POWER GENERATION POTENTIAL OF BIOMASS GASIFICATION SYSTEMS

By Charles M. Kinoshita,1 Scott Q. Turn,2 Ralph P. Overend,3 and Richard L. Bain4

ABSTRACT: Biomass has the potential to contribute a significant portion of the electricity consumed in industrialized nations and a major share of the power mix in developing countries. In addition to providing an alternative to fossil-fuel-based energy and creating new markets for agriculture, a renewable resource like biomass used in a sustainable fashion facilitates closure of the carbon cycle. To realize these benefits, particularly in the shadow of uncertainties cast by deregulation and recent changes in federal energy and agricultural policies, biomass power systems must be competitive with incumbent power-generation technologies in terms of generation efficiency and overall cost. Anticipated performance and cost of biomass-based integrated gasification, combined-cycle power systems are discussed. The electric power that can be generated worldwide using existing biomass resources (primarily crop residues and wastes) and the potential amount that could be generated from crops grown specifically for electricity generation are projected. Technical and economic obstacles that must be overcome before advanced biomass-power systems based on aeroderivative turbines or fuel cells can become fully commercial are identified. Research, development, and demonstration efforts under way or being planned to overcome those obstacles are described; developments in a major biomass gasification demonstration project taking place in Hawaii under the auspices of the U.S. Department of Energy and the State of Hawaii are detailed.

INTRODUCTION

Biomass is, arguably, the most flexible nonpetroleum energy resource available—it can be burned for direct heating in various industrial and domestic applications or for producing steam to generate electricity; it can be converted into gaseous or liquid fuels for use in all of the aforementioned processes or serve as transportation fuels. Biomass resources also offer environmental advantages over many fossil fuels. Biomass has much lower sulfur and ash content than most coals, thereby reducing sulfur emission and ash disposal problems. In addition, biomass feedstocks, grown and consumed on a sustained-energy basis, do not add carbon dioxide to the atmosphere over their life cycle. Energy crops can be grown on fragile lands and help to reduce fertilizer and pesticide runoff. Additionally, increased use of bioenergy would benefit agribusiness by creating new markets to supplement traditional food and fiber markets, and rural communities would benefit by gaining additional jobs created by bioenergy production.

The United States has seen a significant increase in bioenergy use in the

1Res. Engr., Hawaii Natural Energy Inst. Univ. of Hawaii, 2540 Dole St., Holmes 246, Honolulu, HI 96822; Chair, Dept. of Biosys. Engrg., Univ. of Hawaii, 3050 Maile Way, Gilmore 111, Honolulu, HI.
2Asst. Res., Hawaii Natural Energy Inst., Univ. of Hawaii, 2540 Dole St., Holmes 246, Honolulu, HI.

Note. Discussion open until May 1, 1998. To extend the closing date one month, a written request must be filed with the ASCE Manager of Journals. The manuscript for this paper was submitted for review and possible publication on June 3, 1996. This paper is part of the Journal of Energy Engineering, Vol. 123, No. 3, December, 1997. ©ASCE, ISSN 0733-9402/97/0003-0088—0099/$4.00 + $.25 per page. Paper No. 13388.

88 / JOURNAL OF ENERGY ENGINEERING / DECEMBER 1997
last two decades, especially wood residues burned in steam plants that co-generate thermal and electrical energy. During that period, the wood products sector became ~70% self-sufficient in energy, and the amount of grid-connected electric capacity increased from less than 200 MWe prior to 1978 [the year in which the landmark Public Utilities Regulatory Policies Act (PURPA) was enacted] to over 7,500 MWe today. Most of the grid-connected biomass power facilities are independent (nonutility) cogeneration systems, ≤25 MWe in capacity, having net efficiencies of ~20% (heat rates on the order of 18,000 kJ/kW-h ~ 17,000 Btu/kW-h). To date, utilities have been involved in only a handful of wood-fired facilities in the 40–50 MWe size range, and in some cofiring of wood and municipal solid waste in conventional coal-fired plants.

