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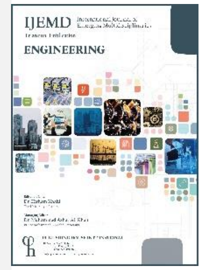

A Method to Compare Renewable Fuels

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Abstract

Biofuel is a renewable energy source and has been proven to be a suitable and useful alternative to traditional fossil fuels. Different processes can produce different types of biofuel. Furthermore, different comparison strategies have been implemented for the various criteria. The current article compares two different processes for producing bio-SNG and investigates the comparison criteria to find a method for comparing the biofuel processes. The processes used in the comparison are gasification and anaerobic digestion. Rice straw is used as a feedstock in each process, to evaluate the applied processes, and to compare the performance of those processes applied on the same feedstock. The Aspen-plus software is used to simulate the processes and the input data were obtained from the literature. Two cases are studied and for each case, energy and exergy balances are calculated to evaluate the processes. The energy efficiency is then calculated based on the Lower heat value (LHV) and the Higher heat value (HHV). The results show that the energy efficiency based on HHV and exergy efficiency are approved methods to evaluate the process when the processes produce bio-methane.

Keywords: Anaerobic digestion; Comparison method; Gasification; Renewable fuels

1. Introduction

Biofuel, a renewable energy source, has been proven to be a suitable alternative to traditional fossil fuels, different processes can produce different types of biofuel. Several studies have been dedicated to studying and comparing different types of fuel. Different comparisons have been done with different criteria.

Emission comparative analysis from the raw materials to the final use was studied in reference [1], form the studied case the authors found that the use of biodiesel fuel reduces emissions by 75%-83% if compared to the petro-diesel fuel. Life Cycle Assessment (LCA) methodology was used to study the environmental performance of bio-methane, which can be used as a fuel for busses, and to compare this fuel with natural gas, electricity, biodiesel, and fossil diesel. The authors obtained that bio-methane has a relatively low contribution to environmental impact categories [2]. On the other hand, LCA was used to compare two

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types of feedstock, palm oil, and rapeseed oil, to produce biodiesel by calculating the energy content of biodiesel and byproduct and the ratio of output energy to the input fossil-based energy (EROI ratio). The results showed that palm oil is more efficient than rapeseed oil and has a higher EROI ratio compared to rapeseed oil [3]. Exergetic life cycle assessment (ELCA) and LCA were used to assess the environmental impact of producing one ton of biodiesel production from used cooking oil (UCO), the life cycle studied four production stages: collection, pre-treatment, delivery, and transesterification, it found that the transesterification stage causes 68% of the total environmental impact [4]. While Vitasari et al [5] used exergy analysis to compare three various biomass feedstock materials (treated wood, municipal solid waste (MSW), and sludge) for producing synthetic natural gas (SNG) from indirect gasification. The results show that the exergy efficiency for the treated wood is the highest followed by sludge and MSW. Camilo et al. [6] compared biogas from anaerobic digestion (AD) and syngas from gasification to generate heat and power using the Colombian oil palm crop as a raw material in both processes. The authors found that biogas can produce more heat and power than syngas. The processes of anaerobic digestion and steam gasification (using the GoBiGas demonstration plant as reference) have been compared by Li et al. [7] from the energy efficiency perspective (based on LHV as daf). The authors obtained that the efficiency in anaerobic digestion is 62-64%, while it is 65% in the GoBiGas gasification. This research compares only the efficiency of the processes without considering the exergy value and CO2 emissions.

Based on the research mentioned above, different types of comparisons have been done with different criteria methods. The comparison of biofuel processes is not covered sufficiently, and it is, therefore, important to study the comparison criteria and investigate what comparison can be used to decide the more efficient process. The current article studies the comparison of two different processes (Gasification) and (Anaerobic digestion) to produce bio-SNG and investigates the comparison criteria to find a method for comparing biofuel processes from a technical perspective. Rice straw is used as a feedstock to investigate the suitable method for the process comparison. The process boundary starts from the feedstock pretreatment and ends by producing the bio-SNG with the same quality requirements to use as vehicle fuel. Modeling was done in a software program called ‘Aspen Plus.

Gasification Process Model

The gasification process simulation has different stages, see Fig.1. Biomass dryer is the first step to reduce the amount of moisture in the feedstock to 10% [8]. An RStoic reactor (DRYER) is used to simulate the dryer reactor. Two feed streams enter the reactor, wet biomass (BIO-WET1), and air (AIR-DR25). To reduce the moisture a heater (HEATER1) is used to heat the air (AIR-DR25) to 130 °C before the dryer [9]. The air and water are then separated from the stream ((BIO-WAT2) by using a separator (SEP1) to produce dry biomass (BIO-DRY). The dried biomass then enters the gasifier reactor.

