ADVANCED TECHNOLOGIES FOR BIOMASS CONVERSION TO ENERGY

Eric D. Larson
Princeton University
Center for Energy and Environmental Studies
Princeton, New Jersey, 08544-5263, USA
609-258-4966, 609-258-3661, elarson@princeton.edu

ABSTRACT

Recent long-term scenarios for future global energy supply published by the Intergovernmental Panel on Climate Change (IPCC), the Shell International Petroleum Company, the World Energy Council, and others show a substantially expanded role for biomass energy in the 21st century. For example, the most biomass-intensive of the IPCC scenarios shows biomass providing ⅓ of global primary energy by 2050, with biomass plantations covering nearly 400 million hectares by that time. For such a biomass contribution to be realized, considerable scientific, technological, and commercial advances are required in biomass production and in biomass conversion to high-quality energy carriers. This paper describes some advanced biomass conversion systems that may play important roles in a future world where biomass is a major energy source. Thermochemical gasification is likely to be a key component of many such systems. The discussion includes systems for combined heat and power generation at large and at small scales, as well as processes for biomass-derived fluid fuels production.

INTRODUCTION

The Intergovernmental Panel on Climate Change (IPCC) has explored five scenarios for satisfying the world's growing demand for energy services in the 21st century while simultaneously limiting CO_2 emissions (IPCC, 1996). The use of carbon-neutral biomass energy is greatest, and requirements for below-ground sequestration of fossil carbon are smallest, in the "biomass-intensive" (BI) scenario, but all scenarios include a substantial contribution from biomass as a fossil fuel substitute. In the BI scenario, biomass contributes 180 EJ/year to global energy supply by 2050, about ⅔ of which derives from high-yield energy plantations covering nearly 400 million hectares--an area equivalent to ¼ of planted agricultural area today. [For comparison, biomass use today is about 50 EJ/yr (Reddy et al., 1997; Hall, et al., 1993), very little is grown specifically for energy, and most is used very inefficiently.] Other assessments of future global energy supply show similarly large potential roles for biomass, including scenarios developed by the Shell International Petroleum Company (Kassler, 1994) and by the World Energy Council in a joint study with the International Institute for Applied Systems Analysis (Nakicenovic et al., 1998).

A key assumption behind such biomass-intensive energy scenarios is that biomass energy systems are modernized: they are made widely attractive and competitive in energy markets by high-yield production of feedstocks, efficient conversion of feedstocks to convenient-to-use energy carriers, and high-efficiency use of these carriers. Modernized biomass conversion, the focus of this paper, implies the use of technologies that offer, at the scales appropriate for biomass energy conversion facilities, low unit capital costs and high thermodynamic efficiencies for making modern energy carriers--mainly electricity and high-quality liquid and gaseous fuels. The high value of such energy carriers would enable biomass to be more highly valued, making it possible to provide greater inputs of material and labor into producing biomass, which can help insure sustainable production. It follows, however, that high conversion efficiencies are needed to enable competitive use of relatively high cost biomass (such as dedicated energy crops). Also, because long-distance biomass transport is costly, conversion facilities must be modest in scale (compared to coal conversion) to be competitive.

Thermochemical gasification is likely to be an important sub-component in many advanced biomass conversion systems because of its high throughput capabilities and flexibility with regard to feedstock. With gasification-based conversion, the primary technical criteria for designing biomass production systems are simply high yield, low cost, and low environmental impact. This offers more flexibility in the design of the feedstock production system than with other conversion processes, such as fermentation, where starch or sugar content and other feedstock characteristics are important. This paper discusses advanced gasification-based biomass conversion technologies for power generation and for fluid fuels production that might play significant roles in a biomass-intensive energy future.

BIOMASS CONVERSION TO ELECTRIC POWER

For modernizing biomass electric power generation, the gas turbine is an important class of technology.

Multi-MW Biomass-Gasifier/Gas Turbine Systems

At multi-MW scales, gas turbine-based systems dominate new fossil fuel-fired generating capacity additions worldwide today because of competitive economics with natural gas as fuel. Competition in electricity generation has been driving down unit capital costs for gas turbines (Fig. 1), even as performance improves (Fig. 2). These trends will continue. For example, the goal of the Advanced Turbine Systems (ATS) program in the United States is to commercialize by the year 2000 utility-scale gas turbine systems having electric efficiencies of at least 60% (LHV), emitting less than 10 ppm NO_x, and having generating costs at least 10% below current state-of-the-art systems (USDOE, 1998). The ATS designs being developed to meet these objectives are in the range of 400 MW_e total capacity, which may be too large for most biomass applications. However, materials, blade cooling, and other technological advances that will be incorporated in these large-scale units are likely to be transferred into smaller-capacity engines in the future, as has been done in the past. Also, the ATS program includes development of 15-MW_e class engines, for which performance targets are appropriately aggressive. Interestingly, one stipulated design requirement for all ATS designs is the capability to use biomass fuels.

