BIOMASS ENERGY

1. Introduction

Energy supplies in the United States and around the world are primarily based on the supply of fossil fuels, coal, petroleum, and natural gas. Concerns about the long-term stability of supply of these fossil fuel resources coupled with concerns about the environmental impacts of the use of these fuels has led to the investigation of the use of more renewable resources. Primary among these renewable resources is biomass. Biomass currently provides a $\sim$10–11% of the worlds primary energy, however, the various forms of biomass can potentially supply a quantity of energy several times that of the current global demand (1,2). In the United States, a ~4% of the primary energy supply is provided by biomass. A significant increase to 20% of primary energy is possible within know sustainable supplies of biomass, without having an adverse effect on prices of biomass derived products such as lumber or food (4). Developing countries utilize more biomass, proportionately, than industrialized countries. The United Nations reports that 38% of primary energy is supplied by biomass in developing countries (5). In these developing countries, biomass is used for heating, cooking, and in some instances, power generation. In the more industrialized countries, these energy uses have been replaced by fossil fuels.

Even in the more developed countries, biomass played a key role until the second World War. In the mid-1800s, 85% of the United States' primary energy was derived from biomass. This figure declined to only 2.5% when, in the mid-1970s, the energy crisis resulted in a renewed emphasis by government and the public to expand the use of alternative energy sources, including biomass. Increased environmental pressures including concerns relative to air quality and to the disposal of biomass containing wastes such as construction and demolition wastes, municipal solid wastes, sewage sludges, and urban biomass (yard) wastes further expanded the interest in energy production from biomass materials.

2. What Is Biomass?

Biomass quite simply is any organic material that is or was derived from plants or animals. The most common example of biomass is fuelwood. Other typical forms include crops, animal manures, agricultural residues (examples include sugarcane baggasse, corn stover, rice hulls, nutshells, and straw), sludges from municipal or pulp and paper wastewater treatment, and even portions of municipal solid waste (food residues, yard wastes, and paper). There are also a number of aquatic based biomass forms such as kelp and seaweed. A more legalistic definition has been proposed by researchers and several governments throughout the world. This definition describes biomass as "all nonfossil organic materials that have an intrinsic chemical energy content. This includes all water- and land-based vegetation and trees, or virgin biomass, and organic components of waste materials such as municipal solid waste (MSW), municipal biosolids (sewage) and animal wastes (manures), forestry and agricultural residues, and certain types of industrial wastes" (6).

3. Why Biomass Energy?

Biomass derived energy is considered a "renewable" energy source. That is, it is a source of energy that can be utilized without depleting the reserves. As long as the conditions exist (sunlight, water, and the organic substrate) additional biomass can be produced to replenish that used for energy. Interest in renewable energy is increasing due to dwindling supplies of petroleum and natural gas, two fossil fuels, and to mitigate global climate change. For some time, a worldwide debate continued regarding the case of an accumulation of carbon dioxide in the atmosphere. As more and more data becomes available, there is an increasing concensus that the most significant cause of this accumulation is human activity the affects the natural carbon cycle. The primary causes of the increase are the use of fossil fuels and the deforestation of large land areas (6). During the 1990s, 6.3 Gtonnes of carbon were released to the atmosphere each year from the burning of fossil fuels and an additional 1.6 Gtonnes released from deforestation activities. Of this amount, 4.6 Gtonnes is absorbed annually by the world's oceans and terrestrial vegetation resulting in an annual increase in the atmosphere of 3.3 Gtonnes (7).

An increase in the use of biomass energy provides a means to both reduce the consumption of fossil fuels and to reclaim a portion of land that has been deforested. Because solar energy is an integral part of the production of most biomass, some consider biomass a form of stored solar energy. Biomass based energy, however, provides the advantage of being available at all times (dispatchable) regardless of atmospheric conditions. Further, as biomass is produced from sunlight by the following reaction,

$$CO_2 + H_2O + \text{light} + \text{chlorophyll} \rightarrow (CH_2O) + O_2$$

[The generic carbohydrate formula, (CH_2O), represents the primary building block of the organic product. Woody biomass is richer in lignocellulosic material and has the average formula of $CH_{1.4}O_{0.6}$ due to the higher lignin content.] carbon dioxide, a primary greenhouse gas, is consumed as new biomass is formed in a quantity equal to that produced when biomass is used as an energy source. As a result, biomass provides environmental advantages in relation to greenhouse gases when compared to fossil fuels. When considered as a stand alone process, photosynthesis is a very low efficiency process (<1% or the solar energy is converted into biomass) (8), but due to its simplicity and wide range of products produced, it provide the potential for not only food (energy of a sort for other living organisms) but as a simple to acquire form of thermal energy.

Biomass as an energy source is not free of environmental issues. Biomass is renewable and carbon-neutral only if replacement through new growth occurs at, at least, the same rate at which it is harvested. Furthermore, in many undeveloped countries, cooking and heating using biomass is accomplished in relatively crude stoves or fireplaces. These devices can release carbon monoxide, unburned hydrocarbons, and particulates (as smoke) (9). More advanced, high efficiency biomass-to-energy conversion systems introduce their own unique set of environmental and safety concerns. Intermediate products such as synthesis gas or biomass derived liquids can be hazardous, flammable, or toxic. Most, if not all, of these potential intermediates can be handled safely through proper application of industry accepted safety and health guidelines without any widespread expansion.

Biomass ash, from any conversion system, is generally recyclable to the soil unless the incoming biomass has been contaminated with heavy metals (as is the case with some municipal residues). However, biomass ash, particularly from combustion devices, is a very fine (sometimes $<5\ \mu$) material leading to potential emissions of fine particulate matter, PM-2.5. The control of PM-2.5 emissions will be necessary from biomass based sources as newer environmental regulations are implemented.

4. Historical Uses of Biomass Energy

Biomass in the United States historically was used for simple heating by direct combustion in wood stoves or fireplaces. Such technologically simple uses continue today in developing countries throughout the world. Biomass, due to its ready availability, provides a simple and reliable energy supply that can be adapted for home and simple industrial purposes. In the United States, the primary form of biomass used for these simple applications is fuelwood. Fuelwood, in the form of logs or brush is burned in air to provide heat. The combustion of biomass in a fireplace or wood stove is accomplished by reacting the biomass feed material in air according to the following reactions:

$$C + O_2 \rightarrow CO_2 \tag{1}$$

and

$$2\ H + 1/2\ O_2 \rightarrow H_2O \tag{2}$$

Fuelwood continues to be the primary heating fuel in some 3 million homes in the United States (10). Such simple heating with wood is by nature a very low efficiency operation when practiced in an open fireplace ($\sim$7% efficiency) or even in a fireplace with convective tubes ($\sim$15%) providing only a small fraction of the energy available in the incoming biomass to heat, the remainder being lost to the flue or the general environment as unburned fuel. Efficiency improvements have been realized in modern log, chip, and pellet fuel appliances by finer control of the combustion process and by the use of factory fabricated combustion equipment (50–76% overall efficiency) (11). At larger scale, efficiency improvements are realized by larger scale combustion processes in boilers or furnaces, thus improving heat recovery and therefore overall efficiency.

4.1. Power Generation from Biomass.

Boiler applications further provide the opportunity to generate electric power from the incoming biomass. Biomass is burned to generate steam. The steam is then used to turn a turbine for the generation of electric power. In the United States, several hundred such biomass based power plants have a combined capacity of >10.3 GW and annually generate 65 Teraw-h of electricity (12,13). The majority of these biomass-based power plants are found in the pulp and paper industry where biomass residues from the pulping operation are used to generate necessary power for plant operations.

Types of Biomass Combustion Devices. To adequately process biomass, a stoker-grate boiler is the usual combustion device of choice. While suspension-type boilers, similar to those used in pulverized coal combustion systems, are also used, these require the biomass to be ground to a fine particle size, thereby consuming additional energy (estimated at >80 kWh tonne^{-1}) and further reducing the efficiency of the power generation process (14). Stoker-grate boilers, on the other hand, can accept much larger particle size material (up to three inches or larger) less reducing overall plant energy consumption. Furthermore, because an inventory of material is continuously present on the grate, significant changes in the feedstock can be tolerated (15,16). Biomass by its very nature is heterogeneous therefore combustion systems that are tolerant of changes in feedstock provide advantages over other types of combustion systems. Furthermore a stoker-grate boiler allows the use of low heating value and high moisture content feedstocks. When viewed on a moisture and ash-free basis, however, much of the apparent variability of biomass fuels disappears. Typically, dry woody biomass will have a heating value in the range of 18.5 MJ kg^{-1}. A similar dry, ash free heating value is obtained for many agricultural residues (17). There is a considerable variation, however, in the moisture content of biomass materials. Most woody biomass will have an as fired moisture content between 40 and 50% thereby lowering its effective heating value by 50%. By comparison, the typical coal feedstock used for power generation will have a heating value in the range of 27.6 MJ kg^{-1} and a moisture content in the range of 10% or less. The moisture in the biomass fuels has the effect of lowering the overall power generation efficiency of stoker-grate boilers to an average of ~20% due to the high excess air levels of air required and the energy required to evaporate the moisture in the incoming biomass fuel. The maximum efficiency for this type of conversion device is ~25% (18).

