



California Integrated Waste
Management Board

June 2007

Staff Report
To The Board



*New and Emerging Conversion Technologies
Report to the Legislature*

STATE OF CALIFORNIA

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The CIWMB contracted with RTI International to conduct a life cycle and market impact analysis of conversion technologies. The CIWMB also contracted with the University of California-Riverside's Bourne College of Engineering, Center for Environmental Research & Technology, to conduct an analysis of conversion technology processes and products.

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Unless otherwise noted, the source documents for this report were the Evaluation of Conversion Technology Processes and Product study prepared by UC Riverside and the Life Cycle and Market Impact Assessment of Noncombustion Waste Conversion Technologies prepared by RTI International. Sections of those studies have been excerpted into this report.

Executive Summary

Assembly Bill 2770, Mathews, Chapter 740, Statutes of 2002 (AB 2770) requires the California Integrated Waste Management Board (CIWMB) to include, as part of our annual report, a report on new and emerging conversion technologies, including but not limited to, non-combustion thermal technologies, including gasification and pyrolysis, chemical technologies such as acid hydrolysis or distillation and biological technologies; and their impacts on recycling and other diversion activities.

Specifically, AB 2770 requires that the report contain the following:

Specific and discrete definitions and descriptions of each conversion technology evaluated as accepted in the scientific community.

A description and evaluation of the life cycle environmental and public health impacts of each conversion technology in comparison to the environmental and public health impacts from the transformation and disposal of solid waste.

A description and evaluation of the technical performance characteristics, feedstocks, emissions, and residues used by each conversion technology and identification of the cleanest, least-polluting conversion technology.

A description and evaluation of the impacts on recycling and composting markets as a result of each conversion technology.

To comply with this legislative-mandate report, the CIWMB contracted with the University of California-Riverside's Bourne College of Engineering, Center for Environmental Research & Technology, to conduct an analysis of conversion technology processes and products. To conduct life cycle and market impact analyses of conversion technologies, the CIWMB contracted with RTI International. Their studies served as the major source of information for the CIWMB *Conversion Technologies Report to the Legislature* (the Report). In addition, the CIWMB consulted with the State Energy Resources Conservation and Development Commission (CEC), whose Research and Development program staff participated in the scientific peer review process.

Definitions and Descriptions

Thermochemical Conversion

By definition includes thermal gasification and pyrolysis along with a number of variants involving microwave, reforming, plasma arc, supercritical fluid, and other processing techniques generally occurring at elevated temperatures such as catalytic cracking. Products include heat, fuel gases, synthesis gases, ammonia, hydrogen, alcohols, Fischer-Tropsch hydrocarbons, other liquids, and solids. Thermochemical techniques tend to be high rate as compared with biochemical processes and relatively non-

selective for individual biomass components in that the chemically complex biomass is substantially degraded into simple compounds. Thermochemical techniques are also being developed for the purposes of producing ethanol from cellulosic biomass such as wood and straw. Byproducts include ash, chars, and liquid effluents for disposal or recovery as commercial products.

Pyrolysis

Pyrolysis is a process that can be defined as the thermal decomposition of feedstock at high temperatures (greater than 400°F) in the absence of air.

Gasification

Gasification is a process that uses air or oxygen and high heat—typically above 1300°F—to convert feedstock into a synthetic gas or fuel gas. Gasification uses less air or oxygen than incineration processes. By definition, gasification is a partial combustion process. The existing definition for gasification in Public Resources Code Section 40117, while it is law, is scientifically incorrect and actually describes pyrolysis. Furthermore, it is in direct conflict with the definition of solid waste conversion in Public Resources Code Section 25741 (The CEC's Warren-Alquist Act).

For example, gasification technologies do use some amount of air or oxygen in the process, while pyrolysis does not use air or oxygen in the conversion process. A more scientifically accurate definition would be: "Gasification" means the conversion of solid or liquid carbon-based materials by direct or indirect heating. For direct heating, partial oxidation occurs where the gasification medium is steam and air or oxygen. Indirect heating uses an external heat source such as a hot circulating medium and steam as the gasification medium. Gasification produces a fuel gas (synthesis gas, producer gas), which is principally carbon monoxide, hydrogen, methane, and lighter hydrocarbons in association with carbon dioxide and nitrogen, depending on the process used.

Plasma Arc

Plasma arc technology is a heating method that can be used in both pyrolysis and gasification systems. This technology was developed for the metals industry in the late nineteenth century. Plasma arc technology uses very high temperatures to break down the feedstock into elemental by-products. Plasma arc devices, or "plasma torches," can be one of two types: the transferred torch, and the non-transferred torch.

The transferred torch creates an electric field between an electrode (the tip of the torch) and the reactor wall or conducting slag bath. When the field strength is sufficiently high, an electric arc is created between the electrode and reactor (much like an automotive spark plug). The non-transferred torch creates the electric arc internal to the torch and sends a process gas (such as air or nitrogen) through the arc, where it is heated, and then leaves the torch as a hot gas. Very high temperatures are created in the ionized plasma (the plasma can reach temperatures of 7000°F and above; the non-ionized

gases in the reactor chamber can reach 1700°F–2200°F; and the molten slag is typically around 3000°F).

Catalytic Cracking

Catalytic cracking is a thermochemical conversion process that uses catalysts to accelerate the breakdown of polymers—such as plastics—into a basic unit, called a monomer. The monomers can then be processed using typical cracking methods, often used in oil refinery operations, to produce fuels such as low-sulfur diesel and gasoline.

Biochemical Conversion

By definition, biochemical conversion processes include fermentation to produce alcohols, fuel gases (such as methane by anaerobic digestion), acids and other chemicals, and aerobic processes used for waste stabilization and composting. Anaerobic and other biological processes are also being explored for the production of hydrogen. Byproducts include organic solids and liquid effluents. Where feedstocks are uncontaminated by heavy metals or other toxic compounds not degraded by the process, byproducts can be recovered as commercial products for uses including animal feeds, fertilizers, and soil amendments. Proper handling and sterilization is required for byproducts from processes employing genetically modified or recombinant organisms.

Anaerobic Digestion

Anaerobic digestion is the bacterial breakdown of biodegradable organic material in the absence of oxygen. It can occur over a wide temperature range, from 50° to 160°F. The temperature of the reaction has a very strong influence on the anaerobic activity, but mesophilic and thermophilic temperature ranges are two optimal temperature ranges in which microbial activity and biogas production rates are highest. Mesophilic systems operate at temperatures around 95°F and the thermophilic systems operate at a temperature around 130°F.

Fermentation

Fermentation is an anaerobic process and is used to produce fuel liquids such as ethanol and other chemicals. Although fermentation and anaerobic digestion are commonly classified separately, both are fermentation methods designed to produce different products.

Prior to fermentation for alcohol production, the feedstock must be prepared using a method called hydrolysis. Cellulosic ethanol processes can be differentiated primarily by the hydrolysis pre-treatment method. Methods that have undergone the most investigation are acid processes (dilute and concentrated acid), enzymatic hydrolysis, and steam explosion. Enzymatic hydrolysis uses enzymes derived from common fungi. Steam explosion involves pressurizing the biomass with steam for a period followed by

rapid depressurization. Once the cellulose has been hydrolyzed and conditions made favorable (for example, pH- and temperature-adjusted), ethanol is produced from microbial fermentation. A variety of microorganisms, generally bacteria, yeast, or fungi, are used to ferment carbohydrates to ethanol under anaerobic conditions.

Life Cycle Environmental and Public Health Impact Assessment

The goal of the life cycle and market impact assessment was to address the following two primary questions:

- What are the life cycle environmental impacts of conversion technologies and how do these compare to transformation and disposal of solid waste?
- What are the economic, financial, and institutional impacts of conversion technologies on recycling and composting markets?

To conduct life cycle analyses, three conversion technologies were selected:

- Concentrated acid hydrolysis;
- Gasification; and
- Catalytic Cracking.

These were chosen because California municipalities have shown particular interest, as evidenced by requests for information, are commercially ready based on research conducted prior to the start of this project, and readily available data describing these technologies.

The San Francisco Bay Area and the Greater Los Angeles Area were selected for the study because a large percentage of California's municipal solid waste (MSW) is generated and processed within these regions. For purposes of this study, it was assumed that Greater Los Angeles includes the counties of Los Angeles, Orange, Riverside, and San Bernardino.

Key findings from the life cycle analysis are:

- Conversion technologies produce more energy than landfilling and transformation. This creates large life cycle benefits such as less dependence on non-renewable fuels such as natural gas.
- There are lower emissions of criteria air pollutants (NO_x and SO_x) from conversion technologies than from landfilling and transformation.
- There are lower emissions of CO₂ from conversion technologies than from landfilling and transformation. This is important from a climate change perspective.

- Limited data is available to adequately assess the impacts of dioxins, furans, and other hazardous air pollutants.
- The environmental benefits of the hypothetical conversion technology scenario are highly dependent upon their ability to achieve high conversion efficiencies and high materials recycling rates.
- Conversion technologies would decrease the amount of waste disposed in landfills.
- No conversion technology facilities exist in the U.S. for MSW. Therefore, there is a high level of uncertainty regarding their environmental performance.

Public Health Risk

Several methods to assess the public health impacts of conversion technologies can be considered. One is to work with the Office of Environmental Health Hazard Assessment (OEHHA). The primary goal of a human health risk assessment is to determine if the risk to human health posed by pollution released from a facility is unacceptable and requires regulatory intervention. However, since the Life Cycle report is not a human health risk assessment, and data provided by the UC researchers and RTI was not of the type sufficient for OEHHA to efficiently assess the potential public health impacts of conversion technologies; the CIWMB will continue to work with OEHHA as new facilities are sited in California and this specific data is acquired.

A second method would be to review research data collected from the CEC. In 1996, the California Legislature established the Public Interest Energy Research (PIER) program at the CEC. The PIER program conducts public interest energy research that seeks to improve the quality of life for California citizens by developing environmentally sound, safe, reliable, and affordable electricity services and products. The seven mandated Research, Development, and Demonstration (RD&D) subject areas include environmentally preferred advanced generation, renewable energy technologies and alternative transportation fuels. In 2005, the CEC published the *Biomass Strategic Value Analysis* (publication 500-2005-109-SD). According to their findings bioenergy public benefits included improving forest, human and animal health. Although, these technologies are more expensive, the analysis seems to conclude that converting biomass and MSW offers unparalleled environmental benefits and significant public benefits, including reduced health risks.

Technical Evaluation and Cleanest, Least Polluting Technology

Current Status

Development and deployment of conversion technologies has occurred in Japan, Germany, and the United Kingdom, with more than 50 thermochemical facilities and more than 80 anaerobic digestion facilities that use unsorted MSW as a feedstock.

Feedstocks

Thermochemical processes can potentially convert all the landfill organic waste into heat and other useful products. Since most thermochemical processes operate at elevated temperatures, the fate of trace inorganic elements, such as metals that may be present in MSW, needs to be considered in the process design. Further sorting and/or processing of MSW after it passes through the materials recovery facility (MRF) would normally be conducted prior to thermal conversion. Sorting would involve extracting recyclable materials, reducing particle sizes to those compatible with the process, and drying the material if needed.

Biochemical processes can convert only the biodegradable fraction of feedstocks. Metals, glass, mineral matter, and most of the current plastic waste stream would not be converted. However, some of the newer plastics do include biodegradable fractions and are fully biodegradable. The fraction of these plastics in the waste stream is currently very small but may increase over time. Higher-moisture feedstocks such as green waste or food waste are better suited for biochemical processes, partly because extra energy is required for drying before use in most thermochemical processes. Biochemical conversion technologies are better suited for source-separated green or food waste, or the biomass fraction of mixed MSW after sorting. Some biochemical systems can accept unsorted MSW (shredded or crushed to appropriate size) in the reactor, though this is not optimal from the standpoint of material handling, reactor volume utilization, and disposal or use of residuals.

Products

Products from conversion technologies differ based on the technology used and the feedstock that is converted. Products include, but not limited to the following:

Gasification:

1. Fuel gases (CO, CH₄, H₂, CO₂, other hydrocarbons such as C₂H₂, C₂H₄, C₂H₆ and N₂) or synthesis gas.
2. Heat that can be transferred to the process to displace a fuel.
3. Tars and other condensable substances, if present after gasification process.
4. Char and ash.

Pyrolysis:

1. Fuel gases (CO₂, CO, CH₄, H₂) containing less chemical energy than equivalent product gases for gasification of the same feedstock.
2. Ash and char (fixed carbon not pyrolyzed) containing significant quantities of feedstock chemical energy.
3. Pyrolytic tars and other high molecular mass hydrocarbons, also containing significant quantities of feedstock chemical energy.

4. Pyrolytic oils and/or other condensable substances, containing significant quantities of feedstock chemical energy.

Biochemical processes can yield the following:

1. Biogas (a mixture of methane and carbon dioxide). Biogas contains less chemical energy than the equivalent products from gasification of the same feedstock.
2. Ethanol.
3. Solvents, organic acids, and other bio-based chemicals for refining to end products.
4. Residues that can be used for compost/soil amendment/fertilizer if permitted by local regulations or a feedstock for thermochemical conversion.

Environmental Impacts and Controls

A number of environmental factors will impact conversion technologies. These impacts include:

- Air emissions, particularly dioxin, furans, heavy metals, and greenhouse gas emissions.
- Management of ash, char, and other solid residues.
- Management of any liquid residues.

Air emissions from thermochemical and biochemical systems include NO_x, SO_x, hydrocarbons, carbon monoxide, particulate matter (PM), heavy metals, greenhouse gas emissions such as methane and CO₂, dioxins/furans and H₂S could be an issue as well. In addition, fugitive gas and dust emissions may be present. The management of these emissions would depend on control strategies, operational practices, and level of maintenance at a particular facility.

All organic matter including biomass and MSW contains trace quantities of heavy metals. Whether the feedstock is landfilled, composted, gasified, or incinerated, the heavy metal quantity remains identical; the only difference is that thermal decomposition processes retain most of the heavy metals in their residue and ash in a concentrated form. More volatile heavy metals, such as mercury, will enter the gas phase in thermal conversion and must be managed or captured. Conversion technologies do not create new heavy metals in ash but do concentrate heavy metals already present in the feedstock that would otherwise be landfilled. However, under proper controls, the concentrated heavy metals can be treated and disposed of in a manner that poses no greater environmental threat than landfilling.

Biochemical conversion processes generate more solid residue than that from thermochemical processes. However, biochemical conversion requires more residence time compared with thermochemical methods, so practical systems are not large enough to convert all biodegradable components. This, combined with the lignin components of

biomass—which are not biodegradable in practical systems—plus the ash in the material, results in substantial solid residue that may or may not have commercial use.

Conversion technologies will also generate liquid residues that must be managed appropriately. As with the solids residue, the amount of liquid residue is dependent on the specific conversion process and feedstock. Pyrolytic oil can contain toxic substances including acids, alcohols, aldehydes, ketones, esters, heterocyclic derivatives, and phenols. Most of these compounds are used in current industrial operations. Spent scrubber solutions from air pollution control equipment or boiler blow-down water must also be managed appropriately. The liquid wastes generated by these conversion processes include spent acid solutions from acid hydrolysis and liquid digestate from biochemical systems. Surplus water is usually generated from anaerobic digestion systems. Water quantity depends on the digestion technology as well as the substrate. In many instances, the liquid has a value as a fertilizer for agriculture application. Some compost operations can accept the liquid for compost moistening.

Other potential environmental factors associated with conversion technologies could include noise, odors, fugitive emissions, dust, litter and debris, increased local traffic, aesthetics, and animal and insect pests. The CEC's PIER program has committed to research these conversion technology methodologies; for instance:

Thermochemical Conversion

- Demonstrate in California advanced heat, power, and syngas systems for improved efficiency and environmental performance. Some will have potential application to thermochemical and advanced biorefineries (i.e. Biomass integrated gasifier combined cycle (BIGCC));
- Replicate BIGCC demonstrations and improve economics and performance;
- Improve and demonstrate advanced systems that can meet environmental performance requirements (especially air permitting and NO_x issues) e.g., distributed generation (DG), combined heat and power (CHP), and cooling technologies;
- Demonstrate and verify municipal solid waste conversion systems;
- Deploy and commercialize these advanced thermochemical systems.

Biochemical Conversion

- Determine food and food processor residue amounts and location for siting of anaerobic digestion/co-digestion systems. Demonstrate advanced co-digestion systems (accept combinations of food, industrial, animal residues, MSW);
- Improve manure and feedstock collection/handling systems for anaerobic digestion;

- Improve or develop technologies to treat anaerobic digestion effluent for nutrient, water, and salt management;
- Demonstrate and commercialize biomethane systems for pipeline and vehicle fuel application;
- Develop inexpensive and robust sensor and control systems to improve anaerobic digestion process stability for systems with varying loading rates and feedstock types;
- Conduct basic research on microbiology for biogas and bio-hydrogen production.

Cleanest, Least Polluting Technologies

AB 2770 required the CIWMB to identify the cleanest, least polluting technologies. Both biological and thermal technologies have advantages and disadvantages when compared to each other. The limited data and contractor studies contain no scientific basis to classify one technology as the cleanest and least polluting. However, CEC's PIER program is currently conducting long-term research projects related to biomass waste and residuals, although not projects that necessarily use solid waste as a feedstock. The public interest energy research includes a full range of RD&D activities that advance science and technology not adequately provided by competitive and regulated markets. These projects include: accelerated anaerobic composting project for energy generation; technology assessment for advanced biomass power generation; distributed biogas energy systems utilizing organic solid wastes; technology assessment for dairy and food waste to energy; and demonstrate landfill gas technology to maximize gas recovery efficiency and peaking power potential. These ongoing projects should expand the data necessary to determine the cleanest, least polluting technologies once their research is completed.

Market Impact Assessment

The general approach of this study was to collect data regarding the current marketplace, including quantities and compositions of various wastes and recycling streams. The data collect is from the entities that make decisions regarding disposition of these materials, these entities include: generators, jurisdictions, MRF operators, and haulers. The data collected also covers the quality and quantity needs of paper and plastic recycling processors and exporters and the composting/mulch industry.

The relationships of material movement through the system were then modeled and overlaid with the conversion technology system configurations, quality, composition, and price of material needs. This produced estimated impacts to the recycling and composting industries that would occur if such conversion technology facilities were to be developed.

This study looked at the possibility of using the following feedstocks for conversion technologies:

- Paper
- Plastic
- Organics and green waste
- Material destined for landfilling (including residuals from materials recovery facilities)

The technologies studied are anticipated to receive material normally destined for landfills, not source-separated recyclables or green waste. One of the primary study objectives was to estimate impacts that the development of new and emerging conversion technologies would have on the existing recycling and composting industries. Pricing and availability of suitable feedstock materials are the basis for most of the findings presented. The following findings assume that the conversion technologies would be developed under the current statutory framework (that is to say, not receive diversion credit):

Finding #1: There is a projected net positive impact on glass, metal, and plastic recycling under the “base case” conversion technology scenarios in life cycle/market impact study.

Finding #2: Implementation of any of the three selected technologies is not likely to increase or decrease the recycling of paper.

Finding #3: In the cases where conversion technology facilities accept materials that currently have no recycling or composting markets, and there are no new recycling markets for those materials in the foreseeable future, conversion technology facilities will have no impact on recycling and composting markets.

Finding #4: The impact of recent Chinese demand is a far more dominant force on the paper and plastics markets than potential development of conversion technologies in California, even on the fairly large scale that was assumed for this study.

Finding #5: Future recycling growth could be negatively impacted in the following three primary ways if recyclables were redirected to conversion technology facilities:

1. If source-separated recyclables or green waste flowed to conversion technology facilities rather than recycling facilities.
2. If waste streams that are currently untapped for recycling became unavailable to new recycling efforts in the future.
3. If local jurisdictions eliminated recycling and green waste collection programs and redirected mixed waste to conversion technology facilities. However, this scenario is unlikely given the enormous capital investment made by local jurisdictions and waste management companies and existing law in the California Integrated Waste Management Act of 1989 (AB 939, (Sher), Chapter 1095, Statutes of 1989, as amended, or IWMA) that requires jurisdictions to maintain their diversion programs.

Finding #6: Based on pricing differentials, source-separated recyclables (paper and plastics) are not likely to flow to conversion technology facilities.

Finding #7: Conversion technology facilities may have a minimal negative impact on the ability of municipalities and private companies to increase recycling from currently untapped waste streams and generators.

Finding #8: Source-separated green waste could conceivably flow to conversion technology facilities under certain circumstances.

