Life Cycle Assessments of Energy Recovery from the Organic Fraction: Bio-Methane or Bio-Hydrogen, for Vehicle Fuel or for Electricity?

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ABSTRACT

The recovery of clean energy in the form of methane-containing biogas is starting to receive tremendous attention in South Africa. However, it is unclear whether the transition from standard bio-methane production to waste-based bio-hydrogen production would improve or worsen the environmental and energetic performance as quantified by Life Cycle Assessment (LCA). The results of this study show that the use of bio-methane application in combined heat and power systems provide the most significant environmental benefits estimated at 20%, whereas natural gas stands at 36%. In the case of bio-hydrogen application in fuel cell systems for electricity generation, it appears that that bio-hydrogen has the worst performance which stands at 39%. In case of vehicle operations, application of bio-methane commands the worst environmental impact which stands at 49%, when compared to 27% for bio-hydrogen for application in fuel cell vehicles (FCV) and 46% is estimated for natural gas application.

1. INTRODUCTION

Biofuels such as bio-methane and bio-hydrogen could provide an opportunity to diversify energy supply, reduce dependence on fossil fuels and contribute to economic growth in a sustainable manner. According to Melamu 2008, these fuels might carry lower sustainability risks because they can be generated from inexpensive organic waste residues rather than purposely grown plants. The city of Cape Town sends about 1.6 million tons of waste to landfills each year, of which 11% consists of compostable organic waste. This is equivalent to an estimated average of 21kg/household/month of organic waste that ends up in a landfill (Munganga et al. 2010).

In South Africa, it is estimated that there are as few as 150 biogas digesters and 10 at commercial facilities that are currently in operation across the country (Griffiths 2013). These digesters are based on a biological process known as anaerobic digestion (AD), whereby micro-organisms break down biodegradable material in the absence of oxygen to produce biogas. The biogas can either be used with minimal upgrading, e.g. for household lighting or cooking energy needs, or upgraded before in combined heat and power systems. In the light of a growing demand for renewable transportation fuels, a “hydrogen economy” remains an option also in Africa, with bio-hydrogen a possible improved version on 1st generation bio-methane investments. Interestingly, it is possible to modify AD to instead produce bio-hydrogen in a process known as anaerobic dark fermentation (ADF). Dark fermentation is the biological process for hydrogen production from a wide variety of renewable resources. Proponents of bio-hydrogen technology claim that the technical feasibility of this technology for large scale production is not beyond reach (Ngoma et al. 2011 and Obazu et al. 2012).

In recent years, studies have shown that some biofuels might actually contribute more to climate change than gasoline and diesel, since not all biofuels are low-carbon fuels. There has been a growing concern that the production of some biofuels is unsustainable, both environmentally and socially. In some countries these biofuels are starting to penetrate into the energy systems, resulting in a need for standards and regulations to ensure that these biofuels are indeed reducing greenhouse gas (GHG) emissions and promoting a sustainable development (European Commission 2012).

Little is known about the energetic and environmental performance of waste-based biofuels in Africa, with only a few Life Cycle Assessments (LCAs) so far published on African energy systems. Therefore, this study investigates the environment and energy performance of emerging technologies (e.g. bio-hydrogen) in comparison with the traditional treatment options (bio-methane) from well-to-wheel (WTW) analysis. The comparison involves the system-wide energetic efficiencies of utilization of these fuels for electricity generation and fuel vehicles. The specific objectives are to (i) compare the life cycle environmental impacts of bio-hydrogen and bio-methane production and application using Life Cycle Assessment (LCA), (ii) investigate energy efficiency of bio-methane and bio-hydrogen for electricity generation in cogeneration for heat and power and fuel cell (FC) systems, (iii) calculate energy efficiency of bio-methane and bio-hydrogen as a fuel for vehicles in compressed natural gas vehicles (CNGVs) and hydrogen fuel cell vehicles (HFCVs).

