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Exergetic and Life Cycle Assessment Analyses of Integrated Biowaste Gasification-Combustion System: A Study Case

Anabel Fernandez, Leandro Rodriguez-Ortiz, Rosa Rodríguez

Abstract**—**Due to the negative impact of fossil fuels, renewable energies are promising sources to limit global temperature rise and damage to the environment. Also, the development of technology is focused on obtaining energetic products from renewable sources. In this study, a thermodynamic model including exergy balance and a subsequent Life Cycle Assessment (LCA) were carried out for four subsystems of the integrated gasification-combustion of pinewood. Results of exergy analysis and LCA showed the process feasibility in terms of exergy efficiency and global energy efficiency of the life cycle (GEELC). Moreover, the energy return on investment (EROI) index was calculated. The global exergy efficiency resulted in 67%. For pretreatment, reaction, cleaning, and electric generation subsystems, the results were 85%, 59%, 87%, and 29%, respectively. Results of LCA indicated that the emissions from the electric generation caused the most damage to the atmosphere, water, and soil. GEELC resulted in 31.09% for the global process. This result suggested the environmental feasibility of an integrated gasification-combustion system. EROI resulted in 3.15, which determines the sustainability of the process.

Keywords**—**Exergy analysis, Life Cycle Assessment, LCA, renewability, sustainability.

I. INTRODUCTION

THE use of fossil fuels causes a negative impact so that renewable energies are promising sources to limit global temperature rise and damage to the environment. In this sense, the energetic products containing hydrogen, such as those from biomass, may be considered a promising source to substitute fossil fuels [1].

There are efforts by world governments to decrease global warming. Thus, the Paris Agreement informed several climate goals to reach a neutral balance or remove emissions of atmospheric CO_2 [2]. The European Union (EU) proposed to avoid climate change by dropping the emissions of greenhouse gas. The EU foresees for 2050 about 60% in reduction of these emissions [3]-[5]. In Latin America, Cuba implemented a strategy to exploit renewable sources by 2030. The electric generation in Cuba is about 95% originated from fossil fuel sources [6], [7]. On the other hand, biomass involves raw material from natural and organic materials and can be converted into value-added products with high quality [8], [9]. Important compounds may be obtained from biomass as bioactive compounds, essential oils, bio-oil, bioenergy, lignin oligomers, cellulose, activated carbon, bioethanol, natural dyes, biodiesel, hemicelluloses, lycopene, platform molecules [10].

Biochemical and thermochemical processes can convert biomass into energetic products. Moreover, gasification converts biomass into a gas (syngas), solid products (biochar), and liquid products (water and tar). This technological process has a neutral balance of CO_2 emission and low harmful emissions of SO_x and NO_x species [11]-[15].

Most research has developed thermodynamic modeling to predict the effect of the simultaneous variables on performance [16]-[19]. The use of these models allows the advantage of evaluating numerous scenarios avoiding the high cost associated [16]. Taking into account the assumptions, most of the works reported in literature use the black-box or zero-dimension models. These models are simpler and more suitable for several applications, such as initial studies [16]. Hence, few works do not refer to the application of detailed models on each unit of the process. Therefore, there is a research gap in the detailed analysis focused on each subsystem that makes up the integrated gasification-combustion system. On the other hand, the exergy of a stream represents the potential amount of suitable work that it may perform. For this reason, the exergy analysis allows evaluating the sustainability of a process. Echegaray et al. [18] carried out an exergy assessment describing sustainability indexes and the behavior of biomass gasification. These authors informed that when the exergy efficiency increases, the exergy loss decreased and increase the sustainability index of energy use. In this way, LCA is another appropriate tool to assess the environmental impacts [9], [20]. Loução et al. [21] applied the LCA complemented by sensitivity analysis to different technologic ways of biomass transformation to produce electricity.

Zang et al. [20] assessed several alternatives of biomass integrated gasification combined cycle through an LCA. They concluded that this system emits low values of warming potential (WP) and results in negative emissions of WP when these types of systems are integrated with CO_2 capture and storage technology.

The literature review reveals few research works that studied gasification plants using biomass for electric energy generation with techno-environmental-health feasibility. Moreover, there is no detailed assessment that emphasizes each subsystem that constitutes the global gasification process. Thus, this work

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applied exergy assessment and LCA to a study case of an industrial sawmill plant localized in Cuba. It is due to the lack of similar works in the literature. This study allowed us to calculate exergy loss, exergy wasted, exergy destroyed, and exergy efficiency for each subsystem of the global process. Also, potential environmental impacts, the GEELC, and EROI were evaluated because of 18 categories of damage impacts.