On April 15, 2004, the CIWMB held a stakeholder workshop to discuss the initial findings of the lifecycle and market impact assessment. Many stakeholders were of the opinion that the true market impact could only be assessed if diversion credits were a factor in evaluating market impacts. The RTI Project Team concurred and conducted sensitivity analysis to analyze the effects that diversion credits for conversion technologies would have on recycling and composting markets.

The following four scenarios were developed for the diversion credit sensitivity analysis:

1. Full diversion credit, diversion program maintained.
2. Ten percent diversion cap, diversion programs maintained.
3. Full diversion credit, diversion programs discontinued.
4. Full diversion credit, recycling programs continued, green waste programs discontinued.

Finding #9: No negative impact on existing recycling and compost markets would occur if diversion credit were given for conversion technologies.

Finding #10: No negative impact on existing recycling and compost markets would occur if diversion credit were considered for MSW, which would otherwise go to a landfill, is used as feedstock to bioenergy products through the use of conversion technologies.

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Introduction

The IWMA requires local jurisdictions and the CIWMB to cooperatively reduce the amount of solid waste disposed in landfills by promoting the reduction, recycling, and reuse of solid waste. A 2003 survey of California's composting infrastructure shows that 170 permitted composting facilities process 10 million tons of organic materials annually.

Of the 10 million tons processed, 46 percent is used as ADC. In addition, California has achieved a statewide diversion rate of 52 percent. In spite of all these efforts, more than 42 million tons of material was disposed of in landfills in 2005. Of the amount disposed in landfills, nearly 80 percent is organic material and can be retrieved for use (paper, wood, green waste, food waste, etc.).

As directed by the Legislature, the CIWMB has been researching and evaluating new and emerging non-combustion conversion technologies that would be best suited for materials that have traditionally been landfilled. Recent law has expanded that research and evaluation to include new and emerging chemical and biological conversion technologies.

Legislative Requirement

AB 2770, signed by Governor Davis in September 2002, requires the CIWMB to research and evaluate new and emerging non-combustion thermal, chemical, and biological technologies and to include those findings in the CIWMB's Annual Report.

Definitions and Descriptions

Conversion of municipal solid waste, and in particular organic material can be accomplished by using thermochemical and biochemical pathways. These descriptions and definitions are described below.

To provide a frame of reference between combustion and non-combustion technologies, combustion is the thermal destruction, in an oxygen-rich environment, of solid waste for the generation of heat and subsequent energy production. Flame temperatures for combustion and incineration range from 1500°F to 3000°F. Thermochemical conversion technologies includes combustion, however, this report will emphasize the CIWMB research on new and emerging non-combustion technologies.

The University of California (UC) researchers have also stated that thermochemical conversion technologies considered in this report differ dramatically from incineration and combustion in several key respects:

- The volume of output gases from a pyrolysis reactor or gasifier is much smaller per ton of feedstock processed than an equivalent incineration process. While these output gases may be eventually combusted, the alternative processes provide an intermediate step where gas cleanup can occur. Mass burn incineration is limited by application of air pollution control equipment to the fully combusted exhaust only.
- Output gases from pyrolysis reactors or gasifiers are typically in a reducing environment, and can be treated with different technologies compared with a fully combusted (oxidative) exhaust. Reactant media for gasification and pyrolysis can also be hydrogen or steam as compared to air or oxygen for incineration and combustion.
- Gasification and pyrolysis produce intermediate synthesis gases composed of lower molecular weight species such as natural gas, which are cleaner to combust than raw MSW.
- Pyrolysis and gasification processes use very little air/oxygen or none at all.

Thermochemical Conversion

Thermochemical conversion processes use higher temperatures and have higher conversion rates when compared to other conversion pathways. Thermochemical conversion pathways considered in this report include processes such as pyrolysis, gasification, plasma arc, and catalytic cracking. Each process can operate within a specific temperature range and operating pressure. Pyrolysis, gasification, and plasma arc technologies are not new technologies, having been used for coal and other materials since the early twentieth century. While the application of these technologies to solid waste feedstocks is new in California, these are not unproven technologies in other parts of the world such as Japan and Europe.

By definition, thermochemical conversion includes thermal gasification and pyrolysis, along with a number of variants involving microwave, reforming, plasma arc, supercritical fluid, and other processing techniques generally occurring at elevated temperatures. Products include heat, fuel gases, synthesis gases, ammonia, hydrogen, alcohols, Fischer-Tropsch hydrocarbons, other liquids, and solids. Thermochemical techniques tend to be high rate as compared with biochemical processes and relatively non-selective for individual biomass components in that the chemically complex biomass is substantially degraded into simple compounds. Thermochemical techniques are also being developed for the purposes of producing ethanol from cellulosic biomass such as wood and straw. Byproducts include ash, chars, and liquid effluents for disposal or recovery as commercial products.

New and emerging thermochemical conversion includes improved performance and efficiency and also reduced costs.

Pyrolysis

Pyrolysis is a process that can be defined as the thermal decomposition of feedstock at high temperatures (greater than 400°F) in the absence of air. The end product of pyrolysis is a mixture of solids (char), liquids (oxygenated oils), and gases (methane, carbon monoxide, and carbon dioxide) with proportions determined by operating temperature, pressure, oxygen content, and other conditions. Pyrolysis produces pyrolytic oils and fuel gases that can be used directly as boiler fuel or refined for higher quality uses such as engine fuels, chemicals, adhesives, and other products. Solid residues from pyrolysis contain most of the inorganic portion of the feedstock as well as large amounts of solid carbon or char.

Pyrolysis typically occurs at temperatures in the range of 750°F–1500°F and thermochemically degrades the feedstock without the addition of air or oxygen. Because air or oxygen is not intentionally introduced or used in the reaction, pyrolysis requires thermal energy that is typically applied indirectly by thermal conduction through the walls of the containment reactor. The reactor is usually filled with an inert gas to aid in heat transfer from the reactor walls and to provide a transport medium for removal of the gaseous products.

The composition of the pyrolytic product can be changed by the temperature, speed of process, and rate of heat transfer. Lower pyrolysis temperatures usually produce more liquid products, and higher temperatures produce more gases. Slow pyrolysis can be used to maximize the yield of solid char and is commonly used to make charcoal from wood feedstock. Fast or “flash” pyrolysis is a process that uses a shorter exposure time to temperatures of approximately 930°F. Typical exposure times for fast pyrolysis are less than one second. Rapid quenching of pyrolytic decomposition products is used to “freeze” the decomposition products and condense the liquids before they become low molecular weight gaseous products. This process results in a product that is up to 80 percent liquid by weight.

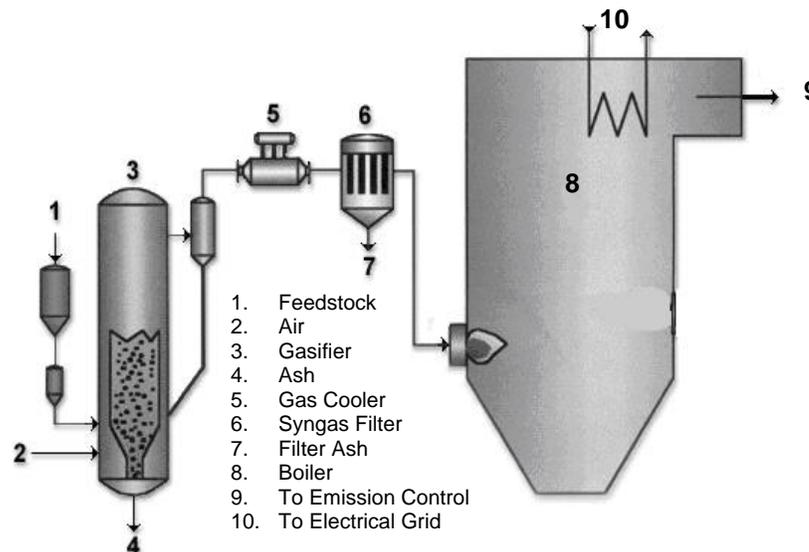
Gases produced during the pyrolysis reaction can be utilized in a separate reaction chamber to produce thermal energy. The thermal energy can be used to produce steam for electricity production. It can be used to heat the pyrolytic reaction chamber or dry the

feedstock entering the reaction chamber. If pyrolytic gases are combusted to produce electricity, emission control equipment will be needed to meet regulatory standards.

Gasification

Gasification typically refers to the conversion of feedstock materials by either direct or indirect heating, depending on the specific configuration of the gasification system. While gasification processes vary considerably, typical gasifiers operate from 1300°F and higher and from atmospheric pressure to five atmospheres or higher. The process is optimized to produce fuel gases (methane and lighter hydrocarbons) and synthetic gases (carbon monoxide, hydrogen); hence, the term gasification. The product fuel gases can be used in internal and external combustion engines and fuel cells. Synthetic gases can be used to produce methanol, ethanol, and other fuel liquids and chemicals. Figure 1 is a diagram of a typical gasification system.

Figure 1. Gasification Diagram



An important aspect of gasification is that the chemical reactions can be controlled for the production of different products. The gases produced by gasification can be cleaned to remove any unwanted particulates and compounds and then used as fuel in internal or external combustion engines or fuel cells.

AB 2770 included the following definition for gasification in the Public Resources Code (PRC):

40117. "Gasification" means a technology that uses a noncombustion thermal process to convert solid waste to a clean burning fuel for the purpose of generating electricity, and that, at minimum, meets all of the following criteria:

(a) The technology does not use air or oxygen in the conversion process, except ambient air to maintain temperature control.

(b) The technology produces no discharges of air contaminants or emissions, including greenhouse gases, as defined in subdivision (g) of Section 42801.1 of the Health and Safety Code.

(c) The technology produces no discharges to surface or ground waters of the state.

(d) The technology produces no hazardous waste.

(e) To the maximum extent feasible, the technology removes all recyclable materials and marketable green waste compostable materials from the solid waste stream prior to the conversion process and the owner or operator of the facility certifies that those materials will be recycled or composted.

(f) The facility where the technology is used is in compliance with all applicable laws, regulations, and ordinances.

(g) The facility certifies to the board that any local agency sending solid waste to the facility is in compliance with this division and has reduced, recycled, or composted solid waste to the maximum extent feasible, and the board makes a finding that the local agency has diverted at least 30 percent of all solid waste through source reduction, recycling, and composting.

The existing definition for gasification in PRC section 40117, while it is law, is scientifically incorrect and actually describes pyrolysis. For example, gasification technologies do use some amount of air or oxygen in the process, while pyrolysis does not use air or oxygen in the conversion process. A more scientifically accurate definition would include the following:

“Gasification” means the conversion of solid or liquid carbon-based materials by direct or indirect heating. For direct heating, partial oxidation occurs where the gasification medium is steam and air or oxygen. By definition, gasification is also a partial combustion process. Indirect heating uses an external heat source such as a hot circulating medium and steam as the gasification medium. Gasification produces a fuel gas (synthesis gas, producer gas), which is principally carbon monoxide, hydrogen, methane, and lighter hydrocarbons in association with carbon dioxide and nitrogen, depending on the process used.

Statutory changes are required to be scientifically accurate as well as consistent with PRC 25741 which uses this definition for the general purposes of solid waste conversion.

Plasma Arc

Plasma arc technology is a heating method that can be used in both pyrolysis and gasification systems. This technology was developed for the metals industry in the late nineteenth century. Plasma arc technology uses very high temperatures to break down the feedstock into elemental by-products.

Plasma is a collection of free-moving electrons and ions that is typically formed by applying a large voltage across a gas volume at reduced or atmospheric pressure. When the voltage is high enough and the gas pressure low enough, electrons in the gas

molecules break away and flow towards the positive side of the applied voltage. The gas molecules (losing one or more electrons) become positively charged ions that are capable of transporting an electric current and generating heat when the electrons drop to a stable state and release energy. This is the same phenomenon that creates lightning.

Plasma arc devices or “plasma torches” can be one of two types: the transferred torch, and the non-transferred torch. The transferred torch creates an electric field between an electrode (the tip of the torch) and the reactor wall or conducting slag bath. When the field strength is sufficiently high, an electric arc is created between the electrode and reactor (much like an automotive spark plug). The non-transferred torch creates the electric arc internal to the torch and sends a process gas (such as air or nitrogen) through the arc, where it is heated, and then leaves the torch as a hot gas.

Very high temperatures are created in the ionized plasma (the plasma can reach temperatures of 7000°F and above; the non-ionized gases in the reactor chamber can reach 1700°F to 2200°F; and the molten slag is typically around 3000°F). For applications in processing MSW, the intense heat actually breaks up the molecular structure of the organic material to produce simpler gaseous molecules such as carbon monoxide (CO), hydrogen (H₂), and carbon dioxide (CO₂). The inorganic material is vitrified to form a glassy residue. A main disadvantage of the plasma arc systems used in power generation is that a large fraction of the generated electricity is required to operate the plasma torches, which reduces net electrical output of the facility.

Catalytic Cracking

Catalytic cracking is a thermochemical conversion process that uses catalysts to accelerate the breakdown of polymers—such as plastics—into its basic unit, called a monomer. The monomers can then be processed using other processes, often used in oil refinery operations, to produce fuels such as low-sulfur diesel and gasoline.

Biochemical Conversion

Biochemical conversion processes such as anaerobic digestion and fermentation occur at lower temperatures and have lower reaction rates than thermochemical technologies. Higher moisture feedstocks are generally better candidates for biochemical processes. Non-biodegradable feedstocks, such as plastics and metals, are not suitable feedstocks for biochemical conversion and are not converted. Applying biochemical processes to MSW as a pre-treatment step before it is landfilled can reduce both the volume of material being landfilled and the production of leachate. At the same time, this process extracts the embodied energy value from the feedstock prior to landfilling.

A large number of anaerobic digestion facilities are operating in Europe and Canada that use unsorted MSW as a feedstock. As a result, more experience and information is available from anaerobic digestion processes. Fermentation processes for the

production of ethanol from MSW have not matured to the same extent as anaerobic digestion, and available information is only theoretical in nature.

Biochemical conversion: Conversion systems using biological processes include fermentation to produce alcohols, fuel gases (such as methane by anaerobic digestion), acids and other chemicals, and aerobic processes used for waste stabilization and composting. Anaerobic and other biological processes are also being explored for the production of hydrogen. Byproducts include organic solids and liquid effluents. Where feedstocks are uncontaminated by heavy metals or other toxic compounds not degraded by the process, byproducts can be recovered as commercial products for uses including animal feeds, fertilizers, and soil amendments. Proper handling and sterilization is required for byproducts from processes employing genetically modified or recombinant organisms.

Anaerobic Digestion

Anaerobic digestion is the bacterial breakdown of biodegradable organic material in the absence of oxygen. It can occur over a wide temperature range, from 50° to 160°F. The temperature of the reaction has a very strong influence on the anaerobic activity, but mesophilic and thermophilic temperature ranges are two optimal temperature ranges in which microbial activity and biogas production rates are highest. Mesophilic systems operate at temperatures around 95°F, and the thermophilic systems operate at a temperature around 130°F.

Operation at thermophilic temperature allows for shorter retention time and a higher biogas production rate. However, maintaining the high temperature generally requires an outside heat source because anaerobic bacteria do not generate sufficient heat. These biological processes produce a gas principally composed of methane (CH₄) and carbon dioxide (CO₂), but gas also has impurities such as hydrogen sulfide (H₂S). This gas is produced from feedstocks such as sewage sludge, livestock manure, and other wet organic materials.

The process of anaerobic digestion typically consists of the following three steps (shown in Figure 2):

1. Decomposition of plant or animal matter by bacteria into molecules such as sugar (hydrolysis).
2. Conversion of decomposed matter to organic acids (acetogenesis).
3. Organic acid conversion to methane gas (methanogenesis).

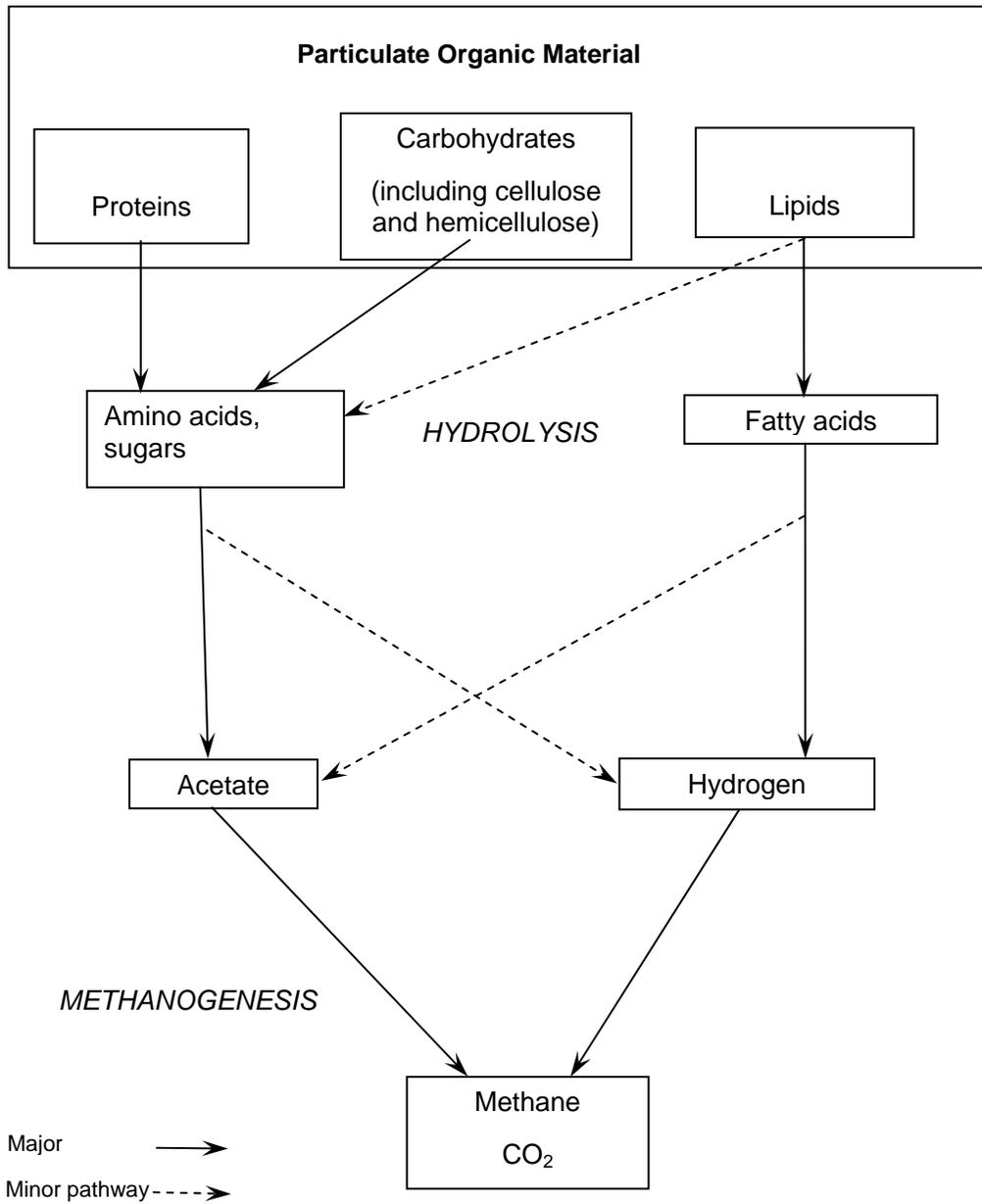
The molecular structure of the biodegradable portion of the waste that contains proteins and carbohydrates is first broken down through hydrolysis. The fats are converted to volatile fatty acids and amino acids. Carbohydrates and proteins are broken down to sugars and amino acids. In acetogenesis, acid-forming bacteria use these by-products to generate intermediary products such as propionate and butyrate. Further microbial action results in the degradation of these intermediary products into hydrogen and

acetate. Methane-generating bacteria consume the hydrogen and acetate to produce methane and carbon dioxide.

Anaerobic processes can occur naturally or in a controlled environment such as a biogas plant. In controlled environments, organic materials such as sewage sludge and other relatively wet organic materials, along with various types of bacteria, are put in an airtight container called a digester, where the process occurs. Depending on the waste feedstock and the system design, biogas is typically 55 to 75 percent pure methane, although state-of-the-art systems report producing biogas that is more than 95 percent pure methane. Biogas can be used as fuel for engines, gas turbines, fuel cells, boilers, and industrial heaters. It can also be used in other processes and in the manufacturing of chemicals (with emissions and impacts commensurate with those from natural gas feedstocks).

Anaerobic digester systems can be categorized according to whether the system uses a single reactor stage or multiple reactors. In single-stage systems, the essential reactions occur simultaneously in a single vessel. With two-stage or multi-stage reactors, the reactions take place sequentially in at least two reactors.