4.2. Other Commercial Uses of Biomass Combustion. The pulp and paper industry is a primary user of biomass combustion for its energy needs. The industry as a whole derives ~56% of its total energy from wood and wood residues (19). In addition to direct combustion of wood and woody residues as described above, a significant portion of the energy in a modern pulp mill is derived from the combustion of black liquor, a by-product of the pulping operation. Black liquor contains the spent pulping chemicals and lignin content from the incoming wood pulp. The lignin content provides the energy content in the liquor. When black liquor is burned for energy recovery, the pulping chemicals are recovered and recycled, thus further increasing energy efficiency and reducing costs.

Wood and wood residues (bark, twigs, etc) are collectively known as hog fuel. In a pulp mill, the hog fuel is burned in a power boiler and produces steam for power generation. Typically, the power produced will provide nearly all of the requirements for the mill, and in some cases power for export to the grid.

4.3. District Heating and Combined Heat and Power. In many European countries, biomass based combined heat and power (CHP) systems provide the primary energy for large segments of the population. These systems typically combust biomass to produce high pressure steam that is used for power generation. Lower pressure steam is then extracted from the turbine system and used for district heating. In some of the Scandinavian countries, biomass enjoys an economic advantage over fossil fuels thus encouraging the development of more advanced CHP systems (20). In Sweden, eg, two-thirds of the power generated from CHP facilities is biofuel based amounting to approximately 18 GWe with an additional 22 GWth supplied through 9600 km of mains as district heating. In Finland, 37% of the country's electrical energy is derived from CHP plants (21).

4.4. Charcoal. While not used extensively in the United States as an energy source, charcoal plays a major role in many countries as a primary source of fuel for heating, cooking, power production, and metal processing. In some Southeast Asian countires, eg, up to 15% of the primary energy supply of the country is derived from charcoal (22). Likewise, in many African countries, charcoal consumption is higher than gross electricity consumption (23). Charcoal can be made from virtually any organic material. The primary source is fuelwood or coconut shells. The production of charcoal involves heating the incoming biomass under starved air conditions (in a pit, or a kiln) to drive off water, volatiles, and tars. The remaining material, which is primarily carbon, with traces of ash and a few remaining volatiles is charcoal. In a typical charcoal making process, ~20% of the incoming biomass is converted to charcoal. Charcoal has a heating value approximately twice that of fuelwood on an equal weight basis (28–30 MJ kg^{-1}) thereby increasing its ease of transportation. The increased heat content also allows a smaller volume of fuel to be used for domestic heating applications. As many of the biomass materials used in the production of charcoal are residues from agricultural sources, the energy lost in charcoal production is outweighed by the increased flexibility of the charcoal fuel.

Environmental concerns regarding charcoal have recently become important. As the production of charcoal releases volatile organics into the environment and the burning of charcoal releases CO_2, some environmentalists believe that the production of charcoal should be halted completely. World consumption of charcoal, however, is increasing raising concerns about the supply of fuelwood and other biomass resources. If charcoal is produced on a sustainable basis, ie, without deforestation, many of these concerns can be alleviated.

5. Other Energy Recovery Systems

In an attempt to enhance the supply of petroleum in the 1970s a number of methods were used to recover energy from biomass sources much of this work was supported by the United States government through research grants and support for the construction of larger scale facilities. These included wastes to energy facilities utilizing post consumer residues (municipal solid waste) and additional fuelwood fired power facilities and the construction of the number of ethanol producing facilities.

5.1. Waste-to-Energy Facilities.

Waste-to-energy facilities typically use the same type of stoker-grate combustor as described above for wood fired power generation. The incoming postconsumer residues from municipalities are generally combusted in a “mass burn” system. In such systems, the incoming residues are dumped in mass into a large holding pit and then transferred by an overhead crane directly into the combustion chamber. No additional preparation of the fuels is performed. Large pieces of oversize material (including large metallic items such a bicycles, containers, etc) are removed along with ash from the base of the combustion chamber. As might be expected, maintenance on these combustors is quite high due to the large variety of materials that is being combusted. An improvement in waste-to-energy facilities is accomplished by performing some preparation of the incoming feed material prior to combustion. This preparation removes much of the metallic materials and glass from the feed material and additionally is used to reduce the size of the incoming feed material so that combustion properties can be enhanced. The resulting prepared municipal waste is referred to as refuse derived fuel (RDF). The RDF plants generally have lower maintenance requirements and higher efficiency and mass burn facilities but are much more expensive than a similar size mass burn facility. Both of these methods require large capital investments thus requiring subsidies in the form of "tipping fees" in excess (sometimes double or triple the fee) of those charged for landfill operations to provide adequate returns on the capital investment. A step-change in technology is required to overcome these financial limitations.

Environmental Considerations. Furthermore, waste-to-energy facilities have potential environmental impacts on the surrounding community. Many of the environmental contaminants present in the exhaust from a waste to energy facility can be controlled by the use of flue gas scrubbers. Contaminants such as nitrogen oxides and particulate are removed in this manner from larger scale coal fired utility boilers. The environmental control systems for waste to energy facilities utilize this same technology. Because waste-to-energy facilities process a fuel that can contain significant quantities of chlorine (from materials such as polyvinyl chloride), much more hazardous contaminants can be produced. These included dioxins and furans. These contaminants, too, can be removed from the exhaust of the facilities but the cost of scrubbing these materials is significantly higher than to remove nitrogen oxides or particulates.

These potential environmental issues have resulted in a reluctance by municipalities to install additional waste to energy facilities thus limiting the amount of energy that can be derived from these wastes. Other forms of urban derived biomass wastes have been included, by association, in the same category as MSW. These other wastes, however, do not contain the same contaminants (such as chlorine) present in MSW, and therefore would not be expected to have the same environmental issues. Included in these other biomass wastes are tree trimmings, yard wastes, and construction and demolition wastes. In large urban areas, hundreds of tons of these materials are produced on a daily basis providing a significant resource for energy recovery (24).

5.2. Ethanol. Ethanol is a form of alcohol found in beverages such as wine and beer. It is readily produced through the natural fermentation of the starches and complex sugars present in many forms of biomass. Grains such as wheat or corn are typically used as the primary sources for ethanol production. The fermentation reactions are accomplished by naturally occurring biological organisms. When used for fuel, ethanol is blended with other liquid fuels (typically gasoline) (25,26).

Ethanol Production. Large-scale production of ethanol for energy is produced in a process similar to brewing beer. Fermentation of the sugars and starches in the biomass is accomplished by blending with yeast and water. The mixture is then heated to ~30°C to initiate the fermentation reactions (27). The yeast breaks down the complex sugars and starches into simple sugars and ultimately into ethanol. The fermentation reactions take place in an anaerobic environment and take ~1–2 days for completion. After fermentation the ethanol is filtered and then distilled to increase its concentration from 10 to 95%. The concentrated ethanol is then blended with petroleum-based fuels to the desired concentration. About 5.7 GL of ethanol are produced in this manner in the United

States annually (28,29). The ethanol industry has shown significant growth in the period 1980 to 2002 by producing over 20 times the product annually that was produced in 1980. This dramatic growth is possible due to advances in both chemical and biological process engineering (30,31). In addition to the primary use as a blend in gasoline, ethanol can also be used as a chemical intermediate in the production of other organic chemicals.

