



Research Paper

Thermoeconomic analysis of hydrogen incorporation in a biodiesel plant



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HIGHLIGHTS

- Exergetic contribution of all equipments in the BHPP is determined.
- Hydrogen production in the BHPP makes possible the energetic use of glycerine.
- Simultaneous production of biodiesel and hydrogen is a feasible alternative.

ARTICLE INFO

Article history:

Received 2 June 2016

Revised 6 October 2016

Accepted 27 October 2016

Available online 28 October 2016

Keywords:

Thermoeconomic
Hydrogen
Biodiesel
Functional diagram
Glycerine
Cost

ABSTRACT

The paper develops a methodology that uses the thermoeconomic functional diagram applied for allocating cost of products obtained by the plant and afterwards demonstrates how it is possible to calculate the marginal cost in US\$/kW h of the production. The methodology which was adopted includes the plant exergetic analysis development, the function system identification through physical diagram of the plant, construction of the Thermoeconomic Functional Diagram and the determination of the expressions for the plant's exergetic functions. The methodology also includes the determination of some parameters such as, investments, maintenance, operation, raw materials (canola oil, catalysts, methanol, glycerine and natural gas) and utility costs (electricity and steam water). As a result, it can be said that the simultaneous production of biodiesel and hydrogen is a suitable technology to minimize biodiesel production cost. About 6% of the thermoeconomic cost of biodiesel production was diminished when compared to the values previously published in the present literature. In relation to the hydrogen production thermoeconomic costs, the values are closer when they are compared to the ones which were identified in the literature. As a contribution to the scientific knowledge, it can be said that the obtained results shows the high performance of simultaneous biodiesel and hydrogen production, especially when glycerine is further processed into valuable energetic matter, in other words, considering economic aspects associated with the exergy conception, in order to develop a tool to assist the equipment operation, as well as to optimize the biodiesel plant design. Also shows that in a biodiesel production plant the hydrogen technology is more sustainable than the traditional one. The paper aims to innovate the production process of biodiesel by incorporating the hydrogen production process through glycerine steam reforming.

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1. Introduction

The competitiveness of biodiesel production has become a very important topic of research by the fact that it is largely used in the energetic and transport sector. An earlier paper which aims to study the competitiveness of biodiesel production was performed by

Zhang et al. [1,2], where the economic feasibilities of four continuous processes to produce biodiesel were assessed. Later, Coronado et al. [3] applied the thermoeconomic methodology to study a biodiesel production plant, in which were determined the irreversibilities in each component of the plant, allowing the achievement of biodiesel and glycerine production costs. The paper includes the costs of carbon credits for the carbon dioxide, which is not released to the atmosphere. Kligerman and Bouwer [4] focuses on the feasibility of utilizing wastewater to cultivate algae for the production of biodiesel in Brazil. Johari et al. [5] seeks to critically examine challenges afflicting the biodiesel industry in Malaysia by analysing the

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Nomenclature

C_{AF}	auxiliary facility cost [US\$]	FP_{H_2}	hydrogen production weighting factor
C_{BASE}	basic module cost [US\$]	H	plant operation time [h/year]
$C_{BIODIESEL}$	biodiesel production cost [US\$/kW h]	Inv	investment [US\$]
$C_{CATALYSTS}$	catalysts cost (NaOH, H ₃ PO ₄) [(US\$/h)]	$Inv_{BIODIESEL}$	biodiesel production capital investment [US\$]
C_{FC}	fixed capital cost [US\$]	Inv_{H_2}	hydrogen production capital investment [US\$]
$C_{GLYCERINE}$	purified glycerine cost [US\$/kW h]	k	amortization period [Years]
$C_{HYDROGEN}$	hydrogen production cost [US\$/kW h]	m	mass flow [kg/h]
$C_{METHANOL}$	methanol cost [US\$/h]	m_{H_2}	hydrogen volumetric flow [N m ³ /h]
C_{Mi}	equipment module cost i [US\$]	q	capital value
$C_{NATURAL GAS}$	natural gas cost [US\$/h]	r	annual interest rate [%]
C_{OPMAN}	maintenance and operation cost [US\$/year]	U	represent unit or equipment
C_{OIL}	canola oil cost [US\$/h]	Y	exergetic functions (in incremental base) [kW]
C_{TM}	total module cost [US\$]	$Y_{i,j}$	j -th input to the i -th unit [kW]
$C_{UTILITIES}$	utilities cost [US\$/year]	$Y_{i,k}$	k -th output to the i -th unit [kW]
C_{WC}	working capital cost [US\$]	0	standard
E	electricity		
EX	total exergy [kW]		
ex	specific exergy [kJ/kg]		
f	annuity factor [1/year]		
F_{301}	light phase Ponderation Factor (biodiesel)		
F_{302}	heavy phase Ponderation Factor (glycerol)		
$FP_{BIODIESEL}$	biodiesel production weighting factor		

Abbreviations

ECT	Exergetic Cost Theory
GAMS	General Algebraic Modeling System
TFD	Thermoeconomic Functional Diagram
WGSR	Water Gas Shift Reactor

key policies, framework and institutions in the country. Olkiewicz et al. [6] studied the influence of different reaction variables on the biodiesel yield using [mimC4SO3H][SO3CF3] as a catalyst. One common drawback in the competitiveness of biodiesel production is the energetic use of glycerine via steam reforming. Recently, significant advances in the glycerine steam reforming for hydrogen production have been achieved [7–10]. Best conditions for steam reforming were studied by Adhikari et al. [11]. Nonlinear programming model implemented in GAMS considering the ideal gaseous phase and formation of solid carbon was also proposed by Rossi et al. [12]. For hydrogen use in low temperature proton exchange fuel cell, it has been acknowledged that optimal production conditions were temperature equal to 1000 K and steam to glycerol molar ratio equal to 6 [13]. For high temperature proton exchange membrane fuel cells the optimal conditions were: higher carbon monoxide tolerances and higher reform temperatures [13]. Thermodynamic analysis of glycerol steam reforming with hydrogen or carbon dioxide co-fed as carbon gasifying agents in order to mitigate carbon deposition was performed by Cheng et al. [14]. In the scientific literature, there are methodologies applying the thermoeconomic analysis to the study of a biodiesel production plant. Previously a paper mentioning the Exergy Cost Theory uses was performed by Mora [15], where a new sustainability indicator was introduced to analyse a biodiesel production plant. Integrate glycerin steam reform process in a biodiesel plant is a simple way to produce simultaneously biodiesel and hydrogen with low costs. Additionally, incorporation of hydrogen production process in a biodiesel plant opens conditions for cogeneration systems introduction in the plant, taking advantage of the production low costs. In this paper, a detailed thermoeconomic analysis of hydrogen production process incorporation in a biodiesel plant is investigated, and the reason for its relatively low costs is discussed.