Figure 2. Anaerobic Digestion Pathways ¹

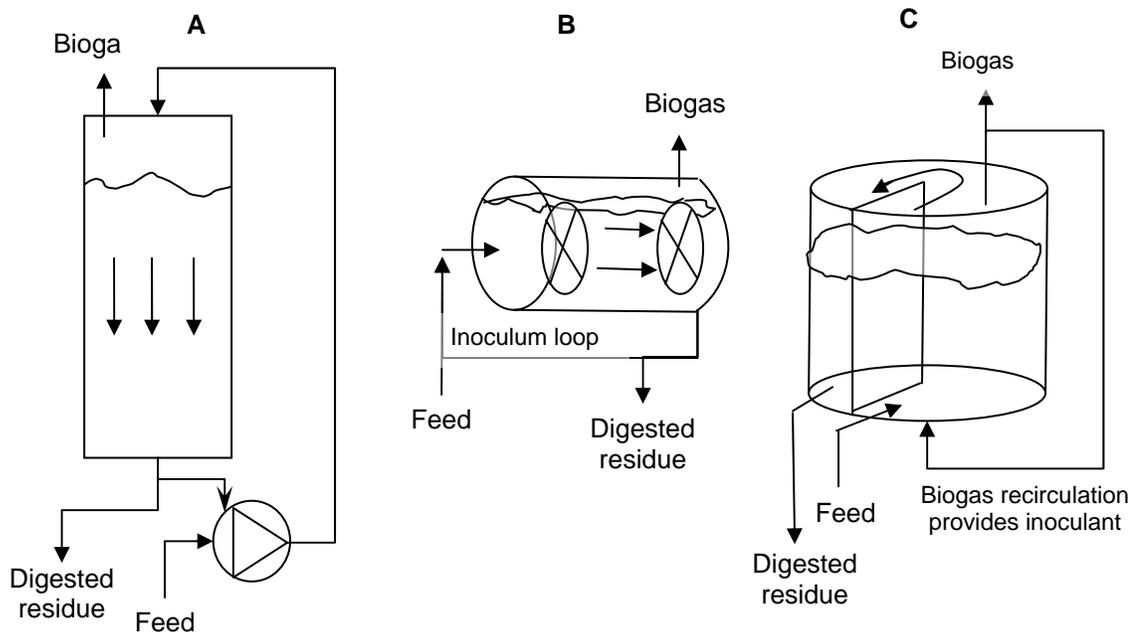


Single Stage Anaerobic Digestion

Single stage systems, as shown in Figure 3, are generally simpler to operate, have fewer components for maintenance or failure, and have smaller capital costs. Single-stage systems can be further classified into low-solids or high-solids systems. Feedstock material for single-stage low solids systems are usually pulped and slurried to a consistency of less than 15 percent total solids (TS).

Though conceptually simple, there are certain drawbacks to single-stage wet systems, including extensive pretreatment, higher water consumption, and potentially high energy requirements to operate the system. A single-stage high solids system has total solids ranging from 20 to 40 percent. The high-solids system has several advantages over a low-solids system, including being more robust and flexible regarding acceptance of rocks, glass, metals, plastics, and wood pieces in the reactor. These materials are not biodegradable and won't contribute to biogas production, but they generally can pass through the reactor without affecting conversion of the biomass components. The only pretreatment required is removal of the larger pieces (greater than 2 inches) and minimal dilution with water to keep solids content in the desired range.

Figure 3. High Solids Single-Stage Digester Designs (A—Dranco, B—Kompogas, C—Valorga)²



Two-Stage Anaerobic Digestion

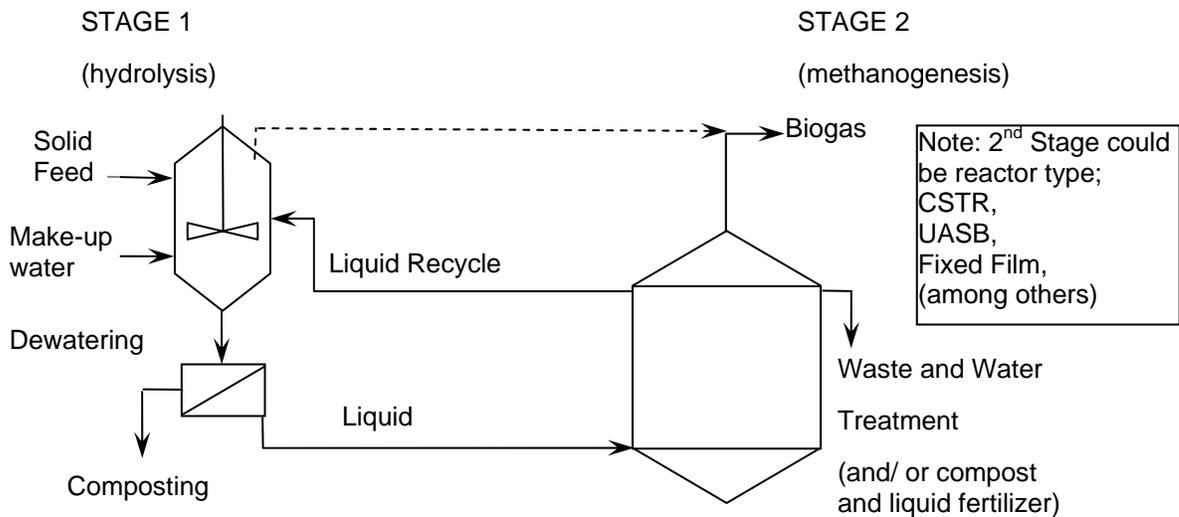
Two-stage reactors, as shown in Figure 4, separate the hydrolysis stage from the acetogenesis and methanogenesis stages. They have the potential to increase the rate of methane production and the amount of overall biodegradation of the feedstock by separating and optimizing the different steps of the biochemical process.

The reason for separating the biochemical process is because the different stages have different optimal conditions. Typically two-stage processes attempt to optimize the hydrolysis reactions in the first stage where the rate is limited by hydrolysis of cellulose. The second stage is optimized for acetogenesis and methanogenesis, where the rate in this stage is limited by microbial growth rate. With multi-staging, it is possible to increase the hydrolysis rate by applying a microaerophilic process. This process uses minimal air to allow some aerobic organisms to break down some of the lignin, which makes more cellulose available for hydrolysis. A greater proportion of air would inhibit the methanogenic organisms if they were present as they would be in a single-stage reactor.

One unique example of a two-stage digestion system that uses a watery system for separation and biological treatment of waste is Arrow Ecology's ArrowBio Process. The system uses an Upflow Anaerobic Sludge Blanket (UASB) method of digestion, which produces biogas, digester culture (solids to be used as soil conditioners), and source-separated non-degradable substances for further recycling.

This system differs from conventional two-stage anaerobic digestion systems in its ability to use the inherent moisture content from MSW to aid in mechanical separation of non-degradable solids. The ArrowBio system also produces the slurry necessary to further process the organic residuals. Contrary to conventional systems, no water or energy inputs are needed. This creates a more efficient closed-loop system for biogas and digestate production.

Figure 4. Two-Stage Anaerobic Digestion System (high solids first stage, low solids second stage)³



Anaerobic digestion technologies are considered in-vessel composting systems and would be technologies that are eligible for diversion credit. Anaerobic digestion systems have the added advantage of extracting intrinsic heat value, in the form of biogas for

energy production, from the feedstock. And the compost is also a valuable commodity for improvement of soil health.

Fermentation

Fermentation is an anaerobic process and is used to produce fuel liquids such as ethanol and other chemicals. This is similar to the process to produce beer and wine. Although fermentation and anaerobic digestion are commonly classified separately, both are fermentation methods designed to produce different products.

Cellulosic feedstocks, including the majority of the organic fraction of MSW, must undergo a pretreatment step to break down cellulose and hemicellulose to simple sugars used by the yeast and bacteria for the fermentation process. Pretreatment steps that have been researched include acid hydrolysis and enzymatic hydrolysis.

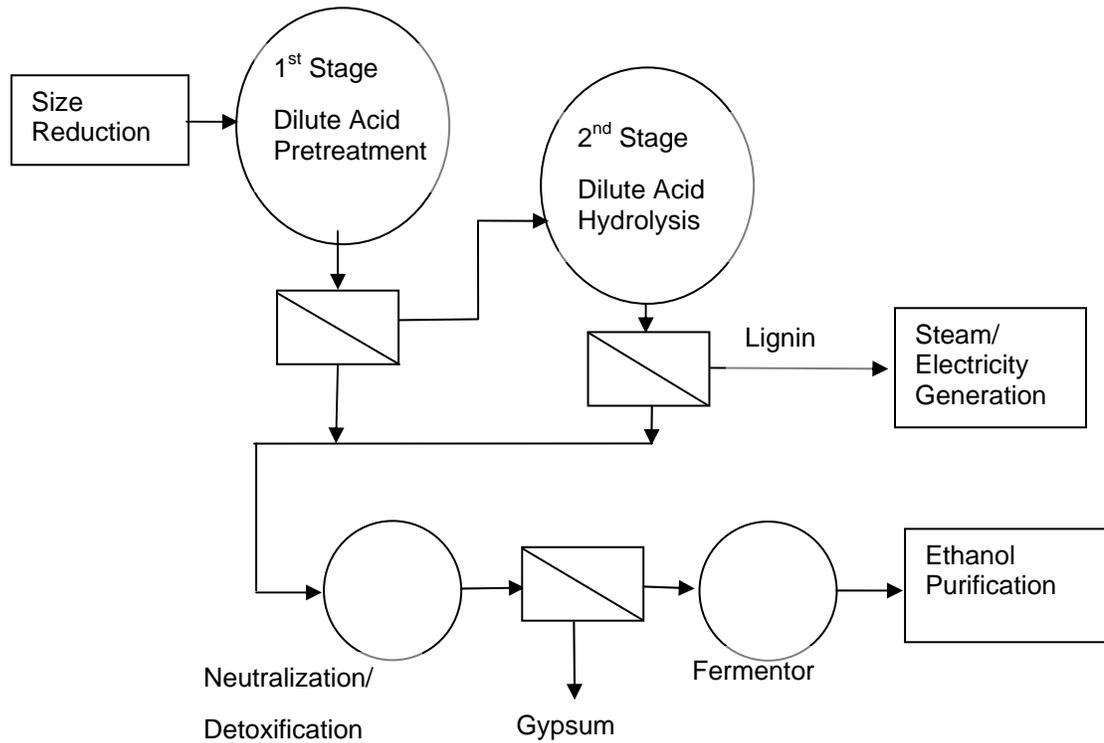
Cellulosic ethanol processes can be differentiated primarily by the hydrolysis pretreatment method. Methods that have undergone the most investigation are acid processes, enzymatic hydrolysis, and steam explosion. Acid hydrolysis, and subsequent fermentation, is technologically mature. But no facilities are operating in the United States (U.S.) or the world, and these are essentially unproven technologies from a commercial perspective. Enzymatic processes are projected to have a significant cost advantage once improved but are also commercially unproven. Steam explosion requires less initial size reduction of the feedstock. But it yields less pentose, the sugars that contain five carbon atoms, and it releases more material that can inhibit the fermentation process.

The ideal pretreatment process would have these attributes:

- Produce reactive fiber.
- Yield pentoses in non-degraded form.
- Yield no fermentation inhibitors.
- Require little or no size reduction.
- Require moderate size and cost reactors.
- Produce no solid residues.
- Simple process.
- Effective with low-moisture feedstocks.

In dilute-acid hydrolysis, biomass that has been chopped or pulverized is treated in a dilute acid medium. Most current dilute acid hydrolysis processes employ two stages (Figure 5), one optimized for the hemicellulose component, and the other, a more severe stage for the cellulose. Cellulose is more difficult to hydrolyze because much of it is bound up in a structural matrix that includes lignin and cellulose. Process temperatures are typically near 460°F. The use of dilute acid hydrolysis is the oldest technology for converting biomass into its component sugars for subsequent fermentation to ethanol.

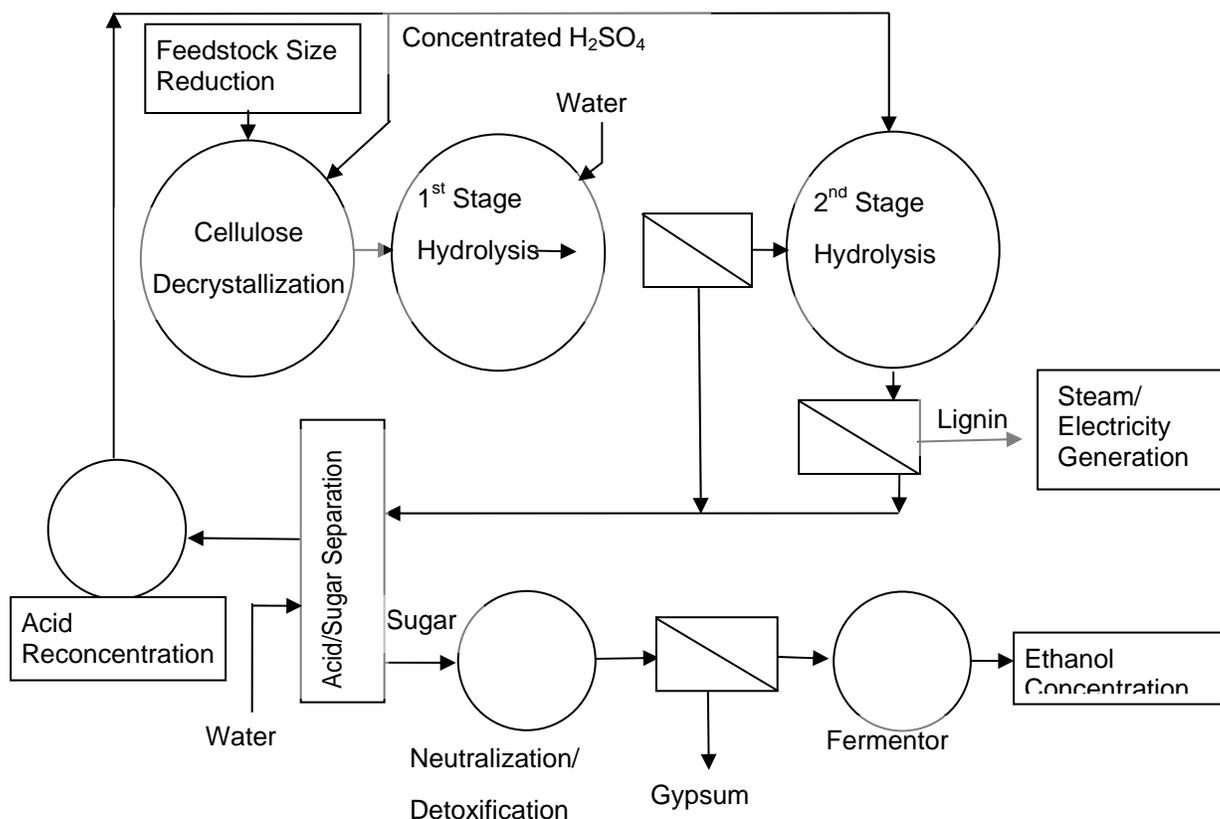
Figure 5. Typical Two-Stage Dilute Acid Hydrolysis Fermentation



Concentrated-acid hydrolysis (Figure 6) uses concentrated sulfuric acid to decrystallize the cellulose followed by dilute acid hydrolysis. Critical operations include separation of sugar from acid and acid recovery with re-concentration. The concentrated acid process includes a step to separate the acid-sugar stream through a separation column that yields a 25 percent concentrated acid stream and a 12 to 15 percent concentrated sugar stream.

The sugar recovery can be up to 95 percent, whereas the acid recovery is typically about 98 percent. The recovered acid is concentrated and reused. The sugar stream, which contains no more than 1 percent acid, can then be fermented. Concentrated acid hydrolysis releases more compounds that inhibit fermentation.

Figure 6. Concentrated Acid Hydrolysis Fermentation.



Ethanol production using enzymatic hydrolysis uses enzymes derived from common fungi. Research has been directed at improving cost and performance of cellulase (a substance used to break down cellulose). Research is ongoing worldwide at both public and private institutions such as the National Renewable Energy Laboratory, a subcontractor for the CIWMB's *Life Cycle and Market Impact Study*. Improvements in enzymatic hydrolysis are expected that will make ethanol production from cellulosic biomass competitive with that produced by the starch/sugar platform.

Hydrothermal hydrolysis processes include the relatively simple hot-compressed water (HCW) as well as steam explosion and supercritical water techniques. The ionic properties of water change with the temperature, and they reach the maximum value at around 480°F. Therefore, HCW conducted at around 480°F is considered optimal for this method of hydrolysis. Steam explosion involves pressurizing the biomass with steam for a period followed by rapid depressurization. The result is a lignocellulosic mulch with much more of the cellulose exposed and more accessible to hydrolysis.

Fermentation of biomass material into ethanol is fully commercial for sugar- and starch-based feedstocks such as corn and sugar cane. But fermentation is not yet commercial for cellulosic biomass because of the high expense or low sugar yields from the hydrolysis pretreatment process, and it is the subject of intense research. The biodegradable fraction of most MSW streams contains significant amounts of cellulosic

biomass (for example, paper, woody residues, yard wastes, and some food waste) that are more difficult than starch and sugars to convert to ethanol. Systems that propose to use post-recycled MSW for fermentation feedstock rely on the expectation that the feed material has a tipping fee associated with it.

Cellulosic feedstock material must be hydrolyzed to break the cellulose and hemicellulose polymers into simple sugars that are fermentable by yeasts. As with anaerobic digestion to biogas, lignin cannot be hydrolyzed or fermented but may be a good feedstock for thermochemical processes or typical biomass-to-energy processes.

Once the cellulose has been hydrolyzed and conditions made favorable (for example, pH- and temperature-adjusted), ethanol is produced from microbial fermentation. A variety of microorganisms, generally bacteria, yeast, or fungi, are used to ferment carbohydrates to ethanol under anaerobic conditions; however, as the ethanol level rises, the microbial growth is inhibited. Ethanol must be separated from the fermentation broth and concentrated by conventional distillation technology and dehydrated to yield fuel-grade ethanol. The remaining liquid broth is recycled or sent to a wastewater treatment facility for appropriate management.

Technical Evaluation and Cleanest, Least Polluting Technologies

AB 2770 required the report to include a description and evaluation of the technical performance characteristics, feedstocks, emissions, and residues used by each conversion technology and an identification of the cleanest, least polluting technology.

Current Status

Much of the development and deployment of new and emerging conversion technologies has occurred in Japan, Germany, and the United Kingdom, with more than 50 thermochemical facilities and more than 80 anaerobic digestion facilities that use unsorted MSW as a feedstock.

Thermochemical Conversion

A large number of gasification and pyrolysis technologies have been developed and demonstrated on levels from laboratory scale through pilot and fully commercial scale. Coal remains the predominant feedstock that is gasified, but the commercialization of gasification for waste is growing. In general, most of the commercially identified pyrolysis and gasification facilities are operational at levels between 100 and 500 tons per day (TPD) capacity.

More than 50 pyrolysis or gasification facilities commercially processing unsorted MSW were identified. The four largest facilities alone represent processing capacities of more than 2.5 million tons of MSW each year. Table 1 lists all the commercially active pyrolysis facilities that use MSW. Table 2 lists all commercially active gasification facilities.

The use of pyrolysis and gasification for MSW has occurred mostly in Japan, where landfill space and resources are limited. In examining the three largest suppliers in Japan, the capacities of their plants represent more than 2 million tons of material each year, with additional plants being planned. Much of this capacity has been installed in the past five years. Japan is currently the leader in the use of pyrolysis systems for MSW.

