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OPPORTUNITIES FOR SMALL BIOMASS POWER SYSTEMS

Final Technical Report

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OPPORTUNITIES FOR SMALL BIOMASS POWER SYSTEMS

EXECUTIVE SUMMARY

The purpose of this study was to provide information to key stakeholders and the general public about biomass resource potential for power generation. Ten types of biomass were identified and evaluated. The quantities available for power generation were estimated separately for five U.S. regions and Canada. A method entitled "competitive resource profile" was used to rank resources based on economics, utilization, and environmental impact. The results of the analysis may be used to set priorities for utilization of biomass in each U.S. region. A review of current biomass conversion technologies was accomplished, linking technologies to resources. An overview of results is as follows.

Animal manure offers the best overall potential for commercialization in the western region. The selection is in line with the general economic growth model being followed for the western region. However, two states, Arizona and California, stand out separately from the general conclusions derived for the region. Municipal solid waste (MSW), including urban, industrial, and construction and demolition (C&D) wood waste categories, provides the best promise for further development in Arizona and California. Anaerobic digestion is highly recommended for both animal manure and MSW. In spite of a disappointing track record for animal manure digestion, there does not seem to be any other commercially available alternative. Anaerobic digestion for MSW in California and Arizona can reduce the pressure on landfilling/thermal incineration and reduce resultant air/water pollution. It is hoped that the additional cost of separation (from organic to inorganic) in anaerobic digestion will be offset by the added economic/environmental benefits.

Mill waste (comprising the waste generated during the primary and secondary processing of forest products) is recommended for further commercialization in both the northwestern and southeastern regions. Fortunately, many mature technology options like direct combustion and cofiring are available for exploiting mill waste.

MSW (even after excluding urban, industrial, and C&D wood waste categories) offers a great potential for commercialization in the northeastern region. It should be noted that MSW being recommended for potential development does not include the quantities accounted for by recycling and composting. The exploitation of the MSW resource in the northeastern region presents several economic, environmental, and social benefits. A combination of anaerobic digestion and landfill gas technologies is recommended for exploiting the huge reserves of MSW in the densely populated northeastern region. The two technologies offer the advantages of reduced landfills, increased gas rates, and utilization of existing landfills.

Finally, crop residue is strongly recommended for the Great Lakes region with its vast agriculture-based economy, although the tool suggests MSW as the preferred option. The huge contribution of crop residue, i.e., around 50%, to the region's total biomass resource can offset some of the demerits like high transportation cost and combustion constraints. Until the technical

constraints are solved for burning difficult fuels (like straws), crop residues can be converted for power generation through direct firing and cofiring options. Also, the small, modular combustion turbine option can be chosen for select applications.

Because of the rapid urbanization of Canada, it appears that MSW is fast becoming the single largest biomass resource that can be exploited either through anaerobic digestion and/or thermal incineration.

OPPORTUNITIES FOR SMALL BIOMASS POWER SYSTEMS

1.0 INTRODUCTION

Biomass consists of renewable material such as trees, agricultural crops, and matter derived from living organisms such as animal manure, human sludge, and organic municipal solid waste (MSW). These products can be converted to liquid or gas or used to supply electricity, heat, and fuel for transportation.

The key drivers for using biomass include energy security, economic competitiveness, electricity restructuring, environmental quality, and climate change. Biomass provides for a more diverse U.S. energy mix, improving our national security relative to energy. Currently petroleum accounts for 39% of our energy mix, with 46% imported. Growing the biomass industry can create new markets and employment for farmers and foresters, many of whom face economic hardship. Energy crops provide new uses for agricultural land that may be currently out of production. Biomass can establish new processing, distribution, and service industries in rural communities. Using residues rather than disposing in landfills can also reduce a major land use problem. Current electric utility restructuring measures are providing incentives for using biomass for power. Creating electricity from biomass is done in conversion systems similar to those used for fossil fuels, but with three key differences: the resource is renewable; there is less than 0.1% sulfur, which causes acid rain; and when biomass is burned, the carbon (found in such gases as CO_2) is recycled back into the next generation of growing plants. This results in a zero net production of greenhouse gas, which is suspect in contributing to global climate change. Biomass can also improve the environmental performance of utility power stations when cofired with coal.

Biomass is the second most utilized renewable energy resource; however, it could contribute more to the U.S. energy mix. The Energy Information Administration cites the following statistics (1, 2): Total domestic energy consumption is 94.2 quadrillion Btu; renewable energy comprises a modest 8% of the total; and biomass is 38% of renewable energy consumption, which shows that biomass is already a competitive renewable resource. The consumption of biomass contributes very little to the overall electricity generation portfolio. Only 22% of domestic biomass consumption is used to generate electricity. Currently, it is more competitive to use biomass for heat. As shown in Figure 1, this is a contribution of only 2% of the total electrical generation in the United States. Another way to view the overall electrical generation picture is to look at fuel consumption. Again, biomass contributes only 2%, as shown in Figure 2. This report will demonstrate how biomass consumption for electrical generation could potentially be increased by a factor of 7. Figure 3 projects what the fuel consumption distribution would look like if biomass use was maximized and directly offset the consumption of coal. This independent study takes into consideration that not all of our biomass resources are collectible for power generation and are sometimes better suited for other uses. Also, biomass is better suited economically for small power systems rather than large central generating stations. The fact that 97% of current biomass electrical generation comes from cogenerators, independent power producers (IPP), and small power stations reinforces this notion.

Figure 1. Sources of energy for electrical generation in the United States (% of 1,154,862 million kWh, 1997).

Figure 2. Fuel consumption by source for electrical generation.

Figure 3. Potential fuel consumption contribution of biomass to the U.S. electrical production mix.

Biomass is a growing market with great potential. Consumption of biomass has been increasing 2% per year since 1990. Approximately 125 U.S. power plants fire biomass, which includes refuse-derived fuel (RDF), segregated MSW, wood, agricultural residues, tires, and landfill gas (LFG). Almost all of these power plants are under 50 MWe. In 1997, the total U.S. biomass consumption was 2.723 quadrillion Btu. This study estimates a total collectible quantity of 6.65 quadrillion Btu. If we subtract out quantities of biomass that already have significant dedicated use, it appears that biomass use could be doubled based on existing residues.

Some key features should be recognized when considering the biomass power generation market. First, biomass is a very distributed resource and often expensive to transport. Costs can range from \$30 to \$60/ton. Cost is dependent on transportation distance and energy density of the fuel. This economic factor drives the potential for small power systems in the 100-kW to 2-MWe range. Small power systems can utilize residues generated on-site or in close proximity, which can reduce fuel costs to under \$10/ton.

There are also numerous other challenges. First, there has been a lack of off-the-shelf commercial technologies that require minimal capital investment. Recent U.S. Department of Energy (DOE) initiatives are addressing this challenge. Second, biomass can have associated environmental impacts: animal manure left unused results in odor problems and potential leaching into groundwater; dead standing forests or forests catastrophically damaged by weather can become fire hazards; and MSW continues to offer waste disposal challenges, given limited landfill space and difficulties in permitting waste incinerators. Third, converting biomass creates

its own set of technical challenges. Projects have failed because of fuel-handling difficulties. Biomass can contain high levels of silica or potassium that can create fouling and slagging problems in combustion units. MSW or RDF may present operational difficulties because of the inconsistency in heating value. It is important to recognize these challenges and address the issues prior to proceeding with small power projects.

2.0 PROJECT OBJECTIVES AND STRUCTURE

The objectives of this project include:

- Identification of biomass resource potential for specific areas of the United States and Canada.
- Evaluation and selection of biomass resource for five regions of the United States and Canada.
- Assessment of biomass conversion technologies.
- Information dissemination to key stakeholders and the public.

The objectives are being achieved through several tasks. First, ten types of biomass resources were identified from the literature. The quantities of each are estimated separately for the five biomass regions designated by DOE, as shown in Figure 4. Second, these resources are compared and ranked based on various factors that affect economics, utilization, and environmental impact. The results of this analysis set priorities for resource utilization and development. Third, these resources are linked to potential cost-effective technologies. The results of this analysis are presented and published in the proceedings of the Bioenergy 2000 conference and also made available via the Web at www.undeerc.org, along with this report. This work was carried out as a \$50,000 grant over a 1-year time frame.

Figure 4. Regional biomass energy program areas.

3.0 BIOMASS RESOURCE CLASSIFICATION, ESTIMATION, AND QUANTIFICATION

3.1 Resource Categorization and Quantification

The biomass resources are categorized and selected based on adequate quantities for commercialization, reliability of supply, and availability in all regions. Considering the macro-level nature of the study as well as the above criteria, miscellaneous sources of biomass were excluded from study. The ten biomass resources selected for analysis are furnished below:

- 1) **Mill waste** is the waste generated in primary and secondary processing of forest round (wood) products. Mill waste (coarse and fine) typically consists of chips, trimmings, shavings, sawdust, bark chips, veneer chippings, cores, and pulp screenings. This definition includes mill residues recycled as byproducts as well as those left unutilized and disposed of as waste.
- 2) **Animal manure** is defined as the collectible dry manure from beef and dairy cattle, swine, sheep, and poultry.
- 3) **Crop residue** consists of collectible residues from fields after accounting for the quantities required for the prevention of soil erosion due to wind and water.
- 4) **Agricultural processing waste** comprises the waste generated during the processing of raw agricultural commodities. The data in this category are difficult to obtain. It is suggested that specific data collection might produce useful quantities for end users. However, the contribution of agricultural processing waste to the total is taken as around 1%–2% (3, 4). The individual regional contributions are calculated by assuming 8%–15% of crop residue totals.
- 5) **Forest waste** consists of logging residues and other removable material left after carrying out silviculture operations and site conversions. Logging residue comprises unused portions of trees cut or killed by logging and left in the woods. Other removable materials are the unutilized volume of trees cut or killed during logging operations.
- 6) **MSW without wood waste** consists of solid waste after recycling and composting.
- 7) **MSW wood** includes all types of wood commonly found in mixed residential, commercial, and institutional waste streams. This includes wood residues produced by households and commercial generators that are typically handled by haulers and disposal facilities.
- 8) **Municipal sludge** comprises **sewage sludge**.
- 9) **Industrial wood waste** is the waste wood from pallets and other sources.

- 10) **Urban construction and demolition (C&D) debris** is material generated specifically by major construction activity and land clearing.

In many cases, 100% of the resource cannot be collected for power generation. The collectible quantity is defined separately for each resource category and is described as follows.

Animal waste and crop residues are developed based on livestock population and crop production figures obtained from the National Agricultural Statistical Services (5). Collectible percentages are discussed in several publications (3, 4, 6, 7). Tables 1 and 2 list the crops that generate a significant amount of biomass. Note that crops such as cotton, which generate little residue during harvest, are not listed in Table 2. While cotton does generate residue when processed at a cotton gin, cotton gin trash is considered an agricultural processing waste and is not included in the crop residue figures.

TABLE 1

Collectible Quantities of Animal Manure			
Livestock	Tons Dry Manure/ Animal/Year	Percent Collectible	Tons Dry Manure/ Animal/Year
Cattle and Calves	0.73	100	0.73
Milk Cows/Dairy Cattle	2.13	80	1.7
Hogs and Pigs	0.27	100	0.27
Chickens	0.01644	100	0.01644
Sheep and Lambs	0.106	50	0.053

TABLE 2

Collectible Quantities of Crop Residues		
Crop	Residue Generation Factor	Residue Collection Factor
Corn Grain	1.0	0.55
Barley	1.5	0.55
Oats	1.4	0.5
Sorghum	0.9	0.5
Wheat	0.9	0.25
Peanuts	1.25	0.3

Mill and forest residue statistics are obtained from the timber product output database (8). Assumptions referenced by the U.S. Department of Agriculture (USDA) under the definitions of mill and forest residue define the collectible quantity. In this study, we use 100% of this value. Power producers willing to pay more for resources than the existing price could take advantage of the quantities reported. Definitions of mill residue according to the Timber Product output database are as follows. Fiber byproducts are used in the manufacture of pulp, paper, paperboard,

waferboard, etc. Fuel wood byproducts are used to generate energy for residential, industrial, and institutional uses. Miscellaneous byproducts are used for charcoal manufacture, bedding, mulch, etc. Material defined as not used is either landfilled or burned. The average percentage of by weight per category is as follows: Fiber byproducts 40.3%, fuel wood 43.7%, miscellaneous 13.9%, and unused 2.1%. It could be reasonable to assume that lower amounts of mill residues are actually available than reported based on the definitions provided; however, 100% of this resource is available on a competitive basis. The following volume conversion factor is used for computation:

$$1 \text{ mcf} = 0.0125 \text{ MDBT, where } 1 \text{ mcf} = 1000 \text{ ft}^3 \text{ and } 1 \text{ MDBT} = 1000 \text{ bone dry tons (BDT)}$$

MSW data were obtained from the U.S. Environmental Protection Agency (EPA) (9). Definitions are as follows:

• Per capita generation of MSW in 2000	4.42 lb/person/day
• Per capita generation of MSW wood waste	0.33 lb/person/day
• Per capita generation of MSW excluding wood waste	$4.42 - 0.33 =$ 4.09 lb/person/day
• Per capita recovery of MSW through recycling and composting	30%
• Per capita MSW generation after recovery	$4.09 \times 0.7 = 2.863$ lb/person/day

Sewage sludge figures were taken from a publication of the Southeastern Regional Biomass Energy Program (7). The per capita generation of municipal sewage sludge is 0.25 lb/person/day.

