Biomass Conversion Technologies

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Abstract

Today the dominant biomass conversion technology consists of the combustion of biomass as fuelwood, as field and forest residues, or as process residues, such as bagasse and black liquor. Many of the combustion processes in use today have poor environmental characteristics and low efficiency. This is especially true of cookstoves in developing countries; they are a major cause of respiratory disease and also contribute to greenhouse gas production. Modern industrial combustion technologies are now available, through which is realized the goal of a closed-loop carbon cycle with very low greenhouse impacts from biomass. Environmental technologies, especially those based on anaerobic digestion, are moving into commercialization following the large scale success of using landfill gas for power generation. Charcoal and ethanol (which are the leading biofuels), advances in the production of liquid fuels from lignocellulosics, and high efficiency integrated gasification combined cycles for electricity production are described.

Introduction

According to the International Energy Agency [1], in 1999, the total primary energy supply (TPES) of 406 EJ, included 11.1% from the category, *Combustible Renewables and Waste*, which consists mainly of biomass resources. This fraction is little changed from 1973, when it was also 11.1% of a TPES of 253 EJ. About 97% of all biomass fuels are used directly in combustion systems of varying efficiency and environmental impact. In the industrialized countries, the efficiency is rarely less than 70%, while in many developing country applications, the efficiency is less than 50%, and in household cooking use much less than 20%. The two most important biofuels are charcoal (~ 1.0 EJ) for heating and metallurgical applications, and ethanol for transportation in Brazil and the United States (~ 0.45 EJ). A rapidly growing biofuel resource is the methane produced from the anaerobic digestion of residues that have accumulated in landfills, as well as from the increasing application of anaerobic digestion technologies to the clean up of contaminated water streams.

While almost half of all biomass TPES is used in developing country cookstoves, this application uses biomass in extremely inefficient combustion. This is both a major threat to the health of a large population in developing countries, probably accounting for about 5% of the world's health problems, and is also a significant contributor, at about the 10% level, to the global burden of greenhouse gases [2]. Since this topic is a global issue linked to poverty and development that has to be resolved on a systems basis, and is not central to the theme of biomass conversion technologies, it is only noted here as a major challenge to the future sustainable use of biomass. Industrial- and community-scale biomass conversion systems are the topic of this paper and will be covered in the order of heat, power (combined heat and power), and biofuels.

Heat, Power and Combined Heat and Power (CHP)

Biomass combustion, such as burning fuelwood to provide heat, power, or combined heat and power (CHP), is a link in the energy chain from producing renewable biomass resources to providing sustainable services in the form of heat (or refrigeration), shaft power, and electricity. The heat produced in a combustor or furnace can be used directly in a manufacturing process, or to raise steam in a boiler, which can then expanded through a steam turbine (or Rankine cycle) to generate shaft power. Other prime movers include the Brayton cycle of gas turbines, Stirling engines, as well as thermoelectric and thermovoltaic possibilities. Shaft power from these cycles can be used directly to drive a mill or other machine, or to power an alternator to produce electricity. In combined heat and power, the most common variant is when the electricity is generated first and the heat is taken from the exhaust of the electricity cycle [3].

As with fossil fuels, the key biomass combustion issues today are efficiency and environmental performance. Since many furnaces and boiler systems can be operated at relatively high efficiency, even quite close to their theoretical efficiencies, the most important development issue is the environmental performance. Nevertheless, biomass has one clear advantage over fossil fuels in that the emissions of carbon dioxide derived from biomass combustion to the atmosphere are essentially in an equilibrium with the uptake of carbon dioxide by the biosphere through photosynthesis.

Industrial-Scale Biomass Combustion Technologies

Industrial boilers range from 100 to around 300 MW_{th} output. Smaller scale versions are used in district heating and small processes down to as low as 10 MW_{th}, usually without the same level of emissions control. The major types of boilers installed are: pile burners, grate boilers, suspension fired boilers, fluidized beds, and circulating fluid beds.

