

# Biomass Conversion to Fuels and Electric Power

Robert C. Brown and Mark Wright

*Center for Sustainable Environmental Technologies,  
Iowa State University, Ames, IA, USA*

## Options for Fuels and Electric Power from Biomass

Biomass can be converted into a variety of solid, gaseous, and liquid fuels using both thermal and biological processes. The choice of process and product depends upon the nature of the biomass feedstock and the market into which it is being sold. Solid bio-energy products include torrefied biomass and charcoal. Gaseous bio-energy products can be formed via anaerobic digestion (biogas), thermal or supercritical gasification (producer gas, or syngas), or by upgrading of the primary products of anaerobic digestion or gasification (hydrogen and methane). Liquid bio-energy products are conveniently classified according to the intermediate substrate derived from physically, chemically, or thermally processing biomass: carbohydrates, triglycerides, syngas, and bio-oil/biocrude. Liquid fuel production from carbohydrates has traditionally focused on ethanol, although butanol, isoprenes, furans, and even alkanes can also be produced. Similarly, production from triglycerides has traditionally focused

on methyl-esters (biodiesel), but conversion to alkanes and propane via hydrotreating is receiving increasing attention. Liquid fuels from syngas include Fischer-Tropsch liquids, methanol, ethanol, dimethyl ether (DME), and methanol-to-gasoline (MTG). Liquid fuels from bio-oil and biocrude include a range of hydrocarbons suitable as gasoline, diesel fuel, or aviation fuel. Finally, biomass can be converted to electricity, which offers an alternative approach to providing energy for transportation.

## Conversion of Biomass to Gaseous Fuels

Both biological and thermal processes can yield gaseous fuels although the composition of the gas is quite different for each. Biological conversion is usually applied to high moisture biomass while thermal processes demand moisture contents less than about 20 wt-%.

Anaerobic digestion is the decomposition of organic materials to gaseous fuel by bacteria

Brown, R.C. And M. Wright. 2009. Biomass conversion to fuels and electric power. Pages 53-64, in R.W. Howarth and S. Bringezu (eds) *Biofuels: Environmental Consequences and Interactions with Changing Land Use*. Proceedings of the Scientific Committee on Problems of the Environment (SCOPE) International Biofuels Project Rapid Assessment, 22-25 September 2008, Gummersbach Germany. Cornell University, Ithaca NY, USA. (<http://cip.cornell.edu/biofuels/>)

in an oxygen-free environment (Chynoweth et al. 2001). The resulting biogas is a mixture of primarily methane ( $\text{CH}_4$ ) and carbon dioxide ( $\text{CO}_2$ ). Most digestion systems produce biogas that is 55%-75% methane by volume. Biogas can substitute for natural gas in many applications once it is treated to remove sulfur. Examples of biogas applications are engine generator sets, small gas turbines, and some kinds of fuel cells.

Anaerobic digestion consists of three steps: hydrolysis and fermentation, transitional acetogenic dehydrogenation, and methanogenesis. Hydrolysis and fermentation involve hydrolytic and fermentative bacteria that break down proteins, carbohydrates, and fats into simpler acids, alcohols, neutral compounds, and some carbon monoxide ( $\text{CO}$ ) and hydrogen ( $\text{H}_2$ ). Products of fermentation that are too complex for methane-forming bacteria to consume are further degraded to acetate, hydrogen, and carbon dioxide in transitional digestion, which is carried out by acid-forming bacteria. Traces of oxygen in the feedstock are consumed in this step, which benefits oxygen-sensitive, methane-forming bacteria. The final step, methanogenesis, uses methane-forming bacteria to convert acetate to methane.

Examples of anaerobic reactor designs include the simple batch reactor, plug-flow reactors, continuously stirred tank reactors (CSTR), upflow reactors, and two-tank reactor systems. More advanced reactor designs aim to improve waste contact with active bacteria and/or to separate and control the environments for acid-forming and methane-forming bacteria (Demirel and Yeniguen 2002).

Thermal gasification is the conversion of solid, carbonaceous fuels into flammable gas

mixtures consisting of  $\text{CO}$ ,  $\text{H}_2$ ,  $\text{CH}_4$ ,  $\text{CO}_2$ , and nitrogen ( $\text{N}_2$ ), in addition to smaller quantities of hydrocarbons. (Reed 1981) This gas can be burned directly in a furnace to generate process heat or to fuel internal combustion engines, gas turbines, or fuel cells. The presence of inert gases such as  $\text{N}_2$  and  $\text{CO}_2$  can reduce the calorific value of gasification products from 16 to 6 megajoules per cubic meter (Bridgwater et al. 2002).

