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AN OVERVIEW OF HYDROGEN FUEL FROM BIOMASS GASIFICATION - COST EFFECTIVE ENERGY FOR DEVELOPING ECONOMY

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ABSTRACT

Hydrogen has the potential to be a clean and sustainable alternative to fossil fuel especially if it is produced from renewable sources such as biomass. Gasification is the thermochemical conversion of biomass to a mixture of gases including hydrogen. The percentage yield of each constituent of the mixture is a function of some factors. This article highlights various parameters such as operating conditions; gasifier type; biomass type and composition; and gasification agents that influence the yield of hydrogen in the product gas. Economic evaluation of hydrogen from different sources was also presented. The hydrogen production from gasification process appears to be the most economic process amongst other hydrogen production processes considered. The process has the potential to be developed as an alternative to the conventional hydrogen production process.

1.0 INTRODUCTION

Biomass is the largest renewable energy and it has a major share of about 90% of the total energy supply in the remote and rural areas of developing world (Demirbas, 2001). While burning of fossil fuel converts carbon that has been confined underground (as crude oil, coal and gas) to carbon dioxide (CO_2) thereby increasing CO_2 in circulation and hence the greenhouse gas (GNG) effects, the combustion of biomass recycles the CO_2 captured during photosynthesis and thus maintains the CO_2 balance in the atmosphere (Ahmad *et al*., 2016). Biomass can therefore be said to possess a zero CO_2 net emission (Mohammed *et al.,* 2011).

Most often, biomass is from agricultural by products but sometimes, it could be directly cultivated (McKendry, 2002a). The routes to convert biomass into useful products will depend on the form of the biomass. For agricultural residues, forest residues and wood, thermo-chemical conversion routes are the widely-used methods to extract energy from biomass. Thermochemical processes can be categorized into combustion, pyrolysis and gasification where the syngas and bio-oil produced as intermediate products can be subsequently converted to valuable fuels and chemicals. Combustion is the direct burning of biomass in air to convert the chemical energy in biomass to heat, electricity or mechanical power. The energy efficiency of this process is between 10-30% (Ni *et al*., 2006). Pyrolysis is the burning of biomass in the absence of air. Slow pyrolysis gives high yield of charcoals whereas rapid heating of biomass at high temperature (fast pyrolysis) gives products in the liquid, gaseous and solid states (Cao *et al*., 2020; Yang *et al*., 2018). Gasification is the conversion of biomass into a combustible gas mixture (syngas) by heating in a gasification medium such as air, oxygen or steam. Gasification of biomass leads to the production of syngas of which carbon monoxide, methane, and hydrogen are some of the constituents (Brachi *et al*., 2018; Qiu *et al*., 2018).

Of all the three thermochemical routes, gasification is being considered in this research work as a promising technology to treat biomass. This is because it produces minimal emissions, can be easily adapted to treat different materials and the process conditions can be altered selectively to isolate different gaseous products (Sikarwar *et al*., 2017; Molino *et al.,* 2018). Furthermore, gasification is likely to be commercially viable based on the consideration of overall conversion efficiency and proven operational history and performance (Barbuzza *et al*., 2019; Catalan-Martinez *et al*., 2018; Qiu *et al*., 2018).

Hydrogen - one of the constituents of syngas has been dubbed the energy carrier of the future and has gained reputation as a potential substitute to fossil fuels. This is because hydrogen, when combusted or used in a fuel cell, does not emit greenhouse gas (GHG), it has a high energy content on a mass basis when compared to gasoline or natural gas and it can be easily and efficiently converted to electricity using fuel cells. Hydrogen, as a high efficiency low polluting fuel, can be used for transportation, heating and power generation (Orhan *et al.*, 2011). Hydrogen is also a raw material for chemical, petroleum and agro-based industries (Lewis *et al.*, 2009 and Naterer *et al.*, 2010).

Converting biomass to aqueous and gaseous fuel most especially hydrogen could be a more efficient way of utilizing biomass. This is good for developed nations because the problem of GHG emissions will be dealt with and for developing nations with power generation problems by providing access to electricity and power supply from relatively available sources.

This study is focused on highlighting the potential of hydrogen generated from biomass gasification to be effective solution to the menace of inadequate power supply in rural areas. It could also serve as source of energy generation for both small and medium scale industries. This is much more apt for a developing nation like Nigeria which has an agrarian based economy. The vast amount of biomass as agricultural byproducts and abundant virgin land that could be put to use for more cultivation of biomass is a great motivation for this study.

2.0 HYDROGEN PRODUCTION

Although abundant on earth as an element, hydrogen is almost always found as part of another compound, such as water (H_2O) and some other compounds, and must be separated from the compounds that contain it. Once separated, hydrogen can be used in diverse ways. In addition, hydrogen can be produced using diverse resources. The environmental impact and energy efficiency of hydrogen depends on how it is produced. Figure 1 depicts some sources through which hydrogen can be generated.

2.1 Production from Natural Gas: Hydrogen can be produced from natural gas through three different chemical processes. Steam reforming involves the endothermic conversion of methane and water vapour into hydrogen and carbon monoxide as given in equation 1. The product gas CO can be further converted to CO_2 and H_2 through the water-gas shift reaction as given in equation 2 (Holladay *et al.*, 2009).

$$CH_4 + H_2O + heat \rightarrow CO + 3H_2 \qquad (1)$$

$$CO + H_2O \rightarrow CO_2 + H_2 + heat \qquad (2)$$

Partial oxidation involves the production of hydrogen through the partial combustion of methane with oxygen rich gas to yield carbon monoxide and hydrogen according to equation 3 (Ahmed *et al*., 2017). The CO can be further converted through the water-gas shift reaction of equation 2 (Cormos *et al*., 2018).

$$CH_4 + \frac{1}{2}O_2 \rightarrow CO + 2H_2 \qquad (3)$$

Autothermal reforming is a combination of both steam reforming and partial oxidation. This method of producing hydrogen has developed technology and has been commercialized. However, the hydrogen generated from this source can only be sustainable if it is from renewable source such as biogas or syngas (Dincer and Acar, 2015).