Table 1. Commercially Active Pyrolysis Facilities Using MSW

Location	Company	Began Operation	MSW Capacity
Toyohashi City, Japan Aichi Prefecture	Mitsui Babcock	March 2002	2 x 220 tons per day (TPD) 77 TPD bulky waste facility
Hamm, Germany	Techtrade	2002	353 TPD
Koga Seibu, Japan Fukuoka Prefecture	Mitsui Babcock	January 2003	2 x 143 TPD No bulky waste facility
Yame Seibu, Japan Fukuoka Prefecture	Mitsui Babcock	March 2000	2 x 121 TPD 55 TPD bulky waste facility
Izumo, Japan	Thidde/Hitachi	2003	70,000 tons per year (TPY)
Nishi Iburi, Japan Hokkaido Prefecture	Mitsui Babcock	March 2003	2 x 115 TPD 63 TPD bulky waste facility
Kokubu, Japan	Takuma	2003	2 x 89 TPD
Kyohoku, Japan Prefecture	Mitsui Babcock	January 2003	2 x 88 TPD No bulky waste facility
Ebetsu City, Japan Hokkaido Prefecture	Mitsui Babcock	November 2002	2 x 77 TPD 38 TPD bulky waste facility
Oshima, Hokkaido Is., Japan	Takuma		2 x 66 TPD
Burgau, Germany	Technip/Waste Gen	1987	40,000 TPY
Itoigawa, Japan	Thidde/Hitachi	2002	25,000 TPY

Table 2. Commercially Active Gasification Facilities Using MSW

Location	Company	Began Operation	MSW Capacity
SVZ, Germany	Envirotherm	2001	275,000 TPY
Ibaraki, Japan	Nippon Steel	1980	500 TDP
Aomori, Japan	Ebara	2001	500 tpd (ASR)
Kawaguchi, Japan	Ebara	2002	475 TPD
Akita, Japan	Nippon Steel	2002	440 TPD
Oita, Japan	Nippon Steel	2003	428 TPD
Chiba, Japan	Thermoselect/JFE	2001	330 TPD
Ibaraki #2, Japan	Nippon Steel	1996	332 TPD
Utashinai City, Japan	Hitachi Metals		300 TPD
Kagawa, Japan	Hitachi Zosen	2004	300 TPD
Nagareyama, Japan	Ebara	2004	229 TPD
Narashino City, Japan	Nippon Steel	2002	222 TPD
Itoshima-Kumiai, Japan	Nippon Steel	2000	220 TPD

Location	Company	Began Operation	MSW Capacity
Kazusa, Japan	Nippon Steel	2002	220 TPD
Ube City, Japan	Ebara	2002	218 TPD
Sakata, Japan	Ebara	2002	217 TPD
Kagawatobu-Kumiai, Japan	Nippon Steel	1997	216 TPD
Lizuka City, Japan	Nippon Steel	1998	198 TPD
Tajimi City, Japan	Nippon Steel	2003	188 TPD
Chuno Union, Japan	Ebara	2003	186 TPD
Genkai Envir. Union, Japan	Nippon Steel	2003	176 TPD
Iabarki #3, Japan	Nippon Steel	1999	166 TPD
Ishikawa, Japan	Hitachi-Zosen	2003	160 TPD
Kocki West Envir., Japan	Nippon Steel	2002	154 TPD
Nara, Japan	Hitachi-Zosen	2001	150 TPD
Toyokama Union, Japan	Nippon Steel	2003	144 TPD
Mutsu, Japan	Thermoselect/JFE	2003	140 TPD
Minami-Shinshu, Japan	Ebara	2003	155 TPD
Iryu-Kumiai, Japan	Nippon Steel	1997	132 TPD
Maki-machi-kumiai, Japan	Nippon Steel	2002	132 TPD
Kamaishi, Japan	Nippon Steel	1979	110 TPD
Takizawa, Japan	Nippon Steel	2002	110 TPD
Seino Waste, Japan	Nippon Steel	2004	99 TPD
Kameyama, Japan	Nippon Steel	2000	88 TPD
Nagasaki, Japan	Hitachi Zosen	2003	58 TPD
Aalen, Germany	PKA	2001	27,000 TPY
Gifu, Japan	Hitachi Zosen	1998	33 TPD
Bristol, UK	Compact Power	2002	9,000 TPY

UC researchers have concluded that the rapid progress toward commercialization during the past five years, especially in Japan, shows that gasification and pyrolysis technologies appear to be well on their way to technological maturity in terms of efficiency, reliability, and environmental performance.

Several thermochemical conversion facilities have experienced technical problems during the course of operation or commissioning. A facility in Furth, Germany, experienced considerable problems that culminated in a serious accident at the site. The

accident was reportedly due to a plug of waste that formed in the pyrolysis chamber that resulted in an overpressure and escape of pyrolysis gas. European sources indicate that the problem was the result of processing full-size mattresses, an issue that has been resolved in newer versions of the technology by addition of an up-front shredder.

A gasification facility built by Brightstar Environmental in Wollongong, New South Wales, Australia, has had problems with the char gasification component of the process.

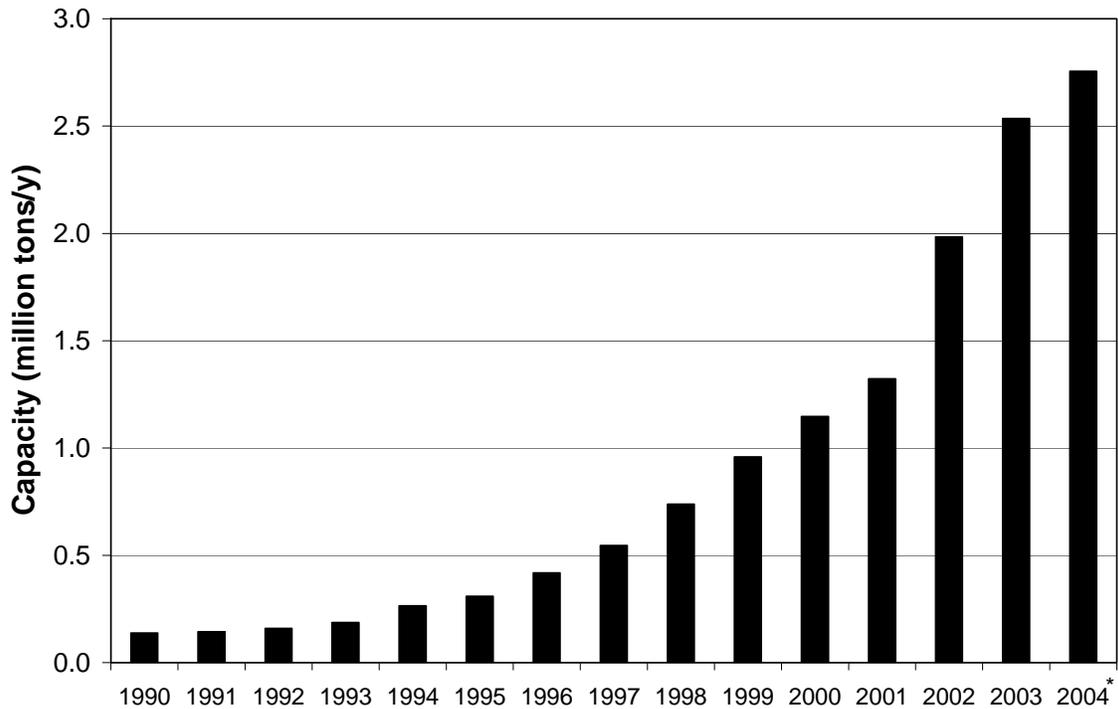
Technological risks remain when using alternative thermochemical conversion technologies to process heterogeneous and highly variable feedstocks such as post-recycled MSW. For this reason, the importance of feedstock preparation and pre-processing is vital to the success of thermochemical technologies.

Biochemical Conversion

The installed capacity of anaerobic digestion facilities in Europe is responsible for processing more than 3,000 tons per year (TPY). The feedstock must be pre-sorted and is composed of at least 10 percent from municipal or commercial organic waste. Many of these facilities co-digest with animal wastes and municipal wastewater sludges. In Spain, 13 large capacity plants, averaging 70,000 TPY, were projected to be anaerobically treating nearly 7 percent of Spain's biodegradable MSW by the end of 2004.

For all of Europe, the installed capacity has grown from 1.1 million TPY in 2000 and was projected to be 2.8 million TPY in 2004, an increase of more than 250 percent in four years. Figure 7 shows development of installed capacity of MSW anaerobic digestion facilities in Europe between 1990 and 2004. The annual capacity growth rate is above 20 percent. Single-stage anaerobic digesters account for approximately 92 percent of this installed anaerobic digestion (AD) capacity.

Figure 7. Anaerobic Digester Capacity Growth in Europe* 4



A demonstration pilot-scale facility is currently in operation with preliminary positive results at the University of California-Davis using a design developed at UC Davis and partially funded by the CEC's PIER program. The facility uses green waste, animal bedding, and food waste as feedstock for the process.

Fermentation of biomass into ethanol is fully commercial for sugar and starch-based feedstocks. It is not yet commercial for cellulosic biomass, which is what the organic fraction of MSW would primarily consist of, because of technical difficulties and cost, but this remains an active area of research and development. The Masada OxyNol process is permitted and expected to begin construction soon in Middletown, New York. This facility is permitted for 230,000 TPY of MSW and 71,000 bone-dry TPY of biosolids, with an expected annual output of 8.5 million gallons of ethanol.

Feedstocks

According to the 2003 waste characterization study conducted by the CIWMB, organic materials make up more than 30 percent of the waste stream in California. Although this is slightly less than what was reported from the 1999 waste characterization study, organics materials are still the largest category of material being landfilled. Organic materials such as paper, cardboard, plastic, food waste, and green waste may be

* NOTE: Capacity projected for 2004.

acceptable feedstock for use in conversion processes such as gasification, pyrolysis, fermentation, and anaerobic digestion.

Thermochemical processes can potentially convert all the organic portion of the waste stream that is currently going to landfill into heat and other useful products. Most thermochemical processes operate at elevated temperatures, the fate of trace inorganic elements, such as metals that may be present in MSW, needs to be considered in the process design. Further sorting and/or processing of post-MRF MSW would normally be conducted prior to thermal conversion to extract recyclable materials, reduce particle sizes to those compatible with the process, and dry the material if needed.

Another element of the sorting process would be to remove, to the extent possible, materials such as polyvinyl chloride, batteries, or feedstocks with copper (Cu) that can contribute to the formation of toxic emissions. Metals, glass, and ash do not contribute substantially to energy value in thermochemical processing but may be substantially transformed due to the high temperatures involved. Unrecyclable plastics such as plastic resin #4 through #7 may also be converted by thermochemical processing.

Biochemical processes can convert only the biodegradable fraction of feedstocks. Metals, glass, mineral matter, and most of the current plastic stream will not be converted. Some of the newer plastics include biodegradable fractions or are fully biodegradable. The fraction of these plastics in the waste stream is currently very small but may increase over time. Higher-moisture feedstocks such as green waste or food waste are better suited for biochemical processes, partly because extra energy is required for drying before use in most thermochemical processes.

Biochemical conversion technologies are better suited for source-separated green or food waste, or the biomass fraction of mixed MSW after sorting. Some biochemical systems can accept unsorted MSW (shredded or crushed to appropriate size) in the reactor, though this is not optimal from the standpoint of material handling, reactor volume utilization, and disposal or use of residuals.

The 2003 waste characterization information was not available at the time the contractor studies were being conducted. As a result, all the numbers, tables, and graphs in this report are based on 1999 waste characterization information. Paper and cardboard is the largest category of materials currently landfilled (on both a mass and energy basis) that could be processed by conversion technologies. Paper and cardboard material comprise 11 million tons or 30 percent of the materials currently landfilled. On an energy basis, however, paper/cardboard represents nearly half (44 percent) of the potential chemical energy in the waste stream.

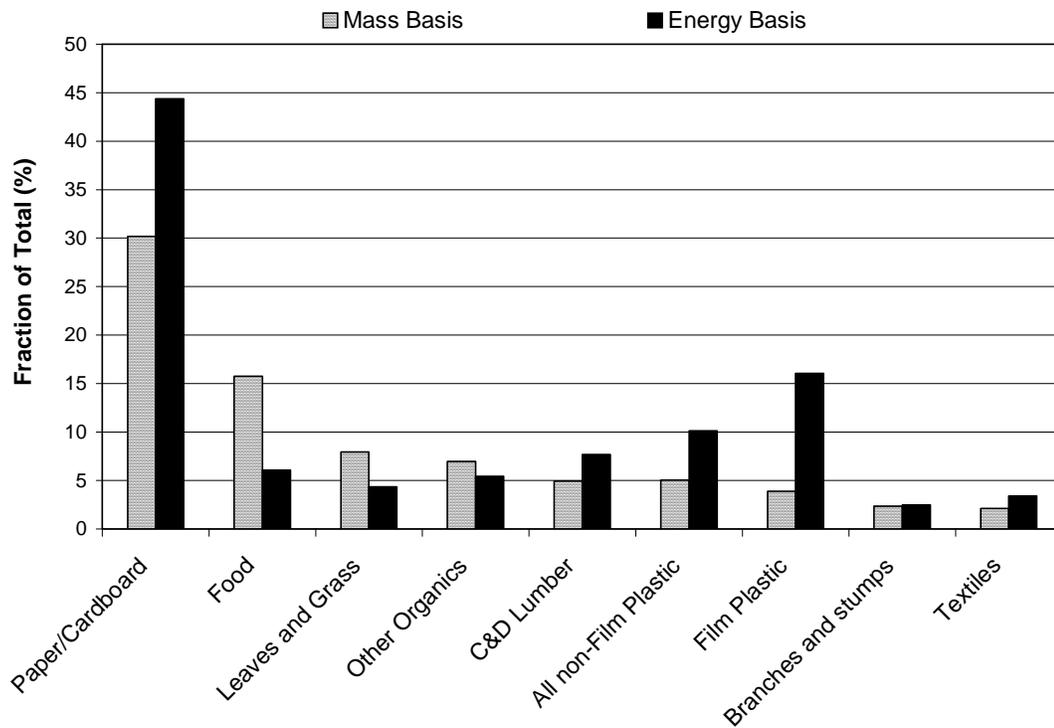
From an energy standpoint, plastics and other organic components of fossil origin in MSW are the second-largest component of the waste stream, representing some 30 percent of the chemical energy. On a weight basis, plastics and textiles represent 11 percent or 4.2 million tons of material landfilled. On a volumetric basis, however, plastic materials occupy as much as 22 percent of the space in a landfill due to their comparatively lower density.

Plastic materials present in the waste stream in the highest amounts include high-density polyethylene (HDPE), polyethylene terephthalate (PET), film plastics, and other durable plastics. Some gasification technologies can use film plastic as a feedstock to

make ethylene gas which, in turn, can be used to produce more film plastic. Some stakeholders have commented that conversion processes could serve as a disincentive to reduce the amount of plastic produced. However, others have stated that this type of process could serve as a recycling technology for a feedstock that historically could not be recycled.

Figure 8 presents graphically the fractions of the energetic components of the landfilled stream (displayed both by mass and energy bases). Note that while paper and cardboard account for about 30 percent of the disposed stream by mass, the category contains nearly 45 percent of the total stream primary chemical energy. Plastics weigh in at about 9 percent of the disposed stream and more than 25 percent of the MSW primary chemical energy, due to their significantly higher chemical energy content per unit mass when compared with biomass organic materials.

Figure 8. Fractions of Total Mass and Energy of Waste Stream Components ⁵



With a high percentage of the total available chemical energy in mixed MSW, non-recycled plastics could be attractive materials for alternative conversion processes. Thermochemical processes currently represent the only means for plastics conversion. With the appropriate thermochemical processes, gasoline, diesel, and other fuels could be produced, as could petroleum-like base products such as ethylene for new plastics production.

These technologies have the potential to save valuable natural resources by avoiding the extraction of non-renewable crude oil, coal, and natural gas. Thermochemical techniques have previously been commercialized for plastics recycling. These conversion technologies could also be applied to the growing problem areas of

electronic components, consumer appliances, and plastic packaging materials. Since chlorine is a precursor to dioxin formation, the chlorinated plastics components would either have to be separated from the feed stream or include appropriate remediation technology in the process.

Primary feedstocks for biochemical processes would be green and food wastes, although other biomass sources such as sludge could also be used. Sludge may have value as fertilizer or soil additives if heavy metal concentrations can be kept sufficiently low. Lignin is largely undegraded in most fermentation systems, including anaerobic digestion, and hence remains as a residue of the process. Lignin represents approximately 28 percent of typical soft wood, up to 50 percent for nut shells, with lower percentages for grasses, straws, and other herbaceous materials.

Paper is primarily cellulose but may be coated or otherwise treated, and it may include other constituents such as clay and heavy metals from pigments.

Overall, the amount of energy that is derived for different processes is a function of both the feedstock and the method used to produce the energy. Feedstocks with high heat values, such as plastics, tires, or rubber, can produce generally higher energy outputs. On a per-mass basis, the greater the preprocessing, the greater the potential energy output. This is particularly true with respect to removal of inorganic material such as metals and glass.

Products

Products from conversion technologies will differ based on the technology used and the feedstock that is converted. Generally speaking, products consist of the following:

Gasification:

- Fuel gases (CO, CH₄, H₂, N₂, CO₂ & other hydrocarbons such as C₂H₂, C₂H₄, C₂H₆) or synthesis gas.
- Heat that can be transferred to the process to displace a fuel.
- Tars and other condensable substances, if present after gasification process.
- Char and ash.

Pyrolysis:

- Fuel gases (CO₂, CO, CH₄, H₂) containing less chemical energy than equivalent product gases for gasification of the same feedstock.
- Ash and char (fixed carbon not pyrolyzed) containing significant quantities of feedstock chemical energy.
- Pyrolytic tars and other high molecular mass hydrocarbons, also containing significant quantities of feedstock chemical energy.

- Pyrolytic oils and/or other condensable substances, containing significant quantities of feedstock chemical energy.

Biochemical processes can yield:

- Biogas (a mixture of methane and carbon dioxide). Biogas contains less chemical energy than the equivalent products from gasification of the same feedstock.
- Ethanol.
- Solvents, organic acids, and other bio-based chemicals for refining to end products.
- Residues that can be used for compost/soil amendment/fertilizer if permitted by local regulations or a feedstock for thermochemical conversion.

Fuels and chemicals can be produced from the synthesis gas derived from gasification and pyrolysis of the feedstocks. Storable gas, liquid, and chemicals can be produced by conversion technologies. The secondary processing of synthesis gas can be used to produce a range of liquid fuels and chemicals including methanol, dimethyl ether (DME), Fischer-Tropsch diesel fuel, hydrogen, ethanol, ethylene, or substitute natural gas.

For the production of these fuels or synthetic chemicals, the synthesis gases from gasification processes generally require less additional processing to produce valuable products than any other form of conversion technology except the methane-rich biogas produced through anaerobic digestion. Interestingly enough, film plastic is produced from ethylene gas, which is derived from non-renewable natural gas.

Products of biochemical processes include biogas, ethanol, and other alcohols for use as fuels or as chemical feedstocks. Biochemical processes can also be used to produce higher value chemical products. Biogas can be upgraded to natural gas pipeline quality and compressed for use as a transportation fuel much like compressed natural gas (CNG). Ethanol is produced from a fermentation process, distilled and dehydrated to yield fuel-grade ethanol.

Digestate from digestion processes including lignin and other non-degraded components of the feedstock can be processed for fertilizer and soil conditioning applications. Alternatively, the material can be used in compost or dried and used as a boiler fuel for heat and power or converted to fuels through thermochemical means.

Biomass can be hydrolyzed to create fermentable sugars for producing ethanol. Sugars can also be converted to levulinic acid and citric acid. Levulinic acid is a versatile chemical that is a precursor to other specialty chemicals, fuels and fuels additives, herbicides, and pesticides. The largest application for citric acid is in the beverage industry, which accounts for about 45 percent of the market for this product. Citric acid is also used in a wide variety of candies, frozen foods, and processed cheeses and as a preservative in canned goods, meats, jellies, and preserves.

Products that can be created from conversion technologies are listed below in Table 3. In general, however, no quantitative market analysis data is available.

Table 3. Products of Conversion Technologies

Conversion Technology	Primary Product	Secondary Products	Solid Residues	Value of Secondary Products	Feedstocks Processed
Complete gasification	Synthesis gas	Fuels, chemicals, and electricity	Ash metals, recycle or landfill	Very high and flexible	All organics, low moisture
Incomplete gasification (See pyrolysis)	Fuel and synthesis gas	Electricity, some marketable fuels	Char ash, metals, recycle	Moderate, may need refining at additional expense	All organics, low moisture
Indirectly fired pyrolysis with drier & gasifier	Fuel and synthesis gas	Electricity, some marketable fuels	Char ash, metals recycle or landfill	Moderate may need refining at additional expense	All organics, low moisture
Anaerobic digestion	Fuel gas (CH ₄ and CO ₂)	Heat, power, fuels, chemicals, soil amendment	Inorganics, metals, glass, undegraded biomass	Moderate to high	Biodegradable components
Fermentation	Ethanol	Chemicals, heat, soil amendment	Inorganics, metals, glass, undegraded biomass	Moderate to High	Biodegradable Components

Environmental Impacts and Controls

AB 2770 required the CIWMB to assess the environmental and public health impacts of each conversion technology in comparison to those environmental and public health impacts from the transformation and disposal of solid waste.

A number of environmental factors will impact conversion technologies. These impacts include:

- Air emissions, particularly dioxin, furans, heavy metals, and greenhouse gas emissions.
- Management of ash, char, and other solid residues.
- Management of any liquid residues.