Thermal gasification consists of two processes acting in parallel: pyrolysis and combustion (Balat 2008). Pyrolysis is the thermal degradation of solid fuel into non-condensable gases and organic vapors and liquid aerosols. Depending on the reaction conditions, pyrolysis products undergo secondary reactions that can substantially alter the final gas composition and the amount of tar and char co-products. Pyrolysis is an endothermic process, requiring a source of thermal energy for reaction to progress. This can be provided by heat transfer or transport of heat carrier into the reactor in a process referred to as indirect gasification. More commonly, part of the biomass is burned in the reactor by addition of air or oxygen to the gasifier to drive pyrolysis. If air is employed for combustion the resulting nitrogen-rich gas mixture is referred to as producer gas. The gaseous product of indirect gasification, or oxygen-blown gasification, is commonly called syngas in reference to its suitability for synthesizing liquid fuels, as subsequently described.

Thermal gasifiers are generally classified according to the method of contacting fuel and gas. The four main types are updraft (counterflow), downdraft (co-flow), fluidized bed, and entrained flow. Biomass gasifiers commonly operate near atmospheric pressure, although some designs

operate at ten atmospheres of pressure or more for use with gas turbines or for catalytic synthesis.

Gasification in supercritical water has been proposed for high moisture biomass feedstocks such as wastewater, manure, or kelp (Elliott et al. 2004). Supercritical conditions prevail at 600-650 °C and 300 bar pressures, which is able to convert biomass into gas within 0.5-2.0 minutes. The combination of relatively low temperature and high pressure makes for high methane yields, which is problematic for Fischer-Tropsch synthesis and steam reforming.

Pure hydrogen and methane can be produced from biological and thermal processes usually through additional upgrading and purification steps. For example, the biogas from anaerobic digestion is mostly methane, which can be purified to pipeline quality natural gas. Process conditions during anaerobic digestion can be altered to yield hydrogen instead of methane (Chen et al. 2006). The carbon monoxide and hydrocarbons in producer gas or syngas can be reacted with steam to increase the yield of hydrogen, which can then be separated as hydrogen fuel (Zhang et al. 2005).

### **Conversion of Carbohydrate to Liquid Fuels**

Carbohydrates are derived from sugar crops such as sugarcane, starch crops such as maize, and cellulosic biomass such as switchgrass. Different types of treatments are required to recover carbohydrate in forms suitable for conversion to fuels. Carbohydrate recovery is as simple as crushing sugarcane stalks to release sucrose-rich syrup or as complicated as enzymatic hydrolysis of ligno-cellulosic fibers to convert hemicellulose and cellulose into pentose and hexose. Processes that convert carbohydrate to fuels, whether

biologically or catalytically based, usually require monosaccharides or disaccharides although some experimental processes have demonstrated direct conversion of cellulose into fuel (Pandey 2003; Carlson et al. 2008).

Fermentation is the biological conversion of carbohydrate into ethanol. Fermentation has been widely practiced for thousands of years and can use a variety of commodity grains as feedstock, which explains ethanol's early leadership in biofuels markets. Plant materials high in sugar, such as sugarcane, sugar beets, and sweet sorghum provide the most cost-effective ethanol since sugars can be directly fermented. Starch, a storage carbohydrate in plants, must be hydrolyzed to glucose, a process that cooks milled starch granules with thermophilic (heat tolerant) enzymes. Starch crops suitable as feedstock include corn, grains, and potatoes. Cellulose, a structural carbohydrate in plants, is considerably more difficult to hydrolyze to glucose because of the presence of hemicellulose and lignin in plant fibers (Sjöström 1981). A wide variety of cellulose crops are under consideration for advanced biofuels production including crop residues, wood wastes, and switchgrass.

Grain-based ethanol plants are categorized as either dry- or wet-milling depending on the pretreatment method. Dry milling plants grind the whole kernel while wet milling plants soak the grain with water and acid to separate the corn germ, fiber, gluten, and starch components before mechanical grinding. The capital investment for dry milling is less than that for a comparably sized wet-milling plant. However, the higher value of byproducts, greater product flexibility, and simpler ethanol production can make a wet-milling plant a more profitable investment.

A modern dry milling plant will produce in excess of 10.2 liters (2.7 gal) of ethanol per bushel of corn processed. Yields of co-products per bushel of corn are 7.7-8.2 kg (17-18 lb) of dry distiller's grain with solubles (DDGS) and 7.3-7.7 kg (16-17 lb) of carbon dioxide evolved from fermentation, the latter of which can be sold to the carbonated beverage industry. As a rule of thumb, the three products are produced in approximately equal weight per bushel, with each accounting for approximately one-third of the initial weight of the corn. A 151 million liter per year ethanol plant could be built in 2005 for \$46.7 million USD with annual operating costs of \$41.3 million USD (Table 3.1; Kwiatkowski et al. 2006). Construction costs have escalated very recently due to rapid expansion of the industry, almost doubling the projected capital costs for such a plant.

