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Review of Biomass Gasification Technologies: Guidelines for the Ghanaian Situation

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Abstract- Biomass energy as an alternative source of energy promises to be a more sustainable replacement of depleting fossil energy supplies and exhibits the potential for energy independence in emerging economies because biomass resources used for producing biomass energy, especially lignocellulosic wastes are much easily obtained and processed for energy. Despite the limitations of the current biomass energy production technologies, in terms of resource potential, greenhouse gas emission reduction, ease of application and economic viability, there is considerable interest in biomass gasification. Over the years lots of gasification technologies have been developed worldwide. This study examines gasification technologies that have been presented by different authors for the last 35 years with emphasis on the situation in Ghana. The study found out that small scale, direct heating and fixed bed gasification devices are more suitable for the Ghanaian energy sector. For electrical power production, small scale and fixed bed gasifiers coupled with ICE engines generator were found to be the best for Ghana. This perfectly meets the available local technical skills, the feedstock availability and market demand (mainly for cooking fuel).

Keywords Gasification, Mathematical Model, Biomass, Biochar, Biofuels.

1. Introduction

The part that energy plays in the sustainable development process has become more conspicuous in recent times [1, 2]. Bioenergy has shown a lot of potential in replacing depleting fossil energy supplies and providing energy independence in emerging and underdeveloped economies because biomass, especially lignocellulosic wastes, are much easily accessible and easier to convert to energy than other alternatives in developing countries. Biomass has become a potentially vital source of renewable and sustainable energy due to the global challenges in the energy sector. These challenges are mainly environmental destruction concerns, depleting oil reserves and increased global demand [3-6]. In Ghana, biomass is traditionally the main source of energy but use technologies that are efficient. These technologies are mostly firewood and charcoal stoves for cooking and heating [9-11].

There are currently two main ways by which biomass can be turned into useful products; either biological or thermochemical processes [13-16]. The biochemical route uses enzymes and/or microorganism in the breakdown of cellulosic and hemi cellulosic component of biomass feedstock to sugar. The sugar is later fermented to produces bio ethanol. In the thermochemical route of bioenergy and co-product production involves heating biomass to temperatures above 50 ºC during a variable residence time with the aim of producing liquid, solid and or gaseous fuels and industrial/chemical co-products[17]. The thermochemical pathway of biomass conversion suffer less from the technical hurdles because most of its technologies are proven and more advanced [12]. In developing countries, biomass conversion to energy is achieved in a great portion through thermochemical pathways mainly as firewood and charcoal for cooking and heating [7]. Ghana has a diverse energy demand dynamics and the breakdown of the total energy consumption of the country is given as 111 PJ liquid fuel energy, 25 PJ electrical energy and 360 PJ thermal energy [7, 22]. The liquid fuels are gotten from petroleum crude oil/products which is mostly imported[23]. The petroleum products are imported either in the refined form or as crude, which is then refined by the Tema Oil Refinery (TOR) and sold on commercial basis for cooking, transportation and the generation of power [7, 23]. The electrical energy is harnessed from hydro-dams, thermal and solar sources and transmitted to Ghanaian homes and industries for use. The reduction in rainfall coupled with increase in the demand for electricity has thrown Ghana into a lot of crisis economically and politically in recent times [24]. In 2010, thermal generation contributed about 31% of the electricity supply of Ghana but this is expected to increase in the near future [24]. The wood energy is mostly obtained from the forest zones of the country and turned to usable energy mainly by thermochemical methods of energy conversion. It goes to prove that thermo-chemical pathways of energy generation contributes a greater percentage of the energy supply of Ghana than any other pathway. The popularity of the thermochemical energy generation infrastructure gives thermo-chemical biomass conversion technologies a head start as far as potential success is concerned. The technical workforce of the country is already familiar with thermo-chemical energy technologies. It will relatively be easy for them to understand, use, manufacture and maintain new systems with similar principles. This paper aims to assess the various gasification technologies that have been presented by different authors. The critical questions addressed in this paper are: 1) which of the gasification technologies is most suitable for the Ghanaian energy sector? 2) how much energy can be injected into the energy sector of Ghana through gasification? 3) how should the gasification industry of Ghana be shaped 4) what are the emerging trends in Biomass Gasification? 5) how can biomass gasification in Ghana be improved?