A number of studies have characterized emissions from individual waste conversion processes. But they lack the consistent, comprehensive data necessary to make comparative analyses and broad conclusions within and among technology classes. This is due to the wide variety of process configurations, feedstock processed, and control

strategies that are uniquely applied to individual facilities. The lack of data is also due to the general immaturity of conversion technologies as applied to MSW.

Air Emissions

Emissions from thermochemical and biochemical systems include such things as NO_x, SO_x, hydrocarbons, carbon monoxide, particulate matter (PM), heavy metals, greenhouse gas emissions such as methane and CO₂, and dioxins/furans. In addition, fugitive gas and dust emissions may be present that depend on control strategies, operational practices, and level of maintenance at a particular facility.

For example, enclosed receiving buildings may have exhaust air treatment to minimize volatile organic compounds (VOC) and dust emissions from unloading and feedstock storage. Conversion processes, particularly thermochemical conversion, may use air pollution control devices at the reactor outlet as well as the exhaust gas outlet. This will allow for redundant control and monitoring. Table 4 lists typical air pollution control technologies that have been used for emission control.

Table 4. Air Pollution Control Technologies ⁶

Contaminant	Control Technology
Particulate matter (PM) and aerosols	Inertial separation, baghouse, scrubbers, electrostatic precipitators (ESP)
Volatile metals (vapor state)	Carbon filters (or condense to PM or aerosols and use PM separation techniques)
Dioxin/furans	Limit chlorine mass input in feedstock, cold-quenching and/or catalytic/thermal combustion
Carbon monoxide (CO) and Hydrocarbon (HC) gases	Process design, catalytic/thermal combustion, re-burning, carbon filters
Oxides of nitrogen (NO _x)	Flame temperature control, low NO _x combustors, fuel nitrogen management, selective catalytic reduction, water injection, re-burning
Oxides of sulfur (SO _x)	Limit sulfur mass input scrubber
Acid gases	Scrubber

Dioxins and furans are of particular concern in terms of potential environmental consequences. These compounds are formed under high temperatures when chlorine and complex mixtures containing carbon are present, and they can be found in the gas and liquid phases. Dioxins and furans are typically formed downstream of the combustion process as the flue gases cool in a temperature range of 400°F–1290°F, with a maximum formation rate at approximately 600°F. Conditions that enhance the

downstream formation of dioxins and furans include poor gas-phase mixing during combustion, low combustion temperatures, and incomplete combustion.

Proper design of thermochemical conversion processes and pollution control equipment is critical to addressing the risks associated with dioxins and furans. An operator can limit the amounts of chlorine and copper in the feedstock to minimize potential formation. In cases where this is not feasible, a process called cold-quenching and/or high-temperature incineration of intermediate products is recommended to prevent release to the atmosphere.

In cold-quenching, intermediate gases are quickly cooled in a caustic scrubber solution in order to prevent the re-formation of dioxins and furans. Alternatively, or in addition to cold-quenching, high-temperature combustion of intermediate gases can prevent the re-formation and destroy dioxins/furans already present.

The Stockholm Convention on Persistent Organic Pollutants (May 2001), which the U.S. has signed, has established a goal of reducing or eliminating the creation of persistent organic pollutants such as dioxins and furans. The convention provides guidance for best available techniques for achieving its specific goals. These techniques include use of cold-quenching, improved flue-gas cleaning such as thermal or catalytic oxidation, dust precipitation, or adsorption.

Other techniques mentioned in the convention include treatment of residuals, wastewater, and wastes and sewage sludge by thermal treatment. Also included were modifications of process designs to improve combustion and prevent formation of the chemicals through the control of parameters such as incineration temperature or residence time. As Table 4 shows, many of the air pollution controls suggested by the convention have been used historically.

There are instances where the amount of dioxin present in the effluent stream (air, solid, and liquid) of the combustion facility is less than that present in the feedstock. This may suggest that high-temperature conversion technologies, such as gasification, could serve as a method to destroy dioxins in some instances.

Methane present in landfill gas is another pollutant of concern. The bacterial decomposition of landfilled material produces significant quantities of landfill gas that can be captured by landfill gas extraction methods; however, there is not 100 percent capture of the landfill gas. The methane emissions from landfills are particularly important, since methane is 21 times more potent as a greenhouse gas than carbon dioxide. Landfills represent the second largest source of anthropogenic methane emissions. By contrast, thermal facilities are designed to produce a fuel gas or synthesis gas that may contain methane. In addition, thermal facilities are designed for 100 percent capture of the produced gas, including methane.

Solid Residues

Essentially all conversion technologies will produce a solid residue because all components of the solid waste stream contain inorganic material, or ash. The amount of ash varies with the material and how it is handled before it becomes a feedstock.

Depending on markets and hazardous content of solid residue, it may find commercial use or may need to be disposed in non-hazardous or hazardous waste landfills.

Thermochemical

All organic matter including biomass and solid waste contains trace quantities of heavy metals. Whether the feedstock is landfilled, composted, gasified, or incinerated, the heavy metal quantity remains identical; the only difference is that thermal decomposition processes retain most of the heavy metals in their residue/ash in a concentrated form. More volatile heavy metals, such as mercury, will enter the gas phase in thermal conversion and must be managed or captured before being exhausted to the atmosphere.

Conversion technologies do not create new heavy metals in ash but do concentrate heavy metals already present in the feedstock that would otherwise be landfilled. With proper management, the concentrated heavy metals can be treated and disposed of in a controlled manner that poses no greater environmental threat than landfilling.

In some cases, metals may even be reclaimed from the solid residue. Leachability testing is done by using the Toxicity Characteristic Leaching Procedure (TCLP). Normally these residues are classified as “Non-Hazardous” and “Non-Specialist” under regulations in the United Kingdom, European Union, and the U.S.

In many processes, the ash is vitrified by heating above the melting point or fusion temperature of the ash. This material is a hard glassy substance that has little if any leachability. The bottom ash and slag may also be used in different construction and other applications. A small amount of residue is generated by baghouse filters and scrubber solids, which must be periodically cleaned.

Table 5 shows results of ash leaching tests from various thermochemical vendors. Testing is typically conducted by a certified, independent laboratory, though not necessarily verified by an independent third party. The data show that results of leaching tests are below the standards established by the U.S. Environmental Protection Agency (U.S. EPA).

Table 5. Ash Leaching Data from Pyrolysis/Gasification Facilities

	Units	As	Ba	Cd	Cr	Pb	Hg
U.S. EPA TCLP Test Limit	mg/l	5.0	100	1.0	5.0	5.0	0.2
BalPac	mg/l	0.05	0.37	0.1	0.01	0.58	-
Compact Power	mg/kg	-	-	4	-	-	0.1
Ebara/Alstom (glass granulate)	mg/l	-	-	<0.001	<0.005	0.013	<0.0005
GEM	Ppm	<100	-	<100	1330	<100	<100
Nexus	mg/kg	<1	-	<0.05	<0.05	<1	<0.05
PKA	mg/l	0.002	-	<0.001	<0.01	-	<0.002

Notes: 1) As=Arsenic, Ba=Barium, Cd = Cadmium, Cr = Chromium, Pb=Lead, Hg=Mercury
 2) 1 mg/l = 1 mg/kg = 1 ppm

Regardless of the management process used, the amount of heavy metals contained in the feedstock itself primarily determines the metals concentration in the emissions and/or ash. For any given technology, removing the main source of heavy metals is the most effective method for minimizing the level of trace heavy metals.

According to the UC researchers, any claim by suppliers that a particular management process can eliminate or produce fewer trace heavy metals is not factual. However, residues from varying processes can have different leachability levels. Trace metals partitioning to air, solid, or liquid residues may vary.

Biochemical

In general, biochemical conversion processes have the potential for much more solid residue than that from thermochemical processes. Biochemical conversion requires more residence time compared with thermochemical methods, so practical systems are not large enough to convert all biodegradable components. This, combined with the lignin components of biomass—which are not biodegradable in practical systems—plus the ash in the material, results in substantial solid residue that may or may not have commercial use.

Liquid Residue

Conversion technologies will also generate liquid residues that must be managed appropriately. As with the solids residue, the amount of liquid residue is dependent on the specific conversion process and feedstock. Well-defined mechanisms are already in place for dealing with these waste streams. Generally, these waste streams are subjected to conventional chemical treatment processes typically used at waste water treatment facilities. Products from the gas-cleaning and water recovery processes include industrial-grade salts and a separate precipitate containing the heavy metals from the feedstock stream. In some cases, this precipitate may be rich enough in zinc and lead for recovery in a smelter operation.

Thermochemical

Pyrolytic oil can contain toxic substances including acids, alcohols, aldehydes, ketones, esters, heterocyclic derivatives, and phenols. Most of these compounds are used in current industrial operations. Although these pyrolysis oils must be handled using appropriate precautions, they should pose no greater hazard than other industries where toxic substances are commonly used.

When feedstocks containing elevated levels of chlorine are used, chlorinated hydrocarbon species can be expected to be found in the pyrolysis products, unless a strongly reducing high-pressure hydrogen atmosphere is used to prevent their formation. A study published in the technical journal *Chemosphere* (“Formation Characteristics of PCDD and PCDF during Pyrolysis Process”) found that the pyrolysis of the residue from shredding industrial light bulbs and refrigerators resulted in the formation of dioxins/furans of about 1,500 to 10,000 nanograms/per gram in the pyrolysis oil.⁷

Spent scrubber solutions from air pollution control equipment or boiler blow-down water must also be managed appropriately.

Biochemical

The liquid wastes generated by conversion processes include spent acid solutions from acid hydrolysis and liquid digestate from biochemical systems. Surplus water is usually generated from anaerobic digestion systems. Water quantity depends on the digestion technology as well as the substrate. In many instances, the liquid has a value as a fertilizer for agriculture application. Some compost operations can accept the liquid for compost moistening.

Nuisance Factors

The nuisance factors associated with conversion technologies include noise, odors, fugitive emissions, dust, litter and debris, increased local traffic, aesthetics, and animal and insect pests. In general, these impacts would not be expected to increase and may be reduced compared with what is experienced in existing solid waste facilities. The use of engines, turbines, and generators to produce electricity may result in increased noise, but this is commonly mitigated by enclosing the generating equipment.

Conversion processes generally occur in an enclosed vessel so odors, fugitive dust, and litter are not typically associated with the reactor component of the system. Co-location of conversion facilities at existing solid waste facilities could minimize any increased traffic because the existing transportation infrastructure can be used and material can be transported via conveyor belts. However, some minor traffic impacts may be associated with off-site transportation of commercial products and by-products for marketing and disposal.

Data Acquisition and Other Studies

Acquiring data from operating facilities has been difficult because of the absence of operating conversion technology facilities that use post-MRF or otherwise sorted MSW residuals in California or the U.S. To address this data gap, the UC researchers conducted a survey of known conversion technology vendors.

The survey asked for information such as commercial status, types of feedstock processed, process design and description, and emissions data (Table 6). The University researchers did receive some emissions data from vendors. Although data may come from vendors, the actual testing of samples is conducted by certified laboratories and not the vendors themselves. In addition, continuous emissions monitoring of criteria pollutants such as NO_x and CO takes place, with simultaneous monitoring available to local air pollution control districts.

Table 6. Emission Results for Various Pyrolysis/Gasification Facilities (mg/Nm³ unless noted)

	PM	NO _x	CO	VOC	SO ₂	Dioxins/ furan (ng/Nm ³)	HCl	HF	Cd	Pb	Hg
U.S. EPA limits	18.4	219.8	89.2	-	61.2	-	29.1	-	0.01533	0.1533	0.0613
German limits	10	200	50	-	50	0.10	10	-	0.03	0.50	0.03
Brightstar	1.6-10	40-96	440-625	0.05	<0.1	0.0331	<1.0	0.59	<0.0002	0.0051	-
Compact Power	0.11	26.49	7.13	0.49	3.37		0.17	-	-	-	-
GEM	3	262	8	6	79	0.02	4	ND	ND	-	ND
Mitsui Babcock	-	75 ppm	5 ppm	-	8 ppm	0.016	9 ppm	-	-	-	-
Mitsui Babcock	-	<35 ppm	-	-	<10 ppm	<0.005	<31 ppm	-	-	-	-
PKA	2.3	54	38	-	7.7	0.02	2.3	0.15	0.002	-	0.002
Pyromex	1	135	38	-	20	0.005	1	0.03	-	-	
Serpac	4.2-5.2	61-189	0.5-2.5	-	0.0-5.6	0.002	1.7-5	<0.1	-	-	0.05
Technip	3	180	10	-	5	0.001	5	ND	0.02		0.02
Thermoselect	0.84	21.76	2.95	-	0.16	0.0007-0.0011			0.001	0.013	0.0018
Thide-Eddith	-	470	50	-	<200		30	<1	-	-	-
Thide	<3	-	<20	-	<4	<0.01	<10		-	-	-
TPS	3-7	200-300	2.5-5	-	5-15	0.013	0.6-2	<0.1	<0.004	0.005	0.008-0.05

Notes: PM = particulate matter, PPM =parts per million, VOC=volatile organic compound, Cd = Cadmium, Pb=Lead, Hg=Mercury, ND=not detected.

Conversion technologies in Europe and Japan must meet regulatory standards based on policies adopted by the European Union and Japan. A number of studies provide emissions data from processes that employ similar pollution control strategies to those used in conversion technologies. Some of this data is useful in predicting potential environmental impacts of conversion facilities. University researchers reviewed scientific literature and journals for available data and found the following:

MSW Gasification Study

A July 2004 technical report published by JFE Group describes the results of a 1999 study in which MSW was processed at a gasification facility in Chiba City, Japan. The facility processed approximately 15,000 tons of MSW over a continuous period of 93 days and a total of 130 days. The facility is designed to process 300 TPD of material. The synthesis gas was held at 2,192°F for two seconds or longer followed by a cold-

water quench to approximately 158°F in an oxygen-free environment to suppress the production of dioxins to an absolute minimum.

The concentration of dioxins in the synthetic gas was 0.00039 ng-TEQ/Nm³, or approximately 1,000 times less than the 0.1 ng-TEQ/Nm³ standard set by Japan's Ministry of the Environment. The slag that was produced also satisfied the leaching standard established by Japan's "Guideline for Recycling of Melted Solids of Municipal Solid Waste." The main metal component was iron.

However, since the average copper content was as high as 17.5 percent, it was recovered as a material for copper smelting. Sulfur was recovered as a material for the production of sulfuric acid, and metal hydroxides were used as material for zinc smelting. The total release of dioxins from the synthetic gas, slag, sulfur, metal hydroxides, and recovered water was 0.00069 µg-TEQ/Nm³ (micrograms-TEQ/Nm³), which is below Japan's future target of 5µg-TEQ/Nm³.

The authors of the paper assumed that the feedstock used for testing had a dioxin content of 10 µg-TEQ/Nm³. They concluded that the gasification process used for testing proved its performance in the decomposition of dioxins. Similar tests were conducted using industrial waste, which consisted of waste plastics, sludge, wood chips, and waste paper. Table 7 and Table 8 show the results of the testing.

Table 7. Total Dioxin Emitted—Chiba Recycling Center (MSW)

Product	Dioxin Content	Recovered Material	Dioxin Output (µg-TEQ/t-waste)
Synthesis gas	0.00039 ng-TEQ/Nm ³	722 Nm ³ /ton	0.000 28
Slag	0.0007 ng-TEQ/kg-dry	65 kg/ton	0.000 04
Sulfur	0.35 ng-TEQ/kg-dry	0.52 kg/ton	0.000 18
Metal hydroxide	0.29 ng-TEQ/kg-dry	0.63 kg/ton	0.000 18
Recovered water	0.00001 ng-TEQ/liter	680 liters/ton	0.000 01
Total dioxins emitted			0.000 69
Japan future target			5

Table 8. Total Dioxin Emitted—Chiba Recycling Center (Industrial Waste)

Product	Dioxin Content	Recovered Material	Dioxin Output (µg-TEQ/t-waste)
Synthesis gas	0.00030 ng-TEQ/Nm ³	826 Nm ³ /ton	0.000 248
Slag	0.00049 ng-TEQ/kg-dry	109 kg/ton	0.000 053
Metal	0.00013 ng-TEQ/kg-dry	24.1 kg/ton	0.000 003
Sulfur	0.0022 ng-TEQ/kg-dry	2.23 kg/ton	0.000 005
Metal hydroxide	0.00068 ng-TEQ/kg-dry	2.29 kg/ton	0.000 002
Recovered water	0.00006 ng-TEQ/liter	899 liters/ton	0
Total dioxins emitted			0.000 31
Japan future target			5

No data was presented on other hazardous air pollutants or metal species. At present, gasification projects are under construction in Japan that will use the same process as that of the Chiba City test. These projects range in size from 120 TPD to 555 TPD.

Plastics Gasification Study

The Environmental Plastics Industry Council of Canada (EPIC) commissioned a separate report, which provides data from the gasification of two types of plastic residue. The testing project used a fluidized bed gasification process owned by ENERKEM Technologies Inc., which is affiliated with an advanced research laboratory at the University of Sherbrooke in Sherbrooke, Quebec, Canada. An average of 195 pounds per hour was processed for the tests. The sampled feedstock was identified as EPIC 1 (polyethylene film) and EPIC 2 (#1 through #7 plastics). Arthur Gordon Environmental Evaluators Ltd., an independent testing contractor, was retained by ENERKEM to conduct the testing and assess the environmental performance of ENERKEM's gasification process. Table 9 summarizes air emissions data and includes regulatory limits for the province of Ontario.

Table 9. Air Emissions Summary[†]

Species	EPIC 1	EPIC 2	Ontario Limit	Units
O ₂	11	11	-	%
CO ₂	8.68	7.94	-	%
CO	0.9	1.3	50	mg/Rm ³
SO ₂	1	1	56	mg/Rm ³
NO _x	48.6	47.1	110	PPMV
THC	15	10	100	mg/Rm ₃
Dioxins/Furans	0.005	0.03	0.08	ng-TEQ/Rm ₃
Particulates	4.5	4.4	17	mg/Rm ³
HCl	2.3	1.5	27	mg/Rm ³
Chromium	20.08	7.73	-	µg/Rm ³
Cadmium	1	7.46	14	-
Mercury	0.62	3.82	20	-
Lead	35.27	44.19	142	-
PCB	0.1	0.11	-	-
CP	0.64	0.33	-	-
CB	0.51	0.55	-	-

[†] The units of measure use the symbol R, which stands for the reference conditions of 25°C at 1 atmosphere.

Acquisition of data from existing facilities in Europe and Japan has been very difficult and several questions are generated from this data. What are the similarities between the European/Japanese test methodologies and those used in California? How do emissions limits in other countries compare to emissions limits in California? What are the conditions under which data were acquired? Was the data verified by a third party?

Emissions testing of post-MRF municipal solid waste were conducted at a pyrolysis facility in Romoland, Calif. (Riverside County) in late March 2005. Testing was conducted using South Coast Air Quality Management District (SCAQMD) protocols. Samples were taken to an independent laboratory approved by the SCAQMD. The protocols required testing for the following:

1. Toxic air contaminants such as benzene, dioxins, furans, and multiple metals (including mercury).
2. Criteria pollutants such as NO_x and SO_x.
3. Carbon dioxide and carbon monoxide.
4. Total particulates.

Data from the emissions testing will be shared with OEHHA for additional analysis. In addition, the UC researchers continue to seek emissions data from European and Japanese regulatory agencies. This data will also be shared with OEHHA for its analysis.

Cleanest, Least Polluting Technology

AB 2770 required the CIWMB to identify the cleanest, least polluting technologies. Biological technologies and thermal technologies may each have advantages and disadvantages when compared to each other. The limited data and contractor studies contain no scientific basis to classify one technology as the cleanest and least polluting. If temperature ranges or the fact that the resulting product is subsequently combusted were the sole criteria, then other high-temperature processes that can lead to dioxin formation, such as secondary smelting of aluminum and glass recycling, could be looked at less favorably. In addition, electricity production from biogas derived from anaerobic digestion or methane from landfills could also be looked at less favorably because the gas is subsequently combusted.

Thermochemical technologies can process a wider variety of feedstocks and can have a greater effect on landfill reduction. Thermochemical technologies can also produce a larger variety of products, which can displace the need for non-renewable petroleum resources. Although some stakeholders have greater concerns with emissions from this family of technologies, the limited data that was acquired all indicate that emissions levels are below the regulatory limits placed upon them. The disadvantage of thermochemical technologies is potential for heavy metals in the ash or char that could require special handling like disposal in a hazardous waste landfill.