2. Methodology

This paper uses of a methodology, which aims the building of the thermoeconomic functional diagram of biodiesel production

plant, also seeks the determination of the production costs of hydrogen and biodiesel. A biodiesel production plant, which was studied and simulated using Hysys software by Boloy et al. [16], was used as benchmark.

Thermoeconomic analysis is defined as an appropriate combination of exergetic and economic analysis, where exergetic incremental costs are associated to each flow of the system. Recently, two thermoeconomic methodologies have been used aiming the study of thermal systems: Exergetic Cost Theory (ECT) [17] and Thermoeconomic Functional Diagram (TFD) [18–21].

2.1. Identification of systems functions. Construction of physical diagram

To identify the systems functions within the plant, a physical diagram of simultaneous production of biodiesel and hydrogen was built as shown in Figs. 1 and 2.

2.2. Construction of the thermoeconomic functional diagram

Figs. 3 and 4 show the thermoeconomic functional diagram. The diagram is composed by functional lines of frontier and geometric figures (equipments and process of the plant). These geometric figures are linked with lines representing the functions in terms of exergy unit increments [22–24]. According to Silveira et al. [22] the notation used in the Thermoeconomic Functional Diagram is:

- U – Represent unit or equipment;
- Y – Exergetic functions (in incremental base);
- $Y_{i,j}$ – j -th input to the i -th unit;
- $Y_{i,k}$ – k -th output to the i -th unit.

2.3. Determination of the expressions for the plant's exergetic functions

In order to calculate the exergetic functions, all the losses at the pipes will not be considered. The formulated expressions were

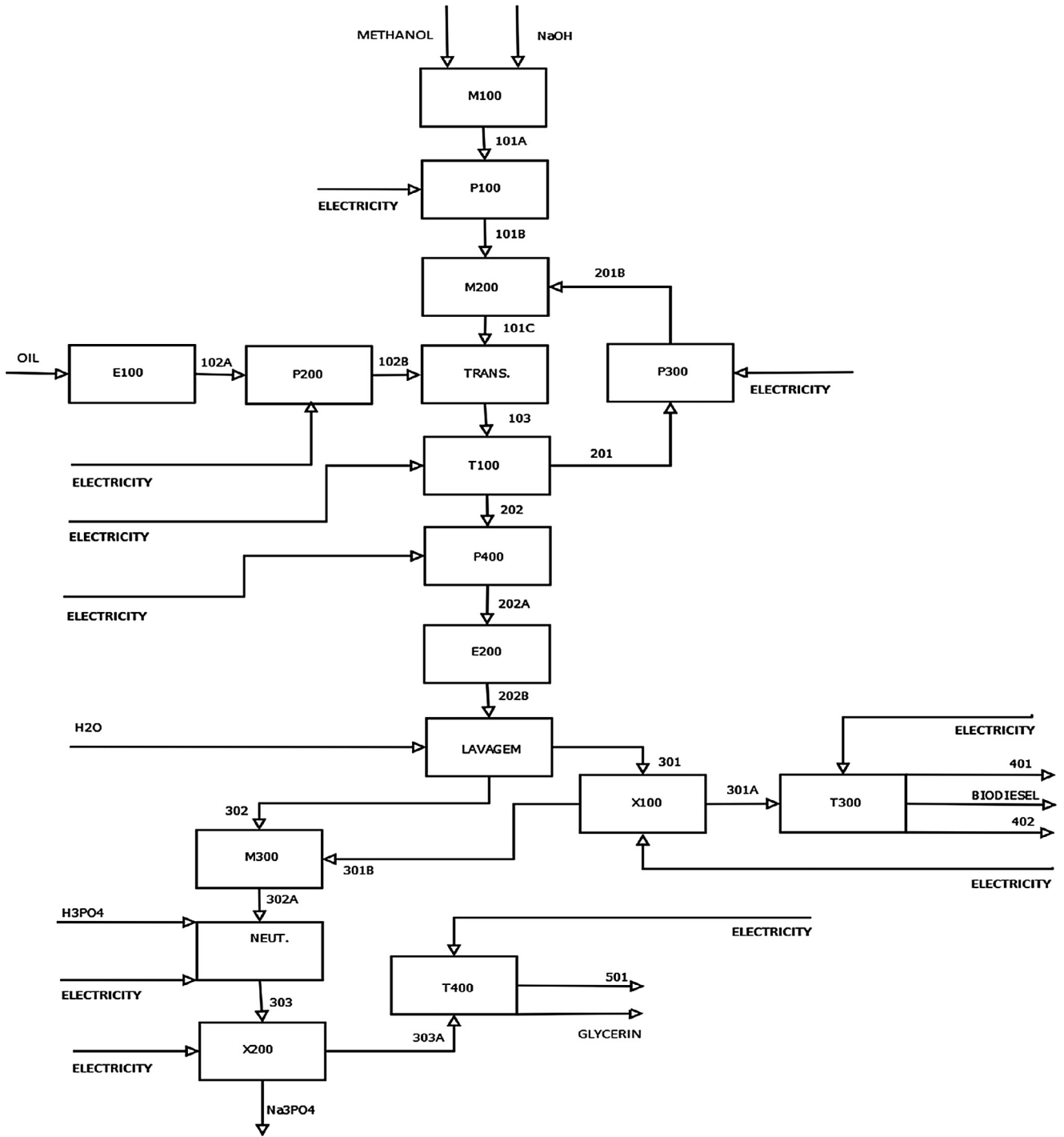


Fig. 1. Physical diagram of simultaneous production of biodiesel and hydrogen.

based on physical and thermo-economic functional diagram and depends on thermodynamic properties and the exergetic values obtained in the plant by Boloy et al. [16]. The expressions are shown below.

