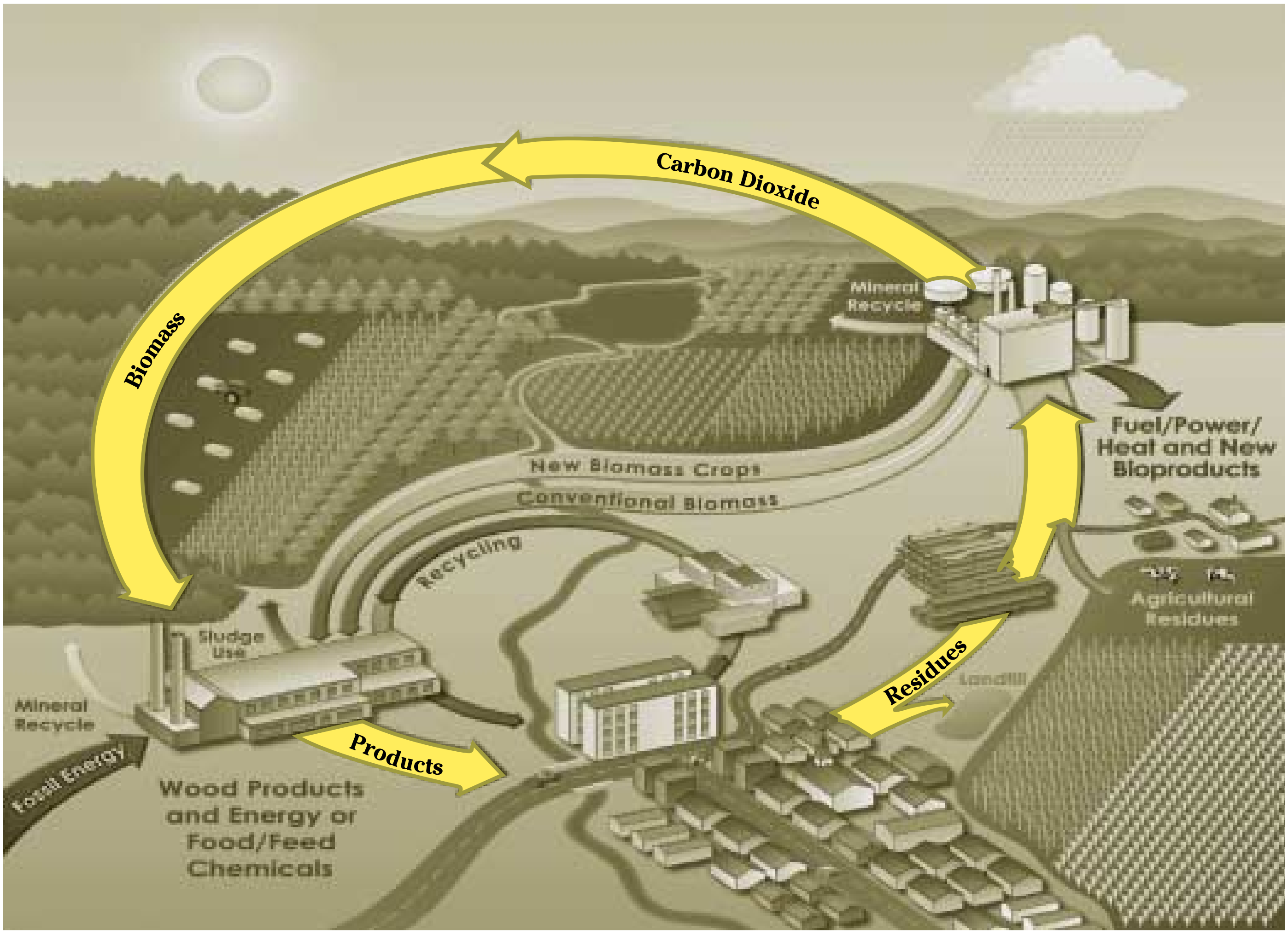

BIOMASS FOR HEAT AND POWER

By Richard L. Bain and Ralph P. Overend

Biopower is the production of electricity from renewable biomass resources. The production cycle has five key elements: biomass supply, transportation, handling, conversion, and electricity generation. Biopower is a proven commercial electricity generating option in the United States, and with about 11 GW of installed capacity, is the single largest source of non-hydro renewable electricity (Fig. 1). This 11 GW of capacity encompasses about 7.5 GW of forest product and agricultural industry residues, about 3.0 GW of generating capacity from municipal solid waste, and 0.5 GW of other capacity (e.g., landfill gas). The majority of electricity production from biomass is being used and is expected to continue to be used as base load power in the existing electrical distribution system.

Figure 2 shows the evolution of biomass use in the United States. In 1850, fuelwood represented about 91 percent of the total energy supply of the United States. Statistics on fuelwood use but not necessarily on industrial use go back to 1850

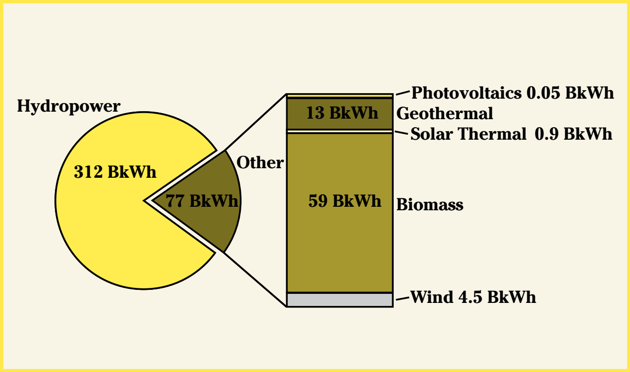

Figure 1. – 1999 Renewable Energy Electricity Generation (EIA).

(USDOC 1975). Data are missing for the interval of 1950 to 1970 when statistics on fuelwood were not collected at the Bureau of Mines. Improved statistics on biomass use including fuelwood and industrial wood use became available in 1982 for the 1970s decade including a baseline just before the first energy crisis of 1973 struck (Norwood and Warnick 1982). The