

Exergy Analysis of a Fixed-Bed, Batch Type Rice Husk Fuelled Downdraft Gasifier

Alhaji Bukar Abubakar¹, Mohammed B. Oumarou^{2,*}, Fasiu A. Oluwole², Sahabo Abubakar¹

¹Department of Mechanical Engineering, Ramat Polytechnic, Maiduguri, Borno State; Nigeria

²Department of Mechanical Engineering, University of Maiduguri, Borno State; Nigeria

*Corresponding author: mmbenomar@yahoo.com

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Abstract This paper treats exergy analysis of rice husk at various loading rates of 1 kg, 1.5 kg and 2 kg of feedstock, using a batch type, fixed-bed gasifier, equipped with a gas filtering system and between the operating temperatures of 690 K and 1100 K, operated for the whole year. Exergy analysis is a thermodynamic technique which uses conservation of mass and energy principles to design thermal systems with maximum efficiency and it is based on First and Second law of thermodynamics. Formulas from literature and previous researches as well as Microsoft Excel 2007 were used to make calculations and graphically interpret the results. The exergoeconomic analysis is based on location specific and national data collected from official sources. A MATLAB based hybrid model developed from a combination of other studies is used to generate the exergoeconomic analysis results. Methane was found with the highest total exergies where values of exergies were varying between 1110126 kJ and 1066279 kJ for 2kg; 1037525 kJ and 1004639 kJ for 1.5 kg and finally, 965559.3kJ and 943635.6kJ for a feedstock mass of 1 kg between 690 K and 960 K respectively. From the overall results obtained, the gasification efficiency can be improved by increasing the temperature with an addition of heat in the process. The R^2 values of 0.999 to 1 show the true behavior and similarities of the graphs and highlighting the enormous exergy destruction rate in the process. The CO_2 , CO and NO_x capture/avoidance increases the plant efficiency by producing more electricity thereby increasing the financial potential of the plant. From the total exergies of CO_2 , CO and NO_x , \$0.156/kg, \$0.20/kg and \$12.335/kg could be made when sold respectively. The total exergies of gases considerably assist in the exergoeconomic analysis of the gasification plant, when the environmental aspect is considered.

Keywords: exergy analysis, downdraft gasification, batch loading, fixed-bed, rice husk, sustainable development, energy

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1. Introduction

Worldwide growing demand for energy consumption in recent years arising from industrialization development and increasing earth population has caused more environmental concerns to emerge. On the other hand, specific issues related to the use of fossil fuels as a nonrenewable source of energy has caused alternative fuels like biomass to be investigated with more concern. Generally, gasification is a process which converts organic matter to gas and tar. Also, through the gasification, biomass as a fuel is converted to the combustible gas (syngas) [1]. Biomass gasification involves the production of a gaseous fuel by partial oxidation of a solid fuel [2]. Clean synthesis (syn) gas, produced from partial combustion of biomass, can be burnt in a gas turbine combustion chamber to run a biomass based combined cycle power plant.

Exergy analysis is a thermodynamic technique which uses conservation of mass and energy principles to design thermal systems with maximum efficiency and it is based on First and Second law of thermodynamics. Magnitude and location of energy degradation in a process identified by exergy analysis, energy consumption minimization leads to better utilization of available energy, environmental impact reduction and gasifier design improvement [3].

Across the world, exergy analysis has received considerable attention from researchers. Ptasiński [4] presented an efficiency analysis based on the Second Law of Thermodynamics for production of energy carriers from biomass. It was shown that the exergetic efficiency of renewable energy carriers is lower than that for fossil fuels. The highest efficiency was achieved for hydrogen production from high quality feedstock that is comparable with fossil fuels. Exergy analysis is powerful tools that can be used to evaluate energy systems with the advantages of determining energy loss locations, types and magnitudes [5].

Dudgeon [6] conducted an equilibrium modeling in Aspen Plus[®] in order to develop a methodology for evaluating different fuels for gasification based on exergy analysis. The exergetic efficiency of gasifying a fuel strongly depended on the carbon boundary point, which is the equivalence ratio limit at which all carbon is converted to gaseous products in an adiabatic system. Using flue gas recirculation allowed the gasifier equivalence ratio to be increased without solid carbon in the products. Karamarkovic and Karamarkovic [7] focused on air gasification of biomass with different moisture at different gasification temperatures. A chemical equilibrium model was developed and analyses were carried out at pressures of 1 and 10 bar with the typical biomass feed represented by $\text{CH}_{1.4}\text{O}_{0.59}\text{N}_{0.0017}$. At the temperature range 900–1373 K, the increase of moisture in biomass leads to the decrease of efficiencies for the examined processes. The moisture content of biomass may be designated as “optimal” only if the gasification temperature is equal to the carbon-boundary temperature for biomass with that specific moisture content. The gasification process at a given gasification temperature can be improved by the use of dry biomass and by the carbon-boundary temperature approaching the required temperature with the change of gasification pressure or with the addition of heat in the process.

Xianan *et al.*, [8] established an exergy balance model of steady-state flow system for gasification of village-level solid waste. The authors provided a new path for the reasonable evaluation of gasification process and studied the effects of different conditions on the exergy efficiency and LHV. The research concluded that the updraft fixed bed should be used for gasification of village-level solid waste.

Closely similar to Karamarkovic & Karamarkovic, Kasembe *et al.* [9] addressed the gasifier performance analysis using the exergy analysis modeling which utilizes both the first and second laws of thermodynamics. An exergy model incorporating a chemical equilibrium model was developed. Gasification was envisaged to be carried out at atmospheric pressure of 1 bar with the typical biomass feed, sugarcane bagasse, represented by the formula $\text{CH}_{1.42}\text{O}_{0.65}\text{N}_{0.0026}$ at the temperature range of 800–1400K. The maximum efficiencies value obtained based on chemical energy and physical exergy was lower than the efficiency value based on chemical exergy (84.64% vs. 76.94%). Reem *et al.*, [10] investigated the physical and chemical energy and exergy of product gas at different equivalent ratios (ER). The ER was also be used to determine whether the cold gas, exergy, and energy efficiencies of gases may be maximized by using secondary air injected to gasification zone under various ratios (0, 0.5, 1, and 1.5) at optimum ER of 0.195. From the results obtained, it was indicated that the chemical energy and exergy of producer gas were magnified by 5 and 10 times higher than their corresponding physical values, respectively. The cold gas, energy, and exergy efficiencies of DRS gasification are in the ranges of 22.9–55.5%, 43.7–72.4%, and 42.5–50.4%, respectively. Initially, all 3 efficiencies increased until they reach a maximum at the optimum ER of 0.195; thereafter, they declined with further increase in ER values. Yueshi *et al.*, [11] developed a chemical equilibrium model to predict the product composition of a biomass gasification system

using highly preheated air and steam. The advantages and limitations of this system were discussed from a thermodynamic viewpoint. The results demonstrated that the chemical energy output of the produced syngas is highest when the steam /biomass mass (S/B) ratio is 1.83 under the conditions used in this study. However, higher S/B ratios have a negative effect on the energy and exergy efficiencies. Echegaray *et al.*, [12] focused on the process of biomass wastes gasification, using biomass wastes from canneries (peach pits) and wine industry (marcs and stalks). Exergy analysis was utilized in order to evaluate the effect of different operational parameters (temperature, supply air/stoichiometric air, supply steam/carbon ratio and moisture feed). The exergetic efficiency of the gasification process decreases when the all considered operational parameters increase. More recently however, other researchers have worked on exergy analysis, using various techniques and /or set-ups [1,13,14,15], exergoeconomic, techno-economic analyses and costing [5,16–27].

This paper treats exergy analysis of rice husk at various loading rates of 1 kg, 1.5 kg and 2 kg of feedstock, using a batch type, fixed-bed gasifier, equipped with a gas filtering system and between the operating temperatures of 690 K and 1100 K, operated for the whole year (i.e. 8760 hrs). Formulas and models from literature and previous researches as well as Microsoft Excel 2007 were used to make calculations and graphically interpret the results. The exergoeconomic analysis is based on location specific and national data collected from official sources. A MATLAB based hybrid model developed from a combination of other studies is used to generate results.