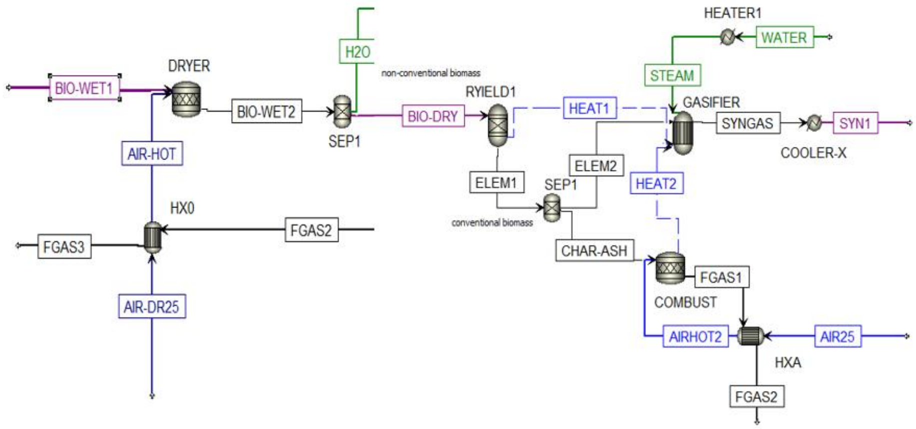

Fig: 1 Biomass dryer section with dual fluidized bed gasification (DFB) reactor simulation.

Dual Fluidized Beds (DFB) gasifier is used in the simulation [10]. The operation condition for the DFB gasification and input data is set up close to the input data from a real demonstration plant in Sweden (GoBigas) [11]. The pressure drop is neglected and the condition is isothermal and steady-state. The gasifier bed temperature is 850 °C and the Combustor temperature is 900 °C. The steam temperature is 550 °C while the steam to biomass ratio (STBR) is 0.5 [11,12]. The syngas (SYNGAS), which is the produced gas from the gasification must be cleaned to remove H2S and other impurities by cooling down before using it in the methanation process to fulfill the natural gas requirement (bio-SNG) [13]. The heat throughout from syngas cooling can be used to generate the most required steam for gasification reactions by using a heat exchanger (HXS).

The cooled and cleaned syngas stream (SYN-1) is pressurized to 30 bar, which is the operating pressure of the methanation reactor, and the temperature inside the methanation reactor is set from 300 °C to 250 °C [14,15]. An RGibbs reactor is used to simulate the methanation reactors, which allow all exothermic reactions to reach equilibrium. After every methanation reactor, the product stream must be cooled to meet the methanation reaction temperature.

Anaerobic Digestion Process Model

The pretreatment of the rice straw is required as the first step in the AD simulation. The steam explosion method is used to open the structure of the woody material (200°C, 15 bar) [16,17]. The untreated feedstock (DRYBIO) and pretreatment steam (STEAM-P) enter the RGibbs reactor (PRE-TR) to pretreat the feedstock.

The feedstock material used in this study has already been tested laboratory in another study and the amount of each component in the product is given [16] therefore, the complexity of the model and simulation can be reduced by reproducing experimental and laboratory data of AD to get the amount of energy from the process. The digester operated at mesophilic conditions of 37°C, and then the digestion reactor and the biogas upgrading were implemented [13]. The pretreated stream (WOODTR2), is mixed with the required water before it is fed to the AD reactor, and the digestion system is wet (10% - 20% solid content) [18], see Fig.2.

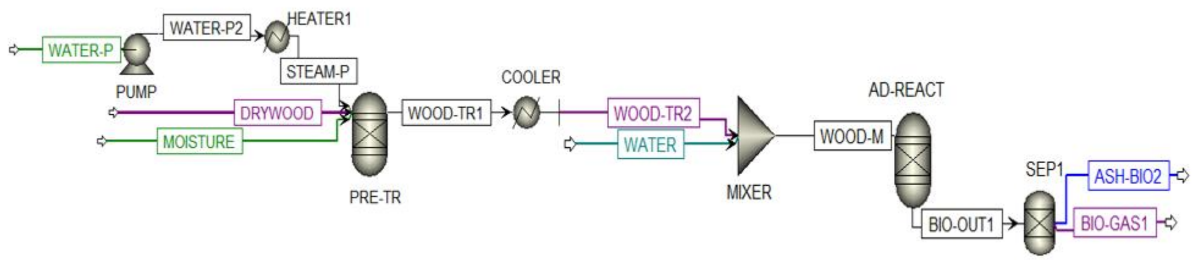

Fig.2: Biomass dryer section with dual fluidized bed gasification (DFB) reactor simulation.

