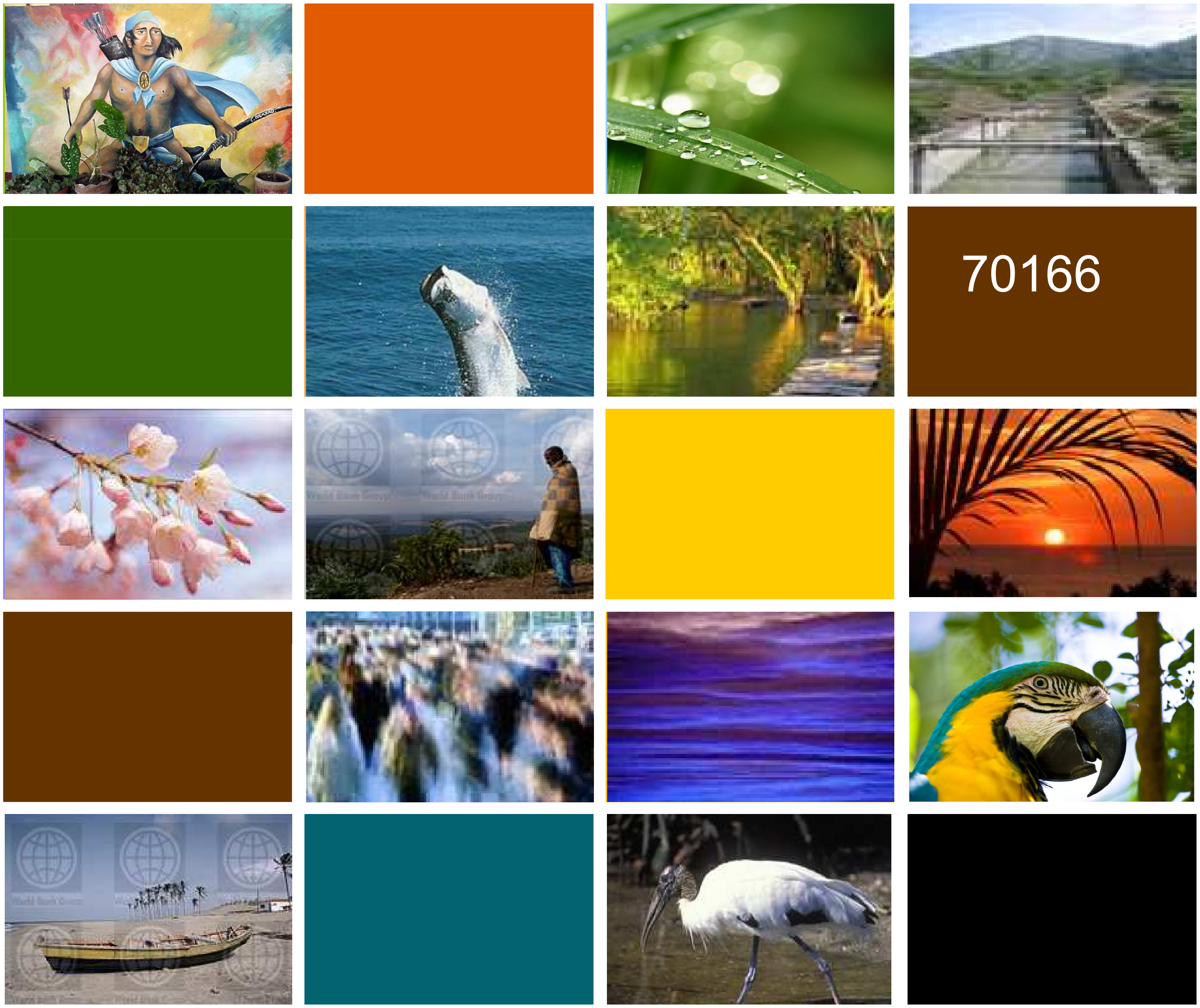

Report

Viability of Current and Emerging Technologies for Domestic Solid Waste Treatment and Disposal:

Implications on Dioxin and Furan Emissions

May 2011

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Prepared for:

The World Bank Washington, DC

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FINAL REPORT

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ERM Project: 0130996

World Bank Vendor ID Number: 125432

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EXECUTIVE SUMMARY

This study was undertaken to identify and assess the technologies available worldwide for treatment and disposal of municipal solid waste (MSW), and to make a general assessment of the applicability of these technologies to various waste management "settings" within the Latin American and Caribbean (LAC) Region. Each technology was evaluated for a number of key attributes, including demonstrated commercial viability, economics, institutional factors, sustainability metrics, and environmental attributes, including emissions of dioxins/furans. The study focused on the waste treatment technologies that have been commercially demonstrated worldwide; however, selected alternative and emerging technologies were also considered. After profiling the available waste management technologies, an assessment was then made of the general applicability of these technologies to various characteristic settings found within the LAC Region. Technology applicability assessment at *specific* locations within the LAC region would require detailed, site-specific evaluation. Such site-specific evaluations of applicable technologies would be the subject of subsequent studies.

Substantial progress in adopting modern waste management practices has been achieved in the largest cities of the LAC region, but waste management remains deficient outside of the major urban areas. Estimates vary, but approximately one-quarter to one-half of all the MSW generated in the LAC region is still being disposed in open dumps. Waste management throughout the LAC region can be improved by implementing modern techniques for waste minimization, recycling, resource recovery, and disposal that have been proven effective in many developed countries of the world. For MSW treatment and disposal, modern methods now exist that would enable Latin American countries to phase out open dumping and open burning of MSW, markedly reducing the associated environmental burdens, including dioxins and furans emissions. Potential technology alternatives include landfills of modern design, composting and anaerobic digestion, modern conventional waste-to-energy (WTE) technology, and advanced, non-burn technologies for energy recovery such as MSW gasification.

The specific technologies assessed in this study are:

Commercially Demonstrated Technologies:

- Modern sanitary landfill
- Combustion waste-to-energy (WTE)
- Gasification WTE
- Anaerobic digestion (AD)
- Composting using air only, and also using worms

Alternative Demonstrated Technology:

- Production of waste-derived-fuel (WDF) by the municipality, with offsite combustion of the WDF for energy recovery at an existing coal utility boiler, industrial boiler, or cement kiln

Emerging Technology:

- Gasification of MSW and conversion the resulting gas to liquid fuel products (e.g., ethanol, diesel fuel)

Each of these technologies is described in **Table 1**, along with summary information on available processing capacities and the extent of commercial deployment worldwide. The attributes for which each technology was evaluated are as follows:

- Technical
- Sustainability attributes
- Environmental attributes
- Economics - capital and operating costs
- Institutional attributes for each technology - operating complexity and public acceptance

Regarding the sustainability attributes above, the specific sustainability attributes considered included:

Resource Recovery - the recovery of energy (e.g., electricity, steam or hot water, liquid fuels) or beneficial materials (e.g., compost, construction aggregate, chemicals)

Waste Diversion from Landfill - the fraction of post-recycling MSW processed by the technology that is diverted from landfill disposal to beneficial use

Greenhouse Gas Emissions -the extent to which the technology causes a decrease or increase in the emissions of greenhouse gases

Land Resource Consumption - the relative amount of land area required to site and operate the technology

Water Use - the amount of fresh process water consumed in operating the technology

Regarding the environmental attributes above, the specific attributes considered were:

Air Pollutant Emissions, including combustion-related emissions, as well as emissions, specifically, of dioxins/furans and mercury. Dioxin/furan emissions resulting from MSW combustion became controversial in the 1980's; however, advanced emission controls have abated dioxin/furan emissions to minor levels. Mercury is present in MSW and is not destroyed by any of the technologies for MSW treatment and disposal. Accordingly, if not adequately controlled (removed) by the MSW processing or disposal technology, that mercury will enter the environment.

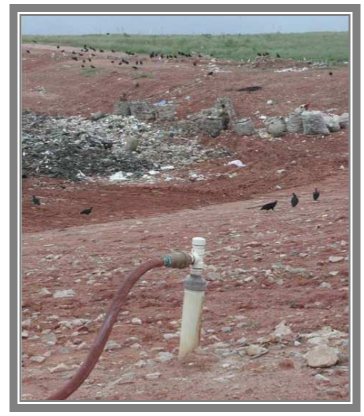
Odor Nuisance – the potential for the technology to cause odor nuisance offsite.

Solid Waste Generation - the amount of solid residue requiring landfilling that is produced by the technology.

Process Wastewater Discharge - the amount of process wastewater requiring discharge to the environment that is generated by the technology.

Storm Water Discharge – the potential for the technology to create contaminated storm water that could flow offsite into the environment.


Typical Modern Landfill
(Source: DSW via World Bank)


Landfill Gas Collection in Peru
(Source: World Bank)

In **Table 2**, the relative rankings for the technologies are summarized from favorable to unfavorable, against selected attributes described above. Clearly, no single technology dominates in the favorability rankings across all the various attributes. Landfills are favorable for costs, operating simplicity, and flexible range of operating capacities, but unfavorable for sustainability. Composting is favorable for costs, operating simplicity, materials recovery (compost), and environmental attributes, but unfavorable for potential odor impacts and its limitation to smaller operating capacities. Anaerobic digestion is favorable for the sustainability metric of materials recovery (compost), but is neither decidedly favorable nor unfavorable for most other attributes. Combustion waste-to-energy (WTE) and gasification WTE are favorable for the sustainability metrics of energy recovery and greenhouse gas abatement, as well as odor prevention, but unfavorable for costs, unavailability at small scale, operating complexity, and emissions to the air. Production of waste-derived fuel (WDF) has a similar favorability profile to combustion WTE, but is much more favorable for costs and operating complexity.

Not shown in **Table 2** is the emerging technology for conversion of MSW into liquid fuels such as ethanol or synthetic diesel. This is because waste-to-liquid fuel technology has not yet been implemented anywhere in the world at commercial scale. However, this emerging technology has its first, commercial scale facility in construction presently in Canada and commercial operation is expected within two years. If this technology becomes commercially established, it would provide a novel alternative to combustion WTE or gasification WTE by converting the MSW into a valuable energy product (liquid fuel), rather than converting the MSW to energy directly onsite. Production of such liquid fuels from MSW could be of interest in countries where petroleum is imported and expensive, or where cleaner-burning transportation fuels are desired.

Following evaluation of the technologies as summarized in **Table 2**, the technologies were then assessed for their general applicability to various waste management settings found within the LAC region. The waste management settings and their defining characteristics are summarized in **Table 3**. Those settings are intended to be representative and are not meant to include all waste management settings found within the LAC region.

Small WTE Facility in Martinique

MSW Gasification at Small Scale in U.K.

Source: Energos. Note that World Bank does not make commercial endorsements.

MSW Anaerobic Digester and Biogas Energy, Barcelona, Spain

Photo credit: L. Arsova

MSW Composting in the State of California, U.S.

Source: City of San Jose, California (U.S.), November 2008, Final Report - Appendix E: Conversion Technologies and Facilities for the Integrated Waste Management Zero Waste Strategic Plan Development, prepared by HDR Engineering, Inc.

For each of these characteristic, waste-management settings, the applicability of the various technologies for MSW treatment and disposal was assessed. Findings are summarized in **Table 4**, including the key reasons for a given technology being favorable or unfavorable for a particular waste setting. Composting of food waste and yard waste at varying scales of operation is the only technology that is favorable across all waste management settings. The applicability of all other technologies varies from setting to setting, as shown in the table. Finally, it is noted again that the assessments presented here of the applicability of the technologies to various waste management settings are general assessments. For any particular locale within the LAC Region, determination of the "best" technologies for that locale requires a case-specific evaluation.

For the assessments of waste management, technology attributes, and technology applicability summarized above, more detailed analyses are presented in the subsequent sections of this report:

- Background on waste management policy and practices
- Current waste management practices in Latin America
- Evaluation of technologies available for MSW treatment and disposal
- Technology applicability in Latin American settings
- Annexes providing in-depth profiles of each technology

Table 1: Technologies for MSW Treatment and Disposal

Technology	Description	Processing Capacity (Tons per Day)	Extent Commercially Demonstrated
Modern Sanitary Landfill	Liner beneath fill area to protect ground water; leachate collection and control; landfill gas collection and control; daily compaction of deposited MSW and covering with soil. Impervious cap installed at landfill closure.	50 to 10,000 TPD	The most extensive commercial experience worldwide, including in LAC
Thermal Processes (High Heat)			
Combustion Waste-to-Energy (WTE)	MSW is combusted at high temperature and energy is recovered (electricity or steam/hot water). Stringent controls on air emissions, including dioxins. Ash is landfilled or beneficially used, depending on facility design and national laws.	100 to 1,000 TPD, per module 5 TPD is smallest	Extensive commercial experience in North America, Europe, and Japan. None in Latin America. Limited in Caribbean.
Thermal Gasification	MSW is pre-processed, then gasified in the presence of limited oxygen. The resulting syngas is used as a fuel to generate energy (electricity or steam/hot water). Air pollutants are either removed from the syngas pre-combustion, or removed via control of the emissions from syngas combustion as a fuel. Ash/char residue is landfilled or beneficially used.	40 to 900 TPD, per module	Substantial commercial experience in Europe and Japan. None in the Americas to date.
Pyrolysis Gasification	MSW is pre-processed, placed in a closed vessel, then gasified in the absence of oxygen, by externally heating the vessel. The resulting pyrolysis gas is used as a fuel to generate energy (electricity or steam/hot water). Air pollutants are either removed from the gas pre-combustion, or removed via control of the emissions from gas combustion as a fuel. Char/tarry/oily residue is landfilled or beneficially used.	100 to 700 TPD, per module	Commercial experience in Europe and Japan. None in the Americas to date.