2. Thermal Systems Using Biomass in Ghana

There are many thermal biomass energy systems in Ghana. The greater number of these thermal biomass energy devices are used for cooking at the domestic and at the commercial settings. These technologies can be divided into three main types namely, combustion, pyrolysis and gasification technologies. There are, however, a less popular thermal treatment of biomass, which happens at a milder temperature called torrefaction or roasting. Torrefaction is usually used as a pretreatment method to improve the quality of biomass feedstock in terms of fuel characteristics especially the quality of the fuel's moisture content[17]. According to Bridgeman et al. [29], torrefaction is mainly, a moisture reduction and low weight organic compounds removal process, which can also lead to depolymerization of long polysaccharide chains [29]. The abundance of the sun's energy can be harnessed (using solar thermal systems) to perform torrefaction to improve the energy density of biomass at very low cost since the sun's energy is freely available in Ghana. The improved biomass energy density will help increase the overall efficiency of the thermochemical system in Ghana.

2.1. Combustion Technologies

The biomass combustions technologies retrieve the energy stored in biomass by thermally decomposing the materials in the presence of stoichiometric amount of oxygen. The combustion reaction is exothermic and produces oxidation temperature of about 1450 oC [20]. Combustion of biomass and other feedstock is commercially used all over the whole world to provide heat and power. In Ghana, the combustion technologies in wide use are cookstoves (improved and traditional ones), boilers, and steam generator for power plants [9]. The cookstoves are mostly used in homes, restaurants and hotels for cooking of various meals. Boilers are used in breweries, and herbal medicine production facilities. Steam generators also produce steam by burning biomass or petroleum products as fuel. In combustion technologies, carbon dioxide and water are produced due to the presence of carbon and hydrogen in the fuel. The carbon contained in the carbon dioxide is harmful to the health of the user and to the ozone layer. The release of black carbon into the atmosphere due to incomplete combustion contribute significantly to global warming. The deaths caused worldwide by continuous exposure to smoke from cooking devices are approximately 4.3 million per year, more than those caused by malaria [31, 32].

2.2. Pyrolysis Technologies

: Pyrolysis is thermochemical decomposition of an organic matter in the presence of limited amount of oxygen (less than the stoichiometric) that yields large proportion of solids, less liquid and little gas products [9, 33]. The proportions of solid, liquid and gas yields in the pyrolysis process can be manipulated using the heating rate, temperature level and residence time [33, 34]. Generally, the process of pyrolysis can be group into three main classifications namely; slow pyrolysis, fast pyrolysis and flash pyrolysis. Many different kinds of pyrolysis devices exist, namely the rotary hearth furnace, rotary kiln and fluidized bed furnace. Slow pyrolysis is the traditional and widely used process, which is achieved at relatively low temperatures (300 – 600°C). The slow pyrolysis process yields more solids (20% to 40% of solids/biochar/charcoal). Fast pyrolysis is used for the production of bio-oil and it is characterized by relatively faster heating rate, higher temperatures (usually above 500oC) and shorter residence time usually fraction of a minute [17, 30]. In fast pyrolysis, the proportion of liquids can go up to 75% and between 10-15% of solids mostly used as biochar. Flash pyrolysis process makes of special reactor configuration and heat transfer mediums to introduce feedstock into the pyrolyzer enable it to pyrolyze biomass in a few seconds. Flash pyrolysis occurs at temperatures up to about 950 oC and produces almost only bio-oil [33]. Pyrolysis is an important process as far as the Ghanaian energy sector is concerned. Many Ghanaians use charcoal daily, which is a product of the slow pyrolysis process. According to Ameyaw [35], approximately 50 percent of the total wood consumption of Ghana is in the form of charcoal. This translate to about 9 million tons (since annual wood consumption of Ghana is 18 million tons) of wood being pyrolyzed in Ghana annually (Charcoal production). In Ghana, the most prominent pyrolysis technology therefore is the traditional earth mound pyrolyzer. In this technology, the earth serve as a container for the syngas generated in the process, limits the amount of oxygen present in the reactor and maintains the required temperature necessary for the process [36]. The most widely used products of pyrolysis in Ghana is the solid component (mainly Charcoal), whilst the liquid and gas components are either burnt to support the process or are allowed to go waste. The efficiency of this method of charcoal production is about 10-20% by weight or 20-40% by energy and it has high GHG emission [54]. The charcoal is mostly used in Ghana as a cooking fuel and even though research have shown that it can be used as a soil amendment tool, not much of it is being applied in the latter option. As a cooking fuel, the charcoal is combusted in clay cookstoves, most of which are inefficient for the production of heat energy. More than 90% of the woodfuel supply of Ghana is cut from the natural forest reserves causing a high rate of deforestation.