Integrated with thermochemical gasification of biomass, gas turbine cycles at the scale of tens of MWs have the potential to double the efficiency of electric power generation over conventional (biomass-steam turbine) technology and decrease capital costs (Williams and Larson, 1996). The gas turbine cycle receiving the most attention in commercial development efforts is the biomass integrated-gasifier/gas turbine combined cycle (BIG/GTCC).
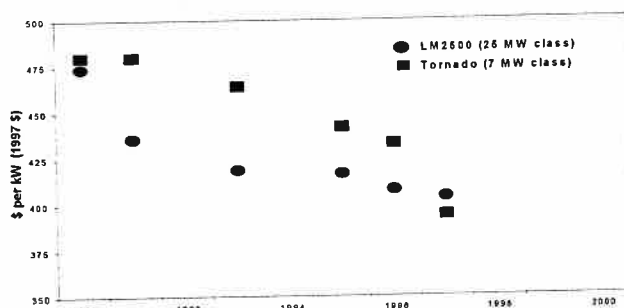

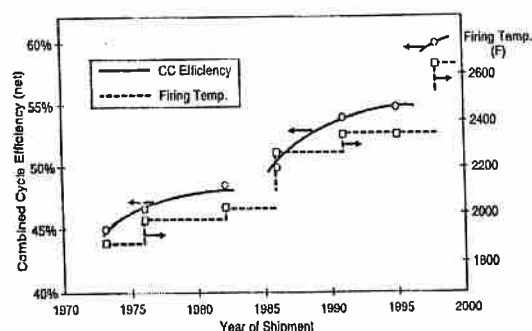Fig. 1 Gas turbine simple-cycle equipment price trend (in 1997 US$/kW). Source: Gas Turbine World Handbook.

Fig. 2. Twenty-five year trend in General Electric gas turbine firing temperatures (°F) and combined cycle generating efficiencies (LHV basis) (Corman, 1996).

$$P_{net} = 26 \text{ MW}_e$$
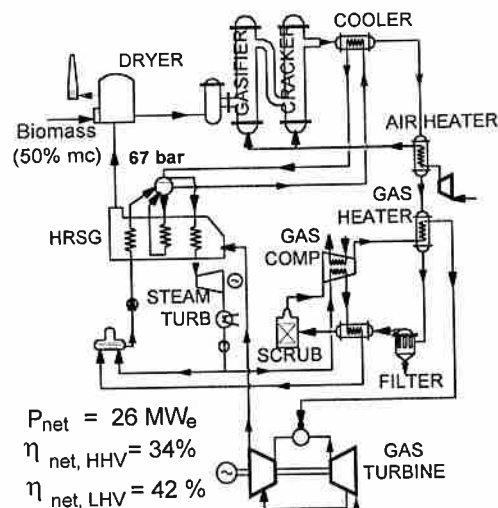$$\eta_{net, HHV} = 34\%$$
$$\eta_{net, LHV} = 42\%$$

Fig. 3(a). Biomass-integrated gasifier/gas turbine cycle using atmospheric-pressure, air-blown gasifier. The indicated plant performance is with a gas turbine like the General Electric LM2500 (Consonni and Larson, 1996).

Commercially proposed BIG/GTCC design configurations include atmospheric-pressure air-blown fluidized-bed gasification and gas cleanup by wet scrubbing (Fig. 3a), e.g., see Waldheim and Carpentieri (1998); pressurized air-blown fluidized bed gasification with hot-gas cleanup (Fig. 3b), e.g., see Salo et al. (1998); and atmospheric-pressure indirectly-heated gasification with wet scrubbing (Fig. 3c), e.g., see Paisley and Anson (1997). For additional discussion of the status and performance of BIG/GTCC systems, see Larson et al., 1998a; Consonni and Larson (1996); Larson and Raymond (1997a); Williams and Larson (1996); and Weyerhaeuser et al., (1995).

While costs for BIG/GTCC systems will not reach commercially mature levels for at least several years, there are opportunities for competitive introduction of BIG/GTCC technologies in the near term. These include combined heat and power applications in industries that generate biomass or biomass-derived fuels as byproducts of the process. In industrialized countries, the most attractive applications in this regard today are in the kraft pulp industry. In developing countries potentially attractive applications include industries making sugar and/or ethanol from sugarcane.

Pulp and paper industry. In the kraft process for paper pulp production, which accounts for about two-thirds of all global pulp production, two byproduct biomass fuels are generated: black liquor, the mix of lignin and pulping chemicals that results after fiber extraction, and "hog fuel", consisting of bark and other solid biomass residues generated in the wood yard. Kraft mills burn these fuels today to raise steam used to generate power (in back-pressure steam turbines) and to meet process heat needs. Additionally, the design of the furnace in which black liquor is burned (called a Tomlinson recovery furnace) is such that pulping chemicals (sulfur and sodium compounds) are recovered and processed for reuse in pulping. Demonstration projects aimed at speeding the commercial introduction of gasifier/GTCC technologies into kraft mills have recently been launched in Sweden and in the United States (AFPA, 1998).
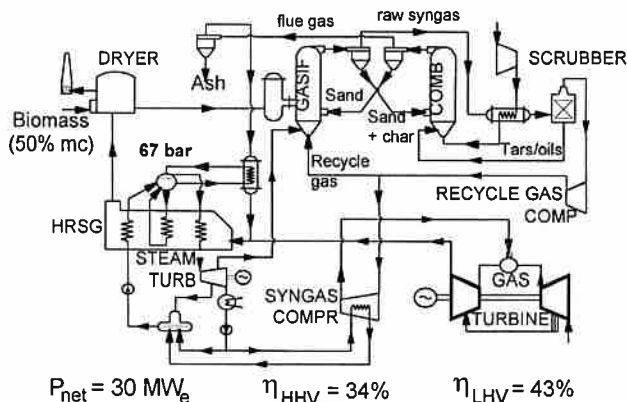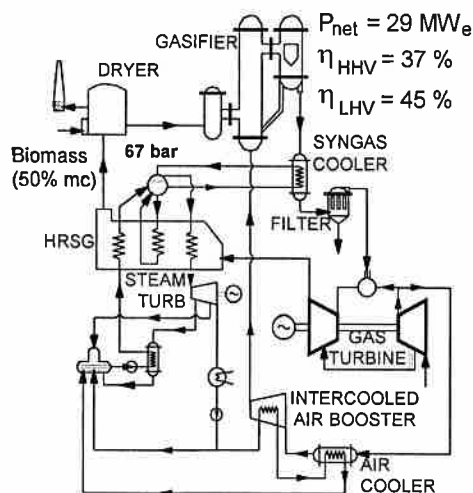
Fig. 3(b and c). Biomass-integrated gasifier/gas turbine cycle using (left--b) a pressurized, air-blown gasifier and (right--c) an atmospheric-pressure, indirectly -heated gasifier design of the Battelle Columbus Laboratory. The indicated overall plant performances are with a gas turbine like the General Electric LM2500 (Consonni and Larson, 1996).

