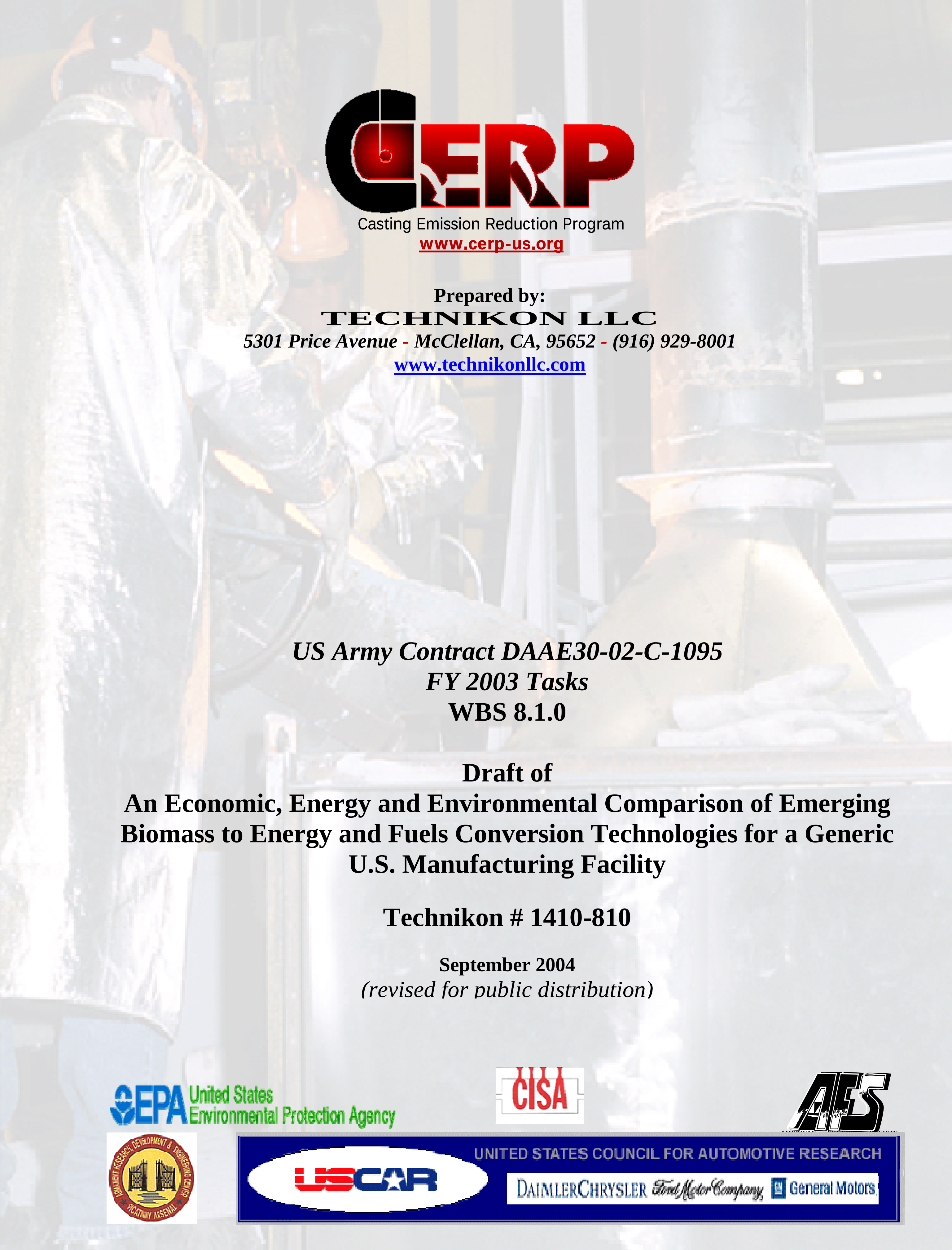

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US Army Contract DAAE30-02-C-1095
FY 2003 Tasks
WBS 8.1.0

Draft of
An Economic, Energy and Environmental Comparison of Emerging Biomass to Energy and Fuels Conversion Technologies for a Generic U.S. Manufacturing Facility

Technikon # 1410-810

September 2004

(revised for public distribution)

EPA United States Environmental Protection Agency

CISA

AFS

UNITED STATES COUNCIL FOR AUTOMOTIVE RESEARCH

USCAR

DaimlerChrysler Ford Motor Company General Motors

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Draft of An Economic, Energy and Environmental Comparison of Emerging Biomass to Energy and Fuels Conversion Technologies for a Generic U.S. Manufacturing Facility

Technikon # 1410-810

This report has been reviewed for completeness and accuracy and approved for release by the following:

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Executive Summary

An economic, energy and environmental assessment for biomass conversion technologies was carried out to determine the most effective processes for the conversion of waste biomass materials to energy and/or fuels. With the expected increase of electricity and natural gas prices in the near future, additional annual cost savings could be realized by supplementing the energy demands at a U.S. manufacturing facility with energy developed by a biomass to energy conversion system. Waste biomass generated from a generic U.S. manufacturing facility was used for the model assessment. The biomass conversion systems evaluated included 1) Thermal gasification, 2) Thermal pyrolysis steam reforming, 3) Thermal oxidation systems and 4) Thermogenic anaerobic digestion.

These technologies were evaluated using a "3E" assessment approach. The "3E" approach was used to compare processes with respect to economics (E1), energy efficiency (E2), and environmental impacts (E3). This approach helped identify technologies that have low cost, high-energy efficiency, and minimal environmental impact.

After reviewing the four technologies based on the "3E" assessment approach, the following table was developed to compare the conversion technologies analyzed in this report. The economic impact of each system is based on feedstock preparation, conversion and electricity generation. Energy output is based on the feedstock assumptions used for this study and known conversion efficiencies of each technology. Environmental impact is measured by emissions generation and ash disposal. Table 1 shows the varying cost, energy output, and environmental impact of each conversion technology based on a 50 ton per day input of biomass.

Table 1 "3E" Assessment of Biomass to Energy Conversion Technologies

Conversion Technology	Economic Impact (E1)	Energy Output (E2)	Environmental Impact (E3)
Thermal Gasification	$7.8-8.6 M	12,456 MW-hrs/Year	Negligible with proper emissions control
Thermal Pyrolysis	$5.8-6.4 M	28,225 MW-hrs/Year	Negligible with proper emissions control
Thermal Oxidation a) Traditional	$9.96-11.0 M	11,038 MW-hrs/Year	Possible Impact
Thermal Oxidation b) Next Generation	$5.2-5.8 M	14,349 MW-hrs/year	Negligible with proper emissions control
Thermogenic Anaerobic Digestion	$17.5-20.2 M	1,303 MW-hrs/Year	Negligible Impact

The thermal gasification system has cost of approximately $7.8 – $8.6 M. The operating and maintenance costs are estimated to be approximately $345 – $380 K per year. Based on the assumptions of this report the thermal gasification system can produce 12,456 MW-hrs/Year of electricity per manufacturer's specifications. Due to the system design, an efficient thermal gasifier will produce small amounts of inert ash and no emissions during the conversion process. Emissions will develop when the synthesis gas (syngas), or other fuel, is combusted. Emissions can be controlled with the appropriate emissions control technologies.

The thermal pyrolysis steam reforming system has costs of approximately $5.8 – $6.4 M to install with an annual operating cost of $828 – $911 K. The thermal pyrolysis steam reforming system would be able to produce 28,225 MW-hrs/Year of electricity per manufacturer's specifications. Similar to the thermal gasifier, emissions won't be produced in the thermal pyrolysis steam reforming system until the syngas is combusted, which can be controlled with the appropriate technologies.

The thermal oxidation systems evaluated by this report are both traditional and next generation in nature. Advances in oxidation technology design and engineering have led to lower costs, improved conversion efficiencies and lower emissions than traditional oxidation technologies. The traditional thermal oxidation to energy system would cost $9.96 – $11.0 M to install and have an annual operating cost of $1.2 – $1.3 M per year. Higher operating costs can be attributed to the high ash generation rate and high ash disposal costs. The thermal oxidation system would be able to produce approximately 11,038 MW-hrs/Year of electricity per manufacturer's specifications. The thermal oxidation system provides lower energy output due to lower conversion efficiencies. Traditional thermal oxidation systems have a high ash generation rate and can produce a high level of emissions.

The next generation thermal oxidation process is a subset of thermal oxidation, which has proved to convert various feed stocks more efficiently and with fewer emissions than traditional thermal oxidation systems. The capital cost for installation of this system is approximately $5.2 – $5.8 M with an annual operating cost of $155 – $190 K per year. The electricity generated has a potential value of 14,349 MW-hrs/Year of energy. Next generation thermal oxidation systems have decreased the ash rate, through more complete oxidation of the feedstock, and also reduced emissions.

The thermogenic anaerobic digestion system costs approximately $17.5 – $20.2 M to install and has an annual operating cost of $605 – $639 K per year. The system has the potential to produce 1,303 MW-hrs/Year of electricity based on the waste stream presented in this report per manufacturer's specifications. Lower energy output by the thermogenic anaerobic digestion system can be attributed to the limited feedstock it is able to convert and lower overall conversion efficiency. The thermogenic anaerobic digester has minimal environmental impact. Emissions produced when syngas is combusted can be controlled with the appropriate technologies. The digestate can be used as soil amendment, landfill cover or compost.

The chemical makeup of the waste stream, availability of capital, energy generation requirements, and environmental impact will determine the most appropriate conversion technology for each individual waste to energy project. Each biomass to energy conversion system provides benefits and costs for the conversion of waste biomass and other appropriate industrial wastes (50 tons/day) into energy. Estimated payback period for each system is listed in Table 2 below.