3. The Implication Gasification in Ghana

Ghana is endowed with high sunlight and temperature. This implies that the feedstock can be thermally treated to go into gasifiers with relatively lower moisture contents. The lower moisture content of the feedstock can help makes the gasification process deliver more energy since less process heat is required to attain oxidation/gasification temperatures. Also, the abundant heat from the sun can be harnessed for torrefaction as a pretreatment of biomass, before the biomass is fed into the reactor. With good process designs, it is possible to attain about 100 oC as entry temperature of feedstock into the reactors.

There has been a lot of interest in the production of liquid biofuels using gasification and, as such, research have geared towards the following directions;

• The potential for gasification industry to achieve high affordability, high efficiency, and greenhouse gas emission reduction. The provision and application various cheap and clean/green feedstock, in addition to the use of efficient conversion process can help lower the cost and greenhouse gas emissions for the whole fuel production chain.

• The capability of gasification devices to convert a wider range of biomass feedstock as compared to the biological routes. Thermochemical method of conversion can process lignocellulosic (woody) feedstock and wastes, which cannot be converted by the current biochemical processes. Many of the feedstock (lignocellulosic biomass) can be obtained at lower cost, no charge or even negative costs (gate fees).

• The capability of gasifiers to process different biomass feedstock mixed. Biological methods of producing energy using lignocellulosic feedstock, mainly ethanol production through hydrolysis and fermentation, requires feedstock to meet certain specific characteristics. Therefore, pre-treatment steps are usually required for optimal performance. As such, many of these conversion methods have a limited capability of processing many different kinds feedstock including agricultural wastes. The capability of thermochemical conversion methods to apply multi- feedstock makes them better alternative as compared to the biochemical ones. This advantage is in the fact the feedstock can be changed at different seasons depending on what is available which can be a way to adapt to feedstock accessibility challenges.

Ghana will benefit immensely from the success of these research target in ways such as; 1) affordable but more efficient gasification system will be adopted widely by Ghanaians. 2) Higher efficiency and energy density gasification systems will help reduce deforestation, which results from higher firewood and charcoal demands and it will as well reduce the overdependence on fossil fuels. 3) Ghana is blessed with a huge amount of agricultural, industrial and forest residue and municipal solid waste, which can be of use in waste to energy.

4. Gasification Technologies in Ghana

Thermochemical route of energy conversion can convert feedstock to energy through three different processes: combustion, pyrolysis and gasification. Among these three processes, gasification is considered as the most influential with higher efficiency for electricity generation and lower GHG emission compared with the other technologies [49, 50]. However, a greater amount of feedstock (more than 60%) in Ghana are burnt openly as firewood and charcoal for heat energy [51]. Biomass fuel provides more than 70% of Ghana's total annual energy demand. This biomass fuel supports domestic cooking and the informal enterprises including bread-baking, oil-palm processing, local alcoholic beverage brewing, traditional textiles, traditional soap making, fish smoking and traditional food services [51]. A number of biomass projects with the aim of efficient production of charcoal, heat and power were piloted in Ghana but had little success. Some of these projects are:

• Building and Road Research Institute and the Technology Consultancy Centre of the Kwame Nkrumah University of Science and Technology (KNUST), Kumasi and Georgia University of Technology, USA collaborated in a project in 1980. The project which was later closed down had the aimed of determining the feasibility of generating power from pyrolysis of biomass.

• CSIR-IIR collaborated with University of Southampton, UK to fabricate pyrolysis technology for the production of bio-oil using waste from agriculture and wood processing factories in Ghana.