Technology	Description	Processing Capacity (Tons per Day)	Extent Commercially Demonstrated
Plasma Gasification	MSW is pre-processed, then gasified at extremely high temperature, using an electric arc. The resulting syngas is used as a fuel to generate energy (electricity or steam/hot water). Air pollutants are either removed from the syngas pre-combustion, or removed via control of the emissions from syngas combustion as a fuel. The slag residue is inert and is beneficially used.	200 to 500 TPD, per module	Limited commercial experience in Japan. None in the Americas or Europe to date.
Biological Processes			
Anaerobic Digestion (AD)	Yard waste, food waste, or mixed MSW is pre-processed and placed in a closed vessel, where it biologically degrades in the absence of oxygen. A methane-rich biogas is produced that is used as a fuel to generate energy (electricity or steam/hot water). The compost residue is marketed for land application. Reject material culled from the MSW during pre-processing is landfilled.	60 to 700 TPD, yard and food waste	Extensive commercial experience in Europe for digestion of organic components of MSW, and very limited experience in N. America; none in LAC. Only one known digestion facility for mixed MSW (Israel).
Composting	Yard waste, food waste, or mixed MSW is pre-processed, placed in rows, piles, or in a closed vessel, then allowed to biologically degrade in the presence of oxygen. The compost product is marketed. Reject material culled from the MSW during pre-processing is landfilled.	6 to 270 TPD, for both mixed MSW and for organic components	Substantial commercial experience in Europe. Experience varies in North America and LAC, depending on whether mixed MSW, yard waste, or food waste is composted.
Alternative Technology: Waste-Derived Fuel (WDF)	MSW is mechanically processed into a more uniform, waste-derived-fuel (WDF) under municipal auspices. Then, the WDF is trucked to an existing coal-fueled utility power plant, industrial boiler, or cement kiln, where it is converted to energy by a third party.	100 to 700 TPD	Commercial experience for decades in the U.S. and Europe
Emerging Technology: Waste-to-Liquid Fuels Conversion	MSW is pre-processed, then gasified. The resulting syngas is purified, then converted using a chemical process such as the catalytic Fischer-Tropsch process to liquid fuels (ethanol, butanol, synthetic diesel) or chemicals.	80 to 600 TPD	Emerging technology: No commercially operating facilities operating yet worldwide.

Table 2: Technology Comparisons for Operating Capacities, Economics, Sustainability, and Air Emissions

<table>
<tr><th rowspan="2">Technology Favorability</th><th colspan="2">Operating Capacity</th><th colspan="2">Costs</th><th colspan="4">Sustainability</th><th colspan="4">Air Pollutant Emissions</th></tr>
<tr><th>Large</th><th>Small</th><th>Capital</th><th>Operate</th><th>Energy Recovery</th><th>Material Recovery</th><th>Waste Diversion from Landfill</th><th>Greenhouse Gas Emissions</th><th>Odor</th><th>Combustion Emissions</th><th>Dioxin</th><th>Mercury</th></tr>
<tr><td>Most Favorable</td><td>Landfill</td><td>Compost</td><td>Compost</td><td>Compost
Landfill</td><td>Gasify
WTE
WDF</td><td>Compost
Ad</td><td>Gasify
WTE
WDF</td><td>Gasify
WTE
WDF</td><td>Gasify
WTE
WDF</td><td>Compost</td><td>Compost</td><td>Compost</td></tr>
<tr><td rowspan="3"></td><td>WTE
WDF</td><td>Landfill
Digest</td><td>Landfill</td><td>AD</td><td>AD</td><td rowspan="3">Gasify
WTE
WDF</td><td rowspan="3">AD
Compost</td><td>AD</td><td rowspan="3">AD
Compost</td><td rowspan="3">AD
Landfill</td><td rowspan="2">AD
Landfill</td><td>AD</td></tr>
<tr><td>Gasify</td><td>Gasify</td><td>WDF</td><td rowspan="2">WDF
WTE</td><td rowspan="2">Landfill</td><td rowspan="2">Compost</td><td>Landfill</td></tr>
<tr><td>AD</td><td>WDF</td><td>AD
WTE</td><td>Gasify</td><td>Gasify</td></tr>
<tr><td>Least Favorable</td><td>Compost</td><td>WTE</td><td>**Gasify**</td><td>**Gasify**</td><td>Compost</td><td>Landfill</td><td>Landfill</td><td>Landfill</td><td>Landfill</td><td>Gasify
WTE
WDF</td><td>WTE
WDF</td><td>WTE
WDF</td></tr>
</table>

Notes:
WTE = Combustion waste-to-energy (WTE); WDF = production of waste-derived fuel; Gasify = gasification WTE; AD = Anaerobic digestion; Compost = Composting.
The relative inter-comparison of technologies in this table is a general indication and could differ somewhat under case-specific conditions.

Table 3: Characteristic Waste Management Settings within the LAC Region

Largest Cities, **Higher Income** **(*Stronger* Municipal Investment Capacity)**	The largest-population cities, typically, capital cities Stronger municipal financial/investment capacity Higher per-capita incomes Higher cost of living Municipal waste collection Good road network
Smaller Cities, **Lower Income** **(*Limited* Municipal Investment Capacity)**	Small, medium, and some large cities More limited municipal financial/investment capacity Lower per-capita incomes Lower cost of living Municipal waste collection, but adequacy varies Adequacy of regional road network varies
Rural, **Low Income** **(*Little* Municipal Investment Capacity)**	Rural developed areas and very small cities Little municipal financial/investment capacity Low per-capita incomes Low cost of living Municipal waste collection unlikely Regional road network is limited
Land-Constrained **(Small Islands, Mountains)**	Regions with special land constraints Population density, municipal capacity, income levels, and road infrastructure varies with the locale.
Remote Areas **(Primitive Economy)**	Remote primitive areas, tribal Limited, if any centralized, local government Subsistence economy

Table 4: Matching MSW Technologies with Waste Management Settings within the LAC Region

Waste Management "Settings" in LAC	Engineered Sanitary Landfill	Controlled Landfill/Dump	Combustion WTE	WDF Production (Municipal) + Combustion WTE (by 3rd Party)	Gasification	Anaerobic Digestion	Composting
Largest Cities, Higher Income (Stronger Municipal Investment Capacity)	Very Favorable • Large Capacity • Lowest Cost	Unfavorable • Environmental burdens	Favorable, if: • Environmental benefits desired • Renewable energy needed • adequate investment capacity	Very Favorable • Large Capacity • Environmental and energy benefits • Low Cost ("Affordable" WTE)	Unfavorable, if public project due to technology risk • Acceptable, if private project • Large Capacity • Environmental and energy benefits	Acceptable, if: • Locally-generated energy needed • Combustion WTE strongly opposed	Very Favorable for food- and yard waste • Large capacity • Lowest Cost
Smaller Cities, Lower Income (Limited Municipal Investment Capacity)	Favorable • Large Capacity • Lowest Cost	Acceptable, as interim solution until investment capacity grows	Unfavorable, unless private project (limited municipal investment capacity)	Favorable • Large Capacity • Environmental and energy benefits • Low Cost ("Affordable" WTE)	Same as above	Unfavorable, unless private project (limited municipal investment capacity)	Very Favorable for food/yard waste • Large capacity • Lowest Cost
Rural, Low Income (Little Municipal Investment Capacity)	Unfavorable • Economics (limited investment capacity)	Acceptable, as best solution given a limited local investment capacity	Very Unfavorable, Insufficient amount of waste	Very Unfavorable, Insufficient amount of waste	Very Unfavorable, Insufficient amount of waste	Very Unfavorable, Insufficient amount of waste	Very Favorable for food/ yard waste • Small capacity feasible • Lowest Cost • Worm composting possible

Waste Management "Settings" in LAC	Engineered Sanitary Landfill	Controlled Landfill/Dump	Combustion WTE	WDF Production (Municipal) + Combustion WTE (by 3rd Party)	Gasification	Anaerobic Digestion	Composting
Land-Constrained (Small Islands, Mountains)	Unfavorable • Land constraints	Unfavorable • Land constraints	Favorable • Insufficient land for landfill • Power prices often high	Very Favorable • Large Capacity • Environmental and energy benefits Low Cost ("Affordable" WTE)	Unfavorable, if public project due to technology risk Acceptable, if private project • Large Capacity • Environmental and energy benefits	Acceptable, if: • Locally-generated energy needed • Combustion WTE strongly opposed	Very Favorable for food/yard waste • Large or small capacity • Lowest Cost
Remote Areas (Primitive Economy)	Composting of food waste and yard waste (back yard and small communal facilities). Small, communal, controlled dumps (no scavenging).						

Note: This table illustrates the general applicability of the technologies to various settings in the LAC Region. Actual applicability must be determined case-specifically for a particular location.

Definitions:

"Controlled Landfill/Dump" = Landfill with minimal environmental controls, where scavenging is controlled (prohibited).;

"WTE" = Combustion waste-to-energy (WTE)

"WDF Production + Combustion WTE (3rd Party)" = Convert waste to waste-derived fuel (WDA) under municipal auspices, then burn the WDF as a fuel for energy recovery at an existing coal power boiler, industrial boiler ,or cement kiln, owned by a private, third party.

1 TERMINOLOGY

A number of acronyms and specialized terms are used in this report, and these are defined below as an aid to the reader.

AD	Anaerobic Digestion
Biogenic	Biogenic material is organic material (i.e., material containing carbon) that was recently alive such as plant matter and animal tissue
Btu/lb	British Thermal Units of energy content per pound of fuel
$	U.S. Dollars
F-T	Fischer-Tropsch process for converting gas to liquid fuel
GHG	Greenhouse Gas
HHV	Higher Heating Value (measure of fuel heat content)
kW-h/ton	Kilowatt-hours of energy generated per short ton of MSW processed
LAC	Latin America and Caribbean
LFG	Landfill Gas
LHV	Lower Heating Value (measure of fuel heat content)
Mgy	Millions of gallons per year
MJ/kg	Mega-joules of energy content per kilogram of fuel
MRF	Materials Recovery Facility (also called a Materials Recycling Facility)
MSW	Municipal Solid Waste
Organic	Organic matter is any material that contains substantial amounts of carbon, including biogenic organic matter (defined above) as well as non-biogenic organic matter such as fossil fuels and petroleum-based plastics and rubber
RDF	Refuse Derived Fuel, known also as Waste Derived Fuel (WDF)
SSO	Source-Separated Organic Waste, such as yard waste and food waste
Syngas	Synthesis Gas, produced from high-temperature gasification of organic materials
TPD	Tons per Day (short tons)

TPY	Tons per Year (short tons)
WDF (RDF)	Waste Derived Fuel, known also as Refuse Derived Fuel
WTE	Waste-to-Energy

2 BACKGROUND ON WASTE MANAGEMENT POLICY AND PRACTICES

Modern waste-management policy follows a hierarchy of preferred waste management techniques. In descending order of preference, the solid waste management hierarchy entails the following waste management techniques and outcomes:

1. ***Waste prevention*** (e.g., reducing packaging of consumer goods, use of re-usable shopping bags, home composting of food and yard waste, de-constructing and reusing old electronics)
2. ***Recycling*** (recovery and re-use of recyclable materials)
3. ***Composting*** (of yard waste and food waste)
4. ***Resource Recovery*** (recovery of energy from post-recycling waste, or recovery of useful materials such as construction aggregate, fuels, or chemicals)
5. ***Disposal*** (landfilling of waste components that can not be reclaimed economically via recycling or resource recovery)

There is no single mix of these techniques that is universally "the right" mix. Rather, the optimum mix of these techniques will vary significantly, depending on many local factors. Determining the best mix of these techniques for a given locale is referred to as "integrated solid waste management." With regard to the waste management hierarchy, the present study focuses on waste treatment technologies for resource recovery as well as for waste disposal. The waste prevention and recycling components of the hierarchy are the subject matter of ongoing companion studies.