2. Materials and Methods

2.1. Exergy Analysis

Typically, the gasification processes in downdraft gasifier are as shown in Figure 1 [28].

Energy and exergetic efficiencies are useful tools for energy conversion assessment and energy improvement [3]. Energy balance represented by eq. (1).

$$E_{\text{ricehusk}} + E_{\text{air}} = E_{\text{gas}} + E_{\text{char}} + E_{\text{loss}} \quad (1)$$

where $E_{\text{rice husk}}$, E_{air} , E_{gas} , E_{char} , and E_{loss} represents energy present in rice husk, air, product gas, unreacted carbon, and energy loss, respectively.

Unequal distribution of air inside the gasifier is responsible for localized pyrolysis, pyrolysis ends at 600 °C. At higher temperatures, thermal cracking reduces the tar content. The total exergy of gas mixture calculated by eq. (2):

$$Ex_{\text{total}} = Ex_{\text{ch}} + Ex_{\text{ph}} + Ex_{\text{mixing}} \quad (2)$$

Where Ex_{ch} , Ex_{ph} , Ex_{mixing} are chemical exergy, physical exergy, and exergy lost due to mixing of gas.

Chemical exergy of a substance is the maximum possible useful work done by the process when the substance brought from environment state to dead state. Chemical exergy of substances obtained from standard chemical exergy tables, specific chemical exergy of substance shown in Table 1.

The specific physical exergy can be calculated [3] using eq. (3):

$$Ex^{ph} = (h - h_0) - T_0 (s - s_0) \quad (3)$$

Thus the Total physical exergy can be obtained from:

$$Ex^{ph} = m[(h - h_0) - T_0 (s - s_0)] \quad (4)$$

where h , s , h_0 , and s_0 represent specific enthalpy, specific entropy, standard specific enthalpy, and entropy, T_0 is atmospheric temperature, and m represents the mass of the component in the stream.

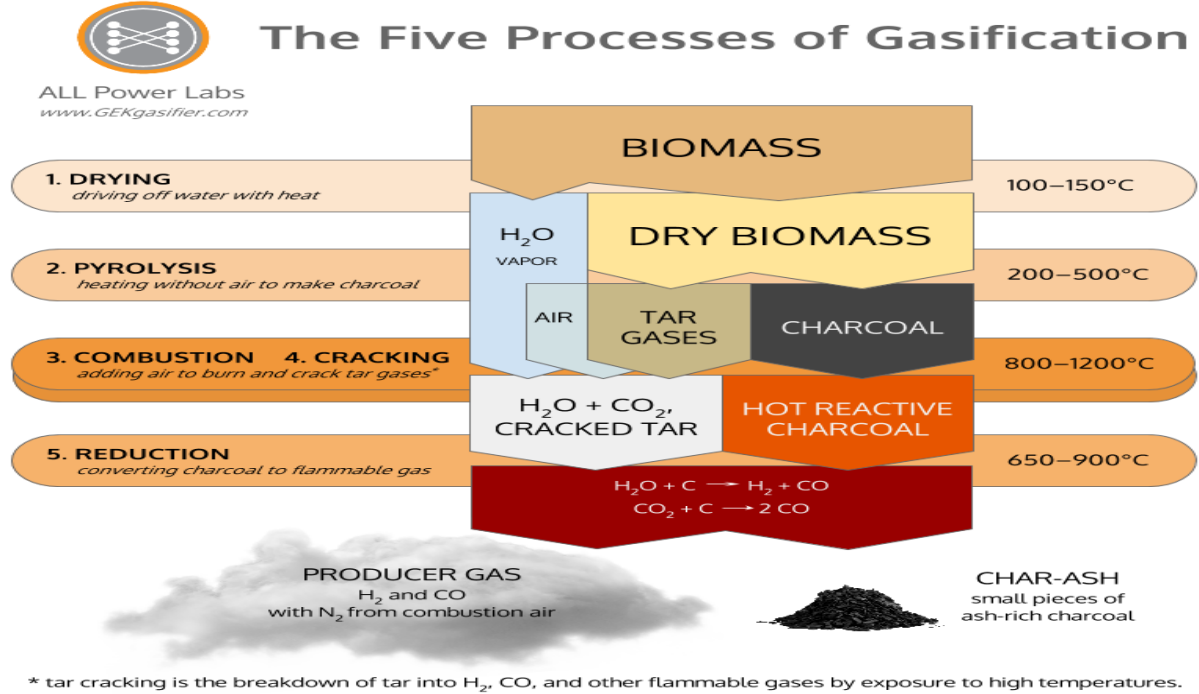


Figure 1. 5 Reactions Processes in a Downdraft Gasifier [28]

Table 1. Specific chemical exergy of gases [29]

Gas component	Specific chemical exergy (kJmol ⁻¹)
N ₂	0.72
O ₂	3.97
H ₂	236.09
CO	274.71
CO ₂	19.48
CH ₄	831.2

Specific enthalpy and entropy of gases are calculated as function of temperature given in Table 2 and Table 3.

Table 2. Specific enthalpy of gases [14]

Gases	Enthalpy as a function of temperature (kJkmol ⁻¹)	Temperature range (K)
H ₂	$h = -13779.82 + 19.83T + 1.54 \times 10^{-3}T^2 + 295179.97T^{-1} + 4.77 \times 10^{-7}T^3 + 389.72T^{0.5}$	310<T<1200
CO	$h = -235743.85 + 90.75T - 3.12 \times 10^{-3}T^2 + 1541255T^{-1} + 32063.32 \ln(T) - 5178.51T^{0.5}$	310<T<1700
CO ₂	$h^* = 426583.55 + 103.34T - 2.37 \times 10^{-3}T^2 + 40249.04T^{-1} - 3496.57T^{0.5} + 11004.74 \ln(T)$	310<T<1900
N ₂	$h = -23347.54 + 17.08T + 8.69 \times 10^{-3}T^2 + 230154.97T^{-1} - 1.51 \times 10^{-6}T^3 + 2939.81 \ln(T)$	310<T<1600
CH ₄	$h = -458850.73 + 304.93T - 9.39 \times 10^{-3}T^2 + 4193372.13T^{-1} + 110598.4 \ln(T) - 20287.96T^{0.5}$	310<T<1300

* modified for this work.

Table 3. Specific entropy of gases [14]

Gases	Enthalpy as a function of temperature (kJkmol ⁻¹)	Temperature range (K)
H ₂	$s = 37.54 + 19.83 \ln(T) - 8.02 \times 10^{-3}T + 3.08 \times 10^{-3}T^2 + 147589.95T^{-2} + 7.15 \times 10^{-7}T^2 - 389.73T^{-0.5}$	310<T<1200
CO	$s = -518.71 + 90.75 \ln(T) - 6.24 \times 10^{-3}T + 770627.67T^{-2} - 32063.32T^{-1} + 5178.51T^{-0.5}$	310<T<1700
CO ₂	$s = -539.42 + 103.34 \ln(T) - 4.74 \times 10^{-3}T + 20124.52T^{-2} + 3496.57T^{-0.5} - 11004.74T^{-1}$	310<T<1900
N ₂	$s = 97.76 + 17.08 \ln(T) + 1.74 \times 10^{-2}T + 115077.48T^{-2} - 2.26 \times 10^{-6}T^2 - 2939.81T^{-1}$	310<T<1600
CH ₄	$s = -2373.23 + 304.93 \ln(T) - 1.88 \times 10^{-2}T + 2096686.07T^{-2} - 110598.4T^{-1} + 2087.96T^{-0.5}$	310<T<1300

Exergy lost due to gas mixing [16] calculated from eq. (5):

$$E_{x}^{mixing} = RT_0 \ln(x) \quad (5)$$

where x is the mole fraction of gas component, $R=$ [8.314 kJ/kmolK]-universal gas constant.

