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Overview of Various Biomass Energy Conversion Routes

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Abstract: Biomass usage for energy generation has come a long way and appears to be presently far from being outmoded in many parts of the world. The dependence of the world energy market on fossil fuel, particularly petroleum, has not relieved the majority of the inhabitants of the developing countries especially those of the sub-Saharan Africa of the use of biomass energy. The number of these users is on the increase perhaps owing to prevalent demographic characteristics, socio-economic realities and interplay between them. The experience in developed industrialized countries also showed that they are increasing the use of biomass in their energy mix, the source of which is likely to be from the developing countries. The effect of unsustainable use of biomass energy on the environment and by extension on the well being of human can be better imagined. Most technologies of preparation and usage of biomass energy in the developing countries have been found to be outdated as compared to that of the developed countries, thereby, requiring improvement. This paper is therefore, aimed at attempting to assess the present biomass energy conversion processes routes, the emerging ones and improvement possibilities.

Key words: Biofuels · biomass energy · conversion technologies · developing countries

INTRODUCTION

Energy is an important, if not the most critical factor in developmental activities of any nation. The measure of level of socio-economic growth and standard of living of the people of any nation are largely energy dependent.

Until the late 19th century wood was the primary source of fuel in the world. Gradually, coal replaced it and only in the 1960's did oil took over. Since then, the developed world has become heavily reliant on oil, doubling its consumption approximately every 10 years [1]. This was largely due to the flexibility of oil as fuel and its value as raw material in the chemical industry.

Conversely, irrespective of the fact that substantial quantity of crude oil is obtained from the developing countries, large proportion of the population in this part of the world depend on biomass for energy [2]. Temu [3] put the proportion of Africa's population that depend on either firewood or charcoal for cooking and heating at 90% and it has been predicted that the majority of African households will continue to depend on biomass fuel to meet their daily energy needs for many decades to come [4-6].

Thus, it follows that if the bulk of energy demand in the developing world is at the household level and biomass energy has been its major source, then it is not surprising that the level of technological development and quality of life of the citizens of sub-Saharan Africa is still at its present state.

The growing world population, industrialization, technological advancement and transportation had brought energy demand under an increased pressure recently. The world's energy markets rely heavily on the fossil derived fuels whose reserves are finite. The possibility of the future shortage of the conventional fossil oil reserve has generated an overwhelming interest in exploring an alternative sources of energy, one of which biomass is vital [7] although, the energy crisis of 1973 and 1979 had earlier highlighted the uncertainty of price and supply of crude oil and promoted research for alternative sources of energy.

Although, biomass energy content and efficiency of use might be far incomparable to that of crude oil, coupled with the disadvantages of current high(er) costs of biofuels and the large land areas required for substantial amounts of bio-energy but the large number of people in developing world that depend on it, possibility of sustainable generation of renewable raw material for biomass energy in Africa and the increasing interest of the developed countries in biomass energy conversion

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technologies, has made it necessary to review the present state, emerging conversion technologies and improvement possibilities that exist for the benefit of the developing economies.

Biomass as renewable natural resource: The 6th Edn. of Oxford Advanced Learner's Dictionary defined biomass as the total quantity or weight of plants and animals in a particular area or volume. The natural energy resources from biomass are mostly from plant and the most significant is the wood and wood "waste". "Biowaste" is an engineering classification of plant (and animal) parts unused in an industrial process [8]. This dated human concept is completely alien to natural ecosystems, which must recycle their matter completely in order to survive [9, 10].

Woodfuel both in form firewood and charcoal constituted 53% of world's total round wood production in 1997 and it was as high as 87% of Africa's total production [11]. There has been an increased projection of the global quantity of wood needed as fuel by 2010 [12].

In principle, biomass-based fuels need not be a net source of CO_2 emissions into the environment because CO_2 released during combustion would be cycled back into plant materials by photosynthesis [13]. Thus, wood use as fuel may not necessarily be detrimental to the environment and biodiversity stability as long as the world practices Sustainable Forest Management (SFM).