North America accounts for approximately 55% of the world's kraft pulp production and Scandinavia accounts for an additional 15%. In North America, some 80% of all currently-operating recovery boilers were built or rebuilt before 1980 (Fig. 4), so most of the recovery boilers in this region will need major rebuilding or replacement over the next 5 to 20 years. A similar age distribution characterizes hog fuel boilers. The need to replace Tomlinson and biomass boilers over the next two decades provides a rare window of opportunity to make a major technology change (to gasification) that has large potential environmental, energy efficiency, safety, and return-on-investment benefits (Larson and Raymond, 1997b; Consonni et al., 1998; Larson et al., 1998b, 1998c).

Black liquor gasification technologies for GTCC applications that have been the focus of recent development efforts can be classified according to operating temperature, or equivalently, according to the physical state in which the majority of the inorganic chemicals in the black liquor leave the gasifier. High-temperature, air- or oxygen-blown gasifiers operate at about 1000°C and produce a molten smelt of inorganic chemicals. Low-temperature air-blown or indirectly-heated gasifiers operate at 700°C or lower in order to insure that the inorganics leave as dry solids. For additional discussion of designs, see (Brown and Hunter, 1998; Consonni et al., 1998; Stigsson, 1998; Larson and Raymond, 1997a; Lorson et al., 1996a; Aghamohammadi et al., 1995; Grace and Timmer, 1995; Dahlquist and Jacobs, 1992). One configuration for a black liquor gasifier/GTCC is shown in Fig. 5. In this configuration, steam production from the gas turbine heat recovery steam generator (HRSG) is insufficient to meet the process steam needs of a typical pulp mill. A hog fuel boiler is included to raise additional

steam. Alternatively, the hog fuel could be gasified and used in a gas turbine to produce power and additional process steam (Larson et al., 1998a).

Figure 6 shows potential power generation and carbon emissions for five CHP configurations at an hypothetical kraft pulp mill. The amount of supplemental biomass required to meet the full process steam demand is also shown. [For results of detailed performance simulations that are the basis for this figure, see Consonni, et al. (1998) and Larson, et al. (1998a).] The first three sets of bars correspond to the case where the available black liquor is burned in a conventional Tomlinson boiler: the first set of bars assumes that the supplemental fuel is fossil fuel burned in a boiler; the second set assumes biomass is the supplemental fuel and is burned in a boiler; the third set assumes that the supplemental biomass is used to fuel a gasifier/GTCC. The two rightmost sets of bars assume a configuration involving high-temperature oxygen-blown black liquor gasifier/GTCC. In one case, the supplemental biomass is burned in a boiler (as in Fig. 5). In the other, the biomass is used in a BIG/GTCC system.
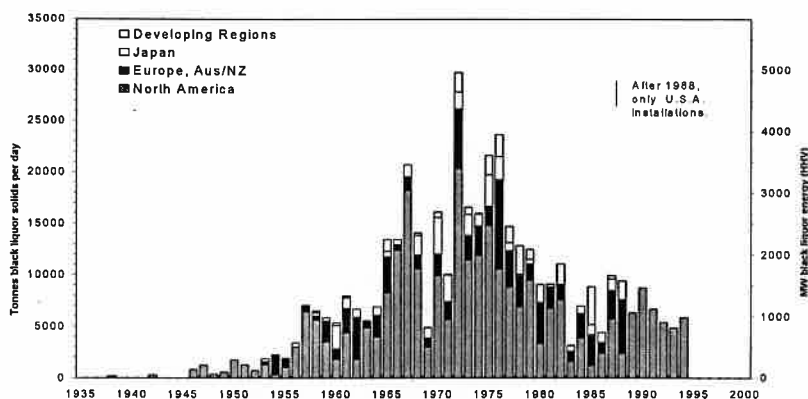

Fig. 4. Global installed Tomlinsn black liquor recovery boiler capacity by year of startup (Consonnit et al., 1998).

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Fig. 5. A black liquor gasifier/gas turbine combined cycle configuration with oxygen-blown gasification (Larson *et al.*, 1998b).

Process electricity needs are met in all cases, with excess available for export from the mill. The availability of excess power is modest in the cases involving the Tomlinson boiler, but with black liquor gasification, power output is 3 to 5 times greater than the process demand level. While the fraction of input fuel energy converted to electricity is higher when gasifier/GTCC technologies are used, the fraction converted to process steam is lower. Greater amounts of the supplemental fuel must be used, therefore, to meet process steam demand. For comparison with the supplemental biomass consumption levels shown in Fig. 6, a typical North American pulp mill today might have 250 to 300 kg (dry) of hog fuel available per tonne of pulp produced. There is the potential at many mills to bring in much greater amounts of waste biomass at reasonable cost, however. For example, one detailed study around a Weyerhaeuser mill in the Southeastern U.S.

