

Conversion Technologies Report to the Legislature

February 2005



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Executive Summary

Although California has achieved a 47 percent statewide diversion rate and has a current composting infrastructure that processes approximately 10 million tons annually, more than 39 million tons of material was disposed of in landfills in 2003. Of the amount disposed in landfills, nearly 80 percent is organic material (paper, wood, green waste, food waste, etc.).

Conversion technologies could be an alternative to landfilling, however these technologies are viewed by some stakeholders with skepticism and fear that these technologies will discourage source reduction and recycling efforts. A philosophical debate rages as to what is considered a “higher and better” use for materials. The CIWMB embarked on a research endeavor to determine what technologies would be best suited for materials that have traditionally been landfilled while at the same time ensuring that the existing recycling and composting infrastructure is maintained.

Thermochemical Conversion

Thermochemical conversion technologies, such as gasification and pyrolysis are technologies that use high heat that can treat nearly the entire organic fraction of municipal solid waste. These technologies can, in general, treat a wider array of material than biochemical conversion technologies, including high energy content plastics that have no market value.

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. Pyrolysis is also a high heat technology but differs from gasification in that there is no oxygen employed in the process. Temperatures for pyrolysis processes range from 750°F to 1500°F. Pyrolysis and gasification applications for MSW have expanded considerably in the past five years, especially in Japan which has limited domestic resources and limited landfill space. Over 50 commercial facilities are operating in Japan and process a total capacity representing approximately eight percent of current disposal in California. Of the two methods, gasification is more technologically complex and offers the capability of producing a broader array of products such as electricity, alternative fuels such as ethanol and diesel, and chemical precursors.

In 1998, the Center for the Analysis & Dissemination of Demonstrated Energy Technologies (CADET)¹ 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 municipal solid waste. CADET 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 the need for sorting and size reduction of the feedstock prior to conversion.

¹ The CADET program was established in 1998 with an agreement with IEA to promote the international exchange of information on energy-efficient technologies. The program is supported by 10 counties including the United States.

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- 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 sorting and size reduction prior to conversion. Sorting and size reduction prior to conversion provides an opportunity to remove additional recyclables from the feedstock. The report from CADDET did not have any data on air emissions, particularly dioxins and furans, nor any data regarding solid and liquids residuals.

Biochemical Conversion

Biochemical technologies such as anaerobic digestion and fermentation operate at lower temperatures than thermochemical technologies.

Anaerobic digestion is the bacterial breakdown of organic material in the absence of oxygen and 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 there are two optimal temperature ranges in which microbial activity and biogas production rate are highest, mesophilic and thermophilic temperature ranges. 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 produces a gas principally composed of methane (CH₄) and carbon dioxide (CO₂) but also has impurities such as hydrogen sulfide (H₂S).

Fermentation is also an anaerobic process and is used to produce alcohols and other chemicals. Feedstocks containing cellulose, a long-chain molecule made up of linked glucose sugar, need a treatment step called hydrolysis to break up the larger chain of sugars into basic sugars so yeasts and bacteria can process the sugars to make an alcohol such as ethanol. Cellulose and hemicellulose (a 5-carbon sugar) can be hydrolyzed using acids, enzymes, or a hydrothermal method called steam explosion.

The use of alternative biochemical technologies for processing fractions of the MSW stream, particularly anaerobic digestion, has also increased significantly during the past five years. Biochemical technologies are more limited in their application since they can only process biodegradable feedstocks. Most of the growth in biochemical technologies has been in Europe and is due to a combination of high tipping fees, restrictions on landfilling untreated waste, and high prices for renewable energy products. Currently, the European capacity of anaerobic digestion for MSW components represents approximately seven percent of current disposal in California. Biochemical technologies could also be used in combination with alternative thermochemical or other processes to provide broader reduction of landfilled material.

Current Status of Technologies

Much of the development and deployment of conversion technologies has occurred in Japan and Europe. There are over 50 thermochemical facilities that use MSW feedstock operating in Japan and Europe and over 80 anaerobic digestion facilities in Europe.

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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 two 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.

The installed capacity of anaerobic digestion facilities in Europe process more than 3000 TPY using mandatory pre-sorted feedstock 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, are 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 is projected to be 2.8 million TPY in 2004, an increase of more than 250 percent in four years.

Fermentation of biomass into ethanol is fully commercial for sugar and starch based feedstocks. It is not yet commercial for cellulosic biomass because of technical difficulties and cost, but this remains an active area of research and development.

Feedstocks

Thermochemical processes can convert potentially all the organic portion of the waste stream that is currently going to landfill into heat and other useful products. Biochemical processes can convert only biodegradable material such as green waste, food waste, or the biogenic fraction of MSW. Metals, glass, mineral matter, and most of the current plastic stream will not be converted by biochemical processes. 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.

Table ES-1. Feedstocks and Residues

Conversion Technology	Feedstocks Processed	Solid Residues
Complete gasification	All organics low moisture	Ash, metals, recycle, or landfill
Incomplete gasification (See pyrolysis)	All organics low moisture	Char, ash, metals, recycle
Indirectly fired pyrolysis & gasifier	All organics low moisture	Char, ash, metals, recycle or landfill
Anaerobic Digestion	Biodegradable Components	Inorganics, metals, glass, undegraded biomass

Conversion Technology	Feedstocks Processed	Solid Residues
Fermentation	Biodegradable Components	Inorganics, metals, glass, undegraded biomass

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) 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.

Table ES-2 below describes primary and secondary products from various types of conversion technologies.

Table ES-2. Products of Conversion Technologies

Conversion Technology	Primary Product	Secondary Products	Solid Residues	Value of secondary products	Feedstocks Processed
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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	Ethanol, Chemicals, Heat, Soil Amendment	Inorganics, metals, glass, undegraded biomass	Moderate to High	Biodegradable Components

Environmental and Public Health Impacts

Emissions from thermochemical and biochemical systems include such things as oxides of nitrogen and sulfur (NO_x and SO_x), hydrocarbons, carbon monoxide, particulate matter (PM), heavy metals, greenhouse gas emissions such as CO₂, and dioxins/furans. In addition, there can be fugitive gas and dust emissions that depend on control strategies, operational practices, and level of maintenance at a particular facility (e.g., enclosed receiving buildings with may have exhaust air treatment to minimize VOC and dust emissions from unloading and feedstock storage). Conversion processes, particularly thermochemical conversion, may employ air pollution control at the reactor outlet as well as the exhaust gas outlet.

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 can be found in the gas and liquid phases. However, existing data from facilities in Japan and Europe indicate that thermochemical conversion technologies can operate within constraints established by their local regulatory agencies. There has also been considerable technological progress in emissions controls over the past decade that can be directly applied to conversion technologies. This is corroborated by data from the U.S. EPA showing over a 99 percent reduction in the release of dioxins and over 90 percent reduction in the release of heavy metals such as lead and mercury from MSW incinerators (See Table 5). Although this data is from MSW incinerators, these factors indicate that it is very likely that conversion technologies with the most advanced environmental controls would be able to meet regulatory requirements in California.

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Biochemical technologies operate at lower temperatures than thermochemical technologies so the potential for production of dioxins/furans is eliminated. However, if biogas is produced from biochemical technologies and subsequently used in a generator or internal combustion engine for electricity production, there is a potential for dioxin formation. Biochemical technologies can produce NO_x and ammonia which may be cause for concern in some local air districts.

Essentially all conversion technologies will produce a solid residue because all components of the solid waste stream contain inorganic material or ash and are not converted into a gas or liquid. More volatile heavy metals, such as mercury, will enter the gas phase in thermal conversion and must be managed or captured before exhaust to atmosphere. Conversion technologies do not generate 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.

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. There are well-defined mechanisms already in place for dealing with these waste streams.

Although most of the data that was provided by vendors to the UC Researchers and RTI was not subjected to a third-party analysis, it is important to remember that facility operators typically do not have laboratory facilities to test air and ash samples. Testing is usually conducted by certified laboratories using specified testing methodologies and certain criteria pollutants are monitored using continuous emissions monitoring systems. The data that has been obtained shows promise; however, data on other hazardous air pollutants and metal species, using known methodologies, is needed before a definitive conclusion can be made about thermochemical conversion technologies.

The CIWMB entered into an interagency agreement with the Office of Environmental Health Hazard Assessment (OEHHA) to review the *Lifecycle and Market Impact Assessment of Noncombustion Conversion Technologies* to determine if the information it contains would be adequate for an assessment of risks to humans that may result from conversion technologies. 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. The Lifecycle Report is not a human health risk assessment and data provided by the UC Researchers and RTI was not complete enough for OEHHA to fully assess the public health impacts of conversion technologies.

The lifecycle assessments analyzed the impacts of one particular hypothetical scenario for the development of conversion technologies in California. There are currently no operating conversion facilities that use municipal solid waste as a feedstock which presented a problem for data acquisition. RTI relied upon 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. Prior to initiating the analyses, detailed methodologies were developed and were discussed at a focus group meeting hosted by the CIWMB. The methodologies were also subjected to a third-party peer review.

Life cycle inventory results were developed for the hypothetical scenario in the assumed geographic locations of the San Francisco Bay Area and the Los Angeles Area. The conversion technologies modeled for the lifecycle study would be handling waste material that would otherwise be disposed of in landfills.

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Based on the results of the peer reviewed lifecycle analyses, conversion technologies have many advantages over landfilling, composting, transformation, and recycling such as:

- Greater potential for energy production.
- Fewer emissions of NO_x.
- Fewer carbon emissions which is important from a global warming perspective.

With respect to SO_x, conversion technologies produce fewer emissions of SO_x when compared to landfilling but transformation produces fewer emissions of SO_x when compared to conversion technologies.

The main advantage that conversion technologies have over landfilling is the reduction of material that is landfilled and converted into a product that has a higher and better use such as electricity or alternative fuels. Life cycle studies conducted in Korea and Europe have shown that anaerobic digestion processes have fewer environmental impacts when compared to landfilling. Another potential advantage with conversion technologies is the reduction of post-closure landfill maintenance and long-term liability.

Market Impact Assessment

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

Additionally, the contractor evaluated how these findings would change if the State adopted certain adjustments to State policy on allowing diversion credit for waste sent to conversion technology facilities. The study findings are based on the assumption that private sector decision-makers act to maximize profit, and that public sector decision-makers act to minimize cost with the additional responsibility of achieving Integrated Waste Management Act (IWMA) diversion mandates and operating environmentally sound solid waste management systems.

It should also be noted that 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 Research Division. The peer reviewers all stated that the proposed methodology was sound.

Exports of paper and plastics, particularly to China, have increased over the past five years. This trend may change dramatically as China's internal recycling infrastructure matures. If that is the case then California's recycling infrastructure may not be able to adequately recover and we will not be able to handle the increase in feedstock should the export market collapse. California needs to look at keeping its resources within California and developing internal infrastructure and markets to sustain them.

The CIWMB adopted a policy allowing diversion credit if the following findings were made: (1) the jurisdiction continues to implement the recycling and diversion programs in the jurisdiction's source reduction and recycling element or its modified annual report; (2) the facility complements the existing recycling and diversion infrastructure and is converting solid waste that was previously disposed; (3) the facility maintains or enhances environmental benefits; and (4) the facility maintains or enhances the economic sustainability of the integrated waste management system." The policy also stated that jurisdictions that meet all of the above will be eligible for 10 percent diversion credit. The policy also required the CIWMB to annually evaluate the amount of diversion credit that can be claimed by a jurisdiction, on a case-by-case basis, that sends materials

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to that facility. Although this policy was passed by the CIWMB, there is no statutory authority given to the CIWMB for implementing this policy.

To assess the market impact of this policy, a market analysis was conducted using the CIWMB-adopted policies. 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, and green waste programs discontinued.

Under Scenario 1 and 2 of the diversion credit analysis, there would be no negative impact on existing recycling and compost markets and it may actually have a positive impact. Both scenarios would provide increased recycling market revenue, jobs, and tonnage. However, landfill revenue, tonnage, and jobs would decrease under both scenarios.

There may be a negative impact on recycling and composting if diversion credit was granted and local jurisdictions discontinued their traditional diversion programs as described in Scenario 3 and 4. If the CIWMB is given statutory authority to implement its policy regarding diversion credit, diversion programs will not be discontinued if local jurisdictions want diversion credit for material sent to conversion technology facilities.

Overall, conversion technologies will have a positive impact on recycling because of the potential for additional recyclables such as glass, metals, and some plastics entering the market stream from pre-processing of the feedstock. Future recycling growth could be negatively impacted in the following way if recyclables were redirected to conversion technology facilities:

- If source-separated recyclables or green waste flowed to conversion technology facilities rather than recycling facilities.
- If waste streams that are currently untapped for recycling became unavailable to new recycling efforts in the future.
- If local jurisdictions eliminated recycling and green waste collection programs and redirected mixed waste to conversion technology facilities; however, this scenario seems unlikely given the enormous capital investment made by local jurisdictions and waste management companies.

This scenario is unlikely to happen because of existing statutory requirements for local jurisdictions to achieve a 50 percent recycling goal and to maintain or expand their existing recycling programs.

Conversion technologies may have the largest market and economic impact on the landfills given that potential tipping fees for conversion technologies may be competitive with current landfill prices.

Conclusions

Based on the peer reviewed information from the *Evaluation of Conversion Technology Processes and Product* report prepared by UC Riverside, the *Life Cycle and Market Impact Assessment of Noncombustion Waste Conversion Technologies* prepared by RTI International and reports from other organizations, alternative thermochemical and biochemical conversion technologies may be technically viable options for the conversion of post recycled MSW and

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offer better solutions to landfilling and transformation. Thermochemical and biochemical conversion technologies possess unique characteristics which have varying potentials to reduce the amount of material that is ultimately landfilled.

Based on input from a number of stakeholders, it is concluded that existing statutory definitions should be amended. For example, the definition in “gasification” in Public Resources Code Section 40117 is scientifically inaccurate. Transformation” is defined Public Resources Code Section 40201 as “incineration, pyrolysis, distillation, or biological conversion other than composting, gasification, or biomass conversion.” This definition includes distillation and biological conversion which are low heat technologies. Distillation is a purification step for products such as alcohols and is carried out at temperatures dramatically below those for thermochemical technologies and transformation.

Anaerobic digestion can be considered both a biological conversion technology and a composting technology because the digestate is a compostable residue. As a biological conversion technology material sent to an anaerobic digestion facility would not qualify for diversion credit, however, as a composting technology material would qualify for diversion credit. For purposes of clarity, biological technologies should be removed from the transformation definition.

Data gaps do exist and it would be beneficial to conduct source testing where possible. The CIWMB should work with other Cal/EPA boards and departments to develop a research agenda for conversion technologies. AB 2770 provided an appropriation of \$1.5 million however the bulk of the funds were used for the lifecycle assessment, market impact assessment, and technology identification and assessment. Thorough testing of air emissions, solid, and liquid residues could not be done with the balance of the appropriation. These data gaps preclude the CIWMB from determining the public health impacts that each conversion technology would have. Some stakeholders have also expressed their desire for additional data before there is widespread support for certain types of conversion technologies. However it is difficult to acquire data without any operating conversion technology facilities in California.

While no one technology is suitable for all waste streams, no single waste management practice, be it landfilling, recycling, composting, or conversion can handle the full array of waste sources. Each can form part of an integrated waste management system which is based on the idea of an overall approach for the management of waste streams, recyclable streams, treatment technologies, and markets.

When the waste management hierarchy was developed in 1989, conversion technologies using solid waste were still being analyzed and had not reached the mature state that exists today. This may suggest that the hierarchy may need to be revised to incorporate conversion technologies as part of an integrated waste management approach and evolve into an integrated *resource* management approach. The waste hierarchy in the European Union (EU) is similar to that in California. The EU Hierarchy declares waste prevention as the first priority, followed by recovery and finally by the safe disposal of waste. It differs in that ‘recovery’ includes re-use, recycling and extraction of materials and energy from solid waste. Article 3 of the Council Directive 75/442/EEC² states the following:

“Article 3

1. Member States shall take appropriate steps to encourage the prevention, recycling and

² Directive (75/442/EEC)

http://europa.eu.int/smartapi/cgi/sga_doc?smartapi!celexplus!prod!DocNumber&lg=en&type_doc=Directive&an_doc=1975&nu_doc=442

processing of waste, the extraction of raw materials and possibly of energy there from and any other process for the re-use of waste.”