The general exergy balance of a system can be written as [5]:

$$\dot{E}_{xq} + \sum_i \dot{E}_{xi} = \sum_e \dot{E}_{xe} + \dot{E}_{xw} + \dot{E}_{xd} \quad (6)$$

where the subscripts I and e denote the inlet and outlet condition of any component k. The terms \dot{E}_{xi} , \dot{E}_{xe} , \dot{E}_{xq} and

\dot{E}_{xw} refer to inlet and outlet exergy rates, heat transfer exergy rate and exergy due to work, respectively.

In steady state conditions, these quantities can be related as [5]:

$$\dot{E}_{xi} = \dot{E}_{xe} + \dot{E}_{xd} + \dot{E}_{xl} \quad (7)$$

where \dot{E}_{xd} represents the exergy destruction, while \dot{E}_{xl} represents the waste exergy. The system inefficiencies and exergetic efficiencies for all combined cycle power plants components can be measured from exergy destruction and exergy loss (Table 4) [5,16,23]. The exergetic efficiency is the ratio of extracted product exergy to the fuel exergy supplied to the component or entire system [5].

Table 4. Expression for Exergy Destruction rate and Exergy Efficiency for Different Components at Steady State Conditions [23]

Plant Component	Exergy Destruction Rate	Exergy Efficiency
Air Compressor	$\dot{E}_{xd,AC} = \dot{E}_{xi} - \dot{E}_{xe} + \dot{W}_{AC}$	$\eta_{ex,AC} = \frac{\dot{E}_{xi} - \dot{E}_{xe}}{\dot{W}_{AC}}$
Combustion Chamber	$\dot{E}_{xd,CC} = \dot{E}_{xi} + \dot{E}_{xf} - \dot{E}_{xe}$	$\eta_{ex} = \frac{\dot{E}_{xe}}{\dot{E}_{xi} + \dot{E}_{xf}}$
Gas Turbines	$\dot{E}_{xd,GT} = \dot{E}_{xi} - \dot{E}_{xe} - \dot{W}_{GT}$	$\eta_{ex} = \frac{\dot{W}_{GT}}{\dot{E}_{xi} + \dot{E}_{xe}}$
The Cycle	$\dot{E}_{xd} = \sum_k \dot{E}_{xd,k}$	$\eta_{ex,AC} = \frac{\dot{E}_{xp}}{\dot{E}_{xf}} = 1 - \frac{\dot{E}_{xd} - \dot{E}_{xi}}{\dot{E}_{xf}}$

2.2. Exergoeconomic Analysis

Exergy costing analysis is a tool used to evaluate the cost of inefficiencies or the costs of individual process streams (including intermediate and final products) but also to improve overall system efficiency and lower life cycle costs of a thermodynamic system. A complete exergoeconomic analysis consists of (1) an exergetic analysis, (2) an economic analysis, and (3) an exergoeconomic evaluation [16,27]. Several studies have focused on exergy costing analyses of power plants and other energy systems have been carried out by researchers [8,23]. The techno-economic feasibility of thermal engineering systems is usually investigated using Life Cycle Cost (LCC) analysis over their expected lifetime. In LCC, the effect of inflation and interest rate, maintenance ratio, operating and purchase cost of equipment is used to determine the net cost savings and payback period of initial investment on thermal engineering systems[24]. The exergoeconomic approach combines the concepts of exergy and economics to assess the energy system's cost-effectiveness. The deficiencies of a system can be measured, appraised and, therefore, reduced either during the design or operation stage [5].

2.2.1. Economic Data

The economic data required for the techno-economic study include the cost of electricity per kWh in the selected area, the yearly interest rate for each location, capital cost of acquisition, operation, maintenance cost of the energy scheme as well as its lifetime. For this study, factors such as cost of electricity, yearly interest rate and inflation rate are obtained from the Nigerian Electricity Regulatory Commission (NERC) and National Bureau for Statistics (NBS) respectively. The urban inflation rate increased by 17.59 per cent in August 2021 [31] while the

electricity tariff in Nigeria as issued by NERC to the Electricity Distribution Companies (DisCos) and Electricity Generation Companies (GenCos) is =N= 24.290 (\$0.059) per kWh (household) and =N= 39.838 (\$0.097) per kWh for businesses [32]. Table 5 shows some economic data and assumptions to be used in the course of this study.

Table 5. Economic Data and Assumptions for the Study

Parameter	Unit	Value
Annual operation hours (τ_a)	hr/year	8656
Plant life time (n)	year	15
Fuel Price (FP)	\$/GJ	0.001
Lower heating value (LHV)	kJ/kg	20.3
Charge factor		0.112
Base capacity factor		70%

2.2.2. Power Plant Costs

Costs are essential and key parameters in power plants. Some of the commonly used metrics [19] are the plant's capital cost (\$), operational and maintenance (O&M) cost (\$/year) and the cost of electricity (\$/MWh). O&M costs can be divided further, into fixed O&M (FOM), variable O&M (VOM) and fuel cost (FC). This study adopts a hybrid model based and developed from various researches [19,33,34,35].

(a) The total investment cost:

$$C = C_G + C_{PM} + C_{CW} + C_A + C_F + C_R \quad (8)$$

(b) Annual Amount of Electricity (E_t) sent out by the power plant in kWh net:

$$E_t = P_{rated} \times 8760CF \left(1 - \frac{P_{aux}}{100} \right) (1 - MLF) \quad (9)$$

(c) Operating and maintenance cost (O&M):

$$M = K_G C_G + K_{PM} C_{PM} + K_{CW} C_{CW} + K_A C_A + K_F C_F + K_R C_R + (8760 \times CF \times M p_n W_r) \quad (10)$$

(d) Annual revenue (AR) from the sale of electricity:

$$AR = \frac{C}{n} \left[\left\{ 1 + m \left(\frac{(1+I)^n - 1}{I(1+I)^n} \right) \right\} \right] \quad (11)$$

(e) Cost of Fuel (FC):

$$C_F = 8760 \times CF \times P_{rated} \times C_B \times SFCR \quad (12)$$

(f) Cost of one kWh of Biomass Gasification electricity generated:

$$C_{pkW} = \frac{C}{Nn} \left[\left(\frac{1}{P_R C_F} \right) \left\{ 1 + m \left(\frac{(1+I)^n - 1}{I(1+I)^n} \right) \right\} \right] \quad (13)$$

(g) Benefit delivered annually by the Gasification plant:

$$B_A = E_t C_{pkW} \quad (14)$$

(h) The payback period (PBP) of the gasification project:

$$PBP = - \frac{\ln \left(1 - \frac{IC}{B_A - mC} \right)}{\ln(1+I)} \quad (15)$$

(i) The net present value (NPV) of the gasification project:

$$NPV = B_A \left[\frac{(1+I)^n - 1}{I(1+I)^n} \right] - \left[C \left\{ 1 + m \left(\frac{(1+I)^n - 1}{I(1+I)^n} \right) \right\} \right] \quad (16)$$

(j) The benefit cost ratio (BCR):

$$BCR = \frac{B_A}{C} \left[\frac{\left(\frac{(1+I)^n - 1}{I(1+I)^n} \right)}{1 + m \left(\frac{(1+I)^n - 1}{I(1+I)^n} \right)} \right] \quad (17)$$

(k) The Internal Rate of Return (IRR):

$$B_A \left[\frac{(1+IRR)^n - 1}{IRR(1+IRR)^n} \right] = \left[C \left\{ 1 + m \left(\frac{(1+IRR)^n - 1}{IRR(1+IRR)^n} \right) \right\} \right] \quad (18)$$