• Various departments in KNUST such as The Energy Center (TEC), Agricultural Engineering Department and Technology Consultancy Center (TCC) have in the past developed laboratory scale gasifiers and piloted these Technologies in Ghana. TCC has a 10 kW gasification power plant currently in operation and is being used for research purposes. These projects were all carried out within the period of 1983 [55] to 2015 [56].

Apart from the combustion and pyrolysis technologies, there are many gasification devices being piloted in Ghana. Most of these technologies are still on pilot scale and this makes it difficult to accurately find out how well they can be adopted in Ghana [57]. A few test studies were carried out on cogeneration from waste from sawmills. Some of the project which became successful are; the Letus Power Plant, and SAMATEX Ltd's co-generation plant in Ghana [36, 55, 57]. Research institutions in Ghana that are involved in the development and studies of gasification (which mostly comes with pyrolysis are Kwame Nkrumah University of Science and Technology (KNUST), University of Ghana, University of Energy and Natural Resource (UENR), Council for Scientific and Industrial Research (CSIR), Kumasi Polytechnic and Zoomlion Ghana [36].

5. Demand and Use of Products of Gasification: Energy and Biochar

According to the Energy Commission of Ghana, the energy demand of the country far outweighs the supply in areas such as electricity, Liquefied Petroleum Gas (LPG), charcoal and firewood [89]. In the area of electricity, the country will need an additional capacity requirement of 450-550 MW to eliminate load shedding in Ghana [58]. LPG penetration in Ghana increased from 6% in 2000 to 18% in 2010, whereas the sector ministry targets 50% penetration by 2016. Charcoal and firewood demand is also increasing due to increasing population. Akolgo et al. [59] determined that cooking fuels in Ghana are about 41% of charcoal and 31% of firewood. It is evident from the above-mentioned outlook that the demand for energy in Ghana has huge deficits. The energy product of gasification, which comes in the forms of heat and syngas, can be of help in the quest to satisfy the energy needs. The heat can be used for cooking and heating and the produced gas (the lower heating value of which can go as high as 28 MJ Nm-1) from gasification can be used in cooking, generation of power, as transportation fuel (bio-fuel) in cars and others [60]. The energy product of biomass gasification can help reduce the electricity, heat energy (cooking and industrial process heat) and transportation fuel deficit of Ghana. Electricity can be produced from biomass through the process of gasification by combusting the syngas in an internal combustion engine (ICE) and converting the mechanical power from the ICE into electricity. Alternative ways of operating steam turbines, include the utilization of steam obtained through burning of the products (syngas and char) of gasification. The steam drives the turbines leading to the production of electricity, which can be used to provide modern services. Mostly, electricity producing plants using the biomass gasification technology are small scale types and the majority of them make use of the ICE. The turbines that are currently being applied are relatively few, new and in the form of micro Gas Turbines (μGT). Additionally Fuel cells (FC) or combined/hybrid μGT/FC power plants are being developed into an upcoming gasification electricity producing technologies but are still at the development stage, thus the power plant data in this case are only theoretical [61]. Since the development of gasification technologies in Ghana are still in elementary stages, the use of fixed bed gasifiers for gas production is the most appropriate. This argument is strengthened by the review of gasifiers integrated with ICE/generator sets, which was carried out by Lee et al. [62]. The review revealed that about 80% of these gasifiers are fixed bed gasifiers. An unavoidable element in a plant of this nature is the clean-up – gas conditioning system, because the ICE, FC and turbines require high purity levels of syngas. The cleaning systems are usually of high cost and sophistication, even greater than the gasifier units [61]. The cold dry method, which uses the bag and sand filters, can be used since it is less technically complicated and has very high efficiency of removing particulates and TAR [61]. Therefore, for the Ghanaian setting, a biomass power plant set-up with high success chances should consist of a fixed bed gasifier, a cold dry filter gas cleaning system, and ICE generator set for electricity production.

The non-energy products of gasification are biochar, fertilizers and other industrial chemicals. These bio-chemicals can be used to improve the agricultural production of Ghana. Biochar has been found to be capable of providing an alternative agricultural management practice that can be employed to achieve food security and at the same time, contribute to climate change mitigation, poverty reduction, meeting farmers' needs and minimizing the impact on environmental resources [36]. The lands used for agricultural purposes in Ghana contain extremely weathered parent materials, with alluvial soils (Fluvisols) and eroded soils (Leptosols) common to all the agro-ecological zones. The nutrient levels in these soils have been lowered considerably through inherent or human factors [63-65]. These problems mentioned above can be reduced or mitigated by the application of biochar to the agricultural soils of Ghana.