The various sources of urban wood waste, including MSW, industrial wood, and C&D debris, are obtained from the national averages reported by the National Renewable Energy Laboratory (10):

• Per capita generation of industrial wood waste, tons/year	$0.04 \times \text{Population}$
• Per capita generation of MSW urban wood	0.33 lb/day/person
• C&D debris, tons/year	$0.09 \times \text{Population}$

3.2 Biomass Quantity Analysis for the United States

The quantities of ten biomass categories for each state under five regions are listed in Appendix A. The tables also indicate the percentage contribution of each source to the regions' totals.

The summary of all five regions is furnished in the appendix as the biomass resource distribution for the United States. The resource distribution pie charts for type, energy content, and region are developed in Figures A-1-A-4, in the appendix. The salient points of the appendix are summarized below.

The major contributors to the total biomass mass stock in United States are crop residue (24%), MSW (21%), animal manure (18%), and mill waste (16%).

The agriculture-based biomass is the single largest resource (if animal manure, agricultural processing waste, and crop residues sources are combined) in the country, amounting to around 45%. Agriculture-based biomass resource is mostly distributed in rural areas.

The wood-based biomass is the second largest resource (if forest, mill, and urban wood resources are combined) in the country, amounting to around 34%. However, wood as biomass resource is widely dispersed and distributed. This is evident from the fact that the wood is dispersed from forest areas to industrial sites and finally to urban areas.

As for the regional distribution of biomass resources, the three regions, namely western, southeastern, and Great Lakes, contribute more or less equally to the U.S. total.

Western – 28%, Southeastern – 27.35%, and Great Lakes – 27% (Total – 82%)

Again, the remainder of the balance of biomass resource, i.e., $100\% - 82\% = 18\%$, is shared equally by two other regions.

Northwestern – 8% and Northeastern – 11%

The pattern clearly indicates that biomass as a resource in general is fairly well distributed across all the regions of the United States.

3.3 Biomass Estimation and Quantification for Canada

Canada was chosen as the foreign country for biomass quantification based on potential and data availability. Canada differs from the United States in cultivation methods, forest operations, climate, and demographic features. However, for the macro-level estimation of resources—more so at the national level—the norms used for the United States can be safely used. The population figures are taken from the CIA World Fact Book (11). The crop production, livestock numbers, and mill residues are taken from the United Nations Food and Agricultural Organization (FAO) databases (12). The summary of the results is furnished in the appendix.

Because of the existence of well-established pulp and paper as well as other ancillary industries in Canada, very little wood waste goes unused. Also, Canadian forestry operations are optimized to minimize logging residues. It appears that Canada has reached a plateau as far as the availability of mill waste/forest waste for power generation. The mill waste indicated in Table A-7 (in the appendix) does not include wood fuel produced and marketed separately.

MSW (excluding the wood waste) and urban wood waste will offer the potential for commercialization. This could be due to the emphasis placed by the government on economic development of cities and towns. The federal policy of encouraging habitation of empty lands and new tracts through immigration is continuously increasing MSW generation.

3.4 Miscellaneous Biomass Resources

As mentioned earlier, the biomass resources are classified based on the quantity available for commercialization. However, in addition to the ten categories identified, there exist many miscellaneous biomass resources that offer potential sources for power generation in niche and select applications. Some of them are listed below.

3.4.1 Forest Fires

Thousands of acres of forests spanning several states of the United States are burnt either because of prescribed/manmade fires or unexpected climatic conditions. According to the USDA forest service, the acreage burnt in the current fiscal year, around 6.5 million acres, is twice the 10-year average (13).

Although it is difficult to predict and avoid unexpected fires due to adverse climate, every effort should be made to minimize prescribed fires so that the corresponding woody biomass can be utilized for power generation. The 10-year average of prescribed fires is around 1 million acres (14). If a yield of 4 tons/acre of biomass is assumed, 1 million acres is equivalent to about 400 MW of power.

3.4.2 Open Burning of Agricultural Waste

Every year, thousands of tons of agricultural waste are burnt in open fields, thus causing air pollution. Some of the wastes being burnt that can be utilized for power generation are listed below:

- Food-processing residues such as pits, shells, and hulls
- Orchard and vineyard removals
- Orchard and vineyard pruning
- Field straws and stalks

It is estimated that every year, around 2.3 million BDT of the above categories of waste are burnt in open fields (15). This is equivalent to roughly 300 MW of power.

3.4.3 Dead and Infected Forest Biomass

Through an integrated forest management approach, the dead and damaged forest biomass can be salvaged and used exclusively for power generation. Spruce bark beetle infestations have caused significant depletion of trees in Alaska, and other areas in the United States have various problems with insects that can devalue timber stands.

3.4.4 Christmas Trees

Dedicated but temporary systems can be instituted for the collection Christmas trees. This category of biomass is reasonably uniform in energy content/moisture content and size that it can be utilized on a 100% basis for a few days, either in direct combustion or cofiring power plants.

For example, according to the Wyoming Biomass Inventory Report (16), approximately 62,000 Christmas trees were available during the year 1990 from all counties and municipalities whose populations exceed 5000. Considering an average tree weight of 20 pounds, the total woody biomass available for further processing (chips) and direct firing/cofiring will be around 0.5636 million tons per year. If we assume all 50 states have the same output as Wyoming, we could estimate that 25 million tons, or about 2500 MW of power, is available from Christmas trees.

4.0 EVALUATION AND SELECTION OF BIOMASS RESOURCES

The methodology considers the following three major criteria for the evaluation and selection of biomass resources:

- Economics
- Utilization
- Environmental impact

Each of the three major criterion can, in turn, have subvariables that affect the commercialization of an individual biomass resource. The subvariables can include quantity, cost/ton, air pollution, combustion constraints, etc. A quantitative tool, henceforth called "Competitive Resource Profile" (CRP), was developed by assigning weights and ratings to the subvariables. Specifically, a weight ranging from 0.0 (not important) to 0.3 (very important) is assigned to each subvariable. The weight indicates the relative importance of that subvariable in the successful commercialization of a particular biomass resource. The sum of all weights assigned to the subvariables must equal 1.0. The following are the subvariables and the justification for each weight used.

4.1 Quantity

The available quantity of a given resource plays a vital role in the initial feasibility as well as subsequent operation of a biomass power project. The main reasons for the failure of biomass power projects are usually interruption in fuel supply (assumed at the time of planning stage) and changes in fuel quality. Considering the criticality of this subvariable, we assign a weight of 0.3.

4.2 Cost/Ton Delivered

The second subvariable (under the major criterion of Economics) is the cost in U.S. dollars per ton of fuel delivered at the plant site. The cost per ton delivered can sometimes include the processing expenses in addition to transportation costs. The processing expenses can be a major contributing factor in the selection of urban wood waste/industrial wood waste/C&D wood waste where a high degree of manual labor is involved for segregation of wood waste. A weight of 0.25 is assigned to the cost/ton of biomass delivered at the plant site.

4.3 Government Support

Potential biomass power projects can now avail several tax credits and subsidized financing issued by federal and state governments. For example, the climate change technology initiative (CCTI) of the federal government now extends the production tax credit (PTC) for biomass for 5 years through June 30, 2004. However, the PTC cannot be applied to the generation of LFG using MSW. Because of the restrictions involved in obtaining such benefits, a weight of 0.1 is assigned.

4.4 Technical Feasibility

Although the technical feasibility of converting a biomass resource into useful heat and power is a critical subvariable, nearly all of the ten biomass resources considered in our study are technically feasible for further conversion. A weight of 0.05 is tentatively assigned for this subvariable. It is to be noted that technical feasibility is different from the suitability of a given technology for a given biomass resource.

4.5 Combustion Constraints

A few of the biomass resources like crop residue and agricultural process waste can pose difficulties during the combustion process. For example, the combustion of crop residues can result in alkali slagging (the buildup of a glasslike agglomerate on the boiler surfaces when inert alkalis fail to aggregate as particulates) (17). Such combustion constraints impose high operating and maintenance (O&M) expenditures, as the cleaning of heat-transfer surfaces becomes more frequent. On the other hand, the combustion of wood residues is a relatively well proven process with few constraints. The subvariable of combustion constraints is given a weight of 0.15.

4.6 Air Pollution

There are a number of areas in which biomass energy use provides significant environmental benefits. These include a significant reduction in greenhouse gas emissions relative to fossil fuels. Biomass emits less sulfur to the atmosphere when burned, and carbon dioxide can be recycled into the next generation of growing biomass. Also, by using biomass as fuel, open burning of agricultural and forest residues is prevented along with mitigation of forest fires. However, if adequate care is not taken in fuel conditioning and combustor designs, then the biomass power projects can be equally harmful in polluting the environment. For example, the nitrogen content of agricultural-based biomass is higher than that of wood wastes, thus requiring a more expensive NO_x abatement system. The CRP evaluation tool incorporates this variance by assigning a weight of 0.05 to air pollution.

4.7 Water Pollution

The issue of water pollution is not significant in either forest-based or some agricultural-based residues. But while animal manure is considered a biomass resource, the effects of groundwater and sewage pollution need to be considered. A weight of 0.05 is assigned to water pollution.

4.8 Ash Disposal

The combustion of certain biomass resources can result in the generation of ash, which is high in alkaline materials like potassium, sodium, calcium, and magnesium. The conventional method of ash disposal, like landfilling, can affect not only the land usage but also the

environment because of the corrosive nature of the ash constituents (18). The CRP tool accommodates for this impact by assigning a weight of 0.05 to the ash disposal subvariable.

Table 3 lists the major criteria, subvariables, and weights used in developing the CRP.

TABLE 3

Weighted Assignments			
Major Criterion	Subvariable	Weight	Remarks
Economics	Quantity	0.3	
	Cost/ton delivered	0.25	Considers the effect of the location
	Government support	0.1	
Conversion Technologies	Technical feasibility	0.05	
	Combustion constraints	0.15	Affects O&M
Environmental Impact	Air pollution	0.05	NO _x , SO _x , CO ₂
	Water pollution	0.05	Groundwater
	Ash disposal	0.05	Issues of land usage
Total:		1.0	

A 1–3 rating is assigned to each subvariable to indicate how it affects the commercialization of a given biomass resource. The ratings values are as follows: 1 = major weakness, 2 = neutral impact, 3 = major strength.

Each subvariable weight is multiplied by its rating to determine a weighted score. Weighted scores are summed for all subvariables to determine the total weighted score for each biomass source. Regardless of the number of subvariables included in the CRP tool, the highest possible total weighted score for a given biomass resource is 3.0, and the lowest possible total weighted score is 1.0. A total weighted score of 3.0 indicates that the particular biomass resource offers a maximum number of advantages and minimum number of demerits and, hence, is ideally suited for further commercialization. A total score of 1.0 indicates that the biomass suffers from many disadvantages. It is important to note here that a thorough understanding of subvariables being used in the CRP tool is more important than the actual weights and ratings assigned. Table 4 describes the justification used to quantify the ratings relative to all subvariables.

TABLE 4

Justification for Quantifying Ratings Relative to Subvariables

S. No.	Subvariable	Ratings	Quantifiable Scenario
1	Quantity	1	Available quantity less than 10% of region's total
		1.5	Available quantity >10% but less than 20% of region's total
		2	Available quantity >20% but less than 30% of region's total
		3	Available quantity >30% of region's total
2	Cost/ton delivered	0.5	45–55 \$/ton
		1	35–45 \$/ton
		1.5	30–35 \$/ton
		2	20–30 \$/ton
		3	Negligible cost and/or waste generators deliver material at plant site
3	Government support	1	Outside the purview of IRC 29 and CCTI
		2	Applicability of IRC 29 biomass gas credit or unconventional fuels credit
		3	Applicability of PTC under CCTI
4	Technical feasibility	1	Pilot-scale usage of biomass resource
		2	Demonstration stage for biomass resource
		3	Proven technical feasibility
5	Combustion constraints	1	High alkali, maximum deposition and slagging problems
		2	Moderate impact
		3	No deposition and slagging problems
6	Air pollution	1	High NO _x emissions requiring expensive pollution control equipment like ammonia injection, SCR, etc.
		2	Moderate impact
		3	No sulfur emissions, acceptable NO _x without special NO _x abatement equipments ESP or baghouse acceptable
7	Water pollution	1	Maximum pollution to groundwater/surface water/sewage, difficult to achieve zero discharge, expensive effluent water treatment
		2	Moderate impact
		3	Minimum pollution to groundwater and sewage, possible zero discharge, no special effluent treatment plant required
8	Ash disposal	1	Highly alkaline and corrosive in nature
		2	Moderate impact
		3	Suitable for landfilling or for production of byproducts

Note: The tipping fee in the case of MSW and agricultural process waste is considered to take care of O&M expenses of fuel conditioning/processing expenses at the plant site. Hence, the cost for the fuel is considered negligible.