Biochemical technologies such as anaerobic digestion operate at lower temperatures and may be considered cleaner by some stakeholders since the process extracts some of the intrinsic heat value from the feedstock. The residue from the process may have some nutritive value and can be composted. Lower temperatures may also reduce the potential for the production of dioxin/furans and heavy metal content in ash or air emissions. The disadvantage of biochemical technologies is that these technologies may produce VOCs and ammonia, can only process biodegradable materials, and would contribute less to actual landfill diversion.

The subsequent use of the biogas from biochemical technologies and synthesis gas or fuel gas from thermochemical technologies may result in the formation of dioxins and furans.

There are no acid or enzymatic hydrolysis facilities operating on a commercial scale in the world. Without data from this class of biochemical technology, there can be no determination that this class of technology is cleaner or less polluting than other conversion technologies.

Life Cycle Environmental and Public Health Impact Assessment

AB 2770 required the CIWMB to describe and evaluate their life cycle environmental and public health impacts of each conversion technology evaluated in comparison to transformation and disposal of solid waste. With CIWMB oversight, RTI managed the project and was the lead on the life cycle assessment.

The National Renewable Energy Laboratory prepared a materials and energy balance for selected conversion technologies and assisted RTI with the life cycle assessment.

The goal of the life cycle and market impact assessment was to address two primary questions:

1. What are the life cycle environmental impacts of conversion technologies and how do these compare to transformation and disposal of solid waste.
2. What are the economic, financial, and institutional impacts of conversion technologies on recycling and composting markets?

This is the first study to attempt to comprehensively analyze environmental, health, and market impacts of conversion technologies that utilize post-MRF municipal solid waste as a feedstock. The technologies analyzed do not operate at commercial scale in the U.S., so acquisition of primary data was very difficult. RTI relied on data provided by vendors, but some stakeholder groups have expressed concern over the use of emissions data provided by vendors and question the accuracy of the reported data.

The study approach is based on reasonable and conservative assumptions of conversion technologies. Data acquired was from conversion technology vendors and was not independently verified by a third party.

Prior to beginning research, detailed technical memoranda were prepared describing the study methodologies. The draft methodologies were discussed at a focus group meeting hosted by the CIWMB in Sacramento on August 11, 2003, and circulated to a peer review group. The proposed methodologies were subsequently revised based on input received from the meeting participants and peer reviewers. Analysis was conducted using the peer reviewed methodologies. Preliminary findings from the life cycle assessment and the market impact assessment were circulated to peer reviewers and were also discussed at a public workshop on April 15, 2004. Further revisions and analysis were conducted after this review.

The life cycle study analyzed the impacts of one particular hypothetical scenario for the development of conversion technologies in California. This scenario includes the siting of 12 facilities using three specific technologies in two regions over a period of seven years.

Selected Conversion Technologies

Three conversion technologies were selected for study. The selected technologies were concentrated acid hydrolysis, gasification, and catalytic cracking. They were chosen because municipalities in California have shown particular interest in them, as evidenced by requests for information. The technologies are commercial-ready, based on research conducted prior to the start of this project, and data describing the technologies were relatively available.

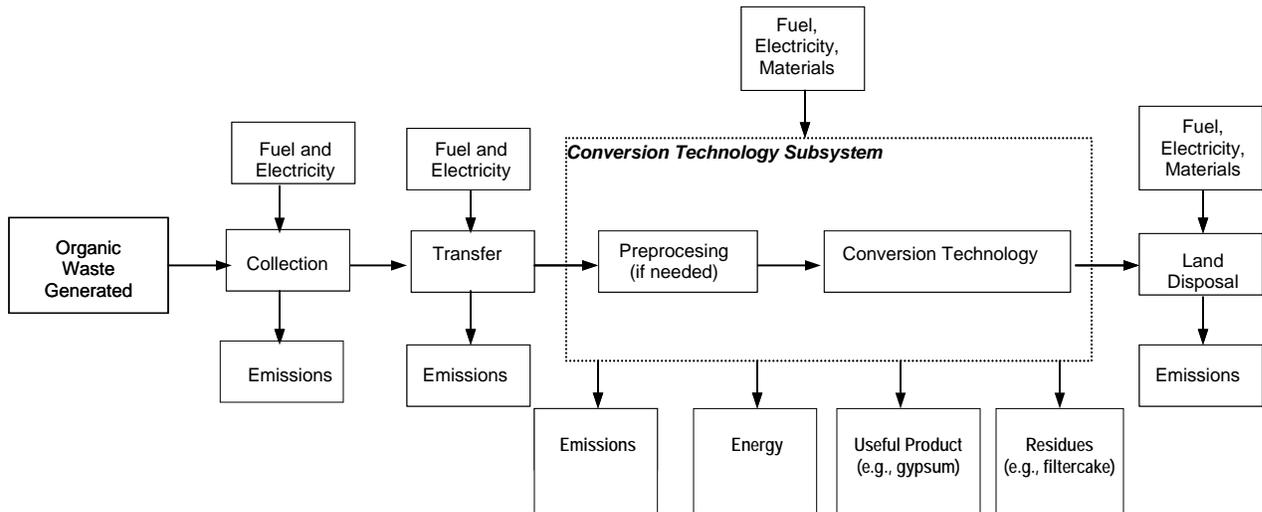
Approach

The term “life cycle assessment” describes a type of systems analysis that accounts for the complete set of upstream and downstream energy use and environmental impacts associated with production systems. A life cycle assessment is not designed to analyze or estimate potential human health risks. A life cycle assessment was conducted to assess the environmental performance of hypothetical conversion technology growth scenarios when compared to several alternative management scenarios involving landfill disposal and waste-to-energy. The contractors approached the study by taking the following steps:

1. Defined the scope, boundaries, and specific process steps for the acid hydrolysis, gasification, and catalytic cracking technologies.
2. Collected data and developed materials and energy balance models for each conversion technology.
3. Constructed life cycle inventory modules for each conversion technology by adding life cycle burdens and benefits to the materials and energy balance models.
4. Applied RTI’s Municipal Solid Waste Decision Support Tool (MSW DST) to inventory the full life cycle impacts of the conversion technology scenarios (from the collection of waste to its ultimate disposition) as well as for transformation and landfill disposal.

Figure 9 illustrates the overall life cycle system boundaries for a conversion technology system. In the figure, the boundaries include not only the conversion technology and other MSW management operations, but also the processes that supply inputs to those operations, such as fuels, electricity, and materials production. Likewise, any useful energy or products produced from the conversion technology system are included in the study boundaries as offsets. An offset is the displacement of energy or materials produced from primary (virgin) resources that results from using secondary (recycled) energy or materials.

Figure 9. Life Cycle System Boundaries



Assumed Geographic Locations and Development Rate

The San Francisco Bay Area and the Greater Los Angeles region were selected for study because a large percentage of California’s MSW is generated and processed within them. For purposes of this study, it was assumed that the Greater Los Angeles region includes the counties of Los Angeles, Orange, Riverside, and San Bernardino.

2003 (Base Year)

- Three acid hydrolysis facilities processing 500 dry TPD in each region (1,500 dry TPD total).
- Four gasification facilities processing 500 dry TPD in each region (2,000 dry TPD total).
- One additional stand-alone catalytic cracking facility, processing 50 dry TPD in each region.

Years 2004 to 2010

- One additional gasification plant processing 500 dry TPD built in each region in 2005.
- Two additional acid hydrolysis plants processing 500 dry TPD built in each region in 2007.
- One additional gasification plant processing 500 dry TPD built in each region in 2010.

The conversion technology facilities were assumed to begin operating in both regions at varying capacities from the base year of 2003 to 2010, as summarized in Table 10 below.

Table 10. Facility Configurations, 2003 to 2010, dry tons per day

	2003	2004	2005	2006	2007	2008	2009	2010
Acid Hydrolysis	1,500	1,500	1,500	1,500	2,500	2,500	2,500	2,500
Gasification	2,000	2,000	2,500	2,500	2,500	2,500	2,500	3,000
Catalytic Cracking	50	50	50	50	50	50	50	50
TOTAL	3,550	3,550	4,050	4,050	5,050	5,050	5,050	5,550

Life Cycle Inventory Scenarios Analyzed

RTI generated inventory results for the hypothetical conversion technology growth scenario outlined in Table 13, as well as for several alternative management scenarios. The life cycle inventory results were generated for the Greater Los Angeles and San Francisco Bay Area regions for the conversion technology scenarios when compared to scenarios using existing MSW management practices from 2003 to 2010. The complete set of scenarios analyzed consists of the following:

1. Conversion technologies.
2. Landfill with no gas collection (worst landfill case).
3. Landfill with gas collection and flaring (average landfill case).
4. Landfill with gas collection and energy recovery (best landfill case).
5. Waste-to-energy combustion with ferrous recovery and disposal of combustion ash.

Conversion Technology Feedstock Assumptions

The conversion technologies modeled for this study would be handling waste material that would otherwise be disposed in landfills. Because each conversion technology facility can only accept certain materials in its process, the scenarios included up-front material separation activities similar to those found in a mixed-waste MRF and would be consistent with policy recommendations adopted by the CIWMB at its April 2002 meeting.

Table 11 summarizes the assumed annual capacities and incoming feedstock needs based on the composition (see Table 12) of feedstock in the Greater Los Angeles and San Francisco Bay Area regions.

Landfills operate as material is brought in and are typically shut down on Sundays and holidays. Conversion technology facilities will not operate in the same manner, because it is time-consuming and economically prohibitive to shut down and bring an operating plant back online unless absolutely necessary. To accommodate for this, the conversion technology facility operator keeps two days' worth of storage for the waste that is

brought to the plant to ensure continuous operation of conversion facilities. The assumption is that the facilities operate 90 percent of the time, with limited down time for machine maintenance and service disruptions. The assumed feedstock tonnage demands are listed in Table 11. These figures are based on 90 percent operating capacity, or operating 329 out of 365 days per year.

Table 11. Assumed Annual Capacities and Incoming Feedstock Needs

Technology	2003	2004	2005	2006	2007	2008	2009	2010
Wet Tons Per Year (based on 329 operating days per year)								
Acid hydrolysis	493,500	493,500	493,500	493,500	822,500	822,500	822,500	822,500
Gasification	658,000	658,000	822,500	822,500	822,500	822,500	822,500	987,000
Catalytic cracking	16,450	16,450	16,450	16,450	16,450	16,450	16,450	16,450
Total	1,167,950	1,167,950	1,332,450	1,332,450	1,661,450	1,661,450	1,661,450	1,825,950
Required Incoming Tonnage (Wet) Before Sorting—Greater Los Angeles Region								
Acid hydrolysis	630,176	629,260	629,260	629,260	1,048,766	1,048,766	1,048,766	1,048,766
Gasification	737,681	734,863	918,579	918,579	918,579	918,579	918,579	1,102,294
Catalytic cracking	1,092,230	1,092,230	1,064,427	1,064,427	1,064,427	1,064,427	1,064,427	1,064,427
Total	1,367,857	1,364,123	1,547,839	1,547,839	1,967,345	1,967,345	1,967,345	2,151,060
Required Incoming Tonnage (Wet) Before Sorting—San Francisco Bay Area Region								
Acid hydrolysis	641,780	643,525	643,525	643,525	1,072,542	1,072,542	1,072,542	1,072,542
Gasification	754,643	754,475	943,093	943,093	943,093	943,093	943,093	1,131,712
Catalytic cracking	1,078,636	1,078,636	1,118,529	1,118,529	1,118,529	1,118,529	1,118,529	1,118,529
Total	1,396,423	1,398,000	1,586,618	1,586,618	2,015,635	2,015,635	2,015,635	2,204,254

Table 12. Assumed Percent Composition of Feedstock Sent to Conversion Technology Facilities^a

Component	Greater Los Angeles Region		San Francisco Bay Area Region	
	2003	2004–2010	2003	2004–2010
Paper	32.5	31.5	32.2	31.6
Plastic	11.5	11.7	10.8	11.1
Metals	7.6	7.3	9.6	9.6
Glass	3.8	3.7	3.9	3.9
Organics	42.8	43.9	41.6	41.9
Miscellaneous	1.9	1.8	1.9	1.9

^a Construction and demolition, industrial, and hazardous waste are assumed not sent to conversion technology facilities.

Note: Values may not sum to 100 percent due to rounding.

The conversion technologies and alternative scenarios were evaluated consistently. RTI assumed that each of the nine scenarios manages the same quantity and composition of waste from each region for each year. For example, the same quantity and composition of MSW from the Greater Los Angeles region is sent to the conversion technology scenario, as well as to the other eight alternative scenarios. Therefore, for each region and study year, the results across the nine scenarios can be directly compared.

Life Cycle Results

From an environmental perspective, the production of fuels and chemicals from materials that would otherwise be landfilled can provide environmental benefits by displacing the extraction of non-renewable petroleum resources such as crude oil and natural gas.

The results for selected life cycle parameters for the hypothetical conversion technology scenarios are shown relative to comparable alternative management scenarios in Figures 14 through 21. These parameters were identified as being the most important and include net annual energy consumption, sulfur oxides (SO_x) emissions, NO_x emissions, and carbon equivalents.

Net Energy Consumption

Energy is consumed by all waste management activities as well as by the processes to produce energy and material inputs that are included in the life cycle inventory. Energy offsets can result from the production of fuels or electrical energy and from the recycling of materials. Energy is an important parameter in life cycle studies, because it often drives the results of the study due to the significant amounts of air and water emissions associated with energy production.

As shown in Figures 10 and 11, the hypothetical conversion technology scenarios for the Greater Los Angeles and San Francisco Bay Area regions result in a large net energy

savings. As compared to the alternative management scenarios, the conversion technology scenario ranges from two times lower in net energy consumption when compared to the WTE scenario to 11 times lower than the landfill without energy recovery scenarios.

Figure 10-17 Definitions

Landfill V- Landfills Gas Venting
 Landfill F- Landfills with Gas Flaring
 Landfill ER- Landfills with Energy Recovery System
 WTE- Waste to Energy Facilities
 CT- Conversion Technology Facilities

Figure 10. Greater Los Angeles Region, Annual Net Energy Consumption

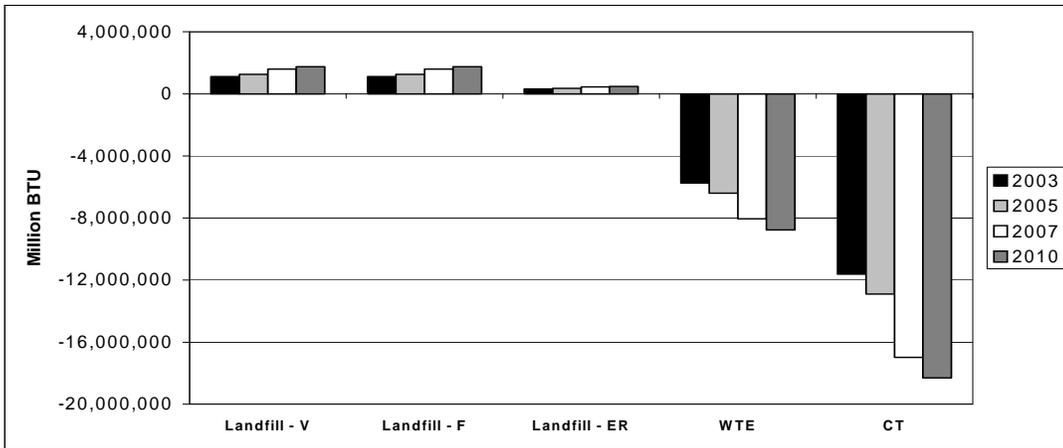
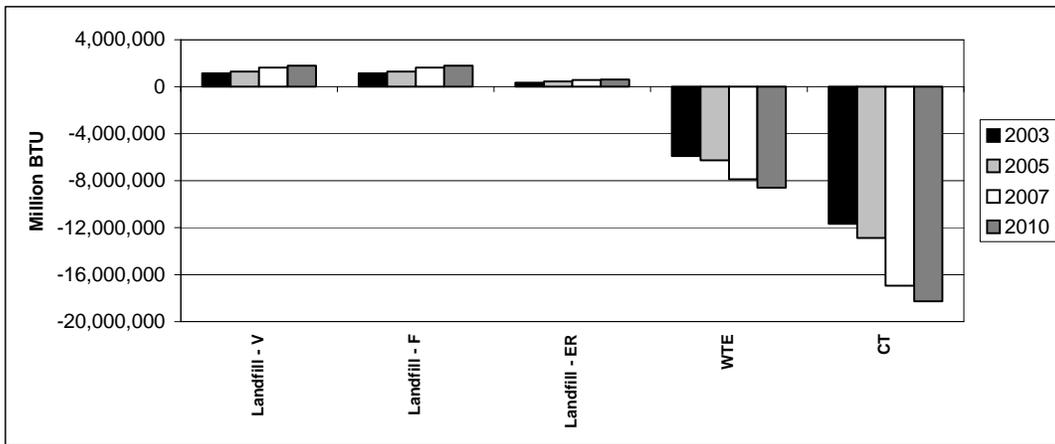


Figure 11. San Francisco Bay Region, Annual Net Energy Consumption



The net energy savings attributed to the hypothetical conversion technology scenario results from the following aspects:

- Electrical energy produced by gasification and acid hydrolysis technologies, which offsets electrical energy produced in the utility sector.
- Fuels produced by acid hydrolysis and catalytic cracking, which offset the production of fuels from fossil sources.
- Materials recovered from the gasification and acid hydrolysis preprocessing steps and sent for recycling, which offsets the extraction of virgin resources and production of virgin materials.

One interesting finding was that the energy savings potential resulting from the additional materials recycling prior to conversion is a significant side benefit of the gasification and acid hydrolysis technologies. Recycling of these additional materials contributes approximately 10 to 20 percent of the total net energy savings.

The landfill scenarios without gas collection and utilization had the highest net energy consumption. Even the best-case landfill scenario (with gas collection and energy recovery) was significantly higher in energy consumption than the conversion technology scenario.

The factors that led to the WTE scenario's high net energy savings include the electricity production offset and some steel-recycling offsets. Although the WTE scenario utilizes more MSW as feedstock than the conversion technologies, the energy offset is not as large as the offset shown by the conversion technology scenario. This is due to the greater efficiency of the conversion technologies in converting waste to energy (that is, more energy is produced per ton of waste input).

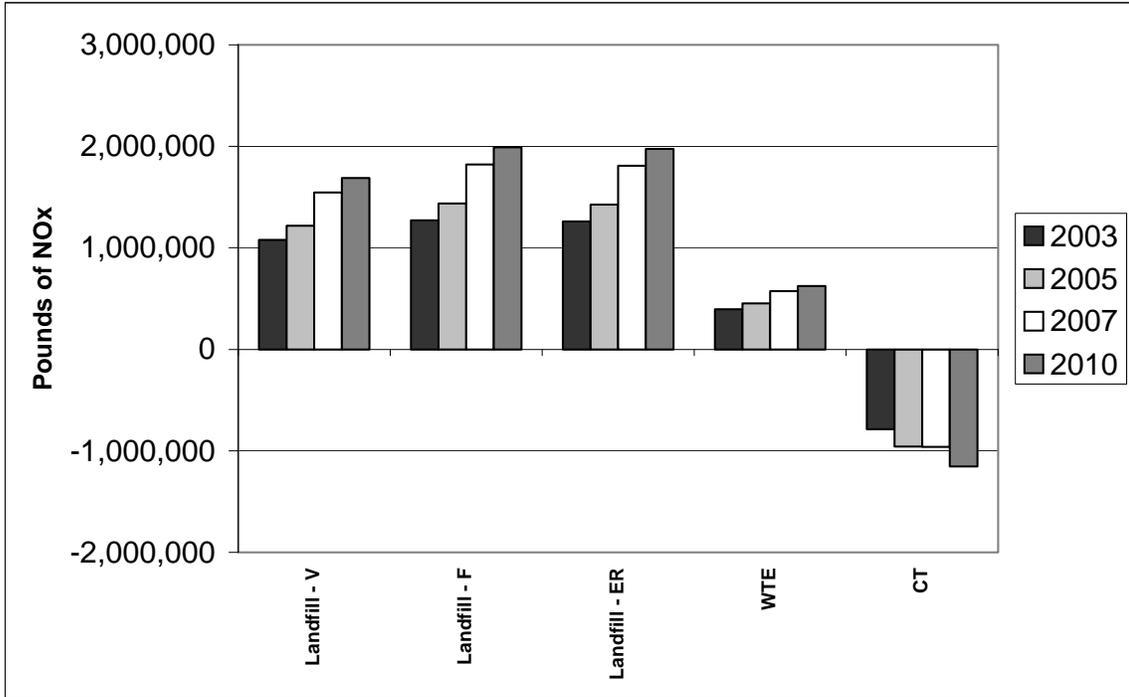
Nitrogen Oxide Emissions

NO_x emissions can lead to such environmental impacts as smog production, acid deposition, and decreased visibility. NO_x emissions are largely the result of fuel combustion processes. Likewise, NO_x emission offsets can result from the displacement of combustion activities, mainly fuels and electrical energy production.