Table 2 Biomass to Energy Conversion System Payback Analysis

Technology	Total Capital Cost	Operating Cost	Yearly Savings	Number of Years for Payback
Thermal Gasification	$7.8 – $8.6 M	$346 – $380K	$1.10 – $1.13 M	6.9 – 7.8 Years
Thermal Pyrolysis Steam Reforming	$5.6 – $6.4 M	$828 – $911K	$1.60 – $1.69 M	3.4 – 4.0 Years
Thermal Oxidation	$10.0 – $11.0 M	$1.30 – 1.43M	($69K) – $189K	52.9 – N/A Years
Next Generation Thermal Oxidation	$5.2 – $5.8 M	$155 – $190K	$1.42 – $1.45 M	3.6 – 4.1 Years
Thermogenic Anaerobic Digestion	$17.5 – $20.2 M	$605 – $639K	($85K) – ($119K)	N/A

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1.0 Approach and Overview of Preprocessing

1.1 INTRODUCTION

A comparison of biomass conversion technologies was carried out to determine the most effective processes for the conversion of waste biomass materials, generated by a generic U.S. manufacturing facility, to usable energy. The four biomass to energy conversion systems evaluated included 1) Thermal gasification, 2) Thermal pyrolysis steam reforming, 3) Thermal oxidation systems and 4) Thermogenic Anaerobic digestion.

Waste biomass to energy conversion technologies have been successfully implemented for large-scale systems (1000 tons of biomass/day). These systems may be difficult to operate on a regular basis due to the need for large amounts of a consistent feedstock. A more feasible system relying on approximately 50 tons of biomass per day was selected. Recent technological developments in smaller conversion systems have allowed these systems to become more economically and energy efficient. Biomass-to-energy conversion technologies, analyzed by this report, are currently in operation or in testing in various countries. The goal of each is to convert agricultural waste, plant waste, biomedical waste, municipal solid waste as well as any combination of the aforementioned wastes to energy and/or fuels.

1.2 WASTE CHARACTERIZATION AND HANDLING

Overview of Waste Handling Processes

Current waste management policies promote the disposal of municipal solid wastes at landfills. With increasing pressures on manufacturing facilities to curb disposal rates, more manufacturing facilities are exploring waste to energy conversion technologies as a viable waste management option.

The waste handling process includes transporting waste from the source to a central location for sorting and shredding. All conversion technologies require shredding of the waste to maximize the conversion efficiency of each system, as smaller particles generally lead to faster and more efficient conversion.

Waste sorting is required, as no single technology will support the conversion of every type of waste. Thermal pyrolysis steam reforming, thermal gasification and the thermal oxidation systems have small tolerances for glass and metals, which reduces conversion efficiencies and increases residual ash disposal costs. Thermogenic anaerobic digestion is not applicable for plastics, Styrofoam, glass and metals.

Costs of waste handling are variable, depending mainly on the transportation distance and amount of sorting necessary. Choosing a technology that cannot process several types of materials will have higher waste sorting and handling costs than those that are more flexible. The conversion technology should be located near sources of waste generation to minimize transportation costs.

Transport and Sorting

Transportation and sorting of waste contribute significantly to operational costs. Inefficient and inconsistent waste handling will increase labor and maintenance costs to an energy facility. Therefore an optimal design for transportation and waste separation should be identified.

Materials recovery and waste separation should occur before conversion. This can be accomplished by one, or any combination of the following methods: source separation, pre-process separation, or post-process separation and screening. A successful materials recovery program can increase the energy content of waste biomass by removing recyclables (e.g., glass, and metals) that are non-combustible or have low energy values. The removal of non-combustibles reduces residual disposal costs and operational costs. The feedstock of materials for a conversion technology should be consistent in order to ensure optimal operational performance and conversion efficiency.

Grinding of Waste

Grinding of waste materials to the manufacturer's specified size is important to ensure increased waste conversion for any of the four waste conversion technologies. Several grinding designs were reviewed for the manufacturing waste stream. Conversion technologies vary with regard to feedstock size and mix; therefore, some technologies evaluated require specialized processing equipment specified by the manufacturer. The successful grinder designs have the ability to effectively reduce the particle size of the waste stream, economically and efficiently. A schematic for a typical grinder is shown in Figure 1-1.

The typical grinder features high torque grinding that can process all biomass components present in the waste stream. Removing all glass and metals prior to grinding will decrease wear and maintenance on the machine.

Figure 1-1 Schematic of a Grinder

Economic and Cost Analysis (E1)

The capital costs of a grinder will vary, depending on the specific costs for transportation and installation. Other additional costs may include those for wiring, or alteration of the system depending on the desired location. The capital costs and estimated installation for a typical grinding system is itemized in Table 1-1.

Table 1-1 Estimated Capital Costs of Waste Grinder

Item	Capital Costs
Grinder	$120,000 – 132,000
Installation	$24,000 – 26,400
Total	$144,000 – 158,400

The estimated operational cost for the grinder is summarized in Table 1-2.

Table 1-2 Estimated Yearly Operational Costs of Waste Grinder

Item	Yearly Operating Costs
Electricity for Grinder	$14,500 – 16,700
Maintenance of Grinder	$20,000 – 23,000
Total	$34,500 – 39,700

Energy Analysis (E2)

The amount of energy required for grinding is considered nominal since the average cost is estimated at $0.0013/kg.

Environmental Assessments (E3)

Although emissions are not generated during the waste handling process, dust and odor from the waste streams can present a problem. Therefore, it is recommended that the waste handling and sorting process be enclosed in a building with the necessary dust collection equipment.

Small amounts of water could be added to selected materials just before they are loaded into the grinder to limit the formation of dust. However, the addition of too much water can affect the efficiency of conversion technologies. For certain conversion technologies, waste streams should maintain a minimum moisture level.

Another concern is odor, especially when food is present. Decaying materials can cause odors and adversely affect the plant workers and possibly the surrounding communities. Odor nuisances can be minimized by optimizing the residence time of decaying material onsite.

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2.0 Biomass to Energy Technologies

2.1 INTRODUCTION

All relevant biomass to energy conversion processes and their associated technologies were evaluated using the “3E Assessment Models.” These models were used to compare processes with respect to economics (E1), energy efficiency (E2) and environmental benefits (E3). These models help streamline the selection process for those technologies that have low cost, high efficiency and minimal environmental impact.

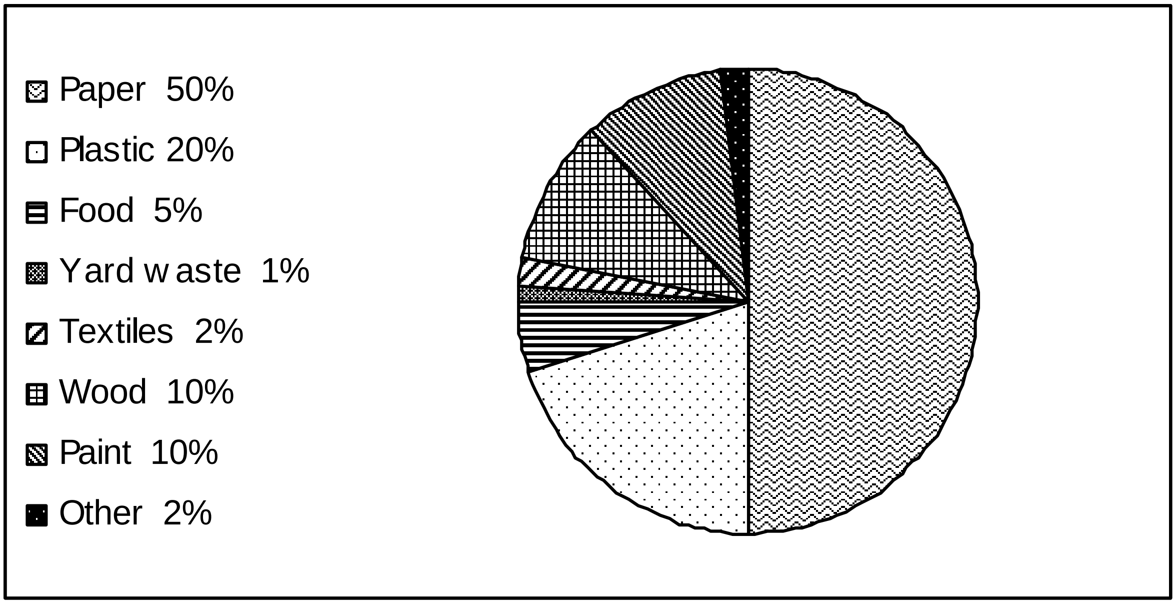
Over 100 processes and suppliers of technologies of thermal gasification, thermal pyrolysis steam reforming, thermal oxidation, next generation thermal oxidation and thermogenic anaerobic digestion systems were evaluated for possible application to the type and magnitude of biomass waste streams generated by a generic U.S. manufacturing facility.

2.2 WASTE STREAM ANALYSIS FOR BIOMASS TO ENERGY

Materials Categorization

Data for this study were gathered by surveying major U.S. manufacturing facilities and used to compile a database for all biomass waste materials and their production quantities that correspond to wastes that could be used in biomass to energy conversion processes. Figure 2-1 illustrates the distribution of waste biomass materials selected for this study.

Figure 2-1 Distribution of Municipal Solid Waste Generated by the Generic U.S. Manufacturing Facility (50 Tons/Day after Recycling)



Compositional Analysis

It is important to carry out a physical and chemical analysis of the waste streams after processing to ensure no toxic materials and all inorganic materials have been removed from the waste stream. The proper design of the thermal gasification, thermal pyrolysis steam reforming, thermal oxidation and next generation thermal oxidation systems requires analyses of the ash and energy content for the processed waste.

Energy Analysis

The theoretical energy output from thermal conversion (thermal gasification, thermal pyrolysis steam reforming, traditional and next generation oxidation) of biomass to energy was calculated from knowing the average energy content (MJ/Kg) for each category of waste material and the quantity of waste generated for each of those categories as given in Table 2-1. The average energy content of the waste stream was calculated by dividing the total energy generating potential (MJ/Year) by the total waste generated (Kg/Year). It was calculated that the average energy content of the entire waste stream is 21.5 MJ/Kg.