(l) The cost of electricity (COE) or levelized COE (LCOE) is the cost of generating a unit of electricity as shown in Equation (19):

$$LCOE = \frac{\sum_{t=1}^N \left[(I_t + (1-T)(C_F + M)) / (1+d)^N \right]}{\sum_{t=1}^N \left[E_t \left[(1+d)^n - 1 \right] / d(1+d)^n \right]} \quad (19)$$

where:

$$d = \frac{W \times R_e}{V} + \frac{X \times R_d}{V} (1-T) \quad (20)$$

As the produced syngas contains CH₄, O₂, H₂, N₂, CO and CO₂, some of these gases or components need to be avoided, captured and taken care of, in order to enhance the economic feasibility of the gasification project. Both the CO₂ captured and avoided can be mathematically expressed as [19]:

$$\begin{aligned} & \text{Cost of CO}_2\text{captured} \left(\frac{\$}{\text{tonne}} \right) \\ &= \frac{LCOE_{CCS} \left(\frac{\$}{\text{MWh}} \right) - LCOE_{ref} \left(\frac{\$}{\text{MWh}} \right)}{\left(\frac{tCO_2}{\text{MWh}} \right)_{\text{captured}}} \quad (21) \end{aligned}$$

$$\begin{aligned} & \text{Cost of CO}_2\text{avoided} \left(\frac{\$}{\text{tonne}} \right) \\ &= \frac{LCOE_{CCS} \left(\frac{\$}{\text{MWh}} \right) - LCOE_{ref} \left(\frac{\$}{\text{MWh}} \right)}{\left(\frac{tCO_2}{\text{MWh}} \right)_{ref} - \left(\frac{tCO_2}{\text{MWh}} \right)_{CCS}} \quad (22) \end{aligned}$$

3. Results and Discussion

From the steam tables [36], the standard specific enthalpy (h_0) and standard specific entropy (s_0) can be calculated. In the study area however, the ambient temperature was found to be 37°C, during the period of study; which corresponds to 310 K. This temperature lies between 300 K and 400 K, and not available in the steam tables. Thus, using the linear interpolation technique, the corresponding values of h_0 and s_0 can be calculated (Table 6).

In order to calculate the molar fraction (x) of each component of the syngas, the typical standard composition of the syngas is used as shown in Table 7 [37].

Thus, the molar fractions for the various feedstock loads are calculated using thermodynamic relations [38] as shown in Table 8.

Using the various molar fractions from Table 9, the expression for exergy loss due to gas mixing (Eq. 5), the value of the exergy loss due to gas mixing can be calculated when the mass of the feedstock is 1 kilogram, 1.5 kilograms and 2 kilograms.

Due to the cumbersome nature of the calculations, the total exergies could not be carried out analytically. Therefore, Microsoft Excel was used to compute the values of the total exergies. Table 10 - Table 24 show extracts of the Microsoft Excel computations results for the total exergies of the various gases. The results obtained were used to generate comparative graphs with respect to feedstock loading as shown in Figure 2, Figure 3, Figure 4, Figure 5 and Figure 6.

For the initial load of 1 kg mass of Rice husk feedstock, Table 10 - Table 14 show an extract of some total exergies.

Table 6. Calculated Standard Specific Enthalpy and Standard Specific Entropy at 37°C (310K)

Temperature (K)	Chemical Component									
	H ₂		CO		CO ₂		N ₂		CH ₄	
	h ₀	s ₀	h ₀	s ₀	h ₀	s ₀	h ₀	s ₀	h ₀	s ₀
310	344.4	131.59	346.1	198.56	461.1	215.05	345.7	192.52	446.5	187.46

Table 7. Syngas Composition of Rice Husk [18]

Gasifier Feedstock	Gasifying Agent	% mole					
		H ₂	CO	CO ₂	H ₂ O	CH ₄	N ₂
Rice Husk	Air	22.9	18.4	13.0	8.3	0.8	36.6
	Oxygen	36.5	21.8	20.2	19.9	0.6	0.4

Table 8. Molar Fraction of Gas Components for Various Feedstock Loads

Gasifier Feedstock Load (kg)	Molar Fraction of Gases Components				
	H ₂	N ₂	CO	CO ₂	CH ₄
1	0.229	0.366	0.184	0.13	0.008
1.5	0.152	0.244	0.122	0.086	0.005
2	0.1145	0.183	0.092	0.065	0.004

Table 9. Exergy Loss Due to Mixing at Various Feedstock Loads

Gasifier Feedstock Load (kg)	Exergy Loss due to Gas Mixing				
	H ₂	N ₂	CO	CO ₂	CH ₄
1	-3,799.08	-2,590.54	-4,362.97	-5,258.34	-12,444.20
1.5	-4,855.38	-3,635.56	-5,422.03	-6,323.26	-13,655.56
2	-5,585.56	-4,377.01	-6,149.44	-7,044.81	-14,230.68

Table 10. Total Exergies for Hydrogen at 1kg load

S/No.	h(H ₂)	T	s(H ₂)	Ho	So	To	Exp _h	Ex _{mixing}	Ex _{ch}	Ext _{total}
39	11457.68	690	149.5676	344.4	131.59	310	5540.209	-3799.08	236100	237841.1
40	11752.1	700	149.9111	344.4	131.59	310	5728.168	-3799.08	236100	238029.1
41	12046.67	710	150.2487	344.4	131.59	310	5918.075	-3799.08	236100	238219
42	12341.41	720	150.5807	344.4	131.59	310	6109.886	-3799.08	236100	238410.8
65	19180.19	950	156.975	344.4	131.59	310	10966.46	-3799.08	236100	243267.4
66	19480.77	960	157.2095	344.4	131.59	310	11194.33	-3799.08	236100	243495.3

Table 11. Total Exergies for Nitrogen at 1kg load

S/No	T	To	Ho	So	h(N ₂)	s(N ₂)	Exp _h	Ex _{mixing}	Ex _{ch}	Ext _{total}
39	690	310	345.7	192.52	11629.11	216.3178	3906.085	-2590.54	720	2035.545
40	700	310	345.7	192.52	11936.35	216.7602	4076.2	-2590.54	720	2205.66
41	710	310	345.7	192.52	12244.24	217.1972	4248.616	-2590.54	720	2378.076
42	720	310	345.7	192.52	12552.76	217.6289	4423.287	-2590.54	720	2552.747
65	950	310	345.7	192.52	19825.51	226.3917	8979.588	-2590.54	720	7109.048
66	960	310	345.7	192.52	20149.24	226.731	9198.136	-2590.54	720	7327.596

Table 12. Total Exergies for Carbon Monoxide at 1kg load

S/No	T	To	Ho	So	h(CO)	s(CO)	Exp _h	Ex _{mixing}	Ex _{ch}	Ext _{total}
39	690	310	346.1	198.56	-98818.6	222.4817	-106580	-4362.97	275100	164156.6
40	700	310	346.1	198.56	-98507.2	222.9298	-106408	-4362.97	275100	164329.1
41	710	310	346.1	198.56	-98195.1	223.3725	-106233	-4362.97	275100	164504
42	720	310	346.1	198.56	-97882.2	223.8101	-106056	-4362.97	275100	164681.2
65	950	310	346.1	198.56	-90496.5	232.702	-101427	-4362.97	275100	169310.4
66	960	310	346.1	198.56	-90167.6	233.0464	-101204	-4362.97	275100	169532.6

Table 13. Total Exergies for Carbon Dioxide at 1kg load

S/No	T	To	Ho	So	h(CO ₂)	s(CO ₂)	Exph	Exmixing	Exch	Exttotal
39	690	310	461.1	215.05	476905.3	250.0166	465604.6	-5258.34	19870	480216.2
40	700	310	461.1	215.05	477400.1	250.7286	465878.7	-5258.34	19870	480490.3
41	710	310	461.1	215.05	477897	251.4333	466157	-5258.34	19870	480768.7
42	720	310	461.1	215.05	478395.8	252.1309	466439.6	-5258.34	19870	481051.2
65	950	310	461.1	215.05	490342	266.5059	473929.6	-5258.34	19870	488541.3
66	960	310	461.1	215.05	490879.2	267.0684	474292.4	-5258.34	19870	488904.1

Table 14. Total Exergies for Methane at 1kg load

S/No	T	To	Ho	So	h(CH ₄)	s(CH ₄)	Exph	Exmixing	Exch	Exttotal
39	690	310	446.5	187.46	-56815.7	-469.365	146353.5	-12444.2	831650	965559.3
40	700	310	446.5	187.46	-56240.3	-463.57	145132.7	-12444.2	831650	964338.5
41	710	310	446.5	187.46	-55659.4	-457.885	143951.1	-12444.2	831650	963156.9
42	720	310	446.5	187.46	-55073.2	-452.306	142807.6	-12444.2	831650	962013.4
65	950	310	446.5	187.46	-40230.8	-346.703	124913.2	-12444.2	831650	944119
66	960	310	446.5	187.46	-39531.3	-342.887	124429.8	-12444.2	831650	943635.6

For the load of 1.5 kg mass of Rice husk feedstock, [Table 15 - Table 19](#) show extract of some total exergies.