Cellulose to ethanol consists of four steps: pretreatment, enzymatic hydrolysis, fermentation, and distillation (Lynd 1996). Of these, pretreatment is the most costly step, accounting for about 33% of the total processing costs. An important goal of all pretreatments is to increase the surface area of lignocellulosic material, thereby making the polysaccharides more susceptible to hydrolysis. Thus, comminution, or size reduction, is an integral part of all pretreatments. Some pretreatments are thought to reduce crystallinity of cellulose, which improves reactivity, but this does not appear to be the key for many successful pretreatments.

Simultaneous saccharification and fermentation (SSF) has been developed for fermenting sugars released from lignocellulose. The SSF process combines hydrolysis (saccharification) and fermentation to overcome end-product

inhibition occurring during hydrolysis of cellobiose. By combining hydrolysis and fermentation in the same reactor, glucose is rapidly removed before it can inhibit further hydrolysis.

The yield of ethanol from energy crops varies considerably. Among sugar crops, sweet sorghum yields 80 liters per ton ( $\text{L t}^{-1}$ ) sugar beets yield 90-100  $\text{L t}^{-1}$ , and sugar cane yields 75  $\text{L t}^{-1}$ . Among starch and inulin crops, the ethanol yield is 350-400  $\text{L t}^{-1}$  of corn, 400  $\text{L t}^{-1}$  of wheat, and 90  $\text{L t}^{-1}$  of Jerusalem artichoke. Among lignocellulosic crops, the potential ethanol yield is 400  $\text{L t}^{-1}$  of hybrid poplar, 450  $\text{L t}^{-1}$  for corn stover, 510  $\text{L t}^{-1}$  for corncobs, and 490  $\text{L t}^{-1}$  for wheat straw. Capital cost of a 190 million liters per year cellulosic ethanol plant is approximately \$294 million with annual operating costs of \$76.0 million (Hamelinck et al. 2005).

Alternative fermentation pathways can produce transportation fuels with properties that are more attractive than ethanol. Butanol is a three-carbon sugar with 91% of the volumetric energy content of gasoline (compared to 66% for ethanol), and can be blended with gasoline or fed directly into an internal combustion engine without major modifications. However, yields from traditional butanol fermentation processes rarely exceed 20 grams per liter ( $\text{g L}^{-1}$ ) while ethanol yields are 150  $\text{g L}^{-1}$ . The toxicity of butanol to microorganisms presents a major challenge in improving yields. The capital cost of a 136 million liters butanol plant is estimated as \$110 million USD with operating costs of \$68.4 million USD (Table 3.1; Qureshi and Blaschek 2000).

Catalytic conversion of monosaccharides to methylated furans has received recent interest (Román-Leshkov et al. 2007; Zhao et al. 2007). Furans are heterocyclic aromatic

Table 3.1 Estimated Costs of Liquid Fuels from Biomass

Reference Data	Grain Ethanol	Cellulosic Ethanol	Butanol	Methanol	Fischer-Tropsch Liquids	Gasoline from Bio-oil
Publication Date	2006	2005	2000	2002	2002	2008
Plant Size (MM Liters)	151	190	136	330	132	-
Capital Cost (MM \$)	46.7	294	110	224	341	-
Operating Cost (MM \$)	41.3	76.0	68.4	60.6	50.8	-
Fuel Cost (liter <sup>-1</sup> )	\$0.27	\$0.40	\$0.50	\$0.18	\$0.38	\$0.48
Fuel Cost (per lge*)	\$0.44	\$0.65	\$0.55	\$0.36	\$0.34	\$0.48

ethers consisting of a ring of four carbon atoms and one oxygen atom. Furans are colorless, water-insoluble, flammable liquids with volatility comparable to hydrocarbons of similar molecular weight. Methylated furans have heating values and octane numbers comparable to gasoline making them attractive as transportation fuel (Hanniff and Dao 1987). However, neither the fuel properties nor toxicity of this compound have been much studied, raising questions as to the ultimate practicality as transportation fuel.

### Conversion of Syngas to Liquid Fuels

Syngas is an attractive intermediate for production of biofuels because it can be generated from almost any carbonaceous feedstock, including biomass and fossil fuels. Syngas can be catalytically and bio-catalytically upgraded to several liquid fuels including methanol, ethanol, dimethyl ether, and Fischer-Tropsch liquids.

Methanol (CH<sub>3</sub>OH) is a clear, odorless, flammable alcohol suitable as high-octane motor fuel (Davenport 2002). The fuel properties of methanol are similar to those

of ethanol: narrow boiling point range, high heat of vaporization, and high octane number (Gray Jr and Alson 1989). It has only 49% of the volumetric heating value of gasoline. However, methanol is considerably more toxic than ethanol. Methanol can also be converted to dimethyl-ether, which can be stored like propane and burned in compression ignition engines, and synthetic gasoline. Methanol is produced by reacting syngas over a copper-zinc catalyst at 5-10 MPa and 250°C. Capital cost for a 330 million liters per year methanol plant is approximately \$224 million USD with annual operating costs of \$60.6 million USD (2002 basis year) (Table 3.1; Hamelinck and Faaij 2002).