II. THEORETICAL FRAMEWORK

A. Thermodynamic Model of Black Box (Reaction Subsystem)

To carry out the thermodynamic model, the flows of mass, energy, and exergy were calculated under steady-state conditions. The main assumptions were considered from [18]. Furthermore, the fraction of carbon unconverted to gas, such as biochar and bio-oil, is characterized by the chemical formulas to be $C_cH_aO_b$ and $C_{ic}H_jO_k$, respectively [22].

In the reaction subsystem, the reaction of gasification is:

$$CH_hO_o + w\,H_2O + m\,(O_2 + 3.76\,N_2) \rightarrow x_1\,CO + x_2\,H_2 + x_3\,CO_2 + x_4\,H_2O + x_5\,CH_4 + x_{biochar}\,C_cH_aO_b + m\,3.76\,N_2 + x_{bio\text{-}oil}\,C_{ic}H_jO_k \tag{1}$$

Tables I-VII detail the equations of the model and exergy balance applied here. They also contain the estimation of chemical formulas, biochar, and bio-oil.

TABLE I
EQUATIONS OF WATER, AIR INPUT AND MOLECULAR WEIGHT OF BIOMASS [23]

$w = (SBR + w_W)\,M_{BM}/18$	(2)
$m = ER(1 + H/4 - O/4)$	(3)
$M_{BM} = (12 + H + 16O)/(1 - w_W)$	(4)

TABLE II
EQUATIONS OF MASS BALANCE FOR C, H, AND O [23]

$x_1 + x_3 + x_5 + c\,x_{biochar} + ic\,x_{bio\text{-}oil} = 1$	(5)
$2\,x_2 + 2\,x_4 + 4\,x_5 + a\,x_{biochar} + j\,x_{bio-oil} - 2\,w - h = 0$	(6)
$x_1 + 2x_3 + x_4 + b\,x_{biochar} + k\,x_{bio-oil} - o - w - 2\,m = 0$	(7)

TABLE III
REACTIONS OF WATER-GAS SHIFT AND METHANE [24]

$CO + H_2O \overset{K_{wgs}}{\Longleftrightarrow} CO_2 + H_2$	(8)
$C + 2H_2 \overset{K_{mt}}{\Leftrightarrow} CH_4$	(9)

TABLE IV
CONSTANT EXPRESSIONS FOR WATER-GAS SHIFT AND METHANE REACTIONS [25]

$K_{wgs} = p_{CO_2}p_{H_2}/(p_{CO}\,p_{H_2O}) = x_2\,x_3/(x_1\,x_4)$	(10)
$K_{mt} = p_{CH_4}/(p_{H2}^2\,p_0) = x_5\,p_0/(x_2^2\,p)\,x_{syngas}$	(11)

TABLE V
EXPRESSIONS FOR EQUILIBRIUM CONSTANT MODIFIED FOR NON-EQUILIBRIUM CONDITIONS [26]

$K_{wgs}^* = K_{wgs}\,f_{wgs}$	(12)
$K_{mt}^* = K_{mt}\,f_{mt}$	(13)
$f_{wgs} = 0.083\exp(2.88\,ER)$	(14)
$f_{mt} = 38.75 - 30.70\,ER$	(15)

TABLE VI
EXPRESSIONS FOR BIOCHAR AND BIO-OIL CONVERSION [26]

Biochar conversion fraction [23]	
$x_{biochar} = 1 - f_{biochar}$	(16)
$f_{biochar} = 0.901 + 0.439\,(1 - \exp(-ER + 0.0003\,T))$	(17)
Bio-oil formation [27]	
$bio - oil_{wt,\%} = 35.98\exp(-0.00298\,T)$	(18)
$m_{bio-oil} = bio - oil_{wt,\%}/100(M_{bm} + SBR\,M_{bm} + w\,M_{bm} + 29\,(m + 3.76))$	(19)
$x_{bio-oil} = m_{bio-oil}/MW_{bio-oil}$	(20)

The energy balance can be written as:

$$Q = \sum_i^p x_i\Delta H_{f,i}^0(298) - \sum_i^r x_i\Delta H_{f,i}^0(298) + \sum_{i=1}^p x_i\left(\int_{298}^T c_{P_i}\,dT\right) + \sum_{i=1}^I x_i\left(\int_{298}^T c_{P_i}\,dT\right) \tag{21}$$

