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Feasible Biomass Energy Conversion Technologies In Developing Countries

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Abstract

Biomass energy refers to energy produced from organic materials. It is the only renewable energy sources that can provide all forms of energy as solid, liquid and gas and furthermore, other essential chemical products from its bio-refinery processes. It can be converted into liquid transportation fuel, in the form of bioethanol and biodiesel, as methane and hydrogen gas, and solid form as fuel wood, charcoal and briquettes. Thermo-chemical, biochemical and physical processes involving different conversion technologies are some of the technologies converted biomass into different forms of energy carriers. While there is a growing interest to use biomass as one of the promising renewable energy sources, its production is limited to inefficient process due to inapplicability of most of the conversion technologies. Particularly lignocelluloses based conversion technologies are still limited to lab scale and has not been yet commercialized. However, some of the conversion technologies are applicable in developing countries to convert available biomasses to efficient form of energy carriers. Anaerobic digestions, densification, fermentation and extraction are some of them applicable to convert biomass into biogas, briquettes, bioethanol and biodiesel. Because these technologies are well matured, requires less technical personnel to operate and they are easily adaptable to any areas where the biomass resources are available.

Key words: biomass, energy conversion, suitable technology, developing country

1. Introduction

Biomass energy refers to energy produced from organic materials. It is the only renewable energy sources that can provide all forms of energy as solid, liquid and gas and furthermore, other essential chemical products from its bio-refinery processes. It can be converted into liquid transportation fuel, in the form of bioethanol and biodiesel, as methane and hydrogen gas, and solid form as fuel wood, charcoal and briquettes. Biomass energies are produced from agricultural and forest products or the biodegradable portion of industrial and municipal waste [1, 2]. Biomass provides multiple essential energy services such as electricity, heating, cooking, and transportation fuels[3]. Biomass energy continues to be the major energy sources of about 40% of the global population living in developing countries despite its many drawbacks. Presently, biomass energy in developing country is used in inefficient stoves where its conversion efficiency is about 10%. Using inefficient system required availability of huge amount of biomass to provide the required cooking energy demands. In rural areas, biomass is perceived as a free commodity collected from their backyard or from common sources. However, in its present form it involves a lot of environmental, economic, social and health issues. Environment friendly and efficient production and consumption system needs to be established.

Many of the biomass energy conversion technology studies rarely made clear distinction on the biomass resources conversion routes which can meet the need of developing countries[4, 5]. Most of these technologies for conversion of biomass is limited to lab scale and rarely commercialized [6]. First generation biofuel from sugary and starchy crops are popular in countries like US and Brazil, with well advanced production efficiencies and commercialization [7]. Second generation biofuels produced from lignocelluloses materials from agricultural and industrial sources are deemed to be a promising feedstock regardless of their technological challenges [8, 9]. Those sophisticated technologies may not be an option but needs to be identified among several technological options. Some of the technologies are already proved to be adapted to bring immediate benefits to solve rural developing countries cooking energy needs [10] but are not sufficient to address rural energy demands. More conversion technologies are required to be explored to identify suitable conversion technologies that can suit to different forms of biomasses, which this paper aims to focus on. This paper is organized as follows. First, available biomass energy conversion technologies are identified and discussed. Second, different forms of biomass energy careers are reviewed and presented in relation to available suitable conversion technologies. The third section discusses different biomass energy conversion technology limitations and identifies suitable options for developing countries. The last section forwards remarking conclusion.