Table 15. Total Exergies for Hydrogen at 1.5 kg load

S/No.	h(H ₂)	T	s(H ₂)	Ho	So	To	Exph	Ex mixing	Exch	Exttotal
39	11457.68	690	149.5676	344.4	131.59	310	8310.314	-4855.38	236100	239554.9
40	11752.1	700	149.9111	344.4	131.59	310	8592.251	-4855.38	236100	239836.9
41	12046.67	710	150.2487	344.4	131.59	310	8877.113	-4855.38	236100	240121.7
42	12341.41	720	150.5807	344.4	131.59	310	9164.829	-4855.38	236100	240409.4
65	19180.19	950	156.975	344.4	131.59	310	16449.68	-4855.38	236100	247694.3
66	19480.77	960	157.2095	344.4	131.59	310	16791.5	-4855.38	236100	248036.1

Table 16. Total Exergies for Nitrogen at 1.5 kg load

S/No	T	To	Ho	So	h(N ₂)	s(N ₂)	Exph	Exmixing	Exch	Exttotal
39	690	310	345.7	192.52	11629.11	216.3178	5859.128	-3635.56	720	2943.568
40	700	310	345.7	192.52	11936.35	216.7602	6114.3	-3635.56	720	3198.74
41	710	310	345.7	192.52	12244.24	217.1972	6372.924	-3635.56	720	3457.364
42	720	310	345.7	192.52	12552.76	217.6289	6634.931	-3635.56	720	3719.371
65	950	310	345.7	192.52	19825.51	226.3917	13469.38	-3635.56	720	10553.82
66	960	310	345.7	192.52	20149.24	226.731	13797.2	-3635.56	720	10881.64

Table 17. Total Exergies for Carbon Monoxide at 1.5 kg load

S/No	T	To	Ho	So	h(CO)	s(CO)	Exph	Exmixing	Exch	Exttotal
39	690	310	346.1	198.56	-98818.6	222.4817	-159871	-5422.03	275100	109807.3
40	700	310	346.1	198.56	-98507.2	222.9298	-159612	-5422.03	275100	110066.1
41	710	310	346.1	198.56	-98195.1	223.3725	-159350	-5422.03	275100	110328.4
42	720	310	346.1	198.56	-97882.2	223.8101	-159084	-5422.03	275100	110594.2
65	950	310	346.1	198.56	-90496.5	232.702	-152140	-5422.03	275100	117538.1
66	960	310	346.1	198.56	-90167.6	233.0464	-151807	-5422.03	275100	117871.3

Table 18. Total Exergies for Carbon Dioxide at 1.5 kg load

S/No	T	To	Ho	So	h(CO ₂)	s(CO ₂)	Exph	Exmixing	Exch	Exttotal
39	690	310	461.1	215.05	476905.3	250.0166	698406.9	-6323.26	19870	711953.6
40	700	310	461.1	215.05	477400.1	250.7286	698818	-6323.26	19870	712364.8
41	710	310	461.1	215.05	477897	251.4333	699235.6	-6323.26	19870	712782.3
42	720	310	461.1	215.05	478395.8	252.1309	699659.4	-6323.26	19870	713206.1
65	950	310	461.1	215.05	490342	266.5059	710894.5	-6323.26	19870	724441.2
66	960	310	461.1	215.05	490879.2	267.0684	711438.7	-6323.26	19870	724985.4

Table 19. Total Exergies for Methane at 1.5 kg load

S/No	T	To	Ho	So	h(CH ₄)	s(CH ₄)	Exph	Exmixing	Exch	Extotal
39	690	310	446.5	187.46	-56815.7	-469.365	219530.3	-13655.6	831650	1037525
40	700	310	446.5	187.46	-56240.3	-463.57	217699	-13655.6	831650	1035693
41	710	310	446.5	187.46	-55659.4	-457.885	215926.6	-13655.6	831650	1033921
42	720	310	446.5	187.46	-55073.2	-452.306	214211.4	-13655.6	831650	1032206
65	950	310	446.5	187.46	-40230.8	-346.703	187369.7	-13655.6	831650	1005364
66	960	310	446.5	187.46	-39531.3	-342.887	186644.7	-13655.6	831650	1004639

For the 2 kg mass of Rice husk feedstock, Table 20 - Table 24 show extracts of some total exergies.

Table 20. Total Exergies for Hydrogen at 2 kg load

S/No.	h(H ₂)	T	s(H ₂)	Ho	So	To	Exph	Ex mixing	Exch	Extotal
39	11457.68	690	149.5676	344.4	131.59	310	11080.42	-5585.56	236100	241594.9
40	11752.1	700	149.9111	344.4	131.59	310	11456.34	-5585.56	236100	241970.8
41	12046.67	710	150.2487	344.4	131.59	310	11836.15	-5585.56	236100	242350.6
42	12341.41	720	150.5807	344.4	131.59	310	12219.77	-5585.56	236100	242734.2
65	19180.19	950	156.975	344.4	131.59	310	21932.91	-5585.56	236100	252447.4
66	19480.77	960	157.2095	344.4	131.59	310	22388.66	-5585.56	236100	252903.1

Table 21. Total Exergies for Nitrogen at 2 kg load

S/No	T	To	Ho	So	h(N ₂)	s(N ₂)	Exph	Exmixing	Exch	Extotal
39	690	310	345.7	192.52	11629.11	216.3178	7812.17	-4377	720	4155.17
40	700	310	345.7	192.52	11936.35	216.7602	8152.4	-4377	720	4495.4
41	710	310	345.7	192.52	12244.24	217.1972	8497.231	-4377	720	4840.231
42	720	310	345.7	192.52	12552.76	217.6289	8846.575	-4377	720	5189.575
65	950	310	345.7	192.52	19825.51	226.3917	17959.18	-4377	720	14302.18
66	960	310	345.7	192.52	20149.24	226.731	18396.27	-4377	720	14739.27

Table 22. Total Exergies for Carbon Monoxide at 2 kg load

S/No	T	To	Ho	So	h(CO)	s(CO)	Exph	Exmixing	Exch	Extotal
39	690	310	346.1	198.56	-98818.6	222.4817	-213161	-6149.44	275100	55789.73
40	700	310	346.1	198.56	-98507.2	222.9298	-212816	-6149.44	275100	56134.73
41	710	310	346.1	198.56	-98195.1	223.3725	-212466	-6149.44	275100	56484.48
42	720	310	346.1	198.56	-97882.2	223.8101	-212112	-6149.44	275100	56838.89
65	950	310	346.1	198.56	-90496.5	232.702	-202853	-6149.44	275100	66097.35
66	960	310	346.1	198.56	-90167.6	233.0464	-202409	-6149.44	275100	66541.6

Table 23. Total Exergies for Carbon Dioxide at 2kg load

S/No	T	To	Ho	So	h(CO ₂)	s(CO ₂)	Exph	Exmixing	Exch	Extotal
39	690	310	461.1	215.05	476905.3	250.0166	931209.2	-7044.81	19870	944034.4
40	700	310	461.1	215.05	477400.1	250.7286	931757.4	-7044.81	19870	944582.5
41	710	310	461.1	215.05	477897	251.4333	932314.1	-7044.81	19870	945139.3
42	720	310	461.1	215.05	478395.8	252.1309	932879.2	-7044.81	19870	945704.3
65	950	310	461.1	215.05	490342	266.5059	947859.3	-7044.81	19870	960684.5
66	960	310	461.1	215.05	490879.2	267.0684	948584.9	-7044.81	19870	961410.1