In ***developed*** countries of the world, the disposal of MSW in communal open piles ("garbage dumps"), as well as in backyard pits and metal drums, was the norm three to four decades ago. The communal open garbage dumps were often periodically burned and/or covered with earth, and backyard garbage pits and drums were regularly burned. Communal open garbage dumps created hazards to both human health and the environment. Open dumping attracted disease carriers such as rats and flies, exposed workers and scavenging trespassers to pathogens, caused fires, and caused water and air pollution. While the uncontrolled burning of both communal open garbage dumps and backyard garbage pits/drums reduces the volume of MSW, it also causes significant air pollution, including emissions of particulate matter and dioxins/furans. While developed countries have long abandoned communal open dumping in favor of engineered landfills and other modern MSW management options, burning garbage in backyard drums persists (illegally) in the rural areas of some developed countries, including the U.S. The poor combustion conditions characteristic of burn barrels/drums are ideal for formation of dioxins/furans. The US EPA has determined that illegal backyard burning of MSW is now the largest known emission source of dioxins/furans in the U.S.♦

In the ***developing*** countries of the world, both communal open dumping of MSW and backyard garbage pits/drums remain common. With the communal open dumps, "open" means that scavenging by trespassers is not prohibited or controlled. Increasingly, however, this has given way to "controlled dumps/landfills," where scavenging is prohibited. Engineered, modern landfills now serve the largest population centers in some developing countries.

As discussed subsequently in this report, substantial progress in adopting modern waste management practices has been achieved in the largest cities of the LAC region, but waste management remains deficient outside of the major urban areas. The majority of MSW generated in the LAC region is still being disposed in open dumps. Waste management throughout the LAC region can be improved by implementing modern techniques for waste minimization, recycling, resource recovery, and disposal that have been proven effective in many developed countries of the world. For MSW treatment and disposal, modern methods now exist that would enable Latin American countries to phase out open dumping and open burning of MSW, markedly reducing the associated environmental burdens, including dioxin emissions. Potential technology alternatives include landfills of modern design, composting and anaerobic digestion, modern conventional waste-to-energy (WTE) technology, and advanced, non-burn technologies for energy recovery such as MSW gasification.

♦US EPA, November 2006. "An Inventory of Sources and Environmental Releases of Dioxin-Like Compounds in the U.S. for the Years 1987, 1995, and 2000". http://cfpub.epa.gov/ncea/CFM/recordisplay.cfm?deid=159286.

3 CURRENT WASTE MANAGEMENT PRACTICES IN LATIN AMERICA

In general, waste generation rates per capita are greater for populous urban regions worldwide, especially in countries with higher incomes. This is true for the LAC region as well. Conversely, waste generation is lower for rural settings and in the urban regions where incomes are lower. Regarding the waste composition in developing countries, higher-income, major population centers tend to produce waste of a composition having similarities to waste in developed countries (more paper, plastics, and metals; less food waste). In the rural regions and in lower-income urban centers, the waste composition features a higher fraction of food waste, with less paper, plastics, and metals. Because of such differences in the waste composition, the waste produced in urban, high-income regions of LAC would have a moisture content that is much lower than with the waste produced in rural and low-income urban regions. The differences from region to region in waste generation rates and waste composition in Latin America have important implications for the types of waste management technologies that would be most suitable for a given region. Generally, the "wetter" waste is more efficiently treated using biological processes such as composting and anaerobic digestion, while the "drier" wastes are suitable for high-temperature processes that recover energy such as combustion waste-to-energy (WTE) and thermal gasification.

The current status of solid waste management in the Latin American and Caribbean Region (LAC) is briefly summarized here, as the backdrop for evaluation of waste management technologies and their applicability in the LAC Region. Summary information for the LAC region regarding relevant demographics and existing waste-management practices is as follows[♦]:

- LAC is highly urbanized: 78% of the 510 million population of the LAC Region lives in cities.
- There is substantial income disparity among LAC countries:
  - High income countries: US $22,000 per person per year
  - Low income countries: US $370 per person per year
- There is substantial disparity in the waste generation rate among LAC countries:

[♦] World Bank, August 2008. Solid Waste Management in LAC: Actual and Future CH4 Emissions, prepared by Catalina Ramirez.

- High income countries: 600 kg per person per year
- Low income countries: 200 kg per person per year

- Solid waste management in the LAC region is advancing, relative to many developing regions of the world, but substantial improvement is still required:
  - Municipal waste collection is good in largest cities, but still deficient elsewhere.
  - Recycling: Limited progress to date, but there is interest in improvement.
  - Disposal of waste generated in LAC region overall: 40%has disposal in known landfills or open dumps. However, the disposal locations are unknown for 60% of waste generated.
  - Disposal of ***collected*** waste in LAC region overall: 24% to modern sanitary landfills; 23%to controlled dumps (scavenging prohibited); 53% is disposed in open dumps or water courses. Very recent data (2010)[♦] indicates improvement, with 55% to modern sanitary landfills; 18% to controlled dumps; and 27% is disposed in open dumps or water courses.
  - Disposal of ***collected*** waste in the largest capital cities: 60% is disposed in modern sanitary landfills, 40% is still disposed in open dumps. Again, very recent data (2010)[♦]indicates improvement, with about 75% being disposed in modern sanitary landfills, and 25% is in open dumps.
  - Disposal of ***collected*** waste in smaller cities: most is disposed in open dumps.
  - Private: sector participation in waste management is growing.

In addition, in the present study, it was found that waste treatment technologies other than landfilling have yet to be applied in the LAC region, with few exceptions. Composting of food waste and yard waste is the exception, as composting is practiced in a number of Latin American countries. However, operating deficiencies are reported to be common, owing to lack of proper operator training. Anaerobic digestion of waste for energy recovery and compost production does not appear to have been undertaken as yet in the LAC region. Traditional waste-to-energy (WTE),

[♦] AIDIS, 2010. "Evaluation of Municipal Solid Waste Management Services in Latin America and the Caribbean for year 2010" (www6.iadb.org/Residuos). This evaluation was a joint effort coordinated by the Inter-American Association of Sanitary and Environmental Engineering (AIDIS for its Spanish acronym) and supported by the Inter American Development Bank.

wherein the waste is combusted and energy is recovered, has not been applied in Latin America, but small facilities do operate on two Caribbean islands. Thermal gasification, which is advanced technology for recovering energy from waste, has not been deployed as yet in the LAC region.

To summarize, substantial progress in adopting modern waste management practices has been achieved in the largest cities of the LAC region, but waste management remains deficient outside of the major urban areas. In the largest cities, municipal waste collection is reliable and 60%of the waste collected is disposed in modern sanitary landfills. Modest recycling programs have started, as well as a limited number of composting programs. Outside the large cities, however, open dumping still predominates and for 60%of all waste generated within the LAC region, the disposal fate is unknown. Achieving rapid progress in improving MSW management in the LAC region will require more pervasive implementation of: (1) MSW collection infrastructure, and;(2) the modern technologies available worldwide for treatment and disposal of municipal solid waste (MSW). The present study assesses the available technologies and evaluates their applicability to various settings within the LAC region.

4 EVALUATION OF TECHNOLOGIES AVAILABLE FOR WASTE TREATMENT AND DISPOSAL

4.1 TREATMENT TECHNOLOGIES, OPERATING CAPACITIES, AND COMMERCIAL EXPERIENCE

The technologies for treatment and disposal of post-recycling MSW that were assessed in this study were presented in **Table 1**. In that table, each technology was described, the available processing capacities were given, and the extent of commercial experience worldwide was summarized. This information is presented in greater depth for each technology in the technology-specific Annexes appended to the report, and references are supplied there for the factual information presented here.

From the table, clearly, modern sanitary landfills are the technology that has the most extensive commercial deployment worldwide, including in the LAC region. Sanitary landfills are also the technology available in the greatest range of processing capacities. Combustion waste-to-energy (WTE) also has an extensive commercial track record in Europe, Japan, and North American, but not yet in Latin America. WTE is also available in a wide range of processing capacities, but generally not in capacities as small as available for landfills. Thermal gasification of MSW for energy recovery, an advanced non-burn technology, has substantial commercial operating experience in Europe and Japan, but not yet in the Americas. The range of processing capacities available for gasification technology is similar to that of combustion WTE. There has been extensive commercial operating experience in Europe with anaerobic digestion (AD) of the organic components of MSW such as yard and food waste; little experience in North America; and no known commercial experience in Latin America. Experience with AD for mixed MSW is minimal worldwide. The range of processing capacities available for AD is approximately similar to that of WTE and gasification. There is substantial experience in Europe for composting of both mixed MSW as well as organic components. There is significant experience in North America and Latin America with composting of food waste and yard waste. Composting technologies are available at advantageously-small capacities relative to the other waste treatment technologies, while still ranging to moderately-large capacity. Production of waste-derived-fuel (WDF) under municipal auspices, with combustion of the WDF to recover energy at existing third-party facilities, has a multi-decade commercial record in Europe and the U.S. WDF technology is available in capacities similar to WTE. Finally, there is an emerging technology, that while not yet demonstrated commercially, is likely to have its first commercial facilities operating within two years in North America. That technology is the conversion of MSW to liquid transportation fuels or chemicals. The technology is being offered in processing capacities similar to those of small- to medium-sized WTE units.

4.2 SUSTAINABILITY ATTRIBUTES OF THE TECHNOLOGIES

The technologies for treatment and disposal of post-recycling MSW were assessed for their sustainability attributes, including the following:

Resource Recovery - the recovery of energy (e.g., electricity, steam or hot water, liquid fuels) or beneficial materials (e.g., compost, construction aggregate, chemicals)

Waste Diversion from Landfill - the fraction of post-recycling MSW processed by the technology that is diverted from landfill disposal to beneficial use

Greenhouse Gas Emissions - the extent to which the technology causes a decrease or increase in the emissions of greenhouse gases

Land Resource Consumption - the relative amount of land area required to site and operate the technology

Water Use - the amount of fresh process water consumed in operating the technology

Detailed assessments of sustainability are presented for each technology in the Annexes to this report and a summary compilation is presented here in **Table 5**. Key points follow:

4.2.1 *Energy Recovery*

Energy recovery is expressed in **Table 2** in units of kilowatt-hours of energy produced by the technology from each ton of MSW processed (kWh/ton). With regard to recovering energy, the greatest energy recovery is achieved by the high-heat processes: combustion WTE, production of waste-derived-fuel (WDF) with subsequent WDF combustion offsite to recover energy, gasification WTE, and also the technology that converts MSW to liquid fuels. These high-heat processes are most favorable for energy recovery because their high heat liberates the energy content from all constituents of MSW, except for inert components such as glass and metals. Anaerobic digestion (AD), which produces methane gas (biogas), also recovers energy when the biogas is combusted as a fuel. The energy recovery with AD, however, is less than with the high-heat processes because AD acts only on the readily biodegradable components of MSW such as food waste and paper, and does not convert the remaining components of the MSW (e.g., plastics, rubber) into energy. Landfills produce landfill gas (a biogas) when the organic components of MSW biodegrade within the landfill. The biodegradation process is similar to that occurring with AD technology, but is less efficient. Accordingly, although landfill gas is commonly used as a fuel to generate electric energy, the energy recovery is less than with AD. Composting technology is least favorable from the singular standpoint of energy recovery, as the technology does not recover energy.

4.2.2 Materials Recovery

From the standpoint of materials recovery for beneficial use, composting and AD are most favorable, as they produce significant amounts of a compost product that is marketed as a soil amendment or fertilizer. The technology for conversion of MSW to liquid fuels is also most favorable for materials recovery, as it produces a valuable transportation fuel, which represents both energy recovery and materials recovery (a liquid fuel product). With combustion WTE and gasification WTE, the solid residue from the process (ash, slag) can sometimes be recovered for beneficial use, for example, as construction aggregate. This represents a modest amount of materials recovery. Often, however, the residue is simply landfilled and there is no associated materials recovery.