Unit 1: Mixer M100

$$Y_{1,1} = Y_{0,1} = E_{X_{METHANOL}} \quad (1)$$

$$Y_{1,2} = Y_{0,2} = E_{X_{NaOH}} \quad (2)$$

$$Y_{1,1} = m_{methanol} * (ex_{101A} - ex_{methanol}) + m_{NaOH} * (ex_{101A} - ex_{NaOH}) \quad (3)$$

Unit 2: Pump P100

$$Y_{2,1} = Y_{1,1} \quad (3)$$

$$Y_{2,2} = Y_{0,3} \quad (4)$$

$$Y_{2,1} = Ex_{101A} - Ex_{101B} \quad (5)$$

Unit 3: Mixer M200

$$Y_{3,1} = Y_{2,1} \quad (6)$$

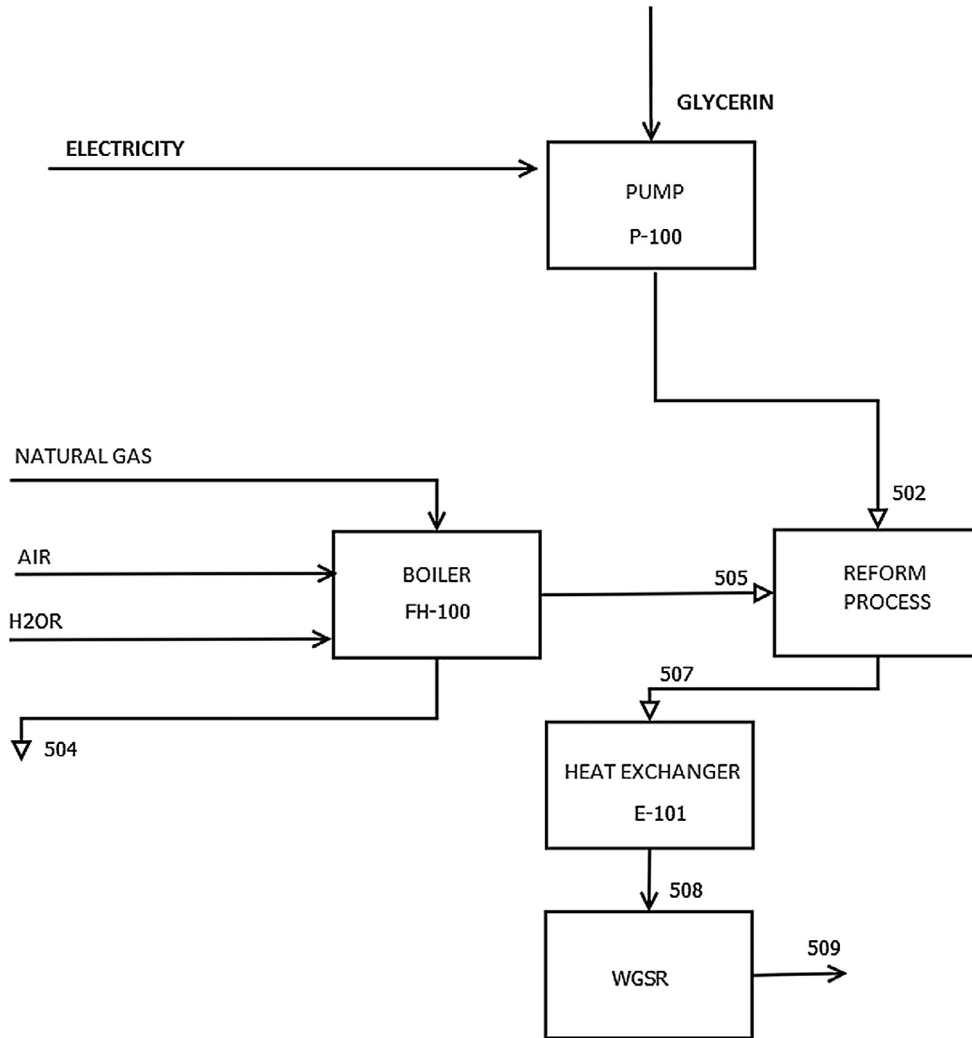


Fig. 2. Physical diagram of simultaneous production of biodiesel and hydrogen. Cont.

$$Y_{3,2} = Y_{8,1} \quad (7)$$

$$Y_{3,1} = m_{101B} * (ex_{101C} - ex_{101B}) + m_{201B} * (ex_{101C} - ex_{201B}) \quad (8)$$