Cleanest, Least Polluting Technologies

AB 2770 requires the CIWMB to identify the cleanest, least polluting technologies. With limited data available it is difficult to identify the cleanest, least polluting technologies because each technology has environmental advantages and disadvantages. 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. However, there are greater concerns with emissions from this family of technologies.

Biochemical technologies such as anaerobic digestion are viewed as less controversial because they operate at lower temperatures which reduce the potential for the production of dioxin/furans and heavy metal content in ash or air emissions. Anaerobic digestion technologies are also viewed more favorably since the process extracts some of the intrinsic heat value from the feedstock and the residue from the process may have some nutritive value and can be composted. The disadvantage of biochemical technologies is that these technologies can only process biodegradable materials and would contribute less to actual landfill diversion. However, the need for additional pre-processing of the feedstock can have a positive impact on recycling. Based on all available data, it appears that anaerobic digestion may be the cleanest and least polluting technology when compared to other conversion technologies.

Recommendations

Based on the analysis provided by the University of California, Riverside, National Renewable Energy Laboratory, and RTI, the following are recommendations for further action related to conversion technologies.

1. Change and clarify statutory definitions:
 - a. The existing definition for “gasification” in Public Resources Code Section 40117 should be amended as follows to be more scientifically accurate:

“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.

This definition is a more appropriate description of gasification processes. Any reference to no discharges of air contaminants or emissions can be included as conditions in an air permit or solid waste facility permit.
 - b. Delete the definition of “Transformation” in Public Resources Code 40201 and create a new definition for “Combustion” as follows:

“Combustion” means the thermal destruction, in an oxygen-rich environment, of solid waste for the generation of heat and subsequent energy production.

The current definition for transformation is intended to mean combustion; however, there are certain terms such as distillation, biological conversion, and pyrolysis that are not combustion technologies. Combustion and incineration differ in the sense that the goal of combustion is

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the production of heat and energy. The goal of incineration is simple volume reduction of the feedstock. Corresponding changes would need to be made throughout the Public Resources Code.

- c. Define “thermochemical conversion” and “biochemical conversion” in the Public Resources Code as follows:

“Thermochemical conversion” means the processing of solid waste using direct or indirect heating methods to produce fuel gases, synthetic gases, or liquid products as a primary product, and char, water and other condensibles as minor products.

“Biochemical conversion” means the processing of solid waste using microorganisms or chemicals for the production of biogas, alternative chemicals, or alcohols as primary products and undegraded biomass as a secondary product.

2. Additional data should be collected on emissions from thermochemical and biochemical conversion technologies. In particular, the CIWMB should work with the California Air Resources Board regarding emission control improvements and maximum/best available control technologies. The emissions studies should be conducted by an independent third-party and could include facilities at locations throughout the world. The emissions studies should include measurement of metals, dioxins and furans, other hazardous compounds, and fugitive gas and particulate matter emissions, in addition to criteria pollutants.
3. Conduct research on the impact of China on the demand for recycled materials. China’s demand for recycled materials is significant to California’s entire recycling infrastructure. This issue transcends the conversion technology issue and relates to all recycling markets including paper and plastic. A larger study should be conducted in consultation with the Department of Conservation to study the recyclable resource export market.
4. Diversion credit for biochemical technologies such as anaerobic digestion should be considered. If the CIWMB is granted statutory authority to allow diversion credit for conversion technologies, it should be granted only under the provisions in the CIWMB adopted-policy.

Acknowledgements

The California Integrated Waste Management Board contracted with RTI International to conduct a lifecycle 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* report prepared by UC Riverside and the *Life Cycle and Market Impact Assessment of Noncombustion Waste Conversion Technologies* prepared by RTI International. Sections of those two reports have been excerpted into this report.

Introduction

The California Integrated Waste Management Act of 1989 (AB 939, Sher, Chapter 1095, Statutes of 1989, as amended) 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 there are 170 permitted composting facilities that process 10 million tons of organic materials annually. Of the 8 million tons processed, 46 percent is used as alternative daily cover. In addition, California has achieved a statewide diversion rate of 47 percent. In spite of all these efforts, more than 39 million tons of material was disposed of in landfills in 2003. Of the amount disposed in landfills, nearly 80 percent is organic material (paper, wood, green waste, food waste, etc.).

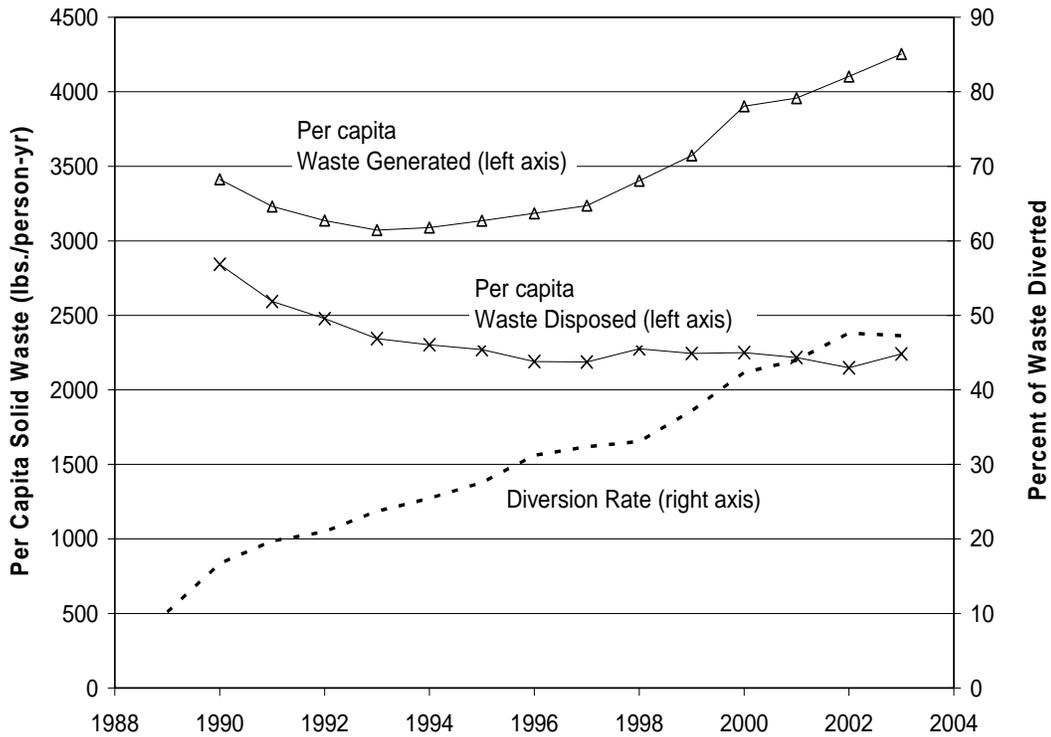
Population has increased from 29.4 million residents in 1989 to 35.6 million residents in 2003. This equates to an average annual increase of 1.3 percent and is expected to continue increasing reaching 45.5 million by 2020 and 58.7 million by 2040. This increase will continue to burden the infrastructure in California, including the solid waste management system. Figure 1 illustrates a trend of increasing per capita waste generation from a low of 3000 pounds per person per year in 1993 to 4250 pounds per person per year in 2003. Figure 1 also shows that the increasing diversion rate has paralleled the increasing per capita waste generation which results in the per capita disposal amount remaining fairly constant at 2200 pounds per person per year since 1995.

If a continued reduction in disposal of solid waste is to be realized, recycling efforts must increase and waste prevention efforts that involve changing the way goods are produced and packaged must continue to expand. Another option to reduce the amount of material disposed of in landfills is to convert this valuable resource into energy, fuels, and other products. This can be accomplished by using non-combustion thermochemical, biochemical, or physicochemical methods. For example, the 31 million tons of organic materials currently landfilled annually contains the equivalent energy of more than 60 million barrels of crude oil or could support 2500 MW of electrical power

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As directed by the Legislature, the CIWMB embarked on a research endeavor to determine what technologies would be best suited for materials that have traditionally been landfilled while at the same time ensuring that the existing recycling and composting infrastructure is maintained

Figure 1 – Per capita waste generation, diversion, and disposal in California



Legislative Requirement

Assembly Bill 2770, Chapter 740, Statutes of 2002, was signed by Governor Davis in September 2002. This bill required the CIWMB to research and evaluate new and emerging non-combustion thermal, chemical, and biological technologies and submit a report to the Legislature.

AB 2770 required that the report must contain the following:

1. Specific and discrete definitions and descriptions of each conversion technology evaluated.
2. A description and evaluation of the lifecycle 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.
3. 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.
4. A description and evaluation of the impacts on recycling and composting markets as a result of each conversion technology.

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. The CIWMB also contracted with RTI, International to conduct life cycle and market impact analyses of conversion technologies. Their reports to the CIWMB serve as the major source of information for the CIWMB Conversion Technology Report to the Legislature.

Conversion Pathways

Conversion of organic material can be accomplished by utilizing thermochemical and biochemical pathways. These pathways are described below.

Thermochemical Conversion

Thermochemical conversion processes utilize higher temperatures and have higher conversion rates when compared to other conversion pathways. Thermochemical conversion pathways include processes such as pyrolysis, gasification, and combustion. Each process can operate within a specific temperature range and operating pressure. Pyrolysis and gasification technologies are not new technologies, having been used for coal since the early 20th Century. The application of these technologies to solid waste feedstocks, however, is new and emerging.

Pyrolysis

Pyrolysis is a process that 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 – 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 which 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.

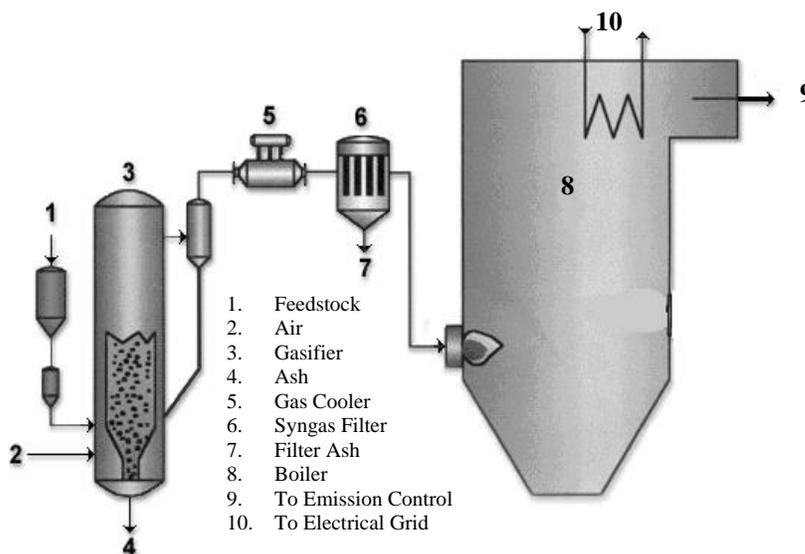
The composition of the pyrolytic product can be changed by the temperature, speed of process, and rate of heat transfer. Lower pyrolysis temperatures usually produce more liquid products and higher temperatures produce more gases. Slow pyrolysis can be used to maximize the yield of solid char and is 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, 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 2 is a diagram of a typical gasification system.

Figure 2. Gasification Diagram



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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.

Assembly Bill 2770 included the following definition for gasification in the Public Resources Code:

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 University of California researchers and other external stakeholders have identified technical inaccuracies with this definition. For example, gasification technologies do use air or oxygen in its process. Under the existing definition for gasification, processes that gasify waste to produce clean burning fuels or chemicals for uses other than for electricity production would not be considered gasification and would still be considered “transformation.” The provision that only allows the use of ambient air for temperature control precludes the use of heated air on the feedstock. The use of heated air is a common method in combined heat and power systems to improve the overall energy conversion efficiency. Furthermore, this definition does not guarantee superior environmental performance and may lead to less efficient energy conversion systems.

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 19th century. Plasma arc technology uses very high temperatures to break down the feedstock into elemental byproducts.

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)

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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, 1) the transferred torch and 2) 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 1700-2200° 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 typical cracking methods, often used in oil refinery operations, to produce fuels such as low-sulfur diesel and gasoline.

Combustion

Combustion is the thermal destruction, in an oxygen-rich environment, of solid waste for the generation of heat and subsequent energy production. Combustion and incineration differ in the sense that the goal of combustion is the production of heat and energy. The goal of incineration is simple volume reduction of the feedstock. Flame temperatures for combustion and incineration range from 1500 to 3000°F.

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 while at the same time extracting the embodied energy value from the feedstock prior to landfilling.

There are a large number of anaerobic digestion facilities operating in Europe and Canada that utilize unsorted MSW as a feedstock. As a result, there is more experience and information available from anaerobic digestion processes. Fermentation processes for the production of ethanol from MSW have not matured to the extent that anaerobic digestion has and available information is only theoretical in nature.

Anaerobic Digestion

Anaerobic digestion is the bacterial breakdown of biodegradable organic material in the absence of oxygen and 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 there are two optimal temperature ranges in which microbial activity and biogas production rates are highest, mesophilic and thermophilic temperature ranges. 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 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 three steps and are shown in Figure 3:

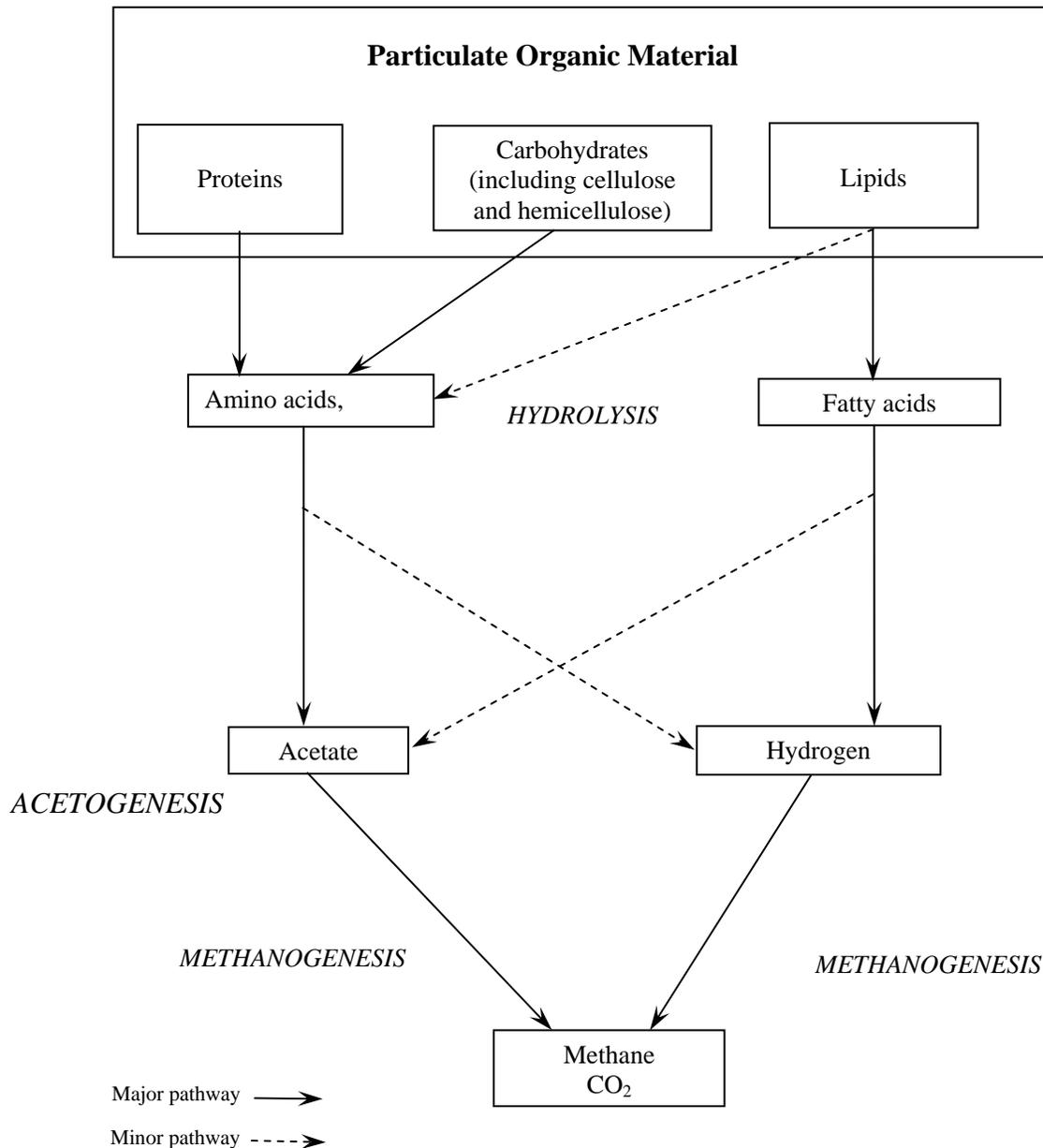
1. Decomposition of plant or animal matter by bacteria into molecules such as sugar (hydrolysis)
2. Conversion of decomposed matter to organic acids (acetogenesis)
3. Organic acid conversion to methane gas (methanogenesis)