2. THE LIFE CYCLE ASSESSMENT (LCA) APPROACH

The LCA methodology was carried out using the LCA software tool, known as Simapro 7.1 software following the ISO 14040 guidelines SimaPro 7.1 Software (PRé Consultants 2006). To date, Life Cycle Assessment (ISO 2006) is the only internationally standardized methodology framework that can be used for environmental assessment of the product, process or service across its entire life cycle, e.g. “from cradle-to-grave.” The LCA assessment approach consists of four steps: i) goal and scope of definition, ii) life cycle inventory (LCI) analysis, iii) life cycle impact assessment (LCIA), and iv) interpretation of the results, as discussed in following sections 2.1, 2.2, 2.3 and 2.4.

2.1. Goal and scope of the study

2.1.1. Goal of the study

The goal of this life cycle assessment (LCA) is to compare the energetic and environmental impacts of application of bio-methane and bio-hydrogen production and the final use in cogeneration unit systems to generate electricity, and also as transportation fuel in vehicles. This fuels are produced from brewery wastewater; bio-methane via anaerobic digestion; and bio-hydrogen via thermophilic dark fermentation process. Furthermore, it should be noted that fossil fuel, for example natural gas was used as a reference case in this study.

2.1.2. Scope of the study

2.1.2.1. System boundary

The system boundaries is presented in the below Figure 1 showing the entire life cycle of production of fuels and their application in electricity generation or as fuels for vehicle. In total six scenario cases were generated in this study: four (4) cases from waste based system, whereby the OFMSW was used as a feedstock for either bio-methane or bio-hydrogen for application in electricity or as vehicle fuels. The other two scenarios were derived from fossil based system whereby natural gas was used as feedstock for hydrogen production and its application in electricity generation or as vehicle fuel.