Table 5: Sustainability Profiles for MSW Treatment and Disposal Technologies

Technology	Resource Recovery		Waste Diversion from Landfill	Greenhouse Gas	Land Resource Consumption	Water Use
	Energy Recovery	Materials Recovery				
Modern Sanitary Landfill	Favorable (40 – 80 kWh/ton)	Unfavorable (No recovery)	Unfavorable	Unfavorable	Very Unfavorable	Very Favorable
Combustion Waste-to-Energy (WTE)	Very Favorable (~ 600 kWh/ton)	Unfavorable to Somewhat Favorable, depending on whether ash is beneficially used or landfilled.	Very Favorable (75% to 90%)	Very Favorable	Favorable	Unfavorable
Gasification WTE	Very Favorable (400 – 700 kWh/ton)	Unfavorable to Somewhat Favorable, depending on whether ash is beneficially used or landfilled.	Very Favorable (72% to 99%)	Very Favorable	Favorable	Varies from Unfavorable to Favorable
Anaerobic Digestion (AD)	Favorable (100 – 245 kWh/ton)	Favorable (Compost product)	Favorable (60% to 75%)	Favorable	Somewhat Unfavorable	Varies from Favorable to Unfavorable
Composting	Unfavorable (no energy recovery)	Favorable (Compost product)	Favorable (60% to 75%)	Somewhat Favorable, but depends on which waste components are composted	Somewhat Unfavorable	Very Favorable
Alternative Technology : **Waste-Derived Fuel (WDF)**	Very Favorable (> 600 kWh/ton)	Unfavorable to Somewhat Favorable, depending on whether ash is beneficially used or landfilled.	Very Favorable (75% to 90%)	Very Favorable	Very Favorable	Very Favorable
Emerging Technology: **Waste-to-Liquid Fuels Conversion**	Very Favorable (Energy in form of liquid fuel)	Very Favorable (Liquid Fuels, an energy product)	Very Favorable (75% to 90%)	Very Favorable	Favorable	Favorable to Very Favorable

4.2.3 *Waste Diversion from Landfill*

With regard to waste diversion from landfill, the most favorable technologies are again the high-heat processes: combustion WTE, production of waste-derived-fuel (WDF) with subsequent WDF combustion offsite to recover energy, gasification WTE, and finally, the technology that converts MSW to liquid fuels. These technologies divert all MSW processed from landfilling, except for the solid residue (ash, char, slag) that is landfilled. Depending on solid residue disposition, these technologies divert 70% to 99% of the MSW from landfill. AD and composting provide lesser diversion from landfill at 60% to 75%, as those processes typically generate significant quantities of reject material that is landfilled. With landfill technology, there is inherently no waste diversion since landfills are the final repository for those waste materials that have no beneficial use or value.

4.2.4 *Greenhouse Gas Emissions*

Landfilling is the least favorable technology from the standpoint of greenhouse gas emissions. While landfill gas is collected and controlled at modern landfills, the collection systems are not 100% efficient. Typically, 20% to 30% of the landfill gas generated by a landfill escapes collection and is emitted. That represents a globally-significant emission of methane greenhouse gas. For reducing greenhouse gas emissions, the most favorable technologies are, again, the high-heat processes: combustion WTE, production of waste-derived-fuel (WDF) with subsequent WDF combustion offsite to recover energy, gasification WTE, and finally, the technology that converts MSW to liquid fuels. This is because these technologies (1) divert the greatest amount of MSW from landfills, reducing landfill emissions of methane and (2) recover the most renewable energy, displacing existing fossil-fuel energy generation. AD is also favorable for reducing greenhouse gas emissions for the same reasons, but does not recover as much energy for displacing fossil-fuel energy generation. Experts consider the greenhouse gas profile for MSW composting to be uncertain at present. Composting does not produce energy, renewable or otherwise, so does not offer that greenhouse gas advantage. But composting does divert waste from landfills, which reduces landfill emissions of methane greenhouse gas. Specifically, it appears that composting does reduce greenhouse gas emissions for composting of food waste, compared with landfilling of food waste, but the comparison is uncertain for composting of other components of MSW such as woody yard waste.

4.2.5 *Land Resource Consumption*

The least favorable technology with regard to minimizing land use is landfilling, as landfilling requires the most land area of all the technologies and that land remains unavailable for other future uses for a century or longer. Most favorable in minimizing land needs is the production of WDF with subsequent combustion of the WDF offsite for energy recovery. This is because new land development is needed only for the WDF production facility; the WDF is taken to an existing power plant or cement kiln for conversion to energy (hence, energy recovery requires no new land development). Combustion WTE, gasification WTE, and waste conversion to liquid fuels are also favorable, but require new land development for energy generation equipment. AD and composting technologies require more land than the high-heat technologies, but less than needed for landfills. Both AD and composting normally require significant land area for piling the waste in rows or piles for processing, but again, much less land area than needed for landfills.

4.2.6 *Water Use*

Landfills and composting are most favorable from the standpoint of water consumption, as those technologies typically do not require process water. AD can also be favorable, as AD typically requires relatively small water input. Also favorable is the technology for conversion of MSW to liquid fuels, which can be a net producer of water. Some gasification WTE processes are also net producers of water. Production of WDF is also very favorable as it consumes no water. The power plant offsite where energy is recovered from combustion of the WDF does have a substantial water requirement, but this is not a new water requirement since the facility is an existing one. Least favorable are combustion WTE and some types of gasification WTE that require significant quantities of water for boiler steam production and boiler cooling during energy recovery.

4.3 *ENVIRONMENTAL ATTRIBUTES OF THE TECHNOLOGIES*

The technologies for treatment and disposal of post-recycling MSW were assessed for their environmental attributes, including the following:

Air Pollutant Emissions - including combustion-related emissions, as well as emissions, specifically, of dioxins/furans and mercury. Dioxin/furan emissions resulting from MSW combustion became controversial in the 1980’s; however, advanced emission controls have abated dioxin/furan emissions to minor levels. Mercury is present in MSW and is not destroyed by any of the technologies for MSW treatment and disposal. Accordingly, if not adequately controlled (removed) by the MSW processing or disposal technology, that mercury will enter the environment.

Odor Nuisance - the potential for the technology to cause odor nuisance offsite.

Solid Waste Generation - the amount of solid residue requiring landfilling that is produced by the technology.

Process Wastewater Discharge - the amount of process wastewater requiring discharge to the environment that is generated by the technology

Storm Water Discharge - the potential for the technology to create contaminated storm water that could flow offsite into the environment.

Detailed environmental assessments for each technology are included in the Annexes to this report and a summary is presented here in **Table 6**. Key points are summarized in the subsections that follow:

Table 6: Environmental Profiles for MSW Treatment and Disposal Technologies

Technology	Air Pollutant Emissions	Dioxin Emissions	Mercury Emissions	Odor Nuisance	Solid Waste Generation	Wastewater Discharge	Storm Water Discharge
Modern Sanitary Landfill	Somewhat Unfavorable (Minor Emission from landfill gas combustion)	Very Favorable (Trace Emission from landfill gas combustion)	Unknown; potentially Somewhat Favorable to Unfavorable (Emission is uncontrolled and uncertain)	Unfavorable	Very Unfavorable	Very Unfavorable (Leachate)	Unfavorable (Landfill runoff)
Combustion Waste-to-Energy (WTE)	Unfavorable (Controlled Emissions)	Somewhat Favorable (Minor Emissions)	Somewhat Favorable (Minor Emissions)	Very Favorable	Somewhat Favorable to Favorable	Unfavorable to Favorable, depending on wastewater disposition	Very Favorable (Enclosed process)
Gasification WTE	Somewhat Unfavorable to Unfavorable (Controlled Emissions)	Somewhat Favorable to Favorable (Emissions are Trace to Minor)	Somewhat Favorable (Minor Emissions)	Very Favorable	Somewhat Favorable to Favorable	Unfavorable to Favorable, depending on type of energy equipment	Very Favorable (Enclosed process)
Anaerobic Digestion (AD)	Somewhat Unfavorable (Minor Emission from biogas combustion)	Very Favorable (Trace Emission from biogas combustion)	Most Favorable for food and yard waste digestion (No emission)	Potentially Unfavorable	Somewhat Favorable	Favorable to Unfavorable, depending on type of AD process, Dry or Wet	Favorable, if indoors. Potentially Unfavorable, if outdoor curing of compost
Composting	Most Favorable (No Emission)	Most Favorable (No Emission)	Most Favorable for food and yard waste composting (No emission)	Potentially Unfavorable	Somewhat Favorable	Very Favorable (No wastewater)	Potentially Unfavorable, unless indoors composting

Technology	Air Pollutant Emissions	Dioxin Emissions	Mercury Emissions	Odor Nuisance	Solid Waste Generation	Wastewater Discharge	Storm Water Discharge
***Alternative Technology* Waste-Derived Fuel (WDF)**	Unfavorable (Controlled Emissions from offsite WDF combustion)	Somewhat Favorable (Minor Emissions from offsite WDF combustion)	Somewhat Favorable (Minor Emissions)	Very Favorable	Somewhat Favorable to Favorable	Favorable, no new discharge	Very Favorable (Enclosed process)
***Emerging Technology:* Waste-to-Liquid Fuels Conversion**	Favorable for emissions onsite (Trace to Minor Emissions) Unfavorable for emissions offsite (Emissions from vehicle engines)	Very Favorable (Trace Emissions from vehicle engine offsite)	Somewhat Favorable (Minor Emissions)	Very Favorable	Somewhat Favorable to Favorable	Unfavorable to Favorable, depending on wastewater disposition	Very Favorable (Enclosed process)

4.3.1 *Air Pollutant Emissions*

From the standpoint of combustion-related emissions, the most favorable technology is composting, which does not involve combustion. The least favorable technologies are combustion WTE, as well a WDF production with offsite combustion. Those technologies entail combustion of a solid fuel (MSW), which generally results in greater emissions of combustion-related air pollutants than combustion of a gaseous fuel, as occurs with gasification WTE, or combustion of liquid fuels, as occurs with combustion by vehicle engines of liquid fuels produced from MSW. With AD and with landfill gas, energy recovery also entails combustion of a gaseous fuel, so emissions are less than with combustion WTE.

4.3.2 *Emissions of Dioxins and Furans*

Composting has the most favorable profile for dioxin, as composting does not involve combustion, as is required for dioxin formation. Combustion WTE is least favorable from the standpoint of dioxin emission. Although combustion WTE has the highest dioxin emissions of all the technologies, the emissions are well-controlled to minor levels. This dioxin profile also applies to WDF production with subsequent WDF combustion offsite for energy recovery. The technologies that combust a gaseous fuel would normally have lower dioxin emissions, including gasification WTE and AD. Lower dioxin emissions would also be expected with combustion by vehicle engines of liquid fuel derived from MSW.

4.3.3 *Emissions of Mercury*

With regard to potential emissions of mercury to the air, the least favorable technologies are the high-heat processes: combustion WTE, production of waste-derived-fuel (WDF) with subsequent WDF combustion offsite to recover energy, gasification WTE, and finally, the technology that converts MSW to liquid fuels. The high-heat processes by their nature volatilize all the mercury present in the MSW and that mercury, unless stringently controlled, would be emitted to the atmosphere. The emission controls widely used today are very effective in reducing the mercury emissions from these technologies to minor levels. The most favorable technologies for mercury emissions are composting and AD, where the feedstock is source-separated food waste or yard waste. This is because those feedstocks are not contaminated with mercury. Importantly, when mixed MSW is composted, anaerobically digested (AD), or landfilled, the fate of the mercury present in the MSW is presently uncertain. Mercury emission controls are not applied to those technologies. Composting, AD, and landfills all biodegrade mixed MSW at low temperature and this would imply less potential for the mercury present in the MSW to volatilize. However, recent research indicates that mercury emissions to the air from landfills may be significant. With regard to composting and AD, it remains uncertain regarding the extent of mercury emissions to the air, and also the extent to which mercury may contaminate the compost product resulting from those technologies.

4.3.4 Odor Nuisance

With regard to the potential for offsite odor nuisance, the least favorable technology is landfilling. Landfilling is an open process, and MSW handling and landfill gas emissions at a landfill are very odorous and often cause odor nuisance in the immediate vicinity of the landfill. That odor nuisance potential can be mitigated by proper landfill operations, but can not eliminated. Composting and AD can also cause offsite odor nuisance, as the compost material produced by both technologies is often managed in rows or piles that are open to the air. AD processes of the batch type also release odors when the digestions vessel is periodically opened. With composting and AD, proper operations can reduce the potential for odorous emissions; however, the most effective odor mitigation measure is to establish a large buffer distance to the nearest sensitive land uses. The most favorable technologies for odor prevention are the high-heat processes: combustion WTE, production of waste-derived-fuel (WDF) with subsequent WDF combustion offsite to recover energy, gasification WTE, and finally, the technology that converts MSW to liquid fuels. This is because those processes are totally enclosed and they apply effective odor controls to interior ventilation air.

4.3.5 Solid Waste Generation

The MSW technologies that generate the least solid residue requiring disposal are the high-heat processes: combustion WTE, production of waste-derived-fuel (WDF) with subsequent WDF combustion offsite to recover energy, gasification WTE, and finally, the technology that converts MSW to liquid fuels. The disposable solid residue generated by these technologies (ash, char, slag) is 1% to 30% of the weight of the MSW input for processing. AD and composting are less favorable, as 25% to 40% of the weight of the input MSW ends up as reject material that requires disposal. With landfill technology, all the input MSW is deposited as solid waste, as landfills are the final repository for those waste materials that have no beneficial use or value.

4.3.6 *Wastewater Discharge*

Most favorable from the standpoint of wastewater discharge is composting, as it uses no process water and has no wastewater discharge. "Dry"AD processes are also advantageous as they would have only a limited wastewater discharge. "Wet" AD processes are less favorable, because they have the potential to generate significant quantities of wastewater that requires treatment prior to discharge into the environment.