Table 2-1 Energy Content of Selected Waste Materials (MJ/Kg) from Manufacturing Operations

Biomass Materials (Categories)	Waste Generated (Tons/Year)	Waste Generated (Kg/Year)	Materials Energy Content (MJ/Kg)	Energy Generating Potential (MJ/Year)
Paper	8225	7.46E+06	17	1.27E+08
Plastic	3290	2.98E+06	40	1.19E+08
Food	823	7.47E+05	10	7.47E+06
Yard waste	165	1.50E+05	15	2.25E+06
Textiles	329	2.98E+05	20	5.97E+06
Wood	1645	1.49E+06	18	2.69E+07
Paint	1645	1.49E+06	10	1.49E+07
Other*****	329	2.98E+05	42	1.25E+07
Total	16,450******	1.49E+07		3.16E+08
Average Energy Content (MJ/Kg)	21.5			

*****Includes oily rags, rubber, Styrofoam, and oily residues.
******Assumes a 90% operational time or 330 days per year at approximately 50 tons per day.

The average amount of energy generated from these thermal conversion processes can then be calculated as follows:

Feedstock Available: 1.49 x 10^7 kg/year = 4.52 x 10^4 kg/day
= 9.97 x 10^4 Lb/day
= 50 tons/day

Average Energy Content: 21.5 MJ/kg or 5.97 kWh/kg

The theoretical energy output is calculated as follows:

Theoretical Energy Output = (4.52 x 10^4 kg/day) (5.97 kWh/kg)
= 2.70 x 10^5 kWh/day = 2.70 x 10^2 MWh/day
= (2.70 x 10^2 MWh/day)/24 hrs/day = 11.3 MW

Economic Analysis

The waste stream categorized in Figure 2-1 has a disposal cost of approximately $658,000 if directly landfilled. This estimate is based on the disposal of a mix waste stream totaling 16,450 tons per year at approximately $40 per ton. This estimate is appropriate for thermal gasification, thermal pyrolysis steam reforming, thermal oxidation and next generation thermal oxidation systems that can accept and convert the entire feedstock. The thermogenic anaerobic digester is able to process only 10,858 tons per year due to the exclusion of non-digestible feed stocks (i.e. plastic, textiles and paint). This will result in some costs for landfilling the non-digestible feedstocks (approximate cost of $434,320).

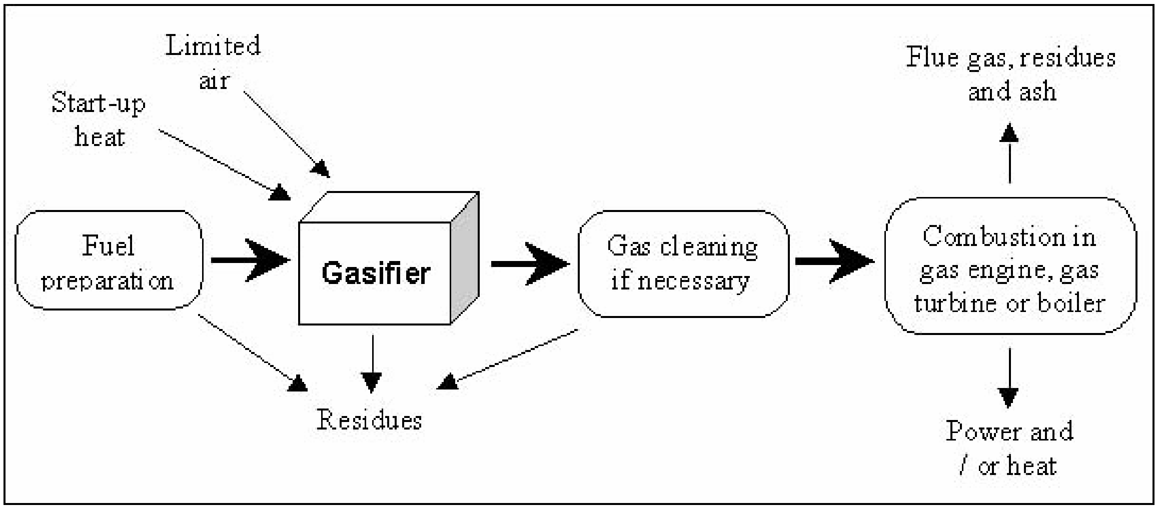
2.3 APPROACH I - THERMAL GASIFICATION

A General Overview of Thermal Gasification Principles

Thermal gasification is a non-combustion process that thermally decomposes biomass materials at high temperatures in a reducing (oxygen-depleted) environment. Carbonaceous material is converted to synthesis gas (syngas), which is composed mainly of hydrogen, methane and carbon monoxide. Syngas may be utilized as a substitute for natural gas in co-generation engines, gas turbines or boilers to produce power and/or heat. Syngas can also be used to develop alcohols, diesel fuel via Fischer-Tropsch processes or Hydrogen through membrane separation. The process flow diagram for a typical thermal gasification process is included as Figure 2-2.

There are four basic steps in the gasification process. First, the feedstock is pre-processed by shredding the material in a grinder to obtain a consistent particle size. To ensure efficient gasification of biomass, it is recommended that the shredded material be mixed to create a more homogeneous blend. Second, the fuel is fed into the oxygen deprived (reducing) gasification chamber where it is heated to the required temperature. In this step, syngas is formed. Syngas has a typical heating value between 35-45% of that for natural gas. Third, particulates, sulfur compounds and other contaminants are removed from the syngas using gas cleanup technologies. Lastly, the clean syngas can be fed directly into an internal combustion engine, turbine or boiler to produce energy and/or heat, or introduced into a natural gas line of a manufacturing facility.

Figure 2-2 Process Flow Diagram for a Typical Gasification System



Although gasification is a high-temperature process, it is quite different from thermal oxidation or combustion. Thermal oxidation or combustion of waste may form toxic dioxins and furans when the gas is cooled in the presence of oxygen. Since gasification occurs in a carefully controlled, closed system, there are no emissions of criteria and toxic air pollutants until the syngas is combusted, at which time emissions control technologies can be applied to manage emissions.

Chevron Texaco, Phillips Conoco (Global Energy) and Shell (Lugi) have developed biomass to syngas production systems for the production of electricity in the 100-500 MW output range. However, these technologies have not proven to be economical and effective for small-scale applications (1-25 MW).

During the past several years several organizations have focused their efforts on the development of small (1-25 MW), economical systems for the conversion of waste materials to energy. Only a few of these companies have successfully demonstrated their technologies by building and systematically testing full-scale operating systems.

Thermal gasification is a conversion technology that can effectively dispose of waste with minimal environmental impact. There are many companies that have explored gasification as an option for reducing waste. In 2000, 102 waste-to-energy facilities were in operation in the United States (Miller, 2002). Although gasification is more popular in Europe, it will become more prominent in the U.S. as waste disposal becomes more costly due to restricted landfill capacities, the associated increase in transportation costs to dispose of waste at alternate sites and higher energy costs. In the year 2000, over 55% of all trash, mainly cardboard boxes, food waste, and newspaper, was still being disposed in landfills in the United States (Miller, 2002).

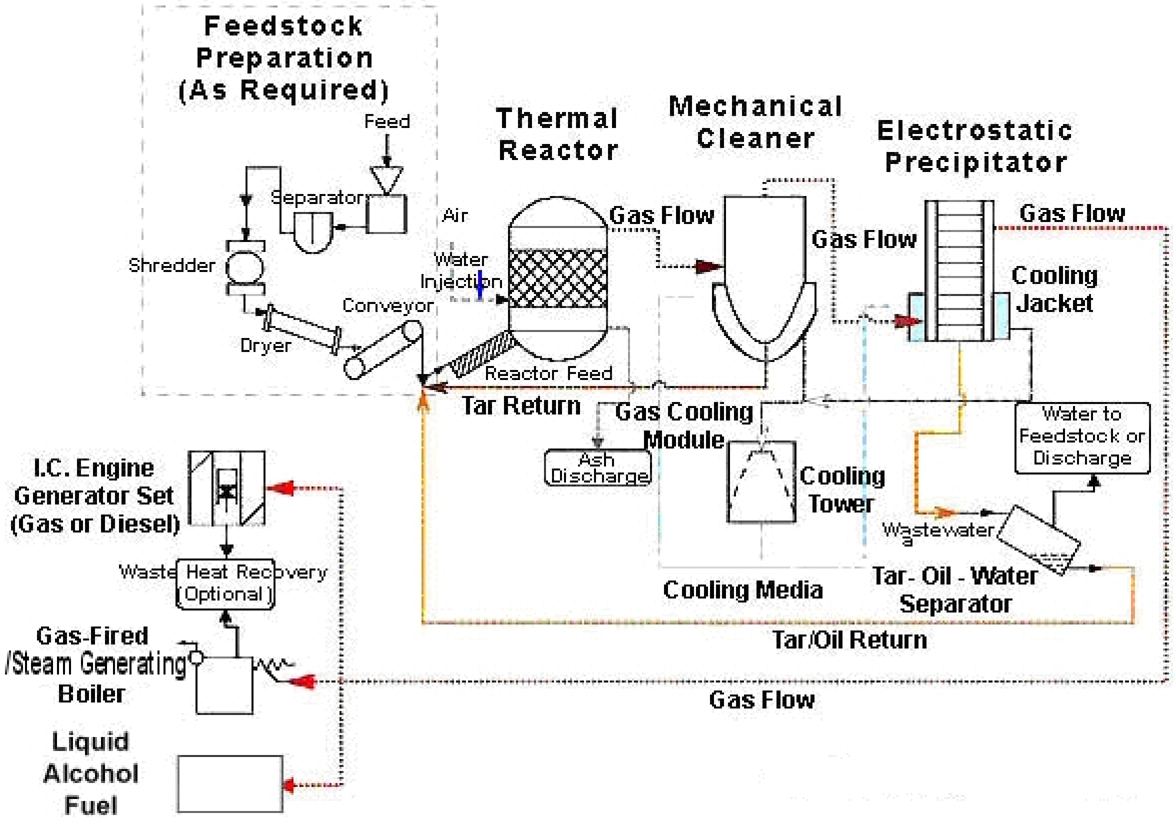
Thermal Gasification System Designs

Waste biomass conversion technologies were systematically evaluated for their potential applicability to the waste biomass stream. The following information was used to help assess the viability of these technologies:

- Concept development, patents, patent applications, technical assessments and peer reviews. Laboratory bench and/or empirical testing data to help prove the viability of the basic technologies and processes.
- Test data for engineering scale pilot plants; typically scaled at 1/100 of a full-scale commercial facility.
- Operational, financial and other relevant data for full-scale, commercial facilities that are producing energy and/or fuels at a profit.