Unit 4: Heat Exchanger E100

$$Y_{4,1} = Y_{0,4} = EX_{OIL} \quad (9)$$

$$Y_{4,2} = Y_{0,5} \quad (10)$$

$$Y_{4,1} = EX_{OIL} - EX_{102A} \quad (11)$$

Unit 5: Pump P200

$$Y_{5,1} = Y_{4,1} \quad (12)$$

$$Y_{5,2} = Y_{0,6} \quad (13)$$

$$Y_{5,1} = EX_{102A} - EX_{102B} \quad (14)$$

Unit 6: Transesterification Reactor R100

$$Y_{6,1} = Y_{3,1} \quad (15)$$

$$Y_{6,2} = Y_{5,1} \quad (16)$$

$$Y_{6,3} = E3 \quad (17)$$

$$Y_{6,1} = EX_{102B} + EX_{101C} - EX_{103} \quad (18)$$

Unit 7: Distillation Tower T100

$$Y_{7,1} = Y_{6,1} \quad (19)$$

$$Y_{7,2} = Y_{0,9} \quad (20)$$

$$Y_{7,1} = m_{201} * (ex_{103} - ex_{201}) \quad (21)$$

$$Y_{7,2} = m_{202} * (ex_{202} - ex_{103}) \quad (22)$$

Unit 8: Pump P300

$$Y_{8,1} = Y_{7,1} \quad (23)$$

$$Y_{8,2} = Y_{0,8} \quad (24)$$

$$Y_{8,1} = EX_{201} - EX_{201B} \quad (25)$$

Unit 9: Pump P400

$$Y_{9,1} = Y_{7,2} \quad (26)$$

$$Y_{0,10} = Y_{9,2} \quad (27)$$

$$Y_{9,1} = EX_{202} - EX_{202A} \quad (28)$$

Unit 10: Heat Exchanger E200

$$Y_{10,1} = Y_{9,1} \quad (29)$$

$$Y_{10,1} = EX_{202A} - EX_{202B} \quad (30)$$

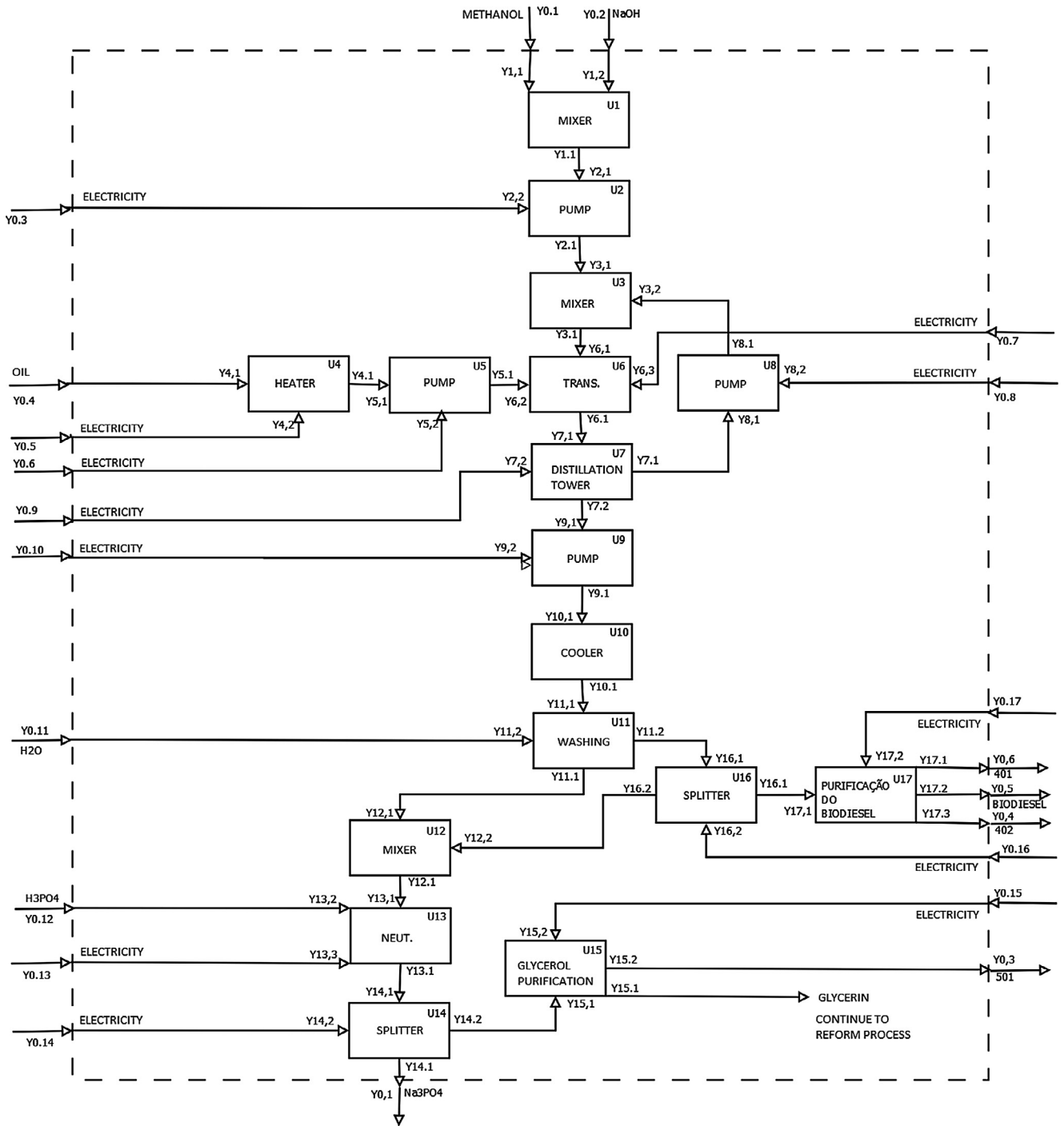


Fig. 3. Thermoeconomic functional diagram of simultaneous production of biodiesel and hydrogen.