6. Barriers to Gasification Technology in Ghana

The barriers to the development of biomass gasification was identified by Kontor and Agbejule [9] as Socio-technical, Economic and Crosscutting barriers. The socio-technical barriers manifest itself in the process of getting all the resources needed for the gasification technology to perform successfully and satisfying the technicalities of all the technologies being employed including ash handling, gas cleaning, tar minimization and cleaning and moisture content reduction as well as availability of qualified technical expertise. Some of the gasification projects in Ghana failed because of resource problems such as poor quality and inadequate feedstock supply (Attakora, n.d). In the past, research found out that products of gasification are not marketed well enough to trigger commercial interest in the area [9]. The area of biomass gasification needs an interdisciplinary and inter- sectorial planning, which will bring together research institutions, government agencies, financial institutions and non-governmental institutions together to build a formidable and an innovative industry – the bio-refinery. According to Attakora (n.d.), lack of funds to conduct repairs, maintenance and modification to adapt to the changing world is one of the stumbling blocks of the gasification projects in Ghana. The solution to this problem was identified as a well-planned management team with the inclusion of commercial user and sound technical support team tasked to run the plants sustainably to achieve payback at a specified deadline. A study conducted by KITE and cited by Attakora (n.d), found out that the low electricity tariffs in Ghana is hampering the success of projects (situated in Ghana) aimed at producing electricity through the gasification of biomass.

The crosscutting barriers deals with the interrelationship between the socio-technical and economic barriers and the flow of information between the agencies and actors involved in the biomass gasification industry [9]. A collaborative approach involving public, private and all stakeholders, which is consolidated by effective communication among all the actors is needed [9].

The success of biomass conversion to electricity are shown in Table 2. These plants were located near sources of adequate feedstock supply. The residues from Oil Palm processing produced by the listed companies are supplied as feedstock to the power plants. These plants are maintained and repaired by qualified technical staff. The primary focus of these companies is to produce oil palm products and to utilize the oil palm processing residues to generate electricity for their operations.

The successful projects mentioned in Table 1, can be used as a lesson to improve the biomass gasification industry in Ghana. Biomass gasification projects need to be associated with a driver as in the cases of the projects in Table 1. The driver must be a product in higher demand with clear commercial potential. The projects above attached the power plants to the production of Palm Oil, which have huge markets. Other possible drivers with higher commercial potential are cooking energy, rice farms and processing sites, timber processing, irrigation sites and other crop plantations. In addition, in order to deal with the problem of feedstock supply, the biomass potential, its seasonality and feasibility studies should be properly carried out, before the setting up of gasification projects. The use of small and portable gasification technologies will help solve the problem of scattered and the dotted nature of available feedstock. The feedstock types are also diverse in nature and, therefore, technologies that use more than one feedstock –multifeed- is more likely to succeed compared to gasifiers that are feed specific.

Table 1: Biomass-fired co-generation plants in Ghana [66]

Plant Location	Installed Capacity, kW	Average Annual Production, GWh
Ghana Oil Development Company, Kwae	2500	6.8
Juaben Oil Mill, Juaben	425	1.5
Benso Oil Mill, Benso	500	1.9
Twifo Oil Palm	610	2.1

7. Conclusions

There have been efforts in Ghana to tap into other renewable and sustainable forms of energy including bioenergy/biofuels, some of which are harnessed through gasification. These efforts have been in existence in Ghana since 1983 as literature available can show. In summary, the way forward for the biomass gasification industry of Ghana in terms of priority steps are as follows:

• The gasification industry can harness the abundant and free sun's energy for pretreatment of biomass to increase the overall efficiency of the gasification process.

• The gasification technologies of Ghana should be able to accept wide range of feedstock types and properties, since Ghana has diverse feedstock base.

• The type of electrical power plants that are likely to be successful in Ghana currently are small scale and composed of fixed bed gasifier coupled with either ICE/steam engine generator, which will make them portable.

• Small scale and portable gasifiers should be the technologies employed in Ghana because of the dotted nature of the feedstock sources.

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