Thermal gasification systems are based on the ability of the system to thermally decompose organic material to synthesis gas. Within the thermal reactor, outlined in Figure 2-3 below, biomass is exposed to high heat in a reducing environment.

Figure 2-3 Thermal Gasification System Schematic



Materials Processing and Introduction

Waste should be sorted before being introduced into a gasification system. Although sorting is costly and time consuming, the feedstock should contain minimal amounts of glass and metal to prevent excessive wear and maintenance on the system. Inorganic materials should be removed and sorted for distribution to a recycling center. The appropriate material sizing is also important to achieving maximum conversion efficiency. Feedstock sizing requirements will depend on the operating parameters and may vary across multiple gasification technologies. In general, feed stocks should be sized below two and a half centimeters in diameter prior to entering the conversion chamber.

Another condition for proper conversion is appropriate moisture content of the feedstock. The moisture content of gasification technologies vary based on the thermodynamics of the system design. Hydro gasification will require the addition of water to the feedstock while thermal gasification technologies will require a dryer feedstock, 30% moisture content, to achieve higher conversion efficiencies.

Economic and Cost Analyses (E1)

The cost of gasification depends on several variables. These factors include: the amount of fuel being processed, the energy content of the fuel, the emissions control equipment, and the process selected to convert syngas to electricity. Additional costs may include those for storage bins and a metering system for the biogas. The capital costs for a gasification system include the gasifier, gas cleaning equipment, gas-fired steam generating boiler and equipment installation itemized in Table 2-2.

Table 2-2 Estimated Capital Costs of Thermal Gasification System

Item	**Capital Costs**
Gasification System (including gas-fired steam generating boiler)	$5,000,000 – 5,500,000
Internal Combustion Engine (ICE)	$1,500,000 – 1,650,000
Grinder	$144,000 – 158,400
Contingency (includes system start up, validation, documentation and training)	$1,046,400 – 1,151,000
Total	**$7,800,000 – 8,580,000**

Annual operational costs of the thermal gasification system include labor, electricity, maintenance, and ash disposal. Exact costs may vary depending on staffing requirements and the price of landfill tipping fees (since residual ash from the gasifier must be disposed in landfills). The operation and maintenance costs of this system are estimated by the manufacturer to be approximately 2% of the capital costs (Table 2-3).

Table 2-3 Estimated Yearly Operational Costs of Thermal Gasification System

Item	**Yearly Operational Costs**
Gasifier Operation and Maintenance	$156,000 – 171,600
Operation and Maintenance of Grinder	$34,500 – 37,950
Operation and Maintenance of ICE	$130,000 – 143,000
Ash Disposal	$25,000 – 27,500
Total	**$345,500 – 380,050**

The capital cost for installation of a 50 ton/day biomass waste thermal gasification system would be $7.8 to $8.6M. The annual operating cost ranges from $345,500 – $380,050. By amortizing the equipment over a ten year period the annual outlay is $1,125,500 – $1,240,050.

Fuels and Energy Production Analyses (E2)

The theoretical energy output is calculated as follows:

$$\begin{aligned}\text{Theoretical Energy Output} &= (4.52 \times 10^4 \text{ kg/day})\ (5.97 \text{ kWh/kg})\\ &= 2.70 \times 10^5 \text{ kWh/day} = 2.70 \times 10^2 \text{ MWh/day}\\ &= (2.70 \times 10^2 \text{ MWh/day})/24 \text{ hrs/day} = 11.3 \text{ MW}\end{aligned}$$

Assuming that the efficiency of this conversion processes is 35%, then the actual energy output can be calculated as follows:

$$\text{Actual Energy Output in MW} = 11.3 \text{ MW} \times 35\% \text{ efficiency} = 3.96 \text{ MW (as syngas)}$$

It is projected that the thermal gasification plant will be operating 7 days/week, three hundred thirty days per the year. This allows for a 10% down time for maintenance and repairs of the system. Therefore, the thermal gasification system will be operating for a total of 7,884 hours per year.

In order to create electricity the produced syngas would have to be used in an internal combustion engine (ICE) or combusted in a boiler in which steam could be produced and used in a steam turbine. Assuming the conversion of syngas to electricity via an ICE or boiler/turbine system has an efficiency of 40%, the electricity output can be calculated as follows:

$$\text{Energy Output in MW} = 3.96 \text{ MW} \times 40\% \text{ efficiency} = 1.58 \text{ MW (as electricity)}$$

The electricity generated by the thermal gasification system has a value of 12,456 MW-hrs/Year.

Alternative electricity generating options include the use of syngas in a molten carbonate fuel cells or micro turbine system. Additional alternative fuels options include Fischer-Tropsch diesel fuel, alcohols and Hydrogen.

Environmental Assessments (E3)

The thermal gasification system provides benefits to the environment by reducing the quantity of solid wastes that would otherwise be sent to landfills.

The emissions generated from thermal gasification are significantly lower than those from traditional thermal oxidation or incineration systems. Gasification occurs in a closed system; therefore, no emissions may escape into the atmosphere until the syngas is combusted. Most pollutants, such as sulfur and heavy metals, are retained in the ash instead of being discharged to the atmosphere.

Emissions will be generated when the syngas is used to produce electrical power, steam or other products. The magnitude of these emissions will be dependent upon the type of technologies that utilize the syngas and the waste stream utilized as feedstock.

Emissions associated with the combustion of the syngas will consist primarily of nitrogen oxides and carbon monoxide, the magnitude of which will depend upon the type of internal combustion engine, boiler, or other electricity generating equipment used as well as the composition of the waste stream utilized as feedstock. For this analysis we have assumed the exclusion of chlorinated waste from the feedstock.

2.4 APPROACH II – THERMAL PYROLYSIS STEAM REFORMING

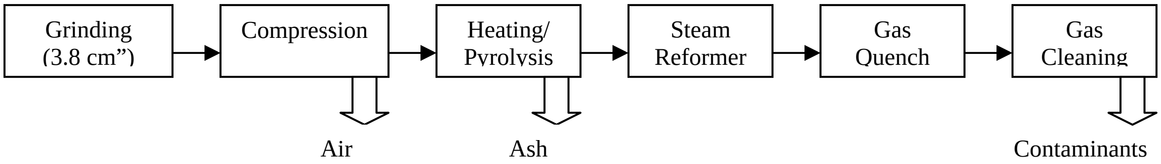
A General Overview of Thermal Pyrolysis Steam Reforming Principles

Thermal pyrolysis steam reforming is a process similar to thermal gasification, except that the thermo chemical process has been optimized for conversion of biomass to liquid fuels. Liquid pyrolysis (or pyrolysis oils) can be used in a boiler or undergo further processing to be used as engine fuels, chemicals and other products. Thermal pyrolysis typically takes place at 750 - 1500°C and is characterized as conversion of biomass without the addition of oxygen or ambient air.

Thermal Pyrolysis Steam Reforming System Designs

The thermal pyrolysis steam reforming system depicted in Figure 2-4 illustrates the process flow of the system. The feedstock should be sized to 3.8 centimeters and smaller to increase conversion efficiency. The feedstock is fed into a compressor to remove excess air for optimal conversion of biomass to syngas. During compression of the feedstock, heat is applied to remove any entrained oxygen prior to pyrolysis. The pyrolysis process converts biomass to pyrolysis products. A steam reforming step (982° C) is utilized to convert the pyrolysis products (large chain molecule, tar and char) into smaller gas molecules. The high temperature gas is then fast quenched and cleaned to remove contaminants. The high Btu syngas (500 Btu/scf) can be used directly in an internal combustion engine, gas turbine, or converted to clean burning diesel fuel, ethanol, or hydrogen. The ash is removed from the system after the pyrolysis step and can be used in a number of inert applications.

Figure 2-4 Process Flow for a Thermal Pyrolysis Steam Reforming System



Materials Processing and Introduction

Similar to the thermal gasification system, the thermal pyrolysis steam reforming system feedstock should be sorted before being introduced into a conversion chamber. In addition to the feedstock sized below 3.8 centimeters, the moisture content should not exceed 40% for this conversion technology.

Economic and Cost Analyses (E1)

Economic and Cost Analyses are based on estimates of waste stream composition; total amount of wastes generated and expected costs. Expected cost may require site-specific adjustments. Tables 2-4 and 2-5 provide the estimated capital and operational costs for what is believed to be the most effective thermal pyrolysis steam reforming system available in the marketplace.

Table 2-4 Estimated Capital Costs of Thermal Pyrolysis Steam Reforming System

Item	Capital Costs
Gasifier	$2,000,000 – 2,200,000
Ancillary Equipment	$200,000 – 220,000
Internal Combustion Engine (ICE)	$1,450,000 – 1,595,000
Grinder	$350,000 – 385,000
Electric Gear	$400,000 – 440,000
Civil Works	$400,000 – 440,000
Engineering, Procurement, Construction and Contingency (includes system start up, validation, documentation and training)	$996,000 – 1,095,600
Total	**$5,796,000 – 6,375,600**

Annual operational costs of the thermal pyrolysis steam reforming system include labor, electricity, maintenance, and ash disposal. Exact costs may vary depending on staffing requirements and the price of ash landfill tipping fees. Residual ash from the conversion chamber may be disposed in landfills if alternative uses cannot be identified.