TABLE VII
EXPRESSIONS FOR EXERGY ANALYSIS

Exergy flow of stream [25]	
$\dot{\varepsilon} = \dot{\varepsilon}_{ph} + \dot{\varepsilon}_{ch}$	(22)
Physical exergy of a pure compound [25]	
$\dot{\varepsilon}_{ph,i} = \int_{T_0}^T C_{Pi}dT - T_0\left(\int_{T_0}^T C_{Pi}/T\,dT\right)$	(23)
Physical and chemical exergies of syngas [25].	
$\dot{\varepsilon}_{ph} = \sum_i y_i\left[\left(\int_{T_0}^T C_{Pi}dT\right) - T_0\left(\int_{T_0}^T C_{Pi}/TdT\right)\right]$	(24)
$\dot{\varepsilon}_{ch} = \sum_i y_i\,\dot{\varepsilon}_{ch,i} + RT_0\sum_i y_i\ln y_i$	(25)
Chemical exergy of bio-waste [23]	
$\dot{\varepsilon}_{ch} = m\,\beta\,LHV$	(26)
Factor β for bio-waste, bio-oil, and biochar [23]	
$\beta = (1.004 + 0.016H/C - 0.3493O/C(1 + 0.0531H/C) + 0.0493N/C)/(1 - 0.4124O/C)$	(27)
$\beta = 1.0374 + 0.0159H/C + 0.0567O/C$	(28)
$\beta = 1.0437 + 0.1869H/C + 0.0617O/C$	(29)
Exergy efficiency [9]	
$\eta_{ex\,g} = \dot{\varepsilon}_{in}/\dot{\varepsilon}_{out}$	(30)
Physic exergy flow [9]	
$\dot{\varepsilon}_{ph} = \dot{\varepsilon}_{phT} + \dot{\varepsilon}_{phP}$	(31)
$\dot{\varepsilon}_{phT} = \Phi\,C_P[+(T - T_0) - T_0\ln T/T_0]$	(32)
$\dot{\varepsilon}_{phP} = \Phi\frac{RT_0}{M}\ln P/P_0$	(33)
Exergy destroyed [9]	
$\dot{\varepsilon}_{destroyed} = \dot{\varepsilon}_{ph\,in} - \dot{\varepsilon}_{ph\,out}$	(34)
Chemical exergy [9]	
$\dot{\varepsilon}_{ch} = \dot{\varepsilon}_{St} + \dot{\varepsilon}_{mix}$	(35)
Flow exergy associated with compound mixing [9]	
$\dot{\varepsilon}_{St} = \Phi\sum_{i=1}^n x_i b_i^0/M_i$	(36)
Exergy wasted [9]	
$\dot{\varepsilon}_{Wasted} = \dot{\varepsilon}_{ch\,in} - \dot{\varepsilon}_{ch\,out}$	(37)

The exergy efficiency η_{exr} is calculated in equation for reaction subsystem (38):

$$\eta_{exr} = (\dot{\varepsilon}_{syngas} + \dot{\varepsilon}_{loss} + \dot{\varepsilon}_{bio-oil} + \dot{\varepsilon}_{biochar})/(\dot{\varepsilon}_{bio-waste} + \dot{\varepsilon}_{air}) \tag{38}$$

B. Exergy Analysis (Pretreatment, Cleaning, and Electricity Subsystems)

Exergy flows for each stream are defined in (39):

$$\dot{\varepsilon}_{in} = \dot{\varepsilon}_{out} + \dot{\varepsilon}_{loss} \tag{39}$$

The sum of exergies wasted and destroyed is the flow of loss exergy [9], [28], [29]. Exergy destroyed denotes the physical exergy loss that is the loss associated with a specific subsystem by heating or cooling. Exergy wasted is the loss of exergy associated with a stream released to the environment (without suitable use) [30].

$$\dot{\varepsilon}_{\mathrm{loss}} \geq 0;\ \dot{\varepsilon}_{\mathrm{loss}} = \dot{\varepsilon}_{\mathrm{wasted}} + \dot{\varepsilon}_{\mathrm{destroyed}} \tag{40}$$

The exergy efficiency of pretreatment subsystem is η_{exp}:

$$\eta_{\mathrm{ex\,b}} = (\dot{\varepsilon}_{\mathrm{ch\ out\ bio-waste}} + W_{\mathrm{u-saw}})/(\dot{\varepsilon}_{\mathrm{ch\ in\ bio-waste}} + P_{\mathrm{e-saw}}) \tag{41}$$

Work of electrical saw can be written as:

$$\dot{W}_{\mathrm{u-saw}} = P_{\mathrm{e-saw}}\eta_{\mathrm{saw}} \tag{42}$$

The exergy efficiency of cleaning subsystem is η_{exc}:

$$\eta_{\mathrm{exc}} = (\dot{\varepsilon}_{\mathrm{ch\ out\ syngas}} + \dot{\varepsilon}_{\mathrm{ph\ out\ syngas}} + \dot{\varepsilon}_{\mathrm{ph\ out\ water}})/(\dot{\varepsilon}_{\mathrm{ph\ in\ water}}\dot{\varepsilon}_{\mathrm{ch\ in\ syngas}} + \dot{\varepsilon}_{\mathrm{ph\ in\ syngas}} + P_{\mathrm{e-pump}}) \tag{43}$$