Fig. 6. Power output and carbon emissions per tonne of air-dried pulp (tp) production at a 1300 tp/day capacity kraft pulp mill for five different cogeneration technology configurations using black liquor as the primary fuel (Larson *et al.*, 1998a). The consumption of supplemental solid-biomass for four of the five cases is also shown. In all cases, the assumed process steam and process electricity demand are 16.3 GJ/tp and 656 kWh/tp, respectively. Power output in excess of process needs is assumed to be exported to the grid where it avoids the need to generate an equivalent amount of electricity using either natural gas (in a combined cycle) or coal (in an integrated gasification combined cycle).

identified up to 3000 kg/tp of available residues at reasonable costs (see Weyerhaeuser *et al.*, 1995).

The carbon emissions estimates in Fig. 6 assume that biomass is carbon-neutral, i.e., it is used renewably, and that any power generated in excess of process needs is exported to a utility grid where it eliminates the need to generate an equivalent amount of power from efficient utility power plants operating on natural gas (combined cycle) or on coal (IGCC). In most of the configurations, there are modest to large net reductions in carbon emissions.

Sugarcane processing industries. Brazil, China, India, Indonesia, and over 70 other developing countries grow sugarcane. The production of sugar or ethanol from sugarcane generates a fibrous biomass byproduct (bagasse) that is typically used as a fuel for combined heat and power generation to supply the sugarcane processing facility with its process energy requirements. The amount of sugarcane tops and leaves (cane trash) that is potentially available as an additional biomass fuel is comparable to the amount of bagasse generated (Goldemberg *et al.*, 1993). Cane trash has

Fig. 7. Electricity generated in excess of on-site requirements per tonne of sugarcane crushed at a sugar or ethanol factory using different cogeneration technologies (Larson, 1994). Existing technology is the back-pressure steam turbine with steam pressure about 20 bar. CEST is a condensing extraction steam turbine with steam pressure about 60 bar.

traditionally been burned on the fields to facilitate replanting or harvesting, though the resulting air pollution has motivated some governments to ban this practice.

Historically, there has been little electricity exported by sugar factories because of the low efficiency of the bagasse-fired CHP systems that are conventionally used. However, the quantities of bagasse and trash are such that typical sugar factories could be major exporters of electricity. With conventionally-generated electricity supplies unable to keep pace with electricity demand in many developing countries, there is growing interest in excess electricity generated at sugar factories.

BIG/GTCC systems have an especially large potential to make sugarcane processing facilities major exporters of electricity. Fig. 7 shows the amount of excess electricity generation possible (above and beyond process electricity needs) per tonne of sugarcane (tc) processed. Most existing

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sugar mills, which use low-pressure (~20 bar) boilers feeding back-pressure steam turbines, generate no excess electricity. A few mills in developing countries now utilize higher-pressure boilers (40-60 bar) and condensing-extraction steam turbines (CEST), which results in excess power generation of the order of 100 kWh/tc. This power is generated from

Table 1. Potential for "excess" electricity generation from sugarcane processing facilities in developing countries.

	1995 Cane Production (million tc)	2025 Cane Prod. @ 2%/yr (million tc)	2025 "Excess" Electricity (TWh/year)	1995 Utility Elec. Prod. (TWh)	2025 Cane Elec./1995 Utility Elec.
Brazil	304	550	330	257	1.3
India	260	470	282	364	0.8
China	70	127	76	859	0.09
Carribean	48	87	52	42	1.2
Indonesia	31	57	34	58	0.6
Other Latin Am.	152	275	165	438	0.4
Others	233	422	253	912	0.3
Totals	1098	1988	1192	2930	0.4

bagasse that is available only during the cane crushing season, which typically lasts about 6 months. By making cost-effective changes to the process to reduce steam consumption, a CEST system can export an additional 20 or 30 kWh/tc (middle bar, Fig. 7). Using cane trash as a supplemental fuel for the non-crushing season would enable year-round power generation: with CEST technology, the excess electricity production nearly triples compared to generating only during the crushing season; with BIG/GTCC technology, excess electricity production is nearly six times as large.

Table 1 gives some perspective on the potential contribution of BIG/GTCC "cane power" to overall electricity supply in developing countries. Shown there is an estimate of the electricity generation potential at sugarcane processing facilities in 2025 in developing countries (assuming the recent average annual rate of increase in sugarcane production.) For some 80 developing countries, "excess" electricity from cane residues in 2025 could amount to 40% of the amount of electricity generated by all utility generating plants in these countries in 1995. For some countries--e.g., Brazil and some Caribbean nations--the contribution of cane-derived power could be proportionally much greater.

Efforts to develop bagasse and cane trash fueled BIG/GTCC systems are ongoing today in Hawaii, Brazil, and elsewhere.

Sub-MW Biomass-Gasifier/Gas Turbine Systems

At sub-MW scales, micro gas turbines as small as 50-250 kW_e and having electric generating efficiencies of up to 30% (LHV) on natural gas, are being commercialized for distributed cogeneration applications. Originally developed for military and aerospace applications, microturbines are now offered by several companies (e.g., Allied Signal, Capstone, Elliot) for stationary power generation. In such applications, micro turbines use recuperation to achieve high efficiencies (Fig. 8a). Capital costs are minimized by use of low compressor pressure ratios, uncooled turbine blades, air bearings (in some designs), and other measures. The small scale of micro turbines makes them well suited to mass production in factories, which further reduces cost.