2.2 Electrolysis: An electric current splits water into hydrogen and oxygen. If the electricity is from renewable sources, such as solar or wind, the resulting hydrogen will be considered renewable as well, and have numerous environmental benefits. Electrolysis is considered as the easiest method of hydrogen production since it yields high level hydrogen purity and requires simple equipment (Badwal *et al*., 2013). It however has low efficiency (Nikolic *et al.,* 2010) and contributes only about 4% of overall hydrogen production (Chakik and Mikou, 2017; Santos *et al.,* 2013).

$$H_2O + electricity \rightarrow H_2 + \frac{1}{2}O_2 \qquad (4)$$

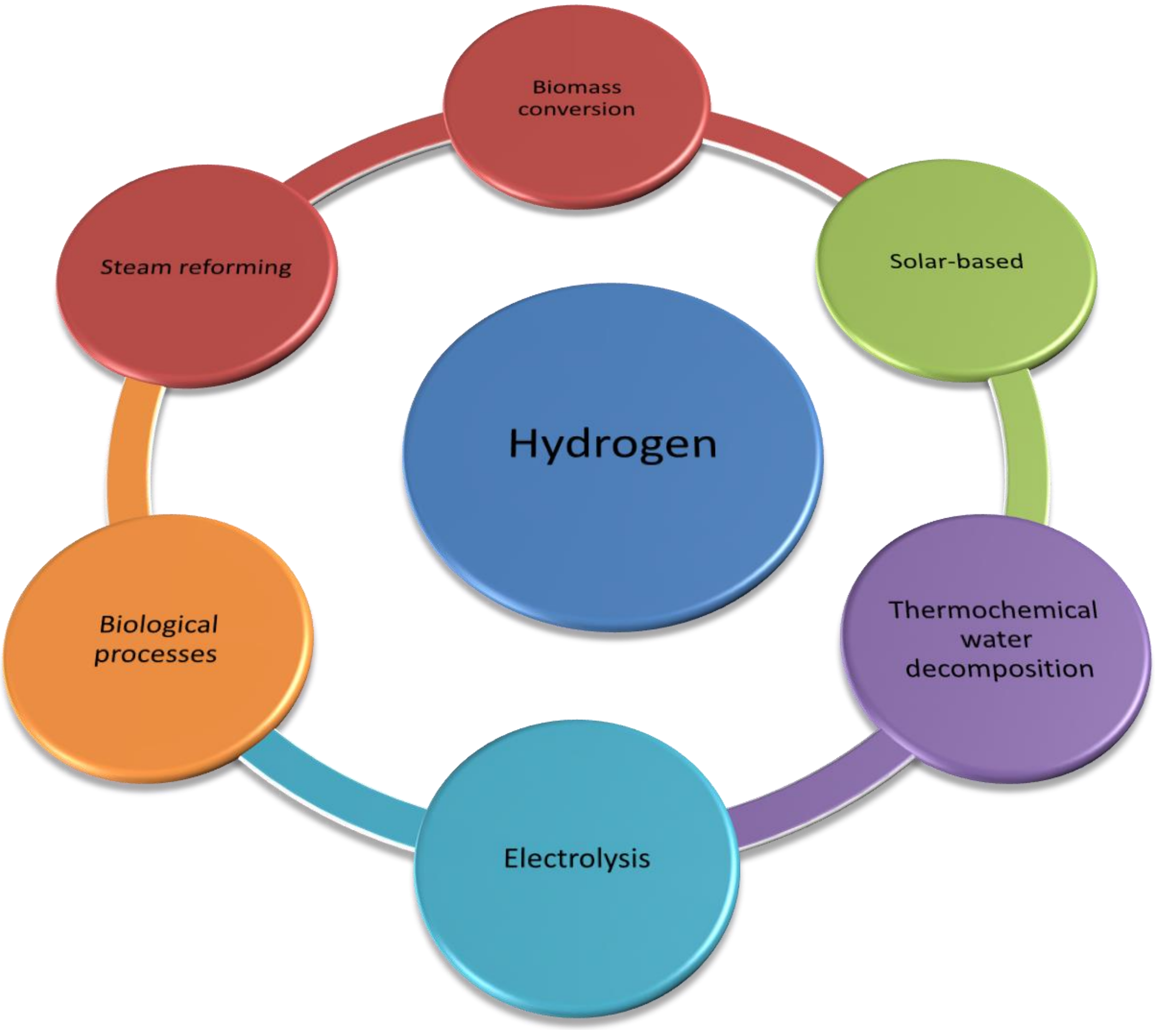

Figure 1: Some hydrogen production processes

2.3 Solar-based Hydrogen Production: Solar energy is readily available at no cost to produce hydrogen; therefore, it may lead to a future clean alternative fuel (hydrogen) for transportation. Direct solar water decomposition, or photolytic, processes use light energy to split water into hydrogen and oxygen (Contreras *et al*., 1999; Do Sacramento *et al.*, 2008). These processes are currently in the very early stages of research but offer long-term potential for sustainable hydrogen production with low environmental impact such as the threatening global warming effects (Liu *et al.*, 2020).

2.4 Biological Processes: Microbes such as bacteria and microalgae can produce hydrogen through biological reactions, using sunlight or organic matter. These technology pathways are at an early stage of research, but in the long term have the potential for sustainable low-carbon hydrogen production. Biological hydrogen can be produced in an algae bioreactor (Hemschemier *et al.*, 2009).