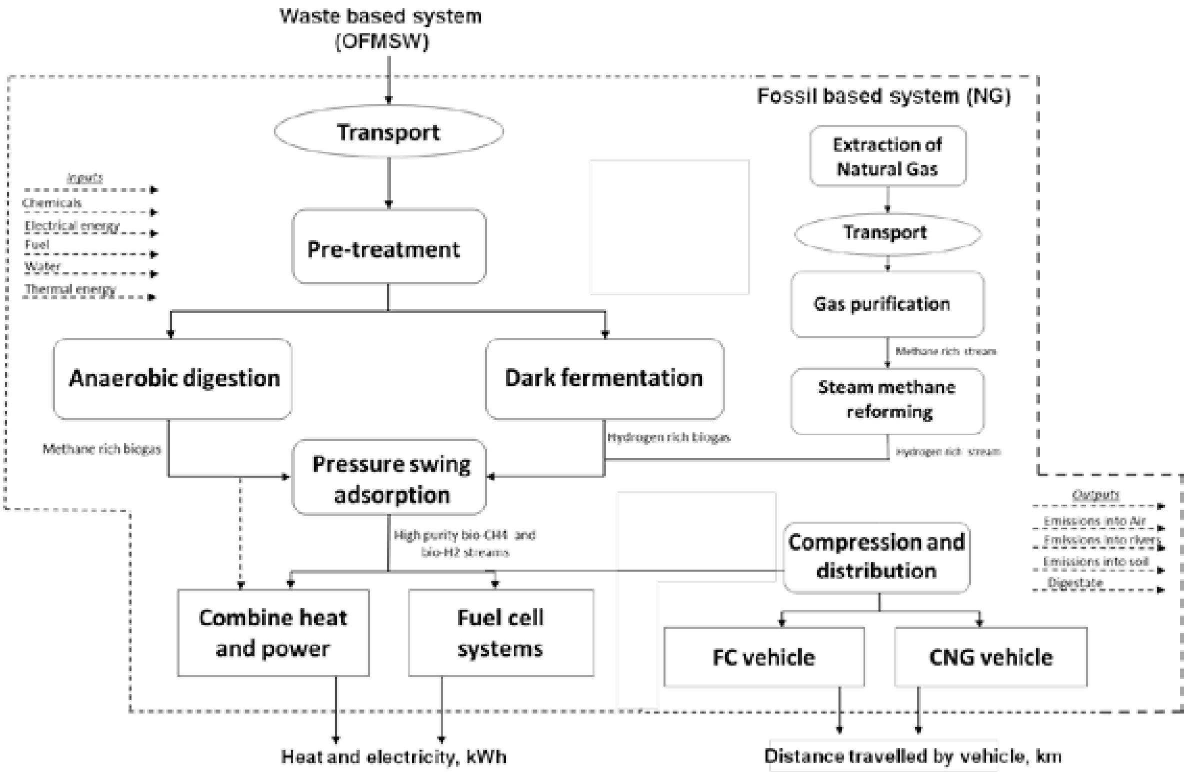

Figure 1: Flow chart showing a system boundary of the processes in LCA for electricity generation and vehicle operation for both the waste based and fossil fuel systems. The dash arrows represent the inputs and outputs from the system, black arrows represent the elementary flow considered in the system boundary.

2.1.2.2. Functional unit

The quantitative input and output data of the unit process are related to the functional unit of 1 kg volatile solid (VS) entering the system, with an exception to the reference case system whereby the systems expansion was taken into account.

2.2. Life cycle inventory (LCI) analysis

The cradle-to-grave analysis was taken into consideration and involved every stage across the production and application of the fuels. The following unit processes were identified across the entire life cycle performance of the fuels, namely: feedstock collection, natural gas extraction, feedstock pretreatment, anaerobic digestion, dark fermentation, steam methane reformation, gas upgrading, compression and distribution, and fuel utilization stage. Each of the identified unitary stage is discussed in details from section 2.3.1 to 2.3.6. The inventory data is shown in Table 1, showing the inputs (consumption of raw material and energy) and outputs (emissions and wastes as well as co-products) across the production and end-use of the fuels considered in this study. The inventory data was compiled based on stoichiometric calculations in relation to the functional unit. The information was gathered from real process data that was obtained from peer reviewed publications from various sources.

Table 1: Life cycle inventory data representing the production of fuels and their application in electricity generation or vehicle operation.

	Electricity Generation			**Vehicle Operation**		
Components	Bio-methane	Bio-hydrogen	Natural gas	Bio-methane	Bio-hydrogen	Natural Gas
Inputs						
Substrate						
Volatile solids (kg)	1.000	1.000		1.000	1.000	
Natural gas (kg)			0.294			0.359
Nutrients:						
Copper sulphate (kg)	0.000259	0.000259		0.000259	0.000259	
Ferrous sulfate (kg)	0.000382	0.000382		0.000382	0.000382	
Dipotassium phosphate (kg)	0.0281	0.0281		0.0281	0.0281	
Natural resources:						
Water (kg)	1.599	1.599	1.485	1.599	1.599	0.181
Diesel (L)	0.0337	0.0337	0.000	0.0438	0.0496	0.0183
Oil (kg)			0.00149			0.000181
pH-adjustments:						
Hydrochloric acid (kg)	0.000	0.0234		0.000	0.0234	
Sodium hydroxide (kg)	0.00570	0.00570		0.00570	0.00570	
	Energy input:					
Electrical energy (MJ)	0.731	0.598	10.141	1.822	1.051	1.760
Output						
Effluent Output:						
Chemical oxygen demand (kg)	0.127	0.888		0.1268	0.888	
Volatile solids (kg)	0.330	0.229		0.330	0.229	
Volatile fatty acids, as acetate (kg)	0.0165	0.0413		0.0165	0.0413	
Phosphate (kg)	0.00146	0.00974		0.00146	0.00974	
Nitrogen (kg)	0.00856	0.0570		0.00856	0.0570	
Ammonia, as NH_3-N (kg)	0.00221	0.0147		0.00221	0.0147	
Sodium hydroxide (kg)	0.000570	0.000570		0.000570	0.000570	
Solid waste (kg)			0.0152			0.00185
Gases:						