The wastewater profile can range from advantageous to disadvantageous for the high-heat processes: combustion WTE, production of waste-derived-fuel (WDF) with subsequent WDF combustion offsite to recover energy, gasification WTE, and finally, the technology that converts MSW to liquid fuels. Most of those technologies generate varying amounts of wastewater that is boiler-related, gasifier-related, or from the air pollution control equipment. While there is often a substantial wastewater generation with these technologies, there is normally significant effort made to recycle and re-use spent process water, which reduces the amount that is discharged to the environment. Some combustion WTE facilities use the wastewater for ash moistening and are "zero discharge" for process wastewater. Least favorable from the standpoint of wastewater discharge is landfilling, as normally, there are significant quantities of contaminated leachate that must be treated and discharged to the environment.

4.3.7 *Storm Water Discharge*

The MSW technologies most favorable with regard to storm water discharge are the high-heat processes: combustion WTE, production of waste-derived-fuel (WDF) with subsequent WDF combustion offsite to recover energy, gasification WTE, and finally, the technology that converts MSW to liquid fuels. This is because those processes are entirely enclosed and rain fall never contacts the MSW or process residues (ash, char). Both composting and AD can be unfavorable for storm water discharge, as there is potential for contaminated storm-water runoff into the environment, when the compost material is managed in rows or piles outdoors. Composting and AD can be favorable for storm water discharge, however, if conducted entirely indoors or under roof. Landfills are unfavorable for storm water discharge as there is a significant potential for contamination of storm water by MSW and leachate leaks.

4.4 MSW TECHNOLOGY ECONOMICS AND INSTITUTIONAL FACTORS

The technologies for treatment and disposal of post-recycling MSW were assessed with regard to economics, including capital costs and operating costs. In addition, the technologies were assessed with regard to two institutional factors, the operating complexity of a technology and the technology's history of public acceptance. Detailed assessments of these economic and institutional factors for each technology are included in the Annexes to this report and a summary is presented here in **Table 7**. Some key points are presented below with regard to economics and the institutional factors.

4.4.1 Economics

Information developed on capital costs and operating costs was based on typical costs for these technologies when deployed in developed countries. Generally, the technology capital cost would be relatively similar in both developed and developing countries; however, labor costs, and hence operating costs, could be much lower in developing countries, especially for the less-complex technologies such as landfilling, composting, anaerobic digestion (AD), and the production of waste-derived-fuel (WDF). Technologies such as combustion waste-to-energy (WTE), gasification WTE, and the conversion of MSW to liquid fuels are highly-complex technologies, requiring very-skilled, highly trained specialists for proper operation. Accordingly, the operating costs for those technologies in developing countries could approach the operating costs in developing countries. Key points follow:

4.4.1.1 Capital Costs

Capital costs are expressed in two ways in the table. First, a "Unit Capital Cost" is given in units of dollars per ton. This is defined as the capital cost in US dollars per annual ton (short ton) of MSW processing capacity. This enables inter-comparison of the technologies for capital cost per ton of waste processed.

Table 7: MSW Technology Economics and Institutional Factors

Technology	Typical Annual Processing Capacity (Tons per Year)	Capital Costs		Operating Cost ($/Ton)	Institutional Factors	
		Unit Cost ($/Annual Ton)	Total Outlay ($)		Operating Complexity	Public Acceptance
Modern Sanitary Landfill	17,000 to 1,650,000	$5 to $30	~ $1,000,000 to $50,000,000	$10 to $30	Low	Opposed by abutting neighbors, but acceptable otherwise
Combustion Waste-to-Energy (WTE)	33,000 to 660,000	$450 to $750	$15,000,000 to $495,000,000	$40 to $50	High	Acceptable generally, but strong opposition in some settings
Gasification WTE	13,000 to 297,000	$485 to $970	$6,000,000 to $288,000,000	~ $50+	High to Very High	Acceptable generally, but strong opposition in some settings
Anaerobic Digestion (AD)	19,000 to 240,000	$200 - $600	$3,800,000 to $144,000,000	$20 to $50	High	Favorable, unless odor nuisance develops
Composting	2,000 to 89,000	$200 to $300	$400,000 to $27,000,000	$20 to $50	Low to Moderate	Favorable, unless odor nuisance develops
Alternative Technology : **Waste-Derived Fuel (WDF)**	33,000 to 231,000	~ $120	$4,000,000 to $28,000,000	~ $50	Moderate to High	Favorable; entails no combustion onsite
Emerging Technology: **Waste-to-Liquid Fuels Conversion**	26,000 to 198,000	Costs are unknown since there are no commercial facilities as yet. Costs are estimated to be approximately similar to Gasification WTE, above.			Very High	Favorable; advanced, non-burn technology

Note: Tons are short tons. All costs are in U.S. dollars and reflect typical costs for facility construction and operation in developed countries.

While comparing the technologies for capital cost on a unit basis is instructive, this provides only part of the information needed for assessing capital costs. One must also consider the total capital outlay required to implement a given technology. That is, the total capital outlay is determined by two factors: (1) the unit capital costs and (2) the range of operating capacities for a given technology. To enable assessment of total capital outlay, the typical range of operating capacities is given in the table for each technology in units of tons of MSW processed per year.

The following points are apparent from comparing capital costs for the technologies, as presented in the table:

- Clearly, for capital costs on a unit basis, the technologies with the highest capital costs are the high-temperature technologies: combustion WTE, gasification WTE, and conversion of MSW to liquid fuel. The high capital cost is attributable to the technical complexity of these processes. From there, the unit capital cost drops among the other technologies, as the complexity of the process decreases. Accordingly, the next-highest unit capital cost is for AD, followed by composting, and finally landfilling. The unit capital cost for landfilling is decidedly less than all other technologies, since comparatively, landfills require little capital expense for buildings and equipment.
- Landfills are the most advantageous technology from the standpoint of both unit capital costs and total capital outlay. The capital cost for a landfill of a given capacity is substantially less than the capital cost for all other technologies for treatment of mixed MSW. In addition, as landfills are constructed in a succession of modules (landfill “cells”) rather than building the total capacity at the outset, the total capital outlay is spread out over multiple decades. Furthermore, landfills can be constructed economically in a very wide range of capacities for mixed MSW, from the smallest capacity to the largest. The comparatively low capital costs for landfills explains why landfills are the dominant modern technology for MSW disposal in both North and South America today.
- For composting, the unit capital cost is much higher than for landfilling; however, the total capital outlay required for a composting facility can be less than that of a landfill, if the capacity of the composting facility is small. The low, total capital outlay required for small-capacity composting makes the technology particularly attractive for composting of source-separated food waste and yard waste.
- Anaerobic digestion (AD) has relatively high unit capital costs and is normally not offered at the very small processing capacities available

with composting. Accordingly, the total capital outlay for AD is higher relative to landfilling and composting. AD may be best suited where there are other reasons for its selection, for example, a local need for energy generation.

- The least favorable technologies from the standpoint of both unit capital costs and total capital outlay are combustion WTE and gasification WTE. These technologies are rarely implemented in processing capacities less than 100 tons per day, so the smallest feasible facilities require a large, total capital outlay. At the smallest, typical capacity, the total capital outlay for combustion WTE or gasification WTE will be $15 to $25 million. The largest-capacity WTE facilities can have a capital cost approaching $1/2 billion.
- From the standpoint of capital cost, a favorable option for implementing waste-to-energy in developing countries is to produce waste-derived-fuel (WDF) under municipal auspices, then to assign the WDF for combustion by third parties for energy recovery at an existing utility boiler, industrial boiler, or cement kiln offsite. The capital cost to the municipality to produce WDF is less than one-quarter the cost for a combustion WTE facility. This is because the high capital cost for the energy generation equipment has already been absorbed by the third-party owner of the offsite facility where the WDF is combusted as a fuel. Because of its comparatively lower cost, WDF production has been called "poor man's waste-to-energy."

4.4.1.2 *Operating Costs*

The operating costs for combustion WTE, WDF production, and gasification WTE are all similarly high. The operating costs for AD and composting are moderate to high by comparison. The operating costs for landfills are the lowest of all the technologies for mixed MSW management, whether a large-capacity or small-capacity landfill, making landfills highly favorable from the standpoint of operating costs. The total annual operating cost for very-small-scale composting facilities for food waste and yard waste can be even smaller than total operating costs for the smallest feasible landfills.

4.4.2 *Institutional Factors*

Key points regarding operating complexity and public acceptance for the technologies follow:

4.4.2.1 *Operating Complexity*

In terms of operating complexity, landfills are most favorable, as they are the least complex to operate. Simple forms of composting are similarly favorable to landfills owing to low operating complexity; however, some composting technology (in-vessel) is moderately complex to operate. Relative to landfills and composting, AD is decidedly more complex to operate properly and requires specialized skills and proper training. Combustion WTE is highly complex to operate and gasification WTE is the most complex technology to operate, both technologies requiring specialized skills and extensive training for proper operation.

4.4.2.2 *Public Acceptance*

Any type of waste management facility has the potential to generate public opposition, especially from people living in close proximity. In some settings, however, wider, organized public opposition develops, based on opponents' negative general perceptions regarding associated environmental impacts. In those settings, elected public officials sometimes join the opposition based on populist political objectives.

Of the MSW treatment technologies assessed, the least likely to cause public opposition are WDF production, the emerging technology of converting MSW to liquid fuels, and composting. WDF production and waste-to-liquid fuels are less likely to incite public opposition because both types of facilities are totally enclosed (less potential for causing odors and littering), neither technology entails waste combustion onsite, and the waste-to-liquid fuel technology is novel. Composting is also favorable with regard to public acceptance, because composting is a simple biological-type processes the public understands and can even perform themselves at small scale in their own back yards. Also important for public acceptance, there is no combustion with composting.

AD, although more complex technology than composting, is still a biological process that does not entail waste combustion; hence, its public acceptance would normally be favorable. However, very importantly, both composting and AD technologies have experienced serious odor nuisance problems in many locations, because of poor operating practices. Such odor problems can turn public acceptance of composting or AD into determined opposition very quickly.

The technologies that typically generate the most public opposition are landfills and waste-to-energy. Strong public opposition to landfills, however, is typically limited to neighbors living in proximity to the landfill site, and such opposition usually tapers off rapidly with distance from the landfill.

The public acceptance profile for combustion waste-to-energy (WTE) varies markedly with location, from favorable to very unfavorable. Combustion waste-to-energy (WTE), while accepted in Europe, Japan, and some regions of the U.S. and Canada, is strongly opposed in other regions of the U.S. and Canada. Of the MSW treatment technologies, combustion WTE has the highest potential to cause broader public opposition beyond affected neighbors, including organized environmental groups and populist politicians. Where WTE has been strongly opposed, the organized resistance is based on opposition to combustion-related emissions of air pollutants, no matter how minor, and is also based on concerns that WTE will compete with traditional recycling.

Gasification WTE does not entail waste combustion, but normally the syngas produced is burned onsite as a fuel to recovery energy. Because gasification WTE does not combust solid waste, it is less likely to generate public opposition than is combustion WTE. But, in those locales where combustion WTE would be strongly opposed, gasification WTE is also finding strong opposition, as opponents in those particular locales object to any type of large-scale combustion (including combustion of syngas) and many of those opponents have a philosophical distrust of large-scale, complex technology.

5 TECHNOLOGY APPLICABILITY IN LATIN AMERICAN SETTINGS

Many factors must be considered in determining which technologies for MSW treatment and disposal are best suited for application in any given setting within the Latin American and Caribbean Region (LAC). Some of the key factors are summarized below.

- Population density – urban versus rural
  - The population density determines how much MSW is generated within a given local region.
  - A significant amount of MSW must be generated locally to make municipal waste collection and central waste management economically feasible.
  - A very large amount of MSW must be generated in the local region in order for complex, waste management technologies to be economically feasible. Expensive, complex technology like combustion WTE and gasification WTE must be large-scale to be economic, and hence, are only potentially feasible for large urban areas.
- Regional road network
  - Centralized waste management requires efficient, regional waste collection for delivery to the centralized processing facility. This, in turn, requires an adequate network of modern roadways within the region served.
- Differences in waste composition
  - In ***developed*** countries, MSW is lower in moisture content, as it contains large fractions of paper and plastics relative to moister food waste. This "drier" MSW makes a good fuel for energy recovery via combustion WTE or gasification WTE.
  - In ***developing*** countries, MSW contains less paper and plastics, and a much greater proportion of food waste. This "wetter" waste is better suited for treatment using biological processes such as composting and anaerobic digestion.
  - Some of the largest cities in the LAC region now generate MSW having a composition more like the developed countries, with higher fractions of paper and plastics, relative to food waste.