Ethanol synthesis is also possible from syngas. Efforts in Germany during World War II to develop alternative motor fuels discovered that iron-based catalysts could yield appreciable quantities of water-soluble alcohols from syngas (Klass 1998). These early efforts yielded liquids containing as much as 45-60% alcohols of which 60-70% was ethanol. Working at pressures of around



50 bar and temperatures in the range of 220–370 °C, researchers have developed catalysts with selectivity to alcohols of over 95%.

The two main approaches to producing ethanol from syngas are catalytic synthesis of mixed alcohols and direct carbonylation of methanol. Although high ethanol concentrations of up to 80% by volume or more are possible, production of pure ethanol has been elusive. Direct carbonylation of methanol has the advantage of yielding ethanol without co-product water, which would eliminate energy-intensive distillations. The cost-effectiveness of this approach to ethanol synthesis has not been proven.

Fischer-Tropsch technology was extensively developed and commercialized in Germany during World War II when it was denied access to petroleum-rich regions of the world. Likewise, when South Africa faced a world oil embargo during their era of apartheid, it employed Fischer-Tropsch technology to sustain its national economy.

Fischer-Tropsch liquids can be refined to various amounts of renewable (green) gasoline, diesel fuel, and aviation fuel depending upon process conditions. The Anderson-Schulz-Flory (ASF) distribution describes the probability of hydrocarbon chain growth (Schulz 1999). Depending on the types and quantities of Fischer-Tropsch products desired, either low (200–240 °C) or high temperature (300–350 °C) synthesis at pressures ranging between 10 to 40 bar are used with either cobalt or iron based catalysts. For example, high gasoline yield can be achieved using high process temperatures and iron catalyst. Non-condensable hydrocarbons (mostly methane) can be fed into a gas turbine to provide power to a manufacturing facility. Fischer-Tropsch synthesis requires careful control of the

H<sub>2</sub>:CO ratio to satisfy the stoichiometry of the synthesis reactions as well as avoid deposition of carbon on the catalysts (coking). An optimal H<sub>2</sub>:CO ratio of 2:1 is maintained through the water-gas shift reaction. Capital cost for a plant producing 132 million liters per year Fischer-Tropsch liquids is approximately \$341 million USD with annual operating costs of \$50.8 million USD (Table 3.1; Tijmensen et al. 2002).

Syngas can also be bio-catalytically upgraded to biofuels in a process known as syngas fermentation (Brown 2007). A number of microorganisms are able to utilize CO, CO<sub>2</sub>, and H<sub>2</sub> as substrates for growth and production. These include autotrophs, which use C<sub>1</sub> compounds as their sole source of carbon and hydrogen as their energy source, and unicarbonotrophs, which use C<sub>1</sub> compounds as their sole source of both carbon and energy. Syngas fermentation avoids the costly and complicated steps of extracting monosaccharide from lignocellulose. It also has the potential for being more energy efficient since it utilizes all plant components, including lignin, which resist biological conversion. Syngas fermentation also has advantages over the use of inorganic catalysts in the production of synthetic fuels (Grethlein and Jain 1992). For instance, sulfur-bearing gases readily poison most catalysts whereas syngas-consuming anaerobes are sulfur tolerant. The H<sub>2</sub>:CO ratio of the syngas is critical to catalytic upgrading whereas biological catalysts are not sensitive to this ratio. Also, gas-phase catalysts typically employ temperatures of several hundreds of degree Centigrade and at least 10 atmospheres of pressure whereas syngas fermentation proceeds at near ambient conditions. Finally, biological catalysts are more product specific than inorganic catalysts. However, syngas fermentation has several barriers to overcome

before it can be commercialized including relatively low rates of growth and production by anaerobes, difficulties in maintaining anaerobic fermentations, product inhibition by acids and alcohols, and difficulties in transferring relatively insoluble CO and H<sub>2</sub> from the gas phase to the liquid phase.

### **Conversion of Bio-oil and Biocrude to Liquid Fuels**

Bio-oil is a complicated mixture of highly oxygenated organic compounds including aldehydes, carboxylic acids, phenols, sugars, and aliphatic and aromatic hydrocarbons.

The relative simplicity of generating bio-oil and the convenience of storing a liquid compared to solids was responsible for much of the early interest in bio-oils. The fuel can be directly substituted for heating oil or, under some circumstances, fired in combustion turbines or modified diesel engines. Liquid yields exceeding 70% are possible for reaction times of less than 2 s and temperatures of 450–600 °C. Rapid quenching is essential if high molecular weight liquids are to be condensed rather than further decomposed to low molecular weight gases. Assuming conversion of 72% of the biomass feedstock to liquid on a weight basis, yield of bio-oil is 560 liters per tonne (L t<sup>-1</sup>). Raw bio-oil, however, has several short-comings including a heating value half that of heating oil, high acidity, and poor stability. For these reasons, recent efforts have focused on upgrading bio-oil through gasification/Fischer-Tropsch catalysis or hydrotreating/hydrocracking.