Ethanol is also produced from cellulosic biomass such as agricultural residues, forestry residues, waste paper, yard wastes, portions of municipal residues, and some industrial residues. The cellulose and hemicellulose in these materials are long-chain polymers made up of sugar molecules. These materials are treated with acids or enzymes to break down the molecules into smaller fractions that can be readily fermented. Dilute acid hydrolysis is carried out at high temperatures ($\sim$240°C) with dilute sulfuric acid to hydrolyze the cellulose and hemicellulose. In this case, the sugars can be degraded due to the high reaction temperature, thus reducing the yield. Conversely, concentrated acids can be used at lower temperatures thereby increasing the yield but necessitating more complex acid recovery systems. Research continues on acid hydrolysis to reduce acid levels and maintain high conversion levels. Alternatively, a small fraction of the biomass can be used to grow fungi or other organisms to produce enzymes called cellulases. These enzymes then hydrolyze the cellulose in pretreated biomass to glucose that can be fermented into ethanol.

Use of Ethanol Containing Fuels. In 1990, the United States government mandated the use of oxygenated transportation fuels to help improve environmental conditions in parts of the country. These mandates have created a strong demand for ethanol–gasoline blends. Mixtures of up to 10% ethanol referred to as (E10) can be utilized in most gasoline designed engines with no modification. More concentrated blends, namely, the E85 and E95 blends (85 and 95% ethanol, respectively) require specifically designed engines, referred to as “flexible fuel” engines to perform properly. These flexible fuel engines can run on either gasoline or the high concentration ethanol blends. Automobile manufacturers are producing more vehicles that can use these higher ethanol blends each year thus increasing demand.

The spark ignition, Otto-cycle engines used in today’s automobiles, even in their early stages of development, were designed to operate with ethanol containing fuels. Henry Ford designed the early Model T to use ethanol as a major fuel source. Such plans were changed subsequently when storage and transportation difficulties combined with high corn prices at the time caused the supply of ethanol containing blends to be reduced. Further efforts to use ethanol containing fuels continued into the 1940s when petroleum became the primary automotive fuel. Today, the petroleum industry is reluctant to accept ethanol on a widespread basis as it is not a fungible fuel due to the storage and transportation issues as well as the potential for phase separation in blends with gasoline.

6. Developing Methods for Conversion of Biomass into Energy

The United States Department of Energy (DOE) along with other similar organizations around the world have been supporting the development of a wide range of biomass to energy conversion technologies. Among these are gasification, pyrolysis, advanced combustion, anaerobic digestion, bio-diesel, and advanced cellulose to ethanol systems. Each of these has unique characteristics and has the potential to provide some energy from biomass. The following sections discuss the characteristics and projected markets for each of these technologies.

6.1. Gasification. Gasification is quite simply the conversion of a solid or liquid material into a gaseous fuel. The resulting fuel gas has an energy content or "heating value" ranging from 10 to 50% of the heating value of natural gas. The wide variation in heating values is a direct result of both the reactor type used and the reactants chosen for the gasification reactions. Gasification is probably the most flexible conversion system for biomass materials as the fuel gas produced can be used directly as a fuel for heating applications, be used for the production of power in gas turbines or fuel cells, or used as a synthesis gas for the production of liquid fuels, chemicals, or hydrogen. Figure 1 shows the many pathways that can be used to produce energy products by gasification.

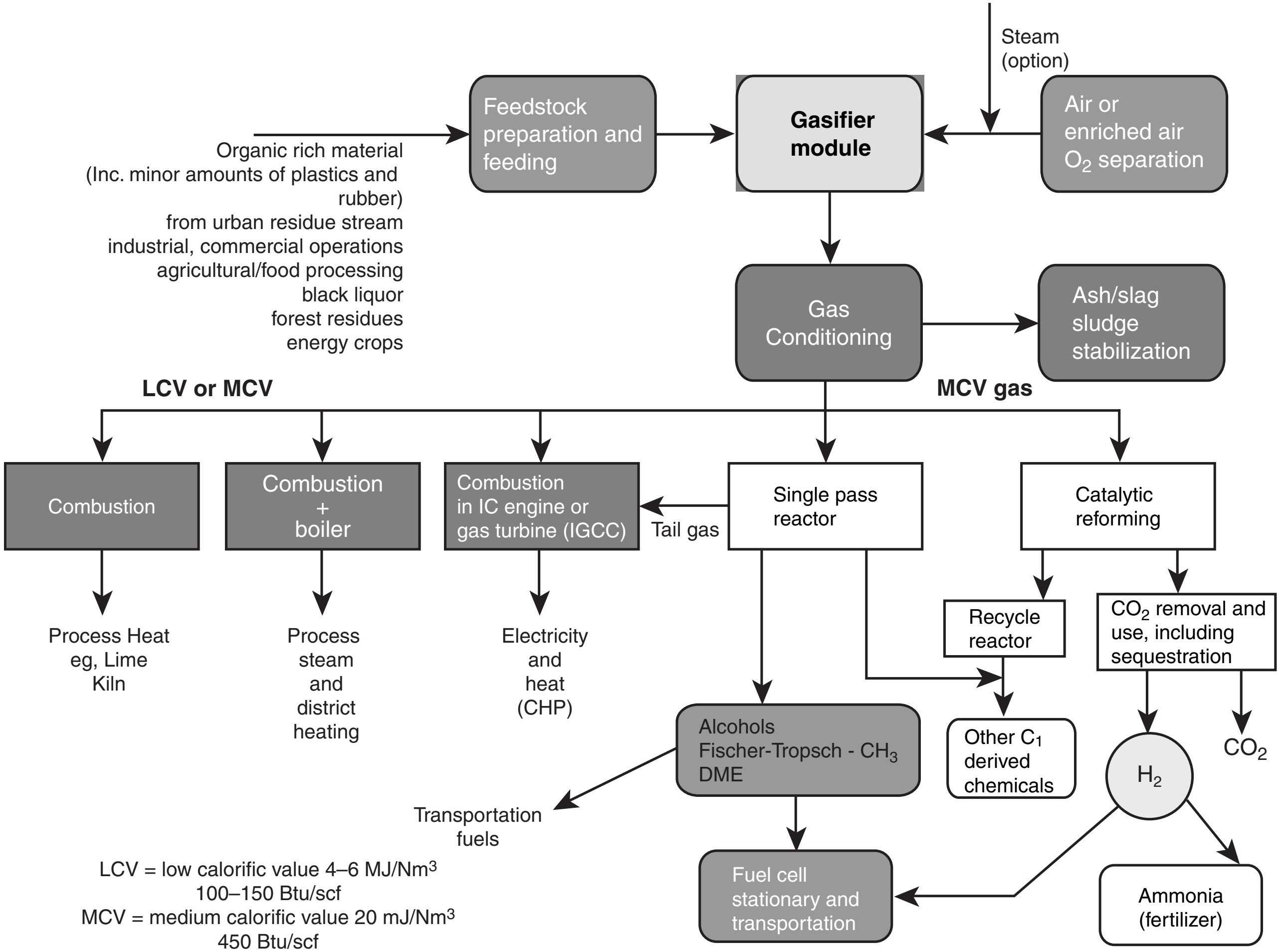
Gasification, despite the current development efforts underway, is a technology that has been utilized at large scale for many years. Coal and biomass gasifiers (referred to as gas producers) were in commercial use in Germany in the mid-1800s. Similarly, in the United States, during the early 1900s gasification plants were producing "town gas" in most major cities (32). This town gas was used for residential and industrial heating, lighting, and cooking at that time. It was not until the 1950s that natural gas replaced the town gas as the gaseous fuel of choice. As late as the 1980s some areas of Europe used gasification derived fuel gas rather than natural gas as a major energy supply (33).

The primary fuel for gasification has historically been coal. But many biomass gasifiers utilizing similar reactor schemes have extensive commercial operating experience. Today's gasification development efforts are focused on improving the efficiency of these early designs and improving the environmental performance of the technology.

Gasification Reactions. The primary gasification reactions are as follows:

Reaction	Reaction heat	
$C + O_2 = CO_2$	$408\ \mathrm{MJ\,mol^{-1}}$	(3)
$C + CO_2 = 2\ CO$	$-162\ \mathrm{MJ\,mol^{-1}}$	(4)
$2\ C + O_2 = 2\ CO$	$246\ \mathrm{MJ\,mol^{-1}}$	(5)
$2\ CO + O_2 = 2\ CO_2$	$570\ \mathrm{MJ\,mol^{-1}}$	(6)
$C + H_2O = CO + H_2$	$-120\ \mathrm{MJ\,mol^{-1}}$	(7)
$C + 2\ H_2O = CO_2 + 2\ H_2$	$-78.6\ \mathrm{MJ\,mol^{-1}}$	(8)
$CO + H_2O = CO_2 + H_2$	$41.8\ \mathrm{MJ\,mol^{-1}}$	(9)

In addition to these reactions, the volatile matter in the incoming feedstock is thermally broken down into a range of aliphatic and aromatic hydrocarbons (34). The simplest of these hydrocarbons, methane (CH_4) and benzene (C_6H_6), can enhance the heating value of the product gas while heavier hydrocarbons (C_{12} and higher) can be problematic when using the fuel gas in downstream equipment. These heavier hydrocarbons are referred to collectively as tars and are a byproduct of all gasification processes.