decline in fuelwood use was rapidly reversed in 1973, and this was followed by determined efforts by the pulp and paper industry to increase their energy self-sufficiency. Since 1980, statistics on all biomass use including urban residues and the use of corn-derived ethanol have been available through the Energy Information Administration (EIA 2000).

In the United States, biopower experienced dramatic growth (Fig. 3) after the Public Utilities Regulatory Policy Act (PURPA) of 1978 guaranteed small electricity producers (less than 80 MW) that utilities would purchase surplus electricity from qualifying facilities at a price equal to the utilities' avoided cost of producing electricity. The passage of PURPA, as well as various state incentives, resulted in a factor-of-three increase in grid-connected

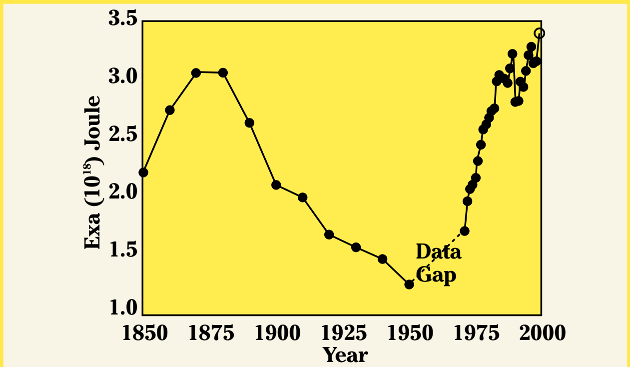

Figure 2. – Biomass Use in the United States, 1850 to 2000.

biopower generating capacity in the period from 1980 to 1990. The certainty of these contracts propelled industry investment to $15 billion, and the creation of 66,000 jobs. Since the PURPA legislation had no energy efficiency criterion or incentives to add capacity at higher efficiency, and given the time needed to recover the investment (less than 10 years), investments were made in state-of-the-art technology at the time (combustion/steam). As a consequence, there was generally fairly low efficiency. Since "conventional" biopower was apparently well on its way in the commercial marketplace, research during the subsequent period focused on more advanced combustion technologies and gasification.