The method for using the CRP tool can be summarized in the following steps:

1. Assign weights to subvariables as shown in Table 3.

2. Assign a 1–3 rating to each subvariable to indicate how it affects the commercialization of a given biomass resource: 1 = major weakness, 2 = neutral impact, 3 = major strength.
3. Multiply each subvariable weight by its rating to determine weighted score.
4. Sum weighted scores for all subvariables to determine the total weighted score for each biomass source.

The above procedure is to be repeated for all five U.S. geographical regions to arrive at the recommended biomass resources. The appendix gives tables representing the CRP for the western, northeastern, southeastern, notheastern, and Great Lakes regions.

4.9 Results

Animal manure offers the best overall potential for commercialization in the western region. The selection is in line with the general economic growth model being followed for the western region. However, the two states, Arizona and California, stand apart from the general conclusions derived for the region. MSW, including urban, industrial, and C&D wood waste categories, provides the best promise for further development in Arizona and California.

Mill waste (comprising the waste generated during primary and secondary processing of forest products) is recommended for further commercialization in both the northwestern and southeastern regions. MSW (even after excluding the urban, industrial, and C&D wood waste categories) offers a great potential for commercialization in the northeastern region. It should be noted that the MSW being recommended for potential development does not include the quantities accounted for in recycling and composting. The exploitation of the MSW resource in the northeastern region presents several economic, environmental, and social benefits. Finally, crop residue is strongly recommended for the Great Lakes region, with its vast agriculture-based economy, although the tool suggests MSW as the preferred option. The huge contribution of crop residue, i.e., around 50% to the region's total biomass resource, can offset some of the demerits like high transportation cost and combustion constraints.

5.0 EVALUATION AND SELECTION OF CONVERSION TECHNOLOGIES FOR POWER GENERATION AND/OR HEAT PRODUCTION

Sections 3.0 and 4.0 presented a detailed discussion of different types of biomass resources as well as selection criteria. The conversion technology occupies the second most important role—next only to the biomass source type (that includes quantity and cost/ton)—in the success of a biomass power project. In the following sections, it can be seen that the criteria for technology selection are interrelated to biomass resource type. This section will attempt to evaluate, select, and link the best technologies to the five biomass resources chosen for five U.S. geographical regions. The task of technology selection is broken down into the following sequence:

- 1) Factors affecting the selection of technology
- 2) Overview of proven and developmental technologies
- 3) Evaluation and linking of resources with technologies

5.1 Evaluation and Selection Criteria

The process of evaluation and selection of a conversion technology considers the following factors.

5.1.1 Fuel Flexibility

The critical driving factor for the commercialization of any technology is its ability to accept a variety of biomass fuels with varying degrees of moisture content and particle size. Many current technologies are either successful or tend only to be identified with one specific biomass resource. This greatly affects plant performance if the promise of assured fuel supply (of specific category) is not met in the future. Within a broad fuel subcategory, the technology selected should be able to accept a multitude of subfuels without adversely affecting conversion efficiency, O&M costs, emissions levels, and reliability. For example, bubbling and circulating fluidized-bed combustion have proven successful in direct firing of many agricultural, municipal, and forest-based biomass resources. Currently, the circulating fluidized-bed combustion (CFBC) technology can burn biomass resources like orchard pruning, pomace, shells, stalks, pits, straws (all agricultural waste), wood waste, bark (all forest-based waste), RDF, and sludge (municipal waste). CFBC can handle fuels with moisture content varying from 15% to 60% (19).

5.1.2 Economics

The economics of selecting a technology, usually expressed in cost/installed kilowatt, can encompass several aspects of process scheme in addition to the core cost of conversion equipment like either boiler/furnace/reactor/gasifier/digester (chemical energy to heat energy) or diesel engines/steam turbines/gas turbines/Stirling engines (heat energy to electrical energy). This can include the costs of fuel receipt, fuel blending and preparation, fuel storage handling, pollution control equipment, waste disposal, civil, structural, electrical, and piping. Depending on the nature and degree of maturity of the technology being selected, the installed cost can vary

anywhere between \$1500/kW to \$2500/kW. The other economic parameter, which affects the profitability of the plant, is the generation cost, usually expressed in cents/kWh. The generation cost plays a very important role if the biomass power generation is conceived as IPP. The generation cost is a good measure of conversion efficiency, capacity utilization, O&M costs, and cost of finance. Again, the generation cost can range from 4¢/kWh to 7¢/kWh, depending on the technology being selected. A word of caution about the economics. The cost/kWh generated generally includes the tax credits and/or federal subsidy. Unlike the conventional fossil fuel power plants (like distributed generation [DG] plants, utility plants, combined cycle power plants), the biomass power plants are less standardized with respect to power cycle design, plant configuration, component design, and plant layouts. Except for select biomass power projects like wood-fired power plants, most of the current technologies/plant configurations/process schemes are site- and/or fuel-specific. Hence, the economic parameters like cost/kW installed or cost/kWh generated should be viewed as plant-specific, rather than the industry norm. Finally, the discussion regarding the economics of biomass power generation would not be complete without considering the environmental benefits. However, there are no universally accepted CO₂ credit norms factored into biomass power cost.

5.1.3 Maturity of Technology

The maturity of the technology indicates the limitations/constraints currently experienced by the technology while evolving toward full commercialization. The constraints can be either technical or economic in nature. Some of the technical barriers would be low conversion efficiency, inability to fire more difficult or alternate fuels, corrosion/deposition of heat-transfer surfaces due to high alkali/chlorine content or higher degree of maintenance in downstream reciprocating/rotating equipment because of impure gases, etc. The economic parameters—direct fallout of technical barriers—can range from high initial plant cost to high O&M cost, and, finally resulting in high generation cost. The proven or fully commercialized technologies are ranked toward the top end of the maturity scale, with few or no barriers. For example, Rankine cycle-based conversion options like cofiring and/or direct combustion are considered as off-the-shelf technologies. On the other hand, some Brayton cycle-based biomass conversion options utilizing combustion turbines are still in the R&D phase.

5.2 Overview of Proven and Developmental Technologies

The technologies to be reviewed can be broadly categorized into proven and developmental based mainly on the degree of maturity as outlined above. The overview would concentrate more on proven technologies so that the information can be readily used by potential investors—in the near to medium term—in linking with resources. The inventory also highlights a few technologies that are in R&D phase but hold promise for potential commercialization. This agrees well with the proposed federal government strategy to enhance biomass power generation in the near future with the help of both proven and new technologies.

5.2.1 Proven Technologies

The technologies that are currently proven and fully commercial are schematically represented in Figure 5.

5.2.1.1 Stoker Firing

Combustion-based conversion technologies are probably the best-known options for simultaneous power generation and heat production. Direct-firing technologies refer to the

Figure 5. Proven commercial technologies.

combustion of 100% biomass in furnaces/reactors/boilers for heat and/or power production. Rankine steam cycle captive power plants/cogeneration plants burning a variety of biomass fuels had been in operation in sugar, pulp and paper, lumber, and many agricultural-based industries. Traditionally, stoker firing had been the preferred option for mill waste, forest waste, and some agricultural wastes. The combustion efficiency of stoker-fired units ranges from 68% to 80%, with fixed/dump grate occupying the lower end of the scale. The current designs for stokers incorporate spreader travelling grates with suspension firing features. This design allows for variations in moisture content and fuel size. The design of fuel preparation/handling/storage as well as pollution control components has reached the maturity stage and is generally reliable with proper O&M procedures. Unlike fossil fuels, biomass fuels are generally low in sulfur. Hence, SO_x abatement is not an issue in biomass power projects. However, if urban wood waste (comprising C&D waste) and/or urban tires are part of the fuel mix, then sulfur can be an issue. In those cases, travelling-grate stoker-fired boilers are usually equipped with a flue gas scrubber system followed by fabric baghouse filters. Many stoker-fired biomass power plants are equipped with cyclone dust collectors followed by electrostatic precipitators, resulting in a particulate collection efficiency of 99%. Depending on the fuel mix being fired, the bottom ash can vary anywhere between 10% to 12% of the total ash generated. Many combustion-based biomass power plants are designed with multifuel capability. This feature ensures combustion efficiency despite the variations in heating value, moisture, and particle size. The stoker-fired combustion systems are not suitable for burning MSW, sewage sludge, industrial process waste, and more difficult forms of agricultural waste like rice/wheat straw.

5.2.1.2 Fluidized-Bed Combustion

The introduction of the fluidized-bed combustion (FBC) concept in the 1980s broadened the fuel choice in biomass power projects. Both bubbling and circulating fluidized-bed boilers now have the capability to burn a variety of forest, agricultural, municipal sewage and solid waste sources. FBC boilers can accept moisture content ranging from 15% to 65%. However, FBC boiler-based power projects can be more expensive in terms of \$/kW installed compared to stoker-fired options. This is due to more sophisticated fuel preparation/conditioning facilities as well as stringent pollution regulation. The same logic is applicable to \$/kWh generated, mainly due to high O&M costs.

Because of the emphasis on NO_x reduction, many FBC boilers are equipped with a NO_x abatement system, either in the form of ammonia injection or selective catalytic reduction systems. This is in addition to particulate collection systems. However, unlike stoker-fired boilers, the operating temperatures of FBC boilers are lower (a critical factor governing NO_x formation), and hence, the system is less prone to NO_x formation.

Despite its well-known multifuel capability, the FBC can pose serious maintenance problems if certain fuel constituents are not controlled before firing. Fuel constituents like K, Cl, Si, and S (relevant for agricultural residues); Ca and Mg (relevant for wood wastes); and P (relevant for animal manure) can react with sand used in FBC boilers (20). This reaction occurs at the boiler operating temperatures of 800°–900°C and will result in hard deposits on heat-

transfer surfaces. The problems of agglomeration and hard deposits can be minimized by improvements in the following areas:

- Proper design of heat-transfer surfaces including lowering of velocities.
- Controlling fuel constituents. One way to achieve this is to ensure that the fuel mix is made of 50% primary fuels (like wood waste), 20%–50% secondary fuels (like pits, shells, stalks, etc.) and 20% tertiary fuels (more difficult fuels like rice/wheat straw) (21).
- Regular O&M procedures.
- Controlling furnace exit gas temperature (22).

Recently, many pilot-scale and demonstration experiments have been carried out to understand the phenomenon of hard deposits, especially while firing agricultural straws. One of the recommended ways to minimize the presence of alkalis is to leach the straws with water. The leaching is very promising in removing alkalis and increasing ash fusion temperature to 1600°C (20). However, the full implications of leaching on combustion efficiency are yet to be determined as leaching increases the moisture content and, hence, requires preheating/drying before firing in the furnace.

5.2.1.3 *Cofiring*

If a promising biomass power project runs into the difficulties of inadequate/unreliable fuel supplies and unattractive power sale cost, then the quickest way to utilize the available resources is through cofiring. Cofiring is the least risky path recommended for utilizing available resources. Community concerns about greenhouse emissions and funding support from DOE have led many utility companies to investigate the possibility of cofiring. Cofiring is the simultaneous combustion of fossil fuels (like coal, petroleum coke, and natural gas) along with biofuels (like wood waste, whole tree chips, agricultural wastes, etc.). Cofiring with wood can bring down NO_x emissions by 13% to 15%. Low fuel-bound nitrogen (<0.2%), lower ignition temperature, and higher volatility of biomass fuels promote staged combustion, resulting in low NO_x production. Biomass with less than 0.03% sulfur can offset the SO_x emissions generated from coal burning (23). In cofiring, the biomass fuels are usually limited to 15%–20% (weight basis)/10% (heat value basis) of total fuel input. Cofiring reduces combustion efficiency by 1.5%–2% (24). The capital investment for cofiring is only 300–500 \$/kW installed, especially for pulverized coal (pc)-fired boilers (25). Cofiring is particularly interesting to utilities as it can offer the following financial incentives:

- Reduced of NO_x, SO_x, and CO₂ emissions at a low price compared to conventional pollution control equipment
- Reduced in fuel prices

- Reduced waste disposal

More and more utilities are viewing cofiring as a viable/economical option to reduce costs rather than an environmental obligation imposed by community and government. Cofiring has been proven successful in different combustion technologies like stoker firing, FBC, and pc firing. If cofiring were to be economically successful without damage to boilers, then attention should be paid to the following areas:

- Fuel characteristics. Low-ash, low-chlorine, low-alkali fuels like wood waste are recommended to minimize ash deposition rates compared to high-alkali, high-ash, and high-chlorine fuels like straws.
- Particle size (preferably less than 1/8 inch) to minimize carbon carryover in fly ash.
- Boiler design. Low surface tube temperatures to minimize corrosion rates due to chlorine.