Micro turbines have the potential for being fueled with gasified biomass. One concept (Fig. 8b) would mimic the design of larger-scale BIG/GT systems using atmospheric-pressure gasification. An alternative concept would involve premixing air and gasified biomass at the intake of the compressor, thereby eliminating the cost of the separate fuel compressor (Fig. 8c). Burning the fuel-air mix in the gas turbine combustor in this case may require a catalyst. For the longer term, a hybrid system that includes a solid-oxide fuel cell (SOFC) operating on gasified biomass, with fuel

unconverted in the SOFC burned to power a microturbine bottoming cycle, would yield an efficiency approaching 45% (HHV) at a scale of 200 kW_e (Kartha, et al. 1997). Little analytical or development effort has been directed to biomass/micro turbine applications to date. This may be due in part to the fact that micro turbine-based biomass power systems are likely to be most attractive for applications in rural areas of developing countries, where labor costs are relatively low and alternative sources of electricity are unreliable and/or expensive.

BIOMASS CONVERSION TO FLUID FUELS

Converted to liquid or gaseous fuels, biomass has the potential to be used much more efficiently and to provide a wider range of energy services, than is possible when used as a solid. For example, cooking food by direct combustion of biomass, as practiced by perhaps 2 billion people in the world today, is far less energy efficient than cooking with a liquid fuel (Fig. 9), even considering losses in converting biomass into a liquid. Converted to a liquid or gaseous fuel, biomass becomes suitable for powering vehicles. An advanced vehicle technology that is of particular interest in this regard is the fuel cell vehicle using a proton exchange membrane (PEM) fuel
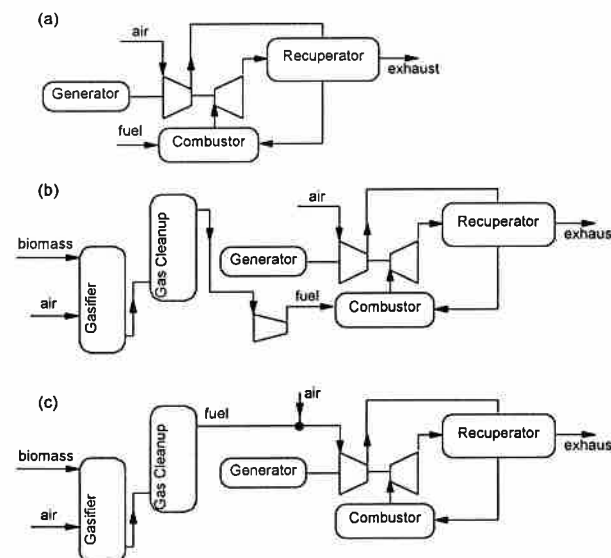

Fig. 8. (a) Cycle concept for natural gas recuperated micro gas turbine; (b) Biomass gasifier/micro turbine concept with separate compression of fuel and air; (c) Biomass-gasifier/micro turbine concept with combined fuel/air compression.
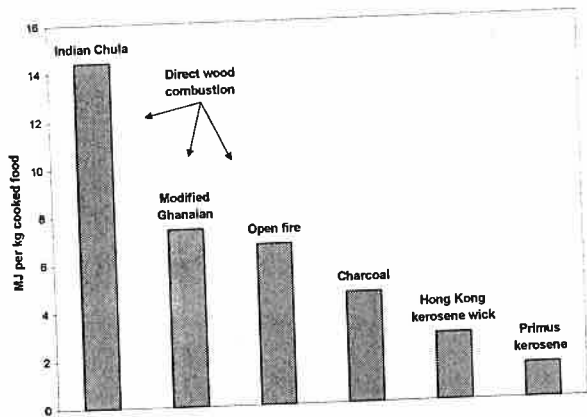
Fig. 9. End-use energy consumption for cooking with alternative cooking fuels and stoves (Dutt and Ravindranath, 1993).
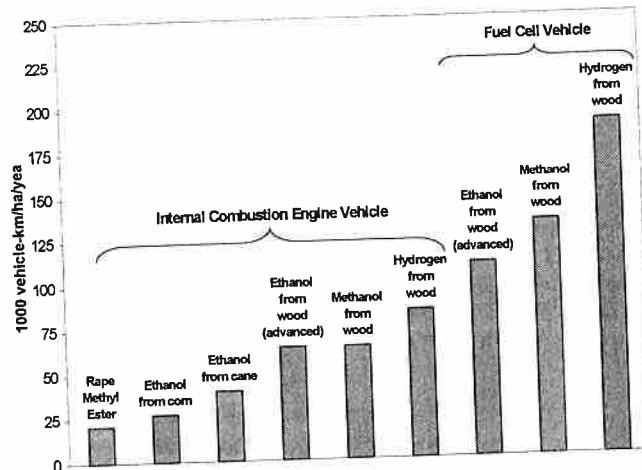

Fig. 10. Potential annual vehicle-kilometers per unit of land derived from alternative biomass feedstocks and conversion technologies, and for two different vehicle technologies (IPCC, 1996).

cell (Steinbugler and Williams, 1998). This vehicle technology is being aggressively developed by most major automobile manufacturers worldwide for commercial introduction in the first decade of the 21st century (National Research Council, 1997). The PEM fuel cell combines hydrogen electrochemically with oxygen from air to efficiently produce electricity (to power the vehicle). Water vapor is the only "tailpipe" emission. Hydrogen and methanol (converted onboard a vehicle to hydrogen) are the leading candidate fuels for fuel cell vehicles. Both can be made from biomass.