By the early 1990s, the biopower industry was beginning to stall for many reasons, including increased feedstock costs caused by inadequate infrastructure; lack of tax credits, regulatory preferences, or increased market prices in recognition of

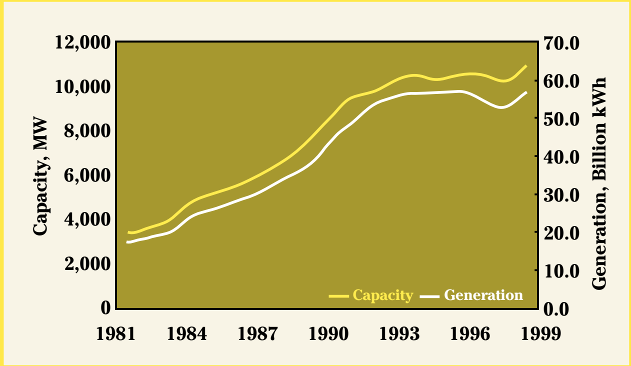

Figure 3. – Bioenergy Electricity Generation, 1981 to 1999 (EIA).

the environmental benefits of biopower; and the much lower new generation costs of natural gas combined cycle systems. In addition, avoided cost contracts signed under PURPA were expiring and the utilities and independent power producers were unsuccessful in negotiating new contracts. More recently, the biopower industry has experienced uncertainty surrounding ongoing or impending utility restructuring in a number of states. This situation has had detrimental effects on the industry because many electricity industry companies have postponed investment decisions for new facilities or new power purchase contracts until the details of restructuring are completed.

The 7.5 GW of traditional biomass capacity represents about 1 percent of total electricity generating capacity and about 8 percent of all non-utility generating capacity. More than 500 facilities around the country are currently using wood or woodwaste to generate electricity. Fewer than 20 of these facilities are owned and operated by investor-owned or municipally owned electric utilities. The majority of the capacity is operated in combined heat and power (CHP) facilities in the industrial sector, primarily in pulp and paper mills and paperboard manufacturing. Some of these facilities have buy-back agreements with local utilities to purchase net excess generation. Additionally, a moderate percentage of biomass power facilities are owned and operated by non-utility generators, such as independent power producers, which have power purchase agreements with local utilities. The number of such facilities is decreasing somewhat as utilities buy back existing contracts. The stand-alone power production facilities largely use non-captive residues, including woodwaste purchased from forest products industries and urban woodwaste streams, agricultural residues from harvesting and processing, used wood pallets, and some waste wood from construction and demolition. In most instances, the generation of biomass power by these facilities also helps reduce local and regional waste streams.

All of today's capacity is based on mature, direct combustion boiler/steam turbine technology. The average size of existing biopower plants is 20 MW (the largest approaches 75 MW) and the average biomass-to-electricity efficiency of the industry is 20 percent. These small plant sizes (which lead to higher capital cost per kilowatt-hour of power produced) and low efficiencies (which increase sensitivity to fluctuation in feedstock price) have led to electricity costs in the range of 8 to 12 cents per kWh.

The next generation of stand-alone biopower production will substantially mitigate the high costs and efficiency disadvantages of today's industry.

The next generation of stand-alone biopower production will substantially mitigate the high costs and efficiency disadvantages of today's industry. The industry is expected to dramatically improve process efficiency through the use of cofiring of biomass in existing coal-fired power stations, through the introduction of high-efficiency gasification combined cycle systems, and through efficiency improvements in direct combustion systems made possible by the addition of dryers and more rigorous steam cycles on a larger scale of operation. Technologies presently at the research and development stage, such as integrated gasification fuel cell systems and modular systems, are expected to be competitive in the future.