According to Patzek and Pimentel [8] the magic words "sustainability" and "renewability" are ubiquitous in agriculture and forestry literature. Unfortunately, these words are not defined rigorously and have almost arbitrary meanings when used by different authors. Sustainability was defined as an ideal conceivable only for cyclic processes. Patzek, [10] submitted that cyclic process is sustainable if and only if:

- It is capable of being sustained, i.e., maintained without interruption, weakening or loss of quality "forever," and
- The environment on which this process feeds and to which it expels its waste is also sustained "forever".

Therefore, as long as sustainable methods are applied, biomass will continue to be a source of energy for the increasing users in the developing world, most especially in the sub-Saharan African countries where painfully, a reliable alternative source of energy has not yet been found.

Nature of lignocellulosic biomass: Lignocellulosic biomass or phytomass is a complex material formed by organisms that possess the ability to build up carbohydrate from carbon (iv) oxide and water in the presence of sunlight and in the process absorbing energy through the process of photosynthesis. Simply put in an equation:

$$\text{Carbon IV Oxide} + \text{Water} + \text{Energy} \longrightarrow \text{Carbohydrate} + \text{Oxygen}$$

Thus, when biomass is burnt, this reaction is reversed and energy is released.

Phytomass consists mainly of lignin and carbohydrate (cellulose and hemicellulose) including small amount of minerals (ash) and various extractives. On dry-weight basis, the representative compositions are as follows: 12-20% lignin, 35-50% cellulose and 20-35% hemicellose.

Cellulose comprises long chains of glucose sugars that can be broken apart by a hydrolysis reaction with water when catalyzed by enzymes known as cellulase or by acids. However, hydrogen bonds hold the long cellulose chains tightly together in a crystalline structure, impeding breakdown to glucose. Hemicellulose is an amorphous chain of a mixture of sugars, usually including arabinose, galactose, glucose, mannose and xylose, as well as smaller amounts of a few other compounds, such as acetic acid. Hemicellulose chains are more easily broken down to form their component sugars than is cellulose. Lignin is not a sugar-based structure but is instead a heterogeneous substance based on a phenol-propene backbone [14].

Biomass energy conversion and processing technologies: Biomass that can be converted into biofuels is of two different phytomass origin: (i) conventional agricultural products and (ii) lingocellulosic products and residues [15]. Biomass can be converted to energy through the following methods:

- Physical processes
- Thermo-chemical processes
- Biological processes

These processes will be assessed based on their application in domestic and non-domestic use.

Physical processes

Densification and drying: Wood densification is the process of taking wood by-products (manufacturing residues) such as slabs, chips, or sawdust and processing them into uniform sized particles so they can be compressed into a fuelwood product [16].

In densification, the dry biomass, primarily ground, is forced through a matrix under high pressure, followed by immediate cooling for durability and stability [15]. The mostly used methods of densification based on shapes and sizes are logs, pellets and briquettes.

Logs are generally produced for temperate residential markets as fireplace and wood stove fuels. Popularity of logs, in part, is due to the fact that they are clean burning, easy to handle and burn longer than traditional cordwood. Logs are also used occasionally in small industries as fuel for boilers.

Pellets are used more in commercial applications for industrial boilers where ease of handling and burning characteristics offer a competitive alternative to coal [16]. The main advantage of pellets is the higher energy density, which reduces significantly transportation advantage, storage and handling costs per energy unit. The drawback of pellets is the global energy efficiency drop and the increasing cost resulting from investment and operation. As drying is actually necessary, the energy costs may rise up to 30 % compared with wood chips.