Table 2-5 Estimated Operational Costs of Thermal Pyrolysis Steam Reforming System

Item	Yearly Operating Costs
Gasifier Operation and Maintenance	$422,900 – 465,200
Operation and Maintenance of ICE	$211,700 – 232,900
Chemicals	$23,500 – 25,900
Ash disposal	$19,000 – 20,900
Spare Parts	$151,200 – 166,300
Total	**$828,300 – 911,200**

In summary, the thermal pyrolysis steam reforming system would cost $5.80 – $6.38 M to install and $828,300 – $911,200/year to operate and maintain. By amortizing the equipment over a ten year period the annual outlay is $1,408,300 – $1,549,200.

Fuels and Energy Production Analyses (E2)

The theoretical energy output is calculated as follows:

$$\begin{aligned}\text{Theoretical Energy Output} &= (4.52 \times 10^4 \text{ kg/day})\ (5.97 \text{ kWh/kg}) \\ &= 2.70 \times 10^5 \text{ kWh/day} = 2.70 \times 10^2 \text{ MWh/day} \\ &= (2.70 \times 10^2 \text{ MWh/day}) / 24 \text{ hrs/day} = 11.3 \text{ MW}\end{aligned}$$

The thermal pyrolysis steam reforming system is able to convert biomass to syngas at a rate of 79.2% efficiency. This conversion efficiency yields approximately 8.95 MW of energy in the form of syngas.

$$\text{Actual Energy Output in MW} = 11.3 \text{ MW} \times 79.2\% \text{ efficiency} = 8.95 \text{ MW (as syngas)}$$

In order to convert the syngas to electricity an internal combustion engine is used at a conversion efficiency of 40%. The actual electrical output is 3.58 MW.

$$\text{Energy Output in MW} = 8.98 \text{ MW} \times 40\% \text{ efficiency} = 3.58 \text{ MW (as electricity)}$$

It is projected that the thermal pyrolysis steam reforming plant will be operating seven days per week, 330 days per the year. This allows for a 10% down time for maintenance and repairs of the system. Therefore, it will be operating for a total of 7,884 hours, and the amount of generated energy will be approximately 28,225 MW-hrs/Year.

Environmental Assessments (E3)

The thermal pyrolysis steam reforming system provides benefit to the environment by reducing the quantity of solid wastes that would otherwise be sent to landfills.

The emissions generated from thermal pyrolysis steam reforming system are similar to the thermal gasification system due to conversion of biomass to energy occurring in a closed system. The closed system prevents the development of emissions until the syngas is combusted. Most pollutants are retained in the ash, which can be reused in other industries.

Emissions will be generated when the syngas is used to produce electrical power, steam or other products. The magnitude of these emissions will be dependent upon the type of technologies that utilize the syngas and the waste stream utilized as feedstock.

2.5 APPROACH III – THERMAL OXIDATION

A General Overview of Thermal Oxidation Principles

Thermal oxidation is the most developed and most frequently applied process because of its proven conversion ability and reliability. Thermal oxidation (combustion) systems usually operate as a two-stage batch process. In the first stage, waste is converted to gas in the primary chamber at 500^{o}C - 650^{o}C. Burners are used to raise the temperature of the primary chamber to dry the waste and bring the chamber up to the combustion temperature of the waste. The process then becomes self-fueling until the original waste volume and weight is reduced by over 90%. In the second stage of the combustion process, the released gases (hydrocarbons, methane, and carbon monoxide) are oxidized to release thermal energy.

A number of studies have shown that the residual ash is non-hazardous, non-leaching and essentially inert. After enduring the oxidation process, metals and glass remain intact but are considered sterilized and safe to handle. This allows for the possibility of post-combustion recycling.

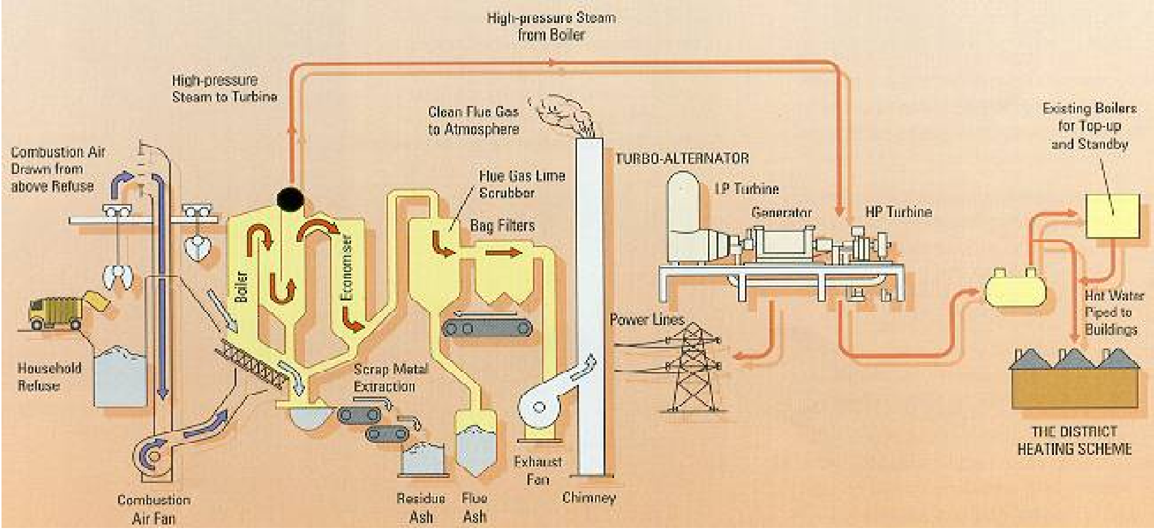
During the oxidation process, gases enter the high temperature (1000^{o}C), oxygenated and turbulent conditions of the secondary oxidation chamber for combustion. Critical process parameters such as temperature, airflow and burner output, are computer controlled in order to maintain optimal oxidation conditions. The process is complete after a minimum retention time of one to two seconds. A number of systems have been developed that provide a consistent and clean burn, ensuring compliance with environmental standards.

Waste-to-energy thermal oxidation plants have a design capacity that is based on a combination of two factors. The first factor considers the physical capacity of the intake system and the grates that transport the waste into the combustion chamber. The second factor to consider is the heat generation capacity of the furnace. There can be difficulties with the functioning of the system if the combustion system is improperly designed for the specific waste stream, if the incoming waste is too wet or too dry, if it is rich in combustibles, or too high in non-combustibles.

Thermal Oxidation System Designs

Figure 2-5 below illustrates the thermal oxidation system.

Figure 2-5 Thermal Oxidation System Schematic



Materials Processing and Introduction

Waste should be sorted before being introduced into the combustor to remove glass and metal recyclables. These materials should be removed and sorted for distribution to a recycling center.

Economic and Cost Analyses (E1)

Economic and cost analyses are based on estimates of waste stream composition; total amount of wastes generated and expected costs. Expected cost may require site-specific adjustments. Tables 2-6 and 2-7 provide the estimated capital and operational costs. The oxidation cost listed in Table 2-6 includes the appropriate scrubbers and loader.

Table 2-6 Estimated Capital Costs of Thermal Oxidation System

Item	Capital Costs
Oxidation Unit and Grinder	\$5,000,000 – 5,500,000
Engineering and Design, Construction Supervision and Installation Supervision	\$924,000 – 1,062,600
System Start up and Validation	\$36,000 - 39,600
Training and Documentation	\$100,000 – 110,000
Contingency	\$1,503,000 – 1,654,000
Total	**\$9,963,000 – 11,006,000**

Annual operational costs of the thermal oxidation system include labor, electricity, maintenance, and ash disposal. Exact costs may vary depending on staffing requirements and the price of ash tipping fees. Residual ash from the oxidizer may be disposed in landfills.

Table 2-7 Estimated Operational Costs of Thermal Oxidation System

Item	Yearly Operating Costs
Operation and Maintenance of Oxidizer and Grinder	\$1,098,000 – 1,207,800
Electricity for Gas Cleaning Equipment	\$40,000 – 44,000
Maintenance of Gas Cleaning Equipment	\$60,000 – 66,000
Total	**\$1,198,000 – 1,317,800**

In summary, the capital cost for installation of a 50 ton/day biomass waste thermal oxidation system would be approximately \$9.96 – \$11.0 M. The annual operating cost ranges from \$1,198,000 to \$1,317,800. By amortizing the equipment over a ten year period the annual outlay is \$2,294,000 – \$2,527,800.

Fuels and Energy Production Analyses (E2)

Table 2-8 provides the estimated power output for a thermal oxidizer system and the energy that could be generated using a single stage turbine. The expected energy output from this system would be 1.4 MW. The theoretical energy content of this waste is 11.3 MW; therefore the thermal efficiency would be 12.4%. The electricity generated by the thermal oxidation system has a value of 11,038 MW-hrs/Year.

Table 2-8 Estimated Power Output for a Thermal Oxidizer System (PPHS to kW Electrical)

Biomass Input (Ton/Day)	Est. Energy Available from Oxidizer (mm BTU/hr	Boiler Size (HP)	PPHS (225-2) psig differential	Single Stage Turbine
50	51.5	1071	36,900	1.4 MW

Assumptions:

- Waste has a heating value of ~21.5 MJ/kg.
- Boilers have rating of 82% efficiency.
- Boilers operate under pressure of 225 psig.
- Steam has a heat content of 1,143 Btu per pound.
- Steam production is available only during the hours the equipment is burning waste.
- All estimates may vary slightly according to actual waste composition, moisture content, loading and operating conditions.

Environmental Assessments (E3)

The proposed combustion system reduces waste to a sterile ash, thereby reducing transport costs and landfill requirements, and saving on the consumption of fossil fuels. It also eliminates the production of methane, a potent greenhouse gas, associated with the degradation of waste that has been sent directly to a landfill. The combustion system has the potential to create toxic dioxins and furans, which would result in increased regulatory and permitting requirements.