LCV = low calorific value 4–6 MJ/Nm^3
100–150 Btu/scf
MCV = medium calorific value 20 mJ/Nm^3
450 Btu/scf

Fig. 1. Gasification technologies provide end-use flexibility.

Some additional methane can be formed by the reaction:

$$C + 2\ H_2 = CH_4 \tag{10}$$

Reaction 10 is favored by higher pressures in the reactor.

Within a gasifier, all of these reactions take place to one degree or another. The specific proportions of the products of the reactions determine the heating value of the product gas produced. Biomass is a more reactive fuel (35) thereby providing the opportunity to process larger quantities of material in the same reactor and at lower temperatures than would be present in a coal gasifier. Biomass gasifiers typically operate at 800–900°C, while coal gasifiers may operate at temperatures of 1000°C or more. In general the reactivity (the ease with which a material can be converted) of the various fuels that are used in gasification systems can be expressed as:

Higher reactivity – liquids > biomass > coal > coke – lower reactivity

Biomass can exhibit a reactivity as much as a factor of 2 to 3 higher than that of coke, eg.

Gasification Reactions. There are three main types of reactors used for biomass gasification. These are fixed, fluidized, and entrained bed. In addition, there are some hybrid reactor types such as circulating fluidized bed and steam reforming fluidized bed that utilize properties of two reactor types to enhance the conversion reactions. In a fixed bed reactor, the incoming biomass is piled into a refractory lined chamber and reacted with an oxidant (air or oxygen) and/or steam to produce the fuel gas. There are two main types of fixed-bed reactor, updraft, illustrated in Figure 2 and downdraft, illustrated in Figure 3. In

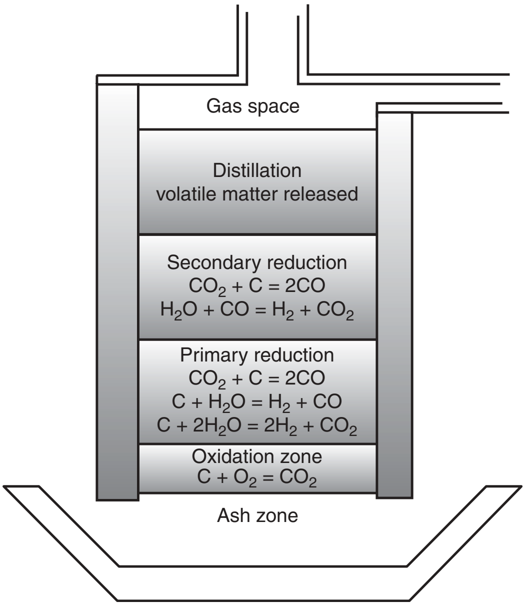


Fig. 2. Fixed-bed gasifier updraft mode.

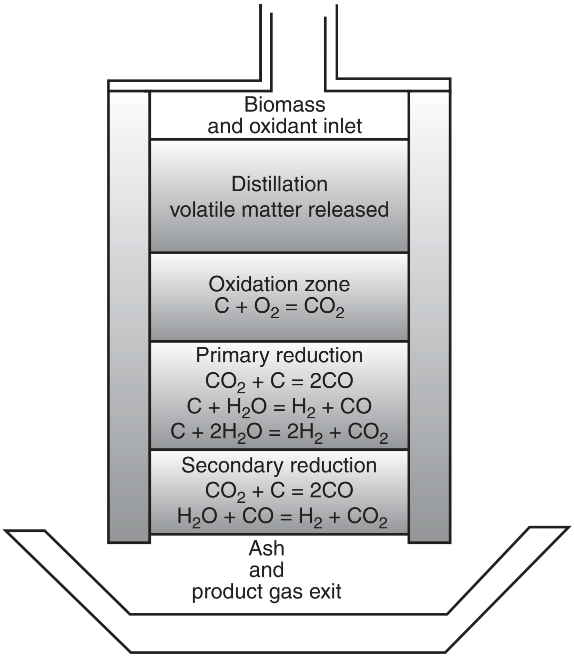


Fig. 3. Fixed-bed gasifier downdraft mode.

the updraft reactor, incoming biomass travels countercurrently to the oxidant source (usually air) while in the downdraft gasifier oxidant and biomass travel cocurrently through the reactor. The volatile matter in the incoming biomass is released at a lower temperature in an updraft reactor and has little opportunity to react with oxidant or steam before exiting the reactor. In contrast, in a downdraft gasifier, the volatiles are released in a higher temperature zone and continue through the reactor bed before exiting the reactor. The product gas from an updraft gasifier therefore will typically have a higher heating value and a higher tar content than the product gas from a downdraft gasifier.

In fixed-bed gasifiers, the inventory within the reactor must be supported by the fuel bed in order to maintain the chemical reactions. As the biomass is converted within the reactor, only the inorganic material (ash) in the biomass remains. Ash strength is therefore an important characteristic of the feedstock. In order to increase the effective strength of the ash in fixed-bed gasifier systems, the incoming biomass is either pelletized to increase its effective density or uniform larger "cubes" (∼10 cm) of biomass are used. The height of the fixed bed within the reactor is also restricted to limit the weight that must be supported by the ash bed. The general limit for bed height is approximately twice the bed diameter. This length to diameter (L/D) ratio is an important design parameter in the other reactor types as well.

The fluidized bed reactor (sometimes referred to as fluid bed reactor) provides more flexibility with regard to feedstock size and shape due to the manner in which the incoming biomass is handled. Within the reactor, incoming biomass particles are suspended in a bed of a finely divided (∼50-particles), inert material

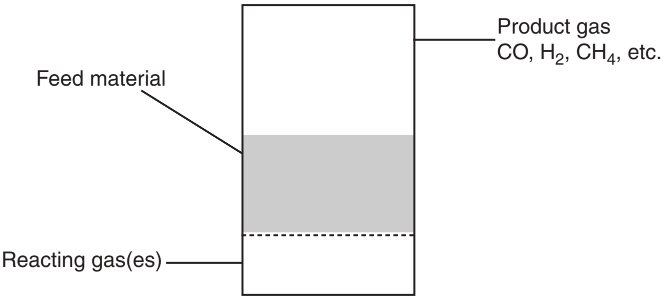


Fig. 4. Fluidized bed gasifier.

(typically sand). This inert bed is “fluidized” by the oxidant and steam reactants entering the reactor. These gaseous reactants are distributed across the reactor by a gas distributor. As they leave the distributor, bubbles are formed in the bed, lifting the particles of the bed material. Because of this bubble formation phenomenon, this reactor type is sometimes referred to as a bubbling fluidized bed. When the incoming velocity of the gas reaches the “minimum fludization velocity,” all of the bed material is suspended and begins to behave as a liquid (hence the terminology “fluidized” bed). Fluidized beds are inherently well mixed chemically and thermally thus providing an excellent medium for the gasification reactions (36). A simplified schematic of a fluid bed reactor is shown in Figure 4.

Biomass feed material is transported into the reactor either above or directly into the fluidized bed. It rapidly mixes with the inert bed material and reacts to form the product gas. Because the inert bed material rather than the biomass provides the inertia within the reactor, fluidized beds can accept a wider range of biomass particle sizes. As a general rule, biomass particles from ~200 μm to 10 cm can be utilized without difficulty in most fluidized bed reactors.

The L/D ratio for a fluidized bed is likewise more flexible, having a typical range from just over 1.0 to ~5.0. Larger L/D ratios are avoided in fluidized bed design to eliminate an operational problem called slugging. Slugging is caused when bubbles within the fluidized bed grow to the reactor internal diameter and lift the bed material as a mass. The slugging results in larger pressure fluctuations within the bed and reduces the effectiveness of the gas–solids contacting within the reactor. The Renugas gasifier developed by the Institute of Gas Technology and being commercialized by Carbona is an example of a bubbling fluidized bed reactor system.