5.2.1.4 *Thermal Gasification*

The conversion technologies based on combustion (despite their reliability and maturity) suffer from one major disadvantage, low overall efficiencies of 20%–22%. The low efficiencies are due to the adoption of the Rankine cycle, resulting in dumping of two-thirds of the available heat to the stack and condenser cooling water. The high efficiencies achieved in combined-cycle power plants (with fossil fuels) during the 1990s stimulated interest in fuel gasification. The option of using the fuel gas derived from biomass fuels like wood waste/agricultural residues in internal combustion (IC) engines/gas turbines can eliminate many auxiliary systems as well as boost overall conversion efficiency levels to 35%. Unfortunately, many medium to large power projects (500 to 10,000 kW) based on gasification of biomass fuels are still in the R&D and/or demonstration stage. The discussion in the following sections deals with some of the basic types of gasifiers as well as small-size units that have reached the commercial stage.

Gasifiers can be classified in several ways, but the most common classification is based on the method in which air and fuel are supported/delivered to the gasifier. Based on this classification, the gasifiers are of the following varieties.

5.2.1.4.1 Fixed-Bed–Updraft (counterflow) and Downdraft (coflow) Gasifiers (26)

In updraft gasifiers, fuel is introduced from the top, whereas the air/O₂ is introduced from the bottom. Counterflow gasifiers are known for high grate temperatures (due to pyrolysis), and hence, air/O₂ needs to be cooled to prevent grate damage. The fuel gas from updraft gasifiers contains around 20% tar and, therefore, is not suitable for combustion in IC engines and gas turbines. However, the updraft gasifiers are suitable for fuels with high water and inorganic content (MSW). The fuel gas from MSW can be combusted directly without the tar removal process.

In downdraft or coflow gasifiers, both biomass and air/O₂ are introduced from the top. These gasifiers are best suited for biomass fuels with high volatile content. Tar removal is far better (nearly 99%) in downdraft gasifiers; hence, the gas is clean. The fuel gas from downdraft gasifiers can be burnt in IC engines or used for process heat. However, the fuel before feeding must be dried to reduce the moisture level to 20%. This can be done by utilizing some of the waste heat.

5.2.1.4.2 Fluid-Bed–Bubbling Fluidized-Bed Gasifier and Circulating Fluidized-Bed Gasifier (26)

Fluidized-bed gasifiers (FBGs) have the highest outputs compared to fixed beds. Fuel is fed at an angle to the reactor, and air/O₂ is introduced through the bottom of the bed as in FBC boilers. FBGs typically accept fuels with a moisture content up to 55%. Many FBGs operate at atmospheric pressure for the purpose of simplicity, although increased pressure enhances the output.

To date, only small-scale (biomass-based) gasifiers have been commercialized in the range of 40 to 500 kW. Ankur Scientific Technologies, India, has successfully designed, commercialized, and supplied hundreds of small gasifiers for irrigation pumping, power generation, and CO₂ manufacturing. Ankur gasifiers are marketed outside India by BG Technologies, USA (27). BG Technologies basically employs fixed-bed, downdraft gasifiers using biomass waste such as sawdust, wood chips, nutshells, and plant stalks. BG Technologies/Ankur gasifiers produce literally tar-free fuel gas (less than 5 mg/nm³) that can be used reliably either in diesel engines or thermal combustors. The plant configuration consists of a downdraft gasifier followed by a gas-cooling/filtering system consisting of a scrubber and fine filter. These gasifiers are ideal for agricultural processing industries or for remote rural sites where utility networks are nonexistent or where diesel is used for power or heat applications. The installed cost in \$/kW for power generation applications is around 1000–1200. The cost of power generation is around 7¢–8¢/kWh, which is still uncompetitive compared to coal/NG power projects in the United States, but can be very attractive over DG power in many developing countries. BG Technologies gasifiers accept biomass sizes of 10 to 150 mm with a moisture content of 10%–15%. The thermal conversion efficiency is 70%–75% (28).

5.2.1.5 *Conventional Landfilling/Landfill Gas*

In the United States, MSW is either recycled/composted or disposed. The disposal of MSW (after recovery) can either take the route of thermal incineration or landfilling. The technologies employed for thermal incineration are dealt with under direct combustion/FBC. MSW that goes into landfilling gets composted over a period of several years and produces biogas, popularly known as LFG. LFG contains around 50% methane, a potential greenhouse gas like CO₂. Also, methane is more harmful to the environment than CO₂ in terms of ozone layer depletion and global temperature changes. Biogas-containing methane plus volatile organic compounds, if left uncontrolled, can also cause immediate area pollution like smog formation. In addition to LFG, the decomposing MSW produces a liquid by-product that leaches from the waste mass and

collects at the bottom. Leachate can be very toxic and flammable in many landfills. If larger quantities of leachate are collected at the bottom, then this liquid can pollute groundwater.

Fortunately, both LFG and leachate can become useful resources if they are collected and treated in a timely manner. Methane in the biogas can either be burnt in boilers/combustors/reactors for process heat/steam or can drive reciprocating engines like IC engines. As of June 1999, there were 270 LFG utilization and recovery projects operational in the United States. Additionally, EPA estimates that 500 other landfill sites present opportunities for potential commercialization (29). The majority of landfill gas-to-energy (LFGTE) projects burn LFG in IC engines for power generation. The power generated can be sold to utility networks or used to run auxiliary facilities at the landfill site. LFGTE projects for power generation can use IC engines, steam turbines, gas turbines, or combined-cycle plants. The projects using IC engines are generally below 3 MW. If the potential of generated landfill gas is more than 3 MW, then the configuration can include gas turbines (either simple cycle or combined cycle) or boilers/steam turbines. The LFG power generation facilities usually comprise a well collection system, condensate collection and treatment system, condensate recirculation system, gas pressure booster station, flare system, and energy recovery system. The gas treatment system for gas turbines/steam turbines tends to be more expensive, incorporating a series of filter components. However, the additional capital investment is compensated by the reduced O&M costs (1.3¢–1.6¢/kWh). On the other hand, LFG treatment for IC engines or for direct combustion is relatively simple and, hence, low capital cost, with knockout drums and traps for condensate collection. But the O&M costs for IC engines vary in the range of 1.8¢–1.9¢/kWh. The IC engine option, despite the advantages of low capital cost, simplicity, and maturity, results in high NO_x emissions and, hence, might not be suitable for all locations (30).

LFGTE facilities for power generation are eligible for two federal assistance programs: 1) IRS Section 29 tax credit and 2) the renewable energy production incentive (RBEI). The Section 29 tax credit comes to around 0.9¢–1.6¢/kWh for a typical landfill electricity project, depending on the efficiency of the generating equipment used. The Section 29 credit applies only to LFG that is produced by one company and sold to an unrelated third party. Hence, many times, the project developers create a different company for power generation for taking advantage of tax credits (30).

RBEI offers a cash subsidy of 1.5¢/kWh to renewable energy projects (solar, wind, biomass including LFG) owned by state, local government, or nonprofit electric cooperatives. Hence, the project finance structure should be funded by municipal bonds to take advantage of the RBEI program.

The second option for LFG is direct combustion, which is relatively simple and does not require a sophisticated treatment system. However, the host facility must be located within the vicinity of the landfill site.

The third use for LFG is as a medium-Btu gas like LFG to liquefied natural gas or compressed natural gas. If the LFG were to be upgraded to a pipeline-quality gas, then more

expensive and complex treatment systems for removing CO₂, particulate, and other impurities must be installed.

The industry rule of thumb for the economic viability of a LFGTE facility is that the gas produced must be 1 million cubic feet/day, which is equivalent to nearly 2 million tons of waste in place (30). However, there are smaller-sized LFG facilities (20,000 cf/day and 40-ft depth) that are operating successfully (30). Hence, it is clear that selection of the LFG option for utilizing biomass depends on several site-specific characteristics like climate (i.e., moisture content), waste type (preferably organic waste like paper/food rather than plastic/construction/demolition waste), host facility location, power sale/buyback cost, and federal incentives in addition to tons of waste in place.

The slow rate of LFG generation (usually 25–30 years), high O&M costs, fugitive methane emissions, low power buyback rates by utilities, and leachate seepage are some of the issues that need to be addressed in depth to popularize LFG power generation.

5.2.1.6 Biological Gasification

It was mentioned in Section 3.0 that animal manure comprises around 18% of the total available biomass in the United States. This huge biomass quantity if uncontrolled can cause air and groundwater pollution on the same lines as LFG. Traditionally, animal manure was disposed of by spreading it on farmlands, and allowing it to dry, where, ultimately, it was converted to a soil-conditioning material. This approach—besides requiring vast tracts of landfill space and high transportation costs—results in polluting the air through odor and released pathogens, volatile organic compounds, and methane from decomposition. Biological gasification refers to the process of decomposing the organic waste—animal, human, agricultural, municipal, and industrial—under aerobic or anaerobic conditions to emit biogas. The biogas generated comprises 55%–75% of methane, with the balance CO₂ and hydrogen sulfide. Anaerobic fermentation or anaerobic digestion is more popular than aerobic digestion because of the advantages of minimal space and low energy requirements. If we look at anaerobic digestion as a mere waste disposal option, then anaerobic digestion converts only 4% of the waste to new biomass solids compared to 40% in aerobic digestion (31). In other words, aerobic digestion—if applied for animal manure—will result in vast quantities of new biomass solids, further complicating waste disposal. However, anaerobic digestion has the limitations of slow rate of decomposition and incomplete digestion of organic waste compared to aerobic digestion. In the case of treatment of industrial water, aerobic digestion is preferable because of the advantages. Anaerobic digestion can be successfully applied to several wastes like animal manure and municipal and industrial waste, including slurries and sludge. Anaerobic digestion for agricultural wastes such as rice/wheat straw is still in the R&D phase. The following sections will discuss anaerobic digestion as it applies to specific types of waste.

5.2.1.7 Livestock

Anaerobic digestion of animal manure is more popular in developing countries based on agricultural economy. In the United States, anaerobic digestion as a technology to capture

methane from biogas for power/heat production has always undergone ups and downs, mainly because of the dynamics of driving forces. As the energy crisis tapered off during the early 1980s, the emphasis on renewable energy sources in general and biogas in particular waned. However, the concern for environmental pollution in the 1990s raised the interest again in anaerobic digestion of livestock manure. An anaerobic digester is a closed vessel designed to retain decomposing manure for a sufficient time at a designed operating temperature to allow the growth of bacteria in a steady-state condition. The biogas generated from digesters can be used for power generation or heat production. Both power and heat can be used on-site, resulting in savings due to reduced waste disposal costs and displaced fuel costs. The liquid waste/effluent from digester operations can be used for growing algae and other aquatic plants that can be used as animal feed and/or soil conditioner.

Anaerobic digestion is ideal for manure from dairy and swine operations because of high liquid content, making the handling easier. On the other hand, the manure from poultry operations contains higher concentration of high solids and can quickly fall out if not continuously agitated. The accumulated solids can reduce effective reactor volume and potential biogas production. The anaerobic digestion system basically comprises four components:

- Manure collection
- Anaerobic digester
- Effluent storage
- Energy use

There are three types of digesters normally used in the United States.

Covered lagoons are used to treat and produce biogas from liquid manure with less than 3% solids. The technology is simple, less expensive, and ideal for operations employing hydraulic flushing to collect manure. Covered lagoon digesters require larger volumes because of high hydraulic retention time (HRT) of 40–60 days. The methane produced in an anaerobic lagoon is trapped by placing a floating cover over the lagoon. Covered lagoon digesters are not externally heated and hence the biogas production depends on the climatic changes. The variation in gas flow can create problems in optimum sizing and capacity utilization of energy recovery equipment. Hence, the covered lagoons are more suitable for warmer climates like the southeastern region. Another disadvantage with covered lagoons is the high possibility of groundwater contamination at sites with high water tables (32).

Complete mix digesters are engineered tanks made of steel or concrete and are suitable for animal manure containing 3%–10% moisture. Complete mix digesters are heated and suitable for all climates. Complete mix digesters require a low HRT of 15 days and, hence, occupy less space than lagoons. A fixed cover is placed over the complete mix digester to maintain the anaerobic conditions and to trap the methane produced. They are suitable for both scrapped and flushed manure. The manure is deliberately mixed in the digester reactor. Mixing and heating improve digester efficiency. The heat for digester heating is taken from engine exhaust. Although the complete digesters handle large volumes and operate at high efficiency, they suffer from the disadvantages of high cost and O&M problems. The majority of the problems are solids settling

scum formation and grit removal. Because of the high costs involved, the complete mix digesters are generally suitable for very large farms or centralized treatment facilities.

Plug flow digesters employ engineered tanks that are rectangular, in-ground tanks. Like mixed-flow digesters, the plug flow types are externally heated, operate at a low HRT of 15 days, and suitable for all climates. Plug flow digesters are basically an improved version of mixed-flow digesters, minimizing the problems of complexity and cost. Plug flow digesters are suitable for treating only dairy manure, not swine manure because of the absence of fiber. Plug flow digesters can become more viable if the by-products in addition to the energy can be sold (32).