2. Biomass energy conversion technologies

Biomass is the only sources of renewable energy exist in three states as solid, liquid and gas. It is also the only renewable energy used for transportation. Different techniques and methodologies have been so far developed to extract the energy in biomass. It is impractical to obtain all the embedded energy with the current existing technologies due to the complexity of the biomass chemical composition, efficiency of the technology and environmental factors. Theoretically, biomass contains about 18MJ/kg of energy but not all this is exploitable; some left unconverted, dissipate during conversion and use, only a fraction of it is obtained. The process of conversion and the amount of biomass energy converted depends on the techniques used, type of carrier and end-use facilities. Combustion, biochemical and thermo-chemical process are some of the technologies used to convert the energy in a biomass. The conversion process varies between first generation and second generation biofuels [11]. First generation biofuel is the bio-based fuel produced from oily and sugary crops through a series of fermentation process as biodiesel, bioethanol and biogas, whereas second generation biofuel refers to advanced form of these fuels produced from lignocelluloses materials collected as feedstock[12]. Today there are three methods available to convert biomass: thermo-chemical, biological conversion and physical conversion routes. A Thermo-chemical biomass conversion route includes combustion, pyrolysis and gasification; the biological process involves fermentation and hydrolysis whereas the physical conversion included densifications and extractions. Diagrammatic representation of the conversion system is presented in fig.1.

2.1 Thermo-chemical conversion

2.1.1 Direct combustion

Combustion is the oldest form of biomass energy conversion techniques used since human started using energy. It had been used for cooking, heating and as a weapon to defend from wild animals attack. This techniques is still functioning today being improved or as it is used in rural developing countries. The amount of energy converted with this technique depends on the moisture content of the biomass. Some of the energy is dissipate to remove the moisture and the useful energy obtained is directly related to its moisture content. To increase the temperature of 1kg of water by 1°C, a kcal or 4.2KJ of energy is required. In traditional combustion only heat for cooking energy is produced unlike that of modern combustion that produces heat and electricity. Since recently biomass co-firing regarded tremendously in most developed countries as semi-renewable technology used to produce heat and electricity[13]. Biomass co-firing increases the share of renewable energy and a means of reducing polluting gas from burning coal alone [14, 15]. Co-firing mostly performed with solid biomass while the liquid and gaseous biomass fuels are gaining some interest as highly efficient co-firing energy sources [14]. Lignocelluloses materials as wood and agricultural residues are most of the biomass energy sources identified to be used as a co-firing. Co-firing technology adapts functioning coal technologies in which coal and biomass combust directly blended, in parallel and indirect co-firing. In the latter two, coal and biomass combust differently and inject to the power system.

2.1.2 Pyrolysis

Pyrolysis is the current important but old thermal processes used to convert biomass into solid, liquid and gas in the oxygen deficient environment. It is an efficient process can be adjusted to favor charcoal, pyrolysis oil, gas, or methanol production with a 95.5% fuel-to-feed efficiency [16]. Pyrolysis of biomass is a promising route for the production of solid (char), liquid (tar) and gaseous products as possible alternate source of energy. Pyrolysis process consists of three subclasses as conventional, fast and flash pyrolysis on the basis of operating conditions[17] such as temperature, reaction rate, residence time and particle size. Pyrolysis achieves complete thermal decomposition of hemicelluloses, cellulose and lignin materials through complex reaction mechanism[16]. Maximization of the yield of liquid products from biomass pyrolysis requires higher heating rate and longer gas residence time, whereas in fuel gas low heating rate is required [18].

2.1.3 Gasification

Gasification for power production involves the conversion of biomass in an atmosphere of steam and air to produce a medium or low calorific value gas [16]. The process of gasification involves reacting biomass with air, oxygen, or steam to produce a gaseous mixture of CO, CO_2, H_2, CH_4, and N_2 either known as producer gas or Syngas. Syngas can be produced from biomass by two routes consisting of catalytic and non-catalytic processes. Non-catalytic process requires a very high temperature of operation, as high as 1300°C, whereas catalytic process can be operated at substantially lower temperature [12]. Producer gas is primarily useful as a fuel for stationary power generation, whereas Syngas may be, and is presently, used to make a range of fuels and chemical intermediates. For transportation fuels, the main Syngas derived routes to fuels are hydrogen by water-gas-shift reaction[19]. This technology is one of the promising techniques to produce hydrogen gas which is superior to any conventional energy carrier.