The Anaerobic Digestion Model No. 1 (ADM1) was used to simulate the AD process [19]. An RYield (AD-REACT) is used to simulate the digester reactor by the total outlet parameters with the non-conversion of feedstock adjusted according to the used atom balance. The unconverted feedstock and ash (ASH-BIO2) are separated from the product gas by using the separator (SEP1). The biogas production (BIO-GAS1) has to be upgraded by removing H2S, NH3, and CO2, in addition to drying the bio-SNG by using different stages of separation.

Evaluation Method

The gasification and AD processes, which are applied in this research, are evaluated thermodynamically to characterize the processes. In the evaluation, both energy and exergy analyses are used.

Energy analysis

Based on the first law of thermodynamics. Three efficiencies are considered in the energy analysis, Bio-SNG efficiency, thermal efficiency, and overall efficiency. The three efficiencies are calculated by using lower heating value (calorific value) LHV, and higher heating value (gross calorific value) HHV on different basis.

Bio-SNG efficiency η_{SNG}.

$$\eta_{SNG} = \frac{\dot{m}_P * HV_P}{\dot{m}_{fc} * HV_{fc}} \quad (1)$$

Where $\dot{m}_p$ and $\dot{m}_{fc}$ are the mass flow rate of the product gas (bio-SNG) and feedstock in kg/hr respectively. HV_P and HV_{fc} is the heating value for the product gas (bio-SNG) and feedstock in MJ/kg, which is given as LHV and HHV.

Thermal efficiency η_{th}

$$\eta_{th} = \frac{\dot{m}_P * HV_P}{\dot{m}_{fc} * HV_{fc} + \dot{W}} \quad (2)$$

Where $\dot{W}$ is the total energy input to the system, including for example the compressor work and separation.

The overall system efficiency η_{system}

$$\eta_{system} = \frac{\dot{m}_P * HV_P + \dot{Q}}{\dot{m}_{fc} * HV_{fc} + \dot{W}} \quad (3)$$

Where η_{system} is the overall system efficiency for the plant, $\dot{Q}$ and $\dot{W}$ are the useful energy product (electricity or district heating) and the energy entering the system, respectively.

Exergy analysis

The exergy of a system is based on the second law of thermodynamics. The reference environment is assumed to be in equilibrium with the surroundings through reversible processes, in which the system is allowed to interact only with the environment [20,21].

In this study, the environmental reference state for the temperature and pressure is 25 °C and 1 atm.

$$Ex_{flow,ph} = (H – Ho) – To(S – So) \quad (4)$$

The standard chemical exergy of the components at the reference environment is used to calculate the chemical exergy for the product streams. While for the feedstock, the chemical exergy can be estimated by using Eq.5 adopted from Eboh et al. [22].

$$Ex = 376.461C + 791.018H – 57.819O + 45.473N – 536.242S + 100.981Cl \text{ (kJ/kg)} \quad (5)$$

Where C, H, O, N, S, and Cl are the chemical composition content of the feedstock materials in dry and free ash wt%.

In exergy analysis, the exergy efficiency of the system is used for the process evaluation.

$$E_x = \frac{\text{Exergy output}}{\text{Exergy input}} \quad (6)$$

The system exergy for the process is represented in Eq.7.

$$E_{x,system} = \frac{E_{ch,p} + E_{\dot{Q}}}{E_{ch,fc} + E_{\dot{W}}} \quad (7)$$

Where $E_{ch,p,}$ and $E_{ch,fc}$ are the exergy of the product gas (bio-methane) and feedstock respectively. $E_{\dot{Q}}$ is the physical exergy for DH or electricity, $E_{\dot{W}}$ is the total work exergy and heat input to the system.

Results and Discussion

The results of the studied cases can be explained as follows.

Case 1 (the plants produce only bio-SNG)

The bio-SNG production from the two processes is shown in Table 1. The bio-SNG efficiency η_{BM} for the gasification and AD is calculated according to Eq.1 based on LHV (daf, dry, and ar), and HHV (daf, dry, and ar). The results of bio-SNG efficiency are shown in Table 2.

The thermal efficiency η_{th} for AD and gasification processes is calculated by using Eq.2 in different LHV and HHV. Table 3 shows the thermal efficiency of the two processes for the same feedstock.

Table 1: The bio-SNG mass flow rate from the two processes

Gasification	AD
(rice straw)	(rice straw)
140.5646	64.36369

The results from Tables 2 and 3 show different values of energy efficiency (bio-SNG and thermal efficiency). The resulting energy efficiency, based on LHV (ar), is higher than the energy efficiency, based on LHV (dry, daf) for the same process. That means the amount of heat needed for evaporation is higher than the amount of energy in the product gases. However, the efficiency results based on HHV (dry, daf, and ar), give the same value on different bases for the same feedstock material.

Table 2: The bio-SNG efficiency for the gasification and AD processes, based on LHV and HHV.

