energy is the sum of the energy provided by virgin oils (VO) and used oils (UO), methanol (CH_3OH), and catalysts - phosphoric acid (H_3PO_4) and the sodium methylate (CH_3NaO). Besides these products, the PEBD unit uses electrical energy (Elec.) that feeds the pumps and the chiller and biomass (Biom.) as the heat source that provides thermal energy to the entire process. From this process, biodiesel (Bio.), glycerine (Gly), and methanol (CH_3OH) are produced. Moreover, part of this energy is lost (Loss), which is obtained by the difference between the energy consumed and produced. The energy balance equations used are expressed in Eqs. (21)-(22). It should be noted that the calculations were conducted in function of mass instead of mass flow rate. Therefore, $\dot{E}$ in section 2.2 becomes E.

$$E_{in} = E_{H3PO4} + E_{CH3NaO} + E_{UO} + E_{VO} + E_{CH3OH} + E_{Bio.\ Rec} + E_{Elec.} + E_{Pellets.} \quad (21)$$

$$E_{out} = E_{Bio.} + E_{CH3OH} + E_{Gly.} \quad (22)$$

Regarding the energy of each product, E_{H3PO4}, E_{CH3NaO}, E_{UO}, E_{VO}, E_{CH3OH}, $E_{Gly.}$and $E_{Bio.}$, only the chemical energy is considered using the data obtained from the mass balance and the LHV of each compound. Based on the literature, the LHV used is as follows: LHV_{H3PO4} = 23.5 MJ/kg, LHV_{CH3OH} = 19.9 MJ/kg, LHV_{UO} = 37.0 MJ/kg, LHV_{VO} = 37.0 MJ/kg, LHV_{Gly} = 19,0 MJ/kg, LHV_{Bio} = 19.0 MJ/kg. No information was found regarding the sodium methylate LHV, therefore it was not considered in the energy balance. Regarding the thermal energy provided by the pellets, Pellets in Figure 10, it is obtained by multiplying the mass of pellets consumed by the PEBD unit by the biomass LHV which was considered equal to 18 MJ/kg.

To determine the pellet consumption of the PEBD, the heat exchanged between the thermal flow (thermal oil heated by the boiler) and the cold stream, which consists of used cooking oils, virgin oils, and biodiesel, in each three heat exchangers of this unit is calculated. From this analysis, it was found that the PEBD unit is responsible for 14 % of the total pellets consumption.

Regarding the consumption of electrical energy consumed by the pumps and the chiller, measurements were conducted. For the case of the power consumed by the pumps, the current and tension were measured, and the total power resulted from the sum of the power consumed by each pump, resulting in 18 % of the total electrical energy consumed. The chiller is used to produce cold water to condensate the methanol evaporated during the process of purification of biodiesel. To determine the power consumed by the chiller, the vapor-compression refrigeration cycle was analyzed. Temperatures involved in the heat exchanged between the cold source and the evaporator and between the hot source and the condenser were recorded. The refrigerant fluid used in this process is R410a. From these temperatures, the properties of the thermodynamic cycle were defined in terms of power consumption for each stage, resulting in a total of 684,050 kWh/year, which represents 36 % of the total electrical energy consumed.

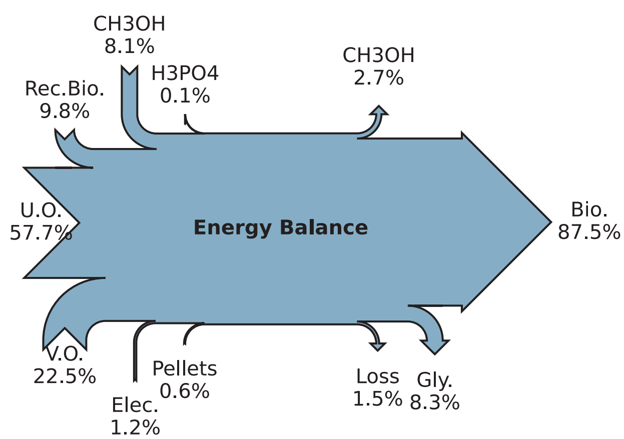

Figure 10. Energy balance of the PEBD Unit.