The molecular structure of the biodegradable portion of the waste that contains proteins and carbohydrates is first broken down through hydrolysis. The lipids are converted to volatile fatty acids and amino acids. Carbohydrates and proteins are hydrolyzed to sugars and amino acids. In acetogenesis, acid forming bacteria use these byproducts to generate intermediary products such as propionate and butyrate. Further microbial action results in the degradation of these intermediary products into hydrogen and acetate. Methanogenic 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, industrial heaters, other processes, and 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 3. Anaerobic Digestion Pathways



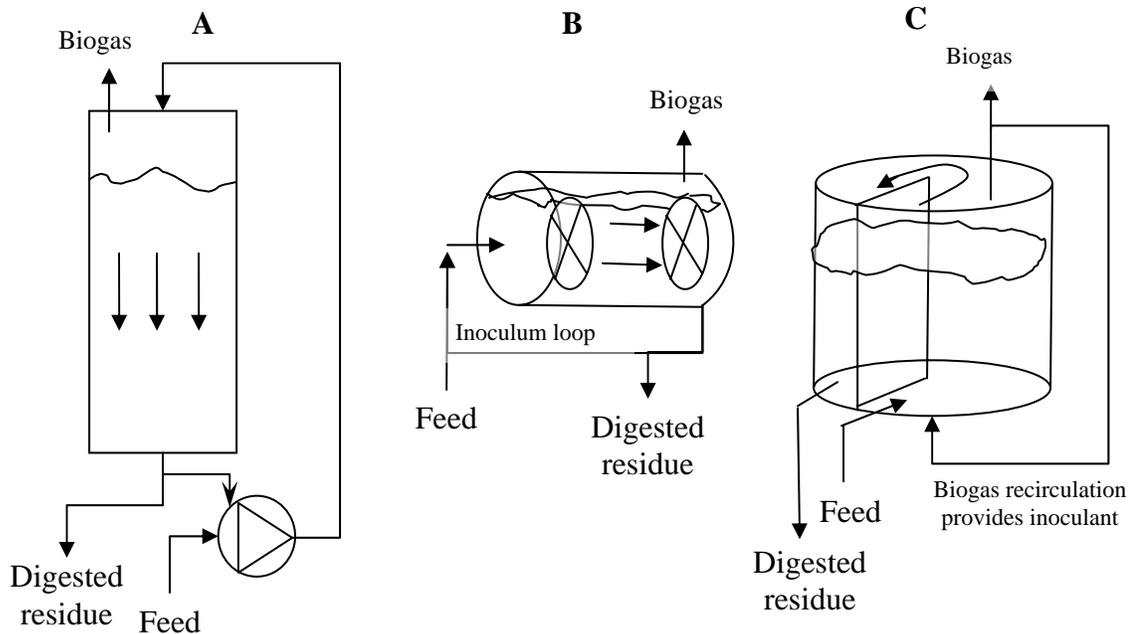
Single Stage Anaerobic Digestion

Single stage systems, as shown in Figure 4, 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 a TS ranging from 20

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to 40 percent. The high-solids system has several advantages of 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 4. High Solids Single Stage Digester Designs (A – Dranco, B – Kompogas, C- Valorga) Adapted from Mata-Alvarez, J. (2003)

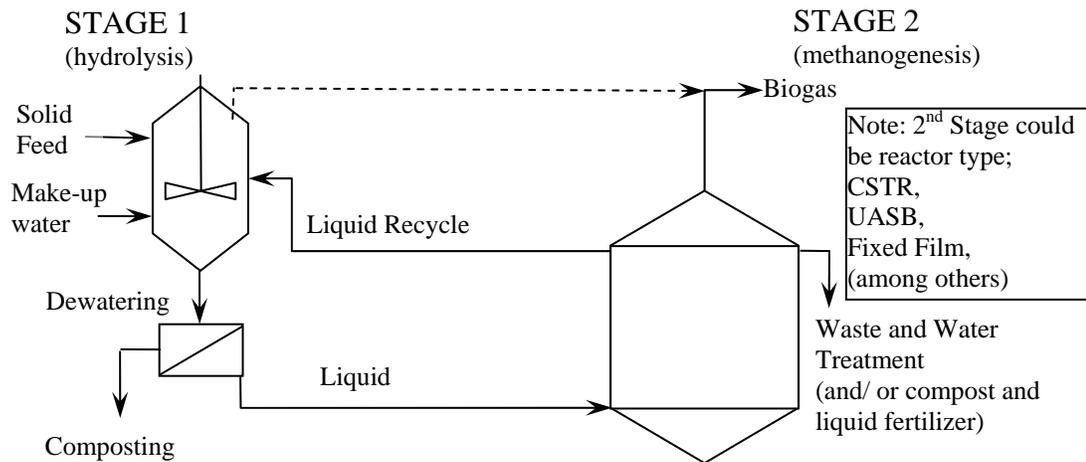


Two-Stage Anaerobic Digestion

Two-stage reactors, as shown in Figure 5, separate the hydrolysis stage from the acetogenesis and methanogenesis stages and 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 purpose 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. The air would inhibit the methanogenic organisms if they were present as they would be in a single stage reactor.

Figure 5. Two-Stage Anaerobic Digestion System (high solids 1st stage, low solids 2nd stage) Adapted from Mata-Alvarez, J. (2003)



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. Cellulosic feedstocks, including the majority of the organic fraction of MSW, need pretreatment (acid, enzymatic, or hydrothermal hydrolysis) to depolymerize cellulose and hemicellulose to monomers used by the yeast and bacteria for the fermentation process.

Cellulosic ethanol processes can be differentiated primarily by the hydrolysis pre-treatment method. Methods that have been investigated the most are acid processes, enzymatic hydrolysis, and steam explosion. Acid hydrolysis is technologically mature, however enzymatic processes are projected to have a significant cost advantage once improved. Steam explosion requires less initial size reduction of the feedstock, but yields less pentose, which are sugars that contain five carbon atoms, and releases more material that can inhibit the fermentation process.

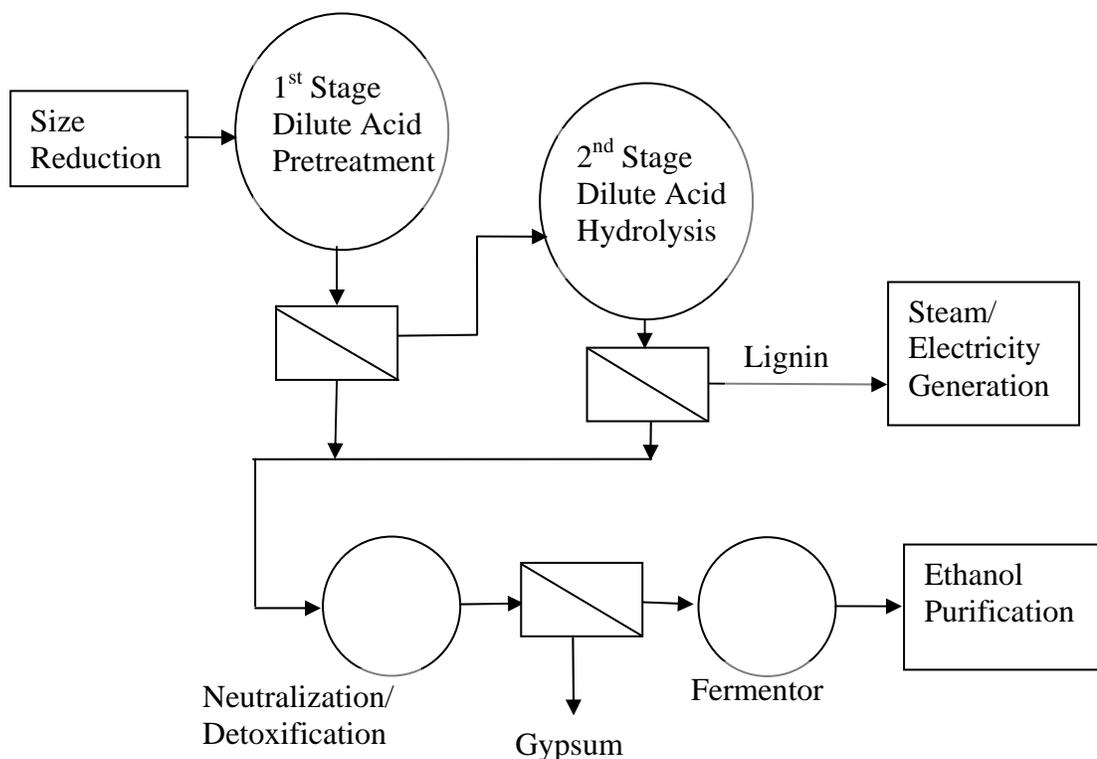
The ideal pretreatment process would have these attributes:

- 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

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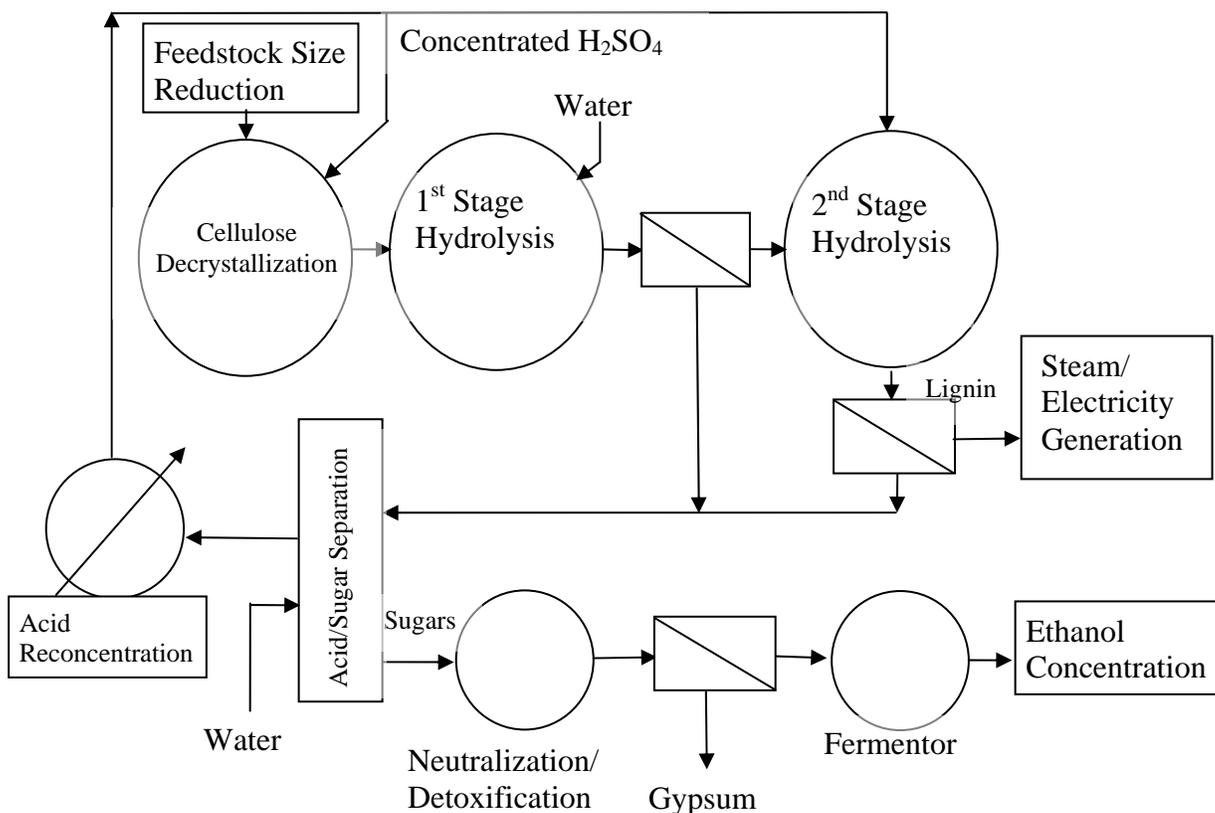
In dilute-acid hydrolysis, biomass that has been chopped or pulverized is treated in a dilute acid medium. Most current dilute acid hydrolysis processes utilize two stages (Figure 6), one optimized for the hemicellulose component and the other a more severe stage for the cellulose. Cellulose is more difficult to hydrolyze because much of it is bound up in a structural matrix that includes lignin and cellulose. Process temperatures are typically near 464°F which by itself is a form of hydrothermal hydrolysis. The use of dilute acid hydrolysis is the oldest technology for converting biomass into its component sugars for subsequent fermentation to ethanol.

Figure 6. Typical two-stage dilute acid hydrolysis fermentation.



Concentrated-acid hydrolysis (Figure 7) 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 7. Concentrated acid hydrolysis fermentation. (Adapted from <http://www.ott.doe.gov/biofuels/concentrated.html>)



Ethanol production using enzymatic hydrolysis uses enzymes derived from common fungi. Research has been directed at improving cost and performance of cellulase and is ongoing worldwide at both public and private research institutions. Improvements in enzymatic hydrolysis are expected which 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 product of water changes with the temperature, and reaches 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 in neutral and/or acidic or alkali solvents.

Fermentation of biomass material into ethanol is fully commercial for sugar and starch based feedstocks such as corn and sugar cane but it is not yet commercial for cellulosic biomass because of the high expense or low sugar yields from the hydrolysis process and 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.

Fermentation by yeast to ethanol is well established for sugar and starch based feedstocks such as sugar cane and corn. Cellulosic feedstock material must be hydrolyzed to break the cellulose and

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hemicellulose polymers into simple sugars which 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 (e.g., pH and temperature adjusted), ethanol is produced from microbial fermentation. A variety of microorganisms, generally bacteria, yeast, or fungi, ferment carbohydrates to ethanol under anaerobic conditions. Ethanol inhibits microbial growth, essentially halting the process when ethanol concentration is near 12 percent. 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.

Current Status

Much of the development and deployment of conversion technologies has occurred in Japan, Germany, and the United Kingdom with over 50 thermochemical facilities and over 80 anaerobic digestion facilities that use 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. Over 50 pyrolysis or gasification facilities commercially processing 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 as a feedstock. Table 2 lists all commercially active gasification facilities using MSW as a feedstock.

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 two 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 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 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

Location	Company	Began Operation	MSW Capacity
Kyouhoku, 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 Pyrolysis Facilities using MSW

Location	Company	Began Operation	MSW Capacity
SVZ, Germany	Envirotherm	2001	275,000 tpy
Karlsruhe, Germany	Thermoselect/JFE	2001	792 tpd
Ibaraki, Japan	Nippon Steel	1980	500 tpd
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, Jp	Nippon Steel	2000	220 tpd
Kazusa, Japan	Nippon Steel	2002	220 tpd
Ube City, Japan	Ebara	2002	218 tpd
Sakata, Japan	Ebara	2002	217 tpd
Kagawatobu-Kumiai, Jp	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, Jp	Nippon Steel	2003	176 tpd
Ibaraki #3, Japan	Nippon Steel	1999	166 tpd
Ishikawa, Japan	Hitachi-Zosen	2003	160 tpd
Kocki West Envir., Jp	Nippon Steel	2002	154 tpd
Nara, Japan	Hitachi-Zosen	2001	150 tpd
Toyokama Union, Jp	Nippon Steel	2003	144 tpd

Location	Company	Began Operation	MSW Capacity
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, Jp	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

Given the potentially large market size and the rapid progress toward commercialization during the past five years, especially in Japan, the technology appears to be well on its way to technological maturity in terms of efficiency, reliability, and environmental performance.