Unit 11: Washing Process T100
 $Y_{11,1} = Y_{10,1}$ (31)

$Y_{11,2} = Y_{0,11} = Ex_{H2O}$ (32)

$Y_{11,1} = F_{302}m_{H2O}(ex_{302} - ex_{H2O}) + F_{302}m_{202B}(ex_{202B} - ex_{302})$ (33)

$Y_{11,2} = F_{301}m_{H2O}(ex_{301} - ex_{H2O}) + F_{301}m_{202B}(ex_{301} - ex_{202B})$ (34)

$F_{301} = \frac{m_{301}}{m_{202B} + m_{H2O}}$ (35)

$F_{302} = \frac{m_{302}}{m_{202B} + m_{H2O}}$ (36)

where
 F_{301} : Ponderation Factor in light phase (Biodiesel)
 F_{302} : Ponderation Factor in heavy phase (Glycerol)
 Unit 12. Mixer M300

$Y_{12,1} = Y_{11,1}$ (37)

$Y_{12,2} = Y_{16,2}$ (38)

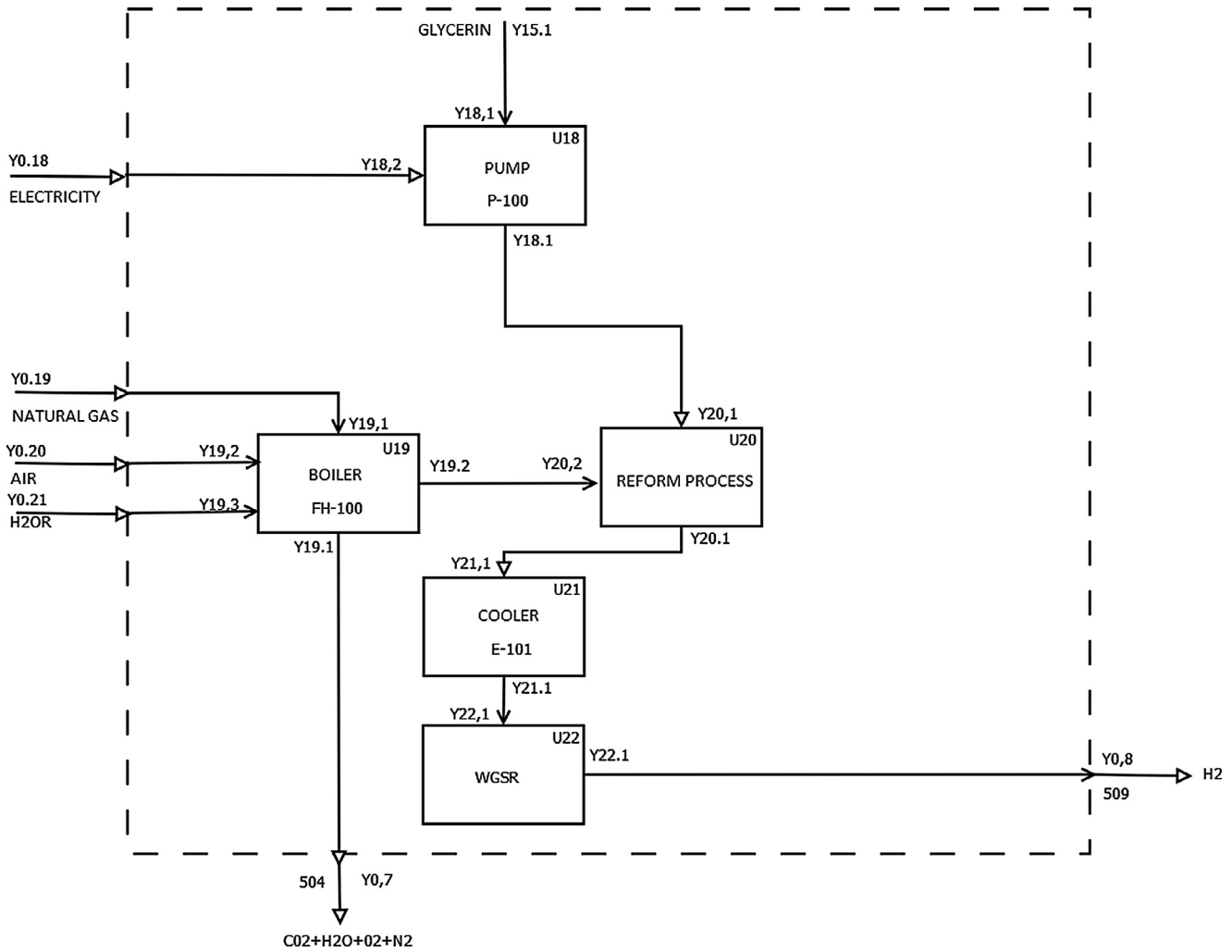


Fig. 4. Thermoeconomic functional diagram of simultaneous production of biodiesel and hydrogen.

$$Y_{12,1} = Ex_{302} + Ex_{301B} - Ex_{302A} \quad (39)$$

Unit 14: Neutralization Reactor R200

$$Y_{13,1} = Y_{12,1} \quad (40)$$

$$Y_{13,2} = Y_{0,12} = Ex_{H3PO4} \quad (41)$$

$$Y_{13,3} = Y_{0,13} \quad (42)$$

$$Y_{13,1} = Ex_{H3PO4} + Ex_{302A} - Ex_{303} \quad (43)$$

Unit 14: Splitter X200

$$Y_{14,1} = Y_{13,1} \quad (44)$$

$$Y_{14,2} = Y_{0,14} \quad (45)$$

$$Y_{14,1} = Ex_{303} - Ex_{303A} \quad (46)$$

$$Y_{14,2} = Ex_{Na3PO4} = Y_{0,1} \quad (47)$$

Unit 15: Distillation Tower T400

$$Y_{15,1} = Y_{14,2} \quad (48)$$

$$Y_{15,2} = Y_{0,15} \quad (49)$$

$$Y_{15,1} = m_{GLYCERIN}(ex_{303A} - ex_{GLYCERIN}) \quad (50)$$

$$Y_{15,2} = Ex_{501} = Y_{0,3} \quad (51)$$

Unit 16: Splitter X100

$$Y_{16,1} = Y_{11,2} \quad (52)$$

$$Y_{16,2} = Y_{0,16} \quad (53)$$

$$Y_{16,1} = m_{301A}(ex_{301} - ex_{301A}) \quad (54)$$

$$Y_{16,2} = m_{301B}(ex_{301} - ex_{301B}) \quad (55)$$

Unit 17: Distillation Tower T300

$$Y_{17,1} = Y_{16,1} \quad (56)$$

$$Y_{17,2} = Y_{0,17} \quad (57)$$

$$Y_{17,1} = Ex_{401} = Y_{0,6} \quad (58)$$

$$Y_{17,2} = Ex_{BIODIESEL} = Y_{0,5} \quad (59)$$

$$Y_{17,3} = Ex_{402} = Y_{0,4} \quad (60)$$

Unit 18: Pump P-100

$$Y_{18,1} = Y_{15,1} \quad (61)$$

$$Y_{18,2} = Y_{0,18} \quad (62)$$

$$Y_{18,1} = Ex_{GLYCERIN} - Ex_{502} \quad (63)$$

Unit 19: Boiler FH-100
 $Y_{19,1} = Y_{0,19} = EX_{NATURALGAS}$ (64)