The pile burner is the original, *circa.* 1700, industrial process-scale biomass burner and can be viewed as a sort of enclosed fire. Pile burners have poor load-following characteristics and typically have low efficiencies in the range of 50% to 60%. Stoker grate combustors improve the operation of the pile burners by providing a moving grate, which permits continuous ash collection, thus eliminating the cyclic operation characteristic of traditional pile burners. In addition, the fuel is spread more evenly (in a thin bed, 5 to 15 cm deep), normally by a pneumatic stoker. The thinner layer in the combustion zone produces a more efficient combustion. More modern designs include the Kabliz grate, a sloping reciprocating water-cooled grate. Reciprocating grates are attractive because of simplicity and low fly ash carryover. Furnace exit temperatures are about 980° C; staged combustion processes have been developed to minimize nitrogen oxide emissions and keep the furnace temperature below the ash deformation temperature of most biomass fuels. Stoker-fired moving grates range in size from 20 to 300 MW_{th} . Since suspension burners require finely divided < 1 mm particle size materials with very low moisture contents, they are relatively rare as the fuel preparation from green biomass is very energy intensive.

Fluidized bed combustors are becoming the systems of choice for biomass fuels. One reason for this is that the fluid bed medium (silica sand, alumina, or olivine) provides a thermal "flywheel" that compensates for variation in moisture content and maintains constant heat output and flue gas quality. The medium also gives the advantage of extremely good mixing and high heat transfer, resulting in very uniform bed conditions. Despite the relatively low temperature of combustion, the three T rule (temperature, time, and turbulence) of high quality combustion is well met, with 99% to 100% carbon burnout being typical [4]. Fluidized beds are either bubbling beds (FB) or circulating (CFB). In the former, the material stays in a fixed zone of the combustor, while in the latter, the flue gas velocity is such that the bed material is suspended and circulates through a return loop to the combustor, by means of a mass or cyclonic separator. In both FB and CFB units, the ash removal is by means of complete ash carryover, necessitating the addition of cyclones and bag houses for particulate control to New Source Performance

Standards (NSPS). It is the emissions performance that is making these units more attractive. In fluidized beds, the uniform, low combustion temperature gives low NO_x emissions, while in the CFB, it is easy to introduce a sorbent solid, such as limestone or dolomite, to control SO_x emissions without the need for back-end sulfur removal equipment. Circulating fluid bed temperatures are maintained at about 870° C, which helps to optimize the limestone-sulfur reactions. A number of CFB power plants have been built in the 25 MW_e size range, primarily in California [5]. The alkali content of the fuels has to be maintained below 340 g GJ^{-1} input, as high alkaline content fuels cause particles in the bed to agglomerate and defluidize, eventually plugging the system [6].

The increasing need for strict environmental compliance to NSPS is changing the technology base for biomass conversion at the medium and large scales. The need for post-combustion pollution controls has meant that small scale systems have become very expensive per unit of output, while larger units can afford to meet environmental regulations. In countries with large coal- or oil-fired generation units, the use of biomass to co-fire these units is becoming more frequent, especially in those countries that are changing their energy policy to meet Kyoto fossil carbon emissions levels. A significant advantage of the co-firing route is that the capital investment is as low as 200 \$ kW^{-1}, while the effective efficiency of biomass combustion is as high as that of the coal unit, at over 34% [7, 8]. The use of biomass in integrated gasification combined cycles is also a high efficiency route (35% - 45%) with very high environmental performance for larger units in the future. Medium size units, for the district heating and small industrial CHP markets, are becoming modular in design, with significant cost reductions and improved energy and environmental performance.

Economics of Power Boilers and Electricity Generation

The economics of power generation are dependent on the capital cost, the operating cost, and the fuel cost, in almost equal measure over the generating plant's life cycle [9-11]. Scale and efficiency are linked and are illustrated in Figure 1, which compares the levelized costs of electricity for biomass-fired systems based on stoker firing and gasification combined cycles, using data from the EPRI - NREL technology assessment [7].