Several thermochemical conversion facilities have experienced technical or financial 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 facility in Karlsruhe, Germany, had problems that led to considerable delays in commissioning. The 792 TPD facility was finally commissioned in 2001 and appears to have operated since then.

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

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 successful deployment of thermochemical technologies.

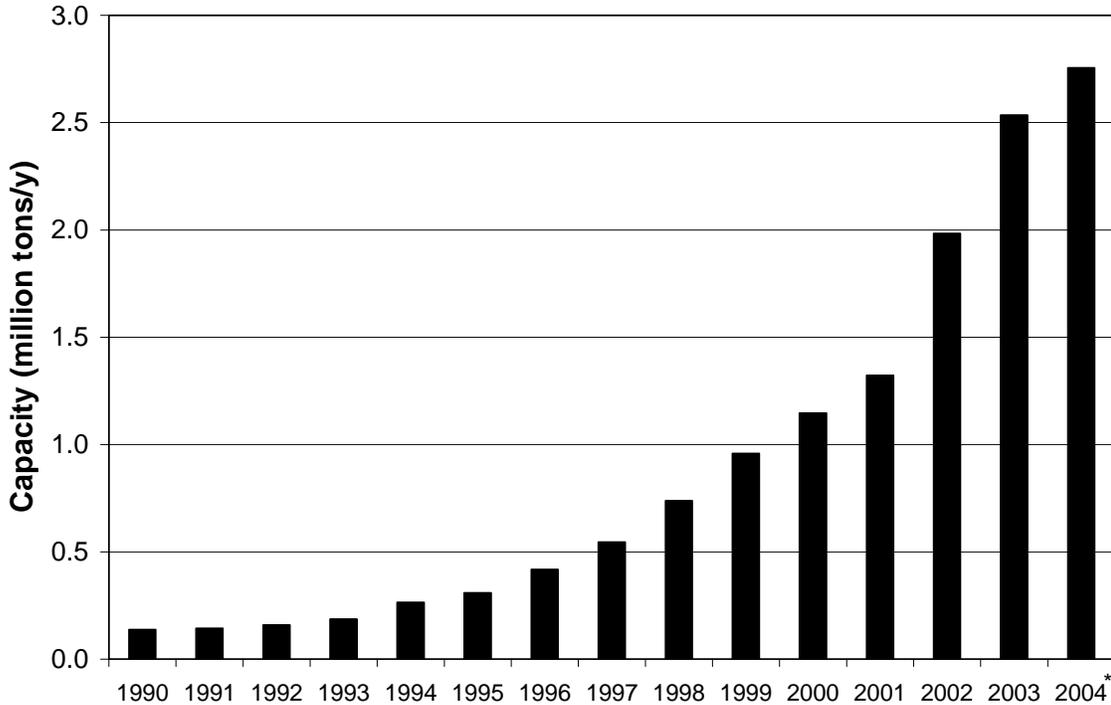
Biochemical Conversion

The installed capacity of anaerobic digestion facilities in Europe process more than 3000 TPY using mandatory pre-sorted feedstock 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, are 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 is projected to be 2.8 million TPY in 2004, an increase of more than 250 percent in four years. Figure 8 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 AD capacity.

Figure 8. Anaerobic Digester Capacity Growth in Europe.



There are several in-vessel digester projects proposed including a commercial scale facility for California State University – Channel Islands and a demonstration pilot scale facility currently under construction at the University of California, Davis, both using a design developed at UC Davis. Recent announcements indicate that Los Angeles and the City of Lancaster are investigating anaerobic digestion projects with Bioconverter LLC. The Coachella Valley Association of Governments, Riverside County and Waste Management Incorporated issued a solicitation for a conversion technology facility that would be co-located adjacent to a transfer station that will be constructed at the closed Edom Hill Landfill near Palm Springs, CA. The finalist selected was an anaerobic digestion vendor. A number of other digestion projects are in development under state incentive programs for animal and food processing wastes.

Fermentation of biomass into ethanol is fully commercial for sugar and starch based feedstocks. It is not yet commercial for cellulosic biomass because of technical difficulties and cost, but this remains an active area of research and development. There are several facilities that are being commissioned. The Masada OxyNol process is permitted and expected to begin construction soon in Middletown, NY. 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. A facility is also planned by Genahol Inc. in Grove City, OH. The facility will be designed for a 275,000 TPY capacity and will process cellulosic and other biomass components of MSW. The annual yield is expected to be ten million gallons of ethanol. Other examples of cellulosic biomass to ethanol commercialization efforts include Iogen in Canada, BCI in Louisiana, and Arkenol with a plant in Japan. Initially, feedstocks in these ventures are intended to be agricultural and wood based residues.

Feedstocks

According to the 2003 waste characterization study conducted by the California Integrated Waste Management Board organic materials make up just over 30% of the waste stream in California. Although this is slightly less than what was reported from the 1999 waste characterization, 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 excellent 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. Furthermore, because 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. Some further sorting and/or processing of post-Materials Recovery Facility (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 PVC, 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. Some Plastics may also be converted by thermochemical processing.

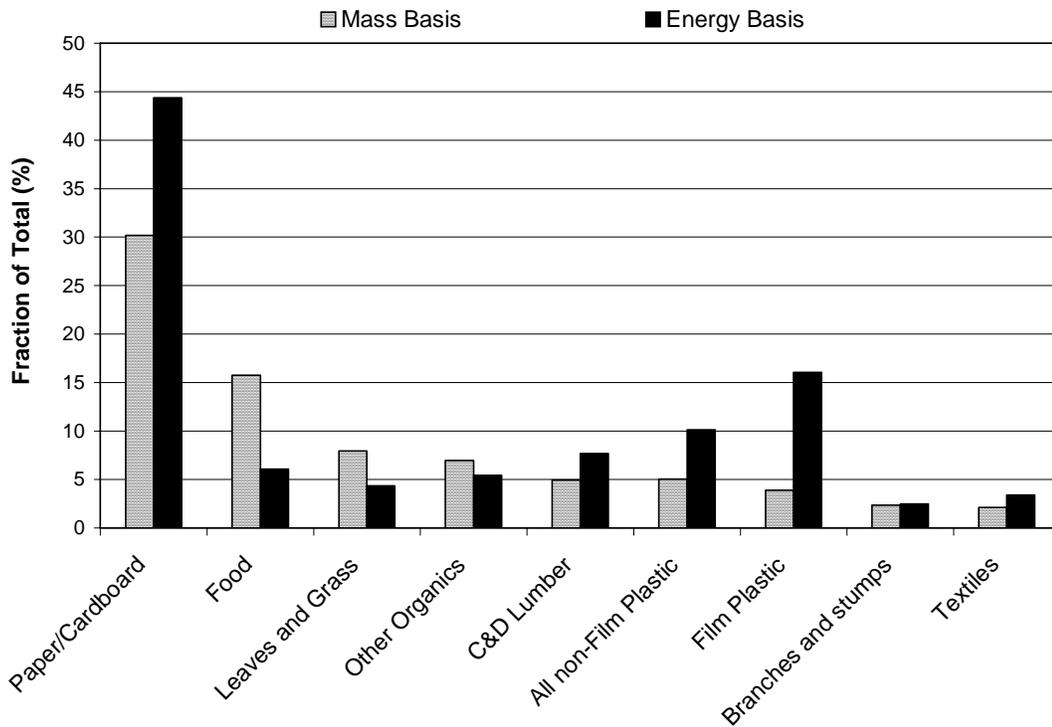
Biochemical processes can convert only the biodegradable fraction of feedstocks. Metals, glass, mineral matter, and most of the current plastic stream will not be converted. Some of the newer plastics include biodegradable fractions or are fully biodegradable. The fraction of these plastics in the waste 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 prefer source-separated green or food waste, or the biogenic fraction of mixed MSW after sorting. Some biochemical systems (so-called “high solids” reactors) 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. Although recycling of old corrugated containers (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. Increase in demand for paper for recycling will depend upon new efforts by government and the private sector to utilize products made with a higher percentage of recycled paper content.

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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. Although some plastic recycling markets are well developed, the overall recovery fraction of plastics is only about 5 percent. 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. 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. Figure 9 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 9. Fractions of Total Mass and Energy of Waste Stream Components.



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

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petroleum-like base products such as ethylene for new plastics production. These would displace fossil petroleum use. Thermochemical techniques have previously been developed 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 (PVC) 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 could also be used. 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 softwood, 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 include other constituents such as clay and heavy metals from pigments. Sludge products may have value as fertilizer or soil additives if heavy metal concentrations can be kept sufficiently low. The lower temperatures of biochemical treatment have some advantages in terms of reducing the potential formation of pollutant and hazardous species compared with higher temperature thermal processes, but cannot process the full waste stream.

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 calorific values, such as plastics, tires or rubber, can produce generally higher energy outputs. On a per mass basis, the greater the preprocessing, particularly with respect to removal of inorganic material such as metals and glass, the greater the potential energy output.

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) 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 other than 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. Gasification technologies exist that 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 this type of process 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.

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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 also 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 waste 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% 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 derived from conversion technologies could have a large economic impact. For example, the production of electricity by conversion of the waste stream could provide up to 8 percent of California’s current electrical needs. Products that can be created from conversion technologies are listed below in Table 3.

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	Ethanol, Chemicals, Heat, Soil Amendment	Inorganics, metals, glass, undegraded biomass	Moderate to High	Biodegradable Components

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.

Environmental and Public Health Impacts

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.

Environmental Impacts

There are a number of environmental factors to take into consideration when assessing the impacts that conversion technologies may have. 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.

While a number of studies have characterized emissions from individual waste conversion processes, there is a lack of consistent comprehensive data for use in comparative analyses to make 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 and 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 CO₂, and dioxins/furans. In addition, there can be fugitive gas and dust emissions that depend on control strategies, operational practices, and level of maintenance at a particular facility (e.g., enclosed receiving buildings with may have exhaust air treatment to minimize VOC and dust emissions from unloading and feedstock storage). Conversion processes, particularly thermochemical conversion, may employ air pollution control at the reactor outlet as well as the exhaust gas outlet. Table 4 lists typical air pollution control technology that may be used for emission control.

Table 4. Air Pollution Control Technologies

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

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Contaminant	Control Technology
Oxides of nitrogen (NOx)	Flame temperature control, Low NOx combustors, Fuel nitrogen management, Selective catalytic reduction Water injection Re-burning
Oxides of sulfur (SOx)	Limit sulfur mass input Scrubber
Acid gases	Scrubber

While biochemical processes have gained widespread acceptance for treating various feedstocks, thermochemical processes have met with resistance from the environmental community and the public. Some of this resistance has stemmed from the perception that pyrolysis and gasification processes are variations of incineration. Some commentators have stated that federal law includes gasification and pyrolysis as part of the definition of incineration. Title 40, Part 60, Standards of Performance for New Stationary Sources, Subpart E—Standards of Performance for Incinerators defines “*Incinerator*” as “...any furnace used in the process of burning solid waste for the purpose of reducing the volume of the waste by removing combustible matter.” The federal definition does not include the term gasification or pyrolysis.

According to the University of California researchers, thermochemical conversion technologies differ dramatically from incineration 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 can also be hydrogen or steam.
- 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.

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 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 400-1290° F, with a maximum formation rate at approximately 600° F. Combustion conditions that enhance the downstream formation of dioxins and furans include poor gas-phase mixing during combustion, low combustion temperatures, incomplete combustion of carbon species, and high PM loading.

In the late 1980s, combustion of MSW was listed as the leading source of dioxin emissions in the country (approximately 60 percent of total). Maximum available control technology (MACT) regulations promulgated by the U.S EPA in 1995 forced the industry to retrofit with better emission control technologies where possible and close facilities that could not be improved. Baseline emissions testing was conducted at all 167 large MSW incinerator facilities in the United States in 1990. Consistent with Section 129 of the Clean Air Act, large MSW incinerators

were required to retrofit their facilities with MACT by December, 2000. Subsequent emissions testing at all facilities was conducted to verify performance. Table 5 illustrates the dramatic improvement in emissions control following the retrofits.

Table 5. Emissions from Large MSW Incinerators

Pollutant	1990 Emissions	2000 Emissions	Percent Reduction
Dioxins/furans, total mass basis	218,000 g/yr	679 g/yr	99+
Dioxins/furans, Toxic equivalent quantity basis	4,260 g/yr	12.0 g/yr	99+
Mercury	45.2 tpy	2.20 tpy	95.1
Cadmium	4.75 tpy	0.333 tpy	93.0
Lead	52.1 tpy	4.76 tpy	90.9
Particulate matter	6,930 tpy	707 tpy	89.8
Hydrochloric acid	46,900 tpy	2,672 tpy	94.3
SO ₂	30,700 tpy	4,076 tpy	86.7
NO _x	56,400 tpy	46,500 tpy	17.6

Source: United States Environmental Protection Agency Memorandum, "Emission from Large MWC Units at MACT Compliance," June 20, 2002.

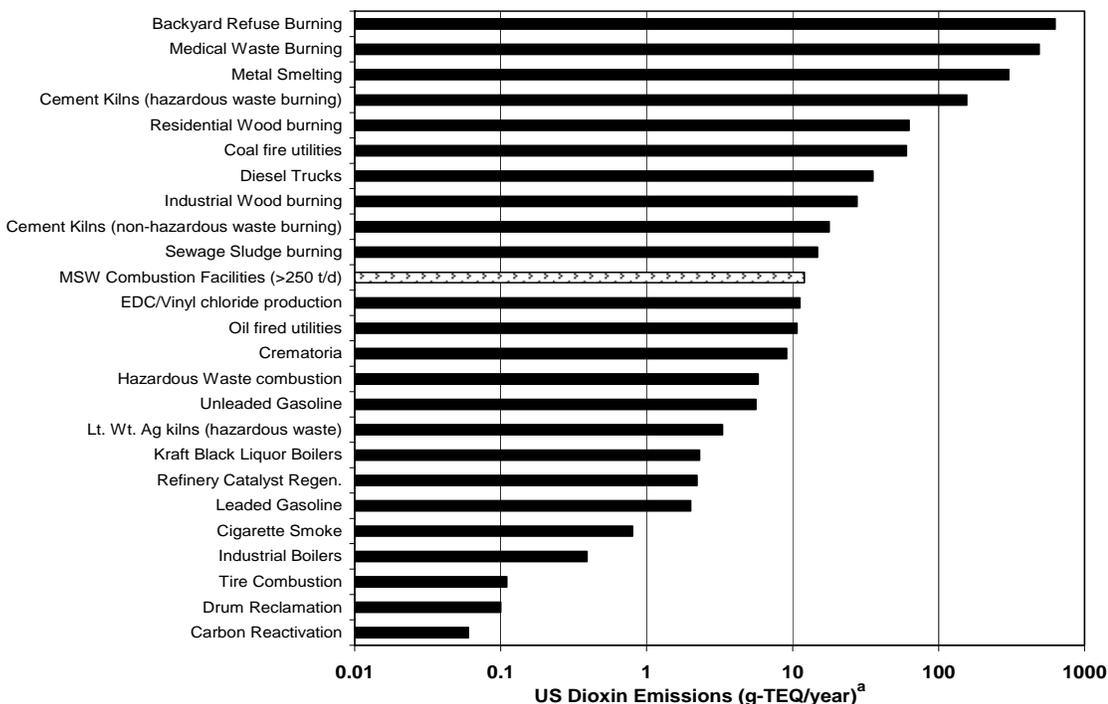
These emission reductions were achieved via a combination of sophisticated process control and technology improvements and are indicative of the maturation of air pollution control equipment over the years. The same air pollution control technologies used in large MSW incinerators that resulted in the dramatic emissions reductions could also be used on thermochemical conversion facilities and could result in much lower emissions if proper feedstock preparation is utilized. Common exhaust gas cleanup technologies include spray dryers, fabric filters, carbon injection, selective non-catalytic reduction, electrostatic precipitation, and duct sorbent injection.