If gas velocities within the reactor are increased beyond minimum fluidization so that materials are carried through the reactor, the reactor is referred to as a “circulating fluidized bed” or an “entrained bed”. In a pure entrained bed no inert medium is used. The incoming biomass is reduced in size to >200 μm and conveyed through the reactor as it reacts with the incoming oxidant and steam. The L/D ratios are less critical in this type of reactor system and may exceed 20 to 1 in some cases. Examples of CFB gasifiers are the Lurgi biomass gasifier and the TPS gasifier, both European developers (37,38). The hybrid “circulating fluidized bed” or CFB uses an inert medium (as in the bubbling fluidized bed, sand is

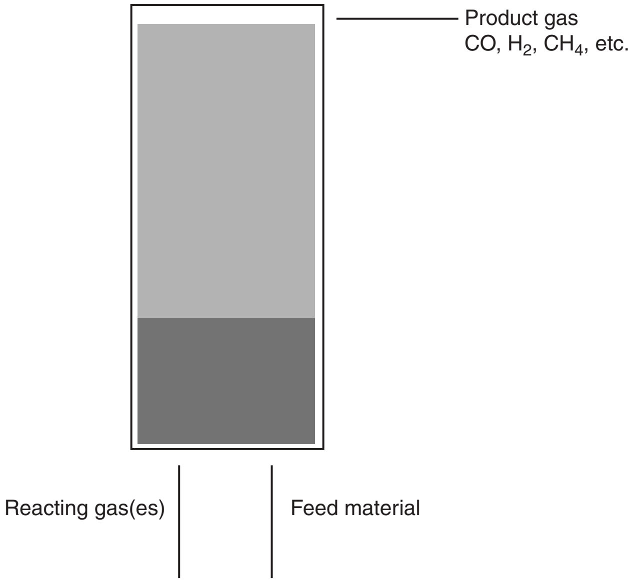


Fig. 5. Entrained bed gasifier.

the typical material) to allow for a wider range in biomass particle sizes to be utilized. The inert bed material is recycled through the reactor at high rates (sometimes 10 times the biomass feed rate or more) and serves as a flywheel stabilizing temperatures and chemical reactions. By using the inert medium, incoming biomass materials may have a much wider range of particle size ranging from the 200 μm used in pure entrained beds to over 5 cm. This flexibility reduces overall operating costs for fuel preparation and expands the range of biomass materials that can be gasified. A CFB reactor schematic is shown in Figure 5.

The CFB reactor in many applications uses an oxidant as the primary conveying gas thus generating product in the same manner as in the fixed or bubbling fluidized bed reactors. Alternatively, a second CFB can be coupled to the gasfier to burn char produced during gasification and heat the circulating sand phase. Such a process, the SilvaGas process, is being commercialized by FERCO Enterprises, Inc. (39). The heated sand is recycled to the gasifier, providing the energy for gasification as shown in Figure 6. In this configuration, referred to as an indirectly heated gasifier, only steam is used as the conveying medium effectively increasing the heating value to a “medium calorific value” (a gas having a heating value in the range of 17 MJ m^{-3}) of the product gas in much the same way as using pure oxygen as the reactant gas in other reactor configurations. The separation of oxygen from air is an expensive unit operation and, therefore, due to the relatively small scale of biomass gasifiers is considered an uneconomical alternative for the production of a medium calorific value gas. An alternative indirect heating method utilizes heat transfer tubes imbedded in a bubbling fluidized bed to provide the heat necessary for the gasification reactions. This type of gasification reactor is being developed and commercialized by Thermochem, Inc. (36) and is shown in Figure 7. As in the CFB case, a medium calorific value gas is produced, but with a slightly higher hydrogen content

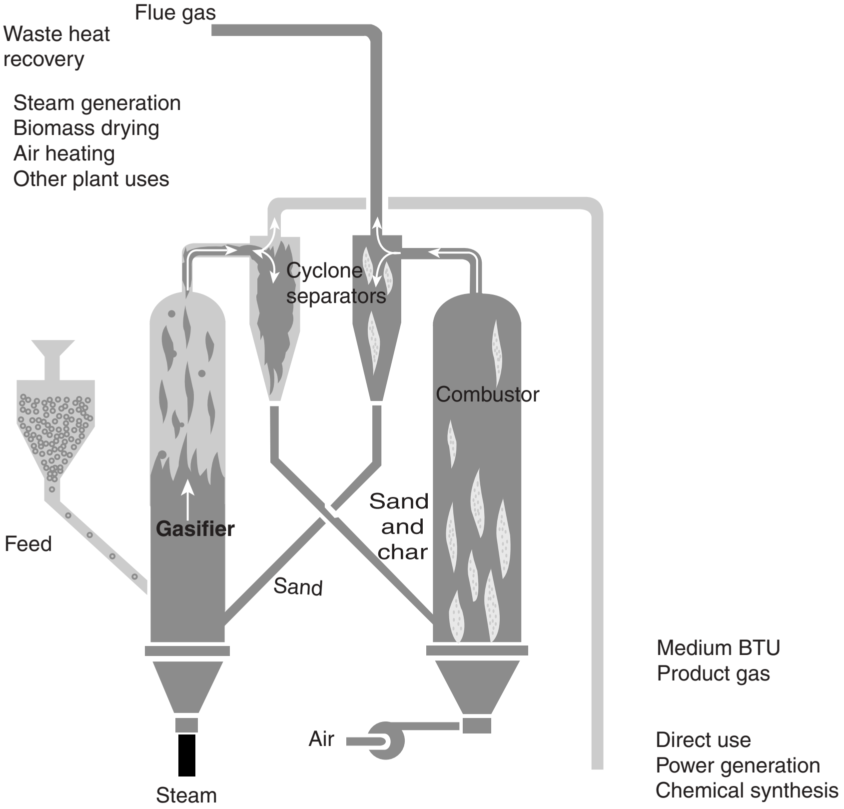


Fig. 6. FERCO Enterprises SilvaGas gasifier.

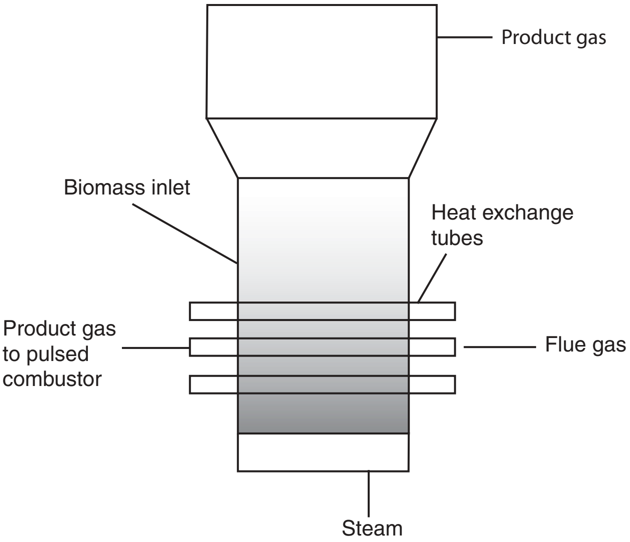


Fig. 7. Thermochem indirectly heated gasifier.

as a result of reaction 9, the water gas shift reaction, more closely approaching equilibrium due to the increased residence time available in the bubbling bed.

The Products from Biomass Gasification. The high reactivity of biomass helps determine the products produced during gasification. In all reactor types listed above, a mixture of gas, char, and liquids (tars) will be produced at varying levels. The levels of each component vary due to specific reactor conditions (temperature, pressure), reactant gases, and reactor heating method. The primary product of interest for gasification reactors is the product gas. In pyrolysis systems, discussed below, the primary product of interest is the liquid product. A characteristic product gas analysis from a number of gasification reactors is shown in the table below (37,39,40).

In addition to the product gas listed, coproducts of char and tars are produced to varying degrees. Char chemically consists of devolatilized biomass and has a higher concentration of carbon and a lower concentration of hydrogen than the incoming biomass. The production of char as a coproduct, therefore, results in a significant reduction in the overall efficiency of the gasification process. Operation of the gasification processes is adjusted in an attempt to minimize the formation of char.

Higher molecular weight hydrocarbons (typically above C_{12}) produced during gasification can condense in downstream unit operations and introduce operational difficulties. These tars vary from a few hundreds ppms to a few percent of the product gas depending on the reactor configuration. In order of the uncontrolled tar concentration produced, the reactor types discussed above are

$$\text{Low tar} < \text{downdraft fixed bed} < \text{indirect CFB} < \text{CFB} \\ = \text{bubbling bed} < \text{updraft fixed bed}$$

Use of the Gas from Gasification. As shown in Figure 1, gases derived from the gasification of biomass have a potentially wide range of end uses. In the simplest application, the gas may simply be used as a fuel for heating or in industrial furnaces such as lime kilns in the pulp and paper industry. Either low calorific value gases from air-blown gasifiers or medium calorific value gases from oxygen blown or indirectly heated gasifiers can be used in this manner. Similarly, both low and medium calorific value gases can be used as boiler fuels for the production of steam for direct use or for the production of electric power.