The exergy efficiency of generation subsystem is η_{exe}:

$$\eta_{\mathrm{exe}} = (\dot{\varepsilon}_{\mathrm{ph\ in\ csyngas}} + \dot{\varepsilon}_{\mathrm{ch\ in\ csyngas}} + \dot{\varepsilon}_{\mathrm{ph\ in\ air}} + \dot{\varepsilon}_{\mathrm{ph\ in\ water}})/(P_{\mathrm{e-engine}} + \dot{\varepsilon}_{\mathrm{ch\ out\ c\ gas}} + \dot{\varepsilon}_{\mathrm{ph\ out\ c\ gas}} + \dot{\varepsilon}_{\mathrm{ph\ out\ excess\ air}} + \dot{\varepsilon}_{\mathrm{ph\ out\ water}}) \tag{44}$$

The exergy of the combustion gases was calculated considering the reaction completed at 773 K with excess air of 30%. The chemical and physical exergies of clear gas are the respective outlet values from the cleaning subsystem. The value of Pe-engine is the power delivered by the engine. The physical exergy of air is calculated as the respective values of gaseous compounds of gas in (32) and (33).

C. Life Cycle Assessment

System Boundaries and Technical Description

In an LCA it is important to provide a quantified reference or functional unit (FU) to represent a quantified description of the performance of the subsystems studied. This analysis was carried out in stages for each subsystem. Fig. 1 shows the subsystem boundaries used for the LCA performance. The life cycle stage (LCS) of the pretreatment subsystem consists of the biomass crushing to reduce its size. The LCA is applied to 1 kg of chips (FU). Ultimate and proximate analyses are indicated in Table VIII.

The results of the ultimate and proximate analysis were used to calculate the chemical formula of biomass, bio-oil, and biochar.

The LCS of the reaction subsystem represents a downdraft gasifier. It operates at 723 K with a fixed bed (wood chips). The reactor uses a motorized system to remove ash and biochar from this subsystem. The LCA is applied for 1 kg of gas produced (FU).

TABLE VIII
ULTIMATE AND PROXIMATE ANALYSIS ON DRY BASIS AND CALORIFIC VALUE OF PINEWOOD

Analysis	Value	Method
Proximate (wt.%) dry basis		
Ash	0.30	ASTM D 3175
Volatile matter	85.47	ASTM D 3174
Fixed carbon	14.23	ASTM D 3172
Ultimate (wt.%) dry basis		
Carbon	47.95	ASTM D 5373-08
Hydrogen	6.03	
Oxygen*	45.3	*(By deference)
Nitrogen	0.72	
LHV (kJ/kg) dry basis [31]		
LHV	19950	

The LCS of the cleaning subsystem removes small solid particles of gas. Hot gas flows through the scrubber, where gas is cleaned and cooled at 320 K. Subsequently, gas flows into a decanter for extracting the water and tar. Then, the gas flows through active and passive filters that recollect particulate material and bio-oil from the gas. Here, the LCA is applied to 1 kg of clean gas produced, which is the FU.

The LCS of the generation subsystem involves an internal combustion engine that releases heat, polluting gases (NO_x, CO_2 with particulate material), and produces electricity due to the connection with the electrical generator. Here, the LCA is applied to 1 kW of electric power delivered (FU).

Goal and Scope Definition

International Organization for Standardization (ISO) standards 14040/44 are used in the LCA. The software used was SIMAPRO with packages of databases of ReCiPe 2016 Midpoint and Recipe Endpoint (E) v.1.03. On the other hand, EROI determinates the ratio of the amount of usable energy gained from a supply to the quantity of energy consumed to produce that net quantity of energy, in (45) [20], [32]:

$$\mathrm{EROI}=\mathrm{OE}/\mathrm{IE} \tag{45}$$

Sheehan et al. [33] and Mayer et al. [32] calculated the GEELC in (46). The index of GEELC contemplates the energy losses, additional energy required in gas production, and renewable energy as input. Moreover, GEELC is considered a suitable tool to create value and improve environmental performance across the lifecycle.

$$\mathrm{GEELC} = \mathrm{FPE}/\mathrm{TPE} \tag{46}$$

EROI and GEELC values contemplate the overall energy efficiency and sustainability [32].