- The municipality's economic and financial strength - municipal financial/investment capacity, per-capita income level, and cost of living
  - *Strong investment capacity and higher income level:* Can consider the more complex, expensive technologies.
  - *Less-developed economy and lower income level:* Must focus on less complex, lower-cost technologies.
  - Generally, the strongest municipal investment capacities will be found in the largest cities. However, there can be local exceptions, such as in more-rural tourist areas where robust tourism may significantly enhance the local revenue base available for funding waste management.
- Availability of skilled work force
  - The more complex technologies such as combustion WTE, gasification WTE, and anaerobic digestion require highly-skilled, trained specialists for proper operation.
  - Technologically skilled personnel would normally only be available in the largest capital cities of LAC countries, and may not be available at all in some LAC countries.
- Interest of private waste-management countries in public-private partnerships
  - If private waste-management companies have interest in a given region of LAC, this provides an opportunity to implement modern MSW treatment technologies by shifting responsibility for the required substantial investment and skilled operations to private sector specialists. This could be of particular interest those medium and large cities that currently have limited investment capacity.
- Locales within the LAC region having unique land constraints
  - Small island countries, being land-constrained, may not desire to consume limited, available land with a landfill, and at the same time, may have an incentive to generate energy using locally available fuels such as MSW rather than imported fossil fuel. This can make MSW treatment technologies attractive, despite their high capital cost.
  - Some regions of LAC may be unsuitable geologically for landfills, such as highly mountainous regions or areas underlain geologically with karst bedrock. Technologies other than landfills are often better suited for application in such regions.

In this study, an assessment has been made of the *general* applicability of the available technologies for MSW treatment and disposal to various waste management settings found within the LAC Region. Those characteristic waste management settings were identified and defined previously above in **Table 3**. Technology applicability assessment for *specific* locations within the LAC region would require detailed, site-specific evaluation, and this would need to be the subject of subsequent studies.

The applicability of the various MSW treatment and disposal technologies was assessed for each of the characteristic waste-management settings described in **Table 3**. The results of that assessment were summarized previously above in **Table 4**. Some conclusions regarding technology applicability follow:

5.1 LARGEST CITIES, STRONGER MUNICIPAL INVESTMENT CAPACITY

- Modern sanitary landfills represent the technology that (1) has lowest capital and operating costs; and (2) is available in the range of capacities required.
- If there is a suitable industry (coal utility boiler, industrial boiler, or cement plant) in the region, then production of WDF municipally, with combustion of that WDF at the offsite industry for energy recovery may be very favorable to both the municipality (low waste treatment costs) and the industrial partner (lower fuel costs).
- Combustion WTE, although costly, may be favorable as a landfill alternative for any of the following reasons, providing there is adequate municipal investment capacity:
  - Renewable energy generation is locally needed or desired.
  - There is a desire to conserve land for more productive uses than landfilling.
  - Environmental policy favors resource recovery over landfill disposal.
- Gasification WTE may also be favorable for the same reasons, if the facility is privately developed, owned, and operated, so that the public sector does not assume the higher technology risks inherent to an advanced, complex technology such as gasification.
- Anaerobic digestion (AD) may be favorable in some cases, for example, if local energy generation is desired, but combustion WTE is locally opposed.

- Central composting of food waste and yard waste would be very favorable as a low-cost technology, if the significant additional cost for separate collection of those waste components is affordable. If not, composting of food waste and yard waste in backyards or at small, local drop-off locations would be a low-cost, very favorable practice.

5.2 SMALLER CITES, LIMITED MUNICIPAL INVESTMENT CAPACITY

- For cities of large- to medium population, modern sanitary landfills represent the technology that (1) has lowest capital and operating costs and (2) is available in the range of capacities required.
- For small cities and rural areas, the lowest cost technology for management of MSW would be Controlled Landfill, as an interim measure, until such time as local conditions evolve to enable upgrading to a modern sanitary landfill (population increase and/or increased municipal investment capacity).
- Combustion WTE and gasification WTE would normally be unfavorable in this setting, as there is typically not enough MSW generated to reach the minimum capacity requirements for these technologies, and the municipality does not normally have sufficient municipal investment capacity. Often, there is not the waste collection infrastructure in place over a large enough region to collect and supply sufficient waste to meet the minimum capacity requirement for a WTE facility. In principle, however, if a small city area has sufficient waste generation and a waste collection infrastructure, but insufficient investment capacity, there may be the potential for implementation of WTE by the private sector.
- If there is a suitable industry (coal utility boiler, industrial boiler, or cement plant) in a small-city region, then production of WDF municipally, with combustion of that WDF at the offsite industry to recover energy may be feasible. If so, this could be very favorable to both the municipality (low waste treatment costs) and the industrial partner (lower fuel costs).
- Anaerobic digestion (AD) is likely unfavorable for application in this setting due to high costs, unless the project is undertaken entirely by the private sector, without economic risk to the municipality.
- Central composting of food waste and yard waste would be very favorable as a low-cost technology, if the significant additional cost for separate collection of those waste components is affordable. If not, composting of food waste and yard waste in backyards or at small, local drop-off locations would be a low-cost, very favorable practice.

5.3 *RURAL AREAS, LITTLE MUNICIPAL INVESTMENT CAPACITY*

- For most rural areas, implementation of a modern sanitary landfill is unlikely to be economic, as there isn't likely enough MSW generated in the region to meet minimum capacity requirements for a sanitary landfill. In addition, the municipal investment capacity is normally too limited.
- For rural areas, the lowest cost technology for management of MSW would be Controlled Landfill, as an interim measure, until such time as local conditions evolve to enable upgrading to a modern sanitary landfill (population increase and/or increased municipal investment capacity).
- Combustion WTE, gasification WTE, and anaerobic digestion are not normally feasible, owing to insufficient MSW generation in the region to meet minimum capacity requirements for those technologies.
- Composting of food waste and yard waste in backyards or at small, local drop-off locations would be a low-cost, very favorable practice.

5.4 *LAND-CONSTRAINED REGIONS*

- Landfilling would be least favorable, owing to a scarcity of available land (small island settings) or to unfavorable terrain/geology (e.g, mountains, karst). Such land constraints can make more costly technologies such as combustion WTE economically feasible.
- Combustion WTE may be very favorable, as it requires little land. In small island countries, electric power costs are very expensive as fossil fuel must be imported. Accordingly, combustion WTE can have an added benefit of reducing local energy costs by producing energy using a fuel from a domestic source (MSW), rather than expensive imported fossil fuel.
- Gasification WTE may also be favorable for the same reasons, if the facility is privately developed, owned, and operated, so that the public sector does not assume the higher technology risks inherent to an advanced, complex technology such as gasification.
- If the land-constrained region has a suitable industry (coal utility boiler, industrial boiler, or cement plant), then production of WDF municipally, with combustion of that WDF at the offsite industry to recover energy may be very favorable to both the municipality (low waste treatment costs) and the industrial partner (lower fuel costs).

- Anaerobic digestion (AD) may be favorable given the need for less-expensive energy generation in the case of a small island country, or if local energy generation is desired, but combustion WTE is locally opposed.
- Central composting of food waste and yard waste would be very favorable as a low-cost technology, if the significant additional cost for separate collection of those waste components is affordable. If not, composting of food waste and yard waste in backyards or at small, very-local drop-off locations would be a low-cost, very favorable practice.

5.5 *REMOTE AREAS (PRIMITIVE ECONOMIES)*

- With a subsistence economy and weak, centralized local government, the only viable technologies for improving waste management may be composting of food waste and yard waste in back yards or at small communal facilities, along with controlled communal dumps (scavenging prohibited) for the small amounts of mixed waste that would be generated.

Finally, it is noted again that for any particular locale within the LAC Region, determination of the "best" technologies for that locale requires a case-specific evaluation.

6 ANNEXES

Annex 1:

Landfill

Technical Description and Operating Scale

<u>Technology Description</u>

Landfill Technology

In developed countries, the disposal of MSW in communal open piles ("garbage dumps"), as well as in backyard pits and metal drums, was the norm three to four decades ago. The communal open garbage dumps were often periodically burned and/or covered with earth, and backyard garbage pits and drums were regularly burned. Communal open garbage dumps created hazards to both human health and the environment. Open dumping attracted disease carriers such as rats and flies, exposed workers and scavenging trespassers to pathogens, caused fires, and caused water and air pollution. While the uncontrolled burning of both communal open garbage dumps and backyard garbage pits/drums reduces the volume of MSW, it also causes significant air pollution, including emissions of particulate matter and dioxins/furans. Today, developed countries have long abandoned communal open dumping, in favor of engineered landfills and other modern MSW management options. However, burning garbage in backyard drums persists in the rural areas of some developed countries, including the U.S.

In the developing countries of the world, both communal open dumping of MSW and backyard garbage pits/drums remain common. With these communal open dumps, scavenging by trespassers is not prohibited or controlled. Increasingly, however, this is giving way to "controlled dumps," where scavenging is prohibited, and engineered landfills now serve the largest population centers in some developing countries.

Landfill technology can be sub-classified with regard to the sophistication of design and operational features incorporated to protect public health and the environment. This is summarized in the table that follows and relevant aspects of landfill engineering design and operation are discussed subsequently.

Landfill Classifications				
Landfill Classes	**Engineering and Operational Features for Environmental Protection**	**Leachate Control**	**Gas Control**	**Scavenging Allowed?**
Open Dumps	• None	• No control	• No control	Yes
Controlled Dumps	• Normally none • Sometimes, daily covering with soil	• Little to No Control	• No Control	No
Basic Sanitary Landfill	• Bottom liner • Compaction of daily waste • Daily covering with soil	• Containment • Some control	• Venting to atmosphere • Sometimes, control via flaring	No
Modern Sanitary Landfill	• Bottom liner • Compaction of daily waste • Daily covering with soil • Top cover seal at closure	• Containment • Collection and Treatment	• Active collection • Venting (small landfills) • Control via flaring or energy recovery (large landfills)	No

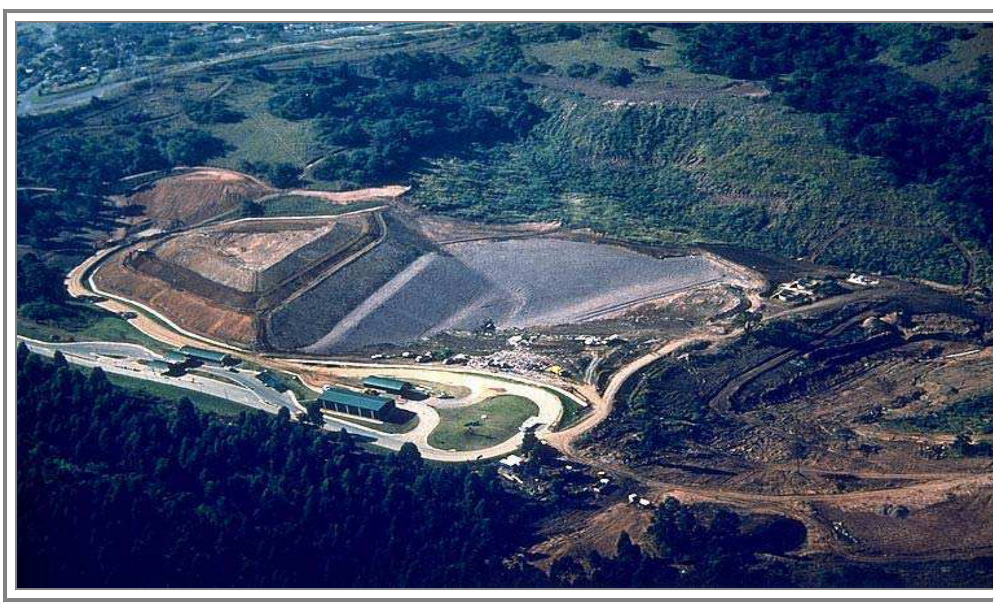
Modern landfills are engineered to protect human health and the environment. In a modern landfill, the MSW discharged into the landfill is compacted using heavy equipment to conserve landfill space. The MSW that is landfilled each day is covered with several inches of soil ("daily cover") to reduce odor, littering, and disease vectors (rats, flies), and to reduce human exposure to pathogens. Once MSW has been buried in a landfill, the organic fraction of the MSW (e.g., food waste, paper, yard waste) decomposes. Two types of bacteria aid in decomposition. One type of bacteria converts the organic fraction into organic acids, then the other type converts the acids into carbon dioxide and methane. The methane and carbon dioxide comprise the landfill gas which builds up within the landfill as the waste decomposes.

In addition, rain falling on the landfill surface can become contaminated as it percolates down through the landfilled MSW. That contaminated water present within the landfill is referred to as landfill leachate. Both landfill gas and landfill leachate must be actively managed, as discussed below.

The design of a modern sanitary landfill includes a number of features for environmental protection:

- *Landfill Liner* – An impervious liner is placed at the base of the landfill, beneath the fill area, to keep contaminants present in the buried MSW from contaminating the ground water. The liner is typically comprised of a synthetic membrane material overlying a layer of compacted clay.
- *Leachate Collection and Removal System* – Landfill leachate is a contaminated waste water. Leachate is acidic and can contain toxic contaminants such as heavy metals and organic compounds. Leachate is collected on the landfill liner using a system of porous piping, then is directed to the surface for proper treatment and disposal. This prevents the contaminated leachate from migrating into the environment, where it can contaminate ground water and surface waters.
- *Landfill Gas Collection System* – Many modern landfills, especially larger ones, have a system of wells, subsurface piping, and blowers/pumps to collect the landfill gas as it forms within the landfill. The collected landfill gas is directed to the surface, where it is managed as further described below.
- *Modular Construction in "Cells"* – Landfills are typically constructed and filled in sequential modules or "landfill cells" over a period of decades before the entire landfill facility reaches capacity and is closed. This modular approach to landfill construction enables spreading the total capital investment over many years and enables more effective environmental management of landfill leachate and gas. The duration of filling activity for a cell is typically five years before the cell is closed and a new cell is started.
- *Landfill Top Seal at Closure* – When a landfill cell has reached capacity and is being closed, the landfill is sealed at the top from further intrusion of rainwater, by fitting the top of the landfill surface with a "cap" made of an impermeable liner material.