Higher overall efficiencies can be achieved by use of the gases in more demanding applications (those requiring a higher degree of cleanup of the gases). These include, use in an internal combustion engine or a gas combustion turbine for the direct production of power. As much as a 60% increase in power generation efficiency can be realized compared to the less demanding steam cycle approach. Again, both low calorific value and medium calorific value gases are suitable for power generation applications (41).

The diluent effect of nitrogen present in low calorific value gases limits their application for more advanced chemical synthesis applications. Medium calorific value gases, on the other hand, are well suited for synthesis applications. A simple and the most commonly considered synthesis application is the production of methanol or other alcohols from the biomass derived gas. This approach provides a means to introduce biomass derived liquid fuels into the existing petrochemical (gasoline) infrastructure in much the same way as the direct production of ethanol. Like ethanol, however, methanol (and higher alcohols) are not fungible fuels, therefore limiting their acceptance by the petroleum industry. Methanol as a fuel is even more susceptible to phase separation in gasoline blends than ethanol. Synthesis gas from biomass can be utilized to generate essentially any product that would be produced from a petrochemical based synthesis gas. This includes chemical intermediates, polymers, fuel additives, or hydrogen.

6.2. Pyrolysis. Pyrolysis is a similar technology to gasification in that biomass feedstocks are heated in an anaerobic (no air present) environment to break down the biomass into primarily liquid hydrocarbons. In pyrolysis systems currently under development, the production of liquids is enhanced by rapidly heating the biomass in a "fast pyrolysis" mode. Fast pyrolysis is a process that yields a liquid product that is referred to by many names including pyrolysis liquid, pyrolysis oil, bio-crude-oil, bio-oil, bio-fuel-oil, pyroligneous tar, pyroligneous acid, wood liquids, wood oil, wood distillates and liquid wood.

A variety of reactor types are used in fast pyrolysis systems. Because a high heating rate enhances the liquid yield, reactors of the fluidized bed type are favored by most developers. Figures 8 and 9 illustrate fluidized bed and CFB reactor systems for the production of oils from biomass (bio-oil). To further enhance liquid yields, reaction temperatures are controlled in the range of 500–600°C (42).

The bio-oil produced in fast pyrolysis systems is a dark brown liquid with a heating value about one-half that of conventional fuel oil (16–19 $\mathrm{MJ/kg^{-1}}$). In

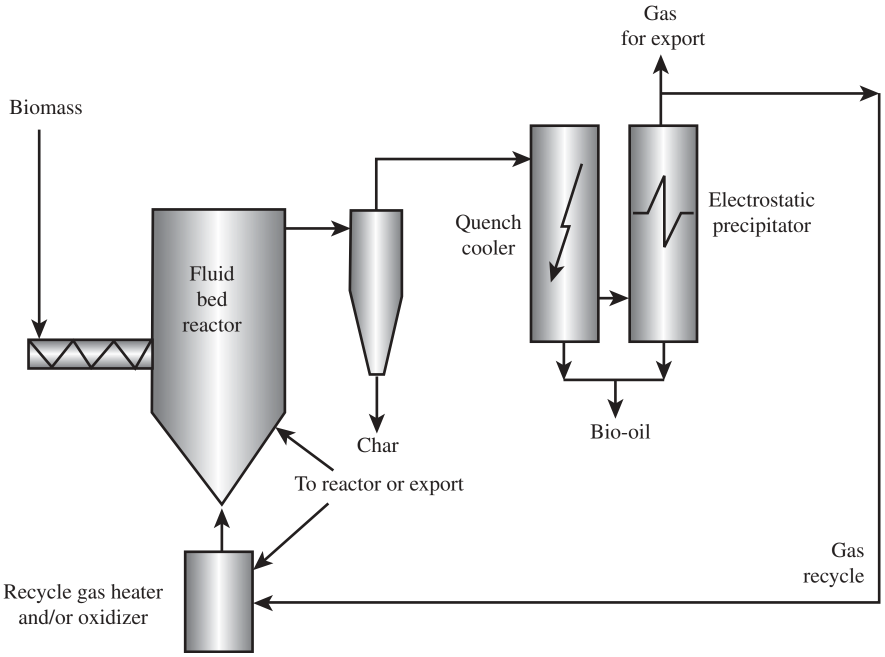


Fig. 8. Fluidized bed fast pyrolysis system.

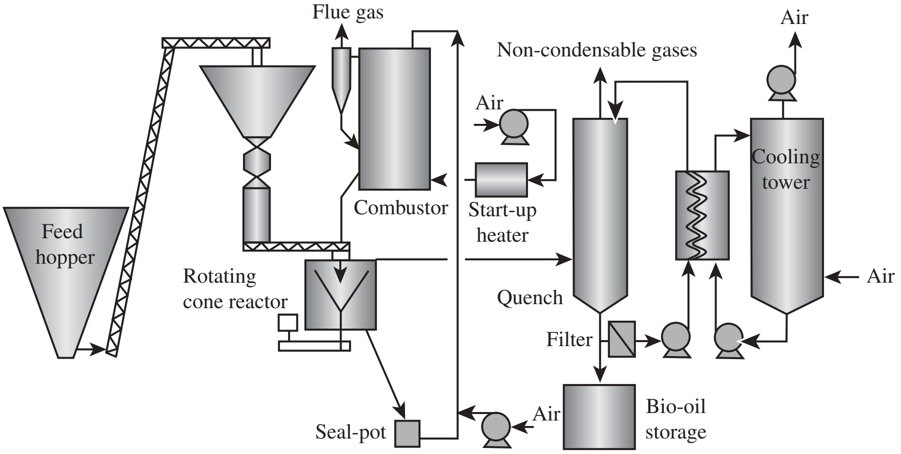


Fig. 9. Entrained reactor fast pyrolysis system.

order to achieve the high heat up rates necessary for the fast pyrolysis reactions, the incoming biomass must be finely ground (~2 mm, typically). Furthermore, the residence times within the heated zones in the reactor must be minimized to prevent polymerization of the bio-oil into undesired products. As in gasification, gases and char are also produced as coproducts of the pyrolysis reactions. These coproducts are typically used as fuels to provide the energy required for the pyrolysis reactions. The incoming biomass is also typically dried to <10% moisture to minimize the quantity of water in the bio-oil product.

Bio-oil Characteristics. Typical characteristics of bio-oil are found in the following table.

Physical property	Typical value
moisture content	15–30%
pH	2.5
specific gravity	1.2
viscosity	40–100 cP

Bio-oil has a distinctive odor, much like that of wood smoke, caused primarily by the phenolic materials present in the oil. It is a mixture of a large number (several hundred, typically) of primarily aromatic hydrocarbons all derived from the thermal decomposition of the incoming biomass. The proportion of the specific compounds varies widely from process to process and is influenced by the specific biomass used as feedstock as well as by the reactor conditions used.

Bio-oils cannot be completely vaporized once they have been recovered from the vapor phase. When they are heated, the oil tends to polymerize and form a char like material and heavier liquid hydrocarbons, that are undesirable as fuels. These polymerization reactions also tend to take place at room temperature, but at a much slower rate, thereby allowing reasonable storage periods for bio-oil products.

Uses of Bio-Oil. Bio-oil can be used in a variety of primarily industrial applications. The primary use is as a substitute or cofired fuel with fuel oil. Such applications include boilers, furnaces, and engines. Because the bio-oils are chemically similar to some organic chemical intermediates, other uses include resins (used in plywood manufacture and as adhesives), agri-chemicals, and other specialty chemicals. Bio-oils can be further upgraded by steam reforming, a process similar to steam gasification, producing a synthesis gas and a hydrogen enriched liquid product (43).

Relatively small quantities of bio-oils are sold as food flavorings and additives. The liquid smoke products found in supermarkets are typical of this type of bio-oil product.

Bio-oils are storable and easier to transport than the gaseous products from gasification systems, however, the end uses are less well defined due to their varying chemical nature.