As an instance, a wood pellet production facility in New Zealand [17] produces 8,000 tonnes of pellets per year by using 36 GWh of steam generated from 20,000 tonnes/yr of "low-quality wood waste" (with the heating value of 6.4 MJ kg^{-1}) as heat and electricity. Therefore, the specific energy requirement to produce wood pellets is:

$$\frac{36\text{ GWh} \times 3{,}600\text{ s/h}}{8{,}000\text{ tonnes of pellets}} = 16\text{MJ kg}^{-1}$$

Thus, the transformation of raw wood into pellets requires 16/20 = 80% of the calorific content of oven-dry hardwood! If wood pellets are produced in small quantities as a by-product of other industrial processes (paper pulp and timber production), this inefficiency may be tolerated because there exists genuine "waste" wood.

If the large-scale production of wood pellets is the only goal, then the whole concept breaks immediately down, because 4 kg of the wood must be burned to produce 1 kg of pellets. However, large volumes of pellets are already subject to international trade. Indeed, Scandinavian countries import large volumes of wood pellets from Canada [15].

Briquettes, although, may not be as popular as pellets in developed countries, is gradually having an increased intensity of production in developing countries and can be used as a fuel source for both residential and industrial applications. An example of a flow diagram for the production of densified fuel from wet or dry raw material is shown in Fig. 1 below.

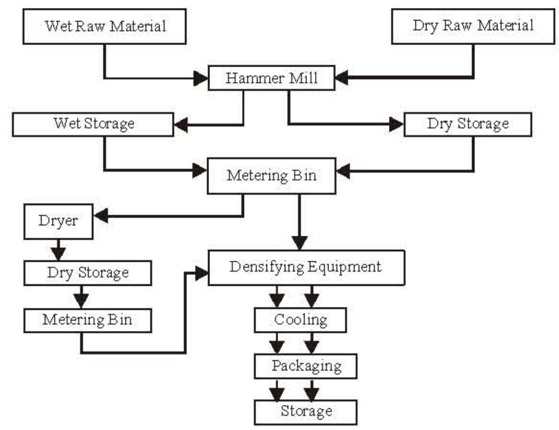

Fig. 1: Flow diagram for wet and dry materials during densification as adapted from Sims *et al.* [16]

Thermo-chemical processes

Direct combustion of biomass: This method of conversion is the most employed method especially in the developing countries where the bulk of the biomass is used in unprocessed form by rural households in traditional and inefficient devices for cooking, space heating and lighting [18]. The appliances employed range from the three-stone fire, improved wood stove, charcoal stove with ceramic liner to sophisticated charcoal burning stoves. Realizing that most of the stoves for direct combustion of biomass give room for waste of resources, researches are ongoing on how to increase the efficiency of these stoves [19, 20]. It is important to note that, unlike as it has become in Western societies, the stove is not merely an appliance for heating food. In most developing countries, people's socio-economic and cultural background is important for the success of any improved stove programme.

Another of many efforts at improving the efficiency of use of biomass as energy source is co-combustion or co-utilization, an application of which is co-firing, which refers to the practice of introducing biomass as a supplementary energy source in high-efficiency boilers [21]. A co-utilization of biomass with other fuels can be advantageous with regard to cost, efficiency and emissions [22]. Some options for co-utilization of biomass with coal as an example are:

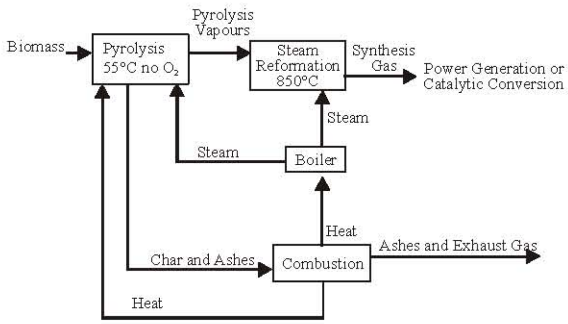

Fig. 2: Biomass Gasification via Staged Steam Reformation with Fluidized Bed Gasifier as adapted from DOE [27]