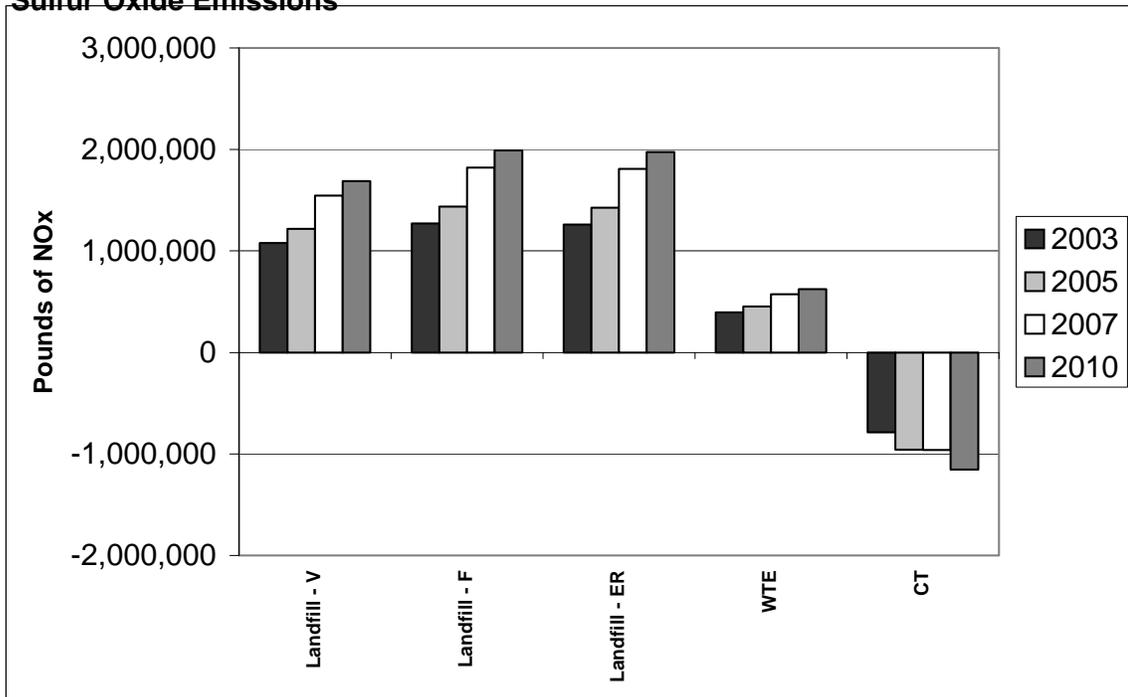
As shown in Figure 12 and Figure 13, the hypothetical conversion technology scenario showed the lowest net levels of NO_x emissions and resulted in a significant net NO_x emissions avoidance. Although the conversion technologies produce NO_x emissions, the net avoidance is a result of significant offsets of NO_x emissions associated with the production of energy and recovery and the recycling of materials, coupled with the low amount of NO_x emissions from the gasification plants.

All of the other management scenarios are net NO_x producers. The landfill scenarios showed the highest levels of NO_x emissions. The WTE scenarios showed about one-half to one-third of the NO_x emissions levels returned by the landfill scenarios. The NO_x associated with the landfill scenario largely results from the collection of waste and fuel combusted by landfill equipment such as graders and compactors.

Figure 12. Greater Los Angeles Region, Annual Net NO_x Emissions



**Figure 13. San Francisco Bay Region, Annual Net NO_x Emissions
Sulfur Oxide Emissions**



SO_x emissions can lead to environmental impacts such as acid deposition, corrosion, and decreased visibility. Like NO_x, SO_x emissions are largely the result of fuel

combustion processes. SO_x emission offsets can also result from the displacement of combustion activities, mainly fuels and electrical energy production, as well as the use of lower sulfur-containing fuels.

As shown in Figures 14 and 15, the WTE scenario resulted in the lowest levels of SO_x emissions and a significant net avoidance of SO_x emissions results for electrical energy production and ferrous metal recovery and recycling. The hypothetical conversion technology scenario resulted in the next lowest levels of SO_x emissions and also a net avoidance of SO_x emissions. The gasification system resulted in a significant SO_x savings from electrical energy offsets, whereas the catalytic cracking and acid hydrolysis technologies resulted in positive SO_x emissions. The main source of SO_x emissions for the acid hydrolysis system came from the production of sulfuric acid, which is a required input for the ethanol production plant. Although catalytic cracking generated an SO_x offset, production of diesel fuel from fossil petroleum is avoided. Because of this, the SO_x emissions from the MRF operations were slightly higher than the offset.

The up-and-down bar pattern in the conversion technology scenario graph was a result of the addition of acid hydrolysis capacity in 2007. Because significant SO_x emissions are associated with sulfuric acid production, when two additional acid hydrolysis plants are put on line in 2007, the net SO_x emissions savings is decreased from 2005, where only a new gasification plant is added.

The landfill with gas collection and energy recovery scenarios also exhibited net SO_x emission savings. These savings were the result of the offsets of fossil fuel production and combustion in the utility sector for the landfill scenario.

Figure 14. Greater Los Angeles Region, Annual Net SO_x Emissions

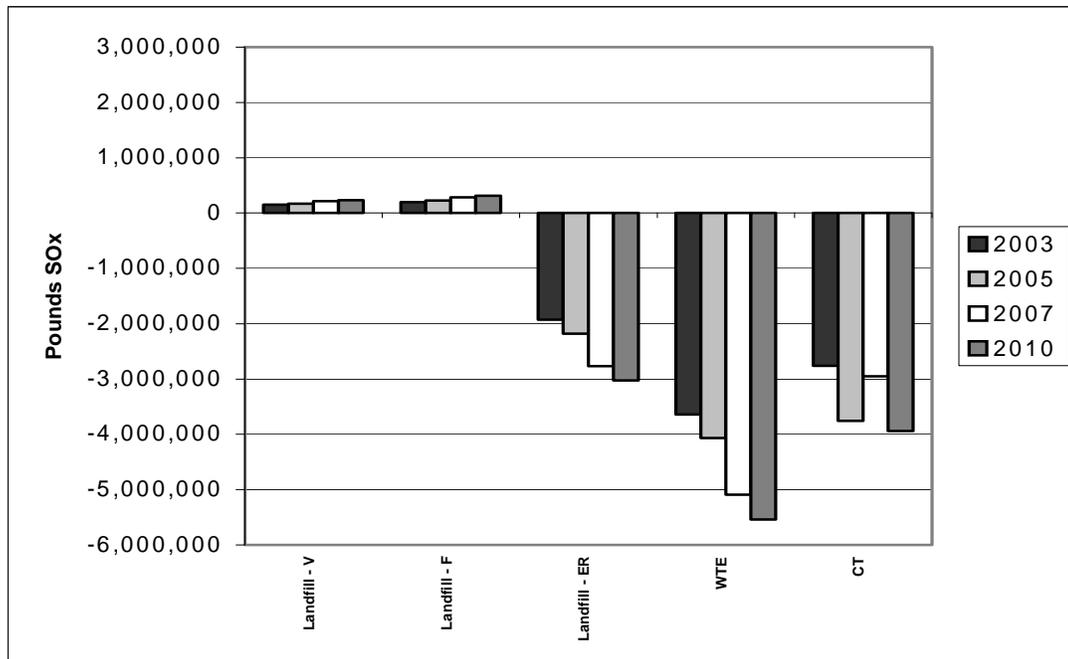
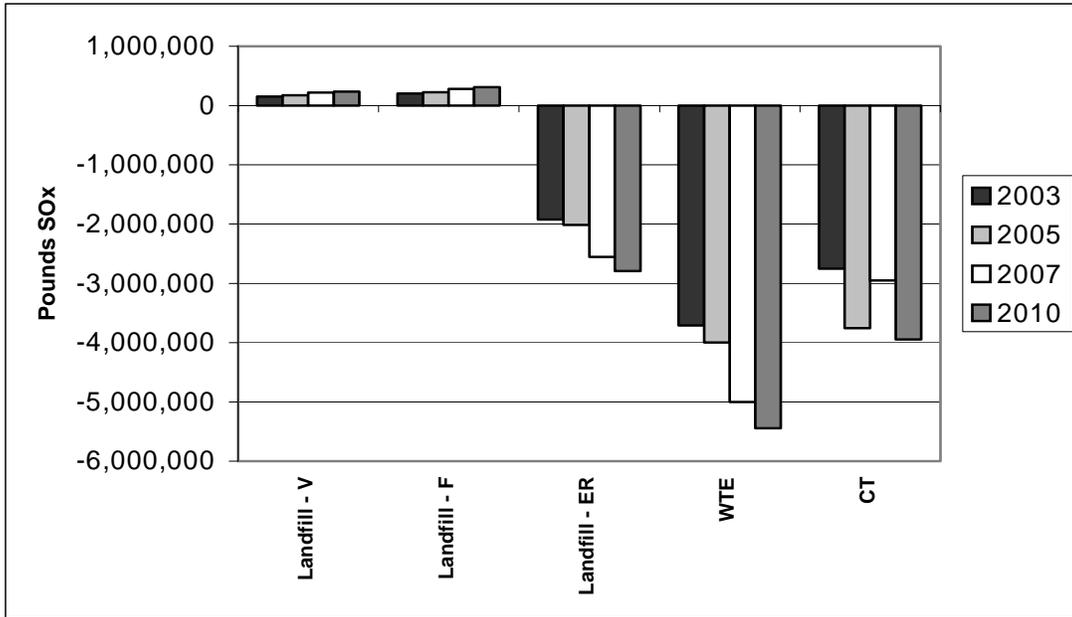


Figure 15. San Francisco Bay Region, Annual Net SO_x Emissions



Carbon Emissions

Carbon emissions contribute to the greenhouse effect; thus, these emissions can lead to climate change and its associated impacts. Carbon emissions can result from the combustion of fossil fuels and the biodegradation of organic materials (for example, methane gas from landfills). Offsets of carbon emissions can result from the displacement of fossil fuels, materials recycling, and the diversion of organic wastes from landfills.

As shown in Figures 16 and 17, both the WTE and hypothetical conversion technology scenarios resulted in a slight net carbon emission savings. As expected, the landfill with the gas venting scenario produced the highest levels of carbon emissions.

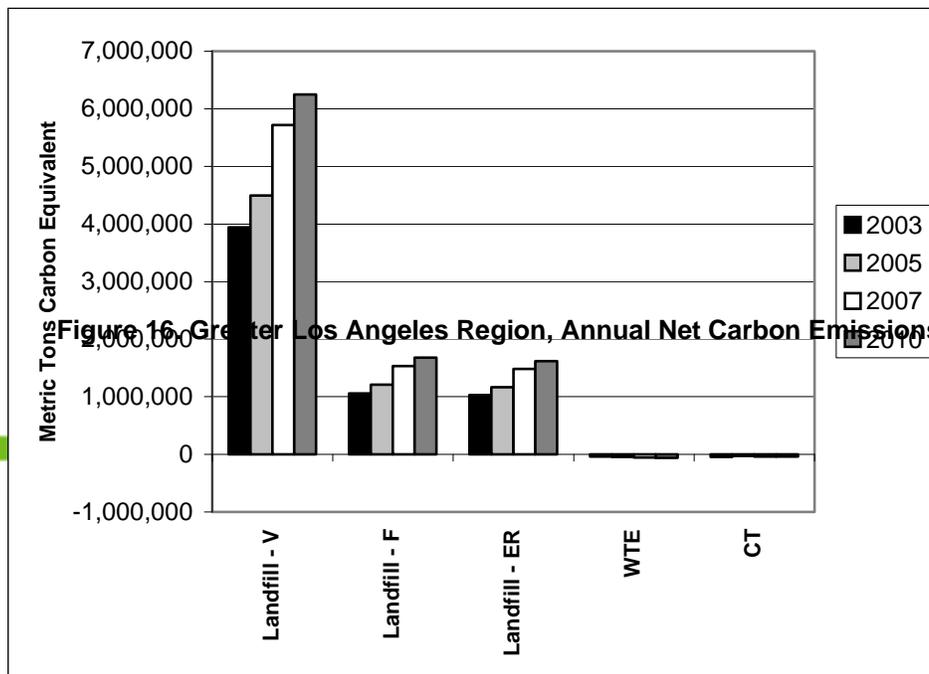


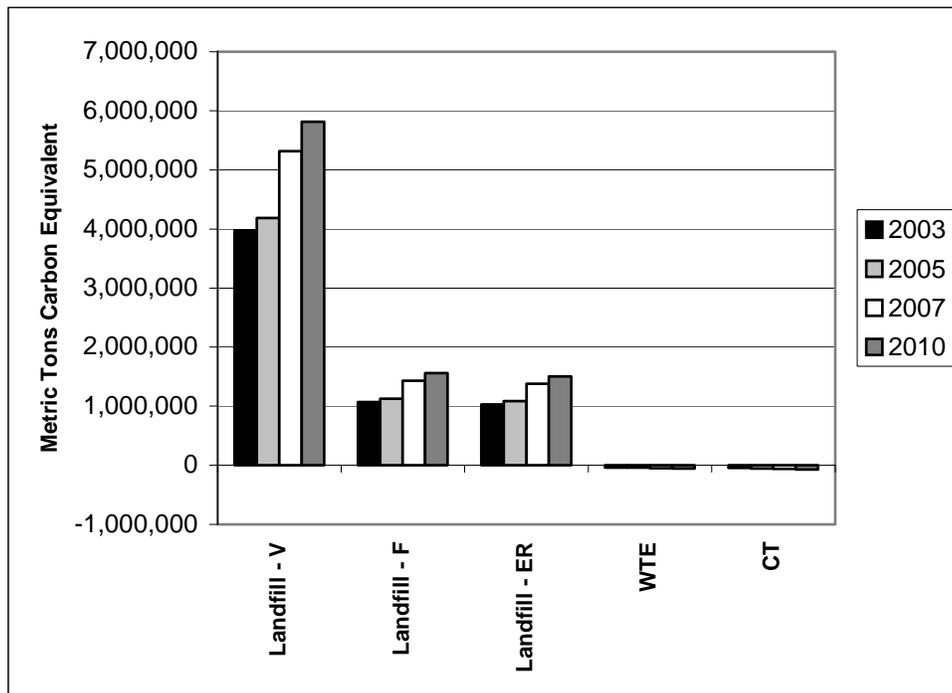
Figure 16. Greater Los Angeles Region, Annual Net Carbon Emissions

Figure 17. San Francisco Bay Region, Annual Net Carbon Emissions

Key Findings

Although the RTI project team used the best available information to characterize the life cycle and market impacts resulting from the hypothetical conversion technology scenarios, these conversion technologies do not currently at market scale exist in California or the U.S. Therefore, a number of assumptions have been made about their design and operating characteristics. Until actual full scale operating facilities become available and primary data can be readily obtained, stakeholders need to consider the following findings as general/directional rather than absolute:

1. Conversion technologies produce more energy than landfilling and transformation. This creates large life cycle benefits.
2. There are lower emissions of criteria air pollutants (NO_x and SO_x) from conversion technologies than from landfilling and transformation.
3. There are lower emissions of CO₂ from conversion technologies than from landfilling and transformation. This is important from a climate change perspective.
4. Limited data is available to adequately assess the impacts of dioxins, furans, and other hazardous air pollutants.
5. The environmental benefits of the hypothetical conversion technology scenario are



highly dependent upon their ability to achieve high conversion efficiencies and high materials recycling rates.

6. Conversion technologies would decrease the amount of waste disposed of in landfills.
7. No conversion technology facilities exist in the U.S. for MSW. Therefore, there is a high level of uncertainty regarding their environmental performance.

In 1998, the Center for the Analysis & Dissemination of Demonstrated Energy Technologies (CADDET)[‡] and the International Energy Agency (IEA) prepared a report on the current status of “Advanced Thermal Conversion Technologies for Energy from Solid Waste.” Advanced thermal technologies referred to pyrolysis and gasification of MSW. CADDET concluded the following:

- Advanced thermal conversion technologies would be able to meet current emission standards as they apply to waste combustion and could meet tighter limits.
- Gasification and pyrolysis have the potential to produce less ash than waste combustion.
- Presence of recycling programs may improve economics by reducing pre-treatment requirements.
- Advanced thermal conversion technologies have several potential benefits over waste incineration, including lower environmental impacts, higher electrical conversion efficiencies, and greater compatibility with recycling.
- Advanced conversion technologies will be most appropriate where these advantages are policy requirements.

The report from CADDET points out that prior to 1990, several facilities using unsorted MSW were abandoned due to technical problems. This proved that advanced technologies require a more homogeneous feedstock and a pre-treatment step (sorting and size reduction) prior to conversion. Pre-treatment provides an opportunity to remove additional recyclables from the feedstock.

According to the U.S. Department of Energy (DOE), the U.S. anthropogenic methane burden from waste management operations or landfills ranges from 29 percent to 37 percent. The range is due to different methane emission inventories maintained by the DOE and U.S. EPA. For thermochemical and biochemical conversion processes, especially anaerobic digestion, the prospect of reducing methane emissions and leachate from landfills is probably the most significant environmental benefit.

Public Health Impacts

[‡] The CADDET program was established in 1998 by an agreement with IEA to promote the international exchange of information on energy-efficient technologies. Ten countries, including the United States, support the program.

Risk assessment guidance published by the U.S. EPA identifies information required for risk assessments. This includes site-specific information, activities of potentially exposed persons, information that is adequate for identifying chemicals of potential concern, and detailed information on the rates of release for these chemicals at the site. In addition, release or leak rates and distance to the facility property boundary are factors that must be determined at a specific facility, or at least represent worst-case scenarios.

Several methods to assess the public health impacts of conversion technologies can be considered. One is to work with the Office of Environmental Health Hazard Assessment (OEHHA). The primary goal of a human health risk assessment is to determine if the risk to human health posed by pollution released from a facility is unacceptable and requires regulatory intervention. However, since the Life Cycle report is not a human health risk assessment, and data provided by the UC researchers and RTI was not of the type sufficient for OEHHA to efficiently assess the potential public health impacts of conversion technologies; the CIWMB will continue to work with OEHHA as new facilities are sited in California and this specific data is acquired.

A second method would be to review research data collected from the CEC. In 1996, the California Legislature established the Public Interest Energy Research (PIER) program at the CEC. The PIER program conducts public interest energy research that seeks to improve the quality of life for California citizens by developing environmentally sound, safe, reliable, and affordable electricity services and products. The seven mandated Research, Development, and Demonstration (RD&D) subject areas include environmentally preferred advanced generation, renewable energy technologies and alternative transportation fuels. In 2005, the CEC published the *Biomass Strategic Value Analysis* (publication 500-2005-109-SD). Their findings did show that bioenergy public benefits included improving forest, human and animal health. Although, these technologies are more expensive, the analysis concluded that converting biomass and MSW offers unparalleled environmental benefits and significant public benefits, including reduced health risks.

Market Impact Assessment

AB 2770 requires the CIWMB's report to include "A description and evaluation of the impacts on the recycling and composting markets as a result of each conversion technology." The general approach was to collect data regarding the current marketplace, including quantities and compositions of various waste and recycling streams.

The report included collecting data from the entities that make decisions regarding disposition of these materials (for example, generators, jurisdictions, MRF operators, and haulers) and the reasons for those decisions (for example, IWMA regulatory mandates, political mandates, costs, and transportation distances). The report also covers the quality and quantity needs of paper and plastic recycling processors and exporters and the composting/mulch industry.

The relationships of material movement through the system were then modeled and overlaid with the conversion technology system configurations, quality, composition, and price of material needs. This produced estimated impacts to the recycling and composting industries that would occur if such conversion technology facilities were to be developed.

Methodology

The methodology for conducting the market impact assessment involved determining baseline projections for waste management practices and recycling in each study region. These baseline projections were adjusted by overlaying the hypothetical conversion technology scenario described earlier and then analyzing the likely impacts.

Additionally, the contractor evaluated how these findings would be affected by changes in market conditions due to State policies.

The RTI project team identified, reviewed, and compiled data and information related to conversion technology facilities and California waste management practices and markets. Primary data sources included interviews with conversion technology developers, government solid waste and recycling officials, industry experts, and review of conversion technology bid and contractual documents.

Secondary data sources included the CIWMB and other State and federal agencies; industry trade associations; industry publications; previously prepared reports; and Hilton, Farnkopf, & Hobson's in-house data and information. The data gathering effort was supplemented by a concurrent UC study of conversion technologies sponsored by the CIWMB, and by information and modeling conducted by the National Renewable Energy Laboratory.