2.2 Biochemical conversion

Biochemical conversion include a variety of chemical reaction catalytically mediated inside microorganisms as whole-cell biocatalyst and enzymes to convert fermentable feedstock substrates into fuels or other useful products[20]. It is one of the environmental friendly energy conversion processes with less by-products and pollutants which can be applicable to broader range of biomass compared to thermo-chemical conversion. It is biologically operates at relatively lower temperature and longer residence time [11]. The biochemical process includes two main processes: anaerobic digestion and fermentation processes. This technology use microorganisms to convert the volatile portion of biomass to biogas in anaerobic digester and sugary portion biomass to ethanol in ethanol producing industries. It is one of the prominent and widely applicable technologies in the world.

2.2.1 Anaerobic digestion

Anaerobic digestion is a biological process in which different species of bacteria act on the biomass decomposition process in oxygen deficient environment. Biogas is the main product containing of 60-70% methane and 20-40% carbon dioxide[11]. The amount of biogas yield depends on the volatile organic content of a variety of biomass sources such as agricultural wastes, animal manure, leftover foods, municipal solid wastes and industrial process wastes. Wood residues containing high lignin content are less favourable to biogas production. Anaerobic digestion is a well-established technology across the world widely applicable to provide clean energy to rural developing countries. It uses to produce heat, light and cooking services while its purified methane can be applied to gas turbine for electricity generation or transportation fuel[11]. Digesters range in size from around $1m^3$ for a small household unit to as large as $2000m^3$ for large commercial installations[18]. There is also a growing interest to advance the anaerobic digestion to production of hydrogen energy through dark reaction.

2.2.2 Fermentation

Fermentation is the well-known process used for alcohol production from a variety of biomass sources containing sugar, starch or cellulose. Sugar cane, corn crops and other sugary crops are the main feedstock, while there is a growing interest to produce from agricultural residues and short rotation coppice crops [21, 22]. Production of ethanol from lignocelluloses material requires advanced technologies due to the complexity of cellulose materials. Lignocelluloses materials need to be disrupted through a series of enzymatic and chemical treatments to produce hydrolytic products like sugar, lignin, cellulose and hemicelluloses. These products further treated to break into simple sugar favourable for fermentation. Different fermentation process can be applied to extract energy and other useful products[23]. The process involves the action of yeast that breaks down sugar and convert to methanol then converted to ethanol through a distillation processes[18]. Ethanol is a comparative cleaner burning fuel with high octane and fuel-extending properties in which it’s blending with petrol contribute in the reduction of carbon monoxide emission from vehicles [23]. Today this technology is practiced in both western and developing countries.

2.3 Physical conversion

Physical conversion involves the application of mechanical forces of extraction and compaction of biomass to obtain densified energy. Crude vegetable oil is extracted from its seed by applying mechanical pressure using screw pressure. Briquetting is another physical conversion process where low density bulk biomass is converted to high density energy[24]. Briquettes can be densified by pyrolysis using a binder, direct densification using binders and without a binder, which can be achieved by compaction technologies like piston, screw, roller press densification, pelletizing and manual presses[25]. One of the main problems associated to agricultural residue to use as fuel is its low bulk density, higher rate of combustion and lower energy intensity and furthermore its unsuitability to modern efficient stove. This can be overcome by converting to briquette, suitable to satisfy the growing energy demand in industries and households. Briquettes and pellets are also suitable to use as co-digestion with coal to produce heat and electricity.