	Electricity Generation			Vehicle Operation		
Components	Bio-methane	Bio-hydrogen	Natural gas	Bio-methane	Bio-hydrogen	Natural Gas
Carbon dioxide (kg)	0.683	0.156	0.569	3.076	0.188	0.105
Carbon monoxide (kg)	0.00151	0.000	0.569	0.0424	0.000	0.0105
Benzene (kg)	0.00151	0.000		0.000	0.000	0.0000128
Formaldehyde (kg)	0.0000997	0.000	0.000	0.0000255	0.0773	0.000
Methane (kg)	0.00699	0.000	0.0110	0.01167	0.00333	0.0904
Nitrogen oxides, NO_x as NO_2 (kg)	0.000173	0.00333	0.241	0.0180	0.000	0.0294
Non-methane hydrocarbons (kg)	0.0000660	0.000	0.00197	0.250	0.000000262	0.0000183
Particulate matter, PM_{10} (kg)	0.000	0.000000262	0.000152	0.0000942	0.0000000933	0.000000302
Particulate matter, $PM_{2.5}$ (kg)	0.000	0.0000000933	0.000000880	0.0000942	0.000129	0.0000889
Sulphur oxides, SO_x as SO_2 (kg)	0.0000905	0.000	0.000739	0.00000457	0.000119	0.0300
Hydrogen (kg)	0.000825	0.000119		0.000825	0.000000258	
Hydrogen sulphide (kg)	0.0000000825	0.000000258	0.000	0.0000000825		0.000
Energy output:						
Thermal energy , as heat (MJ)	10.134	0.475	4.500			
Electrical energy, as electricity (MJ)	6.109	0.382	3.6			
Vehicle performance:						
Distance travelled by vehicle (km)				5.338	0.868	1.00

Assumptions made in this study:

i. Transport of chemicals from suppliers to the plant site is included in the LCA (e.g. medium small truck on a distance of 15 km).
ii. The energy inputs include electricity (South African electricity mix), thermal energy (as heat) and diesel.
iii. Compression and distribution of the fuel the vehicle tank is considered in the LCA.
iv. Fuel storage is not considered in the LCA
v. Inventory does not consider infrastructure
vi. Inventory does not consider the manufacturing and disposing of the vehicles
vii. Disposing and transport of end-product is included in the inventory

2.3. Impact assessment

The impact assessment was performed with ReCiPe midpoint (E) methodology to quantify the potential environmental impacts associated with the systems under the study (PRè Consultants 2008). The ReCiPe midpoint (E) methodology has eighteen different impact categories, and this paper looked at the following impact categories (e.g. climate change, particulate matter formation, freshwater eutrophication, water depletion, and fossil depletion). These impact categories lead to three damage categories, namely: damage to human health, damage to ecosystem and damage to resources.

2.3.1. Organic fraction of municipal solid waste collection and pretreatment

The waste containing organic fraction of value is delivered to the designated areas in the landfill site. The treatment stage starts with the sorting and separate of organic solids from waste material. The waste is collected into the collection thank whereby chemical dosing is done by injecting 1 M HCL and 1 M caustic soda (NaOH) to maintain the incoming effluent at desired pH level. Caustic soda is required to raise the pH of the feed or to increase the alkalinity. Hydrochloric acid is required to reduce the pH in the event that the feed becomes too alkaline and requires pH reduction. After the pretreatment stage the sludge is pumped into the digester for conversion bioprocess to take place.

2.3.2. Biomethane and Biohydrogen production processes

After pretreatment step, the sludge is pumped into the Upflow Anaerobic Sludge Blanket (UASB) bioreactor for biogas generation using anaerobic digestion (AD). The microorganisms convert the organic substrate into biogas (methane rich), carbon dioxide and other by-products such as volatile fatty acids. The bioreactor is maintained at the operational temperature of 35 ºC, with supply of heat. However, the bio-methane production process can be altered to instead produce bio-hydrogen under well-defined operational conditions. The anaerobic fluidized granular bed (AFGB) reactor facilitates the simultaneous achievement of high hydrogen yields (HYs) and high hydrogen productivities (HPs). This prototype AFGB reactor uses of anaerobic bacterial granules, members of the consortium include thermophilic acidogenic bacteria and thermophilic volatile fatty acid (VFA) oxidizing syntrophic bacteria to produce bio-hydrogen, carbon dioxide and other traces of gasses. The operational temperature for the thermophilic bio-hydrogen production process is maintained at 65 ºC using either electricity or steam energy. The effluent digestate from the bioreactor is collected and transported to the farm to use as manure fertilizer.