At the outset of PURPA, power-sales agreements often provided attractive prices to the independent power producer. However, such agreements are virtually nonexistent today; as a result, very few biomass power facilities are able to compete with fossil-fuel-based systems unless biomass generation efficiencies increase significantly above the 20% levels typical of existing steam-based biomass power plants. Improvements in biomass-electricity conversion technology would not only reduce fuel consumption (effectively increasing the power generation potential from a given supply of biomass feedstock, thereby lowering the transportation cost component in the fuel), but reduce the emissions per unit of power output, minimizing environmental impact. Advanced gasification-based biomass power systems being developed and demonstrated in several countries offer the widely sought, clean, economically competitive alternative to fossil-fuel-based electric power.

GASIFICATION-BASED TECHNOLOGIES

Gasification is a two-step process in which a solid fuel is converted thermochromically into a fuel gas. In the first step, pyrolysis, volatile components of the solid fuel are released as combustible and noncombustible gases, tars, and water vapor, leaving residual char (fixed carbon) and ash as by-products. The second step, char conversion, involves the gasification and/or combustion of the residual carbon. In this step, part of the char reacts with oxygen, providing the heat needed to sustain pyrolysis and to gasify any remaining char. Biomass produces a char that is 10–30 times more reactive than that from coal. As a result, gasification of biomass char requires much less heat and proceeds more readily. This reduced heat requirement translates to lower temperatures in biomass gasifiers, thereby improving the efficiency of the process.

Over the last two decades, a number of different biomass gasifiers have been developed worldwide, and several gasifier designs developed for coal have been adapted to biomass. The different designs include fixed-bed, atmospheric– and pressurized– bubbling fluidized-bed, and circulating fluidized-bed reactors, some of which are indirectly heated. The essential features of the competing designs are described in the literature [e.g., Bain and Overend (1992); Williams and Larson (1993)]. The particular application largely dictates the choice of one gasifier design over another. In 1990, approximately 35 commercial biomass gasifiers were operational in the United States, fueled on wood or crop residues (Lee et al. 1990). Among those, fewer than five were being operated to generate electricity (most of the gasifiers were used to produce process heat).

Converting solid biomass into a fuel gas provides the opportunity to integrate biomass gasifiers with advanced fuel-gas-based power generation subsystems. The development of integrated biomass gasification systems has
benefited greatly from the wealth of technological advances and operating experience gained in coal gasification/power generation efforts worldwide. Close-coupling of the gasification unit with the power generation unit increases overall conversion efficiency by utilizing the thermal energy in addition to the chemical energy of the hot product gas stream within the energy conversion system. Two general classes of fuel-gas-based power generation technologies show particular promise (Fig. 1): (1) biomass gasification close-coupled to gas turbine combined cycle systems; and (2) biomass gasification close-coupled to fuel cell systems.

Biomass-gasification-based combined cycles, promising high efficiency and low emissions, are particularly well suited for medium-scale (~50 MWe) power generation. At smaller scales (25–50 MWe), steam-injected gas turbines, through which both combustion gases and steam are expanded to generate power, offer a cost-effective variant to the combined gas and steam cycle configuration.

Close-coupling of the biomass gasification unit with the combustion-turbine plant should reduce generation cost and increase efficiency significantly over steam-based biomass power plants; such integrated systems are, however, constrained by economies of scale, even when employing aeroderivative gas turbines. Replacing the gas turbine with the fuel cell overcomes scale-associated limitations. Projected efficiencies for gasifier/fuel cell systems are as high as 60%. In addition to promising extremely high efficiencies that are largely independent of size or load and that are not constrained by the second law, fuel cells are attractive for several other reasons. Their modular nature allows them to better match capacity with demand and available fuel supplies, reduce financial exposure, increase planning and siting flexibility, and improve system reliability. These factors are especially critical for application in developing countries because of widely differing power requirements in different locales. Fuel cells also have environmental advantages, generating lower noise and emission levels and less wastewater than competing technologies. As with the gas-turbine alternative, waste heat recovery is possible,
allowing cogeneration options to be integrated into the system. The potential for extremely high efficiency and flexibility notwithstanding, biomass-based fuel cells raise a number of concerns over reliability. Gas quality is particularly critical with fuel cells. Much of the work presently being done on hot-gas cleanup for biomass and coal gasifier/gas turbine systems should be directly applicable to fuel cell systems. Phosphoric acid fuel cells, already available in the 50–200 kWe size range, appear to have significant developmental hurdles to overcome for biomass power applications; however, the introduction of molten carbonate or solid oxide fuel cells can reduce raw gas processing requirements.