Table 24. Total Exergies for Methane at 2 kg load

S/No	T	To	Ho	So	h(CH ₄)	s(CH ₄)	Exph	Exmixing	Exch	Extotal
39	690	310	446.5	187.46	-56815.7	-469.365	292707	-14230.7	831650	1110126
40	700	310	446.5	187.46	-56240.3	-463.57	290265.3	-14230.7	831650	1107685
41	710	310	446.5	187.46	-55659.4	-457.885	287902.2	-14230.7	831650	1105321
42	720	310	446.5	187.46	-55073.2	-452.306	285615.3	-14230.7	831650	1103035
65	950	310	446.5	187.46	-40230.8	-346.703	249826.3	-14230.7	831650	1067246
66	960	310	446.5	187.46	-39531.3	-342.887	248859.6	-14230.7	831650	1066279

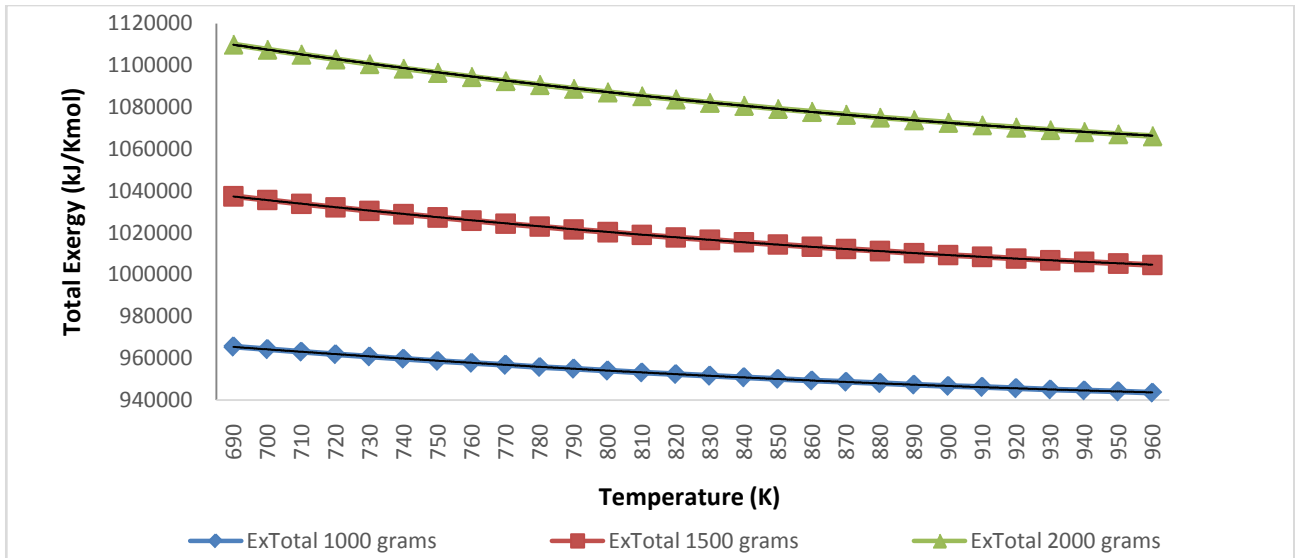


Figure 2. Comparative Graphs of Total Exergies of Methane at Various Load Capacity

Exergy analysis as an important tool to identify and control energy loss during a thermodynamic process, helps determine major contributors to exergy destruction and their readjustment in the process to improve the overall thermodynamic efficiency. For Methane (CH_4), the total exergy increases with an increase in the mass of feedstock as shown in Figure 2. However, the situation is being reversed with temperature, where a decrease is noticed with increasing temperature; where values of exergies vary between 1110126 kJ and 1066279 kJ for 2kg; 1037525 kJ and 1004639 kJ for 1.5 kg and finally, 965559.3kJ and 943635.6kJ for a feedstock mass of 1 kg between 690 K and 960 K respectively.

For Nitrogen (N_2), as the mass of feedstock increases, so does the total exergy of the process. Furthermore, the total exergy increases with increasing temperature with values of total exergies ranging from 2035.545kJ to 7327.596kJ for a feedstock mass of 1 kg between the temperatures of 690 K and 960K and values ranging between 2943.568 and 10881.64kJ; 4155.17 and 14739.27

kJ for feedstock of 1.5 kg and 2 kg respectively as shown in Figure 3.

In the case of Carbon Monoxide (CO), the total exergy of the process decreases as the mass of feedstock increases as shown in Figure 4; but increases with temperature even though it is almost horizontal if not for the values recorded. Between the temperatures of 690k and 960 K, the total exergies vary between 55789.73 kJ and 66541.6 kJ for a feedstock mass of 2 kg; 109807.3 kJ and 117871.3 kJ for a feedstock mass of 1.5 kg and finally; for an initial feedstock mass of 1 kg, the total exergy values range from 164156.6 kJ to 169532.6 kJ between 690 K and 960 K.

For Carbon Dioxide (CO_2), the total exergy of the process increases as the mass of feedstock increases, even though it is almost unnoticeable as shown in Figure 5. So does the total exergy increase with increase in temperature which explains the value of R^2 as unity (1). Between the temperatures of 690k and 960 K, the total exergies vary between 480216.2 kJ and 488904.1kJ; 711953.6kJ and 724985.4 kJ; 944034.4kJ and 961410.1kJ for 1kg, 1.5 kg and 2 kg of feedstock respectively.

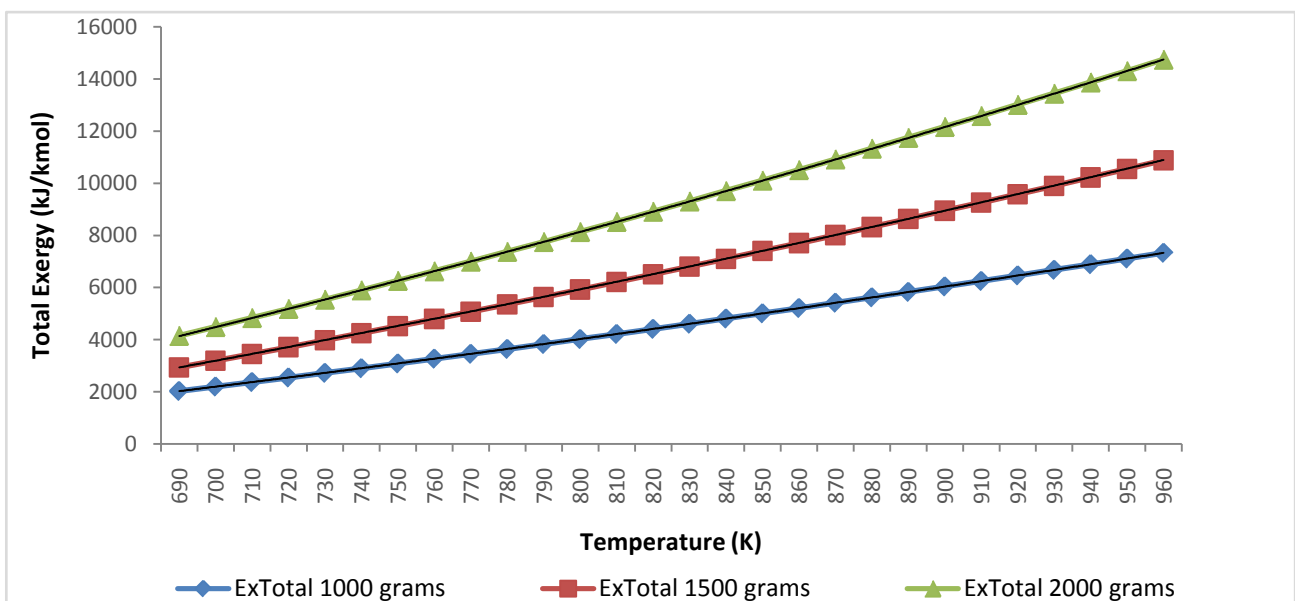


Figure 3. Comparative Graphs of Total Exergies of Nitrogen at Various Load Capacity