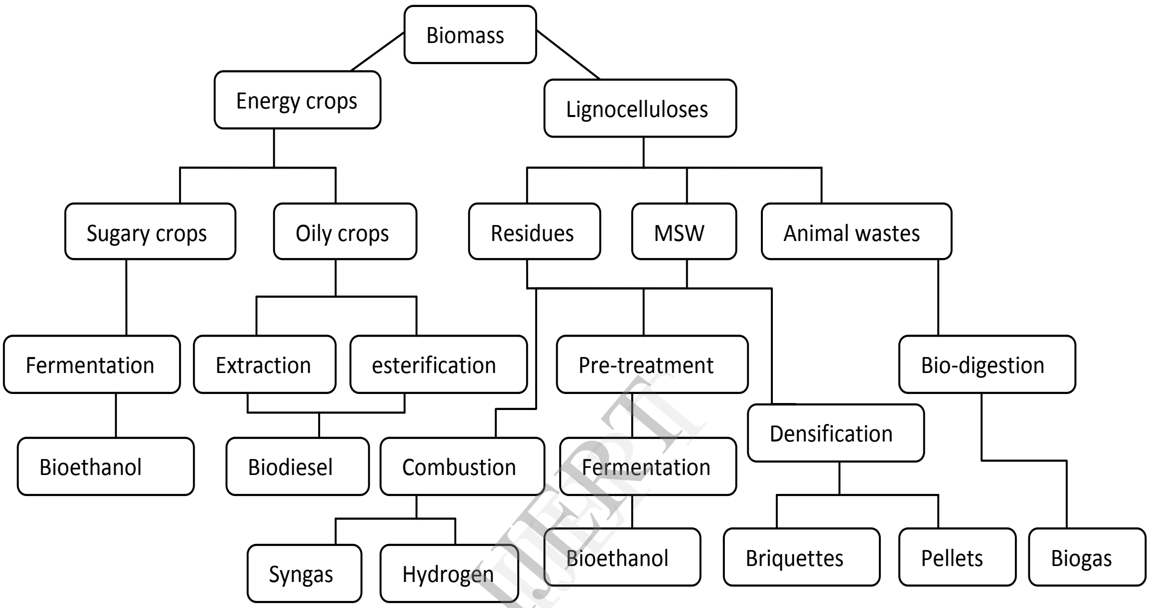

Figure 1 Biomass energy conversion processes

3. Biomass energy carriers

Biomass is a unique renewable energy carrier that can be converted into solids, liquids and gases. It is an indirect form of solar energy converted into complex organic compounds involving carbohydrate and lignocelluloses compounds. These compounds contain different organic molecules capable of converting into variety of simple compounds involving different bio-chemical and thermo-chemical routes [7]. The process of conversion and employed techniques determine its form as solids, liquids and gases.

3.1 Solid biomass energy carriers

3.1.1 Firewood

Firewood is a solid form of biomass energy used without processing. This involves biomass energy from forest, agriculture residue and household wastes that can be burned without further processing. The gross calorific value of a dry biomass ranges from 18-22MJ/kg; but it reduces as its moisture content increases [26, 27]. Moisture content determines the net heat value or the amount of energy actually obtained, due to the fact that some of the energy dissipates as latent heat of vaporization [28]. For instance the energy contained in agricultural wastes at 20% moisture content varies from 11-16MJ/kg[27]. This is also subjected to efficiency of stove, where about 50% of the heat dissipates in three stone open fires. Depending up on the type of utensils, the amount of energy actually delivered for cooking is low. Firewood use varies from open air to co-firing in heat and electricity [26]. To date, this biomass is the main source of energy for about 40% of the global population, despite the growing concern for its deforestation and health effects. It is also one of the promising renewable energy substituting coal in coal firing power plants as co-fire in developed countries.

3.1.2 Charcoal

Charcoal is the solid form of biomass energy derived from biomass through thermal process involving carbonization of wood [29]. About 6-12kg of dry wood is required to produce a kilogram of charcoal, which varies with the type of production processes. The most commonly used charcoal production process in tropical Africa is made in earth kilns of which the pit kiln and the surface earth-mound kiln. The pit kiln is constructed by digging a pit or trench in the ground and filling it with wood before covering the wood pile with green leaves or metal sheets and soil to prevent complete burning of the wood to ash during carbonization. The earth mound kiln is built by covering a pile of wood on the ground with leafy or herbaceous material and soil[30]. These methods are highly inefficient with high emissions rates. About 500g of CO2, 600g of CO and 700g of methane is produced per kg of charcoal produced[31]. The energy content of charcoal varies from plant to plant, but in average about 30MJ/kg of charcoal can be obtained; about 14-25% of the original wood [32]. Charcoal is relatively suitable to use with different stoves, easy to transport, highly energetic than fuel wood and widely used in urban developing countries.