Fast pyrolysis is the thermal decomposition of organic compounds in the absence of oxygen to produce a liquid known as bio-oil (Bridgwater and Peacocke 2000). Bio-oil gasification yields syngas that can be catalytically upgraded to alcohols, ethers, or

alkanes, as previously described. Gasifying bio-oil instead of directly gasifying biomass has its advantages, as the oil is better suited for conventional storage and transportation, as well as injection into high-pressure gasifiers (Wright et al. 2008).

The process of hydrotreating/hydrocracking bio-oil into hydrocarbons suitable as transportation fuel is similar to the process for refining petroleum (Marinangeli et al. 2005). Hydrotreating is the reaction of organic compounds with hydrogen over a catalyst at high pressure to remove sulfur, nitrogen, oxygen, and other contaminants. Whereas oxygen is a relatively minor contaminant in petroleum, it represents a major constituent in bio-oil, which may require catalyst formulations optimized for de-oxygenation of bio-oil. Hydrocracking is the reaction of hydrogen with organic compounds to break long-chain molecules into lower molecular weight compounds. Although fast pyrolysis is a depolymerization process, a number of carbohydrate and lignin oligomers remain in the oil, which hydrocracking can convert into more desirable co-products (i.e. paraffin or naphthene compounds). Recent cost estimates for producing gasoline from bio-oil are \$0.48–\$0.53 USD per liter (Table 3.1; Holmgren 2008).

Biocrude is the name given to the liquid product of hydrothermal processing (HTP) biomass in compressed water at 300–350 °C and 120–180 bar pressure (Elliott et al. 1991). For reaction times of 5–20 minutes, biomass is transformed into up to 45 wt-% liquid. Although superficially resembling bio-oil, it is distinguished by lower oxygen content (10–18 wt-% compared to 45 wt-% for bio-oil), which makes it less miscible in water and more amenable to hydrotreating. Continuous feeding of biomass slurries into high pressure reactors and efficient energy integration

represent engineering challenges that must be overcome before HTP results in a commercially viable technology.

### **Conversion of Triglycerides to Liquid Fuels**

Triglycerides, also known as fats and oils, are esters of glycerol and fatty acids, which are long-chain carboxylic acids containing even numbers of carbon atoms (Ouellette and Rawn 1996). The acid fractions of triglycerides can vary in chain length and degree of saturation. Plant-derived triglycerides are typically oils containing unsaturated fatty acids, including oleic, linoleic, and linolenic acids.

A wide variety of plant species produce triglycerides in commercially significant quantities, most of it occurring in seeds (Lipinsky 1984). Average oil yields range from 150 liters per hectare ( $\text{L ha}^{-1}$ ) for cottonseed to  $814 \text{ L ha}^{-1}$  for peanut oil although intensive cultivation might double these numbers. Soybeans are responsible for more than 50% of world production of oilseed, representing 7.6 – 13 billion liters annually (48–82 million barrels per year). However, the Chinese tallow tree has the potential for several fold higher productivity than soybeans and is particularly attractive for its ability to grow on saline soils that are not currently used for agriculture.

Microorganisms, including yeasts, fungi, and algae are also potential sources of triglycerides (Klass 1998). Anaerobic yeasts and fungi accumulate triglycerides during the latter stages of growth when nutrients other than carbon begin to be exhausted. Algae, which grow over a wide range of temperatures in high-salinity water, can produce as much as 60% of their body weight as lipids when deprived of key nutrients such as silicon for diatoms or nitrogen for green

algae. They employ relatively low substrate concentrations, on the order of  $10 - 40 \text{ g L}^{-1}$ . One suggestion is to build algae ponds or photo-bioreactors in desert regions where inexpensive flat land, water from alkaline aquifers, and carbon dioxide from power plants could be combined to generate triglyceride-based fuel.

The high heating value and cetane number of triglycerides encouraged Rudolph Diesel to experiment with them as fuel for his early compression ignition engines. Subsequently, it was discovered that raw vegetable oils are unsuitable as diesel fuel because their high viscosity leads to coking of fuel injectors and piston rings. Transesterification of vegetable oils to methyl- or ethyl-esters and glycerin (co-product) yields satisfactory diesel-engine fuel although low temperature performance can remain a problem and the glycerin co-product is of relatively low value. Very recently, researchers have discovered that vegetable oils can be hydrotreated and hydrocracked to alkanes indistinguishable from traditional diesel fuel with propane as a valuable co-product (Holmgren 2008). This process has been put into commercial operation by ConocoPhillips and is likely to transform the market for biofuels derived from triglycerides.