2.3.3. Steam methane reformation (SMR)

The reforming of methane is the most important process to produce hydrogen (H_2) from fossil feedstock, such as natural gas. The steam reforming consists of the endothermic reaction which convert hydrocarbons to hydrogen (H_2) and carbon monoxide (CO), and the process place at a temperature higher than 800 °C and a pressure of approximately 30 bar in a presence of a catalyst (Ni-based on Al_2O_3 carrier, K_2O as activator). After the reforming step, product gas is cooled to 180-250 °C for exothermic water-gas shift conversion, which reacting built carbon monoxide (CO) with steam for more hydrogen (H_2) generation.

2.3.4. Gas separation/upgradation

Pressure swing adsorption (PSA) can be used for the purification of gas products to obtain a highly purified gas for either use in electricity generation or as a fuel for vehicles. The PSA system can be design to achieve up to 99.999 % purity, with the product recovery of between 50 % and over 95 %. The industrial unit system ranges from 100 Nm^3/h to 100 000 Nm^3 of output per hour.

2.3.5. Cogeneration in combined heat and power/fuel cell systems

The highly purified gas can be used to generated electricity in combine heat and power (CHP) system or fuel cell (FC) systems. Or else, the purified gas can be used as a fuel for vehicles. If the gas product is used as a fuel for vehicles, then the gas product after purification requires compressions and distribution.

2.3.6. Vehicle operation

A GREET 1.7 (Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation) model database developed by the U.S. Argonne National Laboratory has been used to compare fuel use and carbon emissions of hydrogen, methane and natural gas (Argonne National Laboratory 2011). It computes total energy use, emissions of greenhouse gases (CO_2, CH_4 and N_2O), and emissions of six criteria pollutants: carbon monoxide (CO), volatile organic compounds (VOCs), nitrogen oxides (NO_x), sulphur oxides (SO_x), particulate matter with a diameter below 10 µm (PM10) and particulate matter with a diameter below 2:5 µm (PM2:5). The fuel life cycle consist of fuel production stage, i.e., well to pump (WTP), and fuel utilization stage, i.e., pump to wheel (PTW). The WTP stage includes all activities up through fuel delivery to the filling station. The PTW stage includes all aspects of vehicle operation (combustion) but not vehicle manufacturing. The sum of WTP and PTW is the whole fuel cycle result, also called the well to wheels (WTW), whereby covers all stages of the fuel cycle, from energy feedstock recovery (well) to energy delivery as the vehicle wheels. In this study, the system boundary covers the Well-to-Wheel (WTW) analysis of the fuel use for either electricity generation or as a fuel for vehicles.

2.4. Environmental impact interpretation

The life cycle inventory (LCI) data represented in Table 1 was used to calculate the environmental impacts of each study scenario generated in this study. The environmental performance of the study scenarios were presented in the form of graphs (as seen in Figure 2 to 5 in the below section).

3. Results and Discussion

Figure 2 illustrates that electricity generation using bio-methane from OFMSW, bio-hydrogen from OFMSW and natural gas has the following environmental impacts 20%, 39%, 36, respectively. Based on these findings, anaerobic digestion technology improves the overall environmental impact when contrasted with natural gas by a margin of 16%, and thermophilic fermentation is up by 2%, respectively.

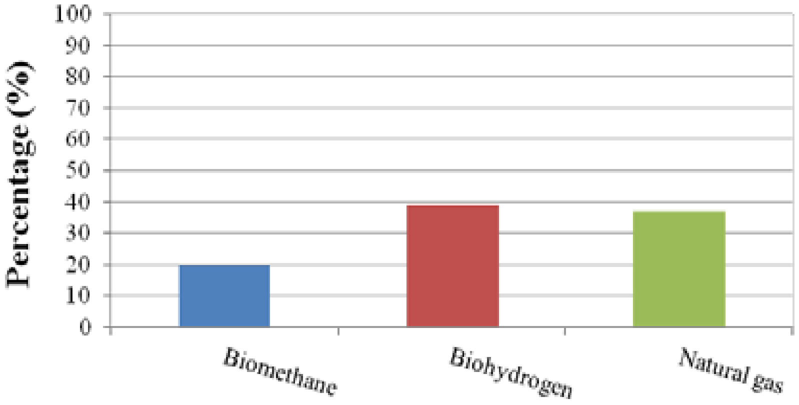

Figure 2: Overall environmental impact of 1 kWh electricity generation from OFMSW and natural gas