2.5 Thermochemical Water Decomposition for Hydrogen Production: This is an emerging and promising technology for large-scale production of

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hydrogen and it is commonly called thermochemical cycles. This is done using intermediate compounds and sequence of chemical reactions to split water into hydrogen and oxygen without polluting the atmosphere (Naterer *et al*., 2009). Many thermochemical cycles have been identified but only a few have been proven to be feasible (McQuillan, 2002).

2.6 Gasification: This conversion route is the focus of this study. It is discussed extensively in the next section.

3.0 BIOMASS GASIFICATION

Gasification is the conversion of biomass into a gaseous product that mainly consist of hydrogen (H_2), and carbon monoxide (CO) with lower amounts of methane (CH_4), carbon dioxide (CO_2), water (H_2O), nitrogen (N_2) and higher hydrocarbons (C+) in the presence of gasifying agents. The gasifying agents could be air, oxygen or steam or a mixture of these components. Gasification is carried out at temperatures between 500 and 1400 ^oC and at atmospheric pressure of 101.325 kPa up to an elevated pressure of 3300 kPa (Ciferno and Marano, 2002). The reactions taking place in the gasifier are summarized in equations 5-7 (Mckendry, 2002b).

$$C + \frac{1}{2}O_2 \rightleftharpoons CO \text{ (partial oxidation)} \quad (5)$$

$$C + O_2 \rightleftharpoons CO_2 \text{ (complete oxidation)} \quad (6)$$

$$C + H_2O \rightleftharpoons CO + H_2 \text{ (water gas reaction)} \quad (7)$$

The hydrogen and steam can undergo further reaction during gasification as given in equations 8 and 9:

$$CO + H_2O \rightleftharpoons CO_2 + H_2 \text{ (water gas shift reaction)} \quad (8)$$

$$CO + 3H_2 \rightleftharpoons CH_4 + H_2O \text{ (methane formation)} \quad (9)$$

The arrows indicate that the reactions are in equilibrium and can proceed in either direction depending on the conditions of reaction (temperature, pressure and concentration)

Main products of gasification are synthesis gas (syngas), char and tars. The content depends on the feedstock, oxidizing agent and the conditions of the process. The gas mainly consists of CO, CO_2, H_2, CH_4 and other hydrocarbons. The gasification process can be summarized as given in equation 10:

$$\gamma C_aH_bO_c + \varphi H_2O \xrightarrow{heat} d\,H_2 + eCO + fCO_2 + gCH_4 + tar \quad (10)$$

where $\gamma C_aH_bO_c$ is the general chemical representation of the biomass.

The syngas produced consists of a mixture of CO_2 (8-10%), H_2 (18-20%), CO (18-20%), CH_4 (2-3%) and traces of other light hydrocarbon and steam (Simonyan and Fasina, 2013). This can be burnt directly or used as a fuel for gas engines and gas turbines in generating electricity (Ben-Iwo *et al*., 2016).

A few parameters have effects on the quality and quantity of the syngas production during gasification. These are discussed as follows.

3.1 Effects of Temperature

Temperature appears to have the greatest influence on the performance of the gasifiers. The composition of the volatiles produced from a gasifier depends on the degree of the equilibrium attained by various gasification reactions. All the gasification reactions are normally reversible and the equilibrium point of any of the reaction can be shifted by changing the temperature. Hydrogen production reactions (water gas shift reaction) is endothermic, a higher gasification temperature will favor the production of hydrogen (Nanda *et al.*, 2016a).

A study of steam gasification of almond shells in a continuous fluidized bed reactor reported the yield of hydrogen as above 50% of the syngas composition (Rapagna and Latif, 1997). The temperature was increased from 600 to 800 ^oC. Similarly, Lv *et al.* (2004) reported an increase in hydrogen production from 21-39 vol.% when the gasification temperature was varied from 700 to 900 ^oC. Sawdust and fluidized bed reactor were the feedstock and type of gasifier, respectively. For all cases considered, the higher temperature favoured higher concentrations of syngas and hydrogen yield but lower concentration of char and heavy tar. The increase in hydrogen yield at higher temperature was due to tar thermal cracking reaction which also decreases the tar concentration (Skoulou *et al.*, 2009). The gasification temperature needed to be selected carefully as a tradeoff between the char conversion and the H_2 output. However, other research shows that high H_2 yield can be obtained at low temperature (600^oC) by using 90% steam content (Gao *et al.*, 2008). Table 1 gives indication of the influence of temperature on hydrogen yield for selected biomass.

Table 1: Hydrogen production of biomass at different gasification temperature (Source: Nanda *et al.*, 2016a; Safari *et al.*, 2018; Lu *et al.*, 2008; Nanda *et al.*, 2016b)

Biomass	Temperature (^oC)	Hydrogen yield (mol/kg)
Orange peel	400	0.08
Orange peel	500	0.58

Biomass	Temperature (ºC)	Hydrogen yield (mol/kg)
Orange peel	600	0.91
Pine wood	300	0.22
Pine wood	400	0.69
Pine wood	500	1.14
Almond shell	380	3.95
Almond shell	400	4.55
Almond shell	420	5.43
Almond shell	440	6.45
Almond shell	460	7.85
Corn cob	550	2.55
Corn cob	600	5.31
Corn cob	650	9.08

3.2 Effects of Biomass Feed Stock

Table 2 shows the hydrogen production from gasification of different biomass subjected to the same conditions. The type of feed stock can be seen to affect the yield of hydrogen at the same process conditions. Sugarcane bagasse from table 2 yielded 1.66 mol/kg hydrogen, while coconut shell yielded 2.17 mol/kg hydrogen at the same process conditions. The general chemical representation of biomass as given in equation 10 indicates that the chemical composition of varying biomass is not the same. Ultimate analysis is often used for the chemical analysis of biomass feedstock. The chemical analysis usually lists the carbon, hydrogen and oxygen of the dry biomass sample on a weight percentage basis. The composition of hydrogen in the biomass feedstock may influence the yield of hydrogen in the gasified biomass.