### **Conversion of Biomass to Electricity**

Electric propulsion is a potential alternative to biofuels for transportation although this option awaits the advent of inexpensive battery technology. In most markets, fueling costs for electric battery-powered vehicles are projected to be a fraction of that for spark-ignition engines powered by gasoline (Idaho National Laboratory 2005). A “wells-to-wheels” analysis of various transportation options suggests that the energy conversion efficiency and environmental impact of



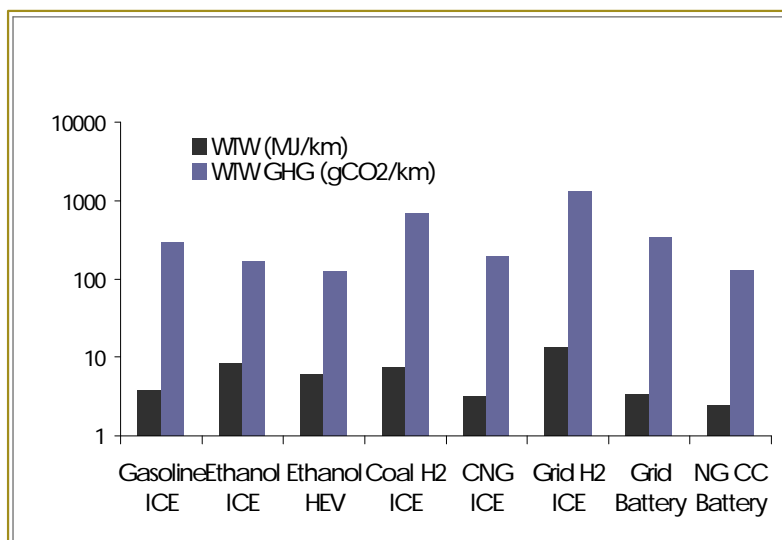


Figure 3.1 Well-to-Wheel Efficiency and Environmental Impact of Vehicle Technologies. WTW: Well-to-Wheel; GHG: greenhouse gases; ICE: internal comb. engine; HEV: hybrid elect. vehicle; CNG: compress. nat. gas; Grid: hydrogen or elect. generated from tradition. electric grid; NG CC: electric. generated from natural gas fired combined cycle power

electric vehicles depends upon the power generation source (Simpson 2004). Figure 3.1, which compares internal combustion engine (ICE) vehicles, hybrid electric vehicles (HEV), and battery powered vehicles, shows that battery powered vehicles charged by traditional electric grids based on coal-fired steam power plants are comparable to gasoline-fired in terms of both energy efficiency and greenhouse gas emissions. However, electricity from natural gas fired combined cycle power plants makes battery powered vehicles among the most attractive vehicle platforms in terms of both energy efficiency and greenhouse gas emissions. Biomass is another possible energy source for generating electric power for electric propulsion. This could be accomplished through Rankine cycles, Brayton cycles, fuel cells, or co-generation based on combinations of these three cycles.

The Rankine cycle involves the direct combustion of fuel to raise pressurized steam that is expanded through a turbine to produce electricity (Singer 1991). Steam power plants are the basis of much of the electric power generation capacity in the

world. The reason for the Rankine cycle's pre-eminence has been its ability to directly fire coal and other inexpensive solid fuels. Constructed at scales of several hundred megawatts, the modern steam power plant can convert as much as 45% of chemical energy in fuel to electricity at a cost of about \$0.05 – \$0.10 USD per kilowatt-hour. Because of fuel supply constraints, biomass power plants are likely to be smaller than 50 MW, which have heat rates that are 20% higher than large, coal-fired power plants. The relatively low thermodynamic efficiency of biomass power systems may ultimately limit the use of direct combustion for bio-energy.

The Brayton cycle produces electric power by expanding hot gas through a turbine (Poullikkas 2005). Directly firing biomass to generate the hot gas stream has proved impractical because particulate matter and corrosive compounds carried with the gas stream damage the gas turbine. Gasification or fast pyrolysis of biomass to generate syngas or bio-oil that can be cleaned before firing in the gas turbine is a more promising option. Brayton cycles are one of the most promising technologies for bio-energy

because of the relative ease of plant construction, cost-effectiveness in a wide range of sizes (from tens of kilowatts to hundreds of megawatts), and the potential for high thermodynamic efficiencies when employed in advanced cycles, as described below.

Fuel cells directly convert chemical energy into work, thus bypassing Carnot limits<sup>1</sup> for heat engines (Dicks and Larminie 2000). This does not imply that fuel cells can convert 100% of the chemical enthalpy of fuel into work. In practice, irreversibilities limit fuel cell conversion efficiencies to 35–60%, depending upon the fuel cell design. Thus, fuel cells can produce significantly more work from a given amount of fuel than can heat engines. However, carbonaceous fuels must first be reformed to hydrogen before they are suitable for use in fuel cells. The energy losses associated with fuel reforming must be included when determining the overall fuel-to-electricity conversion efficiency of a fuel cell. Proton exchange membrane (PEM) fuel cells operate at relatively low temperatures (65 °C) that are suitable for automotive applications, but high costs associated with generating hydrogen without impurities have limited its commercial application. High temperature fuel cells are most favored for stationary power generation because of opportunities for heat recovery.