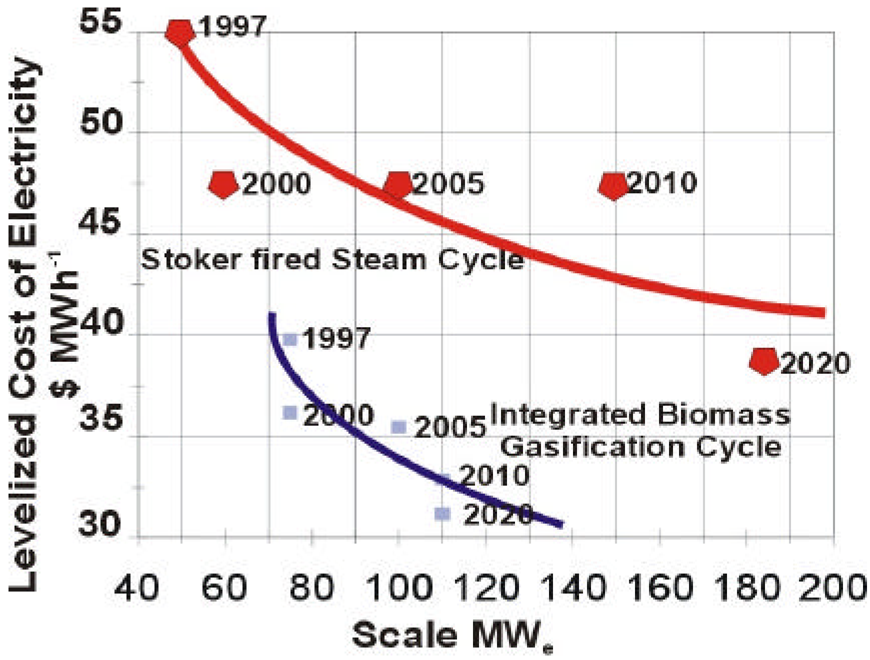

Figure 1. Levelized cost of traditional direct-fired steam cycle power generation and biomass IGCC

Gaseous Biofuels

Gaseous biofuels include biogas from anaerobic digestion (AD), and low and medium heating value gases from thermal processes. Biogas from AD has approximately equal amounts of carbon dioxide and methane, with typically 0.1% to 1% hydrogen sulfide. Thermal processes produce varying compositions of dry gas containing hydrogen, carbon monoxide, and methane, as the fuel gases, in combination with nitrogen and carbon dioxide, as the major constituents. Thermal gases and biogas can be used directly as fuel in gas burners, or in prime movers such as internal combustion engines and gas turbines. Thermally produced gases, after purification and possibly water gas shift to adjust the H_2:CO ratio, can be described as a syngas (a mixture of H_2 and CO), which can be used to manufacture methanol, ammonia, Fischer Tropsch liquids, or hydrogen for use in fuel cells. While thermal gasification is in the early stages of commercial deployment, anaerobic digestion processes are already commercial and widely deployed, either in designed processes for specific environmental problems or in landfills, which are managed to capture the methane that is naturally produced. Presently, the United States has a landfill gas electricity generation capacity of about 1 GW_e, using gas engines and gas turbines [12].

Anaerobic digestion has been used for many years in the treatment of sewage and animal manures to mineralize the carbon in order to reduce the volume of waste sludge for disposal [13]. The carbon is converted into methane and carbon dioxide in about a 60:40 ratio by volume, with a heating value of about 55%–60% that of natural gas. The biomass of the bacteria that carry out the process and the non-digested material remains as a sludge, which can be returned to the soil if there are no heavy metals from the residue stream. A wide range of agricultural, industrial, and urban activities generate residue streams with high organic loadings that are suitable for anaerobic treatment. They include: intensive animal husbandry (excreta, and bedding materials); food processing (sugar production and vegetable preparation); breweries and distilleries; and materials production (such as pulp and paper, pharmaceutical manufacture, and sewage treatment). Absent any treatment, these industries pollute water courses and groundwater with high loadings of biological and chemical oxygen demand, along with large concentrations of nitrates, microbial contaminants, and even pathogens. Progress in the development of high rate

AD technologies has increased the reliability, or the effective time-on-stream of the applications, and has also improved the conversion efficiency or reduction in organic loading. The organic loading is measured by means of a chemical reaction in the laboratory and reported as the chemical oxygen demand (COD). This can be converted into a methane potential of between 0.33–0.35 m^3 kg^{-1} of COD. In a well operating anaerobic process, it is normal to have a COD reduction of between 60% and 80% of the input level.