Method of gasification also influences the yield of hydrogen. In the table, hydrogen yield with supercritical water gasification of biomass is much lower than steam gasification of the same biomass. For example, the yield of hydrogen for cotton stalk was 4.19 mol/kg with supercritical water gasification while steam gasification of the same biomass yielded 8.26 mol/kg of hydrogen, about 97% increment. The same goes for corn stalk with about 111% increment in hydrogen yield for steam gasification process.

Table 2: Hydrogen production from different biomass subjected to the same conditions. (Source: Nanda *et al.*, 2016a; Yanik *et al.*, 2007, Wei *et al.*, 2014; Pala *et al.*, 2017)

Biomass	Hydrogen (mol/kg)	Conditions
Sugarcane bagasse#	1.66	400ºC
Coconut shell#	2.17	400ºC
Cotton stalk#	4.19	500ºC
Corn stalk#	4.15	500ºC
Cotton stalk*	8.26	650ºC
Sawdust*	9.02	650ºC
Corn stalk *	8.79	650ºC
Wood residue	27.86	900ºC
Coffee bean husk	34.32	900ºC

#supercritical water gasification
*Steam gasification

3.3 Effects of Equivalence Ratio

The ratio between the theoretical and practical air demand in steam gasification process utilizing air or O_2 is termed the equivalence ratio (ER). For each kind of biomass, there is a theoretical O_2 demand needed to achieve the combustion based on its contents of combustible materials and since in most cases, gasification is based on realizing relatively partial combustion, a fraction of this ratio is only used. A ratio of 0.15-0.35 has been investigated (Mohammed, 2010). The tar and char yields were discovered to decrease as the ER increased. This is because more oxygen in the gasifier caused the oxidation of the char and tar, and invariably led to the production of more CO and CO_2, and less H_2. Optimum value of the ER for a particular gasification process should be noted. Beyond this optimum, carbon conversion efficiency and gasification efficiency will start to decrease (Gao *et al.*, 2012; Zhao *et al.*, 2010; Xiao *et al.*, 2007).

3.4 Effects of Steam/Biomass (S/B) Ratio

The steam biomass ratio could be varied either by changing the biomass feed rate while keeping the steam flow constant or vice versa. Result from previous researches show an increase in hydrogen production as the ratio increases. However, when S/B ratio is further increased beyond a certain point, hydrogen production declined. The critical S/Bs are generally between 0.70 and 3.41 depending on the conditions (Zhang *et al.,* 2016b). Previous researches by Mahishi and Goswami, (2007); Kalinci *et al.* (2009); Inayat *et al.* (2010) and Moneti *et al.* (2016) obtained optimum yield of hydrogen at steam/biomass ratios of 3, 0.6-10, 2, and 2-3, respectively. Increasing the S/B ratio decreases slightly the CO and favours the water gas shift reaction that results in more hydrogen production. Operating the gasifier at a very high S/B might not be

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energy efficient since the increase in the production of hydrogen at this state may not justify the cost of increasing the steam (Pallozzi *et al.*, 2016).

3.5 Effects of Gasifier

Gasifiers are classified mainly on the basis of their gas solid contacting mode and gasifying medium. Based on the gas solid contacting mode, gasifiers are broadly divided into three principal types:

(i) fixed or moving bed gasifier
(ii) fluidized bed gasifier
(iii) entrained-flow bed gasifier

Each type of gasifier has different ranges of appropriate reaction condition and feedstock. There is an appropriate range of application for each. The moving-bed (updraft and downdraft) type often used for smaller units (10 MW) contains a large amount of tars in its product gas due to flow of biomass and the produced gas (Luo *et al.*, 2009; Li *et al.*, 2009). The fluidized-bed (bubbling and circulating) type is more appropriate for intermediate units (100 MW). Feed stock with high ash content can cause stickiness in the fluidized agent and reduce the fluidity of the inert bed material (Siedleck, 2011). The entrained-flow reactors are used for large capacity units (500 MW). The operating temperatures and pressure of the entrained flow reactor are higher than that of the fluidized bed and the fixed bed (Ghassemi *et al.*, 2016). Several studies have compared the advantages and various gasifiers applying different criteria such as use of material, energy efficiency, technology and environmental impacts. The general consensus is that there was no significant advantage of one reactor type over the other. However, for decentralized power generation and distribution to remote and rural areas as well as for small scale industries fixed bed gasifier such as downdraft gasifier which are typically small scale unit with power generation capacity of up to 10 MW could be used (Li *et al.*, 2009).

3.6 Effects of Catalyst and Biomass Composition

Reactions catalysts have positive effects on the yield of hydrogen. Previous works indicated increase in the yield of hydrogen when a catalyst was added to the reaction (Nanda *et al.*, 2016b; Gong *et al.*, 2014). The catalysts are known for cracking tars to produce gaseous products.

Biomass are essentially made of three major polymers; the lignin, cellulose and hemicellulose. Experiments have shown that compared with lignin, cellulose and hemicellulose produced gases more rapidly with higher CO and CH_4 but lower H_2 and CO_2 concentrations, and higher temperature is needed for optimum hydrogen production. Lignin produced more hydrogen than cellulose and hemicellulose cell (Tian *et al*., 2017).