Markets

Biopower systems consist of an entire cycle, from growing and harvesting the biomass resource, to converting and delivering electricity, to recycling carbon dioxide during growth of additional biomass. There are many types of biomass feedstocks from diverse sources. This creates technical and economic challenges for biopower plant operators because each feedstock has different physical and thermochemical characteristics and delivered costs. Characteristics of biopower facilities, including feedstock flexibility and capacities that are typically much lower than fossil-fuel power plants, present opportunities for market penetrations in unconventional ways. Feedstock type and availability, proximity to users or transmission stations, and markets for potential by-products will influence which biomass conversion technology is selected and the scale of operation. A number of competing technologies, such as those discussed previously, will likely be available that will provide a variety of advantages for the U.S. economy, from creating jobs in rural areas to increasing the demand for engineering and manufacturing of systems designed for biomass.

The near term domestic opportunity for gasification combined cycle technology is in the forest products industry because a majority of the industry's power boilers will reach the end of their useful lives in the next 10 to 15 years. This industry is familiar with use of its low-cost residues ("hog" fuel and a waste product called "black liquor") for generation of electricity and heat for its processing needs. The higher efficiency of gasification-based systems would bolster this self-generation (offsetting increasing electricity imports from the grid) and perhaps allow export of electricity to the grid. The industry is also investigating the use of black liquor gasification in combined cycle to replace the aging fleet of Kraft recovery boilers.

An even nearer and low-cost option for the use of biomass is in cofiring with coal in existing boilers. Cofiring biomass with coal has the potential to produce 7.5 GW by 2010 and 26 GW by 2020. Although the current substitution rate is negligible, a rapid expansion is possible based on wood residues (urban wood, pallets, secondary manufacturing products) and dedicated feedstock supply systems (DFSS) such as willow, poplar, and switchgrass. The carbon replacement rate in 2010 would be 14.5 Tg.

Biomass Supply

Nationally, there appears to be a generous fuel supply; however, lack of infrastructure to obtain fuels and lack of demonstrated technology to combust or gasify new fuels currently prevent utilization of much of this supply. According to Robert Williams of Princeton University (Hall et al 1993), of the total U.S. biomass residues available, half could be economically used as fuel. He estimates that of the 5 EJ of recoverable residues per year, one-third is made up of agricultural wastes and two-thirds are forest products industry residues (60% of these are mill residues). Urban wood and paper waste, recoverable in the amount of 0.56 EJ, will also be an important source. Preconsumer biomass waste is also of increasing interest to urban utilities seeking fuels for cofiring, and such use provides a valuable service to the waste producer

The Southeast is a good example of biomass resources. In the Southeast, 92 Tg of biomass fuel are produced annually, according to a study done in the mid-1990s by the Southeast Regional Biomass Energy Program (SERBEP 1996). This translates to an estimated 2.3 EJ of annual energy. North Carolina and Virginia are the biggest wood fuel producers (10.4 and 10.1 Tg, respectively). These residues come primarily from logging applications, culls, and surplus growth, and are in the form of whole-tree chips.

California is another good example of biomass resources and use. The California biomass market grew from about 0.45 Tg in 1980 to about 5 Tg in the early 1990s. Feedstocks include mill residues, in-forest residues, agricultural wastes, and urban woodwaste.

Because the future supply of biomass fuels and their respective prices can be volatile, many believe that the best way to insure future fuel supply is to develop dedicated feedstocks, such as the switchgrass shown in Figure 4. The Department of Energy's (DOE) Oak Ridge National Laboratory has supported research on short-rotation crops. Unused agricultural lands (31.6 million hectares in 1988) in the United States are primary candidates for tree plantations or herbaceous energy crops. It would take only about 4 percent of unused agricultural land within an 80-km radius to supply a 100-MW plant operating at 70 percent capacity. Of course, there are minimum requirements for water, soil type, and climate that will restrict certain species to certain areas. An assured fuel supply can reduce variability in prices.

Figure 4. – Switchgrass field at the Texas Agricultural Experiment Station, Stephenville, Texas. ***Photo taken by Warren Gretz, NREL.***

Technologies

The nearest term low-cost option for the use of biomass is cofiring with coal in existing boilers. Cofiring refers to the practice of introducing biomass as a supplementary energy source in high-efficiency boilers. Boiler technologies where cofiring has been practiced, tested, or evaluated, include pulverized coal boilers (wall-fired and tangentially fired designs), coal-fired cyclone boilers, fluidized-bed boilers, and spreader stokers. The current coal-fired power generating system represents a direct system for carbon mitigation by substituting biomass-based renewable carbon for fossil carbon.