Inventory Analysis

Due to some data of materials or processes are not obtainable in SIMAPRO, the inventory must contain information about the foreground and background. Thus, Table IX displays the input

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and output streams considered in the LCA for each subsystem. These data were measured following 1682 hours of process operation.

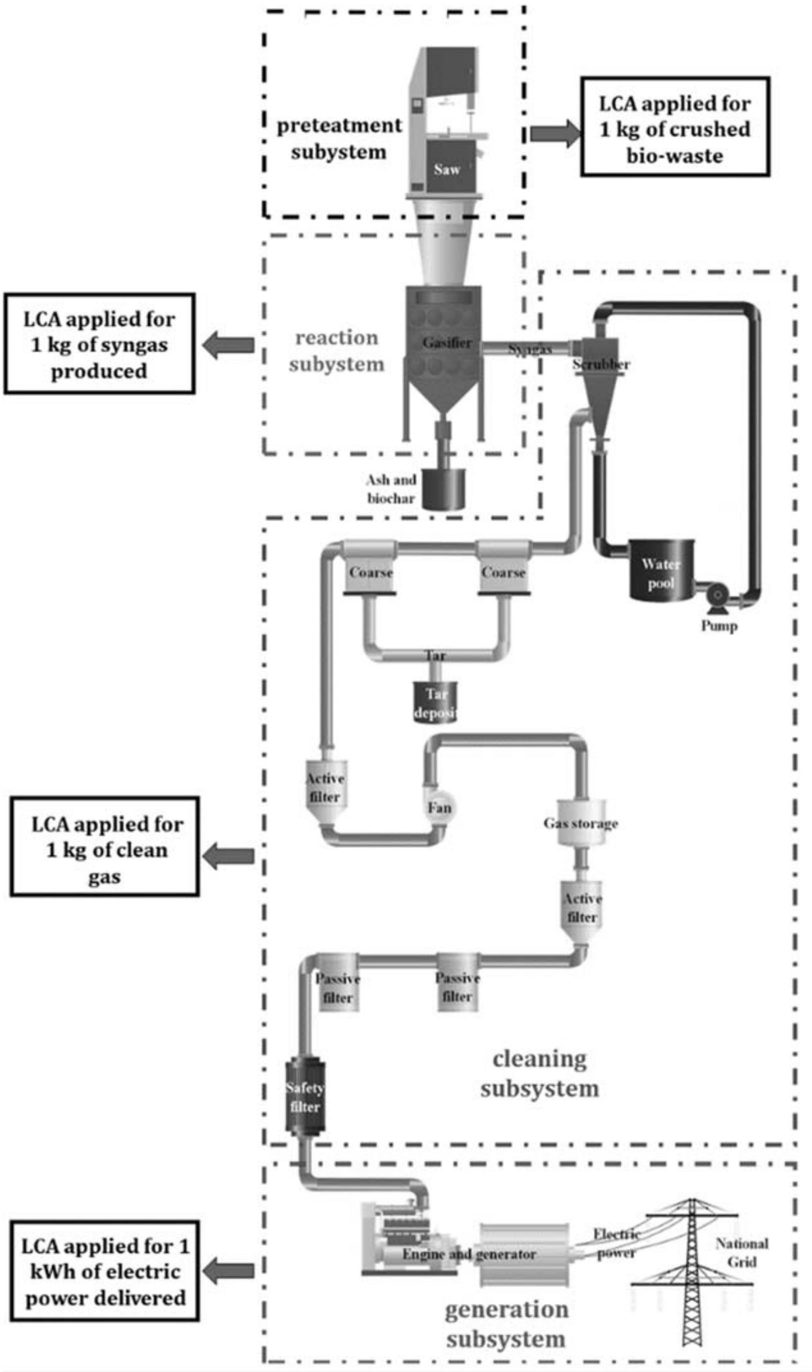

Fig. 1 Subsystem boundaries and life cycle stages

III. RESULTS AND DISCUSSION

A. Results of Exergy Analysis

The basis for the results of exergy analysis is 83 kg/h of biomass into the pretreatment subsystem. The input flow of gas enters into the generation subsystem with a flow of 200 kg/h.

The bases of biomass and gas were measured from the plant of the study case analyzed. Then, the rest of the flows were determined using the model described in Section II *A*.

Fig. 2 displays the input and output exergy flows, wasted, and destroyed of each subsystem.

In the pretreatment subsystem, the exergy loss was produced by 12 kg/h of particulate sawdust discarded. As a recommendation, a dust collector may be connected to the electric saw to recover this material. Thus, sawdust can be used and exploited to obtain energetic products due to its chemical potential.