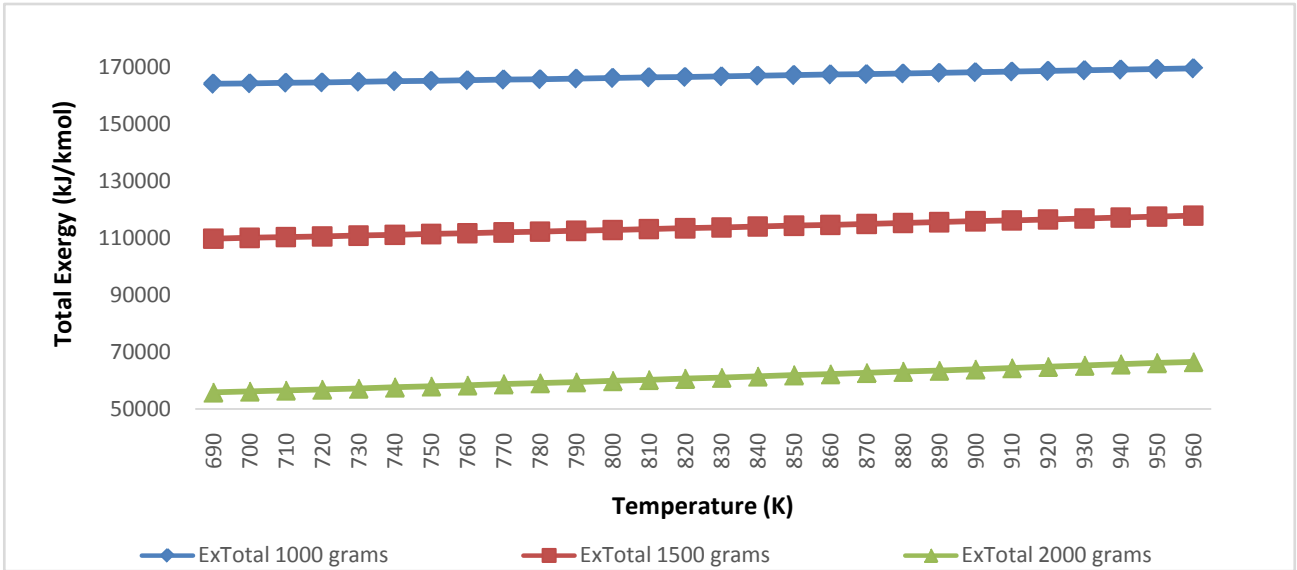


Figure 4. Comparative Graphs of Total Exergies of Carbon Monoxide (CO) at Various Masses

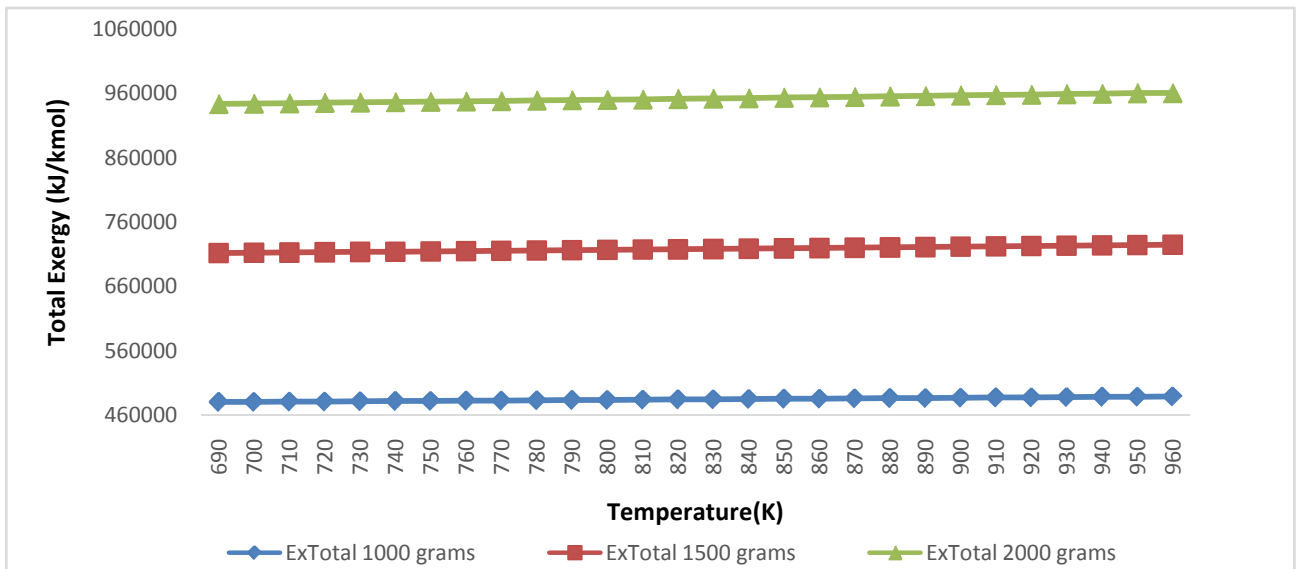


Figure 5. Comparative Graphs of Total Exergies of Carbon Dioxide (CO₂) at Various Masses

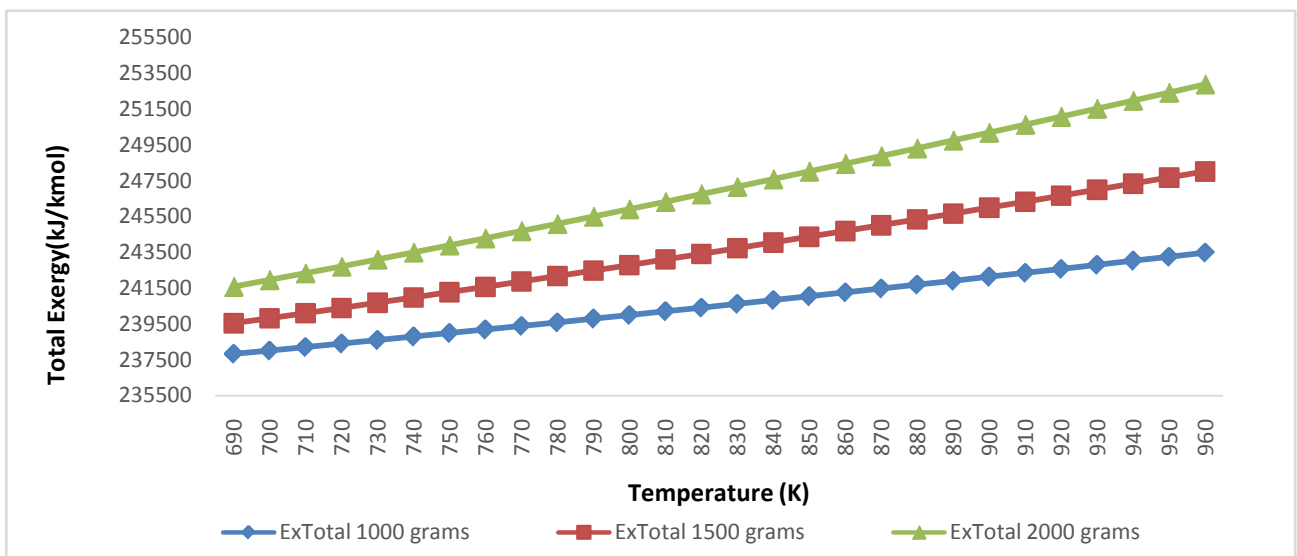


Figure 6. Comparative Graphs of Total Exergies of Hydrogen (H₂) at Various Load Capacity

Just as in the case of nitrogen, for Hydrogen (H₂) too, as the mass of feedstock increases, so does the total exergy of the process. The total exergy increases sharply with increasing temperature as shown in Figure 6 with values of total exergies ranging from 237841.1kJ to 243495.3kJ for a feedstock mass of 1 kg between the temperatures of 690 K and 960 K and values ranging between 239554.9kJ and 248036.1 kJ; 241594.9 kJ and 252903.1 kJ for feedstock of 1.5 kg and 2 kg respectively. These findings are in line with Yueshi *et al.*, [10], who found out that higher preheating temperatures increase the chemical energy of the produced syngas and the two efficiencies.