$Y_{19,2} = Y_{0,20} = EX_{AIR}$ (65)

$Y_{19,3} = Y_{0,21} = EX_{H2OR}$ (66)

$Y_{19,1} = EX_{504} = Y_{0,7}$ (67)

$Y_{19,2} = m_{505}(ex_{505} - ex_{H2OR})$ (68)

Unit 20: Reform Process
 $Y_{20,1} = Y_{18,1}$ (69)

$Y_{20,2} = Y_{19,2}$ (70)

$Y_{20,1} = m_{505}(ex_{507} - ex_{505}) + m_{GLYCERIN}(ex_{507} - ex_{GLYCERIN})$ (71)

Unit 21: Heat Exchanger E101
 $Y_{21,1} = Y_{20,1}$ (72)

$Y_{21,1} = EX_{507} - EX_{508}$ (73)

Unit 22: WGSR
 $Y_{22,1} = Y_{21,1}$ (74)

Table 1
Investment, maintenance, and operation cost [16].

	UM	Hydrogen	Biodiesel	Total
Inv	US\$	836000.30	1764686.87	2600687
C _{OPMAN}	US\$/year	25080.0086	838949.49	864029.50

Table 2
Raw materials costs.

Raw material	UM	Cost	UM	Cost
Methanol	US\$/kg	0.632	US\$/h	74.26
Canola oil	US\$/kg	0.99	US\$/h	1039.50
NaOH	US\$/kg	7.95	US\$/h	79.5
H ₃ PO ₄	US\$/kg	3.3	US\$/h	27.06
Natural gas	R\$/h	24.92	US\$/h	11.33 ^a
Total	US\$/kg	12.312	US\$/h	1231.65

^a 1 US\$ = 2.20 R\$.

Table 3
Utility costs in biodiesel production.

Utilities	Costs (US\$/year)
Electricity + Steam water	86787.88

$Y_{22,1} = EX_{509}$ (75)

2.4. Investments, maintenance, operation, utility, and raw material costs determination

The investments, maintenance, and operation costs were calculated using as benchmark the papers published by Zhang et al. [2] and Coronado et al. [3]. The paper did not consider the hydrogen storage cost because the main objective is to determine the hydrogen production cost.

The biodiesel production investment cost (Eq. (76)) can be defined as the sum of the fixed capital cost (Eq. (77)) and the working capital cost (15% of the fixed capital cost) (Eq. (78)). Moreover the fixed capital cost is defined as the sum of total module cost (Eq. (79)) (contingencies and feed) and the facilities costs auxiliary (30% of the total basic module cost).

$Inv_{BIODIESEL} = C_{FC} + C_{WC}$ (76)

$C_{FC} = C_{TM} + C_{AF}$ (77)

$C_{WC} = 0,15 * C_{FC}$ (78)

$C_{TM} = 1,18 * \sum_{i=1}^n C_{Mi}$ (79)

$C_{AF} = 0,3 * C_{Base}$ (80)

where

- C_{FC}: Fixed capital cost (US\$);
- C_{WC}: Working capital cost (US\$);
- C_{TM}: Total module cost (US\$);
- C_{AF}: Auxiliary facility cost (US\$);
- C_{BASE}: Basic module cost (US\$);
- C_{Mi}: Equipment Module Cost i (US\$).

The hydrogen production investment cost (Eq. (81)) was estimated using the Bohem Method [25], in addition the steam reform system with hydrogen production ranges from 1 N m³/h to 1500 N m³/h.

$Inv_{H2} = 400 \left(\frac{m_{H2}}{750} \right)^{0.5304}$ (81)

where

m_{H2}: Volumetric flow of hydrogen (N m³/h).

The biodiesel production maintenance cost is considered as 6% of investment cost [2]. On the other hand for hydrogen production process the maintenance cost is considered as 3% of the investment cost [26].

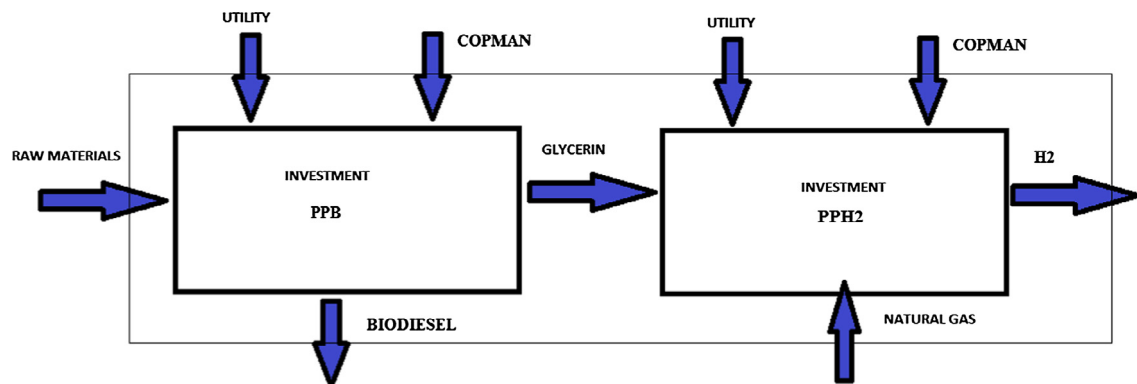


Fig. 5. Structural model based on costs for producing biodiesel and hydrogen.