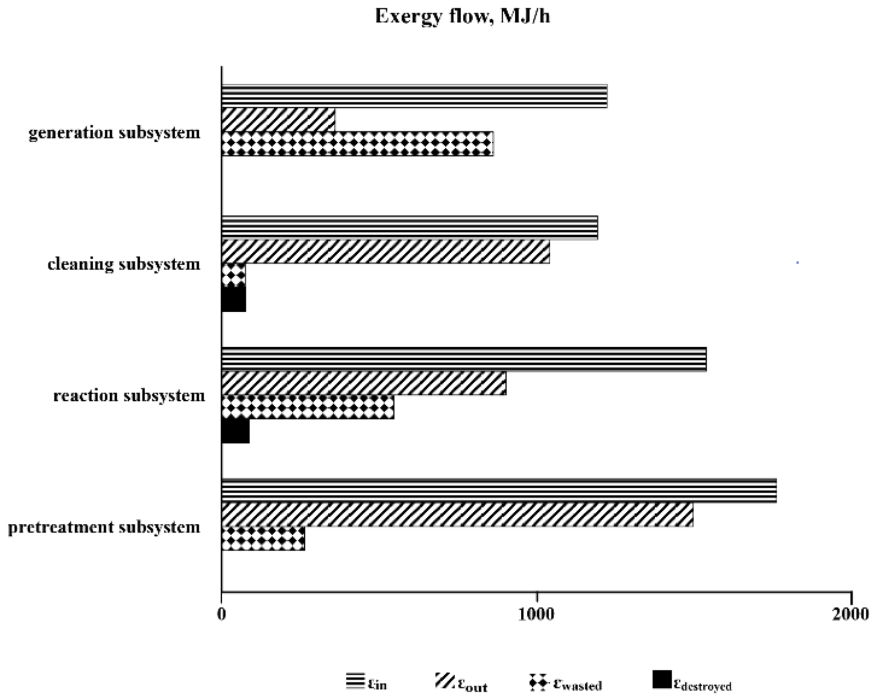

Fig. 2 Exergy flows of the integrated gasification-combustion process

TABLE IX
INPUTS AND OUTPUTS CONSIDERED FOR LCA OF FOUR GASIFICATION SUBSYSTEMS

Concept	Inputs from nature (kg)	Inputs from the Technosphere (materials or fuels) (m^3)	Inputs from the Technosphere (electricity or heat) (kWh)	Tech outputs (products) (kg)	Tech outlets (avoided products) (m^3)
Life cycle Inventory data of the bio-waste pretreatment subsystem					
Bio-waste (kg)	215600	-	-	194040	-
Electricity (kWh)	-	-	4558.4	-	-
Sawdust (m^3)	-	-	-	-	21560
Life cycle Inventory data of the gasification reaction subsystem					
Biomass (kg)	-	100920	-	-	-
Gas (kg)	-	-	-	260576	-
Biochar (kg)	-	-	-	-	9300
Electric power (kWh)	-	-	1367	-	-
Heat (kWh)	-	-	114151	-	-
Ash (kg)	-	-	-	-	185
Air (kg)	159656	-	-	-	-
Life cycle Inventory data of the syngas cleaning subsystem					
Gas (kg)	-	260761	-	234685	-
Electricity (kWh)	-	-	8960	-	-
Bio-oil (kg)	-	-		9800	-
Water consumed (m^3)	4541	-	-	-	-
Life cycle Inventory data of the emissions					
	Ash (kg)			Effluent (kg)	
	185			4541185	
Life cycle Inventory data of the electricity generation subsystem					
Syngas (kg)	-	234685	-	-	-
Air (kg)	217000	-	-	-	-
Cooling water (m^3)	323.57	-	-	-	-
Electric energy (kWh)	-	-	-	46937	
Life cycle Inventory data of the direct emissions					
	CO_2 (kg)		The sensible heat released by the exhaust gases (MJ)		Exhaust Gases (Air emissions, total flow) (kg)
	98331		37.7		451685

In the reaction subsystem (gasifier), the flow of exergy destroyed is 6% and it is caused by the heating of the reaction system. The flow of exergy wasted is 36% and this result determines the portion of biomass that converts into CO_2, H_2O, and ash. These gaseous components do not provide energy causing a decrease in gas quality. Biochar produced is removed without reuse, which contributes to the flow of exergy wasted, too.

In the cleaning subsystem, Fig. 2 displays that this unit consumes 1195 MJ/h. This value is the energetic requirement to pump 200 kg/h of water at 126 kPa. The flow of exergy destroyed represents 6% and is produced by a difference of temperature of 5 °C. The flow of exergy wasted represents 7% and is linked with the removal of bio-oil.