Modern Landfill Design
(Source: World Bank)



Typical Modern Landfill
(Source: DSW via World Bank)

Finally, a variation of the standard modern landfill design has emerged over the past 20 years, called a bioreactor landfill. With the bioreactor type of landfill, the objective is to accelerate the biological decomposition of the organic fraction of MSW so that degradation takes place within approximately 10 years after depositing the waste, rather than the typical period of about 30 years for a standard landfill design. This is accomplished by maintaining the moisture content of the landfilled MSW at an optimal level for biological decomposition. That, in turn, is achieved by pumping water into the landfill system, with the water sources typically being landfill leachate re-injection and storm water injection.

Bioreactors can be of the aerobic or anaerobic designs. With aerobic bioreactors, air is pumped into the landfill along with the water. This encourages the growth of bacteria that require oxygen and results in generation of carbon dioxide gas, rather than methane. The waste degrades to a compost material. The main benefits of the aerobic bioreactor over standard landfill design are the creation of new landfill air space, a reduction in the formation and emission of methane greenhouse gas emissions, and lower leachate disposal costs.

Anaerobic bioreactors inject water, but not air. This encourages growth of bacteria that do not require oxygen and results in increased methane production. The main benefits of the anaerobic bioreactor over standard landfill design include the creation of new landfill air space, accelerated methane production for energy generation, and lower leachate disposal costs.

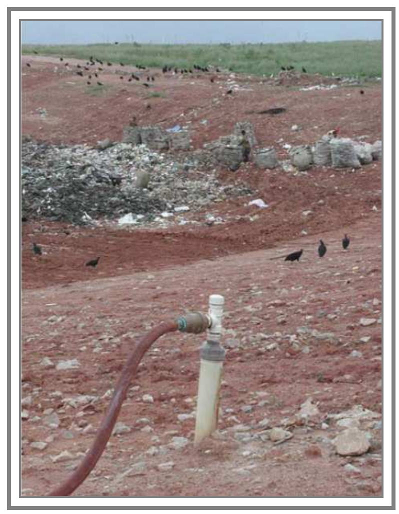
Some bioreactor landfills are now operating; however, the standard landfill design continues to dominate overwhelmingly, owing likely to lower costs and simpler operating requirements.

Landfill Gas Generation, Control and Energy Recovery

Modern landfills are engineered to protect human health and the environment. In this regard, management of landfill gas is essential, especially at large landfills, to prevent safety hazards, odor nuisance, and greenhouse gas emissions. Landfill gas is comprised typically of 50% methane and 50% carbon dioxide. The methane can present a safety risk to and the public due to the potential for methane fires and explosions. This risk of fires and explosions extends to the public because the landfill gas can migrate offsite in the air and can also migrate offsite subsurface through the soil where it can accumulate in confined spaces such as the basements of nearby dwellings. The methane releases from landfills are also a major source of greenhouse gas emissions globally. Landfill gas contains hydrogen sulfide, which is a strong odorant, and without effective management of the landfill gas, offsite odor nuisance is a common problem with landfills. In addition, landfill gas contains small levels of toxic organic compounds and other toxic substances.

Effective control of landfill gas begins with an efficient collection system. Landfill gas collection systems at modern landfills are typically 65% to 90% efficient at capturing the landfill gas that is generated, meaning that the remainder (the uncollected gas) is emitted uncontrolled to the atmosphere as a "fugitive" emission[1]. Following collection, the collected gas is either vented to the atmosphere, controlled via combustion using a flare, or controlled by combusting the gas as a fuel to generate energy. With energy generation, the landfill gas is typically used either to fuel an engine-generator set to produce electric power or to fuel a boiler to make steam energy or electricity. Active control of the collected landfill gas via flaring or energy generation is more economic at larger landfills, while passive venting of collected gas to the atmosphere without control is more economic for small landfills.

Energy Recovery from Landfill Gas, South Africa
(Source: World Bank)



Landfill Gas Collection in Peru
(Source: World Bank)

The landfill gas is produced as the result of principally anaerobic (without oxygen) decomposition of the organic fraction of the landfilled MSW (food waste, yard/garden waste, paper, wood). Because the landfill gas comes from biogenic sources (plant matter that was recently living), its combustion to generate energy is "carbon neutral" from the standpoint of climate change. Accordingly, from the scientific standpoint, energy produced by combusting the landfill gas as a fuel is renewable energy. With landfills, converting the landfill gas to energy results in approximately 55 kW of electric power generated for

1 Source: US EPA: http://epa.gov/climatechange/wycd/waste/downloads/landfilling-chapter10-28-10.pdf -- accessed 11 April 2011.

each ton of MSW that was landfilled. However, because that energy is derived only from the biodegradable fraction of the landfilled MSW, the potential energy value of the remainder of the landfilled material remains unused. Thermal technologies for MSW processing, such as combustion waste-to-energy (WTE), gasification, and pyrolysis convert virtually all the heat content of MSW into energy. Combustion WTE, for example, generates about ten times the energy per ton of MSW processed than landfill-gas energy recovery[2].

Landfill Closure and Post-Closure Care

Depending on factors such as waste composition and local climate, the MSW deposited into a landfill will degrade at differing rates. Once waste has been deposited in a landfill, waste decomposition and landfill gas production typically peak after approximately 7 to 12 years, then declines over many decades (another 30 to 70 years). As a consequence, both landfill leachate and landfill gas continue to be generated within a landfill for decades beyond the date when filling has ceased. Accordingly, when a modern landfill is being closed, there are closure and post-closure care requirements that are needed for continued protection of the environment and human health. At closure, the top surface of the landfill is normally fitted with an impervious cover material (e.g., geotextile). This landfill "cap" decreases rain water penetration into the landfilled material so as to reduce leachate generation by the closed landfill. Following landfill closure, the ground water in the vicinity of the landfill is monitored for decades to ensure that the landfill bottom liner and the closure cap remain intact and are preventing the migration of contaminated leachate into the environment. In addition, the landfill gas collection and control systems continue to operate for many years after landfill closure, until testing indicates that significant new gas generation has ceased. Importantly, some developed countries require the landfill owner to provide a funding mechanism for ensuring adequate closure and post-closure care in future decades following landfill closure.

<u>Waste Types Processed</u>

Modern sanitary landfills are designed to receive MSW, and normally other waste materials such as construction and demolition debris, wastewater sludge, medical waste, and non-hazardous industrial wastes.

2 Kaplan, P. et al., US EPA, Is It Better To Burn or Bury Waste for Clean Electricity Generation?, Environmental Science & Technology, Volume 43, 2009.

Operating Scale

Basic engineered sanitary landfills worldwide have capacities ranging from less than 50 tons per day (TPD) to over 10,000 TPD. Basic engineered landfills in Latin American countries exhibit the same range of landfill capacities, including landfills in Argentina and Brazil with capacities of 6,000 to 8,000 TPD[3].

For modern engineered sanitary landfills, the minimum economically-viable capacity is generally hundreds of tons per day (~ 250 to 500 TPD), as economies of scale are required to accomodate the additional costs of the advanced engineering design and operating features of a modern sanitary landfill.

Commercial Experience and Viability

Landfills represent the first modern method for centralized management of MSW, and have the longest commercial track record of all MSW management methods. The number of engineered landfills worldwide is in the tens of thousands, with most engineered sanitary landfills found in the developed countries and most engineered basic landfills in developing countries. There are thousands of engineered sanitary landfills operating in the U.S. and Canada alone, where landfills remain overwhelmingly the principal method for solid waste management. For developed countries, Japan is an exception. As a populous, industrialized, island nation, Japan has phased out landfills in favor of energy recovery.

While engineered sanitary landfills are the norm in developed countries, they are comparatively rare in developing countries of the world. By contrast, in the many developing countries of the world, centralized open dumping and backyard garbage pits remain common practices for disposition of MSW. Over the past 20 years, however, some developing countries have moved away from open dumping and have implemented basic engineered landfills to serve their major, urban population centers. Developing countries in Asia led this trend; however, many Latin American countries have also made substantial progress. For Latin America overall, 55% of the waste is reportedly disposed in basic engineered landfills, and that disposal figure ranges from 40% to 80% in the countries of Argentina, Brazil, Bolivia, Columbia, Costa Rica, El Salvador, Mexico, Panama, and Peru[4]. Other data[5] indicate that for the Latin America overall, only 23% of the waste is disposed in modern sanitary landfills, 24% is disposed in controlled landfills that include some engineered features, and the

3Kaplan, P. et al., US EPA, Is It Better To Burn or Bury Waste for Clean Electricity Generation?, Environmental Science & Technology, Volume 43, 2009.

4Evaluation of Municipal Solid Waste Management Services in Latin America and the Caribbean for year 2010, Pan American Health Organization (www6.iadb.org/Residuos)

5World Bank, August 2008. Solid Waste Management in LAC: Actual and Future CH4 Emissions, prepared by Catalina Ramirez.

rest (over half) is disposed via open dumping. On a positive note, 60% of the MSW collected in the largest capital cities of Latin America is now disposed in modern sanitary landfill.

In many developed countries, it is common for private-sector waste management companies to operate large publicly-owned landfills under a long-term contract. This trend towards public-private partnerships for waste management is also being adopted for operation of large landfills in Latin America.

Technology Suppliers

While modern landfills are engineered systems, the technology is not highly complex or proprietary in its fundamentals. Accordingly, most developed countries have many domestic engineering-construction firms capable of designing and constructing a modern landfill. While some of these companies operate nationally or even internationally, most provide their services only within a local sub-region of the country.

In many developing countries, particularly in Asia and Latin America, the engineering-construction expertise for developing a landfill exists within the country's principal urban centers. Accordingly, in those developing countries, much, if not all of the required expertise for development of a modern landfill is available in-country. However, in the least developed countries of the world, the required skills may not yet exist and the expertise would need to be imported.

Sustainability

Resource Recovery

With landfills, there is typically no substantive resource recovery, unless the landfill uses the collected landfill gas as a fuel, converting it to energy.

Energy Conversion Efficiency

Landfill gas is typically comprised of approximately 50% methane and 50% CO_2. Landfill gas has value as a fuel due to its methane content; however, landfill gas has only half the calorific value (heat content) of natural gas, which is mostly methane.

When landfill gas is converted to energy at a landfill, the energy is normally electricity. The generation rate of electric energy per ton of MSW landfilled varies, but a typical energy conversion efficiency is 65 kWh/ton, and is reported to vary from approximately 41 to 84 kWh/ton[6]. While a valuable energy contribution, the energy conversion efficiency for landfill gas is ten times less than the energy conversion efficiency of thermal treatment technologies (WTE, gasification), typically 600 kWh/ton or greater[7]. This is explained by the fact that landfills convert only the biodegradeable fraction of MSW into an energy-laden fuel, while with WTE, all components of MSW having fuel value are converted to energy.

Carbon Profile and Renewable Energy

Landfills generate substantial quantities of the greenhouse gas, methane, as the MSW biodegrades over time within the landfill. Landfills are recognized to be a major emissions source of methane globally and in the U.S., it accounts for 17% of all methane emissions caused by human activity[8]. Modern landfills include landfill gas collection systems and many modern landfills then combust the collected landfill gas in flares or as a fuel to generate energy, destroying the collected methane. However, even the best collection systems are not 100% efficient at gas capture, and typically, 20% to 30% of the gas being generated escapes to the atmosphere, uncollected and uncontrolled[9]. That "fugitive" emission of methane can be on the order of 10% of total generation, even after a modern landfill is fully closed. Accordingly, landfills with or without landfill gas controls constitute a major source of greenhouse gas emissions as methane.

Renewable energy is often defined as energy that is derived from renewable sources and does not contribute to global warming. When the landfill gas is used as a fuel to generate energy, the energy comes from combustion of the methane content of the gas. That methane resulted from the anaerobic biodegradation of organic material present in landfilled MSW, constituents such as food waste and paper. As that organic material is biogenic (derived from plants that were recently alive), the energy produced from it is renewable energy. When the landfill gas is combusted as a fuel, an emission of the greenhouse gas carbon dioxide (CO2) results. However, that CO2 represents carbon that was previously circulating in the environment (in plant matter), and accordingly, that CO2 emission is "carbon-neutral," not contributing to climate change. Furthermore, if the energy generated using landfill gas as a fuel displaces energy now being generated using fossil fuel, this can reduce greenhouse gas emissions overall.