4. 0 IMPLICATIONS OF HYDROGEN FUEL

Hydrogen as an energy carrier can be converted into useful forms of energy. For combustion in internal combustion (IC) engines, jet engines and rocket engines; hydrogen powered combustion engines are about 20% more efficient than gasoline engines (Barbir, 2013; Spath and Dayton, 2003). This is because the thermal efficiency of internal combustion engine can be improved by either increasing the compression ratio or the specific ratio both of which are higher in hydrogen engines (Das, 2016).

Hydrogen combusted with pure oxygen can generate steam with a temperature in the flame zone of above 3000 ^oC (Spath and Dayton, 2003). Hydrogen steam generators can be used for industrial steam power supply, for electricity generation and in power plants. Hydrogen steam generator is close to 100% efficient since there are little or no thermal losses and there is no emission other than steam. Gao et al. (2007) estimated that in the near future, there might be entire cities converting to solely hydrogen for heating and cooling.

Hydrogen can be combined with oxygen in an electrochemical reaction in fuel cell to produce electricity (Maleki *et al*., 2016). In the typical IC engine vehicle optimized for a hydrocarbon fuel, only about 15% of the fuel value ends up as kinetic energy moving the vehicle down the road. This value increases to about 25% for an IC engine/electric hybrid (Barbir, 2013). Fuel cell vehicles operating on compressed hydrogen have the potential of achieving over 30% and, unlike the hybrids, would be classed as zero emission vehicles (Dell *et al*., 2014).

In conclusion, gasified biomass can be used to power IC engines, gas turbines and fuel cells, all of which are able to produce electricity at higher efficiency. Therefore, coupling biomass gasifiers with these energy generators has the potential for considerably lowering capital investment than a similarly sized boiler/steam turbine system.

Other energy conversion route of hydrogen includes catalytic conversion to produce heat and conversions involving metal hydrides.

Analysis of biomass gasification options has shown that production of hydrogen is the most economic route for the conversion of syngas to transportation fuels (Spath and Dayton, 2003). An economic and efficiency evaluation of hydrogen from biomass is therefore important for the implementation of the technologies of the gasification processes. Table 3 lists the hydrogen production costs from biomass gasification using different gasifiers from previous studies. Hydrogen production from other sources aside from biomass gasification are also listed on the table. Biomass gasification seems to be the most cost effective for the production of hydrogen and power aside from steam methane reforming (SMR). SMR is a mature technology that uses natural gas which has a well-defined non varying composition and is delivered via pipeline. However, SMR uses fossil fuel which is prone to depletion, environmental pollution and GHG emission. Biomass gasification on the other hand uses renewables which are available and sustainable. In fact, it has been viewed as an important technology for reducing GHG.

The U.S Department of Energy (U.S. DOE) has set a cost goal for hydrogen at $2-$3/kg including production, transportation and delivery for hydrogen to be cost competitive with fossil fuel. The goal for production cost only was set at $1.10/kg (NREL, 2011; Nikolaidis and Poullikkas, 2017). In fact the goal for biofuels production in the US is 36 billion gallons by 2022 (USA Energy Independence, 2007).

None of the gasification process presented in table 3 met up with this goal. One way to reduce cost of production is to use renewables from nonfood biomass such as agricultural residues, energy crops, woody crops, forestry, mill and wood wastes.
Hydrogen energy technologies are particularly interesting for the developing countries that do not have huge energy infrastructures in place. Cost for distribution such as power transmission lines, pipelines, transportation infrastructure might work against centralized production in developing economy. Hence, hydrogen can be produced from low cost biomass to supply off grid electricity to homes using a portable fuel cell power system. Developing countries may adopt dispersed renewable energy sources using both traditional and advanced technologies for their utilization.
Technology improvements of gasification process may reduce the cost of producing hydrogen from biomass. Advances in biotechnology that will produce high yield, low-cost energy crops are one of such ways. Improvement actions leading to an increase in process efficiency that would significantly enhance the system's performance is another way. This is because increase in hydrogen production from gasification of biomass has been linked to improved exergy efficiency of the gasification process (Zhang et al; 2019a).

Table 3: Hydrogen production cost

Process	H_2 production cost	References
Air gasification in a fluidized bed	2.11USD/kg	Mohamed *et al.*, 2011
Steam gasification in fluidized bed with in-situ CO_2 capture	1.91 USD/kg	Inayat *et al.*, 2011
Oxygen gasification in a fixed bed and CO-shift at atmospheric pressure	1.69 USD/kg	Lv *et al.*, (2008)
Large scale gasification	1.38 USD/kg	Spath *et al.*, 2005
Fuel cell Hydrogen	2.76 USD/kg	Ogden, 1999
Electrolysed hydrogen	10 USD/kg	Iwasaki, 2003
Biomass pyrolysis with high pressure	4.28 USD/kg	Iwasaki, 2003
Steam methane reforming	1.25 USD/kg	NREL, 2011

5.0 CONCLUSION

Hydrogen energy system from biomass gasification is a coherent, comprehensive and permanent solution to global energy-economic-environmental problems, and as such deserves support from individual governments, industrial organizations and research institutes. The Hydrogen yield in the syngas composition is influenced by some operating conditions such as steam flow rate and temperature. The choice of materials also has critical influence on the efficiency of the gasification process. Biomass gasification is a renewable and clean energy source with great potentials to replace fossil fuels for hydrogen production. Adopting gasification technology for the main purpose of producing hydrogen may seem expensive but in the long run its benefit might be unquantifiable. Further research efforts to improve the reaction rates and efficiency, reduce the production cost and fast track the large scale production should be encouraged.

REFERENCES

Ahmad, A.A., Zawawi, N.F., Kazim, F.H., Inayat, A., Khasri A. (2016). Assessing the gasification performance of biomass: A review on biomass gasification process conditions, optimization and economic evaluation. *Renewable and Sustainable Energy Reviews,* 53: 1333-1347.