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.

Today, the level of dioxin air emissions from combustion of MSW in the U.S. has decreased from 8900 g-TEQ per year in 1987 to 12 g-TEQ per year by 2000, a decrease of 99.9 percent. The MSW combustion industry represents less than 1 percent of the national dioxin/furan air emission burden.

During this period, the number of operating facilities increased and the amount of waste burned doubled from 15 million to 32 million TPY. Figure 10 illustrates the total inventory of dioxin emissions in the U.S. by source type. Data for MSW combustion is for 2000 (US EPA, 2002, Docket A-90-45, VIII. B.11). All other emissions are from 1995 US EPA Inventory and can be found at <http://cfpub.epa.gov/ncea/cfm/recordisplay.cfm?deid=20797>

Figure 10. US Dioxin Emissions Inventory by Source Type.

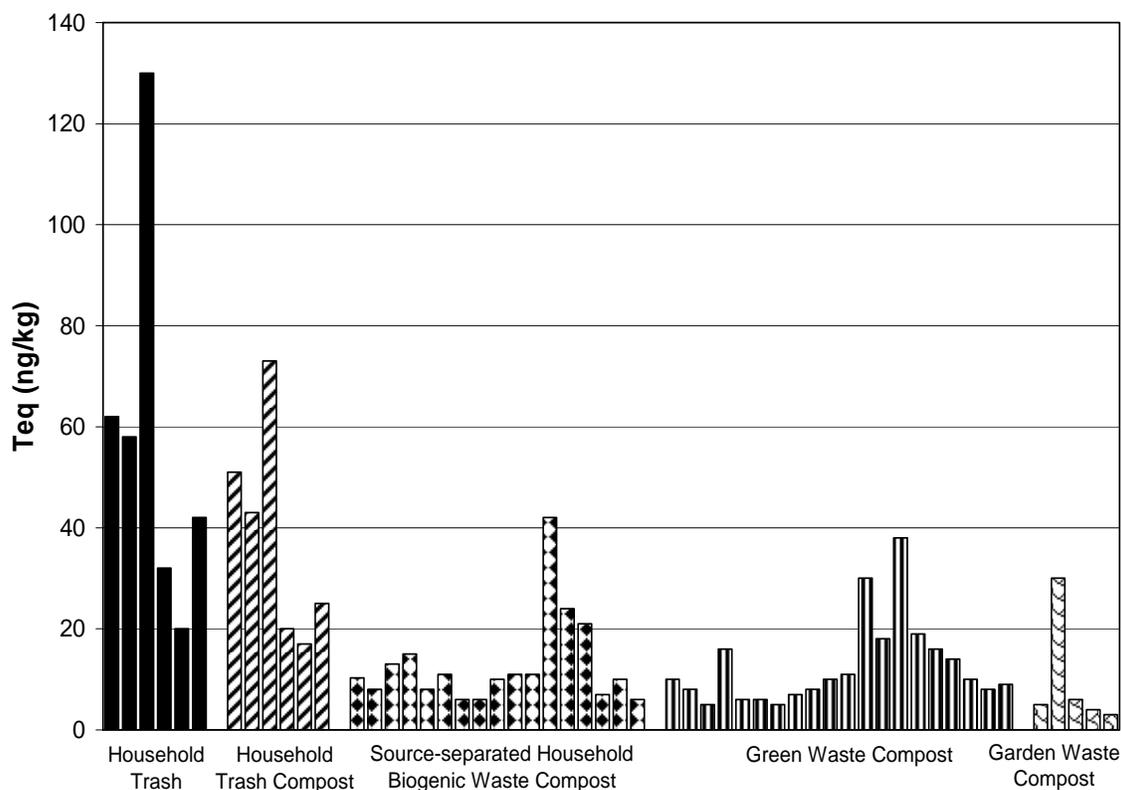


Comments were received regarding the Stockholm Convention on Persistent Organic Pollutants (May 2001), which the U.S. has signed. This Convention has established a goal of reducing or eliminating the creation of persistent organic pollutants such as dioxins and furans. The Convention lists waste incineration as a source of anthropogenic dioxins/furans. Also listed as sources are pulp production using chlorine, secondary smelting of aluminum, copper, and zinc, and fossil-fuel fired power plants. The Convention also provides guidance for best available techniques for achieving specific goals of the Convention and those techniques include use of 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, wastes and sewage sludge by thermal treatment; and modification of process designs to improve combustion and prevent formation of the chemicals through the control of parameters such as incineration temperature or residence time.

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 and help achieve the goal of the Stockholm Convention.

A study in Germany provides data from dioxin analysis of several types of compost and raw household solid waste from Germany. Averages from several samples of each category showed dioxins/furans in raw household mixed waste was present in the amount of 57 ng/kg TEQ. Composted mixed MSW had dioxin/furan levels of 38 ng/kg TEQ, followed by compost of source separated household waste with 14 ng/kg TEQ and about 10 ng/kg TEQ in green and garden waste compost. The study did not indicate whether the composted mixed household waste was from the same source as the raw mixed household waste or why the PCDD/F concentration was lower in the composted mixed house waste. Figure 11 shows results of the analyses. Each column in the table represents an individual sample.

Figure 11. Dioxin/furan content of raw household wastes and several compost types. (Source Kraus and Grammel (1992) as reported in Brinton (2000))ⁱ



The bacterial decomposition of landfilled material produces significant quantities of landfill gas. The methane emissions from landfills are particularly important, since methane is 21 times more potent as a greenhouse gas than carbon dioxide and since landfills represent the second largest source of anthropogenic methane emissions behind the energy industry.

Many stakeholders have commented that composting of green waste, food waste, and other types of potentially compostable material is a “higher and better use” of these types of feedstocks. While composting does have many benefits, it is not without its challenges. One study has shown that open air composting emits volatile organic compounds and ammonia. Smet et al.ⁱⁱ compared VOC and ammonia emissions from two different methods for biochemical treatment of biodegradable wastes. Source separated household and garden wastes (70% garden, 20% kitchen and 10% paper wastes) were treated by (a) standard aerobic composting with upflow aeration and (b) a combination of anaerobic digestion followed by aerobic stabilization of digestate. VOC and ammonia emissions were measured from each process. Table 6 shows the results of testing conducted by Smet. Assuming the biogas produced by anaerobic digestion treatment method (b) is flared or combusted in an engine, then the total volatile emissions for treatment (b) would come only from the aerobic stabilization portion of the treatment or 6% of those from treatment method (a) (for example, 44 mg/ton from treatment (b) versus 742 mg/ton from treatment (a). Most of the volatile emission from treatment (b) was composed of ammonia (NH₃) requiring ammonia scrubbing if the gas is to be passed through a biofilter prior to exhaust.

Table 6. Emissions for Different Treatment Methods.

Emission Compound	Treatment (a)- Aerobic Composting Emission (g/ton)	Treatment (b)	
		Anaerobic Digestion Emission (g/ton)	Aerobic Stabilization Emission (g/ton)
Total VOC	590	217	3
NH ₃	152	1.8	41
H ₂ S	Nd	17	nd
Total Volatiles	742	236	44

Another issue is greenhouse gas emissions, including CO₂ emissions. One important method in reducing equivalent greenhouse gas emissions is through the use of renewable resources for energy production. In response to the Kyoto Protocol, the European Union is implementing European Community Directive 2001/77/EC (27 September 2001). The EC directive states that the “biodegradable fraction of industrial and municipal waste” is considered renewable. Facilities generating electricity using both renewable and non-renewable energy sources are provided credit for only the portion of the feedstock that is renewable.

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 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 exhausted to the atmosphere. Conversion technologies do not generate 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). The limits established by the U.S. EPA are shown in Table 7. Normally these residues are classified as “Non-Hazardous” and “Non-Specialist” under regulations in the United Kingdom, European Union, and the U.S.

Table 7. EPA Leachability Limits for Non-hazardous Waste

METAL (*)	U.S. EPA TCLP Test Limit (mg/L)
Mercury (Hg)	0.2
Cadmium (Cd)	1.0
Arsenic (As)	5.0
Lead (Pb)	5.0
Chromium (Cr)	5.0
Copper (Cu)	Not Applicable
Nickel (Ni)	Not Applicable
Zinc (Zn)	Not Applicable
Barium	100.0
Selenium	1.0

In many processes, the ash is vitrified by heating above the melting point or fusion temperature of the ash. This slag 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 8 shows results of ash leaching tests from various thermochemical vendors. It is not known if the data provided by the vendors was independently verified by a third party, however, testing is typically conducted by a certified, independent laboratory. Regardless, the data shows that results of leaching tests are below the standards established by the U.S. EPA.

Table 8. Leaching Data from Pyrolysis/Gasification Facilities

	Units	As	Ba	Cd	Cr	Pb	Hg
BalPac	mg/l	0.05	0.37	0.1	0.01	0.58	-
Compact Power	m/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: As=Arsenic, Ba=Barium, Cd = Cadmium, Chromium, Pb=Lead, Hg=Mercury

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

Any claim by suppliers that a particular management process can eliminate or produce fewer trace heavy metals is not factual, though residues from varying processes can have different leachability levels and 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. There are well-defined mechanisms already in place for dealing with these waste streams. Generally, these waste streams are subjected to conventional chemical treatment processes. 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 to warrant 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”)ⁱⁱⁱ found that the pyrolysis of the residue from shredding industrial light bulbs and refrigerators resulted in the formation of dioxins/furans on the order of 1,500 to 10,000 ng/g in the pyrolysis oil.

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

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traffic because the existing transportation infrastructure can be used and material can be transported via conveyor belts. However, there may be some minor traffic impacts associated with offsite transportation of commercial products and byproducts for marketing and disposal.

According to the U.S. Department of Energy (DOE), the U.S. anthropogenic methane burden from waste management operations or landfills range 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. Treatment or conversion of the waste stream and utilization of the products of conversion may be more efficient than attempting to capture and use landfill gas.

Data Acquisition and Other Studies

Acquiring data from operating facilities has been difficult because there are no operating conversion technology facilities that use most-MRF MSW residuals in California or the U.S. To address this data gap, the University of California 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 9). The University researchers did receive emissions data from vendors; however, the data were not independently verified. Although data may come from vendors, the actual testing of samples is conducted by certified laboratories and not the vendors themselves. In addition, in many cases there is continuous emissions monitoring of criteria pollutants such as NO_x and CO with simultaneous monitoring available to local air pollution control districts.

Table 9. 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
US 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	-	-	<10ppm	<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	-	-	-

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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 VOC=volatile organic carbon, Cd = Cadmium, Pb=Lead, Hg=Mercury, ND=not detect.

Many existing conversion technologies in Europe and Japan must meet stringent regulatory standards. These standards are based on stringent policies adopted by the European Union and Japan. There are a number of studies that provide emissions data from processes that employ similar pollution control strategies to those used in alternative technologies. Some of this data is useful in predicting potential environmental impacts of California-based alternative waste 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 tons per day of material. The synthesis gas was held at 2192°F for 2 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 1000 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 the 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 at 17.5%, 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 and 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 10 and Table 11 show the results of the testing.

Table 10. 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 liter/ton	0.000 01
Total Dioxins emitted			0.000 69
Japan future target			5

Table 11. 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 liter/ton	0
Total Dioxins emitted			0.000 31
Japan future target			5

There was no data presented on other hazardous air pollutants or metal species. Regardless, based on the results of the testing, the Japan Waste Management Association issued a summary of technical verification and confirmation. At present, there are gasification projects under construction in Japan that will utilize the same process as was tested in Chiba City. These projects range in size from 120 tons/day to 555 tons/day.

Plastics Gasification Study

A separate report was commissioned by the Environmental Plastics Industry Council of Canada (EPIC). The report provides data from the gasification of two types of plastic residue. The testing project utilized 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 12 summarizes air emissions data and includes regulatory limits for the province of Ontario.

Table 12. Air Emissions Summary³

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

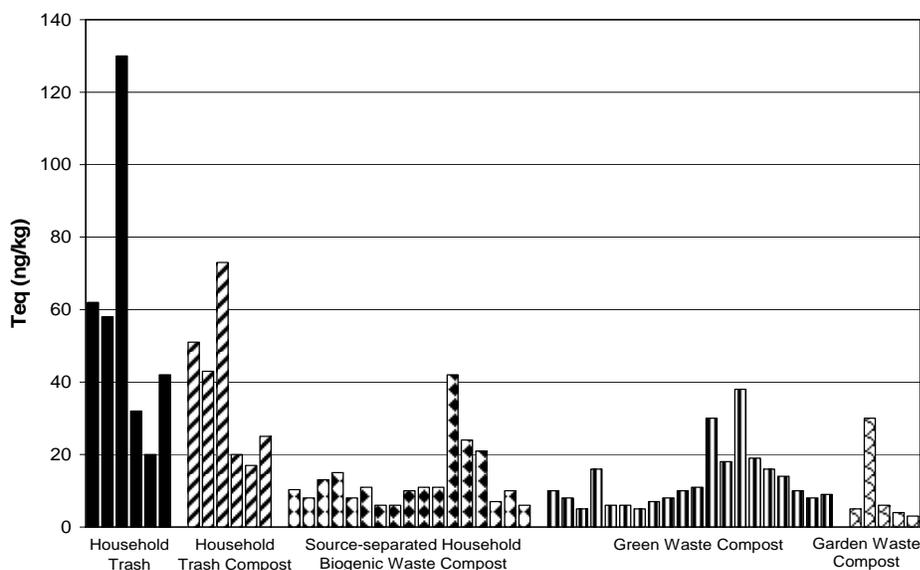
³ The units of measure use the symbol R. R stands for the reference conditions of 25°C at 1 atmosphere.

Species	EPIC 1	EPIC 2	Ontario Limit	Units
Dioxin/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	-	

Dioxin in Trash and Compost

Data from a dioxin analysis of compost and trash was conducted in 1992 and discussed in a detailed report by Brinton (2000).^{iv} The results of this study show averages from several samples of each category showed the presence of dioxins/furans in household mixed waste was present in the amount of 57 ng/kg TEQ. Composted mixed MSW had dioxin/furan levels of 38 ng/kg TEQ, followed by compost of source separated household waste with 14 ng/kg TEQ and about 10 ng/kg TEQ in green and garden waste compost. Brinton (2000) did not indicate whether the composted mixed household waste was from the same source as the raw mixed household waste or why the PCDD/F concentration was lower in the composted mixed house waste. Figure 12 shows results of sample testing.

Figure 12. Dioxins/Furans in raw household wastes and several compost types. (Source Kraus and Grammel (1992) as reported in Brinton (2000))



Public Health Impacts

The CIWMB entered into an interagency agreement with the Office of Environmental Health Hazard Assessment (OEHHA) to review the *Lifecycle and Market Impact Assessment of Noncombustion Conversion Technologies* to determine if the information it contains would be adequate for an assessment of risks to humans that may result from conversion technologies. 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. Risk assessment guidance published by the U.S. Environmental Protection Agency 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. The Lifecycle Report is not a human health risk assessment and data provided by the UC Researchers and RTI was not complete enough for OEHHA to fully assess the public health impacts of conversion technologies. Without additional information, OEHHA was not able to use the emission rate estimates to calculate concentrations of chemicals at locations where humans are exposed.

Lifecycle Assessment

Assembly Bill 2770 required the CIWMB to prepare a report on noncombustion conversion technologies describing and evaluating their potential market and life cycle environmental impacts. The CIWMB awarded a contract to an RTI International (RTI) team to perform this work. 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. Hilton, Farnkopf & Hobson (HFH) was the lead on the market impact assessment. Boisson & Associates coordinated public input and provided advice and assistance related to study design and presentation.

The goal of the lifecycle 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 those of existing MSW management practices?
2. What are the economic, financial, and institutional impacts of conversion technologies on recycling and composting markets?

There are currently no operating conversion facilities that use municipal solid waste as a feedstock which presented a problem for data acquisition. RTI relied upon 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. 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 lifecycle 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.