4.4. Exergy Analysis

The exergy balance is always performed along with the energy balance of the unit. However, energy analysis relates directly to the first law of thermodynamics, where exergy is always destroyed when a system involves an irreversible reaction (21). The irreversibility of the process was calculated using equation (5) by the difference between the exergy that enters the system and the exergy that leaves the system. The determination of the exergy flows was the same principle as the energy flows shown in Eq. (21) and Eq.(22). The electric exergy is the same as the electric energy, and the chemical exergy of the other streams was calculated using Eq. (7). The exergy balance of the PEBD was determined and is depicted in Figure 11.

The irreversibility of the process depends on the system's entropy variation. The literature shows that biodiesel production presents a higher exergy efficiency. This is mainly due to the reversibility of the transesterification reaction and the biodiesel's high chemical exergy in relation to the exergy consumed in the process (22,23). The boiler associated with the unit might be the equipment that most influence the irreversibility of the system. However, the total exergy of the pellets is insignificant compared to the total exergy of the input flows involved in the system (0.6 %) which explains the small difference between heat loss and irreversibility in the system.

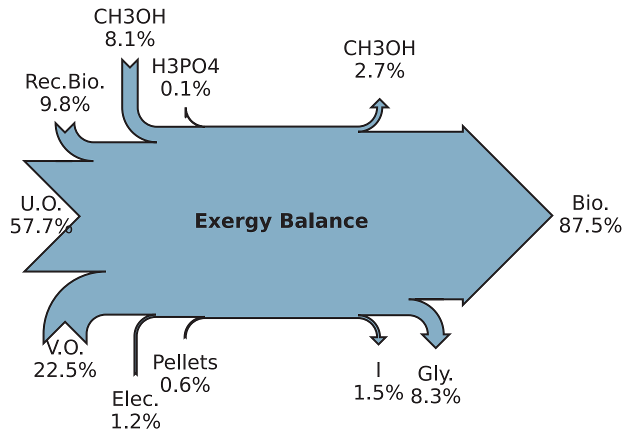

Figure 11. Exergy balance of the PEBD Unit.

4.5. Process enhancement

From the energy balance, it is clear that the PEBD unit is highly optimized in terms of heat consumption, representing around 14% of total pellet consumption this is mainly due to the use of heat exchangers at the beginning of each biodiesel purification stage, allowing the recovery of energy from the hot streams to preheat the cold streams. On the other hand, the use of low vacuum pressures in the evaporators allows operating conditions at lower temperatures, reducing the consumption of electrical energy. However, after a careful analysis of the PEBD unit, it was possible to find some solutions that improve the energetic process performance. Regarding the pellet consumption, it was found that the continuous operation of the heat exchanger HE-33 is redundant and unnecessary since it is expected to keep the operating temperature of Flash 1 near 77 ºC. With proper insulation, the heat exchanger HE-01 could be connected directly to the evaporator FE-31, since the heat lost from the biodiesel flowing through the pipe to the environment between the HR-01 and the HE -33 heat exchangers is of the same order of magnitude as the heat supplied by the HE-33. Thus, HE-33 can operate in a bypass mode during the first few hours of the unit starting time. With thermal equilibrium reached, it was found that deactivating the HE-33 exchanger would result in annual savings of more than 29.5 tonnes of pellets, which represents a decrease of approximately 2.2 % of the annual pellets consumption. Even though this value seems to be irrelevant, it corresponds to cost savings in the order of 7,000 €/year, taking into account the rising in prices observed for this fuel over the last months.

Regarding electricity consumption, an opportunity to improve the methanol recovery/condensation process was identified, by acting on the existing chiller. Measurements reveal a high water flow rate, compared to a low evaporated methanol flow rate, with a maximum ΔT between the inlet and outlet of the chiller of 1.6 ºC, showing that the water flow rate is oversized. Therefore, a need arises to calculate an optimized water flow rate for a minimum ΔT of 5 ºC in the evaporator, as well as an increase of 1 ºC at the cold water outlet, allowing the use of a lower refrigerant flow rate as well as the increase of temperature in the evaporator and, consequently, an increase in its pressure, reducing the compression work. Moreover, this optimized water flow rate allows to estimate the minimum cooling power needed by the process, allowing the selection of a new chiller. With this optimized equipment, a reduction of more than 70 % of the electrical power consumed by the chiller is possible.

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Considering these optimized solutions, the energy and exergy efficiencies of the system were estimated and compared with the present scenario. To conduct this analysis, the equations presented in section 2.2 were used to plot the graphs presented in Figure 12. The results show that in the actual scenario, the energy and exergy efficiencies for biodiesel production are 87.6 % and 87.5 %, respectively. While for the process, which includes the production of both biodiesel and glycerine, the energy and exergy efficiencies are 96.0 % and 95.8 %, respectively. There is not much difference between both efficiencies as the thermal loss and the irreversibility of the system are identical. However, the difference is due to the irreversibility caused by the boiler.