SCALE-UP EFFORTS

Major Projects Under Way

Several major projects are under way, worldwide, to demonstrate biomass gasification at commercial or near-commercial scales. Most involve the scale-up of gasification technologies and integration with various cleanup strategies to produce a fuel gas of sufficient quality to generate electricity using combustion turbines. The Global Environment Facility recently completed an extensive evaluation of two different Scandinavian air-blown gasification systems, high-pressure versus low-pressure, for installation in northeast Brazil. The low-pressure, cold-gas cleanup option was selected to minimize developmental risk. The United States has undertaken a dual-pathway developmental strategy for biomass gasification/power generation. One demonstration project, which commenced recently, involves the production of an unpressurized, medium-heating-value gas using indirectly heated gasification; the other project, which commenced several years ago (see the following section), is seeking to produce a pressurized, low-heating-value gas.

Biomass Gasifier Facility Program in Hawaii

The writers are members of a team, headed by the Pacific International Center for High Technology Research (PICHTR), which is scaling-up pressurized biomass gasification technology for use in converting biomass feedstocks into electricity and transportation fuels. This project is being funded by the federal government through the U.S. Department of Energy and National Renewable Energy Laboratory (NREL), and the state of Hawaii via its Department of Business, Economic Development and Tourism and the University of Hawaii. Participating members of the project team include the Hawaii Natural Energy Institute of the University of Hawaii, the Hawaiian Commercial and Sugar Company (HC&S), the Institute of Gas Technology (IGT), and the Ralph M. Parsons Co. The facility (Fig. 2) is located in the town of Paia on the island of Maui, adjacent to a sugar factory owned by HC&S.

The gasifier facility was designed to operate at pressures up to 20 bars and feed rates as high as 90 t/d (dry basis). Fig. 3 shows the essential features of the demonstration facility. Feedstock is loaded into a walking floor storage bin that meters the fuel onto a conveyor that feeds a rotary-drum dryer. Upon exiting the dryer, feedstock is pneumatically conveyed to the top of the gasifier facility structure where it is disengaged from the flow by a cyclone. A second metering conveyor transfers the feedstock onto a weigh belt, the primary feed control for biomass entering the process stream. Biomass in excess of the desired feed rate is returned to storage via an overruns conveyor. Feedstock falls from the weigh belt through a downcomer and enters a plug-screw feeder that increases the material density sufficiently to seal the feed

system against the pressure of the gasifier reactor. The extruded biomass plug exiting the plug-screw feeder falls onto a water-cooled auger that breaks the plug into discrete fragments and transports them into the reactor. The gasifier is a 10-to-1 scale-up of IGT's RENUGAS process-development unit in Chicago, Ill. It consists of a refractory-lined fluidized-bed reactor with alumina beads as the inert bed media. Air and steam are fed into the reactor through separate sparge rings to control the reaction process and gas composition. Air is supplied to the system by two screw-type compressors and steam is provided by the sugar factory boiler. During start-up, prior to biomass gasification, combustion gases from a propane-fired burner flow through the bed to heat the reactor, bed material, and downstream components to a temperature of \( \sim 550^\circ C \). During the initial stage of biomass gasification, conditions are controlled to increase the reactor temperature to the desired condition. Raw gas exiting the top of the reactor passes through a hot-gas cyclone that removes entrained, unreacted char, and ash particles. The process stream is expanded from reactor pressure to near ambient conditions via a letdown valve before entering the product gas flare where it is combusted and vented.