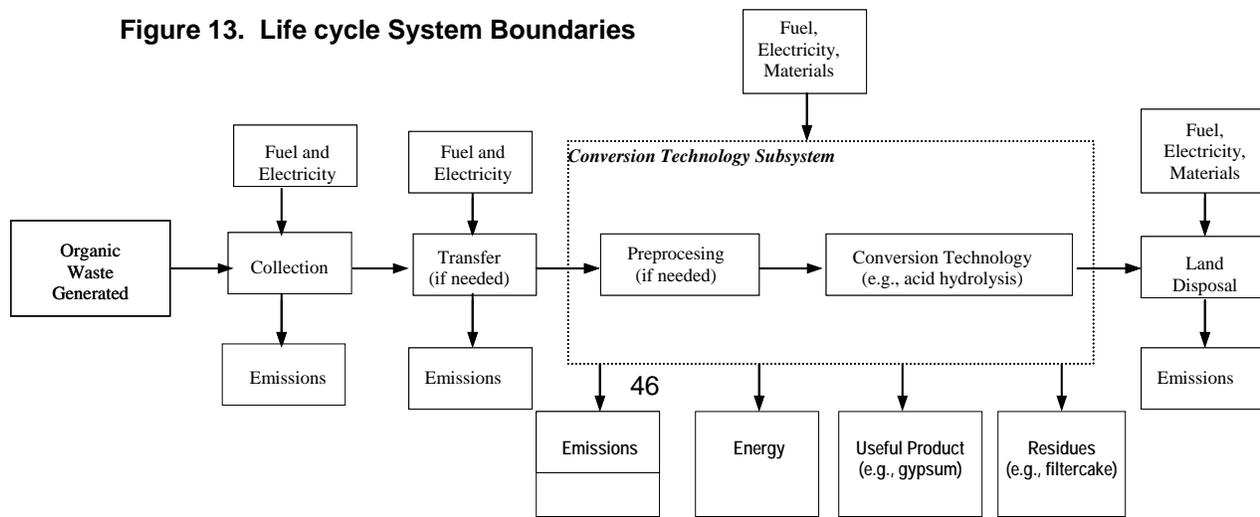
Approach

The term “life cycle assessment” describes a type of systems analysis that accounts for the complete set of upstream and downstream energy and environmental impacts associated with production systems. 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, recycling, composting, and waste-to-energy. The contractors approached the study by the following steps:

1. Define the scope, boundaries, and specific process steps for the acid hydrolysis, gasification, and catalytic cracking technologies.
2. Collect data and develop materials and energy balance models for each conversion technology.
3. Construct life cycle inventory modules for each conversion technology by adding life cycle burdens and benefits to the materials and energy balance models.
4. Apply RTI’s Municipal Solid Waste Decision Support Tool (MSW DST) to inventory the full life cycle impacts of the conversion technologies scenarios (from the collection of waste to its ultimate disposition), as well as for several alternative management practices involving recycling, composting, waste-to-energy, and landfill disposal.

Figure 13 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 13. Life cycle System Boundaries



Assumed Geographic Locations and Development Rate

The San Francisco Bay Area and the Greater Los Angeles Area 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 500 dry tpd acid hydrolysis facilities in each region (1,500 dry tpd total).
- Four 500 dry tpd gasification facilities in each region (2,000 dry tpd total).
- One stand-alone, 50 dry tpd catalytic cracking facility in each region.

Years 2004 to 2010

- One additional 500 dry tpd gasification plant built in each region in the year 2005.
- Two additional 500 dry tpd acid hydrolysis plants built in each region in 2007.
- One additional 500 dry tpd gasification plant 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 13 below.

Table 13. 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 LCI results were generated for the Greater Los Angeles and San Francisco Bay 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. Landfill with no gas collection (worst landfill case).
2. Landfill with gas collection and flaring (average landfill case).
3. Landfill with gas collection and energy recovery (best landfill case).
4. WTE combustion with ferrous recovery and disposal of combustion ash.

5. Organics composting (inorganic wastes are landfilled).
6. Mixed waste recycling (with 35percent separation efficiency at the MRF).
7. Mixed waste recycling (with 55 percent separation efficiency at the MRF).
8. Mixed waste recycling (with 75 percent separation efficiency at the MRF).

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 14 summarizes the assumed annual capacities and incoming waste needs based on the composition (see Table 15) of waste landfilled in the Greater Los Angeles and San Francisco Bay 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 on-line unless absolutely necessary. Therefore, to accommodate for this, there are a couple of days worth of storage for the waste that is brought to the plant to ensure continuous operation. It was assumed that the facilities operate 90 percent of the time, with limited downtime assumed for machine maintenance and service disruptions. Based on 90 percent operating capacity or operating 329 out of 365 days per year, the feedstock tonnage demands that are listed in Table 6 was assumed.

Table 14. Assumed Annual Capacities and Incoming Waste 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 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 15. Assumed Percent Composition of Waste Sent to Conversion Technology Facilities^a

Component	Los Angeles		San Francisco	
	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 on an “apples to apples” basis. 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.

Study Limitations

This is the first study to attempt to comprehensively analyze environmental and market impacts of conversion technologies that utilize post-MRF MSW as a feedstock. The technologies analyzed do not operate at commercial scale in the United States so acquisition of primary data was very difficult. The study approach is based on reasonable and conservative assumptions of conversion technologies. Data that was acquired was from conversion technology vendors and was not independently verified by a third-party.

Lifecycle Results

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 14 and 15, the hypothetical conversion technology scenarios for the Greater Los Angeles and San Francisco Bay regions result in a large net energy savings. As compared to the alternative management scenarios, the conversion technology scenario ranges from about 2 times lower in net energy consumption when compared to the WTE scenario (the next best energy performer), and about 11 times lower than the landfill without energy recovery scenarios (the highest energy consumer). The recycling scenarios also resulted in net energy savings,

although the levels were lower than the levels achieved by the conversion technology scenario and the WTE scenario.

Figure 14. Greater Los Angeles Region, Annual Net Energy Consumption

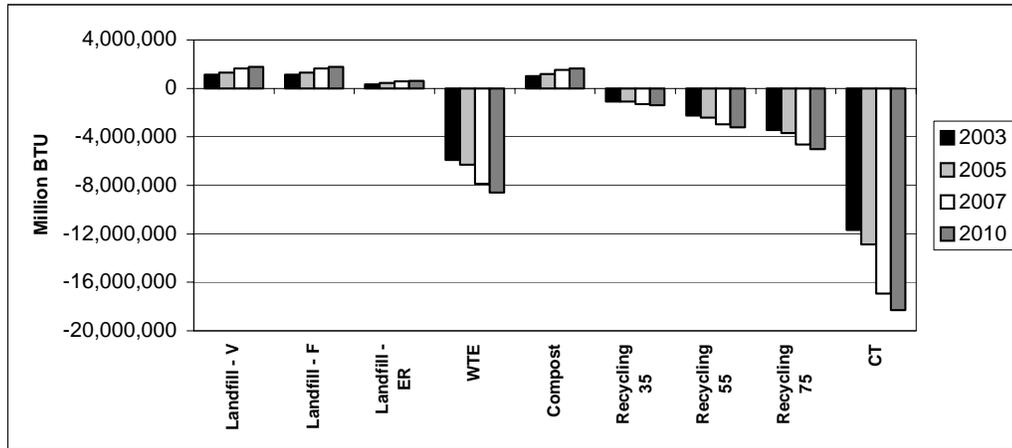
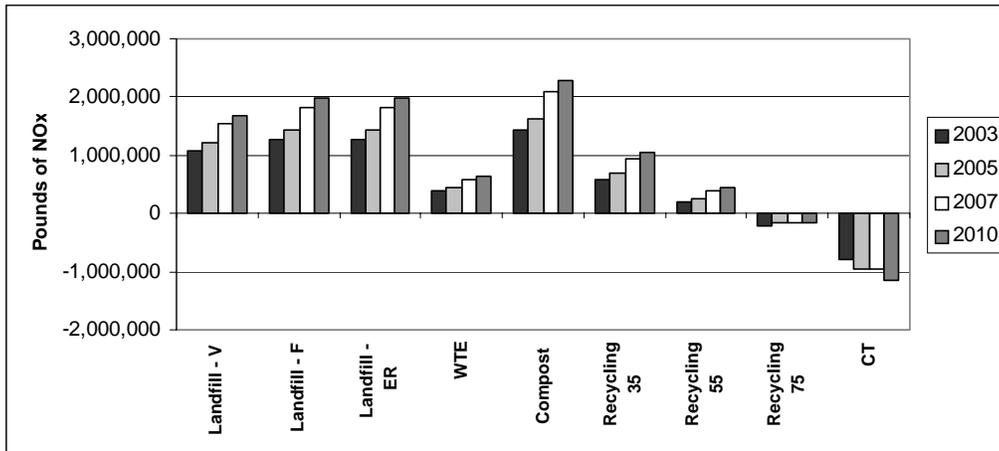


Figure 15. San Francisco Bay Region, Annual Net Energy Consumption



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 is a significant side benefit of the gasification and acid hydrolysis technologies and contributes approximately 10 to 20 percent of the total net energy savings.

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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 compost scenario consumed slightly less energy than the landfill scenarios without energy recovery and was higher in energy consumption when compared to the landfill scenario with gas collection and energy recovery. (Note: No offset was assumed for the compost product. Including an offset would likely drop the energy consumption to near zero and may even result in a net energy savings.)

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).

The recycling scenarios also were net energy savers, although the savings were not as large as that seen in the conversion technology and WTE scenarios. The reason for this is because even with high separation efficiencies (75 percent) at the MRF, a large portion (up to 50 percent or more) of the MSW is non-recyclable material that must be landfilled, such as food waste and non-recyclable material. Therefore, although recycling generates significant energy savings, a significant energy burden is associated with landfill disposal of the non-recyclable portion of the waste.

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 16 and Figure 17, 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.

The only other scenario to show a net NO_x emissions avoidance was the high recycling scenario. All of the other alternative management scenarios are net NO_x producers. The landfill and compost scenarios showed the highest levels of NO_x emissions. The WTE and low- and mid-level recycling scenarios showed about one-half to one-third of the NO_x emissions levels returned by the landfill and compost scenarios. The NO_x associated with the landfill and compost scenario largely results from the collection of waste and fuel combusted by landfill and compost equipment such as graders, compactors, grinders, shredders, and windrow turners.

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

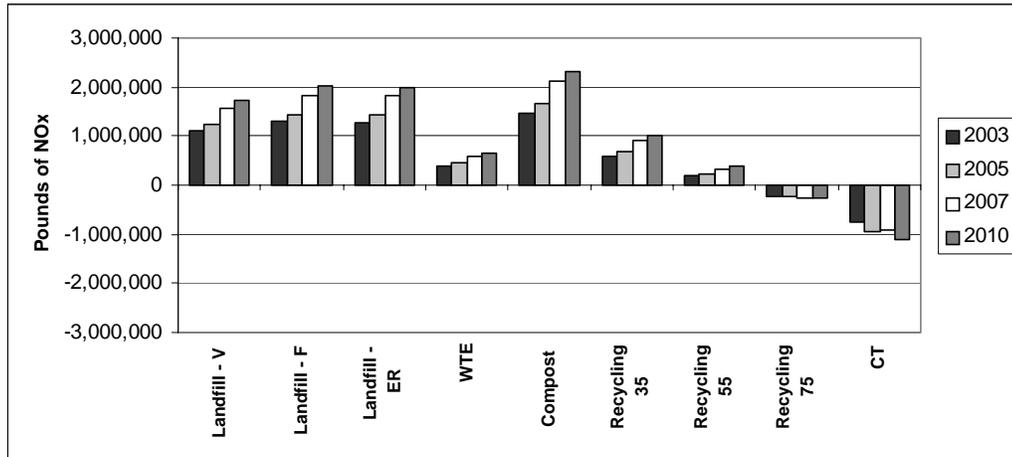
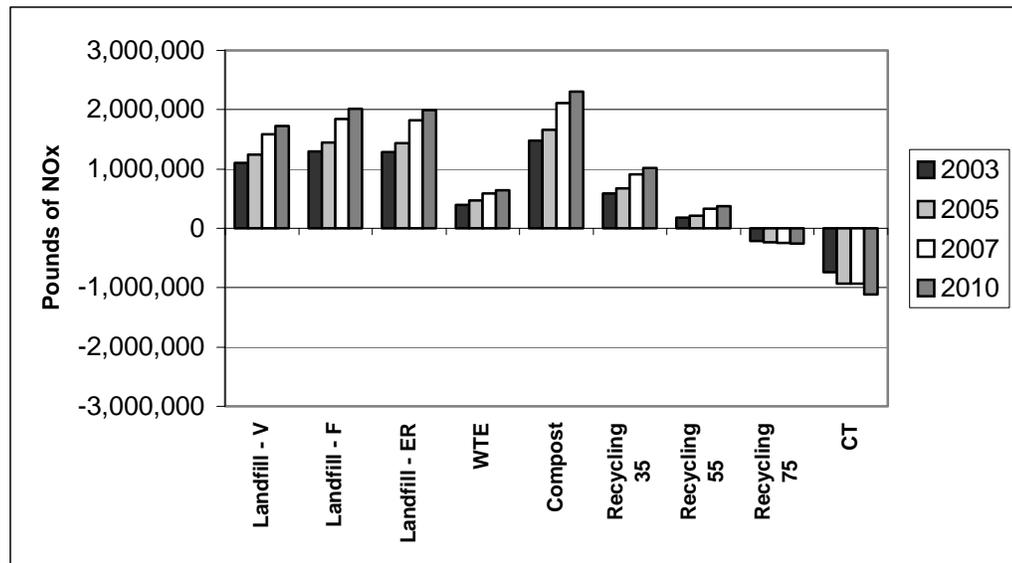


Figure 17. San Francisco Bay Region, Annual Net NO_x Emissions



For the recycling scenarios, the low-separation efficiency (35 percent) system generated NO_x at levels comparable to those from the WTE scenario. Moving from the low- to mid- to high-separation efficiency MRF scenarios, NO_x emissions were greatly reduced, largely as a result of NO_x avoidance associated with the offset of virgin materials production.

Sulfur Oxide Emissions

SO_x emissions can lead to environmental impacts such as acid deposition, corrosion, and decreased visibility. Similar to NO_x, SO_x emissions are largely the result of fuel combustion processes. Likewise, SO_x emission offsets can 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 18 and 19, 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 level of

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savings is approximately on par with that achieved through the 75 percent recycling scenario. 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 a 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 there are significant SO_x emissions 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 and recycling 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, as well as the virgin materials offsets associated with the recycling scenarios.