Extensive demonstrations and trials have shown that effective substitutions of biomass energy can be made up to about 15 percent of the total energy input with little more than burner and feed intake system modifications to existing stations. Since the size of large-scale power boilers in the current 310-GW capacity fleet range from 100 MW to 1.3 GW, the biomass potential in a single boiler ranges from 15 MW to 150 MW. Preparation of biomass for cofiring involves well-known commercial technologies. After "tuning" the boiler's combustion output, there is little or no loss in total efficiency, implying that the biomass combustion efficiency to electricity would be close to the 33 to 37 percent range. Since biomass in general has significantly less sulfur than coal, there is a SO_2 benefit, and early test results suggest that there is a potential reduction of NO_x of up to 30 percent with woody biomass. Investment levels are very site specific and are affected by the available space for yarding and storing biomass, installation of size reduction and drying facilities, and the nature of the boiler burner modifications. Investments are expected to be $100 to $700 per kW of biomass capacity, with a median in the range of $180 to $200 per kW.

Another potentially attractive biopower option is based on gasification. Gasification for power production involves the devolatilization and conversion of biomass in an atmosphere of steam or air to produce a medium- or low-calorific gas. This "biogas" is then used as fuel in combined cycle power generation involving a gas turbine topping cycle and a steam turbine bottoming cycle. A large number of variables influence gasifier design, including gasification medium (oxygen or no oxygen), gasifier operating pressure, and gasifier type. Advanced biomass power systems based on gasification benefit from the substantial investments made in 1) coal-based gasification combined cycle (GCC) systems in the areas of hot gas particulate removal and synthesis gas combustion in gas turbines; 2) the DOE Clean Coal Technology Program (commercial demonstration cleanup and utilization technologies); and 3) the DOE Advanced Turbine Systems (ATS) Program. Biomass gasification systems will also stand ready to provide fuel to fuel-cell and hybrid fuel-cell/gas turbine systems, particularly in developing countries or rural areas that do not have access to cheap fossil fuels or that have an undependable transmission infrastructure. The first generation of biomass GCC systems would realize efficiencies nearly double those of the existing industry. In a cogeneration application, efficiencies could exceed 80 percent. This technology is very near to commercial availability, with one mid-size plant operating in Finland. Costs of a first-of-a-kind biomass GCC plant are estimated to be in the range of $1,800 to $2,000 per kW, with the cost dropping rapidly to about $1,400 per kW for a mature plant in the 2010 time frame.

A significant number of the world's 2 billion people who lack access to electricity have available substantial quantities of biomass resources but lack the means to convert these resources into electricity in a clean, reliable, and efficient manner.

Direct-fired combustion technologies are another option, especially with retrofits of existing facilities to improve process efficiency. Direct combustion involves the oxidation of biomass with excess air, resulting in hot flue gases that produce steam in the heat exchange sections of boilers. The steam is used to produce electricity in a Rankine cycle. In an electricity-only process, all of the steam is condensed in the turbine cycle, and in CHP operation, a portion of the steam is extracted to provide process heat. Today's biomass-fired steam-cycle plants typically use single-pass steam turbines. However, in the past decade, efficiency and design features, found previously in large-scale steam turbine generators, have been transferred to smaller capacity units. These designs include multi-pressure, reheat, and regenerative steam turbine cycles, as well as supercritical steam turbines. The two common boiler designs used for steam generation with biomass are stationary-grate and traveling-grate combustors (stokers) and atmospheric fluid-bed combustors. The addition of dryers and incorporation of more-rigorous steam cycles is expected to raise the efficiency of direct combustion systems by about 10 percent over today's efficiency, and to lower the capital investment from the present $2,000/kW to about $1,275/kW.