The main data analysis steps included the following:

- Characterizing the marketplace for potential conversion technology feedstock types, including mixed MSW; residuals from MRFs; and recyclable paper, plastics, green waste, and other organic materials. This included analysis of the quantity projected to be available, export trends, demand trends, pricing trends, and the key factors influencing future trends. Recycling growth projections were based on municipally planned programs, average growth rates for each material, and consideration of factors affecting markets.
- Characterizing the composition of mixed waste and MRF residuals available to conversion technology facilities. This required developing baseline waste composition estimates based on statewide averages, and then adjusting them to reflect the population of each study region, recycling growth, and population increases.
- Estimating the specific feedstock needs of each type of conversion technology and developing assumptions for the types of sorting and other required preparation. This included estimating the amount of additional recycling likely to occur as a result of feedstock treatment at conversion technology facilities.
- Characterizing the types of existing institutional arrangements, including contractual terms currently used by municipalities related to their solid waste and recycling objectives. This also included an analysis of California jurisdictions interested in conversion technology.
- Analyzing likely conversion technology pricing and contractual arrangements.

- Analyzing typical MRF and recycling collection economics.
- Analyzing typical jobs and revenue associated with recycling and conversion technology activities.

A financial model was developed to input and summarize data and to perform certain calculations.

Prior to commencing any analysis, the methodology used to conduct the market impact assessment was peer reviewed by the University of California and the California Air Resources Board Financial Modeling Section. The peer reviewers all stated that the proposed methodology was sound.

Markets for Feedstock

Potential Sources

This study looked at the possibility of using the following feedstocks for conversion technologies:

- Paper.
- Plastic.
- Organics and green waste.
- Material destined for landfilling, including MRFs' residuals.

The conversion technologies studied are anticipated to receive material normally destined for landfilling, not separated recyclables or green waste. The impact on recycling markets would be from the small amount of additional diversion recovered during presorting of feedstock to prepare it for conversion.

The contractor conducted research on each of the feedstock types listed above to determine current and past pricing, as well as current and historical levels of recovery. In addition, the contractor gathered data based on the historical exports of paper and plastics and the opinions of experts regarding the future of export markets.

Paper

Paper is an acceptable feedstock for acid hydrolysis and gasification because of the cellulosic and calorific value of paper fiber. Once paper is recovered from the waste stream, it may be processed at a recycling facility, sold to a paper broker, and then sent to either an in-country recycler or an exporter. The total amount of paper recovered in the U.S. is tracked by the American Forest and Paper Association (AF&PA); however, the origin of each collection or shipment of recovered paper is not recorded.

In order to approximate the number of tons that are attributable to the San Francisco Bay and the Greater Los Angeles regions, Habitat for Humanity allocated tonnage based

on each region's share of the U.S. population. As shown in Table 13, the Greater Los Angeles region accounted for 5.7 percent of the total national population in 2002, and the San Francisco Bay region accounted for 2.4 percent. Based on these percentages, the contractor estimated that the non-exported recovered paper tonnage was 2.1 million tons for the Greater Los Angeles region and 0.9 million tons for the San Francisco Bay region.

Table 13. Estimates of Paper Recovered in Two Regions for Domestic Use

Area	Population	Percent of Population	In-Country Tonnage
United States ^a	287,973,924	100	36,368,000
Greater Los Angeles Area ^b	16,469,900	5.73	2,084,000
San Francisco Bay Region ^b	6,994,500	2.43	884,000

^aUnited States Census Bureau, July 1, 2002

^b California Department of Finance, Jan. 1, 2003

Scrap Paper Exports

Paper Export Methodology

Because the exporting of scrap paper has been an increasingly significant force that has impacted prices and availability of scrap paper in California for the last several years, and because export issues were of great interest to the focus group on the technical memorandum, a significant portion of the market impact study efforts was devoted to scrap paper exports.

As presented in Table 14, approximately 15.6 million tons of scrap paper was exported through the San Francisco port areas and Los Angeles port areas during the five-year period from calendar years 1998 through 2002. Of the 15.6 million total five-year tonnage, 71 percent originated from the Los Angeles port areas and 29 percent originated from the San Francisco port areas. In 2002, the amount of scrap paper exported from the Los Angeles port areas was 2.6 million tons and 1.1 million tons from the San Francisco Port areas.

Table 14. Summary of Tons and Revenue From Export of Scrap Paper in the San Francisco Port Areas and Los Angeles Port Areas

Year	Tons (in Thousands)			Revenue (in Thousands of Dollars)			Average Revenue/Ton
	SFPA ^a	LAPA ^b	Total	SFPA	LAPA	Total	
1998	632	1,653	2,285	\$54,761	\$139,136	\$193,897	\$84.86
1999	729	1,887	2,616	63,147	168,090	231,237	\$88.39
2000	1,016	2,368	3,384	91,298	245,721	337,019	\$99.59
2001	1,062	2,552	3,614	71,840	187,786	259,626	\$71.84

2002	1,060	2,612	3,672	75,998	212,368	288,366	\$78.53
Total	4,499	11,072	15,571	\$357,044	\$953,101	\$1,310,145	\$84.14
1998–2002 % Growth	68%	58%	61%	39%	53%	49%	N/A
% of Total	29%	71%	100%	27%	73%	100%	N/A

^aSFPA—San Francisco port areas

^bLAPA—Los Angeles port areas

As shown in Table 15, mixed paper, corrugated containers, and newsprint accounted for 79 percent of total scrap paper exports from the San Francisco and Los Angeles port areas over the five-year period from 1998 to 2002. Export of mixed paper had increased by fourfold to 1.6 million tons in 2002, compared to 0.4 million tons in 1998. The growth in exported mixed paper accounted for the bulk of the total exported scrap paper growth of 1.4 million tons from 1998 to 2002.

Table 15. Summary of Exports From the San Francisco Port Area and Los Angeles Port Areas Combined, by Paper Grade

Year	Recycled Paper Grades (Thousands of Tons)						Total
	Chemical Pulp	Corrugated Containers	Deinking	Mechanical Pulp	Mixed Paper	Newsprint	
Total port areas							
1998	268	819	176	168	405	449	2,285
1999	350	689	184	213	619	561	2,616
2000	332	961	209	213	1,089	580	3,384
2001	123	915	222	228	1,580	546	3,614
2002	134	1,045	106	251	1,618	518	3,672
Total	1,207	4,429	897	1,073	5,311	2,654	15,571
Percent of Total	8%	28%	6%	7%	34%	17%	100%
Growth	-51%	28%	-40%	49%	300%	15%	61%

Although recycling of old corrugated cardboard (OCC) and old newspaper (ONP) materials is a well-developed industry in California, the recycling rates for these components are still only 52 and 58 percent, respectively. The collection of materials is one issue with recycling of OCC and ONP, including the problem of capturing OCC from small businesses.

Mixed paper is also recycled, though the value of mixed paper as a commodity has been historically relatively low. More recently, the export market, particularly to China, has resulted in significantly higher prices paid for mixed paper grades. Overall, the paper and cardboard recycling rate in California is only slightly higher than 30 percent, or 4.5 million tons of material.

Plastics

Export data for plastics was not available at the same level as export data for scrap paper. As with paper, regional plastics recycling tracking systems do not exist. Plastics recycling tonnage in the two study regions was estimated by using statewide data that had previously been compiled for the CIWMB, data from California's Beverage Container Recycling and Litter Reduction Act (Bottle Bill) programs, and information from R.W. Beck's *U.S. Recycling Economic Information Study* conducted in July 2001. The data from these sources suggest that 301,969 tons of plastics were recycled in 2003. Of that statewide amount, HFH estimated that 138,906 tons of plastics were recycled in the Los Angeles Basin study region and 60,394 tons of plastics were recycled in the San Francisco Bay Area study region.

According to the CIWMB's *Optimizing Plastics Use, Recycling, and Disposal in California*, published in May 2003, the national production of plastics has grown at a rate of 4.9 percent per year since 1973. However, plastics recycling growth has lagged production growth. Any growth that has occurred can be attributed to the demand in China. According to an article in the March 15, 2004, issue of *Waste News*, the amount of PET collected for recycling in the U.S. has held steady for several years at about 400,000 tons. PET bottles have the highest recycling rate at approximately 35 percent. HDPE containers are the next-highest category of recycled plastics with a rate of 13 percent. However, exports, mainly to China, have risen from 45,000 tons in 1998 to 137,500 tons in 2002. The demand from China could vary tremendously and unpredictably.

Although some plastic recycling markets are well developed, the overall recovery fraction of plastics is only about 5 percent. A primary issue that impedes plastics recycling is that the cost of collecting and processing typically exceeds the value of the material. The number of new containers has also increased in recent years, resulting in corresponding decreases in the overall recycling rate even though the total amount recycled has increased.

Organics

According to the 2003 waste characterization study conducted by the CIWMB, approximately 30 percent of the material currently landfilled is organic in nature. In addition, the CIWMB commissioned the *Second Assessment of California's Compost- and Mulch-Producing Infrastructure*, published in May 2004. Overall, approximately 8 million tons of organic material was collected and processed statewide in 2003. A similar survey was conducted in 2001 that showed that 6 million tons statewide were processed. Table 16 shows survey results for 2001 and 2003.

Table 16. Organics Collection Data

Year	Number of Facilities	Amount Processed (Tons)
2001	160	6,000,000
2003	159	8,000,000

Although there has been some growth in the recovery and processing of organic materials, it has not shown the growth of other recyclable materials. A significant factor in the use of green waste for composting is its use as ADC.

Another factor that may affect future markets for organics is the SCAQMDs Rule 1133. This rule has been established by the district and requires monitoring and reduction of VOCs from compost facilities. More stringent requirements may be imposed in the future. Compliance with these more stringent requirements could be very costly to compost producers, ultimately driving them out of business or to locations outside of the air district. The San Joaquin Valley Unified Air Pollution Control District is contemplating a similar rule which could have a major impact on compost producers in the San Joaquin Valley.

Conclusion

One of the primary study objectives was to estimate impacts that the new and emerging development of conversion technologies would have on the existing recycling and composting industries. Pricing and availability of suitable feedstock materials (for conversion technologies, landfilling, recycling, and green waste) are the basis for most of the final findings presented herein. The findings assume that the conversion technologies would be developed under the current statutory framework:

Finding #1: There is a projected net positive impact on glass, metal, and plastic recycling under the "base case" conversion technology scenarios in life cycle/market impact study.

Using mixed solid waste as feedstock, preprocessing results in removal of 7 to 8 percent of feedstock for recycling at gasification facilities and 12 to 13 percent of feedstock for recycling at acid hydrolysis facilities. The increase in recycling is related to conversion

technology preprocessing operations. Certain materials, such as glass and metals, can reduce the efficiency of conversion technology operations. These materials can improve the economics of the system if they are recovered and sold. Because organics will not be removed through sorting, the base case results in no increases or decreases to compost markets.

In addition, plastics recycling will increase if acid hydrolysis facilities are built because plastics must be removed prior to processing. Currently, only those plastics with positive economic values are typically recycled. In contrast, feedstock preparation for acid hydrolysis would seek to remove all plastics.

The recycling of additional materials that otherwise would have gone to landfills may have positive economic effects on local recycling industries. The quantities recovered, however, would not be large enough to have a price impact on local recycling industries.

Finding #2: Implementation of any of the three selected technologies is not likely to increase or decrease the recycling of paper.

Although paper is an acceptable feedstock for acid hydrolysis and gasification, the recent values of baled paper make it unlikely that paper will be directed to a conversion technology facility. Paper markets have historically been very volatile, with high prices for a given year being twice that of low prices for that year.

Finding #3: In the cases where conversion technology facilities accept materials that currently have no recycling or composting markets, and there are no new recycling markets for those materials in the foreseeable future, conversion technology facilities will have no impact on recycling and composting markets.

For example, if catalytic cracking were to target mixed plastics, grades #4 through #7, it would likely have an insignificant impact on current recycling markets and no impact on composting markets. Many other materials currently have no viable markets, but they could technically undergo various conversion technology processes. The likelihood of this happening will depend on economics and local conditions.

Finding #4: The impact of recent Chinese demand is a far more dominant force on the paper and plastics markets than potential development of conversion technologies in California, even on the fairly large scale that was assumed for this study.

Exports of paper and plastics, particularly to China, have increased dramatically during the past five years. These exports are exerting upward pressure on prices in the paper and plastics markets and are providing an outlet for all of the paper and plastics that are collected. Paper exported from this country has grown significantly in recent years: by 77 percent from 1993 to 2002, or an average of 6.5 percent per year. Nationwide, 24 percent of the paper recovered in the U.S. is exported for recycling.

Finding #5: Future recycling growth could be negatively impacted if:

- a) Source-separated recyclables or green waste flowed to conversion technology facilities rather than recycling facilities.

- b) Waste streams that are currently untapped for recycling became unavailable to new recycling efforts in the future.
- c) Local jurisdictions eliminated recycling and green waste collection programs and redirected mixed waste to conversion technology facilities. However, this scenario is unlikely given the enormous capital investment made by local jurisdictions and waste management companies and existing law in the IWMA that requires jurisdictions to maintain their diversion programs.

Finding #6: Source-separated recyclables (paper and plastics) are not likely to flow to conversion technology facilities, based on pricing differentials.

Source-separated paper and plastics currently are recycled for profit. If this were no longer true and recycling market prices declined dramatically, conversion technology processes would still likely be more expensive than recycling.

Finding #7: Conversion technology facilities may negatively impact the ability of municipalities and private companies to increase recycling from currently untapped waste streams and generators, but the net effect of this is projected to be minimal.

The minimal impact is projected because many municipalities are already planning recycling growth in order to comply with IWMA mandates.

Finding #8: Source-separated green waste could conceivably flow to conversion technology facilities under certain circumstances. However, assuming no diversion credit is allowed for conversion technologies, significant quantities of green waste that are currently delivered to composters or to landfills as ADC will probably not be redirected to conversion technology facilities.

Significant quantities of green waste currently delivered to composters or to landfills as ADC will probably not be redirected to conversion technology facilities for the following reasons:

1. Currently, jurisdictions that contract for source-separated collection of green waste will continue to require their contractors to deliver green waste to facilities that qualify for diversion credit.
2. Sufficient refuse tonnage is available to fill the capacity of the assumed hypothetical conversion technology scenario. This scenario is more economic than separated green waste. As a result, conversion technology facilities, in order to maximize profit, are likely to charge tipping fees that are competitive with landfill costs. For 2003–04, a conversion technology tipping fee of \$30 to \$40 per ton in the Greater Los Angeles region and \$40 to \$50 per ton in the San Francisco Bay region should be able to attract sufficient refuse to be used as feedstock. Lowering conversion technology prices to attract green waste would be unnecessary.

The above assessment is contingent on a policy of not providing diversion credit for conversion technology facilities.

CIWMB staff conducted an external stakeholder workshop on April 15, 2004, to discuss the draft findings of the life cycle and market impact assessment. Many stakeholders were of the opinion that the true market impact could not be assessed if diversion credits were not a factor in evaluating those market impacts and the RTI project team agreed with this comment.

As part of a sensitivity analysis, CIWMB staff asked the RTI project team to analyze the effects that diversion credit for conversion technologies would have on recycling and compost markets. CIWMB staff felt it would be remiss in ignoring this important issue and believed that such a sensitivity analysis would provide a more thorough and complete analysis of all market factors related to conversion technologies and its potential impacts on existing recycling and compost markets. The following scenarios were developed for the diversion credit impact analysis:

1. Full diversion credit, diversion programs maintained.
2. Ten percent diversion credit cap, diversion programs maintained.
3. Full diversion credit, diversion programs discontinued.
4. Full diversion credit, recycling programs continued, green waste programs discontinued.

Finding #9: No negative impact on existing recycling and compost markets would occur if diversion credit were given for conversion technologies.

Under scenario 1 and 2 of the diversion credit analysis, there would be no negative impact on existing recycling and compost markets. This action may actually have a positive impact. Both scenarios would provide increased recycling market revenue, jobs, and tonnage. Increased revenue could be as high as \$171 million to \$400 million per region per year over the study term. Additional jobs could be from 1,500 to 3,600 per region over the study term. Additional recycling tonnage would be 70,000 to 153,000 per region per year over the study term. Landfill revenue, tonnage, and jobs would decrease under both scenarios.

With more than 30 million tons of organic material still being landfilled, enough feedstock may be available for conversion technologies and for the future growth of recycling programs.

Finding #10: A negative impact on recycling and composting will occur if diversion credit is granted and local jurisdictions discontinue their traditional diversion programs.

This scenario assumes all residential material (refuse, recyclables, and green waste) is sent to conversion technology facilities. Jurisdictions could realize significant collection cost savings by collecting all materials with a single truck.

This scenario assumes the gasification and acid hydrolysis facilities operate at full capacity. More than 500,000 fewer tons in each region may be available to the recyclables and organics markets. The materials recovered would be plastic, metal, and glass. Paper and organics, which comprise the majority of the recyclable materials present in the feedstock, would not be recovered.

Far fewer tons of recyclables will be recovered through presorting than would be recovered if the recyclables and organics were separated and sent to other processing facilities.

This scenario is not likely to occur because of existing law in the IWMA that requires local jurisdictions to continue to implement diversion programs described in their source reduction recycling element (SRRE) or annual report submitted to the CIWMB. In addition, if the CIWMB is given the authority to grant diversion credit, it would only do so if a jurisdiction or a regional agency continues to implement the recycling and diversion programs in the jurisdiction's SRRE or its modified annual report.

Because data gaps do exist, conducting source testing where possible at facilities in California would be helpful. The CIWMB should work with other Cal/EPA boards and departments, as well as other appropriate State agencies, to develop a research agenda and address cross-media issues for conversion technologies. A conversion technology task force should be established that includes representatives from all Cal/EPA boards and departments and other relevant State agencies. The task force should also include a local government representative and a representative from an environmental organization.

AB 2770 provided an appropriation for the scientific research on the life cycle assessment, market impact assessment, and technology identification and assessment. Thorough testing of air emissions and solid and liquid residues needs to be further researched and evaluated. Many stakeholders expressed the need for additional data before seeing widespread support for certain types of conversion technologies. However, acquiring data without any full scale operating conversion technology facilities in California will be difficult. The CEC's PIER program has and continues to fund research and development projects in the areas of thermal, chemical and biological conversion technologies. Their research criterion has expanded and acquiring data from these pilot facilities may be a good starting point.

In conclusion, no one technology is suitable for all waste streams, and no single waste management practice, be it landfilling, recycling, composting, or conversion, can handle the full array of waste sources.

However, emerging conversion technologies and eventually new types of conversion technologies could form part of an integrated waste management system that is based on the idea of an overall approach for the management of waste streams, recyclable streams, treatment technologies, and markets.

Endnotes

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Abbreviations and Acronyms

AB: Assembly Bill

AB 2770: Assembly Bill 2770, Matthews, Chapter 740, Statutes of 2002

ADC: alternative daily cover

BIGCC: biogas integrated gasifier combined cycle

CH₄: Methane

C₂H₂: Acetylene

C₂H₄: ethene

C₂H₆: ethane

CADDET: Center for the Analysis and Dissemination of Demonstrated Energy Technologies

Cd: Cadmium

CEC: California Energy Resources Conservation and Development Commission

CHP: Combined Heat and Power

CIWMB: California Integrated Waste Management Board

CO: Carbon monoxide

CO₂: Carbon dioxide

CT: Conversion Technologies

DG: distributed generation

DOE: Department of Energy

EPIC: Environmental Plastics Industry Council of Canada

H₂: Hydrogen

H₂S: Hydrogen sulfide

Hg: Mercury

IEA: International Energy Agency

IWMA: Integrated Waste Management Act

LCA: life cycle assessment

MRF: materials recovery facilities

MSW: municipal solid waste

MSW DST: Municipal Solid Waste Decision Support Tool

N₂: Nitrogen

ND: Not Detected

NO_x: Nitrogen oxides

OEHHA: Office of Environmental Health and Assessment

Pb: Lead

PET: polyethylene terephthalate

PIER: Public Interest Energy Research

PM: particulate matter

PPM: parts per million

PRC: Public Resources Code

RD&D: Research, Development, and Demonstration

the Report: Conversion Technologies Report to the Legislature

SCAQMD: South Coast Air Quality Management District

SO_x: Sulfur oxides

SRRE: source reduction recycling element

TCLP: Toxicity Characteristic Leaching Procedure

TEQ: Toxicity equivalence

TPD: tons per day

TPY: tons per year

TS: total solids

UASB: Upflow Anaerobic Sludge Blanket

UC: University of California

U.S.: United States

VOC: volatile organic compounds

WTE: waste to energy