3.2. Exergoeconomic Analysis Results

Sustainable development not only requires sustainable supply of clean and inexpensive energy source but also efficient use of them. Exergy-based sustainability evaluation is useful to improve efficiency. Table 25 shows a summary of statistical fits for the total exergies per gas and mass of feedstock. From the overall results obtained, the gasification efficiency can be improved by increasing the temperature with an addition of heat in the process. The R² values of 0.999 to 1 show the true behavior and similarities of the graphs and highlighting the enormous exergy destruction rate in the process. This result strongly compliments those from Mehrpooya *et al.*, [1].

Table 25. Summary of Statistical Fits for the Exergy Analysis per Gas and Mass of Feedstock

S/No.	Gases	Mass of Feedstock (grams)	Mathematical Equation	R ²
1	H ₂	1000	$E_x^{Total} = 0.759T^2 + 187.7T + 23764$	1
2		1500	$E_x^{Total} = 1.138T^2 + 281.5T + 23926$	1
3		2000	$E_x^{Total} = 1.518T^2 + 375.3T + 24120$	1
4	N ₂	1000	$E_x^{Total} = 0.139T^2 - 310.9T + 1E + 06$	0.999
5		1500	$E_x^{Total} = 1.387T^2 + 254.2T + 2680$	1
6		2000	$E_x^{Total} = 1.849T^2 + 339T + 3804$	1
7	CO	1000	$E_x^{Total} = 0.947T^2 + 171.9T + 16397$	1
8		1500	$E_x^{Total} = 1.421T^2 + 257.9T + 10954$	1
9		2000	$E_x^{Total} = 1.895T^2 + 343.9T + 55434$	1
10	CO ₂	1000	$E_x^{Total} = 1.694T^2 + 273.2T + 47993$	1
11		1500	$E_x^{Total} = 2.542T^2 + 409.9T + 71152$	1
12		2000	$E_x^{Total} = 2.901T^2 + 557.8T + 94342$	0.999
13	CH ₄	1000	$E_x^{Total} = 13.97T^2 - 1209T + 96664$	0.999
14		1500	$E_x^{Total} = 20.95T^2 - 1813T + 1E + 06$	0.999
15		2000	$E_x^{Total} = 27.94T^2 - 2418T + 1E + 06$	0.999

While some components of the syngas contribute towards the energy and heat produced, others need to be avoided, captured and taken care of, in order to enhance the economic feasibility of the gasification project, as earlier mentioned. These are CO₂, CO and N₂, notably as NO_x, bearing in mind their negative impact on the environment as well as the plant performance. Thus, the adoption of a hybrid model, combining the work of Gbeminiyi [35] with the presence of equations expressing parameters: C_A (additional costs (labour, repair and maintenance, building services, stores, insurance, and taxes costs)) and K_R (fraction of the capital cost of biomass gasification power plant used for the operation and maintenance of accessories and miscellaneous) on one hand. These would not be effective as gases produced are not fully captured. On the other hand, the model presented by Hari [19] mathematically suggested CO₂ capture and avoidance. This capture or avoidance would assess their true influence and /or destruction level in the thermodynamic process, as well as contribute towards the financial viability of the gasification plant.

The cost of emissions for CO₂, CO and NO_x used in this work were adopted from [19] as: 0.024\$/kg, 0.02086 \$/kg and 6.853 \$/kg respectively.

With an increasing awareness of the environmental impacts and practical limitations associated with the traditional fossil energy carriers, many countries aim to increase the efficiency of the processes using energy,

while shifting to more sustainable energy sources [20]. Exergy –based cost analysis permits a decrease in the production charges of electricity as a significance of an improved exergy presentation of the energy conversion processes.

For the purpose of this study, the exergy results for the 2 kg mass of feedstock were considered. Equations (21) and (22) were adapted and used for evaluation of the economic impact of N₂ and eventually NO_x too. Table 26 shows the preliminary exergoeconomic analysis results for the gasification plant based on the biomass feedstock and total exergies of gases contained within the syngas. The batch type of gasifier is not suitable because of the time losses incurred during the frequent cleaning, loading and off-loading of gasifier biomass leftover.

Table 26. Preliminary Exergoeconomic Analysis Results

Parameter	Value
Investment cost (\$/kW)	\$690.01/kW
Electricity tariff	\$ 0.059/kWh
Fuel Cost	\$ 0.001/GJ
Payback period	1.5 years
Predicted CO ₂ contribution to COE	0.156 \$/kg
Predicted CO contribution to COE	0.20 \$/kg
Predicted N ₂ contribution to COE	12.335\$/kg
LCOE	\$ 65.1/MWh

4. Conclusions

- i) The overall results obtained on total exergies of H₂, N₂, CO, CO₂ and CH₄, showed that gasification efficiency can be improved by increasing the temperature with an addition of heat in the process.
- ii) Methane was found with the highest total exergies where values of exergies were varying between 1110126 kJ and 1066279 kJ for 2kg; 1037525 kJ and 1004639 kJ for 1.5 kg and finally, 965559.3kJ and 943635.6kJ for a feedstock mass of 1 kg between 690 K and 960 K respectively.
- iii) The CO₂, N₂ and NO_x capture/ avoidance increases the plant efficiency by producing more electricity thereby increasing the financial potential of the plant.
- iv) The total exergies of gases considerably assist in the exergoeconomic analysis of the gasification plant, when the environmental aspect is considered.

Nomenclature

AR: Annual revenue
 B_A: Benefit delivered annually
 BCR: Benefit cost ratio
 C: Total capital investment cost
 C_{pkw}: Cost of kWh of electricity generated from the biomass gasification plant
 C_A: Cost of electricity, accessories, auxiliaries, and miscellaneous
 C_B: Cost of biomass
 C_F: Cost of fuel (biomass)
 C_G: Cost of gasifier or fuel conversion system
 C_{PM}: Cost of prime mover
 C_I: Total capital investment of the project
 C_{CW}: Cost of civil work
 C_R: Additional costs (labour, repair and maintenance, building services, stores, insurance, and taxes costs)
 C_F: Capacity factor
 d: Inflation-adjusted discount rate
 E: Annual electricity production from the plant
 I_C: Total project investment cost
 I: Real rate of return
 IRR: Internal rate of return
 K_G: Fraction of the capital cost of biomass gasification power plant used for the operation and maintenance of gasifier
 K_{PM}: Fraction of the capital cost of biomass gasification power plant used for the operation and maintenance of prime mover (engine)
 K_{CW}: Fraction of the capital cost of biomass gasification power plant used for the operation and maintenance of engineering and construction work
 K_A: Fraction of the capital cost of biomass gasification power plant used for the operation and maintenance of accessories and miscellaneous
 K_A: Fraction of the capital cost of biomass gasification power plant used for the purchase of fuel and fuel handling
 K_R: Fraction of the capital cost of biomass gasification power plant used for the labour, repair and maintenance, building services, stores, insurance, and taxes

LCOE: Levelized Cost of Electricity
 M_{Ecp}: Biomass mass conversion potential, kg/kWh
 MLF: Marginal loss factor
 MP_n: Number of manpower required
 m: Percentage of initial investment for annual operating and maintenance costs
 N: Annual hour of the plant
 n: Life in years of plant
 NPV: Net present value
 PBP: Payback period of investment
 P_R: Plant installed capacity
 P_{aux}: Percentage power consumption by the auxiliaries
 P_{rated}: Power rated or installed output
 R_e: Nominal cost of debt
 R_d: Nominal cost one equity
 SFCR: Specific fuel consumption rate
 T: Company tax rate
 V: Total market value, %
 W: Market value on equity, %
 W_r: Wage rate for manpower in Nigeria
 X: Market value on debt, %.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of the present paper.

Plagiarism

All works and references consulted have been duly acknowledged. Any omission might have resulted from errors. The authors wish to express their apologies should such a case arise.

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