Regarding the exergy efficiencies, the reaction, cleaning, and electric generation subsystems resulted in 85%, 59%, 87%, and 29%, respectively. Tang et al. [34] informed efficiencies for entire systems of 36.5%, 33.3%, 48.9%, and 32.2% for incineration system, gasification-combustion-turbine system, syngas turbine/combined cycle system, and syngas to internal combustion engine system, respectively. The global exergy efficiency resulted in 67%.

B. *Results of LCA*

Impacts Produced by the Integrated Gasification-Combustion Process

Table IX shows the total emission produced by each subsystem of the entire system here evaluated.

TABLE X
TOTAL EMISSIONS ASSOCIATED TO IMPACTS AND DAMAGE CAUSED BY THE PROCESS

Category	Unit	Subsystems			
		Pretreatment	Reaction	Cleaning	Generation
GW	kg CO_2 eq	$3.21x10^{-03}$	$6.07x10^{-03}$	$4.02x10^{-02}$	$2.01x10^{-01}$
SOD	kg CFC11 eq	$3.45x10^{-09}$	$6.53x10^{-09}$	$4.32x10^{-08}$	$2.16x10^{-07}$
IR	kBq Co-60 eq	$2.27x10^{-04}$	$4.29x10^{-04}$	$2.84x10^{-03}$	$1.42x10^{-02}$
OFHH	kg NO_x eq	$1.02x10^{-05}$	$1.93x10^{-05}$	$1.28x10^{-04}$	$6.38x10^{-04}$
FPMF	kg $PM_{2.5}$ eq	$6.28x10^{-06}$	$1.19x10^{-05}$	$7.86x10^{-05}$	$3.93x10^{-04}$
OFTE	kg NO_x eq	$1.03x10^{-05}$	$1.95x10^{-05}$	$1.29x10^{-04}$	$6.44x10^{-04}$
TA	kg SO_2 eq	$2.00x10^{-05}$	$3.77x10^{-05}$	$2.50x10^{-04}$	$1.25x10^{-03}$
FE	kg P eq	$5.40x10^{-08}$	$1.02x10^{-07}$	$6.75x10^{-07}$	$3.38x10^{-06}$
ME	kg P eq	$4.12x10^{-02}$	$7.79x10^{-09}$	$5.15x10^{-08}$	$2.58x10^{-07}$
TE	kg 1.4-DCB	$1.20x10^{-02}$	$2.27x10^{-02}$	$1.50x10^{-01}$	$7.52x10^{-01}$
FET	kg 1.4-DCB	$2.08x10^{-05}$	$3.93x10^{-05}$	$2.60x10^{-04}$	$1.30x10^{-03}$
MET	kg 1.4-DCB	$1.27x10^{-01}$	$2.40x10^{-01}$	$1.59x10^{00}$	$7.95x10^{00}$
HCT	kg 1.4-DCB	$9.19x10^{-04}$	$1.74x10^{-03}$	$1.15x10^{-02}$	$5.75x10^{-02}$
HNCT	kg 1.4-DCB	$7.80x10^{-02}$	$1.48x10^{-01}$	$9.76x10^{-01}$	$4.88x10^{00}$
LU	m^2 a crop eq	$4.91x10^{-06}$	$9.29x10^{-06}$	$6.15x10^{-05}$	$3.07x10^{-04}$
MRS	kg Cu eq	$1.08x10^{-06}$	$2.05x10^{-06}$	$1.36x10^{-05}$	$6.79x10^{-05}$
FRS	kg oil eq	$9.97x10^{-04}$	$1.88x10^{-03}$	$1.25x10^{-02}$	$6.24 \text{ x } 10^{-02}$
WC	m^3	$8.07x10^{-06}$	$1.53x10^{-05}$	$1.87x10^{-02}$	$1.00x10^{-01}$

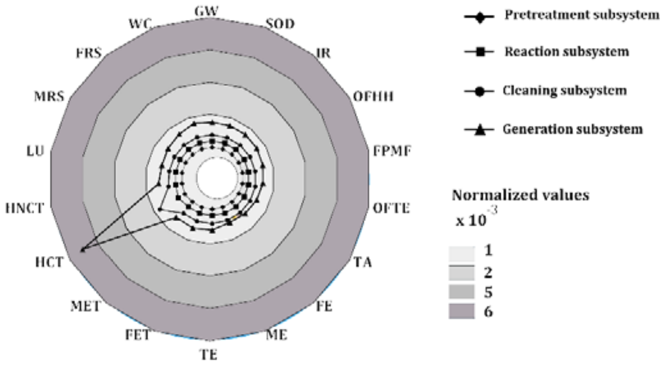

Fig. 3 Normalized values of impacts caused by subsystems of global process

Fig. 3 shows that the generation subsystem produces impacts in human carcinogenic toxicity (HCT). This normalized value is six times higher than the results of the rest of the subsystems. This emission corresponds to 5.7 10^{-2} kg 1,4-DCB, equivalent kilograms of 1.4-dichlorobenzene (Table IX). In this way, Zang et al. [20] informed that the low efficiency of the combustion subsystem causes an increase in HCT. In the study case analyzed here, the exergy efficiency of the internal combustion engine (generation subsystem) is 29% (Section III *A*).