Thermal Gasification

Gasifiers at an industrial scale are generally based on fluidized bed technology. In direct thermal applications, the gas is cleansed of most particulates and passed without any cooling, directly into the process kiln or boiler for combustion. A typical example of this application is the use of a CFB gasifier, fueled with a refuse-derived fuel, wood chips, and peat, to supply a low-heating-value gas to an existing large-scale natural gas and coal utility boiler, at the Kymijärvi 167 MW_e and 240 MW_{th} fossil fired plant close to the Finnish city of Lahti [14]. This project builds on many years of successful operation of biomass CFB gasifiers in thermal applications, and substitutes biomass for about 15% of the total fuel used in the boiler. Though the possibility of using biomass gasification to produce a syngas for the manufacture of transportation fuels such FT liquids or methanol is feasible, most development effort has been put into demonstrating IGCC (Integrated Gasification Combined Cycle). In IGCC the thermal gas from biomass is used to fire a gas turbine, and the steam generated in a heat recovery boiler on the turbine exhaust is used to generate more electricity in a steam (Rankine cycle) turbine. The extensive developments for coal-based IGCC have resulted in a number of turbines that have already been adapted to low-heating-value gas operation, in the size ranges of interest to biomass developers. A higher quality gas, requiring fewer turbine modifications, can be produced in indirect or oxygen-blown gasification cycles, with heating values in the range of 15–20 MJ Nm^{-3}. Current biomass IGCC projects and demonstrations, which illustrate the development of biomass IGCC, clearly show the diversity of the possible technological approaches. The first complete biomass-fueled IGCC, constructed by Sydkraft A.B., is part of the district heating system of the city of Värnarmo in Sweden and is fueled with about 18 MW_{th} equivalent of wood residues. The facility produces about 6 MW_e (4 MW_e from the gas turbine, 2 MW_e from the steam cycle) and 9 MW_{th} for the heating system, and has demonstrated more than 1500 hours of IGCC operation [15]. The gasifier is a pressurized air circulating fluidized bed (CFB) and produces a gas of about 5–6 MJ Nm^{-3}. Several atmospheric pressure gasification power systems are also under development. The ARBRE project in the UK is an atmospheric pressure CFB IGCC, generating 10 MW_e, using SRC (willow in Short Rotation Coppice) on 1000 hectare as the major feedstock. This is the first large-scale power generation project that uses the TPS-CFB system; although, the proposed WPB/SIGAME project in Brazil (that will use eucalyptus to generate 32 MW_e, using a GE LM 2500 gas turbine and a steam cycle), has been in the planning stages for several years. The Future Energy Resources Company (FERCO) unit, located in Burlington, Vermont, USA, is a 40 MW_{th} indirect gasification process operating in a co-firing mode, which supplies a 15–20 MJ Nm^{-3} gas to the McNeil Generating Station of Burlington Electric.

Charcoal

Charcoal is the world's most significant biofuel, with over 3 EJ of wood feedstocks being converted into between 0.7 and 1 EJ of charcoal (despite its production in many instances at low efficiency). Its energy density is such that it can be transported long distances and, with much reduced emissions in cookstoves, it is a fuel that is better suited to developing country urban use than fuelwood. Charcoal is produced from fuelwood and other biomass resources by carbonization in kilns or retorts. In addition to its use as a cooking fuel, a significant amount is used as a chemical reductant in metallurgy, for example, to produce pig iron in Brazil [16]. The co-products of carbonization are the tars and fuel gases. Together these represent as much as 40% of the energy of the wood. In simple charcoal-making these are often not utilized, creating pollution of the soil, water, and air. In the larger industrial systems the recovery of byproducts may not be economic; however, the fuel value of both the gas and the tars (sometimes called pyroligneous liquids) may be utilized in the carbonization process to reduce energy loss, increase the efficiency, and eliminate pollution. Before there was extensive chemical synthesis of methanol and acetic acid from fossil fuels, these were both byproducts of charcoal manufacture. In fact, methanol (CH_3OH) is referred to as wood alcohol in the vernacular. A small fraction of biomass-derived charcoal, mainly from materials such as coconut shell, is used in the production of activated charcoal for environmental applications.