Figure 18. Greater Los Angeles Region, Annual Net SO_x Emissions

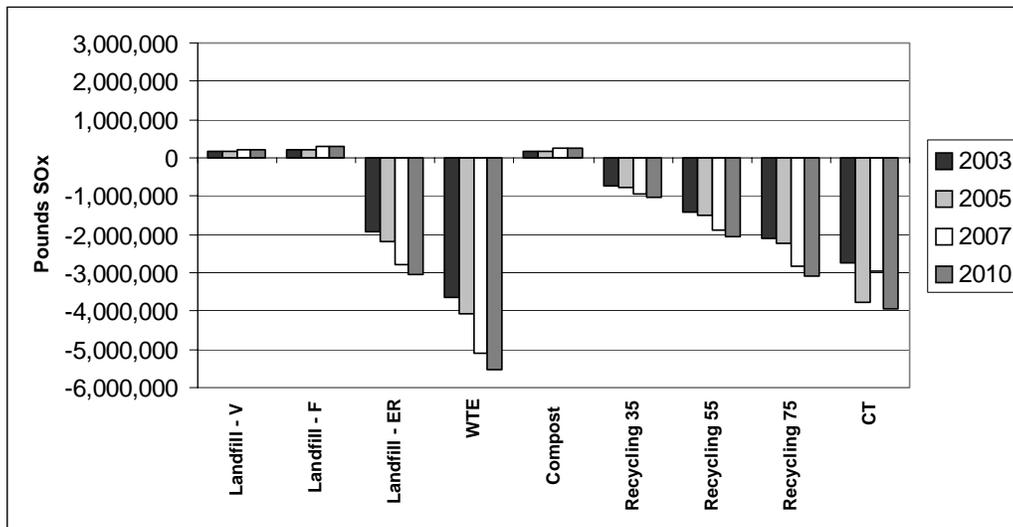
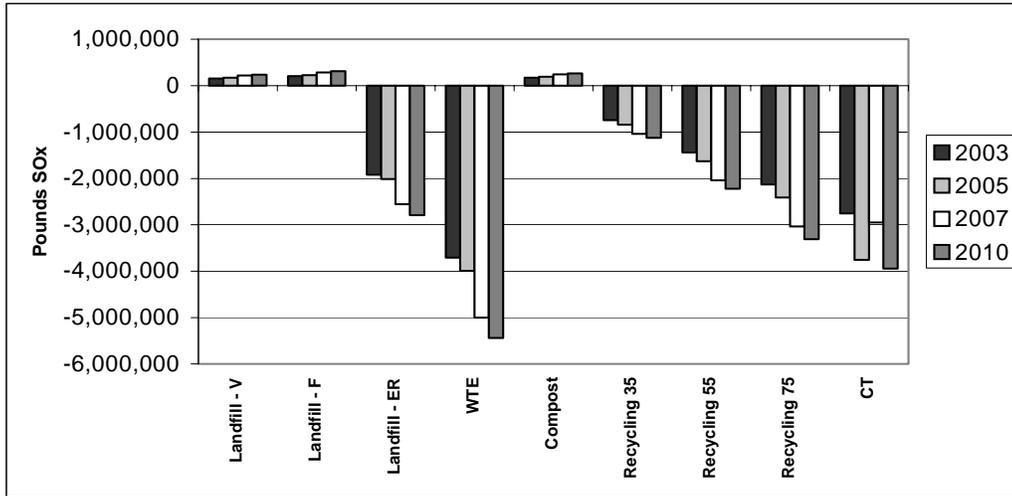


Figure 19. San Francisco Bay Region, Annual Net SO_x Emissions



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 20 and 21, 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. The remaining scenarios (landfill with gas management, compost, and recycling) all produced comparable levels of carbon emissions.

Figure 20. Greater Los Angeles Region, Annual Net Carbon Emissions

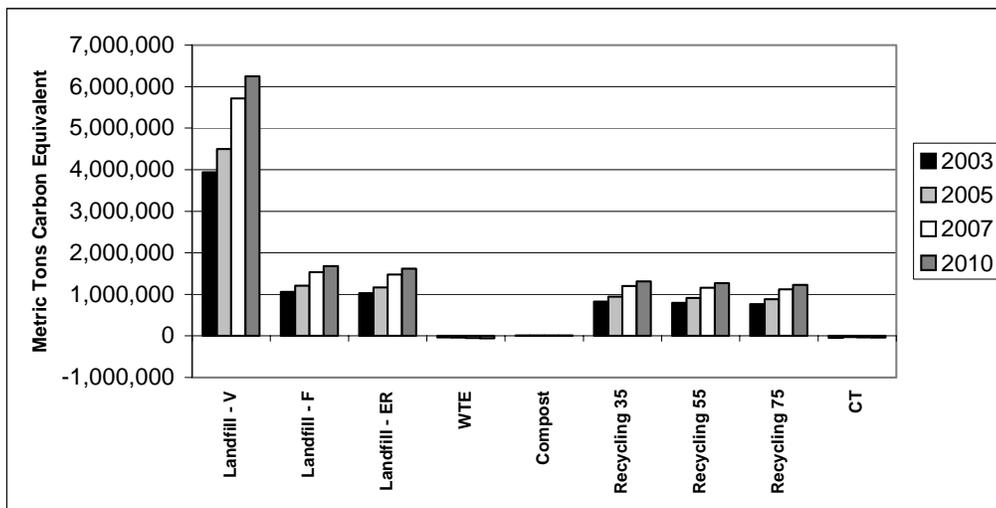
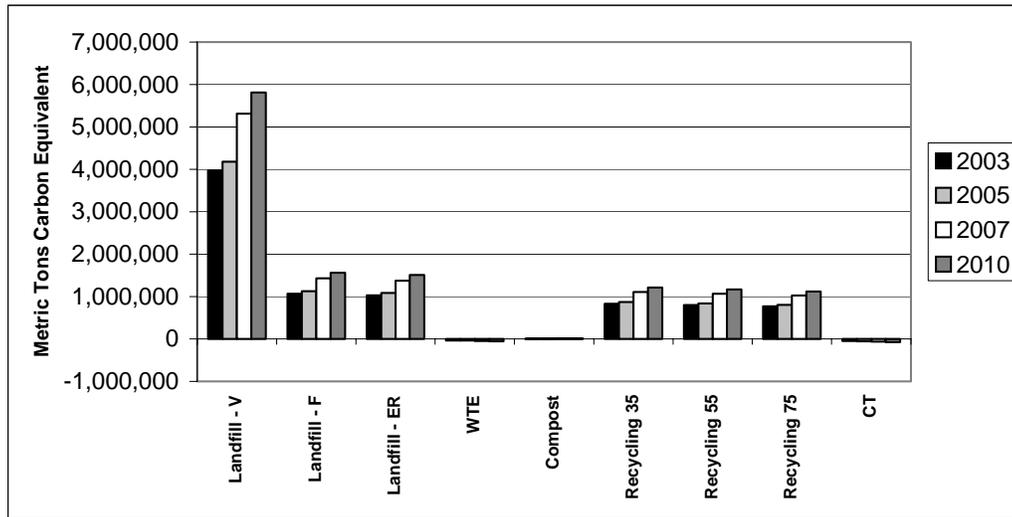


Figure 21. San Francisco Bay Region, Annual Net Carbon Emissions



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, the conversion technologies do not exist in California or the U.S so a number of assumptions have been made about their design and operating characteristics. Until there are actual operating facilities where credible, primary data can be readily obtained, the following findings need to be considered as general directional conclusions rather than absolute conclusions.

1. The amount of energy produced by the hypothetical conversion technology scenario is larger than the alternative management scenarios studied and creates large life cycle benefits.
2. For criteria air pollutants, the hypothetical conversion technology scenario is better when compared to the alternative management scenarios.
3. From a climate change perspective, the hypothetical conversion technology scenario is generally better than the alternative management scenarios.
4. There are not enough data to adequately assess the potential for the hypothetical conversion technology scenario to produce emissions 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 materials recycling rates.
6. Conversion technologies would decrease the amount of waste disposed of in landfills.
7. No conversion technology facilities exist in the United States for MSW. Therefore, there is a high level of uncertainty regarding their environmental performance.

Other Studies

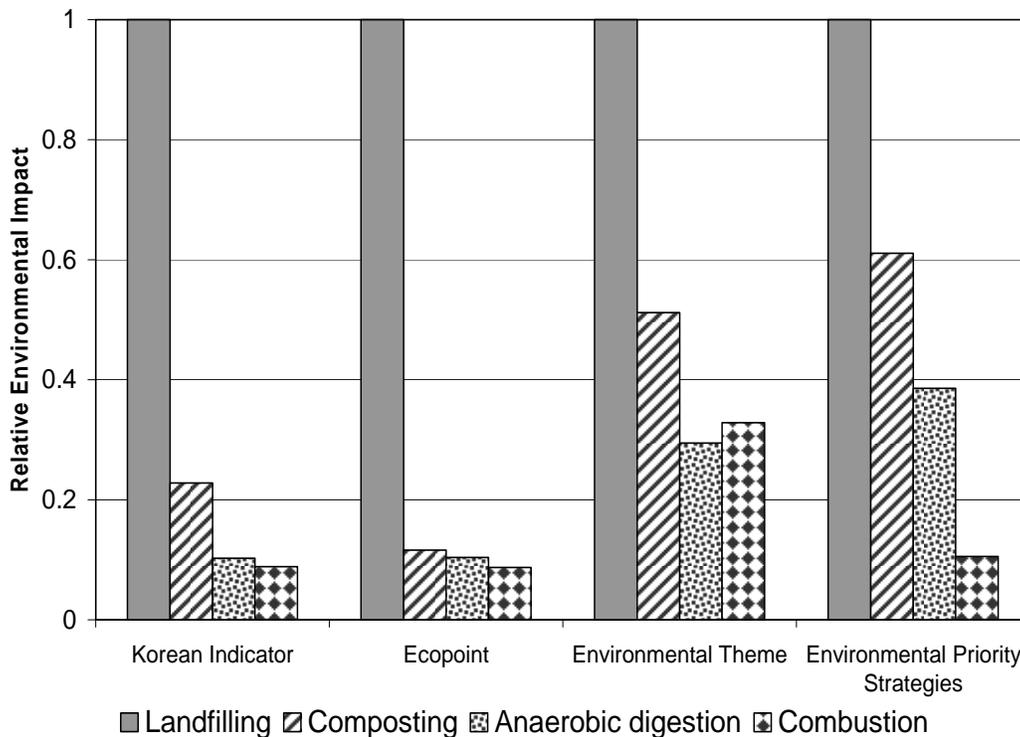
Two papers discussing lifecycle results for solid waste management scenarios were recently released. One study compared results from four lifecycle analysis methods for Korean mixed solid waste and practices with landfilling being the business as usual case.^v The other study

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compared several current European solid waste treatment practices using a single lifecycle methodology.^{vi} The functional unit of waste in the Korean study was one ton of the complete mixed MSW stream whereas the European study used 10,000 tons of source separated household and yard waste (biogenic fraction of solid waste). The European study did not consider landfilling untreated biogenic solid waste in the lifecycle study because landfilling is banned in many countries of the EU and will likely be banned through out the EU in the future.

For the study in Korea, landfilling (with no landfill gas recovery) has the highest life-cycle environmental impact whereas combustion and anaerobic digestion (both with energy recovery) had the lowest (Figure 22). Open composting consistently ranked second highest in lifecycle impacts.

Figure 22. LCA Methodologies Results - Solid Waste Management Scenarios in Korea (adapted from Seo, et al. (2004)).



Impacts are based on equal amounts of “standard” Korean solid waste treated in one of four ways: (1) dry-tomb landfill with no collection of landfill gas, (2) composting with stabilized residue sent to landfill, (3) anaerobic digestion with energy recovery and stabilized residue sent to landfill, and (4) combustion with energy recovery and residue landfilled.

In each case, landfilling had the highest negative environmental impact due largely to global warming contribution and water quality. Averaging the results from the four lifecycle methods, landfilling had three times the negative environmental impact as open composting. Recovery of landfill gas and energy production in the landfill scenario would reduce the negative impacts but would likely still be larger than the compost scenario.

In the Korean study, composting has high impacts due to the relatively large amount of energy required for the process, some emissions of VOCs and its effect on leachate after being landfilled. Using the compost in land application or soil amendment instead of putting in the landfill would likely reduce its overall impact.

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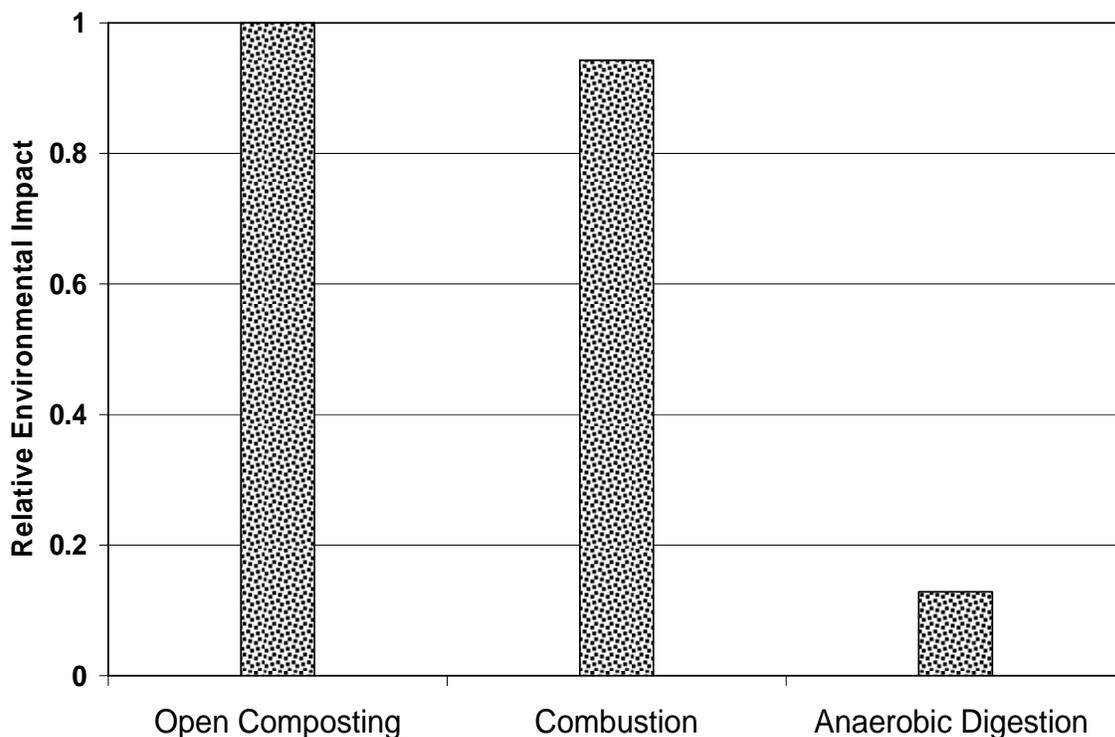
Combustion with energy recovery ranked lowest in environmental impact in three of the four methodologies. Anaerobic digestion with energy recovery and landfilling of the solid residue had very good overall environmental impacts in the study. It was ranked second lowest (in negative impacts) in three methods and lowest by one of the methods.

Caution should be used in generalizing these results for application in California. There are at least two important management practices that are likely to be used in California: landfill gas would be recovered and flared or converted to energy, and some or all composted material would not go to landfill.

The European study used operating data from full size commercial composting and anaerobic digestion facilities in Switzerland. The options evaluated included combustion with energy recovery, anaerobic digestion with energy recovery followed by aerobic stabilization of the digestate, and open composting with periodic windrow turning. The stabilized digestate and compost product were assumed to be land applied.

Figure 23 below shows the relative environmental impact of three treatment options for the biogenic portion of solid waste. Open composting and combustion were nearly equal in terms of environmental impact.

Figure 23. Relative Impact from Treatment Options for Biogenic Wastes for a Scenario in Europe



Landfilling untreated biogenic waste was not evaluated because it is generally no longer practiced in much of Europe.

Anaerobic digestion had the lowest life cycle impact. Because the stabilized solid residuals from the two biochemical treatment types (open composting and anaerobic digestion) were land applied, then the relative impacts of the three treatment methods in the European study are more applicable to comparing to California for source separated biogenic fraction of household and yard wastes.

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In 1998, the Center for the Analysis & Dissemination of Demonstrated Energy Technologies (CADDET)⁴ 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 municipal solid waste. 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.

Market Impact Assessment

AB 2770 requires the CIWMB’s report on conversion technology 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 entities that make decisions regarding disposition of these materials (for example, generators, jurisdictions, MRF operators, and haulers); the reasons for those decisions (for example, Integrated Waste Management Act regulatory mandates, political mandates, costs, and transportation distances); and 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 the conversion technology system configurations, quality, composition, and price of material needs in order to estimate what might occur to the recycling and composting industries if such conversion technology facilities were developed.

Methodology

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

Additionally, the contractor evaluated how these findings would change if the State adopted certain adjustments to State policy on allowing diversion credit for waste sent to conversion

⁴ The CADDET program was established in 1998 with an agreement with IEA to promote the international exchange of information on energy-efficient technologies. The program is supported by 10 counties including the United States.

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technology facilities. The study findings are based on the assumption that private sector decision-makers act to maximize profit, and that public sector decision-makers act to minimize cost with the additional responsibility of achieving Integrated Waste Management Act (IWMA) diversion mandates and operating sound solid waste management systems.

The RTI project team identified, reviewed, and compiled a vast amount of 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 CIWMB-sponsored University of California study of conversion technologies, and by information and modeling conducted by the National Renewable Energy Laboratory.

The main data analysis steps included:

- Characterizing the market place for potential conversion technology feedstock types, including mixed municipal solid waste; residuals from materials recovery facilities; 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 preparation required. This included estimating the amount of additional recycling likely to occur as a result of feedstock treatment at CT 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 materials recovery facility 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. A more detailed description of the financial model is included in Appendix ZZZ.