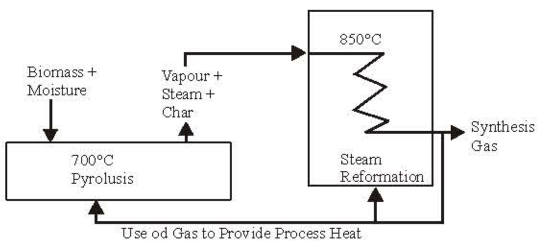

Fig. 3: Biomass Gasification via Staged Steam Reformation with a Screw Auger Gasifier
Source: DOE [27]

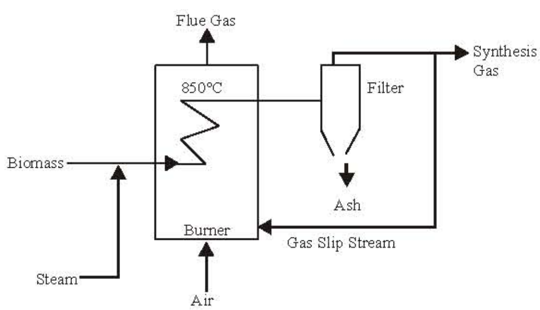

Fig. 4: Biomass Gasification via Enstrained Flow Steam Reformation
Source: DOE [27]

(a) Co-combustion or direct firing where the biomass is directly fed to the boiler furnace, if needed after physical pre-processing of the biomass such as drying, grinding or metal removal is applied.
(b) Indirect co-firing is a process whereby biomass is gasified and the product gas is fed to a boiler furnace.
(C) Parallel combustion is a process whereby the biomass is burnt in a separate boiler for steam generation. The steam is used in a power plant together with the main fuel.

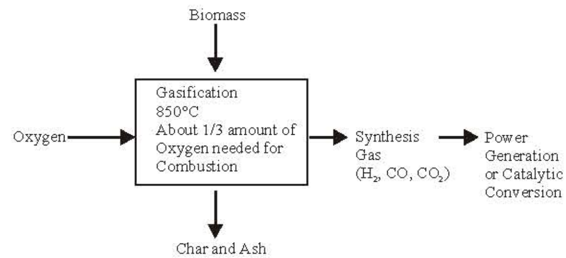

Fig. 5: Biomass Gasification via Partial Oxidation (Auto Thermal)
Source: DOE [27]

Gasification: Gasification is a process by which gaseous combustible fuel (H_2, CO, CH_4 etc.) termed as "producer gas" is obtained from biomass in suitably designed reactors or gasifiers and can be combusted in suitable burners with flame temperature exceeding 10,000°C. Wood gasification takes place at approximately 800-l, 000°C in the presence of a controlled amount of oxidizing agent. The product gas composition depends upon the starting moisture content of the biomass raw material. In addition to the above-mentioned gases, some low molecular weight aliphatic hydrocarbons are also produced. Beenackers, [23] described some of the state of the art both in small scale fixed bed gasification and in the larger scale fluidized bed technology as:

1. Fixed Bed Gasifiers:

- Counter current or up-draft gasifiers
- Down-draft gasifiers
- Cross flow gasifiers

2. (Circulating) Fluidized Bed Biomass Gasifiers with a high ash content that caused chemo-technical difficulties resulting in the closing down of the plant that applied this method of gasification in the US.

Commercial-scale model of a gasifier, with an actual user industry test, which can handle low-density leafy materials like sugarcane leaves and bagasse have been reported [24]. Researches aimed at improving this aspect of biomass energy conversion process are still ongoing [25, 26]. Some examples of large-scale gasification processes flow charts are shown below (Fig. 2-5).

Pyrolysis: Pyrolysis or carbonization or dry distillation is defined as the irreversible thermo-chemical reaction that is started by re-heating to a high temperature (above 180°C) in the absence of oxygen or controlled minimal intake, to start it and to trigger endothermic and exothermic reactions. The biomass produces, as a product of the pyrolysis process under normal conditions, a mixture of complex and highly variable fuel gases, liquid and charcoal [15, 28]. Gaseous fuel released from pyrolysis of wood includes four main gases i.e. H_2, CO, CH_4 and CO_2 [29]. According to Girard *et al.* [15], the process of carbonization follows the general scheme of:

- Between 100° and 170°C all loosely bound water is evaporated.
- Between 170° and 270°C gases develop containing carbon (ii) oxide, carbon (iv) oxide and condensable vapours, which form pyrolysis oil upon cooling.
- Between 270° and 280°C an exothermic reaction starts, which can be detected by the spontaneous generation of heat and rising temperature. Once the carbonization process has entered the exothermic phase, no more outside heating is required.