A significant number of the world's 2 billion people who lack access to electricity have available substantial quantities of biomass resources but lack the means to convert these resources into electricity in a clean, reliable, and efficient manner. In addition, in the developed world, distributed generation is receiving increased attention as a way of increasing energy reliability as well as the efficiency of the transmission and distribution system. To be economically competitive and environmentally acceptable, a new generation of small biopower systems is being developed. These will couple biomass conversion devices (combustors and gasifiers) with conventional and advanced electricity generators such as microturbines, Stirling engines, and eventually fuel cells. These systems must overcome a number of technical issues, including reliable operation of an automated feed system, reliable small-scale combustor and gasifier system development, small-scale gas cleaning systems, and emission reduction methodologies. As an example, research at the National Renewable Energy Laboratory has shown that CO and NO_x emissions from a gasifier/internal combustion engine system (a very common system in the developing world) can be substantially reduced below equivalent emissions with natural gas by carefully tuning engine operation parameters and by using a medium heat content gas.

DOE is supporting four small modular development projects, which are described in the following paragraphs.

Community Power Corporation (CPC), Littleton, Colorado, is developing a system that involves a fixed-bed downdraft gasifier that feeds producer gas to a spark ignition engine coupled to a generator (Fig. 5). With this design, no liquid effluent is produced from the system. The gasifier design also incorporates features that promise to produce a low tar and ash gas stream that will be filtered. Field surveys in the Philippines, conducted by CPC, have identified capacity requirements for these types for systems in the range of 12 kW to 25 kW. The first unit was shipped to the Philippines in February 2001. A second unit was installed at the Hoopa Indian Reservation in California in the summer of 2001. Shell International Renewables, the California Energy Commission, and the Hoopa Indian Tribe are strategic and funding partners.

External Power, LLC, Indianapolis, Indiana, is developing a system that employs a Stirling engine as the prime mover. Heat to drive the Stirling engine is extracted from the combustion gases of a modified pellet stove. This design also recovers significant amounts of heat from the exhaust gases from the Stirling engine and transfers it to the incoming combustion gases to improve the overall combustion efficiencies. Development of very clean biomass burners is another part of this effort. This system is being designed to produce 3 kW to 18 kW, and is targeted at residential and small industrial markets. External Power is focusing on markets in the northern United States and the Scandinavian countries for initial entry of their system. Wood Mizer is the strategic funding partner.

Flex Energies, Inc., Mission Viejo, California, has designed and fabricated a proof of concept (POC) 30-kW Flex-Microturbine™ unit for evaluation purposes. The unit incorporates a unique design that permits the use of very low heating value gases (3.7 MJ/Nm^3) with very low emissions levels, especially NO_x. Following successful completion of the POC test program, the design will be modified and three prototype units will be constructed. Prototypes will be tested using landfill gas, anaerobic digester gas, and gasification producer gas. Capstone Turbine Corporation; the California Energy Commission; University of California, Davis; and Cal Poly Obispo are partners in the project.

Figure 5. – Community Power Corporation's 15-kW system is operating at the Hoopa Indian Reservation in California.

Carbona Corporation, Orinda, California, will design, fabricate, and operate a prototype CHP system using a fluid bed gasifier fueling internal combustion engines. The system will be located in Lemvig, Jutland, Denmark. The capacity of the prototype plant will be 5 MW electric and 9 MJ/s hot water for residential heating and will be fueled primarily by wood chips. Strategic and funding partners are FLS miljø, the Danish Energy Agency, and the European Commission.

Research, Development, and Demonstration Needs

The key technologies operating today are based on the Rankine cycle with stand-alone and CHP installations with grate-fired, circulating-fluid-bed, or bubbling-fluidized-bed combustors. A combination of scale increase and incremental improvements could improve the efficiency of power generation by over 50 percent in the near term. A demonstrated option is cofiring in existing large-scale coal-fired power stations where a modest level of coal substitution would provide similar scale to the stand-alone biopower stations at efficiencies of 33 to 35 percent. This option is not yet commercial, partly due to the challenges of developing local biomass supply options, as well as the need for full performance guarantees and warranties. To date, installations have used custom designs, yet the pulverized coal boiler fleet consists of only three basic models for which standardized packages could be developed. The potential growth in cofiring is very large, in excess of 12 GW. Although it would not increase power availability, biomass cofiring would economically offset sulfur, nitrogen, and greenhouse-gas emissions while enabling the rational management of biomass residues from forests, agriculture, processing plants, and urban areas.