Combined cycle power systems recognize that waste heat from one power cycle can be used to drive a second power cycle and were developed to enhance energy conversion efficiency (Williams and Larson 1993). Combined cycles would be unnecessary if a single heat engine could be built to operate between the temperature extremes of burning fuel and the ambient environment. However, temperature and pressure limita-

tions on materials of construction have prevented this realization. Combined cycles employ a topping cycle operating at high temperatures and a bottoming cycle operating on the rejected heat from the topping cycle. Most commonly, combined cycle power plants employ a gas turbine for the topping cycle and a steam turbine for the bottoming cycle, achieving overall efficiencies of 50% or higher. Power plants based on high temperature fuel cells are sometimes integrated with both a gas turbine topping cycle and a steam turbine bottom cycling to further improve efficiency.

## Notes

1. Carnot limit is defined as a theoretical maximum engine efficiency (i.e. the maximum potential mechanical energy that can be derived from the thermal energy of a working fuel, limited by the laws of thermodynamics)

## References

- Antal, M. and M. Gronli. 2003. The Art, science, and technology of charcoal production. *Ind Eng Chem Res* 42(8): 1619-1640.
- Balat, M. 2008. Mechanisms of thermochemical biomass conversion processes. Part 2: reactions of gasification. *Energy Source* 30 (7): 636-648.
- Bridgeman, T.G., J.M. Jones, I. Shield, P.T. Williams. 2008. Torrefaction of reed canary grass, wheat straw and willow to enhance solid fuel qualities and combustion properties. *Fuel* 87(6): 844-856.
- Bridgwater, A. and G. Peacocke. 2000. Fast pyrolysis processes for biomass. *Renew Sust Ener Rev* 4(1): 1-73.
- Bridgwater, A.V., A.J. Toft, J.G. Brammer. 2002. A techno-economic comparison of power production by biomass fast pyrolysis with gasification and combustion. *Renew Sus. Ene. Rev* 6(3): 181-246.
- Brown, R. C. 2003. Biorenewable Resources: Engineering New Products from Agriculture. Iowa State Press, Ames IA, USA
- Brown, R. C. 2007. Hybrid thermochemical/biological processing. *App Biochem Biotech* 137-140(1): 947-956.
- Carlson, T.R., T.R. Vispute, G.W. Huber. 2008. Green gasoline by catalytic fast pyrolysis of solid biomass