In providing transportation and other energy services using biomass-derived liquids or gases, the choice of biomass feedstock, conversion process, and end-use technology are important in determining the level and the cost of services provided. For example, the choice of a woody biomass feedstock that can be grown with high yields and low costs (e.g., short rotation tree plantations), together with conversion to fuels used in fuel cell vehicles, makes it possible to deliver far more transportation services (measured in vehicle-km driven per hectare per year) than is possible using more traditional food-crop-based fuels, such as ethanol from grain or rape methyl ester from rape seed, in internal combustion engine vehicles (Fig. 10).

Conversion of biomass to methanol, to hydrogen, and to Fischer-Tropsch liquids are discussed here. The concept of "once-through" fuel production may be of particular relevance for biomass. In such systems, gasified biomass is converted in a single pass through processing steps to the fuel of interest, with any remaining unconverted gas going to a gas turbine to generate power rather than being recycled for further conversion to fuel. Once-through configurations are of interest because they may offer large gains in fuels production efficiency and reduced capital costs relative to plants that produce fuels only, e.g., see Choi et al. (1997); Gray and Tomlinson (1997), Tijm et al., 1997.

Biomass Conversion to Methanol or Hydrogen

The production of liquid methanol (MeOH) or gaseous hydrogen (H_2) from biomass involves first gasifying the feedstock in oxygen or indirectly heating to produce a synthesis gas consisting of CO, H_2, CO_2, CH_4, $H_2O_{(g)}$, and small quantities of higher hydrocarbons. After cooling and cleanup, the resulting gas undergoes a series of commercially-

established chemical reactions that lead to the desired end product (Fig. 11). Hydrocarbons in the gas are steam reformed, after which shift reactors are used to establish the $CO:H_2$ ratio desired for the final processing steps.

For MeOH production a molar $H_2:CO$ ratio of about 2 is needed. Following the shift reactor CO_2 and H_2O are removed before the gas is compressed (typically to about 100 bar) and fed to a MeOH synthesis reactor. The CO and H_2 combine over a catalyst at about 250 °C to form MeOH.

For H_2 production the shift reaction converts as much of the CO to H_2 as possible before the gas enters a pressure swing adsorber (PSA), which recovers up to 97% of the input H_2 as final product with greater than 99.999% purity. The H_2 can then be compressed for storage or pipeline transmission.

Table 2, based on detailed process modeling (Katofsky, 1993; Williams et al., 1995), gives overall energy balances for the production of MeOH and H_2 from biomass. Comparative results for coal and natural gas are also shown. For biomass, results are shown for processes using two different gasification technologies: partial oxidation in oxygen (e.g., the gasifier design similar to that in Fig. 3b) and indirect heating
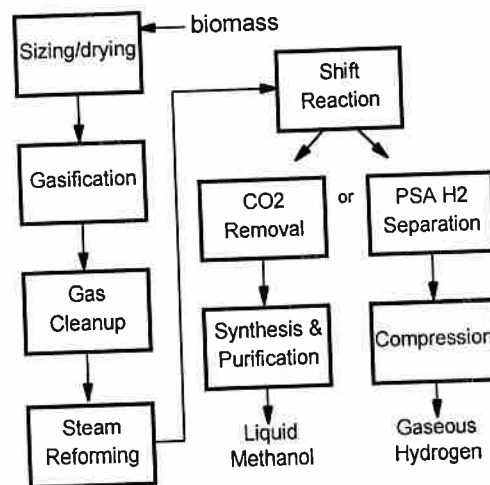

Fig. 11. Methanol or hydrogen production from biomass.

Table 2. Energy balances for production of methanol and hydrogen via thermochemical conversion of biomass (45% moisture content), coal, or natural gas (Williams, *et al.*, 1995).

	Feedstock in (GJ/GJ$_{product}$)	Electricity in (kWh/GJ$_{prod.}$)	Process steam in (kg/kg feedstock)	Product out/Feed in (GJ$_{prod.}$/GJ$_{feed}$)	Thermal efficiency (GJ$_{prod.}$/GJ$_{net\ input}$)
METHANOL					
Biomass-indirect	1.65	29.7	0.38	0.61	0.58
Biomass-partial ox.	1.77	24.3	1.02	0.57	0.54
Coal	1.54	29.1	1.91	0.65	0.61
Natural gas	1.42	13.1	3.23	0.70	0.67
HYDROGEN					
Biomass-indirect	1.37	31.8	0.95	0.73	0.64
Biomass-partial ox.	1.50	33.1	1.30	0.67	0.56
Coal	1.29	35.9	2.99	0.77	0.64
Natural gas	1.11	10.5	2.66	0.90	0.84

Table 3. Cost estimates for thermochemcal production of methanol and hydrogen from biomass (45% moisture content), coal, and natural gas. Original estimates (Williams *et al.*, 1995) converted to 1997 US$ using GNP deflator. (Assumptions: 90% capacity factory; capital charge of 15.1% per year; O&M costs include purchased electricity.)