6.3. Biodiesel. Biodiesel is a term applied to a fuel derived from the transesterification of used vegetable oils or animal fats. In the production of biodiesel, the triglycerides in the fats and oils are reacted with methanol to make methyl esters and glycerine. The glycerine produced can be sold as a by-product, however, due to large supplies of glycerine produced during soap manufacture, the income from the sale is likely to be small. The process uses a catalyst, typically NaOH or KOH to enhance the reaction rates. In the process, a small amount of the oil is converted to soap that is removed from the biodiesel prior to use. Free fatty acids formed during initial use of the vegetable oils and animal fats can be present in high concentrations. These contaminants can interfere with the biodiesel production and therefore the used oils may have to undergo some “pretreatment” prior to reaction with methanol. The reactions take place at low temperature ($\sim 65^\circ C$) and at modest pressure (2 atm). The biodiesel is purified after production by washing and evaporation to remove any remaining methanol. Current dedicated production capacity in the United States is between 60 and 80 million gal/ year (44,45).

Uses of Biodiesel. Much like ethanol, biodiesel is blended with traditional diesel fuel in varying proportions (typically 20% biodiesel to 80% petroleum diesel fuel). Unlike ethanol, however, much higher concentrations of biodiesel can be blended without requiring a modification to the engine.

Biodiesel has undergone extensive testing and conforms to an industry specification (ASTM D6751). As such it is recognized by environmental agencies (notably the US EPA) and is sold as a motor fuel.

6.4. Anaerobic Digestion. Anaerobic digestion is the biological degradation of organic material in the absence of oxygen. The product of such digestion is a gas containing primarily methane (CH_4) and carbon dioxide (CO_2). The digestion process occurs naturally in landfills, manure disposal sites, and other such residue disposal sites. It has also been applied in a more industrial setting in controlled digestors or “biogas” reactors (46,47).

The digestion process is carried out by naturally occurring bacteria. In the case of the industrial digestors, these bacteria have been carefully selected so that both the production rate and the methane content of the biogas produced are enhanced. Biogas typically has a heating value between 50 and 70% of that of natural gas. The energy content of biogas is derived entirely from the methane content of the gas. There are four steps that take place as the organic materials are digested (*1*) hydrolysis—high molecular weight organic molecules are broken down in to smaller molecules like sugars, amino acids, fatty acids, and water; (*2*) acidogenisis—the smaller molecules are further broken down into organic acids, carbon dioxide, hydrogen sulfide, and ammonia; (*3*) acetagenisis—the products of acidogenisis are converted into acetates, carbon dioxide, and hydrogen; and (*4*) methanogenisis—methane is produced from the hydrogen, carbon dioxide, and acetates produced in stages 2 and 3 (48).

The digestion bacteria have temperature ranges in which they are most productive. This results in specific temperature ranges where the digestion can be optimally carried out. These ranges are called mesophilic and thermophilic ranges. The mesophilic range is 25–38°C while the thermophilic range is 50–70°C. In general, the mesophilic digestion is more robust, but requires a longer residence time (typically 15–30 days). Thermophilic digestion, by contrast, reduces the residence time requirements to 12 to 15 days but requires much tighter control of process conditions. Thermophilic digestors produce a higher concentration of methane (up to 70%) thereby increasing the usefulness of the gas produced.

An important benefit of both types of digestion is the reduction of pathogens contained in the feedstock. This characteristic makes digestion processes well suited for the treatment of organic residues such as waste-water sludges and manures. The remaining solids after digestion can be used as a soil conditioner or further processed to produce an organic compost.

Commercial Application of Anaerobic Digestion. The gas produced (landfill gas) from anaerobic digestion in MSW landfills is being collected and used as a fuel for industrial heating and power generation at over 330 MSW landfills in the U.S. More than 500 other MSW landfills flare the gas. Combustion of the landfill gas helps to reduce the environmental impact of landfill gas emissions. Health and environmental concerns are related to the uncontrolled surface emissions of landfill gas into the air. As previously mentioned, landfill gas contains primarily carbon dioxide and methane, but can also contain trace quantities of volatile organic compounds (VOC) or other hazardous materials that can adversely affect public health and the environment. Carbon dioxide and methane are both greenhouse gases that contribute to global climate change. Methane is of particular concern because it is 21 times more effective at trapping heat in the atmosphere than carbon dioxide. Emissions of VOC contribute to ground-level ozone formation (smog). Ozone is capable of reducing or damaging vegetation growth as well as causing respiratory problems in humans.

In the United States, 1.6 GW of electric power are produced from such systems. The gas is cleaned to remove any sulfur compounds and then used as a fuel in gas turbine power generation systems, diesel engines, or other power generation systems (49).

6.5. Advanced Ethanol Production Methods. Lignocellulosics (wood, straw, and grasses) are in abundant supply and can potentially supply a source for the production of ethanol. Over 1 trillion metric tons of cellulose are estimated to be produced by plants annually. Effective utilization of this resource can greatly enhance the quantity of ethanol that is produced for energy. The primary chemical components of these materials, however, are cellulose (∼40–50%)

and hemicellulose (~25–30%). From a theoretical standpoint, the same quantity of ethanol could be realized from these materials as from high sugar containing biomass such as corn. A more complex conversion process is required to realize this potential as the cellulose and hemicellulose must first be converted into sugars so that fermentation can take place. Cellulose converts via hydrolysis into six-carbon sugars (primarily glucose) that are readily fermented with yeasts to produce ethanol.

Hemicellulose, on the other hand, is converted into mainly five-carbon sugar precursors with xylose as a major product. The C_5 sugars are not readily fermented into ethanol without additional conversion steps and they inhibit the hydrolysis reactions once they are formed. Additional pretreatment stages can be added to enhance the conversion to sugars, including steam, acid, or alkali treatments (50).

Research into the conversion of cellulose and hemicellulose into sugars and the subsequent conversion steps necessary for effective fermentation is underway in the United States and a number of European countries. Other methods being developed include the simultaneous saccharification and fermentation of cellulose to remove the sugars as they are produced by immediately converting them into ethanol.

7. Environmental Benefits from Biomass Energy

The use of biomass as an energy source, superficially results in a net zero change in carbon dioxide as illustrated in equation 1 above. Carbon dioxide is the predominant greenhouse gas found in the atmosphere. However, if forests are cleared for agricultural applications or development, this balance is no longer valid. Other greenhouse gases, namely, methane and nitrous oxide, are produced both by fossil energy conversion systems and during the growing and harvesting of biomass. The balance of these emissions and their ultimate impacts on the environment can only be accurately determined by the use of life cycle assessment (LCA) techniques.

The LCA uses rigorous methods to identify the complete production chain of biomass energy systems from seedling to end use. All energy and material inputs are included so that a true picture of the environmental impact can be developed. The results of LCA studies (6,51–54) show that biomass based power generation systems, regardless of the technology employed, have a net negative production in total greenhouse gas emissions (carbon dioxide, methane, and nitrous oxide) due to the elimination of biomass from landfills, thus offsetting emissions of methane that would otherwise be produced. Note that these studies include all of the fossil fuel necessary to transport the biomass to the power station and carry ash away from the station. Fossil fuels, on the other hand, produce 40–250% more greenhouse gases including cases where natural gas is the primary fuel and carbon dioxide sequestration is applied.

Reductions in greenhouse gas emissions are also realized when ethanol is used as a transportation fuel additive. Even with the inefficiencies of internal combustion engines included in the analysis, even a 10% blend of ethanol can

Table 1. **Typical Gas Analyses**

Component	Air blown CFB low press	Air blown bubbling bed high press	Fixed-bed downdraft	Indirect CFB	Indirect bubbling bed
hydrogen	16.7	8.5	19	21.2	46.8
carbon monoxide	21.4	12.3	18	43.2	34.4
carbon dioxide	12.6	15.9	14	13.5	6.6
methane	3.4	7.5	5	15.8	1.6
ethane	0.04	0.02		0.5	0.1
ethylene	1.3	0.7		0.6	0.2
nitrogen	39.6	40.7	44	0	0
water vapor	5.0	14.3	dry	dry	10.3

reduce greenhouse gas emissions by 19–25% depending on the source of the ethanol.

Other environmental benefits beyond the reduction of greenhouse gases can be realized by the use of biomass derived energy products. Cofiring of biomass with fossil fuels in boiler systems results in reductions of both sulfur and nitrogen oxides proportionate to the quantity of biomass being used. If minor modifications to the boiler are made the reduction in nitrogen oxides can be further enhanced. By cofiring the gas produced from a biomass gasifier in either a boiler or a gas turbine, nitrogen oxides can be reduced to levels significantly below those produced with the fossil fuel alone.