Figure 3, deals with the application of fuels as fuels for vehicles, the environmental impact of bio-methane, bio-hydrogen and natural gas stands at 49%, 27%, and 46%, respectively. This suggests that using bio-methane for electricity generation improves the impact on the environment by a margin of 2%, when compared to its application as a vehicle fuel which is detrimental to the environment by 4%. In both application, natural gas seem to have worst environmental impact but performs better than hydrogen in the electricity generation systems, and also better than bio-methane in the application as fuels for vehicles. The highest impact of the reference systems (natural gas) is provoked by fossil fuel use, for example steam methane reforming (SMR) uses natural gas as raw material. Additionally, the main disadvantage of the reference system is the fact that the steam methane reformation (SMR) process requires high energy input due to operational temperatures, for example temperatures of up to 800 °C. It appears that the use of bio-hydrogen generated from renewable sources for application in fuel cell systems for electricity generation and fuel cell vehicles results in a more adverse effect on the environment when compared to fossil based fuel production (i.e. natural gas). The results indicate that the use of bio-hydrogen for application in fuel cell vehicles improves the overall environmental impact when compared to natural gas system.

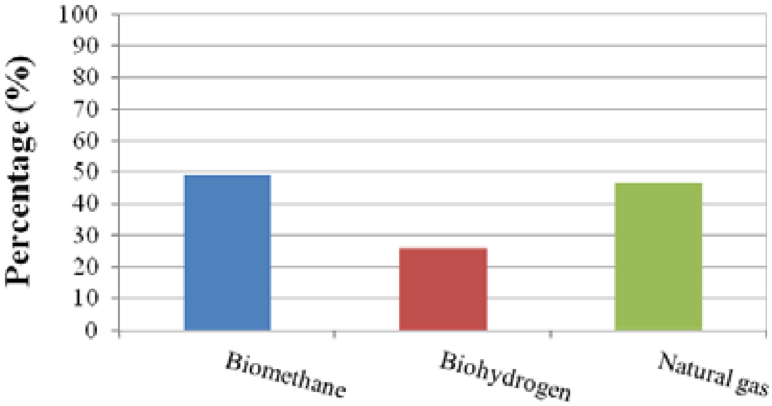

Figure 3: Overall environmental impact of 1 km distance travelled by vehicle fuelled with fuels produced from OFMSW and natural andfuels

In comparing Figure 4 and 5, these graphs show that biomethane has the lowest environmental impact compared to bio-hydrogen, and natural gas is the worst performing in electricity generation systems. Clearly, the application of bio-hydrogen in FC vehicles appears to be the most environmental friendly route than application in electricity generation systems. Natural gas tends to have a lower environmental impact compared vehicles compared to application in electricity generation systems.

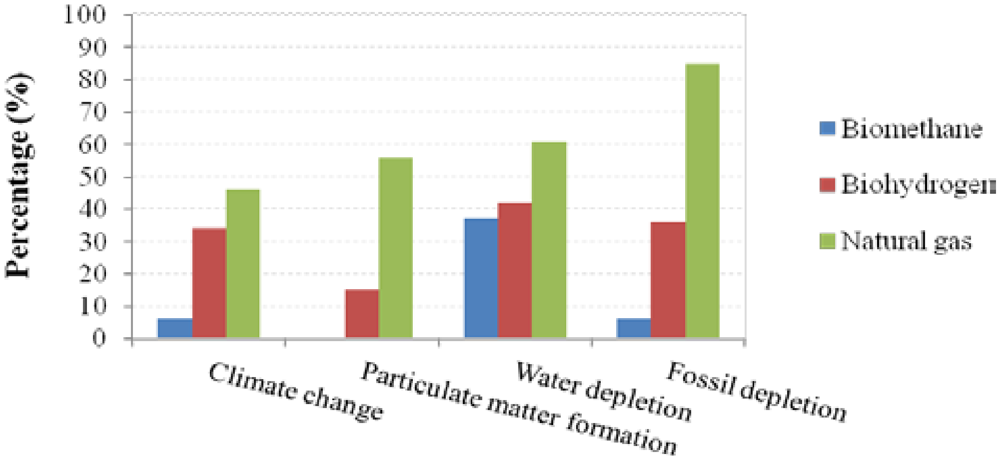

Figure 4: Environmental impact of 1 kWh electricity generation from fuels produced from OFMSW and natural gas