New biomass resources are becoming available as a result of 1) restrictions on using animal wastes from confined animal feeding operations as fertilizer; and 2) forest fire management that includes the removal of understory from forests in the western United States. Use of these resources is potentially very beneficial because they represent materials that have a negative impact on the environment and on quality of life if not managed correctly.

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The Environmental Protection Agency has estimated that animal waste production is more than 13 times human sanitary wastes and is in excess of 112 million tons of dry matter per year (EPA 1998). The waste from a 200-cow dairy herd produces as much nitrogen, and the litter from a 22,000 chicken broiler house contains as much phosphorus, as the sanitary wastes from a community of 5,000 to 10,000 people. Animal feeding operations are estimated to impact about 170,000 miles of rivers, 3 million acres of lakes, and 3,000 estuary square miles in the United States. Much of this waste is used as fertilizer in agricultural fields, but such use has the potential for environmental pollution through runoff. Biopower represents an alternate use that is environmentally advantageous.

Uncontrolled burning (wildfires) represents a major source of global emissions (about 40% of gross carbon dioxide and tropospheric ozone, 30% of carbon monoxide, 25% of non-methane hydrocarbons, 20% of nitric oxides, 10% of methane, 90% of elemental carbon, 7% of total particulate matter, and 40% of particulate organic carbon [Huggett 1995]). Fires annually burn up to 500 million hectares of tropical and subtropical savannas, 20 to 40 million hectares of tropical forest, and 10 to 15 million hectares of temperate and boreal forest (Levine et al. 1999). Forest fire levels in the United States range from 1 to 4 million hectares annually. Uncontrolled burning of temperate forests gives higher levels of incomplete combustion products such carbon monoxide (15%), methane and non-methane hydrocarbons (1.5%), and nitrogen oxides, (0.2%) (Granier et al. 1996). An order of magnitude estimate of the green house warming potential of this mix is about 180 percent of the level of controlled combustion. This does not take into account additional emissions of NO_x and methane from soil biogenic processes resulting from fires, or credit for maintenance of existing sequestered carbon inventory in living biomass. Use of the forest understory as biomass resources would encourage removal of this material and help reduce the risk of wildfires.

Development and demonstration of technologies to help mitigate the impact of animal feeding operations, and that are a suitable-scale for hazardous forest fuel burden removal, are needed. An example of one such technology is the use of portable manufacturing facilities that can be used in the forest to make wood pellets. The pellets are then easier to handle and transport than the original raw material. The creation of biomass fuel markets for these fuels is a high priority, as is the further development of energy crops that are needed in the longer term. Together these resources have the potential for over 10 GW to 20 GW of capacity.

The emerging biomass gasification technologies and their application in combined cycle is a high priority, especially in meeting the needs of the pulp and paper sector where there is an acute need for capital replacement of existing energy systems. Deployment of these technologies opens up worldwide markets in the sugarcane industries as well.

A high priority global issue is the deployment of rural energy systems to meet the needs of 2 billion people without electricity. The economies in these rural areas are based on forestry and agriculture. In conjunction with intermittent renewables such as wind and solar, biomass hybrids could offset fossil fuel use and generate local added value to agricultural residues that are often disposed of in environmentally damaging ways. As discussed previously, the small modular biopower program has highlighted a number of promising systems that would justify continued development and deployment. Domestically, such systems will fit into the distributed generation market.

Very high efficiency natural gas hybrid systems using traditional combined cycles integrated with small-scale fuel cells are already under development. Similar opportunities for biomass could follow, as could the incorporation of efficient biopower cycles into future bioplexes that would take biomass resources and produce bio-based materials, fuels, and chemicals as well as power.

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