Ahmed, U., Kim C., Zahid, U., Lee, C. J., Han C. (2017). Integration of IGCC and methane reforming process for power generation with CO2 capture. *Chem Eng Process Intensif.*, 111:14–24.

Ben-Iwo, J., Manovic, V., Longhurst P. (2016). Biomass resources and biofuels potential for the production of transportation fuels in Nigeria, *Renewable and Sustaianble Energy Reviews*, 63: 172-192.

Badwal, S. P. S., Giddey, S., Munnings C. (2013). Hydrogen production via solid electrolytic routes. *Wiley Interdiscip Rev Energy Environ, 2(5), 473-487.*

Barbir, F. (2013). PEM fuel cells: Theory and practice. United Kingdom, Academic Press, 2nd Ed.

Barbuzza, E., Buceti, G., Pozio, A., Santarelli, M., Tosti, S. (2019). Gasification of wood biomass with renewable hydrogen for the production of synthetic natural gas. *Fuel*, 242:520-531.

Brachi, P., Chirone, R., Miccio, F., Miccio, M., Ruoppolo, G. (2018). Entrained-flow gasification of torrefied tomato peels: Combining torrefaction experiments with chemical equilibrium modeling for gasification. *Fuel*, *220*: 744–753.

Cao, L., Yu, I.K.M., Xiong, X., Tsang, D.C.W., Zhang, S., Clark, J.H., Hu, C., Ng, Y.H., Shang, J., Ok, Y.S. (2020). Biorenewable hydrogen production through biomass gasification: A review and future prospects, *Environmental Research*, doi: https://doi.org/10.1016/j.envres.2020.109547 .

Catalan-Martinez, D., Domine, M. E, Serra, J. M. (2018). Liquid fuels from biomass: An energy self-sustained process integrating H_2 recovery and liquid refining. *Fuel*, 212:353-363.

Chakik F. E, Mikou M. (2017).Effect of operating parameters on hydrogen production by electrolysis of water. *Int J Hydrogen Energy*, 42(40):25550-25557.

Ciferno, J. P.,Marano, J. J. (2002). Benchmarking biomass gasification technologies for fuels, chemicals and hydrogen production. U.S. Department of Energy National Energy Technology Laboratory (Washington, DC); 2002.

Contreras, A., Carpio, J., Molero, M., Veziroglu, T. N. Solar (1999). Hydrogen:an energy system for sustainable development in Spain. *International Journal of Hydrogen Energy*, 24:1041-1052.

Cormos, A.M., Szima, S., Fogarasi, S., Cormos, C.C. (2018).Economic assessments of hydrogen production processes based on natural gas reforming with carbon capture. *ChemEng Trans*, 70:1231–1236.

Das, L.M. (2016).Hydrogen –fueled internal combustion engines In: Compendium of Hydrogen energy, Vol. 3: Hydrogen energy conversion. (Ed Barbir, F., Basile, A., Vesiroglu, T.J.), Wood Head Publishing Series in Energy.

Dell, R.M., Moseley, P.T., Rand, D.A.J. (2014).Towards sustainable road transport. United Kingdom, Academic Press., 1st Ed.

Demirbas, A. (2001). Biomass resource facilities and biomass conversion processing for fuels and chemicals. *Energy conversion management*, 42(11): 1357-1378.

Dincer, I., Acar, C., (2015). A review on clean energy solutions for better sustainability. *Int. J. Energy Res*. 39 (5), 585-606.

Do Sacramento, E.M, De Lima, L.C, Oliviera, C. J., Veziroglu T.N. (2008).A Hydrogen energy system and prospects for reducing emissions of fossil fuels pollutants in the Ceara state Brazil. *International Journal of Hydrogen Energy*, 33:2132-2137.

Gao, N., Li, A., Quan, C., and Gao, F. (2008). Hydrogen-rich gas production from biomass steam gasification in an updraft fixed-bed gasifier combined with a porous ceramic reformer.*International Journal of Hydrogen Energy, 33* (20): 5430-5438.

Gao,N., Li, A., Quan, C., Qu, Y., Mao, L. (2012). Characteristics of hydrogen-rich gas production of biomass gasification with porous ceramic reforming. *Int J Hydrog Energy*, 37:9610–9618.

Gao, H., Zhen, W., Ma, J., Lu, G., (2017). High efficient solar hydrogen generation by modulation of Co-Ni sulfide surface structure and adjusting adsorption hydrogen energy.*Appl. Catal. B Environ*., 206: 353-363.

Ghassemi, H., Mostafavi, S. M., Shahsavan-Markadeh, R. (2016). Modeling of high-ash coal gasification in an entrained-flow gasifier and an IGCC plant. *J Energy Eng*, 40:150-152.

Gong, M., Zhu, W., Zhang, H.W, Ma, Q, Su, Y., Fan, Y.J. (2014). Influence of NaOH and Ni catalysts on hydrogen production from the supercritical water gasification of dewatered sewage sludge *International Journal of Hydrogen Energy,* 39:19947-19954.

Hemschemeier, A., Melis, A., Happe, T., (2009). Analytical approaches to photobiological hydrogen production in unicellular green algae. Photosynthesis Research, 102 (2–3): 523–540.

Holladay, J. D., Hu, J., King, D.L., Wang, Y. (2009). An overview of Hydrogen production technologies. Catalysis, 139: 244-260.

Inayat, A., Ahmad M. M., Abdul Mutalib, M. I, Yusup, S. (2010). Effect of process parameters on hydrogen production and efficiency in biomass gasification using modelling approach. *J Appl Sci*, 10:3183–3190.