It should also be noted that 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 materials recovery facilities’ 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.

Research was conducted 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, data was gathered regarding the historical exports of paper and plastics and experts’ opinions regarding the future of export markets. Detailed information on historical and projected future prices, quantities, market forces affecting demand and pricing for the potential feedstocks, such as paper, plastic, organics, and material destined for landfilling can be found in Appendix AAA – Life Cycle and Market Impact Assessment of Noncombustion Waste Conversion Technologies.

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 United States 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, HFH allocated tonnage based on each region’s share of the U.S. population. As shown in Table 16, 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, it was 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 22: Estimates of Paper Recovered in Two Regions for Domestic Use

Area	Population	% 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 more significant force, impacting 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 17, 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 1998 to 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 the 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 17. Summary of Tons and Revenue from Export of Scrap Paper in the San Francisco Port Areas and Los Angeles Port Areas

Year	Tons (in 1,000)			Revenue (in \$1,000)			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 18, 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 18. Summary of Exports from the San Francisco Port Area and Los Angeles Port Areas Combined, by Paper Grade

Year	Recycled Paper Grades (1,000 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

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	Recycled Paper Grades (1,000 tons)						
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
% of Total	8%	28%	6%	7%	34%	17%	100%
Growth	-51%	28%	-40%	49%	300%	15%	61%

Plastics

Export data for plastics was not available to the same level as export data for scrap paper. Similar to 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, California’s Bottle Bill data 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 recycling in the San Francisco Bay Area study region.

According to the Plastics White Paper, *Optimizing Plastics Use, Recycling, and Disposal in California*, 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 *Waste News* in its March 15, 2004 issue, the amount of PET collected for recycling in the United States has held steady for several years at about 400,000 tons. 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. As with paper recycling, this export factor would have a far greater and less predictable or controllable effect on plastics recycling in California, compared to the conversion technologies proposed in this study.

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 which showed that 6 million tons statewide were processed. Table 19 shows survey results for 2001 and 2003

Table 19. Organics Collection Data

Year	Number of Facilities	Amount Processed
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

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for composting is its use as alternative daily cover (ADC). The use of ADC has grown by 46% from 2001 to 2003 and may be a larger market impact on compost facilities than would conversion facilities.

Another factor that may affect future markets for organics is the South Coast Air Quality Management District's Rule 1133. This rule has been established by the SCAQMD and requires monitoring and reduction of volatile organic compounds from compost facilities. More stringent requirements may be imposed in the future and compliance with these more stringent requirements could be very costly to compost producers with the ultimate consequence of driving them out of business or to locations outside of the air district.

Key Findings

One of the primary study objectives was to estimate impacts that the 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 findings presented herein. The following findings assume that the conversion technologies would 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 lifecycle/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 new recycling is related to conversion technology preprocessing operations. Certain materials, such as glass and metals, can reduce the efficiency of conversion technology operations and 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

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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 United States is exported for recycling.

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

Future recycling growth could be negatively impacted in the following way if recyclables were redirected to conversion technology facilities:

- a) If source-separated recyclables or green waste flowed to conversion technology facilities rather than recycling facilities.
- b) If waste streams that are currently untapped for recycling became unavailable to new recycling efforts in the future.
- c) If local jurisdictions eliminated recycling and green waste collection programs and redirected mixed waste to conversion technology facilities, however, this scenario seems unlikely given the enormous capital investment made by local jurisdictions and waste management companies.

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 affect 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.

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2. Sufficient refuse tonnage is available to fully utilize the capacity of the assumed hypothetical conversion technology scenario that 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, and there would be no need to lower conversion technology prices to attract green waste.

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 lifecycle and market impact assessment. During the workshop many stakeholders believed that analysis on the effect diversion credits for conversion technologies would have on existing recycling and compost markets should be conducted. 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.

The CIWMB adopted a policy allowing diversion credit if the following findings were made: (1) the jurisdiction continues to implement the recycling and diversion programs in the jurisdiction's source reduction and recycling element or its modified annual report; (2) the facility complements the existing recycling and diversion infrastructure and is converting solid waste that was previously disposed; (3) the facility maintains or enhances environmental benefits; and (4) the facility maintains or enhances the economic sustainability of the integrated waste management system." The policy also stated that jurisdictions that meet all of the above will be eligible for 10 percent diversion credit. The policy also required the CIWMB to annually evaluate the amount of diversion credit that can be claimed by a jurisdiction, on a case-by-case basis, that sends materials to that facility. Although this policy was passed by the CIWMB, there is no statutory authority given to the CIWMB for implementing this policy.

Finding #9: There would be no negative impact on existing recycling and compost markets 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 and 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 over 30 million tons of organic material still being landfilled there may be enough feedstock available for conversion technologies and for the future growth of recycling programs.

Finding #10: There will be a negative impact on recycling and composting if diversion credit was granted and local jurisdictions discontinued their traditional diversion programs.

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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. Over 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.

Conclusions

Based on the peer reviewed information from the *Evaluation of Conversion Technology Processes and Product* report prepared by UC Riverside, the *Life Cycle and Market Impact Assessment of Noncombustion Waste Conversion Technologies* prepared by RTI International and reports from other organizations, alternative thermochemical and biochemical conversion technologies may be technically viable options for the conversion of post recycled MSW and offer better solutions to landfilling and transformation. Thermochemical and biochemical conversion technologies possess unique characteristics which have varying potentials to reduce the amount of material that is ultimately landfilled.

Based on input from a number of stakeholders, it is concluded that existing statutory definitions should be amended. For example, the definition in “gasification” in Public Resources Code Section 40117 is scientifically inaccurate. Transformation” is defined Public Resources Code Section 40201 as “incineration, pyrolysis, distillation, or biological conversion other than composting, gasification, or biomass conversion.” This definition includes distillation and biological conversion which are low heat technologies. Distillation is a purification step for products such as alcohols and is carried out at temperatures dramatically below those for thermochemical technologies and transformation.

Anaerobic digestion can be considered both a biological conversion technology and a composting technology because the digestate is a compostable residue. As a biological conversion technology material sent to an anaerobic digestion facility would not qualify for diversion credit, however, as a composting technology material would qualify for diversion credit. For purposes of clarity, biological technologies should be removed from the transformation definition.

Data gaps do exist and it would be beneficial to conduct source testing where possible. The CIWMB should work with other Cal/EPA boards and departments to develop a research agenda for conversion technologies. AB 2770 provided an appropriation of \$1.5 million however the bulk of the funds were used for the lifecycle assessment, market impact assessment, and technology identification and assessment. Thorough testing of air emissions, solid, and liquid residues could not be done with the balance of the appropriation. These data gaps preclude the CIWMB from determining the public health impacts that each conversion technology would have. Some stakeholders have also expressed their desire for additional data before there is widespread support for certain types of conversion technologies. However it is difficult to acquire data without any operating conversion technology facilities in California.

While no one technology is suitable for all waste streams, no single waste management practice, be it landfilling, recycling, composting, or conversion can handle the full array of waste sources. Each can form part of an integrated waste management system which is based on the idea of an

overall approach for the management of waste streams, recyclable streams, treatment technologies, and markets.

When the waste management hierarchy was developed in 1989, conversion technologies using solid waste were still being analyzed and had not reached the mature state that exists today. This may suggest that the hierarchy may need to be revised to incorporate conversion technologies as part of an integrated waste management approach and evolve into an integrated *resource* management approach. The waste hierarchy in the European Union (EU) is similar to that in California. The EU Hierarchy declares waste prevention as the first priority, followed by recovery and finally by the safe disposal of waste. It differs in that ‘recovery’ includes re-use, recycling and extraction of materials and energy from solid waste. Article 3 of the Council Directive 75/442/EEC⁵ states the following:

“Article 3

1. Member States shall take appropriate steps to encourage the prevention, recycling and processing of waste, the extraction of raw materials and possibly of energy there from and any other process for the re-use of waste.”

Specific and Discrete Definitions

AB 2770 requires the CIWMB to include specific and discrete definitions of each conversion technology that was evaluated. The CIWMB has used a broad definition of conversion technology to mean any... A number of stakeholders have stated that the term “conversion technology” as currently defined is too broad and should be more specific. In addition, based on input from a number of stakeholders, it is concluded that existing statutory definitions should be amended. For example, the definition in gasification in Public Resources Code Section is scientifically inaccurate. Transformation” is defined Public Resources Code Section 40201 as “incineration, pyrolysis, distillation, or biological conversion other than composting, gasification, or biomass conversion.” This definition includes processes such as distillation and biological conversion which are low heat technologies. Distillation is a purification step for products such as alcohols and is carried out at temperatures dramatically below those for thermochemical technologies and transformation.

Anaerobic digestion can be considered both a biological conversion technology and a composting technology because the digestate is a compostable residue. As a biological conversion technology material sent to an anaerobic digestion facility would not qualify for diversion credit, however, as a composting technology material would qualify for diversion credit. For purposes of clarity, biological technologies should be removed from the transformation definition.

Specific definitions and suggested revisions to existing definitions are provided in the Recommendations section below.

Lifecycle Impacts

The legislative report required by AB 2770 must include a description and evaluation of the lifecycle environmental and public health impacts of each conversion technology in comparison to those environmental and public health impacts from the disposal and transformation of solid waste. Based on the results of the peer reviewed lifecycle analyses, conversion technologies have many advantages over landfilling, composting, transformation, and recycling such as:

- Greater potential for energy production.

⁵ Directive (75/442/EEC)

http://europa.eu.int/smartapi/cgi/sga_doc?smartapi!celexplus!prod!DocNumber&lg=en&type_doc=Directive&an_doc=1975&nu_doc=442

- Fewer emissions of NO_x.
- Fewer carbon emissions which is important from a global warming perspective.

With respect to SO_x, conversion technologies produce fewer emissions of SO_x when compared to landfilling but transformation produces fewer emissions of SO_x when compared to conversion technologies.

The main advantage that conversion technologies have over landfilling is the reduction of material that is landfilled and converted into a product that has a higher and better use such as electricity or alternative fuels. Another potential advantage with conversion technologies is the reduction of post-closure landfill maintenance and long-term liability.

The environmental risk of conversion technology facilities appears to be comparable with other common industrial practices provided the facilities are properly designed. However, the actual impacts of specific facilities will need to be evaluated on a “case-by case” basis as part of the local permitting process.

Market Impacts

The legislative report must also include a description and evaluation of the impacts on recycling and composting markets as a result of each conversion technology. Overall, conversion technologies will have a positive impact on recycling because of the potential for additional recyclables such as glass, metals, and some plastics entering the market stream from pre-processing of the feedstock. Future recycling growth could be negatively impacted in the following way if recyclables were redirected to conversion technology facilities:

- If source-separated recyclables or green waste flowed to conversion technology facilities rather than recycling facilities.
- If waste streams that are currently untapped for recycling became unavailable to new recycling efforts in the future.
- If local jurisdictions eliminated recycling and green waste collection programs and redirected mixed waste to conversion technology facilities, however, this scenario seems unlikely given the enormous capital investment made by local jurisdictions and waste management companies.

This scenario is unlikely to happen because of existing statutory requirements for local jurisdictions to achieve a 50 percent recycling goal and to maintain or expand their existing recycling programs. Additionally, if the CIWMB is given statutory authority to implement its policy regarding diversion credit, diversion programs will not be discontinued if local jurisdictions want diversion credit material sent to conversion technology facilities.

Conversion technologies may have the largest impact on the landfill market given that potential tipping fees for conversion technologies may be competitive with current landfill prices.

Cleanest, Least Polluting Technologies

AB 2770 requires the CIWMB to identify the cleanest, least polluting technologies. With limited data available it is difficult to identify the cleanest, least polluting technologies because each technology has environmental advantages and disadvantages. 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. However, there are greater concerns with emissions from this family of technologies.

Attachment 1

Biochemical technologies such as anaerobic digestion are viewed as less controversial because they operate at lower temperatures which reduce the potential for the production of dioxin/furans and heavy metal content in ash or air emissions. Anaerobic digestion technologies are also viewed more favorably since the process extracts some of the intrinsic heat value from the feedstock and the residue from the process may have some nutritive value and can be composted. The disadvantage of biochemical technologies is that these technologies can only process biodegradable materials and would contribute less to actual landfill diversion. However, the need for additional pre-processing of the feedstock can have a positive impact on recycling. Based on all available data, it appears that anaerobic digestion may be the cleanest and least polluting technology when compared to other conversion technologies.

Recommendations

Based on the analysis provided by the University of California, Riverside, National Renewable Energy Laboratory, and RTI, the following are recommendations for further action related to conversion technologies.

1. Change and clarify statutory definitions:

- a. The existing definition for “gasification” in Public Resources Code Section 40117 should be amended as follows to be more scientifically accurate:

“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.

This definition is a more appropriate description of gasification processes. Any reference to no discharges of air contaminants or emissions can be included as conditions in an air permit or solid waste facility permit.

- b. Delete the definition of “Transformation” in Public Resources Code 40201 and create a new definition for “Combustion” as follows:

“Combustion” means the thermal destruction, in an oxygen-rich environment, of solid waste for the generation of heat and subsequent energy production.

The current definition for transformation is intended to mean combustion; however, there are certain terms such as distillation, biological conversion, and pyrolysis that are not combustion technologies. Combustion and incineration differ in the sense that the goal of combustion is the production of heat and energy. The goal of incineration is simple volume reduction of the feedstock. Corresponding changes would need to be made in the Public Resources Code.

- c. Define “thermochemical conversion” and “biochemical conversion” in the Public Resources Code as follows:

“Thermochemical conversion” means the processing of solid waste using direct or indirect heating methods to produce fuel gases, synthetic gases, or liquid products as a primary product, and char, water and other condensibles as minor products.

Attachment 1

“Biochemical conversion” means the processing of solid waste using microorganisms or chemicals for the production of biogas, alternative chemicals, or alcohols as primary products and undegraded biomass as a secondary product.

2. Additional data should be collected on emissions from thermochemical and biochemical conversion technologies. The CIWMB should work with other Cal/EPA boards and departments to establish a research agenda. In particular, the CIWMB should work with the California Air Resources Board regarding emission control improvements and maximum/best available control technologies. The emissions studies should be conducted by an independent third-party and could include facilities at locations throughout the world. The emissions studies should include measurement of metals, dioxins and furans, other hazardous compounds, and fugitive gas and particulate matter emissions, in addition to criteria pollutants.
3. Conduct research on the impact of China on the demand for recycled materials. China’s demand for recycled materials is significant to California’s entire recycling infrastructure. This issue transcends the conversion technology issue and relates to all recycling markets including paper and plastic. A larger study should be conducted in consultation with the Department of Conservation to study the recyclable resource export market.
4. Diversion credit for biochemical technologies such as anaerobic digestion should be considered. If the CIWMB is granted statutory authority to allow diversion credit for conversion technologies, it should be granted only under the provisions in the CIWMB adopted-policy.

5.

Endnotes

ⁱ Brinton, W. F. (2000). "Compost quality standards & guidelines: An International View." New York State Association of Recyclers

ⁱⁱ Smet, E., Van Langenhove, H., and De Bo, I. (1999). "The emission of volatile compounds during the aerobic and the combined anaerobic/aerobic composting of biowaste." *Atmospheric Environment*, 33(8), 1295-1303.

ⁱⁱⁱ Weber, R., Sakurai, T., "Formation Characteristics of PCDD and PCDF during Pyrolysis Process," *Chemosphere*, Vol. 45. 2001, pp 1111-1117

^{iv} Brinton, W. F. (2000). "Compost quality standards & guidelines: An International View." New York State Association of Recyclers

^v Seo, S., Aramaki, T., Hwang, Y. W., and Hanaki, K. (2004). "Environmental impact of solid waste treatment methods in Korea." *Journal of Environmental Engineering-ASCE*, 130(1), 81-89.

^{vi} Edelman, W., Baier, U., and Engeli, H. (2004). "Environmental aspects of the anaerobic digestion of the organic fraction of municipal solid wastes and of agricultural wastes." 10th World Congress on Anaerobic Digestion. Montreal, Canada.