- derived compounds. *Chem Sus Chem* 1(5): 397 - 400.
- Chen, W.H., S.Y. Chen, S. K. Khanal, S. Sung. 2006. Kinetic study of biological hydrogen production by anaerobic fermentation. *Int J Hydrogen Energy* 31(15): 2170-2178.
- Chynoweth, D., J. Owens, R. Legrand. 2001. Renewable methane from anaerobic digestion of biomass. *Renew Energy* 22(1-3): 1-8.
- Davenport, B. 2002. Methanol. Chemical Economics Handbook Marketing Research Report. SRI International, Menlo Park CA, USA.
- Demirel, B. and O. Yeniguen. 2002. Two-phase anaerobic digestion processes: a review. *J Chem Tech Biotech* 77(7): 743-755.
- Elliott, D., D. Beckman, A. Bridgwater, J. Diebold, S. Gevert, V. Solantausta. 1991. Developments in direct thermochemical liquefaction of biomass: 1983-1990. *Energy & Fuels* 5(3): 399-410.
- Elliott, D., G. Neuenschwander, T. Hart, R. Butner, A. Zacher, M. Engelhard, J. Young, D. McCready. 2004. Chemical processing in high-pressure aqueous environments: 7 process development for catalytic gasification of wet biomass feedstocks. *Ind Engin Chem Res* 43(9): 1999-2004.
- Gray Jr, C. and J. Alson. 1989. The case for methanol. *Sci Am* 261(5): 108-115.
- Grethlein, A. and M. Jain. 1992. Bioprocessing of coal-derived synthesis gases by anaerobic bacteria. *Trends Biotech* 10(12): 418-423.
- Hamelinck, C.N. and A. Faaij 2002. Future prospects for production of methanol and hydrogen from biomass. *J Power Sources* 111(1): 1-22.
- Hamelinck, C.N., G. van Hooijdonk, A. Faaij. 2005. Ethanol from lignocellulosic biomass: techno-economic performance in short-, middle- and long-term. *Biomass & Bioenergy* 28(4): 384-410.
- Haniff, M.I. and L. H. Dao 1987. Conversion of biomass carbohydrates into hydrocarbon products. *Energy Biomass & Wastes* 10: 831-844
- Holmgren, J., Nair, P., Elliot, D., Bain, R., Marinangeli, R. 2008. Converting pyrolysis oils to renewable transport fuels: processing challenges & opportunities. National Petrochemical & Refiners Association Annual Meeting, 11 Mar. 2008, San Diego CA, USA
- Idaho National Laboratory. 2005. Comparing energy costs per mile for electric and gasoline-fueled vehicle. Advanced Vehicle Testing Activity Report. USDOE-EERE. ([http://www1.eere.energy.gov/vehiclesandfuels/avta/light\\_duty/fsev/fsev\\_gas\\_elec2.html](http://www1.eere.energy.gov/vehiclesandfuels/avta/light_duty/fsev/fsev_gas_elec2.html))
- Klass, D. 1998. Biomass for Renewable Energy, Fuels, and Chemicals. Academic Press, San Diego CA USA.
- Kwiatkowski, J., A. McAloon, F. Taylor, D. Johnston. 2006. Modeling the process and costs of fuel ethanol production by the corn dry-grind process. *Ind Crops Prod* 23(3): 288-296.
- Larminie, J. and A. Dicks. 2000. Fuel Cell Systems Explained (2nd ed.), John Wiley & Sons, Chichester, UK.
- Lipinsky, E. S., T.A. McClure, S. Kresovich, J.L. Otis, C.K. Wagner. 1984. Production potential for fuels from oilseeds in the United States, pp 205-223. In, E. B. Shultz, Jr., and R. P. Morgan (eds.), Fuels and Chemicals from Oilseeds: Technology and Policy Options. AAAS Selected Symposium No. 91. West View Press, Inc., Boulder CO, USA.
- Lynd, L. R. 1996. Overview and evaluation of fuel ethanol from cellulosic biomass: Technology, Economics, the Environment and Policy. *Ann Rev Energy Env* 21(1): 403-465.
- Marker, T., J. Petri, T. Kalnes, M. McCall, D. Mackowiak, B. Jerosky, B. Reagan, L. Nemeth, M. Krawczyk, S. Czernyk, D. Elliott, D. Shonnard. 2005. Opportunities for biorenewables in oil refineries: final technical report. DOE report no. DE-FG36-05GO15085. UOP, Des Plaines IL USA
- Marris, E. 2006. Sequestration: Putting the carbon back: Black is the new green. *Nature* 442: 624-626.
- Ouellette, R.J. and J.D. Rawn 1996. Organic Chemistry. Prentice Hall, Englewood Cliffs NJ, USA.
- Pandey, A. 2003. Solid-state fermentation. *Biochem Engin J* 13(2-3): 81-84.
- Poullikkas, A. 2005. An overview of current and future sustainable gas turbine technologies. *Renew Sust Energy Rev* 9(5): 409-443.
- Qureshi, N. and H. Blaschek. 2000. Economics of butanol fermentation using hyper-butanol producing *Clostridium beijerinckii* BA101. *Food Bioprod Process: Part B* 78(C3): 139-144.
- Reed, T.E. (ed). 1981. Biomass Gasification: Principles and Technology. Noyes Data Corp., Park Ridge NJ, USA.
- Román-Leshkov, Y., C. J. Barrett, Z.Y. Liu, J.A. Dumesic. 2007. Production of dimethylfuran for liquid fuels from biomass-derived carbohydrates. *Nature* 447: 982 - 986.
- Schulz, H. 1999. Short history and present trends of Fischer-Tropsch synthesis. *Appl Catal A-Gen* 186(1-2): 3-12.
- Simpson, A. 2004. Full Cycle Assessment of alternative fuels for light duty road vehicles in Australia. Proceedings of the 2004 World Energy Congress - Youth Symposium, 5-9 Sept. Sydney Australia.

- Singer, J. G. 1991. Combustion, Fossil Power Systems, fourth edition. Combustion Engineering, Inc., Windsor CT, USA
- Sjöström, E. 1981. Wood Chemistry: Fundamentals and Applications. Academic Press, New York NY
- Tijmensen, M., A. Faaij, C. Hamelinck, M. van Hardeveid. 2002. Exploration of the possibilities for production of Fischer Tropsch liquids and power via biomass gasification. *Biomass and Bioenergy* 23(2): 129-152.
- Williams, R.H. and E.D. Larson. 1993. Advanced Gasification-based Biomass Power Generation. Earthscan, London, UK.
- Wright, M.M., Brown, R.C., Boateng, A.A. 2008. Distributed processing of biomass to bio-oil for subsequent production of Fischer-Tropsch liquids. *Biofuels Bioprod. Biorefin* 2:229-238.
- Zhang, R., K. Cummer, A. Suby, R. Brown. 2005. Biomass-derived hydrogen from an air-blown gasifier. *Fuel Process Technol* 86(8): 861-874.
- Zhao, H., J. E. Holladay, H. Brown, Z.C. Zhang. 2007. Metal chlorides in ionic liquid solvents convert sugars to 5-hydroxymethylfurfural. *Science* 316(5831): 1597.