Inayat, A., Ahmad, M.M, Mutalib, M.A, Yusup, S. (2011). Heat integration analysis of gasification process for hydrogen production from oil palm empty fruit bunch. *Chem Eng Trans* 25:971–976.

Iwasaki W. (2003). A consideration of the economic efficiency of hydrogen production from biomass. *Int J Hydrogen Energy*, 28:939–44.

Kalinci Y, Hepbasli A, Dincer I. (2009). Biomass-based hydrogen production: a review and analysis. *Int J Hydrogen Energy,* 34:8799–8817.

Lewis, M.A., Ferrandon, M.S., Tatterson, D.F, Mathias, P. (2009).Evaluation of alternative thermochemical cycles-part III further development of the Cu-Cl cycle, Int J Hydrogen Energy, 34, 4136-4145.

Li, J., Yin, Y., Zhang, X., Liu, J., Yan, R. (2009). Hydrogen-rich gas production by steam gasification of palm oil wastes over supported tri-metallic catalyst. *Int J Hydrog Energy*, 34:9108–9115.

Liu, Y., Zhu, Q., Zhang, T., Yan, Z., Duan, R. (2020) Analysis of chemical-looping hydrogen production and power generation system driven by solar energy, *Renewable Energy*, https://doi.org/10.1016/j.renene.2020.02.109.

Lu, Y., Jin, H., Guo, L., Zhang, X., Cao, C., Guo, X. (2008). Hydrogen production by biomass gasification in supercritical water with a fluidized bed reactor. *Int J Hydrogen Energy,* 33:6066-6075.

Luo, S., Xiao, B., Hu, Z., Liu, S., Guo, X., He, M.(2009). Hydrogen-rich gas from catalytic steam gasification of biomass in a fixed bed reactor: influence of temperature and steam on gasification performance. *Int J Hydrog Energy*, 34:2191–2194.

Lv, P., Wu, C., Ma, L., Yuan, Z. (2008) A study on the economic efficiency of hydrogen production from biomass residues in China. *Renewable Energy*, 33:1874–1879.

Lv, P. M., Xiong, Z. H., Chang, J., Wu, C. Z., Chen, Y., Zhu, J. X. (2004). An experimental study on biomass air–steam gasification in a fluidized bed. *Bioresour Technol*, 95(1):95–101.

Mahishi, M.R., Goswami, D.Y. (2007). Thermodynamic optimization of biomass gasifier for hydrogen production. *Int J Hydrogen Energy* 32:3831–3840.

Maleki, A., Pourfayaz, F., Ahmadi, M.H., (2016). Design of a cost-effective wind/ photovoltaic/ hydrogen energy system for supplying a desalination unit by a heuristic approach. *Sol. Energy*, 139: 666-675.

DOI: 10.51975/WMOV5566
Journal of the Nigerian Society of Chemical Engineers, 36(1), 2021

McKendry, P. (2002a). Energy production from biomass (part 2): conversion technologies. *Bioresource technology, 83*: 47-54.

McKendry, P. (2002b). Energy production from biomass (part 3): gasification technologies. *Bioresource technology, 83*: 55-63.

McQuillan, B.W., Brown, L.C., Besenbruch, G.E., Tolman, R., Cramer, T., Russ, B.E. (2002). High efficiency generation of hydrogen fuels using solar thermochemical splitting of water. Annual Report, GA-A24972, General Atomics, San Diego, CA.

Mohammed, M.A.A, Salmiaton, A, Wan,Azlina WAKG, Mohammad Amran M.S, Fakhru'l-Razi A. (2011). Air gasification of empty fruit bunch for hydrogen-rich gas production in a fluidized-bed reactor. *Energy Conversion Management*, 52(2), 1555–1561.

Molino, A., Larocca, V., Chianese, S., Musmarra, D. (2018) Biofuels production by biomassgasification: A review. *Energies* 11(4): 811-842.

Moneti, M., Di Carlo, A., Bocci, E., Foscolo, P.U, Villarini, M., Carlini M. (2016). Influence of the maingasifier parameters on a real system for hydrogen production from biomass. *Int J Hydrogen Energy*, 1–9.

Nanda, S., Isen J., Dalai A.K., Kozinski J.A.(2016a). Gasification of fruit wastes and agro-food residues in supercritical water. *Energy Convers Manag*, 110:296-306.

Nanda, S., Reddy S.N, Dalai, A. K., Kozinski, J. A.(2016b) Subcritical and supercritical water gasification of lignocellulosic biomass impregnated with nickel nanocatalyst for hydrogen production. *Int J Hydrogen Energy*41:4907-4921.

Naterer, G.F., Suppiah, S., Stolberg, L., Lewis, M., Wang, Z., Daggupati, V., Gabriel, K., Dincer, I., Rosen, M.A, Spekkens, P., Lvov, S., Fowler, M., Tremaine, P.,Mostaghimi, J., Easton, E.B., Trevani, L., Rizvi, G., Ikeda, B.M., Kaye, M.H., Lu, L.,Pioro, I., Smith, W.R., Secnik, E., Jiang, J., Avsec, J., (2010). Canada's program on Nuclear Hydrogen Production and the Thermochemical Cu-Cl cycle, *Int J Hydrogen Energy*, 35: 10905-10926.

National renewable energy laboratory (NREL) (2011). Hydrogen production cost estimate using biomass gasification. www.nrel.gov.

Ni, M., Leung, D.Y, Leung, M.K, Sumathy, K. (2006).An overview of hydrogen production from biomass, *Fuel Process Technol*, 87: 461-472.

Nikolaidis, P. and Poullikkas, A. (2017). A comparative overview of hydrogen production processes. *Renew. Sustain. Energy Rev.*, 67: 597–611.