Shakedown testing of the facility utilizing sugarcane bagasse (the fibrous material that remains after sugar is extracted from cane) as the feedstock took place in October 1995. Fifty-eight hours of essentially steady-state operation were achieved during this period. The process operated in an air-blown mode, with no steam added, at nominal reactor temperature and pressure of 840\(^\circ C\) and 3 bars, respectively. Bagasse from the sugar factory entered the dryer at \( \sim 45\% \) moisture content and exited at \( \sim 25\% \) (wet basis). The fuel feed rate to the reactor was \( \sim 1.05 \text{ t/h} \) (wet basis). The gas composition during the test period is shown in Table 1. The higher heating value of the gas was 3.7 MJ/m\(^3\). Condensable hydrocarbons (C\(_6\) and higher) in the output stream averaged 2.3\% of dry fuel feed, with benzene (C\(_6\)H\(_6\)) and naphthalene (C\(_{10}\)H\(_8\)) being the principal constituents. Gaining operational experience was the primary
objective of the shakedown test; no attempt was made to optimize gas quality. Carbon conversion efficiency, defined as the percentage of fuel carbon converted into gases or liquids, was estimated to be ~96%.

Follow-on testing was carried out in early December, resulting in an additional 60 hours of operation. Air and a mixture of air and steam were utilized as the fluidizing agent and oxidant during this phase of testing. The reactor was operated in an air-blown mode with increased bagasse feed rate.
and reactor pressure, 1.7 t/h (wet basis) and 4.2 bars, respectively. Fuel moisture content was \(~30\%\). These conditions resulted in gas of higher quality than that from the October 1995 test (Table 1). The heating value of the gas increased to 4.5 MJ/m\(^3\). Condensable hydrocarbon yield was substantially reduced to 0.8% of dry fuel mass. Carbon conversion efficiency improved to \(~98\%\), 2% higher than that of the October tests.

In the final test run in December 1995, air and steam were added to the reactor at a temperature and pressure of 860°C and 5 bars. The wet fuel feed rate was approximately 1.6 t/h with a reduced moisture content of 17%. The addition of steam resulted in improved gas quality and an increased heating value of 5.8 MJ/m\(^3\) (Table 1). Carbon conversion efficiency remained about the same.

More extensive trials, at higher pressures and feed rates than those described earlier and with additional conditioning of the gas as described next, are under way in the Technology Verification Phase of this multiphase program. In the next phase, the project team hopes to use the gasifier unit to generate electricity in a combined-cycle system equipped with a gas turbine or fuel cell.

A key technological step in commercializing biomass-gasification-based power systems is conditioning the raw gases generated in the gasifier to make them suitable for use in the power plant. An example of scale-up strategies used for advancing emerging technologies toward commercialization is seen in the development of hot-gas cleanup technologies. Critical information relating to optimal filter face velocity and number of ceramic filter candles, established in IGT’s process development unit under the auspices of NREL and its industrial partners, is being used in slip-stream long-term trials presently under way at the scaled-up Paia biomass gasifier facility. Information gathered in these trials, funded by the U.S. Department of Energy, the state of Hawaii, and the manager of the Technology Verification Phase, Westinghouse Electric Corp., will not only validate data collected in the process development unit, but will also address critical questions relating to the life of ceramic candle materials under actual conditions posed by bagasse ash. The successful conclusion of the long-term trials in Hawaii should yield sufficient experience and confidence in this technology to allow the industrial sector to proceed to commercialization.

**BIOMASS ENERGY POTENTIAL**

Worldwide, biomass ranks fourth as an energy resource, providing \(~14\%\) of the world’s energy needs; biomass is the most important source of energy in developing nations, providing \(~35\%\) of their energy, particularly in rural areas where it often is the only accessible and affordable source of energy (McGowan 1991; Hall et al. 1992). Considering the vastness of the photosynthetic productivity of biomass (conservatively an order of magnitude greater than the world’s total energy consumption), that bioenergy can be produced and used in a clean and sustainable manner, and that technological advancements in biomass conversion are occurring along several fronts worldwide, there is much optimism that biomass will continue to play a significant, and probably increasing, role in the world’s future energy mix. The extent and rate of increase of its use, especially in industrialized countries, will depend on greater exploitation of existing biomass stocks (particularly residues) and the development of dedicated energy feedstock supply systems.