Compared with the present scenario, the optimization proposed increases by almost 0.6 % in both energy and exergy efficiencies. It is not a significant increase as the energy saved is relatively low compared with the overall energy of the process. However, by observing Figure 13, it is possible to conclude that this optimization decreases around 117 toe the annual irreversibility. This may not have a major impact on the energy or exergy balances, however, it will be translated into a reduction in biodiesel production cost.

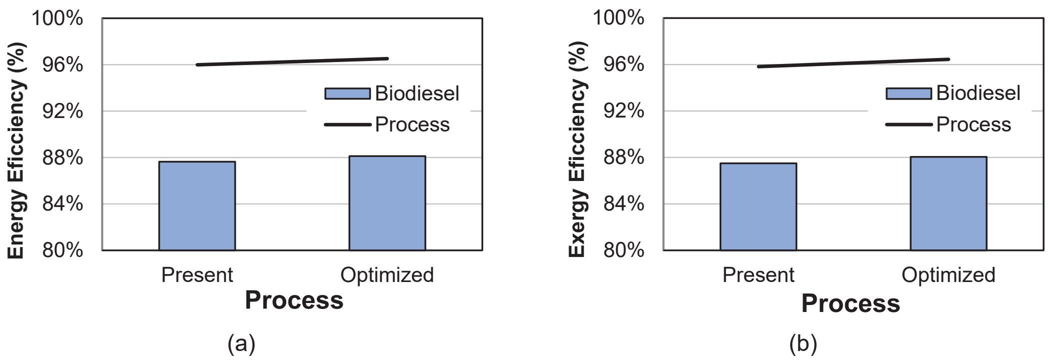

Figure 12. Energy (a) and Exergy (b) efficiency analysis for the present and optimized scenarios.

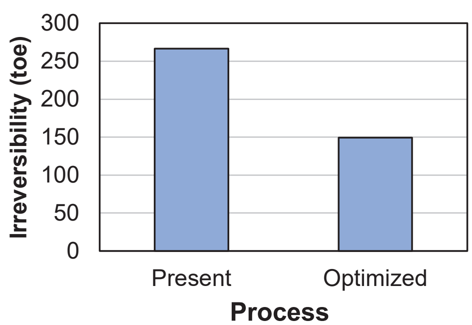

Figure 13. Influence of the optimization in the process irreversibility.

5. Conclusions

This study presents a detailed analysis of a biodiesel power plant. The different products used for biodiesel production are characterized and the different reaction processes are presented. Considering the complexity of analyzing the entire power plant, an energy and exergy analysis is conducted on the specific unit of biodiesel production or PBDE, as previously mentioned. To determine the mass balance, in-site measurements were conducted. From this analysis, a total of 18,504 tons of biodiesel are produced in 2021 as well as 3,433 tons of glycerine, which is sold for other industry sectors. These products represent a total of 87.6 % and 8.4 % of the total energy produced, the remaining percentage is methanol and energy loss. Regarding the sources of energy used for biodiesel production, electricity came from pumps and a chiller, while the thermal energy is provided by pellets burned in a boiler. The study conducted shows that the PEBD is responsible for a total consumption of electrical energy corresponding to 54 %, from which 36 % is consumed by the chiller, while this unit only consumes 14 % of the pellets. In terms of energy efficiency, the biodiesel production process is estimated to be equal to 88.1 %, while the process that includes both the production of biodiesel and glycerine represents an efficiency of 96.5 %. In terms of exergy, the results are slightly different from the energy analysis, being the difference mainly due to the irreversibility caused by the boiler. The entire process was analyzed and solutions were presented in order to enhance the process efficiency. This enhancement results in a slight increase of both energy and exergy efficiencies of the process, approximately 0.6 %. Although this improvement seems to be reduced, it leads to non-negligible cost savings in the power plant.

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Nomenclature

E Energy, J
I Irreversibility, J
$\dot{m}$ mass flow rate, kg/s
$\dot{P}$ Pumping Power, W
Q heat, J
$\dot{W}$ Work, W

Greek symbols

ε exergy
η energy efficiency
φ chemical exergy conversion factor for fuels
ψ exergy efficiency

Subscripts and superscripts

in inflow
out outflow
0 Chemical
k kinetic
ph physical

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