Nikolic, V. M., Tasic, G. S., Maksic, A. D., Saponjic, D.P., Miulovic, S. M., MarcetaKaninski, M. P., (2010). Raising efficiency of hydrogen generation from alkaline water electrolysis - energy saving. *Int J Hydrogen Energy*, 35(22):12369-12373.

Ogden, J. M. (1999).Prospects for building a hydrogen energy infrastructure. *Annu Rev Energy Envision*, 24:227–273.

Orhan, M.F., Ibrahim D., Marc A.R., (2011), Simulation and Exergy Analysis of a Copper-Chlorine Thermochemical Water Decomposition Cycle for Hydrogen Production, *Intl Journal of Hydrogen Energy*, 36, 11309-11320.

Pala, L.P.R., Wang, Q., Kolb, G., Hessel, V.(2017). Steam gasification of biomass with subsequent syngas adjustment using shift reaction for syngas production: an Aspen Plus model. *Renew Energy*, 101:484-492

Pallozzi, V., Di Carlo, A., Bocci, E., Villarini, M., Foscolo, P.U, Carlini, M. (2016). Performance evaluation at different process parameters of an innovative prototype of biomass gasification system aimed to hydrogen production, *Energy Conversion and Management* 130: 34–43

Rapagnà, S., Latif, A. (1997).Steam gasification of almond shells in a fluidised bed reactor: the influence of temperature and particle size on product yield and distribution. *Biomass Bioenergy*, 12(4):281–288.

Qiu, P.H., Du, C.S., Liu, L., Chen, L. (2018). Hydrogen and syngas production from catalytic steam gasification of char derived from ion-exchangeable Na- and Ca-loaded coal. *Int J Hydrogen Energy*, 43:12034-12048.

Safari, F., Javani, N., Yumurtaci, Z. (2018).Hydrogen production via supercritical water gasification of almond shell over algal and agricultural hydrochars as catalysts. *Int J Hydrogen Energy*, 43:1071-1080.

Santos, D. M. F., Sequeira, C. A. C, Figueiredo, J. L. (2013). Hydrogen production by alkaline water electrolysis. *Quim Nova*, 36(8):1176- 1193.

Siedlecki, M., de Jong, W., Verkooijen, A.H.M.(2011). Fluidized bed gasification as a mature and reliable technology for the production of bio-syngas and applied in the production of liquid transportation fuels-a review. *Energies*, 4:389–434.

Sikarwar, V.S., Zhao, M., Fennell, P. S., Shah, N., Anthony, E.J. (2017). Progress in biofuel production from gasification. *Prog. Energy Combust. Sci.*, *61*: 189–248.

Simonyan, K., Fasina O. (2013). Biomass resources and bioenergy potentials in Nigeria, *Afr J Agric*., 8:4975–4989.

Skoulou, V., Swiderski, A., Yang, W., Zabaniotou A.(2009). Process characteristics and products of olive kernel high temperature steam gasification (HTSG). *Bioresour. Technol*. 100(8):2444–2451.

Spath, P.L., Dayton, D.C. (2003). Preliminary Screening Technical and Economic Assessment of Synthesis Gas to Fuels and Chemicals with Emphasis on the Potential for Biomass- Derived Syngas. National Renewable Energy Laboratory: Golden, CO, TP-510-34929.

Spath, P. L., Aden, A., Eggeman, T., Ringer, M., Wallace, B., Jechura, J. (2005). Biomass to Hydrogen Production Detailed Design and Economics Utilizing the Battelle Columbus Laboratory Indirectly Heated Gasifier. National Renewable Energy Laboratory: Golden, CO, TP-510-37408

Tian, T., Li, Q., He, R., Tan, Z., Zhang, Y. (2017). Effects of biochemical composition on hydrogen production by biomass gasification, *International Journal of Hydrogen Energy* 42: (31) 19723-19732.

USA Energy Independence (2007).Security Act of 2007. *Public Law 2007*, 110–140.

Valente, A., Diego, R.,Dufour, J. (2019). Life cycle sustainability assessment of hydrogen from biomass gasification: A comparison with conventional hydrogen, *International Journal of Hydrogen Energy*, 44(38): 21193-21203.

Wei, L., Yang, H., Li, B., Wei, X., Chen, L., Shao, J., Chen, H.(2014). Absorption-enhanced steam gasification of biomass for hydrogen production: effect of calcium oxide addition on steam gasification of pyrolytic volatiles. *Int J Hydrogen Energy* 2014, 39:15416-15423.

Xiao, R., Jin, B., Zhou, H., Zhong, Z., Zhang, M. (2007). Air gasification of polypropylene plastic waste in fluidized bed gasifier. *Energy Convers Manag*., 48:778–786.

Yanik, J., Ebale, S., Kruse, A., Saglam, M., Yuksel, M. (2007). Biomass gasification in supercritical water: Part 1. Effect of the nature of biomass. *Fuel*, 86:2410-2415.

Yang, R.X., Chuang, K.H., Wey, M.Y. (2018). Effects of temperature and equivalence ratio on carbon nanotubes and hydrogen production from waste plastic gasification in fluidized bed. *Energ Fuel*, 32:5462-5470.

Zhao, Y., Sun, S., Zhou, H., Sun, R., Tian, H., Luan, J. (2010). Experimental study on sawdust air gasification in an entrained-flow reactor. *Fuel Process Technol*, 91:910–914.

Zhang, Y., Li, L., Xu, P., Liu, B., Shuai, Y., Li, B. (2019a). Hydrogen production through biomass gasification in supercritical water: A review from exergy aspect, *International Journal of Hydrogen Energy*, 44(30):15727-15736.

Zhang, Y., Li, L., Xu, P., Liu, B., Shuai, Y., Li, B. (2019b). Exergy analysis of hydrogen production from steam gasification of biomass: A review, *International Journal of Hy*