There are several types of pyrolysis processes, with different heating rates: slow pyrolysis, carbonization or torrefaction to produce a coal-like material and fast pyrolysis to produce a liquid similar to a crude oil. The production of charcoal has been the main focus of pyrolysis although, the demand for the byproducts like acetic acid, methanol, acetone, production of fuel gas, liquid (tars), various pyroligneous acids, bio-oils etc. has also been popular in the past [30].

Various methods of producing charcoal have been documented in literature [31, 32]. Generally, charcoal is produced by heating wood in airtight ovens or retorts, in chambers with various gases, or in kilns supplied with limited and controlled amounts of air. High-temperature heating by all methods breaks down the wood into gases, a watery tar mixture and the familiar solid carbon material commonly known as charcoal [31].

Recent studies have shown that vegetal wastes (agricultural residues, renewable wild-grown biomass) can be pyrolysed, transforming them into green carbon; a domestic fuel that performs the same as charcoal made from wood, at half the cost [28].

Liquefaction: The extraction of liquid from biomass for the purpose of generating energy or as a platform intermediates for production of high-value chemicals and materials is known as liquefaction. Solid biomass can be liquefied by pyrolysis, hydrothermal liquefaction, or other thermo-chemical technologies [27]. These liquid substances are mostly hydrocarbons and are also known as bio-oils.

Studies have shown that liquid oil from biomass can be used as fuel. Calvin [33] worked on *Euphorbia lathyris* that is capable of producing a mixture of reduced terpenoids that can be converted to a gasoline-like substance. Alencar [34] also reported that *Copaifera multijuga* which produces the light yellow oil (copaiba oil) that is obtained from the heartwood by tapping is also a suitable bio-oil. It was estimated by Calvin [33] that a single hole through its stem might yield about 25litres of oil in 24hours-a ready-made engine oil. A white amorphous mixture of hydrocarbon comparable with gasoline was also extracted from *Pedilanthus tithymaloides* by [35].

Bio-diesel has also been extracted from biomass using the Fischer-Tropsch (FT) method. The Fischer-Tropsch process is a catalyzed chemical reaction in which carbon (ii) oxide and hydrogen are converted into liquid hydrocarbons of various forms with iron and cobalt as typical catalysts. The large hydrocarbons can be hydrocracked to form mainly diesel of excellent quality [36]. Ptasinski [37] used poplar wood containing 50wt% moisture as a feedstock for the production of bio-diesel using the FT method and obtained 51.2% overall exergy efficiency. Exergy is synonymous with available energy or utilizable energy.

Researches are still ongoing on the conversion of wood and other biomass to bio-oil [38] although, it is important to note that economic development of plant hydrocarbons will ultimately depend upon agronomy and conversion cost [39]. An example of biomass liquefaction process through pyrolysis is shown by the flow chart below (Fig. 6).

Biological processes

Fermentation: Biomass is a mix of three basic components, lignin, cellulose and hemicellulose. Lignin serves as a sort of 'glue' giving the biomass fibers its structural strength, while hemicellulose and cellulose polymers are the basic building blocks of the fibers. In order to break down the hemicellulose and cellulose to sugars, the basic structure of the biomass must be attacked. Once the structure of the biomass is disrupted, the hemicellulose and cellulose can be converted to sugars enzymatically [40, 41].