94 / JOURNAL OF ENERGY ENGINEERING / DECEMBER 1997
Biomass Residues and Dedicated Energy Feedstocks

Biomass residues are the most readily accessible and often least costly (sometimes having a negative cost associated with their disposal) form of biomass available today. The approximate quantities of such feedstocks (not including municipal solid waste) and their energy values are summarized, continent by continent, in Table 2. In many instances, crop processing provides much synergism with power production, the former serving to upgrade the quality of the biomass feedstock to facilitate the latter. An example is seen in sugarcane processed to produce sugar as a primary product and electricity as a by-product. Harvested sugarcane contains >1% alkali compounds per unit of fiber harvested. Alkalis, when reacted with sulfates and chlorine, are problematical for thermochemical conversion systems, fouling heat exchange surfaces, gas-turbine blades, and other power system components. The milling process that extracts sugar from the sugarcane crop produces the fibrous residue, bagasse, which is used as a fuel to generate steam and electric power. The bagasse contains only 0.3% alkali per unit of fiber (<30% the amount contained in the original sugarcane crop) as well as a lower moisture content, and the resulting fuel particle size is better suited for power generation than the original sugarcane received by the mill.

The data in Table 2 show that in some instances, particularly in developing countries, the energy contained in existing biomass residues rivals or exceeds the amount of electric energy generated from traditional sources. A more specific analysis performed by Kinoshita et al. (1997), for the Philippines, Thailand, Malaysia, and Indonesia, shows that the biomass resource base represented in just traditional sugarcane, oil palm, and rice residues (sugarcane bagasse, oil palm fiber, and rice hulls), converted to electricity using commercially available technology, is sufficient to generate more than 8,000 TW-h/yr while displacing roughly 5,500,000 t of the carbon dioxide emitted from the existing power generation mix in those countries. Using advanced gasification technologies, the electricity generation and carbon dioxide reduction potentials could be twice as great.

It must be recognized, however, that biomass residues have many applications, including use as animal feed, soil amendments, industrial feedstock, and commercial products, and that each application carries an economic value for the feedstock; therefore, not all residues can or should be diverted to power generation. Animal wastes are another significant potential biomass resource for electricity generation, and, like crop residues, have many applications, especially in developing countries.

Although residues are most widely used as sources of energy in developing nations, where such resources often are the only form of energy readily available, under favorable circumstances they can contribute significantly to the energy mix even in industrialized countries. For example, in the early 1980s, ~10% of the electricity generated in the state of Hawaii originated from sugarcane bagasse, and in some counties in the state >50% came from bagasse (Kinoshita 1984). However, if biomass is to play a major role in the world’s energy mix in the longer term, crops will need to be grown specifically for energy. Studies performed by a number of investigators [e.g., Graham et al. (1995)] have suggested that within 10 years, the United States could produce large quantities (>5 EJ) of high-yielding energy crops for $30–50/t (dry basis) or lower, potentially making such feedstocks competitive with coal in many locations. These projections will need to be validated in thousand-hectare commercial plantings. Initial installations of energy crops will need to be profitable in order for the concept of dedicated energy feedstock supplies to gain broader acceptance. Increases in fossil fuel prices, rapid
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Africa (1)</th>
<th>North America(^*) (3)</th>
<th>South America (4)</th>
<th>Asia (5)</th>
<th>Europe (6)</th>
<th>Oceania (7)</th>
<th>World (8)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biomass residues ([\text{EJ}(\text{MMt})])(^b)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Selected crop residues(^c)</td>
<td>5 (253)</td>
<td>15 (809)</td>
<td>4 (230)</td>
<td>27 (1,503)</td>
<td>10 (565)</td>
<td>1 (72)</td>
<td>62 (3,433)</td>
</tr>
<tr>
<td>Animal wastes(^d)</td>
<td>5 (347)</td>
<td>3 (198)</td>
<td>7 (465)</td>
<td>20 (1,263)</td>
<td>4 (272)</td>
<td>1 (89)</td>
<td>41 (2,634)</td>
</tr>
<tr>
<td>Roundwoods(^e)</td>
<td>4 (203)</td>
<td>9 (429)</td>
<td>4 (180)</td>
<td>14 (724)</td>
<td>5 (227)</td>
<td>0 (23)</td>
<td>36 (1,785)</td>
</tr>
<tr>
<td>Dedicated feedstocks ([\text{EJ}(\text{MMt})])(^f)</td>
<td>14 (789)</td>
<td>10 (535)</td>
<td>12 (659)</td>
<td>12 (668)</td>
<td>2 (119)</td>
<td>5 (293)</td>
<td>55 (3,063)</td>
</tr>
<tr>
<td>Total biomass energy ([\text{EJ}(\text{MMt})])(^g)</td>
<td>21 (1,190)</td>
<td>23 (1,253)</td>
<td>19 (1,096)</td>
<td>43 (2,413)</td>
<td>12 (651)</td>
<td>7 (385)</td>
<td>124 (6,988)</td>
</tr>
<tr>
<td>Biomass electricity potential ((\text{EJ}))(^h)</td>
<td>7</td>
<td>8</td>
<td>7</td>
<td>15</td>
<td>4</td>
<td>2</td>
<td>44</td>
</tr>
<tr>
<td>Present generation, major sources ((\text{EJ}))(^i)</td>
<td>1</td>
<td>14</td>
<td>2</td>
<td>12</td>
<td>15</td>
<td>1</td>
<td>44</td>
</tr>
<tr>
<td>Biomass potential: present generation ((—))(^j)</td>
<td>6.1</td>
<td>0.6</td>
<td>3.6</td>
<td>1.3</td>
<td>0.3</td>
<td>3.3</td>
<td>1.0</td>
</tr>
</tbody>
</table>