Table 4
Values of exergetic functions [kW] associated to simultaneous production of biodiesel and hydrogen.

Exergetic functions	Value (kW)
Y1,1 (methanol)	731.30
Y1,2 (sodium hidroxide)	5.20
Y1.1	8.45
Y2,1	8.45
Y2,2	0.02
Y2.1	0.30
Y3,1	0.30
Y3,2	6.33
Y3.1	4.46
Y4,1 (oil)	12417.38
Y4,2	0.14
Y4.1	1.00
Y5,1	1.00
Y5,2	0.07
Y5.1	0.05
Y6,1	8.45
Y6,2	0.05
Y6,3	31.64
Y6.1	1049.56
Y7,1	1049.56
Y7,2	37.09
Y7.1	411.02
Y7,2	5072.15
Y8,1	411.02
Y8,2	0.02
Y8.1	6.33
Y9,1	5072.15
Y9,2	0.07
Y9.1	0.50
Y10,1	0.50
Y10.1	6.91
Y11,1	6.91
Y11,2 (water for washing process)	0.15
Y11.1	5248.75
Y11.2	69.44
Y12,1	5248.75
Y12,2	64.98
Y12.1	0.67
Y13,1	0.67
Y13,2 (phosphoric acid)	2.47
Y13,3	5.40
Y13.1	6.08
Y14,1	6.08
Y14,2	0.00
Y14.1	1.16
Y14,2 (sodium phosphate)	64.75
Y15,1	64.75
Y15,2	4.13
Y15.1 (glycerine)	18.10
Y15,2	39.23
Y16,1	69.44
Y16,2	0.45
Y16.1	48.71
Y16,2	64.98
Y17,1	48.71
Y17,2	328.72
Y17.1	69.60
Y17,2 (biodiesel)	10991.53
Y17,3	460.30
Y18,1	18.10
Y18,2	0.02
Y18.1	0.04
Y19,1 (natural gas)	168.53
Y19,2 (air)	0.00
Y19,3 (water for reform process)	1.75
Y19.1 (exhaust gases)	129.28
Y19,2	62.99
Y20,1	0.04
Y20,2	62.99
Y20.1	67.47
Y21,1	67.47
Y21.1	77.94
Y22,1	77.94
Y22,1 (hydrogen)	550.88

The operation costs follows the considerations taken by Zhang et al. [2] and are listed below:

- Operators working for 49 weeks/year.
- The plant works in three shifts per day.
- The Operator salary is estimated in 47.85 US\$/year with the plant running 24 h per day.

Table 1 shows all investments, maintenance and operation plant costs. The values were updated using the inflation factor equals to 1.45 [16]. The inflation factor is defined as the ratio between the value of Chemical Engineering Plant Index for the year 2014 (572.8) and the value of Chemical Engineering Plant Index for the year 2000 (396) [16].

Table 2 shows the raw materials costs used in the plant. All costs are associated to the mass flow required for producing biodiesel and hydrogen [16].

Table 3 shows the biodiesel production utility costs. The values were obtained from the values suggested by Zhang et al. [2].

2.5. Thermoeconomic costs determination of producing biodiesel and hydrogen

The biodiesel and hydrogen production thermoeconomic costs are obtained through the structural model based on costs as shown in Fig. 5. The thermoeconomic costs includes investments, operation, maintenance, utilities, raw materials, and the exergetic functions values.

According to the structural model (Fig. 5) and reallocating the costs of production for both biodiesel and hydrogen taking into account the fact that the glycerine can be sold, the thermoeconomic costs of producing biodiesel and hydrogen would be defined as follows:

$$C_{\text{Biodiesel}} = \frac{\text{Inv}_{\text{BIO DIESEL}} * f}{H * Y_{17,2}} + \frac{C_{\text{METHANOL}}}{Y_{17,2}} + \frac{C_{\text{CATALYSTS}}}{Y_{17,2}} + \frac{C_{\text{OIL}}}{Y_{17,2}} + \frac{C_{\text{UTILITIES}} * FP_{\text{BIO}}}{H * Y_{17,2}} + \frac{C_{\text{OPMAN}} * FP_{\text{BIO}}}{H * Y_{17,2}} \quad (82)$$

$$FP_{\text{Biodiesel}} = \frac{Y_{17,2}}{Y_{17,2} + Y_{22,1}} \quad (83)$$

$$FP_{\text{H}_2} = \frac{Y_{22,1}}{Y_{17,2} + Y_{22,1}} \quad (84)$$

$$C_{\text{H}_2} = \frac{\text{Inv}_{\text{H}_2} * f}{H * Y_{22,1}} + C_{\text{GLYCERIN}} + \frac{C_{\text{NATURALGAS}}}{Y_{22,1}} + \frac{C_{\text{UTILITIES}} * FP_{\text{H}_2}}{H * Y_{22,1}} + \frac{C_{\text{OPMAN}} * FP_{\text{H}_2}}{H * Y_{22,1}} \quad (85)$$

$$f = \frac{q^k(q-1)}{q^k-1} \quad (86)$$

$$q = 1 + \frac{r}{100} \quad (87)$$

where

Inv_{BIO DIESEL}: Biodiesel production capital investment in (US\$);

Inv_{H₂}: Hydrogen production capital investment in (US\$);

f: Annuity factor (1/year);

q: Capital value;

r: Interest rate (%);

H: Plant operation time (h/year);

k: Amortization period (years);

FP_{BIO DIESEL}: Weighting factor for biodiesel production;

FP_{H₂}: Weighting factor for hydrogen production;

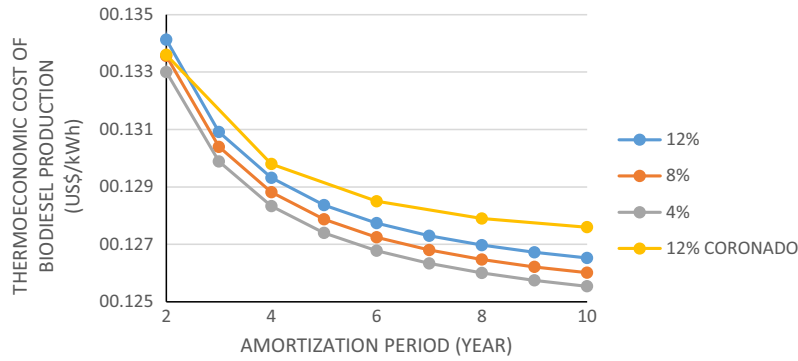


Fig. 6. Comparison of thermo-economic costs for biodiesel production.