There are two basic approaches to biomass breakdown to sugars, (1) acid hydrolysis with a variety of low acid-high temperature or high acid-low temperature conditions being suitable to both breakdown the structure

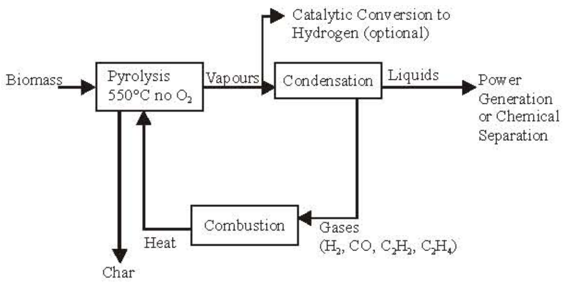

Fig. 6: Biomass liquefaction process via pyrolysis
Source: DOE [27]

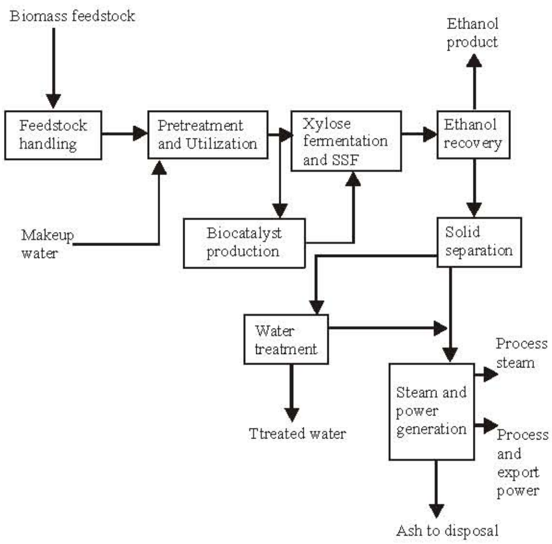

Fig. 7: Block flow diagram for conversion of biomass to ethanol by the NREL[1] process configuration. SSF, Simultaneous saccharification and fermentation
Source: Wyman [41].
[1]NREL is National Renewable Energy Laboratory, US Department of Energy

of the biomass and release free sugars and (2) enzymatic hydrolysis after some sort of pretreatment which allows enzymatic attack of the polymers [42]. The acid hydrolysis is regarded as the most technologically mature method of sugar release from biomass but in this review, the latter approach is considered owing to the fact that it eliminates the need for large quantities of acid (and the neutralization of this acid) although, commercial cellulase enzyme costs are currently high and enzyme attack of the cellulose and hemicellulose polymers can be slow [40].

Although, historically the five-carbon sugars derived by hemicellulose hydrolysis could not be fermented to ethanol at high yields, several bacteria have been genetically engineered to ferment all of these sugars in a breakthrough achievement for ethanol technology [43]. Thus, the hydrolyzate is sent to the five-carbon sugar fermentation step in which genetically engineered *Escherichia coli* or other suitable organisms convert the free sugars to ethanol, as again shown in Fig. 7.

A portion of the hydrolyzate is sent to a separate enzyme production step in which approximately 2% of the total sugars is consumed by an organism such as the fungus *Trichoderma reesei* to make cellulase. The entire broth from enzyme production, including cellulase, the organism that produced it and unconverted substrate, passes to the cellulose hydrolysis process, eliminating enzyme-processing steps, reducing the possibility of introducing invading organisms, using enzyme associated with fungal biomass and converting any cellulose left after cellulase production into ethanol [40, 44, 45].

Cellulase catalyzes the breakdown of cellulose to release glucose, which many organisms, including common yeasts, ferment to ethanol. Although the hydrolysis step can be carried out first followed by fermentation in a separate vessel, most workers in the field prefer the Simultaneous Saccharification and Fermentation (SSF) route, in which enzyme and fermentative organism are added to the same vessel to produce ethanol from sugars as soon as they are released [44, 46, 47]. Because glucose and the short cellulose chains (cellulose) formed during hydrolysis are strong inhibitors of enzymatic action, whereas ethanol has a much weaker impact on enzyme activity [48], the rates of reaction are actually faster for the SSF configuration than for a separate hydrolysis and fermentation approach, even though the temperature must be reduced from optimum levels for cellulase activity to accommodate the fermenting organism [41]. In addition, the SSF process cuts equipment and other vessel-related costs by about half and the presence of ethanol in the fermentation inhibits invasion by organisms that would thrive in a dilute sugar stream and divert sugars to unwanted products such as lactic acid.