	Product Capacity (10^6 GJ/yr)	Feedstock Capacity (10^6 GJ/yr)	Capital charge ($/GJ)	O&M charge ($/GJ)	Fuel charge ($/GJ$_{prod.}$) (P = $/GJ feedstock price)	Total cost ($/GJ)	Feed cost ($/GJ) for total cost = total cost shown for Biomass-ind. case
METHANOL							
Biomass-indirect	7.10	11.7	6.38	2.81	1.65 x P	(P = 2) 12.5	--
Biomass-partial ox.	6.57	11.6	8.66	3.32	1.77 x P	(P = 2) 15.5	0.3
Coal	35.2	54.2	6.45	2.70	1.54 x P	(P = 1) 10.7	2.2
Natural gas	16.7	23.7	2.78	1.41	1.42 x P	(P = 2) 7.03	5.9
HYDROGEN							
Biomass-indirect	8.58	11.7	4.07	2.85	1.34 x P	(P = 2) 9.65	--
Biomass-partial ox.	7.77	11.6	5.52	3.63	1.49 x P	(P = 2) 12.1	0.3
Coal	42.0	54.2	4.63	3.49	1.29 x P	(P = 1) 9.41	1.2
Natural gas	21.2	23.7	1.83	1.18	1.11 x P	(P = 2) 5.23	6.0

(e.g., the gasifier design in Fig. 3c). The thermal efficiency shown in Table 2 is defined as the energy content of the product fuel divided by the energy content of all energy inputs to the process, including the feedstock and additional amounts of feedstock used to generate process heat and electricity requirements.

The efficiency of biomass conversion via indirectly-heated gasification is higher than with partial oxidation gasification. The efficiency of biomass conversion is lower than with natural gas, as expected, since gasification consumes a non-negligible fraction of the feedstock energy. In contrast, the most efficient biomass conversion system is about as efficient as coal conversion. Finally, the efficiency for MeOH production is somewhat lower than for H$_2$ production regardless of the feedstock.

Table 3 summarizes detailed cost estimates for production of methanol and hydrogen from biomass, with comparisons to fossil fuel based production. Biomass-based production is less costly with indirectly-heated gasification than with partial oxidation, and costs for biomass-H$_2$ are about 20% less than for biomass-MeOH. [Also, biomass-H$_2$ is half or less the cost projected for electrolytic-H$_2$ using wind or photovoltaic power, assuming that long-term cost reduction goals for these power sources can be met (Larson, 1993).]
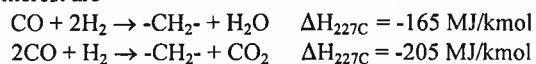
At prevailing world market prices for fossil fuels, the costs of producing methanol or hydrogen from biomass are significantly higher than from fossil fuels. "Once-through" processes for methanol co-production with electricity (Tijm *et al.*, 1997) may improve these economics. Internalizing environmental costs associated with fuel production and use would improve the relative economics of hydrogen or methanol, regardless of the process configuration considered (Williams *et al.*, 1995).

Biomass Conversion to Fischer-Tropsch Liquids

Biomass conversion strategies involving multiple products from single facilities may enable fluid fuels from biomass to be more competitive in the near term with fuels from fossil sources. One interesting possibility is co-production of electricity and multiple fluid fuels using Fischer-Tropsch (F-T) synthesis.

F-T synthesis involves catalytic reactions of CO and H$_2$ to form aliphatic (straight-chain) hydrocarbons (C$_n$H$_{2n+2}$) under reactor conditions of moderate pressure and temperature (typically 20-35 bar and 200-350°C). The primary reactions of interest are

$$CO + 2H_2 \rightarrow -CH_2- + H_2O \quad \Delta H_{227C} = -165 \text{ MJ/kmol}$$
$$2CO + H_2 \rightarrow -CH_2- + CO_2 \quad \Delta H_{227C} = -205 \text{ MJ/kmol}$$

The distribution of hydrocarbon products varies depending on the catalyst used and on reactor temperature, pressure, and residence time. The product slate can include light gases (C$_1$ and C$_2$ hydrocarbons), synthetic LPG (propane and butane: C$_3$ and C$_4$), a light liquid fraction (naphtha-like C$_5$ to C$_{12}$), a middle-distillate fraction (C$_{13}$-C$_{18}$), and waxes (C$_{19}$+).

F-T synthesis was first extensively used in Germany during World War II to make liquid fuels from gasified coal. Similar processes have been used in South Africa since the early 1950s. There is renewed commercial interest in F-T synthesis today to produce liquids from remote natural gas sources having little or no value because of their distance from markets (Fouda, 1998). Of particular interest is the production of a high-cetane number diesel-like middle distillate fuel that
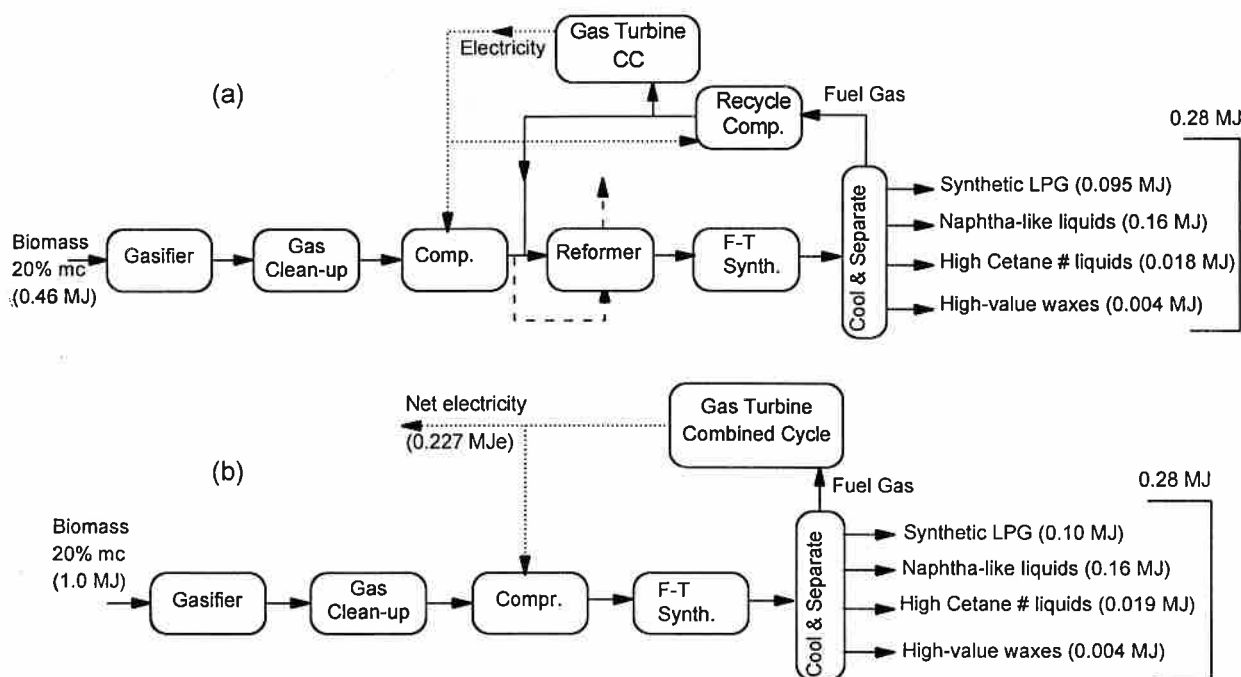
Fig. 12. Preliminary energy balances for production of Fischer-Tropsch liquids from biomass: (a) net production of only F-T liquids; (b) "once-through" F-T synthesis resulting in co-production of electricity with F-T liquids.