2.6 APPROACH IV - NEXT GENERATION THERMAL OXIDATION

A General Overview of Next Generation Thermal Oxidation Principles

The next generation thermal oxidation system is a process which relies on both thermal gasification and oxidation principles for the efficient conversion of biomass to usable energy. Using patented technology the system has the ability to handle a wide range of biomass solids with moisture content less than 50%. The next generation thermal oxidation system is based on high temperature gasification and subsequent oxidation of biomass material. The conversion chamber is ceramic lined with an arched roof allowing for all radiated heat to be reflected back onto the biomass pile. The arched roof and air controls promote multi-level biomass conversion.

The first step in biomass conversion is the gasification of biomass to syngas. This is accomplished in the lower reducing, or oxygen deprived, section of the conversion chamber. In this section the temperature ranges from 600-800°F. As the feedstock is reduced and syngas is produced the gas migrates to the upper section of the conversion chamber where oxidizing conditions exist. In the upper section of the chamber fans introduce oxygen which allows for the oxidation of the syngas, thus producing thermal energy. As thermal energy develops within the conversion chamber the ceramic lined wall radiate energy back onto the biomass pile feeding the conversion process. In the upper portion of the chamber the temperature ranges from 2000-

2400°F. By combusting the syngas within the conversion chamber this system takes advantage of higher biomass conversion efficiency and lower equipment costs. Thermal energy is used to produce super heated steam which can be used for electricity generation in a steam turbine as well as lower grade heat for other processes. This design allows for 99% reduction in biomass.

Traditional thermal oxidation systems rely on the oxidation of biomass to produce relatively small amounts of energy due to low conversion efficiencies. The next generation thermal oxidation system has achieved higher conversion efficiencies and lower environmental impacts through optimal biomass conversion engineering and design.

Materials Processing and Introduction

Waste must be sorted before being introduced into the next generation thermal chamber. As mentioned in previous sections, non-combustible materials (metals and glass) should be removed and sorted for distribution to a recycling center.

Sorted waste is processed to 1 centimeter pieces in a grinder. The waste should have a moisture content of less than 50% to ensure high conversion efficiencies. Since the waste contains mostly paper, cardboard, and plastic, the moisture content should be sufficiently low for the next generation thermal oxidation process.

Economic and Cost Analyses (E1)

Economic and cost analyses are based on estimates of waste stream composition, total amount of wastes generated and expected costs. Expected costs may require site-specific adjustments. Tables 2-9 and 2-10 provide the estimated capital and operational costs for what is believed to be the most effective integrated thermal gasification oxidation system available.

Table 2-9 Estimated Capital Costs of Next Generation Thermal Oxidation System

Item	Capital Cost
Biomass Conversion and Steam System	$2,050,000 – 2,255,000
Multistage Steam Turbine Generator System	$1,300,000 – 1,430,000
Grinder	$144,000 – 158,400
Engineering and Design, Construction Supervision and Installation Supervision	$598,800 – 676,300
System Startup and Validation	$36,000 - 41,400
Training and Documentation	$100,000 – 115,000
Contingency	$998,000 – 1,127,200
Total	**$5,226,800 – 5,803,300**

Annual operational costs of the next generation thermal oxidation system include labor, electricity, maintenance, and ash disposal. Exact costs may vary depending on staffing requirements and the price of landfill tipping fees (since residual digest from the digester may be disposed in landfills).

Table 2-10 Estimated Operational Costs of Next Generation Thermal Oxidation System

Item	**Yearly Operational Costs**
Operation and Maintenance of Biomass Conversion and Steam System	$95,000 – 107,000
Operation and Maintenance of Grinder	$34,500 – 37,950
Ash Disposal	$25,000 – 45,000
Total	**$154,500 – 189,950**

In summary, the next generation thermal oxidation system requires a capital expenditure of $5.23 – $5.80 M to install and $154,500 – $189,950/year to operate. Lower labor costs can be attributed to the relatively simple design and minimal need for operator regulation of the equipment. By amortizing the equipment over a ten year period the annual cost of ownership is $677,180 – $770,280.

Fuels and Energy Production Analyses (E2)

The next generation thermal oxidation system has the capacity to convert a wide range of biomass fuels into usable energy. The following energy production analysis provides a typical energy output using the next generation thermal oxidation system as a biomass to energy conversion process. The following assumes an operation time of 90% and an oxidation system maximum heat rate of 50 MMBTU/Hr (million million BTUs per hour).

In order to estimate the energy efficiency of the system, the following system efficiencies have been used:

- Oxidation efficiency: 97%
- Boiler efficiency: 76%
- Economizer efficiency: 50%
- Total Steam Production Efficiency: 85%

The next generation thermal oxidation system would generate approximately 1.82 MW of energy as it is currently configured. This system is able to convert biomass to energy at an efficiency of 16%. Assuming the conversion system has an uptime of 7884 hours per year the electricity generated by the next generation thermal oxidation system has a value of 14,349 MW-hrs/Year.

Environmental Assessment (E3)

The next generation thermal oxidation system provides benefits to the environment by reducing the quantity of solid wastes that would otherwise be sent to landfills.

Similar to the thermal oxidation process, emissions will be generated when the biomass is converted to thermal energy. The magnitude of these emissions will be dependent upon the composition of the feedstock and type of emissions control technologies utilized to minimize emissions. A single cyclone dust collector and wet electrostatic precipitator are used to control emissions to the requisite agency regulations.

2.7 APPROACH V – THERMOGENIC ANAEROBIC DIGESTION

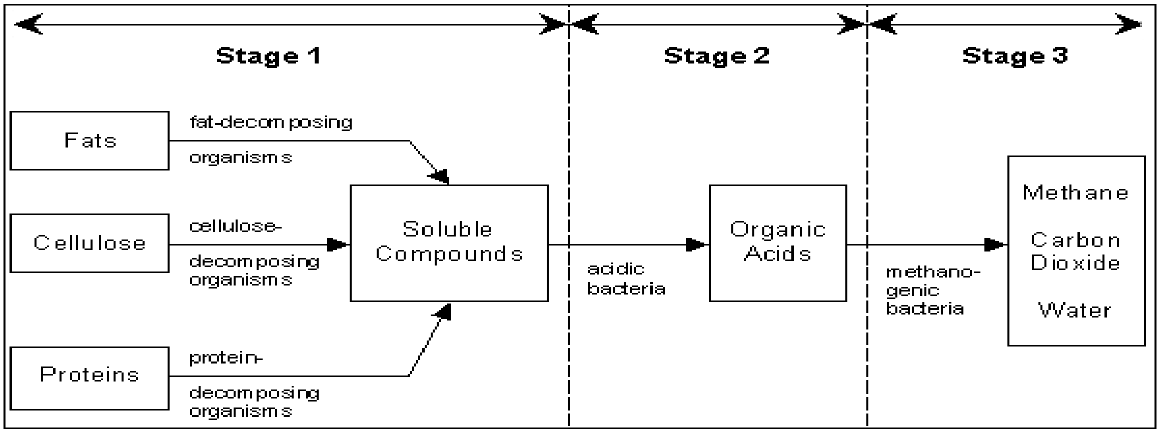
A General Overview of the Thermogenic Anaerobic Digestion Principles

Thermogenic Anaerobic Digestion is a biochemical process by which bacteria decompose organic matter in the absence of oxygen. This process produces biogas, and solid and liquid residues (digestate). Biogas can be used to fuel boilers and internal combustion engines. The biogas produced consists primarily of methane, carbon dioxide, and trace amounts of nitrogen, sulfur compounds, volatile organic compounds and ammonia. The amount of methane produced through thermogenic anaerobic digestion is dependent on the composition of the feedstock provided to the digester. Methane produced in anaerobic digesters may be 50-80% of total gas yields (U.S. Dept of Energy 2003). The digestate can be used as soil conditioner or daily cover at landfill facilities (Waste Research 2003). The main air pollution concern for thermogenic anaerobic digestion systems comes as a result of biogas combustion.

Thermogenic anaerobic digestion differs from traditional composting in that the process is assisted by the addition of the appropriate bacteria in a mesophilic (36.7°C) to thermophilic (54.4°C) environment to optimize bacterial growth. Higher temperature digesters result in shorter biomass residence times and hygenization of digestate. Methane fermentation is assisted by methanogens, which convert simple sugars into methane in a reducing environment.

The first step in the digestion process is the decomposition of organic matter (Stage 1). This step breaks down the organic material such as paper, food wastes, wood, yard waste, cardboard, and agricultural wastes into smaller molecules such as sugar. The second step is the conversion of decomposed matter to organic acids (Stage 2). And finally, the acids are converted to methane gas (Stage 3). Figure 2-6 below details the biochemical process flow within an anaerobic digester.

Figure 2-6 Process Flow for a Thermogenic Anaerobic Digester

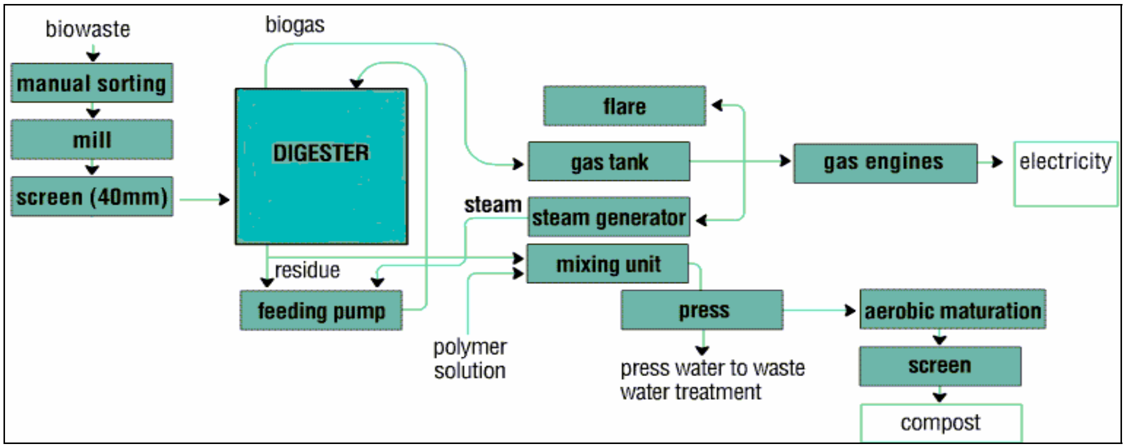


Thermogenic Anaerobic Digestion System Designs

Several anaerobic digestion systems were analyzed for this report. A typical thermogenic anaerobic digestion system is illustrated in Figure 2-7. Prior to entering the system, the organic component of the waste is separated from the glass and metals through manual sorting. The organic portion of the wastes are milled and screened to ensure uniform size of feedstock. Inside the digester various bacteria decompose the organic material.