The biogas from farm digesters is mainly used for power generation in IC engines or for direct combustion for the production of heat. To date, biogas is not commercialized for steam production/gas turbines/sterling engines/fuel cells, although all of them are in some form of R&D or demonstration phase. The most successful engines are industrial natural gas engines that can burn untreated biogas. Gas treatment is generally not necessary if proper O&M procedures are followed. A biogas-fueled reciprocating engine generator can convert biogas to electricity at an efficiency of 18%–25% subject to capacity utilization and basic engine design (33). A biogas transmission system usually provides for flare and condensate collection/drain components.

In spite of the huge potential for biogas from livestock, the number of commercial farm-based digesters in operation in the United States are few. According to DOE (34), only 25 commercial farm digesters are in operation. The reasons for failure include poor system design, noncompatibility of manure handling with digester type, poor operator training, high O&M costs, initial faulty designs for plug flow digesters, and poor financial returns.

5.2.1.8 *Anaerobic Digestion of Municipal and Industrial Wastes*

5.2.1.8.1 Municipal Waste

Anaerobic digestion for treating municipal slurries/sludge has been successful in many municipalities all over the United States. However, the anaerobic digestion of solid waste or MSW is a recent phenomenon. The anaerobic digestion of MSW has several advantages:

- Production of energy
- Lower land requirements compared to aerobic composting or landfilling
- Volume reduction of waste for subsequent disposal
- Production of solid and liquid by-products for sale

However, the anaerobic digestion of MSW—unlike landfilling—requires high capital cost and separation of organic from inorganic wastes. MSW, comprising inorganic wastes like urban wood and C&D waste, is difficult to digest. On the other hand, kitchen/food waste is difficult for aerobic composting, but excellent for anaerobic digestion. The separation of organic from inorganic waste requires additional expenditure unless it is segregated at the source. If we compare anaerobic digestion with landfilling, more biogas is produced for every ton of MSW. Typically, anaerobic digestion produces 1.6–3.2 ft³ of biogas per pound of organic MSW

digested, whereas LFG will be about 0.05–0.2 ft³ per pound of waste per year (30, 31, 35). However, in the case of anaerobic digestion, around 10%–40% of energy production is utilized for pre- and posttreatment of gas, including auxiliary consumption (31). Like LFG, the biogas from anaerobic digestion can be used for power generation in engine generators or for direct combustion.

The City of Los Angeles (36) demonstrated the most innovative and commercial application involving the anaerobic digestion of organic MSW. Its Hyperion treatment plant serves an area of 1500 km² and a population of 4 million. The plant receives the biosolids (collected and harvested by the sewage system) and produces biogas through anaerobic digestion. The biogas is scrubbed (to remove SO₂) and compressed before firing in a gas turbine generator (GTG). The exhaust gas from the GTG is utilized to produce steam in a heat recovery steam generator (HRSG) that drives a steam turbine generator (STG). The digested biosolids or digestate from the anaerobic digester are dewatered and dried before being gasified in a FBG. The fuel gas from the gasifier is passed through a separate HRSG to produce steam that runs the same STG as installed for the combined-cycle plant.

The gross electrical power generation from the Hyperion plant is 25 MW, out of which 15 MW is derived from biogas and 10 MW is derived from gasification of digestate.

5.2.1.8.2 Industrial Waste

Anaerobic digestion can be successfully employed to treat and produce energy from industrial waste if it has the same characteristics as the livestock manure. The anaerobic digestion offers several advantages such as waste reduction, reduced fuel cost (in terms of displaced on-site energy demand), and increased pretreatment capacity. Many industries deploy anaerobic digestion to pretreat the waste before discharging into centralized municipal treatment plants. The industries employing anaerobic digestion are generally bio-related. In other words, the industries utilizing the agricultural produce as their raw material (like starch, sugar processing, alcohol, vegetable, fruit, and yeast) or the industries producing organic products (bakery, candy, canneries, dairy, cheese, fruit juice, etc.) are the ideal candidates for anaerobic digestion (34). The other industry sectors utilizing anaerobic digestion are pulp and paper, chemicals, pharmaceuticals, and breweries.

Anaerobic digestion has produced many technology variations for processing industrial waste. Some of them are listed below (34).

- Uncovered unmixed lagoons
- Completely mixed, stirred tank reactor or continuously stirred tank reactor technology
- Anaerobic filter
- Upflow anaerobic sludge blanket (USAB) process
- Fluidized-bed anaerobic technology

The technology variations basically differ from each other in terms of loading rate, HRT, and digester efficiency. The majority of the systems employed in industries are of USAB type,

which combine the features of contact mixing, internal gas separation, and clarification. The latest technology (already commercialized) that is expected to occupy a greater proportion of industrial waste systems is the ultra-high-rate fluidized-bed reactor.

Table 5 summarizes the various features of proven technologies as discussed above.

5.2.2 Developmental Technologies

The technologies that hold promise for future commercialization are schematically represented in Figure 6.

The summary of various features for the emerging technologies is furnished in Table 6.

5.2.3 Evaluation and Linking of Resources with Technologies

The recommendations of Section 4.0 (regarding selection of biomass resources) for each of the five U.S. geographical regions (according to the guidelines of RBEP) are listed below:

- Western region – animal manure
- Northwestern and southeastern regions – mill waste
- Northeastern region – MSW
- Great Lakes – crop residue
- Canada – MSW

The following attempts to link the best available commercial technologies to the final regional resources listed above.

5.2.3.1 Western Region – Animal Manure

The best available commercial technology for exploiting the vast animal manure resource is anaerobic digestion. In spite of the disappointing track record of farm digesters, the only available technology to reduce environmental pollution and for displacing farm energy demand is anaerobic digestion. The following guidelines and recommendations will contribute to the success of anaerobic digestion of animal manure in western region:

- Covered lagoons must be encouraged, as they are least expensive and low in technology.
- Propagation of centralized farm digesters that allows for pooling of biomass resources as well as sharing of perceived risks.
- Farm management must adopt the idea that farm digesters are an integral part of their operations rather than an added feature.
- Digestion technology being selected must be compatible with manure collection method, site location, moisture content, and available local talent.

TABLE 5

Summary of Proven Technologies

S. No.	Technology Option	Fuels Used	Thermal Efficiency	Overall Conversion Efficiency	Installed Cost \$/KWh	Operating Cost C/KWh (Fuel + O&M)	Potential Benefits	Limitations	
								Technical	Economical
I	Combustion (direct firing)								
a	Grate firing	Forest waste, mill waste, bagasse, urban tires	68%–80%	23%–26%	2100–2400	4–6	Sustainable rural development, reduced GHG, onsite power and heat availability.	Emerging opportunity fuels can not be fired.	Variations in fuel cost can upset the profitability.
b	Fluidized-bed combustion	Forest waste/mill waste/pruning/shells/pits/stalks/straws	80%–90%	27%–28%	2700–3000	3–4.5	Sustainable rural development, reduced GHG, avoidance of farm fires, onsite power, and heat availability.	Alkalis and free chlorine in fuel. 100% of straws cannot be fired. High O&M costs.	High capital costs. Optimum plant size 50 MW.
II	Combustion (cofiring)								
a	Stoker	Coal + (bagasse, forest waste, mill waste + RDF)	66–78	22–24	200–300	NA	Reduced fuel costs and NO _x emissions.	Cofiring limited to coal + forest/mill waste only.	Benefits of cofiring dwindle at higher (>15%) percentages.
b	FBC	Coal + (agricultural/forest/mill waste)	78–88	25–27	300–450	NA	Reduced fuel costs and NO _x emissions.	Cofiring limited to coal + forest/mill waste only.	Benefits of cofiring dwindle at higher (>15%) percentages.
c	pc firing	Coal + mill waste	90–95	31–34	300–500	2.5–3.5	Reduced fuel costs and NO _x emissions.	Cofiring limited to coal + forest/waste mill only.	Benefits of cofiring dwindle at higher (>15%) percentages.
III	Gasification (thermal)								
a	Fixed bed, updraft	Wood chips, sawdust, nut shells, plant stalks	70–75		1000–1200	7–8	Distributed power option generation in developing.		Available for lower ranges only (<500KW). Competitive with DG power only.
IV	Gasification (landfill)	MSW		20–22		4–5	Avoidance of fire hazard, reduced GHG, useful byproducts, reduced air and water pollution, on site power and heat availability	Slow rates of biogas production, expensive gas treatment for GTG applications.	Viable only for sites of 1 Million tons waste in place. Some restrictions apply reg. IRS 29 tax credit.
V	Gasification (biological-anaerobic digestion)								
a	Animal manure	Animal manure		20–22		1–1.5	Reduced water, air pollution, avoidance of odor, onsite power and heat	High civil costs in some cases, variations in gas flow, slow rates of gas flow, expensive treatment for GTG.	Size limited to 2–3 MW, unwillingness of utilities to pay higher power costs.
b	Municipal	Organic MSW		NA		NA	Reduced water, air pollution, avoidance of odor, onsite power and heat.	Separation of organic and inorganic waste	Power generation is economically viable in select and niche applications only.
c	Industrial	Industrial process solid/liquid waste		NA		NA	Reduced treatment cost.	Normally designed in conjunction with aerobic polishing to meet overall pollution standards.

Figure 6. Possible technologies for commercialization.

TABLE 6

Summary of Developmental Technologies

S. No.	Technology Option	Fuels Used	Thermal Efficiency	Overall Conversion Efficiency (expected)	Installed Cost \$/KWh	Operating Cost \$/KWh	Potential Benefits	Limitations
I	Combustion							
a	Direct gas turbine	Wood chips, saw dust	NA	18	1800	Unknown	Modular, portable	Corrosion, erosion, deposition
b	Indirect gas turbine (heat exchange)	Wood chips, saw dust	NA	15	2000	Unknown	Modular, portable	High-temp. heat exchange
c	Boundary layer turbine			21	600	Unknown	Modular, portable	Turbine performance
II	Gasification							
a	Gas turbine	LCV fuel gas	NA	22	1800	Unknown	Higher efficiency	Gas conditioning, high-pressure system.
b	Microturbine	LCV fuel gas from animal manure, landfill, and wood waste	NA	15	1000	Unknown	Multifuel capability	Catalytic combustion, liquid condensate
c	Fuel Cell		NA	25	5000	Unknown	Portable, higher efficiency	High installed costs
d	LFG (advanced bioreactors)	Organic MSW	NA	NA	Unknown	Unknown	High rate of digestion, avoidance of dry toms	

- Sizing of energy equipment must consider the fluctuating production of biogas.
- Full advantage must be taken of IRS Section 29 tax credit and RBEI before finalizing the power buyback arrangement with utilities.

And finally, until more economical and niche technologies are developed, an institutional awareness must be advocated that encourages anaerobic digestion as an essential part of farm operations.

As discussed in Section 5.0, MSW occupies a prominent role in select states like California and Arizona because high population density. MSW abundantly available in these two states must be exploited for power generation through anaerobic digestion.

5.2.3.2 Northwestern/Southeastern Region – Mill Waste

The mill waste recommended for northwestern/southeastern regions could be commercially exploited for power generation through a variety of technology options. Conversion options like direct firing and cofiring are recommended for mill waste. The selection of direct firing or cofiring depends on the availability of adequate biomass resources (within 75–100 mile radius of the plant location) at a competitive price. Under direct firing, the high-efficiency and environmentally friendly circulating fluid-bed option is highly recommended. In cofiring, the contribution of mill waste must be established gradually without compromising O&M schedules and efficiency.

5.2.3.3 Northeastern Region – MSW

MSW is the abundant resource in the northeastern region with its many urban centers. A combination of anaerobic digestion and LFG routes is recommended for exploiting MSW for power generation. The LFG option is less expensive and can take care of the potential biogas emanating from existing landfills. The LFG option can be made more economically attractive by producing salable leachate products. On the other hand, anaerobic digestion helps to avoid future landfills. The additional cost of waste segregation (i.e., organic from inorganic waste) in the case of anaerobic digestion can be compensated for by larger centralized facilities. Innovative plant configurations utilizing biogas as well as digestate (like the city of Los Angeles Hyperion plant) must be explored while designing the plant. Thermal incineration using the CFBC technology can be considered as the last choice because of the high capital costs involved.

5.2.3.4 Great Lakes Region – Crop Residue

Crop residue in the Great Lakes region can be exploited through direct firing and cofiring options. In both options, care should be taken to ensure that an optimum combination of different fuels is selected. In direct firing, the recommended combination should be 50% primary fuels, 20%–50% secondary fuels, and 20% tertiary fuels. The travelling grate with suspension firing and CFBC options are strongly recommended for agricultural residues. If more difficult fuels like

straws are abundant at a specific site, then cofiring should be selected, as 100% straw firing is yet to be commercialized.

Thermal gasification (similar to BG Technologies/Ankur Technologies) is an ideal conversion option for small-scale farm operations.

5.2.3.5 Canada – MSW

The conversion options of anaerobic digestion and direct combustion/thermal incineration are recommended for MSW and RDF.