In some boiler applications, medium calorific value gas from biomass has been used as a reburn fuel in fossil fuel boilers. The reburn fuel provided ~15% of the energy input of the boiler. By proper placement of the reburn fuel introduction points, nitrogen oxides were reduced by up to 70% when compared to the fossil fuel alone.

8. Conclusion

The steady growth in biomass energy is expected to continue. Biomass is one of the largest renewable resources and provides advantages when compared to other renewable resources. Furthermore, biomass is the only renewable carbon-based resource with minimal greenhouse gas emission potential. This anticipated growth is subject only to the economic climate and not constrained by the supply of biomass feedstocks. Due to the flexibility of biomass energy technologies, a wide range of products can be produced ranging from basic energy products to refined chemicals, pharmaceuticals and fertilizers.

BIBLIOGRAPHY

"Fuels from Biomass" in *ECT* 3rd ed., Vol. 11, pp. 334–392, by D. L. Klass, Institute of Gas Technology; "Fuels from Biomass" in *ECT* 4th ed., Vol. 12, pp. 16–110, by D. L. Klass, Institute of Gas Technology; "Fuels from Biomass" in *ECT* (online), posting date: December 4, 2000, by D. L. Klass, Entech International, Inc.

CITED PUBLICATIONS

1. S. Kyritis, Welcome Address, First World Conference on Biomass for Energy and Industry, Seville, Spain, June 5–9, 2000.
2. IEA *World Energy Outlook*, Paris, France, Organization for Economic Co-operation and Development, 2002.
3. United States Energy Information Administration, Renewable Energy Annual 1999, DOE/EIA 0603 (99), Washington, D.C.
4. American Biomass Association, “Biomass Clean Energy for America”, internet site, www.biomass.org.
5. UNEP Division of Technology, Industry and Economics, Energy and OzonAction Unit, “Bioenergy Fact Sheet”.
6. Biomass Energy Research Association, internet site, www.bera1.org.
7. R. Matthews and K. Robertson, “Answers to ten frequently answered questions about bioenergy, carbon sinks, and their role in global climate change,” IEA Bioenergy Task 38, internet site, www.joanneum.at/iea-bioenergy-task38/, 2001.
8. D. O. Hall and K. K. Rao, *Photosynthesis*, Cambridge, Cambridge University Press, 1999.
9. K. R. Smith, “In Praise of Petroleum?”, *Science* **298**, 1847 ff (2002).
10. National Renewable Energy Laboratory, Chemistry for Bioenergy Systems Division, “Biomass Energy”, 2002.
11. J. E. Houck and P. E. Tiegs, *Residential Wood Combustion Review Volume 1, Technical Report* U. S. Environmental Protection Agency, Office of Research and Development, 1998.
12. United States Department of Energy, Office of Energy Efficiency and Renewable Energy, “Bioenergy, an Overview”, 2002.
13. C. Demeter, “Biomass Power in Today’s Energy Landscape”, World Energy Engineering Conference, Atlanta, Ga., October, 2002.
14. T. Miles, “Biomass Preparation for Thermochemical Conversion,” *First European Workshop on Thermochemical Processing of Biomass*, Birmingham, U.K., April 12–13, 1983.
15. K. Taupin, “Modern Wood Fired Boiler Designs—History and Technology Changes”, Second Biomass Conference of the Americas, Portland Oregon, August 21–24, 1995.
16. *Steam—It’s Generation and Use*—40th ed., Babcock and Wilcox, 1992.
17. E. S. Domalski, T. L. Jobe, Jr., and co-workers, *Thermodynamic Data for Biomass Materials and Waste Components*, ASME, New York, 1987.
18. G. Wiltsee, T. McGowin, and E. Hughes, “Biomass Combustion Technologies for Power Generation”, First Biomass Conference of the Americas, Burlington, Vt., 1993.
19. American Forest and Paper Association, internet site www.afandpa.org, 2003.
20. S. Salat, and co-workers “District Heating Biomass for Southern Europe”, First World Conference on Biomass for Energy and Industry, Sevilla, Spain, June 5–9, 2000.
21. International Energy Agency, *Energy Policies of IEA Countries, Sweden 2000 Review*, 2000.
22. T. N. Bhattarai, “Charcoal and its Socio-Economic Importance in Asia: Prospects for Promotion”, Regional Training on Charcoal Production, Pontianak, Indonesia, February, 1998.
23. R. van der Plas, “Burning Charcoal Issues”, FPD Energy Note No. 1, The World Bank Group, April, 1995.
24. G. Wiltsee, “Urban Wood Waste Resource Assessment”, Appel Consultants, Inc., National Renewable Energy Laboratory Report NREL/SR-570-25918, November, 1998.

25. General Biomass Corporation, "Bioenergy and Biofuels," corporate internet site www.generalbiomass.com.
26. United States Department of Energy, Office of Transportation Technologies, "History of Biofuels", 2002.
27. Solar Energy Research Institute, "Fuel from Farms", Report SERI/SP-451-519, February, 1980.
28. National Corn Growers Association, "Ethanol—America's Clean Renewable Fuel", July, 2002.
29. Renewable Fuels Association, "How Ethanol is Made", 2000.
30. C. E. Wyman, *Handbook on Bioethanol: Production and Utilization*, Applied Energy Technology Series, Taylor and Francis, Washington, D.C., 1996.
31. C. Wyman, "Commercializing New Bioethanol Technology", First World Conference on Biomass for Energy and Industry, Sevilla, Spain, June 5–9, 2000.
32. H. H. Lowery, *The Chemistry of Coal Utilization*, Vol. II, John Wiley & Sons, Inc., New York, 1945.
33. E. Mangold and co-workers, Coal Liquefaction and Gasification Technologies, Ann Arbor Science, Mich., 1982.
34. R. Overend and M. Paisley, "A First Gasification Course", UBECA Conference, Washington, D.C., November, 1999.
35. N. Rambush, Modern Gas Producers, Benn Brothers, LTD, London, U.K., 1923.
36. F. Zenz and D. Othmer, *Fluidization and Fluid Particle Systems*, Reinhold Publishing Co., New York, 1960.
37. P. Tam and co-workers, "Forest Sector Table: Assessment of Gasification Technologies and Prospects for Their Commercial Application", National Climate Change Program, April, 1999.
38. T. Reed and S. Gaur, *A Survey of Biomass Gasification, 2001*, BEF Press, 2001.
39. M. Paisley and R. Overend, "Verification of the Performance of the FERCO Gasifier", Pittsburgh Coal Conference, September, 2002.
40. Thermochem, Inc., Corporate Brochure, 2002.
41. M. Welch, "Power Generation from Biomass Using a Small Industrial Gas Turbine", Bioenergy 2002, Boise, Ind., September, 2002.
42. T. Bridgewater, *A Guide to Fast Pyrolysis*, Aston University, Birmingham, U.K., 2001.
43. Pyrolysis Network, internet site, www.pyne.co.uk.
44. National Biodiesel Board, "biodiesel Basics", 2002.
45. T. Reed, *Biodiesel*, BEF Press, 2003, www.woodgas.com.
46. H. Kolk, "Anaerobic Digestion", Biomass Technology Group, Amsterdam, The Netherlands, 2002.
47. British Biogen, "Anaerobic Digestion of Farm and Food Processing Residues—Good Practice Guidelines", 2001.
48. California Energy Commission, "Anaerobic Digestion", 2002.
49. U.S. Environmental Protection Agency, Landfill Outreach Program, Office of Atmospheric Programs, Climate Protection Partnersips Division, Methane and Sequestration Branch, internet site, http://www.epa.gov/lmop/products/factsheet.htm.
50. H. Chum and R. Overend, "Biomass and Bioenergy in the United States", *Advances in Solar Energy*, Vol. 15, American Solar Energy Society, 2002.
51. M. Mann and P. Spaeth, Life Cycle Assessment of a Biomass Gasification Combined Cycle Power System, National Renewable Energy Laboratory, TP-430-23076, 1997.
52. M. Mann and P. Spaeth, Life Cycle Assessment of a Direct-Fired Biomass Power Generation System, National Renewable Energy Laboratory, TP-570-26942, 2000.
53. M. Mann and P. Spaeth, Life Cycle Assessment of Biomass Cofiring in a Coal Fired Power Plant, National Renewable Energy Laboratory, TP-430-26963, 2000.

54. R. Overend and E. Chornet, *Biomass a Growth Opportunity in Green Energy and Value Added Products*, Proceedings of the Fourth Biomass Conference of the Americas, Pergamon, New York, 1999.

Mark A. Paisley
FERCO Enterprises, Inc.