Digesters are typically heated to 37°C to 54°C to facilitate bacterial growth. Thermophilic systems (above 50°C) provide a hygienic benefit of destroying possible pathogens that may exist within the solid and liquid digestate. Retention time of bio-wastes in the digester is between fifteen and thirty days. Produced biogas is piped from the digester to a gas holding container. Anaerobic digesters may be equipped with scrubbers to ensure gas-line quality gas depending on the operating parameters of the boiler systems. The digestate not decomposed by bacteria due to high lignin concentrations is removed from the digestion chamber. A portion of the digestate is collected for reuse in the digester. The digestate is dewatered and aerobically matured to produce soil amendments, fertilizer, and compost or landfill cover.

Figure 2-7 Schematic for the Thermogenic Anaerobic Digestion System



Materials Processing and Introduction

Prior to feeding waste into the anaerobic digester, the waste streams must be sorted to remove inorganic elements. Sorting removes any un-digestible waste streams such as plastics, glass, metals, stones, etc. The wastes are then processed to establish a well-mixed feedstock prior to entering the digester. Anaerobic digesters require sorting and mixing to ensure a homogenous feedstock.

Economic and Cost Analyses (E1)

Economic and Cost Analyses are based on estimates of waste stream composition; total amount of wastes generated and expected costs. Expected cost may require site-specific adjustments. Tables 2-11 and 2-12 provide the estimated capital and operational costs for what is believed to be the most effective thermogenic anaerobic digestion system available in the marketplace.

Table 2-11 Estimated Capital Costs of Thermogenic Anaerobic Digestion System

Item	**Capital Costs**
Digester	$6,000,000 – 6,600,000
Gas and Emissions Treatment Systems	$250,000 – 275,000
Pretreatment (including grinder)	$2,000,000 – 2,200,000
Piping and Metering System for Syngas	$30,000 – 33,000
Engineering and Design, Construction Supervision and Installation Supervision	$1,701,100 – 1,871,100
System Start up and Validation	$36,000 - 39,600
Training and Documentation	$100,000 – 110,000
Post Treatment of Digestate (Including Engineering)	$4,500,000 – 4,950,000
Contingency	$2,835,100 – 3,118,600
Total	**$17,452,200 – 20,197,300**

Annual operational costs of the thermogenic anaerobic digestion system include labor, electricity, maintenance, and residual digestate disposal. Exact costs may vary depending on staffing requirements and the price of landfill tipping fees (since residual digest from the digester may be disposed in landfills).

Table 2-12 Estimated Operational Costs of Thermogenic Anaerobic Digestion System

Item	Yearly Operating Costs
Operation and Maintenance	$330,000 – 380,000
Electricity for Anaerobic Digester	$125,000 – 144,000
Electricity for Gas Cleaning Equipment	$40,000 – 46,000
Maintenance of Gas Cleaning Equipment	$20,000 – 23,000
Disposal of Non-Digested Materials	$40,000 – 46,000
Total	**$605,000 – 639,000**

In summary, the thermogenic anaerobic digestion system would cost $17.5-$20.2 M to install and $605,000 – $639,000/year to operate and maintain. By amortizing the equipment over a ten year period the annual outlay is $2,355,000 – $2,659,000.

Fuels and Energy Production Analyses (E2)

The thermogenic anaerobic digestion system is limited to organic bio-wastes including paper, cardboard, wood, and food waste. Although the calorific value of the waste varies with the content, this analysis estimates the appropriate waste streams contain 10 – 15 MJ/kg. From these waste streams the selected system can produce 100 – 150 normal cubic meters (Nm3) of biogas. The methane content of the produced biogas is 55%, which has a calorific content of 20 MJ/m3. Biogas production can be used to fuel a boiler for hot water, steam or production. When the produced biogas is used to create electricity, it has a value of 1,303 MW-hrs/Year.

Environmental Assessments (E3)

Thermogenic anaerobic digestion provides benefits to the environment through energy and nutrient recycling, while mitigating the impacts of atmospheric methane produced at landfills. Thermogenic anaerobic digestion also displaces wastes that would have otherwise been placed in a landfill.

Using solid and liquid residues from the thermogenic anaerobic digestion processes have environmental benefits as well. The principle solid component, digestate, can be matured further to develop soil amendments, which can be used in nursery or farmland applications and as landfill cover. The liquid fraction of digestate contains nutrients useful for soil fertilization. Furthermore, the use of biogas displaces the consumption of non-renewable fossil fuels. In this way, the conversion of biomass to energy lessens the environmental impact of manufacturing processes.

Similar to the thermal gasification and the thermal pyrolysis steam reforming process, emissions will be generated when the biogas is used to produce electrical power, steam or other products. The magnitude of these emissions will be dependent upon the type of technologies that utilize the biogas and the waste stream utilized as feedstock.

3.0 Payback Analysis

The payback analysis conducted for this report is based on total capital costs, yearly savings, operational costs, and number of years for payback. Total capital costs are based on the total capital required for installation of the conversion system. The yearly savings are based on the total amount of waste converted that would have otherwise been sent to a landfill at $40 per ton, in addition to the energy benefit based on the total amount of electricity produced per year at a rate of 6.6 cents per kilowatt-hour, minus the operating costs of the conversion system. According to the Department of Energy's Energy Information Administration, average U.S. energy prices will remain at approximately 6.6 cents per kilowatt-hour until 2011. From 2011 to 2025 prices are expect to rise 0.3 percent per year to 6.9 cents per kilowatt-hour (U.S. DOE, 2004). Number of years for payback was calculated by dividing the total capital expenditure by yearly savings.

Table 3-1 Biomass to Energy Conversion System Payback Analysis

Technology	Total Capital Cost	Operating Cost	Yearly Savings	Number of Years for Payback
Thermal Gasification	$7.8 – $8.6 M	$346 – $380K	$1.10 – $1.13 M	6.9 – 7.8 Years
Thermal Pyrolysis Steam Reforming	$5.6 – $6.4 M	$828 – $911K	$1.60 – $1.69 M	3.4 – 4.0 Years
Thermal Oxidation	$10.0 – $11.0 M	$1.30 – 1.43M	($69K) – $189K	52.9 – N/A Years
Next Generation Thermal Oxidation	$5.2 – $5.8 M	$155 – $190K	$1.42 – $1.45 M	3.6 – 4.1 Years
Thermogenic Anaerobic Digestion	$17.5 – $20.2 M	$605 – $639K	($85K) – ($119K)	N/A

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4.0 Electricity and Fuel Production Technologies

4.1 INTRODUCTION

Electricity and fuel production technologies associated with the conversion technologies analyzed continue to develop in parallel with many of the systems discussed in this report. As a greater need arises for alternative electricity and fuel sources, these technologies will be in higher demand to become mainstream electricity and fuel production options. This report has discussed the use of electricity and fuel production technologies with mature and emerging technologies such as boilers and steam turbine systems, micro turbines, internal combustion engines, fuel cells, Fischer-Tropsch diesel fuel, alcohols and hydrogen. The use of the aforementioned technologies will depend on the application, need for specific electricity and energy type, and cost.

Boiler and Steam Turbine Systems

The use of mature boiler and steam turbine systems to convert syngas into usable electricity is a proven method. Syngas produced by the conversion technology is piped into the boiler at which point it is combusted to create energy in the form of heat. The heat is used to create steam, which in turn drives a turbine to produce electricity. This option is limited by the generation of air emissions (which must be controlled) and high capital cost. Boilers typically have an efficiency of 76-82%. Steam turbines can have an efficiency of approximately 45% for a total efficiency of 34 – 37%.

Micro Turbine

Micro turbines are small combustion turbines that utilize a pressurized gas combusted to create heat energy. The heat energy expands the surrounding air and this high speed flow of air spins the turbine. There are three basic parts to a micro turbine; the compressor, combustor, and turbine. The compressor creates high pressure air. The combustor burns the fuel (syngas) to create gas under high pressure and velocity. Lastly, the turbine is used to extract energy flowing from the combustor. Micro turbines can produce between 25 kW and 500 kW of electricity with a conversion efficiency of 30%. Micro turbines are an option, commercially available, for electricity generation; however are limited by their energy output capabilities.

Internal Combustion Engines

Internal combustion engines (ICE) convert stored energy (syngas) into mechanical energy. This mechanical energy is used to turn a shaft in the engine. The rotating shaft is attached to a generator to produce electricity. This technology is mature and widely available for 5 kW – 7 MW systems. The conversion efficiency of the system can range from 25-45%.

Fuel Cells

Fuel cells use electrochemical processes to create electricity. In general this is done by combining hydrogen and oxygen to produce water. Electricity is produced as a product of the chemical reaction. There are various types of fuel cells, which are typically classified by the type of electrolyte and materials utilized.

Proton exchange membrane fuel cells (PEMFC) utilize a platinum catalyst to split the hydrogen molecule into two hydrogen ions and two electrons. On the anode side the two electrons go through an external circuit where they can do work such as turn a motor. On the cathode side the oxygen is forced over the catalyst forming two oxygen molecules, which later join the hydrogen atoms and form water. The PEMFC utilizes pure hydrogen at a temperature of 80° C. PEMFCs should be considered for residential, automotive, commercial, light industrial and portable power.