6.0 RESULTS

Animal manure offers the best overall potential for commercialization in the western region. The selection is in line with the general economic growth model being followed for the western region. However, two states, Arizona and California, stand out separately from the general conclusions derived for the region. MSW, including urban, industrial, and C&D wood waste categories, provides the best promise for further development in Arizona and California. Anaerobic digestion is highly recommended for both animal manure and MSW. In spite of a disappointing track record for animal manure digestion, there does not seem to be any other commercially available alternative. Anaerobic digestion for MSW in California and Arizona can reduce the pressure on landfilling/thermal incineration and reduce resultant air/water pollution. It is hoped that the additional cost of separation (from organic to inorganic) in anaerobic digestion will be offset by the added economic/environmental benefits.

Mill waste (comprising the waste generated during the primary and secondary processing of forest products) is recommended for further commercialization in both the northwestern and southeastern regions. Fortunately, many mature technology options like direct combustion and cofiring are available for exploiting mill waste.

MSW (even after excluding urban, industrial, and C&D wood waste categories) offers a great potential for commercialization in the northeastern region. It should be noted that MSW being recommended for potential development does not include the quantities accounted for by recycling and composting. The exploitation of the MSW resource in the northeastern region presents several economic, environmental, and social benefits. A combination of anaerobic digestion and LFG technologies is recommended for exploiting the huge reserves of MSW in the densely populated NE region. The two technologies offer the advantages of reduced landfills, increased gas rates, and utilization of existing landfills.

Finally, crop residue is strongly recommended for the Great Lakes region with its vast agriculture-based economy, although the tool suggests MSW as the preferred option. The huge contribution of crop residue, i.e., around 50%, to the region's total biomass resource can offset some of the demerits like high transportation cost and combustion constraints. Until the technical constraints are solved for burning difficult fuels (like straws), crop residues can be converted for power generation through direct firing and cofiring options. Also, the small, modular combustion turbine option can be chosen for select applications.

Because of the rapid urbanization of Canada, it appears that MSW is fast becoming the single largest biomass resource that can be exploited either through anaerobic digestion and/or thermal incineration.

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APPENDIX A

REGIONAL BIOMASS DATA

TABLE A-1

Biomass Resource Distribution for Western Region

S. No.	State	Population	Source 1	Source 2	Source 3	Source 4	Source 5	Source 6	Source 7	Source 8	Source 9	Source 10	Total of all Biomass, tons/year
			Mill Waste, tons/year	Animal Waste/Manure, tons/year	Crop Residue, tons/year	Agricultural Processing Waste, tons/year	Forest Waste, tons/year	MSW ¹ , tons/year	Municipal Waste (sludge), tons/year	Urban Solid Wood Waste, tons/year	Urban Industrial Wood Waste, tons/year	Urban C&D Wood Waste, tons/year	
1	Arizona	4,778,332	182,700	859,220	185,002		48,637	2,269,696	198,192	261,613	191,133	430,049	4,626,244
2	California	33,145,121	5,064,150	6,584,158	813,280		137,775	15,743,857	1,374,769	1,814,695	1,325,804	2,983,060	35,841,550
3	Colorado	4,056,133	186,000	2,771,056	2,895,035		71,637	1,926,653	168,237	222,073	162,245	365,051	8,767,989
4	Kansas	2,654,052	22,050	5,346,688	10,910,932		128,287	1,260,668	110,082	145,309	106,162	238,864	18,269,044
5	Nebraska	1,666,028	72,450	5,963,543	15,494,426		73,562	791,359	69,102	91,215	66,641	149,942	22,772,241
6	Nevada	1,809,253	0	421,330	14,267		5,375	859,391	75,042	99,056	72,370	162,832	1,709,665
7	New Mexico	1,739,844	217,311	1,585,384	344,781		47,462	826,421	72,163	95,256	69,593	156,585	3,414,960
8	North Dakota	633,666	5,250	1,551,141	3,602,931		28,637	300,989	26,282	34,693	25,346	57,029	5,632,301
9	Oklahoma	3,358,044	732,900	4,631,933	1,741,249		638,075	1,595,063	139,282	183,852	134,321	302,223	10,098,901
10	South Dakota	733,133	129,150	3,383,103	5,565,232		132,387	348,236	30,408	40,139	29,325	65,981	9,723,963
11	Texas	20,044,141	4,245,150	11,414,309	6,016,957		2,836,387	9,520,921	831,376	1,097,416	801,765	1,803,972	38,568,255
12	Utah	2,129,836	107,100	994,385	208,730		30,412	1,011,667	88,339	116,608	85,193	191,685	2,834,121
13	Wyoming	479,602	267,750	1,212,500	252,190		57,575	227,809	19,892	26,258	19,184	43,164	2,126,323
TOTAL OF ALL STATES			11,231,961	46,718,750	48,045,012	5,000,000	4,236,208	36,682,737	3,203,173	4,228,188	3,089,087	6,950,446	169,385,564
			0.06631	0.27581305603	0.283642896843	0.02951845	0.0250092623298	0.2165635402	0.01891054	0.0249619169654	0.018237017	0.0410332881623	
Contribution of Each Biomass Source to the Total			7%	28%	27%	2.95%	2%	22%	2%	2.96%	2%	4%	
			Mill waste	Animal manure	Crop Residue	Ag Pros Waste	Forest Waste	MSW	Sludge	Urban MSW Wood Waste	Urban Wood Waste	C&D Waste	

Note:

1) The MSW Source No. 6 does not include wood waste.

2) The total of all biomass resources (horizontal total) is not equal to states total (vertical total), because of 5 million tons of agricultural processing waste consider for the region.

3) The total of individual biomass contribution percentages may not equal to 100%.

4) The quantities for NM and CO are posted directly from backup data.

TABLE A-2

Biomass Resource Distribution for Southeast Region

S. No	State	Population	Source 1	Source 2	Source 3	Source 4	Source 5	Source 6	Source 7	Source 8	Source 9	Source 10	Total of all Biomass, tons/year
			Mill Waste, tons/year	Animal Waste/Manure, tons/year	Crop Residue, tons/year	Agricultural Processing Waste, tons/year	Forest Waste, tons/year	MSW ¹ , tons/year	Municipal Waste (sludge), tons/year	Urban MSW Wood Waste, tons/year	Urban Industrial Wood Waste, tons/year	Urban C&D Wood Waste, tons/year	
1	Alabama	4,369,862	8,193,150	387,294	377,346		2,878,262	2,075,674	181,249	239,249	174,794	393,287	14,900,305
2	Arkansas	2,551,373	4,940,250	1,845,794	601,247		2,973,450	1,211,896	105,823	139,687	102,054	229,623	12,149,828
3	Florida	15,111,244	2,833,950	1,773,086	93,572		1,802,225	7,177,806	626,773	827,340	604,449	1,360,011	17,099,215
4	Georgia	7,788,240	8,368,500	1,590,966	718,060		4,446,875	3,699,396	323,034	426,406	311,529	700,941	20,585,710
5	Kentucky	3,960,825	2,035,950	2,191,563	1,717,508		1,760,700	1,881,382	164,284	216,855	158,433	356,474	10,483,151
6	Louisiana	4,372,035	3,406,200	805,023	750,137		2,002,075	2,076,706	181,340	239,368	174,881	393,483	10,029,215
7	Mississippi	2,768,619	6,331,500	993,800	559,806		1,196,962	1,315,087	114,834	151,581	110,744	249,175	11,023,493
8	Missouri	5,468,338	1,254,750	4,471,397	3,626,011		1,811,075	2,597,448	226,811	299,391	218,733	492,150	14,997,768
9	North Carolina	7,650,789	5,278,350	3,596,923	917,541		3,122,587	3,634,107	317,333	418,880	306,031	688,571	18,280,326
10	South Carolina	3,885,736	3,551,100	537,058	327,761		2,495,787	1,845,715	161,169	212,744	155,429	349,716	9,636,481
11	Tennessee	5,483,535	2,118,900	1,859,297	1,867,819		1,368,962	2,604,666	227,442	300,223	219,341	493,518	11,060,170
12	Virginia	6,872,912	3,004,050	1,616,289	474,528		2,222,162	3,264,617	285,069	376,291	274,916	618,562	12,136,487
13	Washington	0	0	0	0		0	0	0	0	0	0	0
14	West Virginia	1,806,928	1,016,400	375,852	19,745		1,344,850	858,286	74,946	98,929	72,277	162,623	4,023,910
TOTAL OF ALL STATES			52,333,050	22,044,342	12,051,081	1,000,000	29,425,972	34,242,793	2,990,114	3,946,951	2,883,617	6,488,139	167,406,059
			0.3126114	0.13168186307	0.07198712	0.005974	0.1757760252	0.2045493	0.017861	0.0235771115	0.01722529	0.038756896	154,256,231
Contribution of Each Biomass Source to the Total			31%	13%	7%	0.59%	18%	20%	2%	2.35%	2%	4%	
			Mill Waste	Animal Manure	Crop Residue	AG Pros Waste	Forest Waste	MSW	Sludge	Urban MSW Wood Waste	Urban Wood Waste	C&D Waste	

Note:

1) The MSW Source No. 6 does not include wood waste.

2) The quantity for agricultural processing waste i.e. 1.0 million tons does not appear in states total, but considered in resource total.

3) The total of individual biomass resource percentages may not be equal to 100%.

TABLE A-3

Biomass Resource Distribution for Northwest Region

S. No.	State	Population	Source 1	Source 2	Source 3	Source 4	Source 5	Source 6	Source 7	Source 8	Source 9	Source 10	Total of all Biomass, tons/year
			Mill Waste, tons/year	Animal Waste/Manure, tons/year	Crop Residue, tons/year	Agricultural Processing Waste, tons/year	Forest Waste, tons/year	MSW, other than wood waste, tons/year	MSW (sludge), tons/year	Urban MSW Wood Waste, tons/year	Urban Industrial Wood Waste, tons/year	Urban C&D Waste, tons/year	
1	Alaska (a)	619,500	253,050	10,389	0		908,837	294,261	25,695	33,917	24,780	55,755	1,606,684
2	Idaho	1,251,700	4,620,000	1,918,625	1,643,674		871,825	594,554	51,917	68,530	50,068	112,653	9,931,847
3	Oregon	3,316,154	7,176,750	1,336,440	411,516		964,737	1,575,165	137,545	181,559	132,646	298,453	12,214,811
4	Montana	882,779	2,283,750	2,099,224	1,947,506		716,987	419,318	36,615	48,332	35,311	79,450	7,666,493
5	Washington	5,756,361	5,974,500	1,354,888	1,412,959		1,029,250	2,734,258	238,758	315,160	230,254	518,072	13,808,099
TOTAL OF STATES			20,308,050	6,719,566	5,415,655	500,000	4,491,636	5,617,557	490,530	647,500	473,059	1,064,384	45,727,937
			0.444105942	0.14694661431	0.11843207828	0.0109342	0.0982251983	0.122847383	0.0107272	0.014159845	0.01034509	0.0232764575	
Contribution of Each Biomass Source to the Total			44%	15%	12%	1.09%	10%	12%	1%	1.41%	1%	2%	
			Mill Waste	Animal Manure	Crop Residue	Ag Pros Waste	Forest Waste	MSW	Sludge	Urban MSW Wood Waste	Urban Wood Waste	C&D Waste	

Note:

a) Data for crop residue not available.

b) The total of biomass resource total (horizontal) differs from states total (vertical) by 0.5 million tons considered for agricultural processing for the region.

c) The total of individual biomass contribution (%) may not be equal to 100%.