is free of sulfur and aromatics. Such fuels can be blended with conventional diesel fuels to meet increasingly strict fuel specifications designed to reduce vehicle exhaust emissions. Major commercial efforts in "gas-to-liquids" technology development include those at Exxon, Sasol, Shell, and Syntroleum (Knott, 1997; Parkinson, 1997).

Because a large percentage of the world's gas fields are relatively small (Anonymous, 1998), one segment of the industry developing F-T synthesis processes is focussed on smaller-scale facilities (Knott, 1997; Tijm et al., 1997). Such technological developments might be especially relevant to biomass-based F-T synthesis processes.

Two concepts for conversion of biomass to F-T liquids are shown in Fig. 12. In both cases, the processes begin with gasification. An indirectly-heated gasifier, such as the Battelle Columbus Laboratory design (Anson et al., 1999) or the Brightstar Synfuels Company design (Menville, 1998), is desirable to avoid nitrogen dilution of the synthesis gas, but partial oxidation could also be used.

In one configuration (Fig. 12a), the syngas is compressed after cleanup and passed through a steam reformer to convert hydrocarbons to CO and H_2. Some of the fuel gas leaving the F-T synthesis reactor is used to fire a gas turbine combined cycle that generates electricity, but only enough to meet process needs. The energy balance for this system gives an overall efficiency of biomass conversion to F-T liquids of about 60% (HHV basis).

In a "once-through" system producing F-T liquids and exporting electricity (Fig. 12b), no reformer is used, and all C_1 and C_2 hydrocarbons leaving the F-T reactor are used to fuel a gas turbine combined cycle. A substantial amount of power is exported to the grid in this case. For this configuration, the incremental efficiency of producing F-T liquids is about 80%

(HHV basis).[*] The high efficiency and simpler process configuration of the co-production case are likely to lead to substantially improved economics for F-T liquids production from biomass compared to the production of F-T liquids alone.

One potentially interesting use of F-T liquids from biomass is for cooking in rural areas of developing countries, where direct solid fuels combustion is widely practiced today. Consider Jilin, a major corn-growing province of Northeast China. With only 2% of China's population, Jilin grows 14% of China's corn. Some 35 million tonnes of corn stalks (~490 PJ) are generated annually with the corn harvest, about half of which are used for soil conditioning and fertilization, for livestock fodder, and for industrial feedstock (Cao, 1998). Stalks are also burned in village homes for heating and cooking, with attendant indoor air pollution problems. Based on Fig. 12, if corn stalks generated in Jilin were to be used as feedstock for F-T synthesis, some 25 to 50 PJ of synthetic LPG might be produced (depending on whether the configuration in Fig. 12a or 12b is used), in addition to other products. Since it is estimated that 35 PJ of LPG would be required to meet all of the cooking fuel demands of rural Jilin Province, conversion of corn stalks via F-T synthesis could be one option for providing a substantial amount of clean and efficient cooking fuel for the region.

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[*] The biomass charged to F-T liquids is the total biomass input less the amount of biomass that would be required at a stand-alone BIG/GTCC plant to generate the same amount of electricity as that exported from the co-producing facility. Assuming a generating efficiency of 35% (HHV) for a stand-alone BIG/GTCC, and using the results in Fig. 12, the incremental efficiency of producing F-T liquids with the once-through process is $0.28/[1.0 - (0.227/0.35)] = 0.80$.

CLOSURE

A number of scenarios for future energy supply suggest that renewable biomass energy could play a much more significant role globally in the 21st century than today. For this to happen will require that biomass become widely attractive and competitive in energy markets. This, in turn, requires that biomass be converted at high efficiency and acceptable capital cost into high quality energy carriers such as electricity and fluid fuels. This paper has discussed technical and economic characteristics of some advanced thermochemical biomass conversion systems that might meet the objectives of high efficiency and acceptable capital cost. These include gas turbine-based systems for power generation, and chemical-process systems for methanol, hydrogen, and Fischer-Tropsch liquids production.

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