Phosphoric acid fuel cells (PAFC) use liquid phosphoric acid as the electrolyte. PAFCs are able to reform syngas to a highly concentrated hydrogen gas for use as a fuel. PAFCs can also utilize methanol or ethanol as fuel. The PAFC operates at 200° C, which may limit its application for transportation but would be suitable for small stationary power generation systems. PAFCs are suitable for use in commercial and light industrial applications.

Solid oxide fuel cells (SOFC) utilize a non-porous ceramic as the electrolyte. SOFCs operate at high temperature (650 - 1000° C). Due to the high heat requirement SOFCs can be utilized as cogeneration systems creating electricity and thermal energy. SOFCs should be considered for residential cogeneration, small commercial buildings and industrial facilities.

Molten carbonate fuel cells (MCFC) use a molten salt mixture suspended in a porous, chemically inert ceramic lithium aluminum oxide matrix as an electrolyte. Similar to the SOFCs, the high heat requirement allows MCFCs to be utilized as cogeneration systems. MCFCs should be considered for industrial, government facilities, hospitals and universities.

Fuel cells range in energy output from 1 kW – 10 MW depending on the electrolyte and materials used. Fuel cell efficiencies range from 30 – 55% among the various types of fuel cells. The current limitations for fuel cells are the high capital costs, lack of demonstrated long term dependability and lack of field testing.

Fischer-Tropsch Fuel

Fischer-Tropsch chemistry allows for syngas to be converted to diesel fuel via contact with cobalt, iron or nickel catalysts in the presence of heat. Products from this reaction include light hydrocarbons (CH4) and ethane (C2), LPG (C3-C4), gasoline (C5-C12), diesel (C13-C22), and light oils and waxes (C23-C33). The amount of each product depends on the catalyst and the operating conditions (temperature, pressure and residence time). The limitation to utilizing Fischer-Tropsch chemistry to develop liquid fuels is the complexity of the process and production of multiple products. The complexity of the process requires experienced operators. The production of multiple products ranging from low molecular mass methane to high molecular mass waxes makes the conversion of biomass to energy more complex and thus creates added energy conversion costs.

Alcohol

Methanol is produced by steam reforming of syngas, which is then fed into a reactor vessel. Within the reactor vessel syngas is converted to methanol under high temperature and pressure in the presence of a catalyst. The product is distilled to purify and separate the methanol. Methanol can be used as an alternative fuel or an octane boosting additive for gasoline. Methanol can be blended with unleaded gasoline to create M-85 (85% Methanol and 15% gasoline). Methanol has many advantages as a transportation fuel due to lower emissions, higher performance and lower risk of flammability than traditional gasoline. Additionally, researchers are developing methods to use methanol as a source for hydrogen production.

Hydrogen

The most common process for producing hydrogen from syngas involves steam reforming. Hydrogen production by steam reforming takes place in the presence of a nickel catalyst and results in the production of hydrogen and carbon monoxide. Hydrogen produced by steam reforming can be used for electricity generation in fuel cells. Currently high costs prohibit the widespread use of hydrogen as a fuel.

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5.0 Conclusions

An economic, environmental and energy assessment for four types of biomass conversion technologies was carried out to evaluate conversion of waste biomass materials to energy and/or fuels. Waste biomass generated from a generic U.S. manufacturing facility was used for the model assessment. The biomass conversion systems evaluated included (1) Thermal gasification, (2) Thermal pyrolysis steam reforming (3) Thermal oxidation systems and (4) Thermogenic anaerobic digestion. This study found that each conversion technology analyzed was able to convert part or all of the waste from a typical manufacturing facility. The selection of one technology over another to produce energy from waste should be weighed with respect to the economics, energy conversion efficiency and environmental impact of each technology.

Technologies were evaluated using a "3E" assessment approach. The "3E" approach was used to evaluate the conversion processes with respect to economics (E1), energy efficiency (E2) and environmental impact (E3). Table 5-1 summarizes the result of this assessment for these emerging conversion technologies.

Table 5-1 A Summary of the "3E" Assessments for the Biomass Conversion Processes

Conversion Technology	Economic Impact (E1)	Energy Output (E2)	Environmental Impact (E3)
Thermal Gasification	$7.8-8.6 M	12,456 MW-hrs/Year	Negligible with proper emissions control
Thermal Pyrolysis Steam Reforming	$5.8-6.4 M	28,225 MW-hrs/Year	Negligible with proper emissions control
Thermal Oxidation	$9.96-11.0 M	11,038 MW-hrs/Year	Possible Impact
Next Generation Thermal Oxidation	$5.2-5.8 M	14,349 MW-hrs/year	Negligible with proper emissions control
Thermogenic Anaerobic Digestion	$17.5-20.2 M	1,303 MW-hrs/Year	Negligible Impact

The thermal gasification system has cost of approximately $7.8 – $8.6 M. The operating and maintenance costs are estimated to be approximately $345 – $380 K/Year. Based on the assumptions of this report the thermal gasification system can produce 12,456 MW-hrs/Year of electricity. This conversion technology has a payback of 6.9 – 7.8 Years.

The thermal pyrolysis steam reforming system has costs of approximately $5.8 – $6.4 M to install with an annual operating cost of $828 – $911K. The thermal pyrolysis steam reforming system would be able to produce 28,225 MW-hrs/Year of electricity. This conversion technology has a payback of 3.4 – 4.0 Years.

The thermal oxidation to energy system would cost $9.96 – $11.0 M to install and have an annual operating cost of $1.2 – $1.3 M per year. Higher operating costs can be attributed to the high ash rate and high ash disposal costs. The thermal oxidation system would be able to produce approximately 11,038 MW-hrs/Year of electricity. The thermal oxidation system provides lower energy output due to lower conversion efficiency. This conversion technology has a payback of 52.9 – N/A Years.

The next generation thermal oxidation process is a subset of thermal oxidation, which converts carbonaceous waste to thermal energy and steam and ultimately electricity by way of a steam turbine. This improved design has proved to convert various feed stocks more efficiently and with fewer emissions than traditional thermal oxidation systems. The capital cost for installation of this system is approximately $5.2 – $5.8 M with an annual operating cost of $155 – $190 K per year. The electricity generated has a potential value of 14,349 MW-hrs/year of energy. This conversion technology has a payback of 3.6 – 4.1 Years.

The thermogenic anaerobic digestion system costs approximately $17.5 – $20.2 M to install and has an annual operating cost of $605 – $639K per year. The system has the potential to produce 1,303 MW-hrs/Year of electricity based on the waste steam presented in this report. Lower energy output by the thermogenic anaerobic digestion system can be attributed to the limited feedstock it is able to convert and lower overall conversion efficiency. Due to the exclusion of high energy waste (plastic, rubber, Styrofoam, etc.) that cannot be handled by the thermogenic anaerobic digester, the total energy available for conversion is smaller than other technologies analyzed in this report. This conversion technology does not have a positive payback. Table 3-1 contains biomass to energy conversion system payback analysis data.

Alternative electricity generation options discussed in this report can also be used effectively. Further research and development is needed to fully commercialize the aforementioned energy generating options. In addition, costs need to be reduced in order for these technologies to become commercially viable.

The chemical makeup of the waste stream, availability of capital, energy generation requirements, and environmental impact will determine the most appropriate conversion technology for each individual waste-to-energy project. Each biomass to energy conversion system provides economic benefits, but an individual study would be required to determine return on investment.

This report provides the estimated capital and operating costs for a biomass to energy facility for a manufacturing plant. Depending on current waste disposal fees and energy costs a manufacturing facility can economically convert waste biomass into usable energy to offset current operating costs. The conversion technologies discussed in this document have a wide range of utilization and should be further researched to determine their applicability for common waste streams in particular industries. Conversion technologies need to be validated by a third party to verify the assertion made by technology manufacturers. Conversion technology validation should address the energy conversion efficiency and system emissions. Additionally, further research is needed on the pre-processing of biomass wastes and introduction to conversion systems.

CERP is in an ideal location to validate existing technologies and develop new conversion technologies. A Sacramento Waste Transfer Station is located within a mile of Technikon's building that could supply various waste streams for test. CERP will pursue this opportunity as funding becomes available.

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APPENDIX A GLOSSARY

Anaerobic	Occurring in the absence of free oxygen
Biogas	Mixture of methane and carbon dioxide produced by bacterial degradation of organic matter and used as a fuel
Biomass	Organic wastes used as fuel or energy source
BTU	British thermal unit: the quantity of heat required to raise the temperature of one pound of water from 60^o to 61^oF at constant pressure of one atmosphere
Carbonaceous	Consisting of carbon
Dioxin	Any of several carcinogenic or teratogenic petroleum derived hydrocarbons
DoE	Department of Energy
Furan	A group of colorless, organic compounds obtained from wood oils
Gasification	Conversion into gas
ICE	Internal combustion engine
Kg	Kilogram; unit of mass in the international system equal to 1000 grams.
kW	Kilowatt; a unit of power equal to 1000 watts
KWh	Kilowatt hour
LPG	Liquefied Petroleum Gas
MCFC	Molten Carbonate Fuel Cells
Methane	Odorless, colorless, flammable gas, RH_4, used as a fuel
MJ	Mega Joule
MMBTU/Hr	Million Million BTUs per hour
MW	Megawatt; a unit of power equal to one million watts
MWh	Mega Watt hour
Organic	Material derived from living organism
Oxidation	Combination of a substance with oxygen
PAFC	Phosphoric acid fuel cells
PEMFC	Proton Exchange Membrane Fuel Cell
Pyrolysis	Chemical change brought about by the action of heat
Reducing	To remove oxygen from a compound
Scf	Standard cubic foot
SOFC	Solid Oxide Fuel Cells
Syngas	Synthesis gas produced through gasification of biomass
Thermogenic	Generation or production of heat
Thermophilic	Requiring high temperature for normal development, as certain bacteria

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APPENDIX B REFERENCES

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