TABLE A-4

Biomass Resource Distribution for Northeast Region

S. No.	State	Population	Source 1	Source 2	Source 3	Source 4	Source 5	Source 6	Source 7	Source 8	Source 9	Source 10	Total of all Biomass Sources, tons/year
			Mill Waste, tons/year	Animal Waste/Manure, tons/year	Crop Residue, tons/year	Agricultural Processing Waste, tons/year	Forest Waste, tons/year	MSW ⁵ , tons/year	MSW (sludge), tons/year	Urban MSW Wood Waste, tons/year	Urban Industrial Wood Waste, tons/year	Urban C&D Wood Waste, tons/year	
1	Connecticut ***	3,282,031	94,500	149,433	0		77,550	1,558,957	136,129	179,691	131,281	295,382	2,622,925
2	Delaware *	753,538	16,800	47,160	231,547		47,300	357,928	31,254	41,256	30,141	67,818	871,206
3	Maine	1,253,040	531,300	231,006	19,200		1,578,712	595,191	51,972	68,603	50,121	112,773	3,238,881
4	Maryland	5,171,634	174,300	404,742	560,372		2,202,012	2,456,514	214,505	283,146	206,865	465,447	6,967,905
5	Massachusetts +	6,175,169	141,750	91,930	0		80,437	2,933,191	256,129	338,090	247,006	555,765	4,644,300
6	New Hampshire +	1,201,134	1,165,500	70,356	0		981,950	570,535	49,819	65,762	48,045	108,102	3,060,071
7	New Jersey	8,143,412	21,000	106,402	44,260		29,362	3,868,102	337,766	445,851	325,736	732,907	5,911,388
8	New York	18,196,601	1,338,750	2,330,563	846,660		1,110,662	8,643,344	754,745	996,263	727,864	1,637,694	18,386,547
9	Pennsylvania	11,994,016	1,711,500	2,938,547	1,001,286		1,710,937	5,697,130	497,479	2,398,803	479,760	1,079,461	17,514,905
10	Rhode Island **	990,819	27,300	8,625	0		7,675	470,636	41,096	198,163	39,632	89,173	882,303
11	Vermont +	593,740	130,200	501,764	0		496,037	282,025	24,626	118,748	23,749	53,436	1,630,587
TOTAL OF ALL STATES			5,352,900	6,880,528	2,703,325	300,000	8,322,634	27,433,557	2,395,525	5,134,381	2,310,205	5,197,962	66,031,017
			0.081066445	0.10420146357	0.0409402279	0.0045433	0.12604127621	0.4154646935	0.03627879	0.0777571151	0.0349866679	0.078720003	
Contribution of Each Biomass Source to the Total			8%	10%	4%	0.45%	13%	42%	4%	7.77%	3%	8%	
			Mill Waste	Animal Manure	Crop Residue	Ag Pros Waste	Forest Waste	MSW	Sludge	Urban MSW Wood Waste	Urban Wood Waste	C&D Waste	

Note:

- 1) * No data available for ships and lambs.
- 2) ** No data available for chickens, sheeps, lambs and crop residue.
- 3) + No data available for chickens and crop residue.
- 4) *** No data available for crop residue.
- 5) MSW Resource No. 6 does not include wood waste.
- 6) The total of biomass resources (horizontal) differs from states total (vertical) by 0.3 million tons considered for the region.
- 7) The total of individual biomass percentages may not be equal to 100%.

TABLE A-5

Biomass Resource Distribution for Great Lakes Region

S. No.	State	Population	Source 1	Source 2	Source 3	Source 4	Source 5	Source 6	Source 7	Source 8	Source 9	Source 10	Total of all Biomass Sources, tons/year
			Mill Waste, tons/year	Animal Waste/Manure, tons/year	Crop Residue, tons/year	Agricultural Processing Waste, tons/year	Forest Waste, tons/year	MSW ¹ , tons/year	MSW (sludge), tons/year	Urban MSW Wood Waste, tons/year	Urban Industrial Wood Waste, tons/year	Urban C&D Wood Waste, tons/year	
1	Illinois	12,128,370	295,050	2,464,375	19,161,390		895,275	5,760,948	503,051	664,028	485,134	1,091,553	295,050
2	Indiana	5,942,901	731,850	2,213,989	9,579,777		945,175	2,822,864	246,495	325,373	237,716	534,861	17,638,102
3	Iowa	2,869,413	165,900	7,628,599	22,109,771		355,412	1,362,964	119,015	157,100	114,776	258,247	32,271,786
4	Michigan	9,863,775	1,641,150	1,638,932	3,498,657		1,383,100	4,685,270	409,122	540,041	394,551	887,739	15,078,565
5	Minnesota	4,775,508	1,178,100	4,457,201	13,182,770		2,240,112	2,268,355	198,075	261,459	191,020	429,795	24,406,889
6	Ohio (a)	11,256,654	0	2,219,680	5,558,795		0	5,346,885	466,895	616,301	450,266	1,013,098	15,671,922
7	Wisconsin	5,250,446	1,985,550	5,026,947	5,397,794		2,041,175	2,493,949	217,774	287,461	210,017	472,540	18,133,210
TOTAL OF ALL STATES			5,997,600	25,649,723	78,488,954	9,000,000	7,860,249	24,741,238	2,160,429	2,851,766	2,083,482	4,687,836	163,521,277
Contribution of Each Biomass Source to the Total			0.036678	0.15685862457	0.47999229343	0.05503871	0.0480686613	0.151302867	0.01321192	0.0174397297	0.01274136	0.0286680488	
			4%	16%	50%	5.50%	5%	15%	1%	1.74%	1%	3%	
			Mill Waste	Animal Manure	Crop Residue		Forest Waste	MSW	Sludge	Urban MSW Wood Waste	Urban Wood Waste	C&D Waste	

Note:

1) Data not available for mill waste and forest waste.

2) MSW (Source 6) without wood waste.

3) The biomass resource total (horizontal) differs from states total (vertical) differs by 9 million tons considered for agricultural processing waste for the region.

4) The total of individual biomass contribution percentages (to the total) may not equal to 100%.

TABLE A-6

Biomass Resource Distribution for USA – By Region and Type

S. No.	Region	Source 1	Source 2	Source 3	Source 4 (\$\$\$\$)	Source 5	Source 6	Source 7	Source 8	Source 9	Source 10		
		Mill Waste, tons/year	Animal Waste/Manure, tons/year	Crop Residue, tons/year	Agricultural Processing Waste, tons/year	Forest Waste, tons/year	MSW ¹ , tons/year	Municipal Waste (sludge), tons/year	Urban Municipal Solid Wood Waste, tons/year	Urban Industrial Wood Waste, tons/year	Urban C&D Wood Waste, tons/year	Total of all Biomass, tons/year	Total of all Biomass Energy
1	WESTERN REGION	11,231,961	46,718,750	48,045,012	5,000,000	4,236,208	36,682,737	3,203,173	4,228,188	3,089,087	6,950,446	169,385,562	20,350,160
2	SOUTHEAST REGION	52,333,050	22,044,342	12,051,081	1,000,000	29,425,972	34,242,793	2,990,115	3,946,951	2,883,617	6,488,139	167,406,060	13,392,484
3	NORTHWEST REGION	20,308,050	6,719,566	5,415,655	500,000	4,491,636	5,617,558	490,531	647,500	473,060	1,064,384	45,727,940	3,658,235
4	NORTH EAST REGION	5,352,900	6,880,529	2,703,325	300,000	8,322,634	27,433,557	2,395,525	5,134,382	2,310,205	5,197,962	66,031,019	5,282,481
5	GREAT LAKES REGION	5,997,600	25,649,723	78,488,954	9,000,000	7,860,249	24,741,238	2,160,429	2,851,767	2,083,483	4,687,836	163,521,279	19,622,553
	TOTAL OF ALL REGIONS	95,223,561	108,012,910	146,704,027	15,800,000	54,336,699	128,717,883	11,239,773	16,808,788	10,839,452	24,388,767	612,071,860	612,071,860
		0.1555757863	0.1764709619	0.2396843188 4	0.02581396	0.088775032	0.210298645 1	0.01836349	0.027462115 3	0.017709443 4	0.039846248 8		
	Contribution of Each Biomass Source to the Total Energy	16% Mill Waste	18% Animal Manure	24% Crop Residue	2.58% Agricultural Processing	9% Forest Waste	21% MSW	2% Sludge	2.70% Urban MSW Wood Waste	2% Urban Industrial Wood Waste	4% C&D waste		

Note:

1) The MSW Source No. 6 does not include wood waste.

Figure A-1. Biomass resource distribution (United States).

Figure A-2. Biomass resource distribution – United States (total: 612 million tons).

EERC DS17999.CDR

Figure A-3. Biomass energy distribution – United States (total: 6656 million MMBtu).

EERC DS17997.CDR

Figure A-4. Biomass resource distribution – United States (total: 612 million tons).

TABLE A-7

Biomass Resource Quantification for Canada

S. No.	Resource/Base	Population	31,281,092				
		Livestock	Cattle (No.)	Chickens (No.)	Pigs (No.)	Sheep (No.)	
			12,981,000	145,000,000	12,402,700	656,400	
		Mill Waste	Residues (m ³)				
			600,000				
		Crop Residue	Corn (T/Y)	Barley (T/Y)	Oats (T/Y)	Wheat (T/Y)	
			335,000	13,196,000	3,641,300	26,850,200	
		tons/year	tons/year	tons/year	tons/year	tons/year	Total, tons/year
1	Mill Waste	2,574,609					2,574,609
2	Animal Waste/Manure		0	0	0	0	15,243,448
3	Crop Residue		184,250	9,897,000	2,730,975	6,041,295	18,853,520
4	MSW	89,557,766					89,557,766
5	Municipal Waste (sludge)	7,820,273					7,820,273
6	Urban Municipal Solid Wood Waste	10,322,760					10,322,760
7	Urban Industrial Wood Waste	1,251,243					1,251,243
8	Urban C&D Wood Waste	2,815,298					2,815,298
							148,438,919

TABLE A-8

Competitive Resource Profile for Western Region

		Economics									Conversion Technologies						Environmental Impact									Total Weighted Score
S. No.	Biomass Resource	Quantity			Cost/ton			Government Support			Technical Feasibility			Combustion Constraints			Air Pollution			Water Pollution			Ash Disposal			
		Weight	Rating	Weighted Score	Weight	Rating	Weighted Score	Weight	Rating	Weighted Score	Weight	Rating	Weighted Score	Weight	Rating	Weighted Score	Weight	Rating	Weighted Score	Weight	Rating	Weighted Score	Weight	Rating	Weighted Score	
1	Mill waste	0.3	1	0.3	0.25	1	0.25	0.1	3	0.3	0.05	3	0.15	0.15	3	0.45	0.05	3	0.15	0.05	3	0.15	0.05	3	0.15	1.9
2	Animal manure	0.3	2	0.6	0.25	3	0.75	0.1	3	0.3	0.05	3	0.15	0.15	3	0.45	0.05	2	0.1	0.05	1	0.05	0.05	3	0.15	2.55
3	Crop residue	0.3	2	0.6	0.25	1.5	0.375	0.1	3	0.3	0.05	3	0.15	0.15	1	0.15	0.05	1	0.05	0.05	3	0.15	0.05	1	0.05	1.825
4	Agricultural process waste	0.3	1	0.3	0.25	2	0.5	0.1	3	0.3	0.05	3	0.15	0.15	1	0.15	0.05	1	0.05	0.05	3	0.15	0.05	1	0.05	1.65
5	Forest waste	0.3	1	0.3	0.25	0.5	0.125	0.1	3	0.3	0.05	3	0.15	0.15	3	0.45	0.05	3	0.15	0.05	3	0.15	0.05	3	0.15	1.775
6	MSW excluding wood	0.3	2	0.6	0.25	3	0.75	0.1	2	0.2	0.05	3	0.15	0.15	3	0.45	0.05	3	0.15	0.05	2	0.1	0.05	2	0.1	2.5
7	MSW (sludge)	0.3	1	0.3	0.25	3	0.75	0.1	1	0.1	0.05	3	0.15	0.15	2	0.3	0.05	3	0.15	0.05	2	0.1	0.05	1	0.05	1.9
8	Urban wood waste	0.3	1	0.3	0.25	0.5	0.125	0.1	3	0.3	0.05	3	0.15	0.15	3	0.45	0.05	2	0.1	0.05	3	0.15	0.05	2	0.1	1.675
9	Industrial wood waste	0.3	1	0.3	0.25	0.5	0.125	0.1	3	0.3	0.05	3	0.15	0.15	3	0.45	0.05	2	0.1	0.05	3	0.15	0.05	2	0.1	1.675
10	C&D wood waste	0.3	1	0.3	0.25	0.5	0.125	0.1	3	0.3	0.05	3	0.15	0.15	3	0.45	0.05	2	0.1	0.05	3	0.15	0.05	2	0.1	1.675

Notes:

- 1) Because of the disbursement of forest waste, cost/ton is considered as the highest (45-55 \$/ton).
- 2) Municipal sludge is assumed to have no tangible federal support.
- 3) The three types of wood waste, urban wood waste, industrial wood waste, and C&D wood waste, are given higher cost/ton mainly due to the manual labor involved in fuel conditioning and processing.
- 4) Animal manure is considered to be utilized in farm anaerobic digesters. Hence, no considerable handling charges.
- 5) The higher cost/ton considered for crop residue is due to the expenses involved in fuel conditioning and processing in addition to transportation.