The cleaning is the following subsystem that causes an impact in HCT of 1.15 10^{-2} kg 1,4-DCB. In this stage, the bio-oil discharged into the environment caused this impact. Chidikofan et al. [35] related the effect of HCT to bio-oil formation.

The rest of the subsystems here analyzed do not result in significant differences among them. However, they produce the emissions shown in Table IX.

Fig. 4 displays that the generation subsystem produces the most damage in human health, ecosystems, and resources, followed by the cleaning subsystem, then by reaction subsystem, and pretreatment. The normalized values of damage to human health are generated by emissions of the subsystems and can originate afflictions. Regarding this aspect, these emissions are linked with the release of NO_x during combustion. The NO_x could come from the use of pesticides and fertilizers during the cultivation cycle [36]-[38]. The damage to resources consists of the uncontrolled use of natural sources, like minerals and fossil fuels. Furthermore, emissions of CO and NO_x contribute to photochemical oxidation in the ozone formation [39]. These emissions avoid the absorption of UV radiation; thus, they cause the increase of diseases related to the immune system and ocular pathologies [39].

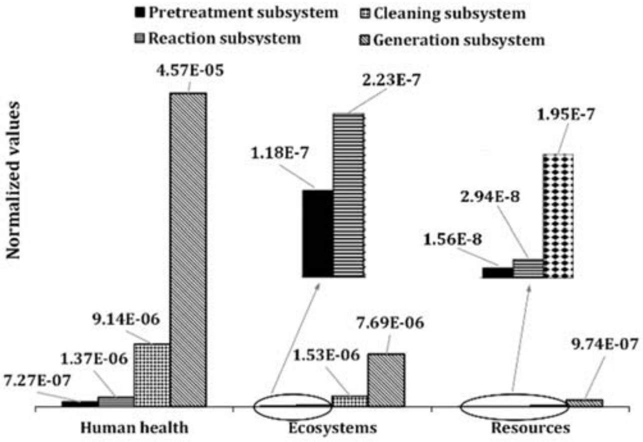

Fig. 4 Normalized values of damage to human health, ecosystems, and resources caused by subsystems of the process

The damage to ecosystems and resources involves emissions that can cause the interruption of their development. In this sense, the NO_x emissions come into contact with the water in the atmosphere, which produces acid rain, affecting terrestrial ecosystems due to the destruction of microorganisms essential to their development [39].

Results of Global Life Cycle Efficiency and EROI

The value of GEELC of the entire process is 30.1%. This indicator permits evaluating the feasibility and sustainability of the syngas produced due to considering the energy total of the syngas obtained and the primary energy content accumulated in natural resources, the biomass of pinewood, extracted from the environment.

The result of EROI applied to the entire process is 3.1, which is greater than 1, and classifies the entire system as renewable. In this context, Mayer et al. [32] reported this criterion of renewability. However, the results of the analysis performed suggest that the minimization of loss in material, energetic resources, and harmful emissions into the environment may enhance the EROI value. Zang et al. [20] informed similar values of EROI (4.21) for the integrated air gasification-combustion systems. Briones-Hidrovo et al. [40] informed values of EROI for the gasification-combined cycle as 3.6.

IV. CONCLUSIONS

This study presented a case of integrated exergy analysis and LCA of a plant of integrated pinewood gasification-combustion localized in Santiago de Cuba, Cuba. The results show that the studied system is a feasible and renewable technological pathway for electricity generation.

The exergy analysis, through a thermodynamic model applied under steady-state conditions, allowed the detection of losses of energy and material resources of each subsystem. The global exergy efficiency resulted in 67%. The stage of generation of electricity had the lowest value of exergy efficiency of 29% due to the low conversion of the internal combustion engine.

The LCA allowed detection of the emissions and damage produced by the integrated gasification-combustion system. The generation subsystem produced the most impact, followed by the cleaning subsystem, on HCT, terrestrial ecotoxicity, water consumption, and marine ecotoxicity. Values of the emissions calculated in this work indicated that a low conversion of the internal combustion engine caused damage to the environment. The quantity of fossil electricity spent is the origin of harmful emissions released by the syngas cleaning subsystem.

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