\(^a\)Includes Central America for all categories except Roundwoods (for which Central America is included with South America).

\(^b\)\text{EJ} = 10^{18} \text{ J}; \text{MMt} = \text{million t}.

\(^c\)Based on crop production information for 1993 from FAO (1994) and residue multipliers from Smil (1983).

\(^d\)Based on animal production information for 1993 from FAO and waste factors reported by Hall et al. (1993).

\(^e\)Based on data from Hall et al. (1993).

\(^f\)Assumes production on 5% of existing pasture and forest lands with yield of 10 t/ha-yr.

\(^g\)Consists of dedicated feedstocks plus 50% of biomass residues.

\(^h\)Assumes generation efficiency = 35%

\(^i\)Based on data for 1993 from United Nations (1995); includes thermal, hydro, nuclear, and geothermal electricity generation.

\(^j\)Ratio, biomass electricity potential divided by present generation, major sources.
advances in gasification-based power generation technology, or more aggressive market development for production of biomass for electricity generation could help to accelerate adoption of the concept. Implementation of policies that discourage greenhouse gas emissions or encourage biomass production on idle lands also could make biomass feedstocks more competitive with fossil fuels. Presently, several incentives are in place or proposed that encourage the installation of dedicated energy feedstocks, e.g., renewable energy production credits and accelerated depreciation for closed-loop biomass energy systems, and potential offsets in emission charges. The quantity and energy value of dedicated energy feedstocks producible on 5% of the lands presently in pasture and forests at an average yield of 10 t/ha-yr (dry basis) are shown in Table 2. The use of such tracts of land for dedicated feedstock supplies is reasonable—in the United States, 50% of pasture and forest lands translates to a total area of roughly 25,000,000 ha, which is on the order of the acreage in conservation and crop set-aside programs in recent years (Graham et al. 1995).

The worldwide biomass energy potential projected in Table 2 assumes that 50% of the biomass residue resource can be recovered for conversion into electricity and that 5% of the pasture and forest lands are used for the production of dedicated energy feedstocks. Combined, the biomass available worldwide would be 7 billion, having an energy value of 124 EJ. Used in advanced gasification-based power generation systems with efficiencies of ~35%, residues and dedicated energy crops have the potential to produce 44 EJ (12,000,000 GW-h) worldwide, which essentially equals the amount of electricity generated from all centralized sources of electricity, including thermal, hydro, nuclear, and geothermal. Indeed, biomass has the potential to contribute significantly to the world’s energy mix.