Liquid fuels from biomass

There are two biomass-based liquid fuels in the market place today, ethanol and biodiesel. Some 20 $Mm^3\ y^{-1}$ of ethanol is produced with an energy content of 425 PJ, making this the second most important biofuel. A much smaller amount of biodiesel (usually an ester of plant lipids such as soybean or rape seed oils) is used in the USA and Europe. Space does not permit a discussion of all of the biofuel options, so the major one described is the ethanol option. Ethanol is produced by means of fermentation of sugar cane in Brazil (11 Mm^3), and from starches in the United States (6 Mm^3) and Europe. Typically a tonne of cane produces between 125 and 140 kg of raw sugar, or between 70 and 80 litres of ethanol, while a tonne of maize, with about 70% to 75% starch content, will produce between 440 and 460 L t^{-1} with wet and dry corn milling, respectively. Most is used in blends in gasoline, typically at 22% to 24% in Brazil, and 10% in the USA. However, there are some motor fleets with flexible fuel vehicles that operate on E-85, a blend of 85% anhydrous alcohol and 15% gasoline, which consume about 0.3% of the U.S. ethanol. In the USA, the production cost of ethanol is higher than gasoline by between 50% and 100%, depending on oil prices and the commodity markets for feed corn.

Brazilian fermentation plants range in size from 150 kL d^{-1} to 2.6 ML d^{-1}, using sugar cane as feedstock. In the United States, which mainly uses corn as feedstock, there were 33 producing plants with the smallest at 6 kL d^{-1}; however, in 1998, over 80% of the production capacity was in just seven plants, ranging from 460 kL d^{-1} to 5.85 ML d^{-1}. There are very significant economies of scale in ethanol production and, thus, large scale plants are favored. Investment costs per daily litre range from over 100 \$ L^{-1} d^{-1} at smaller throughput plants in Brazil to less than 60 \$ L^{-1} d^{-1} for the larger plants. Starch to ethanol plants are about 30% more expensive than cane sugar based units of similar throughput, primarily because there are more process steps, each of which has a small reduction in efficiency. This is mitigated, in part, by greater capacity factors on an annual basis, as corn-based production can operate for the majority of the year on commodity corn, while sugar cane harvest seasons rarely extend beyond six months in most production areas. In addition, the corn process produces saleable co-products in the form of animal feeds such as dried distillers grains.

The major research and development area is in the production of ethanol from lignocellulosics (such as wood, straw, and grasses), which contain cellulose (40% to 50%) and hemicellulose (25% to 30%), with considerable ethanol potential (about the same yield per tonne as corn) and a price structure that is more stable than food prices. The conversion process from lignocellulosics is even more complex than from starches, as the complex nature of lignocellulosics requires extensive effort to break down the lignin, cellulose, and hemicellulose structure so that the individual polymers become available for hydrolysis. Cellulose is hydrolyzed to glucose, a six-carbon sugar (C-6), while hemicellulose is a complex mixture of mainly five-carbon sugar (C-5) precursors with xylose as a major product. While the C-6 sugars are relatively easy to ferment with yeasts such as *Saccharomyces spp*., the C-5 sugars have not been as easy to ferment to ethanol. The pretreatment stages can include steam, acid, and alkali treatments, while the hydrolysis steps can be carried out with acids or enzymes. Because of inhibition of the enzymatic hydrolysis by the sugars produced, NREL developed a simultaneous saccharification and fermentation process to remove the sugars as they are formed, by producing ethanol in the same reactor. Such process integration will be the key to producing low cost sugars, and thus ethanol or other bioproducts in the future [17, 18].

Conclusions

Modern biomass combustion systems are capable of achieving the NSPS of the United States EPA and are a cost effective use of biomass, especially in CHP in applications with a high capacity factor. The use of environmental technologies, especially anaerobic digestion, is increasing as water quality issues become more prevalent, due to concentrations of animal production units in areas that no longer can use the land to absorb the impacts of concentrated animal feed operations. The development of high-efficiency electricity generation systems based on IGCC has reached the successful demonstration stage and awaits commercial deployment. The same gasification technology can serve as the basis for hydrogen production or for the synthesis of liquid fuels such as ethanol and Fischer Tropsch hydrocarbons. The largest liquid fuel contribution today comes from the application of biotechnology in the production of ethanol from sugar and starches, and innovative research is opening the way to utilize the large lignocellulosic resource in the same way.

The data points are for an investor-owned utility operation of stoker-fired and IGCC units. The data are taken from the renewable energy technology characterizations performed by EPRI, USDOE, and NREL [7]. The years shown on Figure 1 are the study's expectation of when the performance and scale shown would be achieved.

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