Base on	Gasification (rice straw)		AD (rice straw)	
	η_{SNG} % (LHV)	η_{SNG} % (HHV)	η_{SNG} % (LHV)	η_{SNG} % (HHV)
(daf) MJ/kg	59.2978	61.8074	27.1521	28.3012
(dry) MJ/kg	59.3084	61.7962	27.1569	28.2961
(ar) MJ/kg	63.6493	61.7745	29.1446	28.2862

Table 3: The thermal efficiency of the two processes on a different basis.

. Base on	Gasification (rice straw)		AD (rice straw)	
	η_{th} % (LHV)	η_{th} % (HHV)	η_{th} % (LHV)	η_{th} (HHV)
(daf)	51.603	54.2211	25.571	26.7493
(dry)	51.611	54.2125	25.5753	26.7447
(ar)	54.8674	54.1958	27.3307	26.7359

Table 4: The exergy efficiency for the gasification and the AD, case 1.

Gasification (rice straw)	AD (rice straw)
E_x %	E_x%
54.08996	24.01083

The exergy efficiency is calculated by using Eq. 7 for the two processes, Table 4 shows the exergy result for case 1.

The efficiency of gasification is higher than AD. The reason is that there is unconverted solid material from AD and this means that a second stage of digestion could be used to decrease the loss. However, this might need additional treatment to liberate the material.

Case 2 (The plants produce another product + bio-SNG)

The processes can generate additional products such as district heating (DH) and electricity (El), in addition to bio-methane production. The overall system efficiency η_{system} is used to calculate the plant efficiency according to Eq.3. The calculation is done twice; first if the plant produces (DH), and second if the plant generates (EL). Table 5 shows the overall system efficiency for the processes for various bases. The overall system efficiency is calculated based on LHV (daf, dry, and ar) and HHV (daf, dry, and ar).

Table 5: The overall system efficiency for the gasification and the AD case 2.

Base on	Gasification (rice straw)		AD (rice straw)
	η_{system} with DH %	η_{system} with EL %	η_{system} with DH %
LHV(daf) MJ/kg	81.18	56.8418	26.4163
LHV(dry) MJ/kg	81.1927	56.8505	26.4207
LHV(ar) MJ/kg	86.4018	60.4365	28.2342
HHV(daf) MJ/kg	82.2123	59.1757	27.5453
HHV(dry) MJ/kg	82.199	59.1663	27.5406
HHV(ar) MJ/kg	82.1733	59.1481	27.5315

From Table 5, the efficiencies from the two cases are higher based on HHV than LHV because the HHV of the product gas is higher than the LHV and the product energy is more than the input energy. Since the AD process doesn't produce sufficient energy, not enough electricity can be generated.

The exergy efficiency $E_{x,system}$ is calculated for case 2 by using Eq.7. Table 6 shows the exergy efficiency for the gasification and the AD.

Table 6: The exergy efficiency for the two processes in the case of generating DH and EL.

Gasification (rice straw)		AD (rice straw)
$E_{x,system}$ with DH %	$E_{x,system}$ with EL %	$E_{x,system}$ with DH %
52.8472	54.4731	23.8496

The results of exergy efficiency presented in Table 6 show the process that is producing bio-SNG with EL has a higher exergy efficiency as compared to producing DH instead of EL. On the other hand, the results of the energy efficiency presented in Table 5 show the process that is producing bio-SNG with DH has a higher energy efficiency as compared to EL. The production of DH depends on the society's demand, if

there is a demand for DH from the process, the energy efficiency gives high values as compared to exergy analysis.
From case 2, the type and amount of the product depend on the process location and the type of feedstock. In cold countries, the gasification and AD processes could produce district heating in addition to bio-SNG. On the other hand, in hot countries, the gasification process can produce electricity with bio-SNG instead of DH. However, there is no possibility of producing EL from AD. The feedstock materials type affects the product efficiency.
Based on the results mentioned above, in case 1 (only Bio-SNG produced), the exergy analysis is used for comparing the two studied processes with different feedstock materials.

2. Conclusions

To evaluate any process it is important to consider; the feedstock available, the feedstock type, the location of the process, the process efficiency (if the process produces only bio-SNG or another product), as well as the product quantity.
The calculation based on LHV shows differences in efficiency results for the same feedstock material in the two studied cases, based on LHV (ar). The major drawback for energy efficiency, based on LHV, is that when the moisture content increases in the feedstock material.
The efficiency, based on the HHV, is higher than the energy efficiency based on LHV.
The exergy efficiency is the proper way to evaluate the process when producing bio-SNG, while when the process produces DH with bio-SNG the energy efficiency based on HHV is recommended.
The gasification process has the advantage of producing DH and EL with good efficiency. The production type depends on the society's demand and the feedstock type. On the other hand, the amount of DH from the AD process is very small and there is no possibility to generate electricity from the AD process.

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