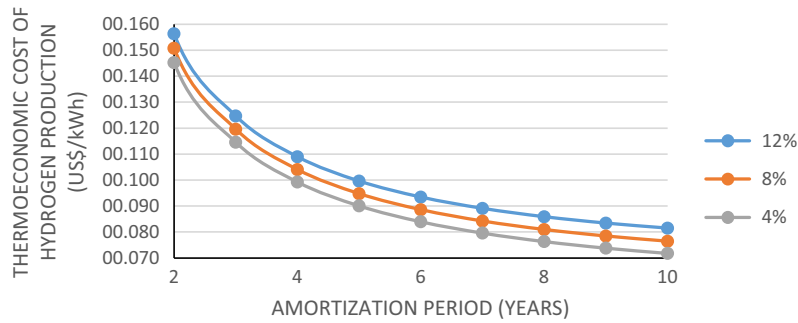


Fig. 7. Thermo-economic costs for hydrogen production.

- $C_{\text{NATURAL GAS}}$: Natural gas cost in (US\$/h);
- C_{METHANOL} : Methanol cost in (US\$/h);
- $C_{\text{ÓLEO}}$: Canola oil cost in (US\$/h);
- $C_{\text{UTILITIES}}$: Utilities cost (US\$/year);
- $C_{\text{CATALYSTS}}$: Catalysts cost (NaOH, H₃PO₄) (US\$/h);
- C_{OPMAN} : Maintenance and operation cost (US\$/year);
- $C_{\text{GLYCERINE}}$: Purified glycerine cost (US\$/kW h).
- Y: Exergetic functions (in incremental base) in (kW);

3. Results and discussion

The present paper main purpose is the thermo-economic analysis of hydrogen incorporation in a Biodiesel plant. Which is a useful methodology which allows determining the values of exergetic functions and marginal costs of products in a given system.

Table 4 presents the values of exergetic functions associated to the units described in thermo-economic functional diagram. With respect to the results presented in the table, it is observed that the canola oil (12417.38 kW), biodiesel (10991.53 kW) and hydrogen (550.88 kW) presents the highest values of exergetic functions. This fact is explained by the highest exergetic contribution provided to the system. This exergetic contribution is located in the transesterification reactor, in the distillation tower and in the steam reformer reactor.

Fig. 6 compares the values of biodiesel production thermo-economic costs, where it can be inferred that the costs obtained in the simultaneous biodiesel and hydrogen production oscillates between 0.1255 US\$/kW h and 0.1341 US\$/kW h. The new biodiesel production innovative technology demonstrates in a better way the thermo-economic costs compared to those reported by Coronado in the previous work where biodiesel thermo-economic costs were ranging between 0.1276 US\$/kW h and

0.1336 US\$/kW h [3]. This decrease can be attained to the energetic glycerine usage for hydrogen production.

The hydrogen production thermo-economic cost is sensitive to the glycerine purification process cost variation, this cost depends on the type of purification technology used, this paper presents a distillation tower, which leads the purified glycerine cost of 0.020 US\$/kW h. Fig. 7 presents the hydrogen production thermo-economic costs, these costs were ranging from 0.07 US\$/kW h (2.22×10^{-5} US\$/kJ) to 0.16 US\$/kW h (4.72×10^{-5} US\$/kJ). As a method to compare, some authors such as Cruz et al. [27], reports hydrogen production cost equal to 1.74×10^{-5} US\$/kJ (0.0623 US\$/kW h) [27], this value is similar to the lower value found in this paper (0.07 US\$/kW h). It can be observed that the value found in this paper is slightly different from the one calculated by Cruz [27] due to the fact that exergetic cost which was calculated in this study takes into account all irreversibilities of the system.

4. Conclusion

Despite the fact that the functional diagram is very complex, it is useful for energy efficiency analysis of hydrogen production in a Biodiesel Plant. The values of exergetic functions associated to thermo-economic functional diagram were also determined. In this analysis, the highest values of exergetic functions are associated to canola oil, biodiesel and hydrogen flows. In this sense, supported by the analysis, it can be affirmed that the simultaneous production of Biodiesel and Hydrogen is a technology that offers technical viability.

According to Eq. (82) that has been obtained in this paper, for the purpose of decreasing the final product costs within the biodiesel production plant, the hydrogen production technology has been incorporated to the plant, making possible the energetic use of glycerine. Based on Eq. (82) and Fig. 6, the biodiesel production

cost reduction can reach 6% when compared to values reported by Coronado. The hydrogen production costs as it is shown in Fig. 7, they are very close to the values reported in the literature. Biodiesel production alone has advantages when comparing with biodiesel and hydrogen simultaneous production due to that their production cost is minor, but in the biodiesel production alone glycerine is obtained. The glycerol crude produced contains lot of contaminants which decreases its quality and has low value, nowadays is relevant the conversion of low value glycerol crude to hydrogen production. The incorporation of hydrogen production in a biodiesel plant indeed offers a brand new and advanced technology for biodiesel production. The findings will assist in the integration of cogeneration system seeking the energetic auto-sufficiency in the plant. In the next part of the paper will be conducted a life cycle analysis of simultaneous biodiesel and hydrogen production. The carbon dioxide emissions results are compared with other processes of hydrogen production including steam reforming of methane. This part will be submitted in the same journal.

Acknowledgements

The authors look forward to acknowledge the financial support provided by the Coordination for the Improvement of Higher Level -or Education- Personnel (CAPES).

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