Converting biomass to ethanol fuel has gained popularity in Brazil since the mid 1970s [49], although, using it as a fuel in the internal-combustion engine has a long history [50]. Global annual ethanol production from biomass is estimated at 18 billion liters, 80% of which is in Brazil [51]. Fuel ethanol is currently produced in Brazil, the U.S.A and several EU countries from sugarcane or starch crops including corn, wheat and sugar beets [52]. Fig. 7 below shows a flow diagram of an example of how ethanol is produced from biomass for the purpose of generating energy.

Table 1: Summary of some biofuel conversion routes

Carrier	Feedstock	Conversion technology
Hydrogen	Any type of biomass, lignocellulosic is preferred	Gasification and shift reaction hydrogen separation
Methanol	Any type of biomass, lignocellulosic preferred	Gasification, synthesis gas processing, methanol synthesis
Synthetic hydrocarbons	Any type of biomass, lignocellulosic is preferred	Gasification, synthesis gas processing and Fischer-Tropsch synthesis
Ethanol	Lignocellulosic biomass	Hydrolysis techniques + fermentation
Ethanol	Sugar and starch crops	Fermentation and distillation
Fatty acids	Oil seeds (e.g. rapeseed)	Extraction, esterification
Bio-oil	Any type of biomass, lignocellulosic is preferred for pyrolysis	-Pyrolysis + upgrading -Hydro Thermal upgrading. Lower oxygen content than pyrolysis

Source: Adapted from Faaij and Hamelinck [56]

Anaerobic digestion: Anaerobic digestion of biomass, although, an important part of modern day waste treatment, can be modulated to yields mainly Carbon IV Oxide (CO_2) and Methane (CH_4) gas [13] typically with a significant excess of methane [53]. The gases obtained this way known as biogas can be used for energy generation since more than 85% of the potential oxidation energy of the organic substrate is retained in the biogas [13].

The development of large-scale anaerobic digestion technology in sub-Saharan Africa is still embryonic but the Zimbabwean experience of using cow dung to generate 75% of the country's rural energy need, South Africa's usage of animal dung to produce substantial amount of energy per year and a US Global Environment Facility (GEF)-financed project in Dar-es-salaam, Tanzania, which was estimated to utilize 23,000m^3 of methane generated by the process of anaerobic digestion in waste landfills of the country's capital to provide a lucrative fuel from urban waste [18] are worth mentioning.

It should be noted that if methane use, as biofuel is to reduce greenhouse gas emissions, its leakage should be prevented or minimized because CH_4 is substantially more potent greenhouse gas than CO_2 [54, 55].

A summary of some major biomass conversion methods is tabulated below.

CONCLUSION

The present state of technologies for conversion and utilization of biomass energy in most developing countries especially those of sub-Saharan Africa (except perhaps South Africa) revealed that they are generally outdated in comparison to those used in developed countries. This prevailing situation needs attention owing to the fact that most of the inhabitants of developing countries depend on biomass for their means of energy generation and the intensity of use is not likely to subside in the foreseeable future.

The developed countries that are at the forefront of research and development of these modern technologies are rich countries that have the financial resources to depend heavily on fossil generated fuels (as they are presently) which thus, point to the fact that they are already looking ahead for other sustainable means of generating energy in case the oil wells dry up.

Although, some are still at research stages, the various present technologies for both conversion and utilization of biomass energy have shown that they have promising future and improvement potentials especially if sustainably sourced with little or no negative impact on the environment and human well being.

This review thus, serves as a wake-up call to all the stakeholders in the issues relating to biomass utilization for energy generation in this part of the world, to brace up for the challenges that lie ahead.

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