TABLE A-9

Competitive Resource Profile for Northwest Region

		Economics									Conversion Technologies						Environmental Impact									Total Weighted Score
S. No.	Biomass Resource	Quantity			Cost/ton			Government Support			Technical Feasibility			Combustion Constraints			Air Pollution			Water Pollution			Ash Disposal			
		Weight	Rating	Weighted Score	Weight	Rating	Weighted Score	Weight	Rating	Weighted Score	Weight	Rating	Weighted Score	Weight	Rating	Weighted Score	Weight	Rating	Weighted Score	Weight	Rating	Weighted Score	Weight	Rating	Weighted Score	
1	Mill waste	0.3	3	0.9	0.25	1	0.25	0.1	3	0.3	0.05	3	0.15	0.15	3	0.45	0.05	3	0.15	0.05	3	0.15	0.05	3	0.15	2.5
2	Animal manure	0.3	1.5	0.45	0.25	3	0.75	0.1	3	0.3	0.05	3	0.15	0.15	3	0.45	0.05	2	0.1	0.05	1	0.05	0.05	3	0.15	2.4
3	Crop residue	0.3	2	0.6	0.25	1.5	0.375	0.1	3	0.3	0.05	3	0.15	0.15	1	0.15	0.05	1	0.05	0.05	3	0.15	0.05	1	0.05	1.825
4	Agricultural process waste	0.3	1	0.3	0.25	2	0.5	0.1	3	0.3	0.05	3	0.15	0.15	1	0.15	0.05	1	0.05	0.05	3	0.15	0.05	1	0.05	1.65
5	Forest waste	0.3	1	0.3	0.25	0.5	0.125	0.1	3	0.3	0.05	3	0.15	0.15	3	0.45	0.05	3	0.15	0.05	3	0.15	0.05	3	0.15	1.775
6	MSW excluding wood	0.3	1	0.3	0.25	3	0.75	0.1	2	0.2	0.05	3	0.15	0.15	3	0.45	0.05	3	0.15	0.05	2	0.1	0.05	2	0.1	2.2
7	MSW (sludge)	0.3	1	0.3	0.25	3	0.75	0.1	1	0.1	0.05	3	0.15	0.15	2	0.3	0.05	3	0.15	0.05	2	0.1	0.05	1	0.05	1.9
8	Urban wood waste	0.3	1	0.3	0.25	0.5	0.125	0.1	3	0.3	0.05	3	0.15	0.15	3	0.45	0.05	2	0.1	0.05	3	0.15	0.05	2	0.1	1.675
9	Industrial wood waste	0.3	1	0.3	0.25	0.5	0.125	0.1	3	0.3	0.05	3	0.15	0.15	3	0.45	0.05	2	0.1	0.05	3	0.15	0.05	2	0.1	1.675
10	C&D wood waste	0.3	1	0.3	0.25	0.5	0.125	0.1	3	0.3	0.05	3	0.15	0.15	3	0.45	0.05	2	0.1	0.05	3	0.15	0.05	2	0.1	1.675

Notes:

- 1) Because of the disbursement of forest waste, cost/ton is considered as the highest (45-55 \$/ton).
- 2) Municipal sludge is assumed to have no tangible federal support.
- 3) The three types of wood waste, urban wood waste, industrial wood waste, and C&D wood waste, are given higher cost/ton mainly due to the manual labor involved in fuel conditioning and processing.
- 4) Animal manure is considered to be utilized in farm anaerobic digesters. Hence, no considerable handling charges.
- 5) The higher cost/ton considered for crop residue is due to the expenses involved in fuel conditioning and processing in addition to transportation.

TABLE A-10

Competitive Resource Profile for Southeast Region

		Economics									Conversion Technologies						Environmental Impact									Total Weighted Score
S. No.	Biomass Resource	Quantity			Cost/ton			Government Support			Technical Feasibility			Combustion Constraints			Air Pollution			Water Pollution			Ash Disposal			
		Weight	Rating	Weighted Score	Weight	Rating	Weighted Score	Weight	Rating	Weighted Score	Weight	Rating	Weighted Score	Weight	Rating	Weighted Score	Weight	Rating	Weighted Score	Weight	Rating	Weighted Score	Weight	Rating	Weighted Score	
1	Mill waste	0.3	3	0.9	0.25	1	0.25	0.1	3	0.3	0.05	3	0.15	0.15	3	0.45	0.05	3	0.15	0.05	3	0.15	0.05	3	0.15	2.5
2	Animal manure	0.3	1.5	0.45	0.25	3	0.75	0.1	3	0.3	0.05	3	0.15	0.15	3	0.45	0.05	2	0.1	0.05	1	0.05	0.05	3	0.15	2.4
3	Crop residue	0.3	1	0.3	0.25	1.5	0.375	0.1	3	0.3	0.05	3	0.15	0.15	1	0.15	0.05	1	0.05	0.05	3	0.15	0.05	1	0.05	1.525
4	Agricultural process waste	0.3	1	0.3	0.25	2	0.5	0.1	3	0.3	0.05	3	0.15	0.15	1	0.15	0.05	1	0.05	0.05	3	0.15	0.05	1	0.05	1.65
5	Forest waste	0.3	1	0.3	0.25	0.5	0.125	0.1	3	0.3	0.05	3	0.15	0.15	3	0.45	0.05	3	0.15	0.05	3	0.15	0.05	3	0.15	1.775
6	MSW excluding wood	0.3	1	0.3	0.25	3	0.75	0.1	2	0.2	0.05	3	0.15	0.15	3	0.45	0.05	3	0.15	0.05	2	0.1	0.05	2	0.1	2.2
7	MSW (sludge)	0.3	1	0.3	0.25	3	0.75	0.1	1	0.1	0.05	3	0.15	0.15	2	0.3	0.05	3	0.15	0.05	2	0.1	0.05	1	0.05	1.9
8	Urban wood waste	0.3	1	0.3	0.25	0.5	0.125	0.1	3	0.3	0.05	3	0.15	0.15	3	0.45	0.05	2	0.1	0.05	3	0.15	0.05	2	0.1	1.675
9	Industrial wood waste	0.3	1	0.3	0.25	0.5	0.125	0.1	3	0.3	0.05	3	0.15	0.15	3	0.45	0.05	2	0.1	0.05	3	0.15	0.05	2	0.1	1.675
10	C&D wood waste	0.3	1	0.3	0.25	0.5	0.125	0.1	3	0.3	0.05	3	0.15	0.15	3	0.45	0.05	2	0.1	0.05	3	0.15	0.05	2	0.1	1.675

Notes:

- 1) Because of the disbursement of forest waste, cost/ton is considered as the highest (45-55 \$/ton).
- 2) Municipal sludge is assumed to have no tangible federal support.
- 3) The three types of wood waste, urban wood waste, industrial wood waste, and C&D wood waste, are given higher cost/ton mainly due to the manual labor involved in fuel conditioning and processing.
- 4) Animal manure is considered to be utilized in farm anaerobic digesters. Hence, no considerable handling charges.
- 5) The higher cost/ton considered for crop residue is due to the expenses involved in fuel conditioning and processing in addition to transportation.

TABLE A-11

Competitive Resource Profile for Northeast Region

		Economics									Conversion Technologies						Environmental Impact									Total Weighted Score
S. No.	Biomass Resource	Quantity			Cost/ton			Government Support			Technical Feasibility			Combustion Constraints			Air Pollution			Water Pollution			Ash Disposal			
		Weight	Rating	Weighted Score	Weight	Rating	Weighted Score	Weight	Rating	Weighted Score	Weight	Rating	Weighted Score	Weight	Rating	Weighted Score	Weight	Rating	Weighted Score	Weight	Rating	Weighted Score	Weight	Rating	Weighted Score	
1	Mill waste	0.3	1	0.3	0.25	1	0.25	0.1	3	0.3	0.05	3	0.15	0.15	3	0.45	0.05	3	0.15	0.05	3	0.15	0.05	3	0.15	1.9
2	Animal manure	0.3	1	0.3	0.25	3	0.75	0.1	3	0.3	0.05	3	0.15	0.15	3	0.45	0.05	2	0.1	0.05	1	0.05	0.05	3	0.15	2.25
3	Crop residue	0.3	1	0.3	0.25	1.5	0.375	0.1	3	0.3	0.05	3	0.15	0.15	1	0.15	0.05	1	0.05	0.05	3	0.15	0.05	1	0.05	1.525
4	Agricultural process waste	0.3	1	0.3	0.25	2	0.5	0.1	3	0.3	0.05	3	0.15	0.15	1	0.15	0.05	1	0.05	0.05	3	0.15	0.05	1	0.05	1.65
5	Forest waste	0.3	1.5	0.45	0.25	0.5	0.125	0.1	3	0.3	0.05	3	0.15	0.15	3	0.45	0.05	3	0.15	0.05	3	0.15	0.05	3	0.15	1.925
6	MSW excluding wood	0.3	3	0.9	0.25	3	0.75	0.1	2	0.2	0.05	3	0.15	0.15	3	0.45	0.05	3	0.15	0.05	2	0.1	0.05	2	0.1	2.8
7	MSW (sludge)	0.3	1	0.3	0.25	3	0.75	0.1	1	0.1	0.05	3	0.15	0.15	2	0.3	0.05	3	0.15	0.05	2	0.1	0.05	1	0.05	1.9
8	Urban wood waste	0.3	1	0.3	0.25	0.5	0.125	0.1	3	0.3	0.05	3	0.15	0.15	3	0.45	0.05	2	0.1	0.05	3	0.15	0.05	2	0.1	1.675
9	Industrial wood waste	0.3	1	0.3	0.25	0.5	0.125	0.1	3	0.3	0.05	3	0.15	0.15	3	0.45	0.05	2	0.1	0.05	3	0.15	0.05	2	0.1	1.675
10	C&D wood waste	0.3	1	0.3	0.25	0.5	0.125	0.1	3	0.3	0.05	3	0.15	0.15	3	0.45	0.05	2	0.1	0.05	3	0.15	0.05	2	0.1	1.675

Notes:

- 1) Because of the disbursement of forest waste, cost/ton is considered as the highest (45-55 \$/ton).
- 2) Municipal sludge is assumed to have no tangible federal support.
- 3) The three types of wood waste, urban wood waste, industrial wood waste, and C&D wood waste, are given higher cost/ton mainly due to the manual labor involved in fuel conditioning and processing.
- 4) Animal manure is considered to be utilized in farm anaerobic digesters. Hence, no considerable handling charges.
- 5) The higher cost/ton considered for crop residue is due to the expenses involved in fuel conditioning and processing in addition to transportation.

TABLE A-12

Competitive Resource Profile for Great Lakes Region

Comprehensive Resource Profile for Green Energy Region																										
		Economics									Conversion Technologies						Environmental Impact								Total Weighted Score	
S. No.	Biomass Resource	Quantity			Cost/ton			Government Support			Technical Feasibility			Combustion Constraints			Air Pollution			Water Pollution			Ash Disposal			
		Weight	Rating	Weighted Score	Weight	Rating	Weighted Score	Weight	Rating	Weighted Score	Weight	Rating	Weighted Score	Weight	Rating	Weighted Score	Weight	Rating	Weighted Score	Weight	Rating	Weighted Score	Weight	Rating		Weighted Score
1	Mill waste	0.3	1	0.3	0.25	1	0.25	0.1	3	0.3	0.05	3	0.15	0.15	3	0.45	0.05	3	0.15	0.05	3	0.15	0.05	3	0.15	1.9
2	Animal manure	0.3	1.5	0.45	0.25	3	0.75	0.1	3	0.3	0.05	3	0.15	0.15	3	0.45	0.05	2	0.1	0.05	1	0.05	0.05	3	0.15	2.4
3	Crop residue	0.3	3	0.9	0.25	1.5	0.375	0.1	3	0.3	0.05	3	0.15	0.15	1	0.15	0.05	1	0.05	0.05	3	0.15	0.05	1	0.05	2.125
4	Agricultural process waste	0.3	1	0.3	0.25	2	0.5	0.1	3	0.3	0.05	3	0.15	0.15	1	0.15	0.05	1	0.05	0.05	3	0.15	0.05	1	0.05	1.65
5	Forest waste	0.3	1	0.3	0.25	0.5	0.125	0.1	3	0.3	0.05	3	0.15	0.15	3	0.45	0.05	3	0.15	0.05	3	0.15	0.05	3	0.15	1.775
6	MSW excluding wood	0.3	1.5	0.45	0.25	3	0.75	0.1	2	0.2	0.05	3	0.15	0.15	3	0.45	0.05	3	0.15	0.05	2	0.1	0.05	2	0.1	2.35
7	MSW (sludge)	0.3	1	0.3	0.25	3	0.75	0.1	1	0.1	0.05	3	0.15	0.15	2	0.3	0.05	3	0.15	0.05	2	0.1	0.05	1	0.05	1.9
8	Urban wood waste	0.3	1	0.3	0.25	0.5	0.125	0.1	3	0.3	0.05	3	0.15	0.15	3	0.45	0.05	2	0.1	0.05	3	0.15	0.05	2	0.1	1.675
9	Industrial wood waste	0.3	1	0.3	0.25	0.5	0.125	0.1	3	0.3	0.05	3	0.15	0.15	3	0.45	0.05	2	0.1	0.05	3	0.15	0.05	2	0.1	1.675
10	C&D wood waste	0.3	1	0.3	0.25	0.5	0.125	0.1	3	0.3	0.05	3	0.15	0.15	3	0.45	0.05	2	0.1	0.05	3	0.15	0.05	2	0.1	1.675

Notes:

- 1) Because of the disbursement of forest waste, cost/ton is considered as the highest (45-55 \$/ton).
- 2) Municipal sludge is assumed to have no tangible federal support.
- 3) The three types of wood waste, urban wood waste, industrial wood waste, and C&D wood waste, are given higher cost/ton mainly due to the manual labor involved in fuel conditioning and processing.
- 4) Animal manure is considered to be utilized in farm anaerobic digesters. Hence, no considerable handling charges.
- 5) The higher cost/ton considered for crop residue is due to the expenses involved in fuel conditioning and processing in addition to transportation.