A worldwide market for more than 600 GW of electric power capacity is expected within the next 10 years (U.S. 1993). In many regions of Asia, Africa, and Latin America, where three-quarters of the world’s population now lives (and 90% of the world will reside by the middle of the 21st century), biomass electricity is the only viable option that will serve national objectives of stimulating employment and improving balance of trade, while meeting increasing energy demands in an environmentally responsible manner. Much of the incremental capacity can be met with biomass feedstocks, provided that biomass production and conversion systems can become more economically competitive with fossil-fuel based systems.

ECONOMICS

A wide disparity existed in the literature in the predictions of efficiencies and costs of gasifier/gas-turbine-based power generation systems. Therefore, a panel consisting of representatives from NREL, the Electric Power Research Institute, the U.S. Environmental Protection Agency (EPA), the U.S. Department of Agriculture, the Princeton Center for Energy and Environmental Studies, and the Colorado School of Mines was convened to arrive at consensus positions on the efficiency and cost of biomass power. The panel agreed on likely ranges of cost and performance for systems using biomass fuels. The data, which were used for modeling by the EPA, are summarized in Table 3 (high-overall-cost, low-efficiency and low-overall-cost, and high-efficiency brackets established by the panel for biomass are presented), and compared with corresponding figures for coal and natural gas technologies.

Capital investment is a major component in the overall cost of generating electricity. Fig. 4 summarizes capital costs for integrated gasification/com-
<table>
<thead>
<tr>
<th>Component</th>
<th>Industrial Turbines</th>
<th>Advanced Turbines</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Biomass (2)</td>
<td>Coal (3)</td>
</tr>
<tr>
<td>Efficiency (% HHV)</td>
<td>39.4</td>
<td>39.2</td>
</tr>
<tr>
<td>Fixed O&amp;M ($/kW)</td>
<td>51.25</td>
<td>51.25</td>
</tr>
<tr>
<td>Variable O&amp;M (mils/kW·h)</td>
<td>3.15</td>
<td>3.15</td>
</tr>
<tr>
<td>Capital cost ($/kW)</td>
<td>1,230</td>
<td>1,254</td>
</tr>
</tbody>
</table>

(a) Leading to Low Overall Cost for Biomass Electricity

<table>
<thead>
<tr>
<th>Component</th>
<th>Industrial Turbines</th>
<th>Advanced Turbines</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Biomass (2)</td>
<td>Coal (3)</td>
</tr>
<tr>
<td>Efficiency (% HHV)</td>
<td>36.3</td>
<td>39.2</td>
</tr>
<tr>
<td>Fixed O&amp;M ($/kW)</td>
<td>44.71</td>
<td>36.44</td>
</tr>
<tr>
<td>Variable O&amp;M (mils/kW·h)</td>
<td>3.65</td>
<td>2.60</td>
</tr>
<tr>
<td>Capital cost ($/kW)</td>
<td>1,488</td>
<td>1,254</td>
</tr>
</tbody>
</table>

(b) Leading to High Overall Cost for Biomass Electricity

---


Combined cycle systems, as projected by various investigators. The two curves in the figure represent 0.8 scale-factor fits using, as bases, the “high” and “low” cost projections from the EPA modeling study. Additional details are provided by Craig et al. (1995).

**SUMMARY AND CONCLUSIONS**

Among the alternative energy sources available today, biomass appears to be best able to contribute to the world’s growing energy needs in an environmentally responsible manner. The potential resource represented in existing biomass residues and future dedicated feedstock supply systems is vast and can displace much of the electricity being generated from fossil fuels and other nonrenewable resources; it can supply much of the incremental
capacity needed over the next several decades. Technological advances in biomass production and conversion are being made that will help bioenergy systems become competitive with fossil-fuel-based technologies. The development of advanced bioenergy systems will have a favorable impact on the U.S. economy by creating new markets for agribusiness, by spurring employment, and by helping to revitalize economically depressed areas in rural America and worldwide. Finally, a note to the reader: The title of this present work was adopted from an article in the Proceedings of the American Power Conference (1996).

APPENDIX. REFERENCES