3.1.3 Briquettes

Briquettes is a solid form of high density biomass energy converted from low bulk density biomass to high density biomass and energy concentrated fuel by using high pressure and binder[33]. Briquettes have high specific density, about 1100-1200 kg/m^3 and bulk density about 600-800 kg/m^3 as compared to the biomass which have a bulk density in the range of 80-200 kg/m^3. Binding materials increases the durability of the briquettes beside to aiding its ignition[34, 35]. Briquettes has an advantage of high and better quality calorific value per volume, require less area of storage and easily transportable than raw biomass[36]. Its energy density can be increased through a process of carbonization in double (25-30MJ/kg) relative to the raw biomass containing about 15MJ/kg [33]. Briquette can substitute forest based charcoal to satisfy the growing energy demand in urban households and commercial areas being converted from agricultural and industrial residues. By this technique it is possible to reduce the growing concern from cutting and burning of forest biomasses which is used as firewood and charcoal.

3.2 Liquid biomass energy carriers

3.2.1 Bioethanol

Bioethanol is a liquid transportation fuel produced from sugary and starchy biomasses. It has a 78.8^{0}C boiling point, a density of 791kg/m^3 and a heating calorific value of 26.8MJ/kg [37, 38]. Due to competing interest on crop based feedstock, currently there is a growing interest and technology to produce from lignocelluloses materials. Production of bioethanol from lignocelluloses still under investigation and did not put into commercial production due to factors related to difficulty to hydrolyze lignocelluloses biomass to sugar. Modern concept relies on the combination of thermo-chemical and biochemical processes as a pretreatment to hydrolyze celluloses[39]. The pretreatment is an additional complex step to traditional process that requires huge energy, chemicals and enzymes to hydrolyze lignocelluloses into fermentable sugar[39, 40]. Cellulosic ethanol is not a new technology, but the question is on the ratio of product to process energy, where huge energy and materials spend on the pretreatment. Bioethanol from bagasse is already in commercial production in both developed and developing countries. In 2011, Ethiopia produced 18 million litres of bioethanol from three sugar factories out of which 15.7 million has been blended with gasoline at 5% and the rest used for household cooking[41]. In spite of such constraints the lignocelluloses feedstock is relatively abundant, inexpensive and less competitive compared to the traditional sugar and starch based production arising a lot of debates.

3.2.2 Biodiesel

Biodiesel is an aromatic and sulphur free iso-paraffin rich diesel fuel with a high Cetane blending value that is fully compatible with the petroleum derived diesel. It has specific gravity of 0.88 and heating value of 38MJ/kg [42]. It is produced by hydro processing of vegetable oils and animal fats. Soybean, rapeseed, palm oils, sunflower and other non-edible oils like Jatropha and algal oils [43-46] are some of the important feedstock in both developed and developing countries in commercial productions. Vegetable oil could be used directly as an engine fuel, but it may hamper engine performance due to high viscosity of vegetable oil. Therefore, trans-esterification of vegetable oils enhances the quality of biodiesel by reducing its viscosity and enhancing other physical and chemical properties[47]. Different technological possibilities developed daily to improve or produce better quality biodiesel, like homogeneous and heterogeneous acidic and basic compounds and enzymes that can speed up the esterification process as well as its physic-chemical composition [48]. Unlike that of cellulose bioethanol, biodiesel have the tendency of resources competition if vegetable oils and productive land is used for its production like Jatropha in developing countries.

3.3 Gaseous biomass energy carrier

3.3.1 Biogas

Biogas is a mixture of 60–75% CH4 and 40–25% CO2, can be produced from a variety of organic compounds through a complex anaerobic digestion processes, and can be upgraded by further steps to bio-methane[49]. It has a calorific value of about 20–25 MJ/m^3 which can be upgraded by removing the carbon dioxide[27]. Biogas production process is a well advanced technology involving simple design and operation, established including rural developing countries. A wide range of biomass wastes from kitchen, sewage sludge, organic effluents from food and dairy industries, agricultural crop residues, municipal solid waste, livestock manure, and others wastes can be used as feedstock. The produced slurry as digester residue has a potential to be used as fertilizer and soil conditioner. Biogas digester can be operated in different range of temperature as thermophilic system operated at high temperature (50-70^{0}C), mesophilic system, moderate temperature ranging between 35-40^{0}C and psychrophilic system that operate at temperature range of 15-25^{0}C. Operating temperature is very detrimental factor to obtain high gas conversion efficiency with short hydraulic retention time[50], it takes up to months in a very low temperature.