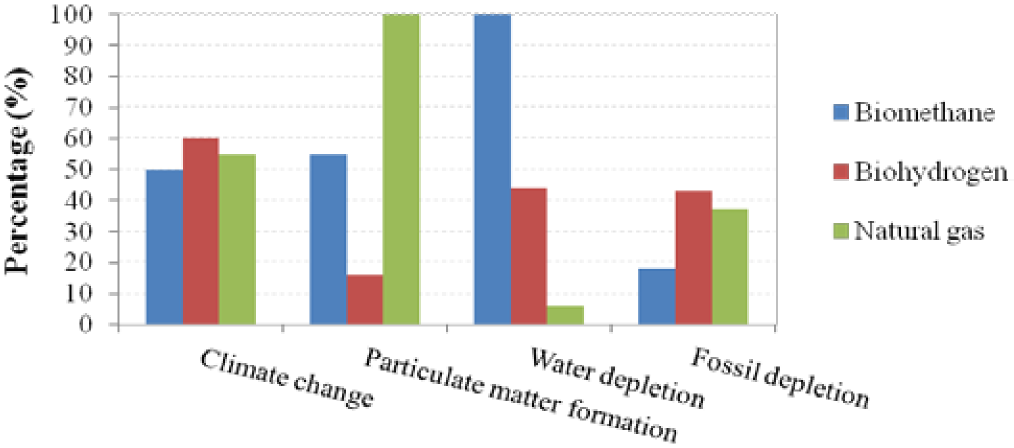

Figure 5: Environmental impact of vehicle operation for 1 km distancee travelled using fuels produced from OFMSW and natural gas

The poor overall environmental performance of bio-hydrogen application in electricity generation and fuel cell vehicles can be attributed to various factors such as lower conversion efficiencies, higher energy inputs and higher chemical inputs during production stages. For example, the anaerobic digestion process for bio-methane production normally, operates in the temperatures between 30-35 °C, whereas thermophilic anaerobic process for bio-hydrogen generation operates in the temperatures between 35-75 °C. This clearly proves that bio-hydrogen generation will consume more heat due to the higher temperatures required for its production during conversion processes, and there is a direct correlation between the high energy inputs and the high environmental performance of the process. The source of heat production for the generation of bio-hydrogen and bio-methane is largely coal-fired and therefore fossil fuel based in the case of South Africa, where approximately 77% of the total primary energy supply originates from coal (Eskom SA 2014).

It must be emphasized that the thermophilic bio-hydrogen production technology is still immature, and requires a lot of improvement in various operational parameters in order to achieve high mitigation effects compared to those of fossil based systems. The process of thermophilic bio-hydrogen production requires well-controlled operational conditions because of the thermodynamic nature of hydrogen. Such conditions include the requirement that the hydrogen partial pressure should be lower within the bioreactor system and one way attaining this is through liquid-gas separation, which depends on the quality of pre-treated sludge in the bioreactor. This pre-treatment stage requires a lot of chemical inputs, which in turn often heightens the negative environmental impact of bio-hydrogen compared to bio-methane generation process. In conclusion, the findings of this study suggest that bio-methane from the investigated renewable waste offers improved environmental performance for applications in electricity generation. However, bio-hydrogen only show environmental improvement in fuel cell vehicles compared to electricity generation. Furthermore, bio-hydrogen production process requires improvements in terms of fermentation conversion efficiencies and reduction in energy inputs in order for the technology to be comparable to those of bio-methane and fossil based systems. These findings are largely influenced by the South African geographical conditions and they should be compared with other developing countries with a similar energy mix, geographical conditions and production systems.

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