3.3.2 Bio-hydrogen gas

Hydrogen is odourless, colourless with a density of 0.0824kg/m3 and flammable velocity of 1.85 m/s. Hydrogen has a lower heating value of 119.7MJ/kg (9.9 MJ/m3), almost three times higher than other energy carriers such as gasoline, diesel and methane. Hydrogen is the most plentiful element in the universe, making up about three-quarters of all matter as part of the molecules of water, methane, fossil fuels and organic materials like biomass[51, 52]. Bio-hydrogen is a new generation biofuel energy produced from biomass sources through thermo-chemical and biochemical processes. Thermo-chemical process involves pyrolysis and gasification of biomass to Syngas rich in hydrogen with a low content of hydrocarbons. The biochemical process involves different fermentation processes of anaerobic bacteria controlled by hydrogen producing enzymes, such as hydrogenase and nitrogenase[49]. Hydrogen is a promising future renewable energy carrier despite its current challenge of its production technology, transportation and storage that requires special precaution.

4. Suitable biomass energy conversion technologies to rural developing countries

Since recently, biomass energy is considered as one of the renewable energy sources that regenerate in a natural process. It is also one of the carbons neutral energy sources stabilize its carbon dioxide through a process of photosynthesis. However, in developing countries biomass is perceived to be a cause for deforestation and impaired health due to heavy reliance as a main cooking energy. As consequences, women in developing countries spend many hours to collect firewood and use in efficient stoves requiring large amount of biomass to satisfy the required cooking energy demands[53]. Due to this, forest based biomass is no more a sustainable option to be used in traditional stoves, further conversion technology is required.

As discussed in section 3 of this paper, different biomass energy conversion technology are available to convert biomass into different forms of energies as solid, liquid and gas which can be used different purposes. All of these biomass conversion technologies have their own comparative limitations to be used in developing[5]. Most of the technologies intended to convert lignocelluloses biomass are still limited to lab scale and has not been yet commercialized due to the costly conversion processes requiring huge energy and chemicals for pre-treatment. However, some of the conversion technologies are capable to be managed and operated by rural households. Anaerobic digestions, fermentations, densification and extraction are among these technologies that could be used by rural peoples. Anaerobic digestion is mostly tested with a wide range of feedstock particularly with cow dung in most developing Asia and Africa [54, 55]. The biogas from the anaerobic digestion provides multiple essential services like cooking and lighting services. Fermentation of molasses for ethanol production from sugar factory is also well established and practiced in most developing countries, where the resulting ethanol is used for cooking. In addition, rural people extract oil mechanically from oily crops which could be used as a substitute for diesel power generators. This is mostly experienced in some Asian and African countries where rural households contribute

Jatropha seed to produce its oil for small scale diesel power generation[3]. The last suitable biomass conversion technology is densification. Densification is a process of solidifying and densifying the low bulky weight biomass to increase its calorific value as well as to make it easily manageable. This technology is widely used in most developing countries to satisfy the increasing energy demand in residential and commercial areas[56]. Hence, these four technologies are technically amenable to be handled at rural areas where the growing concern for firewood is high.

5. Conclusions

Biomass energy is one of the renewable energy sources that can provide multiple essential energy services being converted to different forms of energy as solid, liquid and gases. Biomass use and its efficiency depend on the technology deployed to convert into the energy form desired to be produced. Most of these conversion technologies are limited to lab scale and has not been commercialized, but few of the technologies are easily adaptable to developing countries to change the existing poor conversion technologies. Anaerobic digestions, densification, fermentation and extraction are some of them applicable to convert biomass into biogas, briquettes, bioethanol and biodiesel. Because these technologies are well matured and requires less technical personnel to operate and easily adaptable to any areas where the biomass resources are available.

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