6US EPA: http://www.epa.gov/methane/sources.html. Accessed 18 April 2011.

7Kaplan J, Decarolis, and Thorneloe, US EPA, Is It Better to Burn or Bury Waste for Clean Energy Generation?, Environmental Science & Technology, Volume 43, 2009.

8US EPA: http://www.epa.gov/methane/sources.html. Accessed 18 April 2011.

9Kaplan J, Decarolis, and Thorneloe, US EPA, Is It Better to Burn or Bury Waste for Clean Energy Generation?, Environmental Science & Technology, Volume 43, 2009.

Water Resource Use

Landfills typically do not have process water uses.

Waste Diversion from Landfill

In developed countries, the goal of many solid waste managers is to divert as high a fraction of the MSW from landfill disposal as possible. Landfills are always the final repository of residual MSW after implementing waste diversion measures; i.e., waste minimization, recycling, and resource recovery. As landfills are always the final repository, the "waste diversion from landfill" measure is inherently zero for landfills.

Land Resource Use

Of all MSW management technologies, landfills require the greatest land area. Furthermore, when a landfill closes, the associated land area has only limited potential uses, as the MSW will continue to settle and generate landfill gas for decades after closure. Accordingly, landfills make a long-term claim on the land resource, likely a century or longer.

Environmental Impacts

Air Pollutant Emissions

Air pollutant emissions from landfills are associated primarily with emissions of landfill gas. Landfill gas that is not destroyed by combustion (flaring or energy recovery) is emitted to the atmosphere, either through vent pipes or from leaks in the landfill surface ("fugitive" emissions). The primary air pollutants emitted with landfill gas include methane (greenhouse gas) and odorants (hydrogen sulfide and others). However, landfill gas also contains many toxic air pollutants at trace levels, including organic compounds (some carcinogenic) as well as trace levels of mercury. While the toxic air pollutants are emitted at trace levels, they are emitted near-ground and do not disperse significantly before moving offsite, where any individuals living next to the landfill can be chronically exposed.

At landfills where landfill gas is combusted (flaring or energy recovery), this controls the emission of landfill gas, but also results in new emissions, at relatively low rates, of the standard combustion pollutants, nitrogen oxides, carbon dioxide, sulfur dioxide, and particulate matter. As landfill gas is combusted, the trace toxic organic compounds and odorous compounds present in the landfill gas are destroyed. However, any mercury present in the landfill gas is not destroyed and is emitted. Combustion-related emissions of dioxins/furans are addressed subsequently below. Generally, add-on emission controls for combustion-related pollutants and mercury are not yet used with combustion of landfill gas.

Emissions of Dioxin/Furans and Mercury

As with most combustion processes, combustion of landfill gas results in trace emissions of dioxins/furans, but at levels lower than uncontrolled emissions from modern WTE technology.

As MSW contains mercury, the environmental fate of that mercury is an important issue for all MSW management technologies and methods, including landfills. The emission levels of mercury from landfills are not well characterized. Only in the past decade has focused research yielded detailed data on the levels and forms of mercury emitted to the air from landfills, the mechanisms by which the emissions occur, and the emissions variability. Much uncertainty remains. With landfills, all of the mercury present in the solid waste gets deposited into the landfill with the solid waste, where that mercury can potentially discharge to the environment (air, water, and soils) over time without control. The mercury deposited with the solid waste in the landfill can volatilize to the air; it can contaminate landfill leachate which is then discharged to water bodies; and it can migrate to soils with storm water runoff. In addition, elemental mercury deposited with solid waste in landfills is suspected of converting biologically within the landfill to the organic methylated form[10], resulting in environmental discharges of methylated mercury, the form of most concern for human exposure. While all the mercury deposited to a landfill with the solid waste has the potential to discharge eventually to the environment without control, it is presently unknown what fractions actually do migrate to the air, water, and soils, and over what time periods. It is also possible that some portion of mercury deposited to landfills may become sequestered there, following conversion to stable sulfur compounds.

Recent field research[10] confirms that mercury is commonly emitted to the air at different rates for various phases of landfill operation. That research determined that most (90%) of the emission of mercury to the air at a landfill occurs at the working face of the landfill, as waste is being spread. The remainder of the emission (< 10%) occurs with the escape of landfill gas. Furthermore, the research confirms that mercury emissions from landfills are principally in the

[10] Lindberg, S. E., et al., 2005. "Gaseous methyl- and inorganic mercury in landfill gas from landfills in Florida, Minnesota, Delaware, and California," Atmospheric Environment, Volume 39, 2005, pp. 249,.252-254, 257.

elemental form, but also contain mercury in the organic methylated form, which is of most environmental concern. At landfills where the landfill gas is combusted in a flare or engine, the methylmercury present in the landfill gas would be converted to the inorganic form prior to emission. Nonetheless, cognizant researchers[11] believe that landfill emissions of organic methylmercury from uncombusted landfill gas may be environmentally significant.

Odor

Landfills are known sources of odor nuisance in the vicinity of the landfill site. One source of odor is the smell of decomposing garbage that is emitted as MSW is deposited in the landfill and spread. While the odor is unavoidable, it can be mitigated by keeping the "working face" of the landfill as small as practical and by promptly covering the freshly spread MSW with daily cover material (normally soil).

The other sources of landfill odor are landfill gas, which contains powerful odorants such as hydrogen sulfide, and exposed landfill leachate, which contains odorous organic compounds. Odors from those sources can be mitigated by installing and operating effective control systems for landfill gas and leachate. While odors associated with landfill operation can be mitigated, they can not be totally eliminated. Accordingly, any landfill operation has the potential to create an odor nuisance in the immediate vicinity offsite.

Wastewater Discharges

The leachate generated within landfills is highly contaminated waste water. If not controlled, it can flow into groundwater and contaminate drinking water wells. It can also flow offsite with storm water runoff to pollute surface waters and the land. Accordingly, effective mitigation entails installing a liner system beneath the landfill to protect the ground water, and an effective system for collecting the leachate for treatment before the leachate is discharged back into the environment. Finally, when a landfill closes, further mitigation is provided by fitting the top of the landfill surface with an impermeable liner (a landfill "cap"), which prevents rain water from permeating into the landfilled material to create leachate.

11Lindberg, S. E., et al., 2005. "Gaseous methyl- and inorganic mercury in landfill gas from landfills in Florida, Minnesota, Delaware, and California," Atmospheric Environment, Volume 39, 2005, pp. 249,.252-254, 257.

Solid Waste Generation

As noted above, landfills serve as the final repository for residual waste after all measures for waste minimization, recycling, and resource recovery have been implemented. As the final repository, landfills inherently do not generate solid waste. It is possible that treatment processes for leachate could generate a very small quantity of solid residue, but that would also be disposed in a landfill.

Safety Hazards

The safety hazards specific to landfill facilities would include the following:

- Fires on waste delivery trucks and within the landfill (landfill fires can be difficult to arrest, once started)
- Risks of potentially-fatal fires and explosions from landfill gas build-up, especially in confined spaces
- Risk of asphyxia from exposure to landfill gas in confined spaces
- Exposure to waste-borne and leachate-borne pathogens and toxic substances
- Chronic exposure to low levels of air pollutants present in landfill gas
- Increased traffic hazard from waste delivery trucks
- Safety risks from heavy diesel equipment used to spread and compact the MSW

While these are all safety hazards for workers at a landfill facility, the truck-related safety hazard would likely extend significantly to the public offsite. In addition, depending on site-specific circumstances, other risks could accrue to the public if living in very close proximity. Landfill gas, if not well-controlled, can migrate beneath the surface offsite and accumulate in basements of structures, where it can explode. In addition, people living adjacent to a landfill are exposed chronically to the air pollutants emitted a low levels from the landfill.

Economics/Institutional

Economics

Of the modern technology alternatives for solid waste management, landfilling is the lowest cost among technologies available for disposition of large daily amounts of waste, i.e., several hundred ton per day or more. That is why landfilling remains the predominant method for waste management in North America and is the most common technology being implemented in developing countries that are moving beyond open dumping for waste management. The economic feasibility of modern landfills in developing countries is likely greatest in locations with the following attributes:

- Near a major population center
- Good road network in the metropolitan area
- There is ample open land available in the local region at low cost, that has suitable hydrogeology and has buffer distance from the nearest sensitive land uses.

While some developing countries are implementing modern landfills, including many in Latin America, economics remain a barrier for numerous other developing countries worldwide.

The capital and operating costs for landfill technology will vary with the type of landfill (Basic Sanitary Landfill versus Modern Sanitary Landfill), as well as with the landfill size, the nature of the country's economy, taxation laws, and other factors. Based on review of the literature, the capital cost for a modern engineered landfill is in the general range of US$ 5 to $30 for each ton of annual processing capacity, but cost as high as $120 was reported in the literature. Stated in another common form, the capital cost is approximately US $2,000 to $10,000 for each ton-per-day (TPD) of processing capacity, assuming that the landfill operates 90% of the days in a year (330 days). For example, a landfill processing 100,000 tons per year of MSW (~ 300 TPD) would have a typical total capital cost in a developed country of US $600,000 to $3,000,000.

The typical operating cost for a modern engineered landfill in developed countries can vary significantly, but based on review of the literature, a typical cost is US $10 to $30 per ton of waste processed. In certain circumstances, however, operating costs as high as $120 per ton have been reported.

Summarized below are literature sources consulted in estimating the capital and operating costs for landfill technology:

- Cost information published in a leading handbook on solid waste management[12]
- Information compiled previously for the World Bank[13],[14].

Operational Complexity

Proper operation of a modern engineered landfill requires specialized training. Adequately trained personnel are available in the largest cities of many developing countries, including Latin America and Asia. In Latin America, there has been a trend towards contracting with private waste management companies for landfill operation, as a means to secure the necessary trained operating personnel. In lesser developed countries of the world, however, adequately trained personnel for proper landfill operation may not exist and private contract operations is not affordable.

Public Acceptance

Proposed new landfills typically generate substantial public opposition, but the opposition is generally limited to the local area of the proposed landfill. Local residents simply don't want a new landfill built in their neighborhood. By contrast, at least in North America, WTE is more controversial in general, with strong opposition in some cases, not only from people affected locally, but also from national environmental advocacy groups and some elected officials.

12 Tchobanoglous G, et al., 2002, "Handbook of Solid Waste Management."

13 World Bank, Municipal Solid Waste Treatment Technologies and Carbon Finance, January 2008]; [World Bank presentation, 2005, Urban Week – Isabelle Paris

14 World Bank, March 2008. Landfill ER Revenues versus Landfill Costs, prepared by Sandra Cointreau. http://siteresources.worldbank.org/INTUWM/Resources/340232-1208964677407/Cointreau.pdf

Annex 2:

Waste-to-Energy

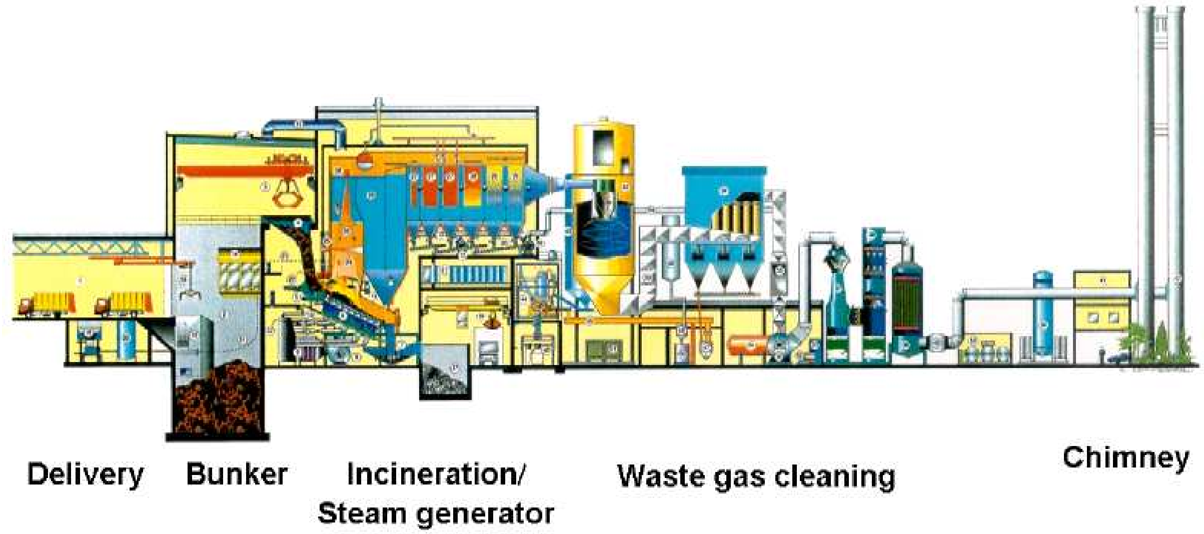
Technology Description and Operating Scale

Technology Description

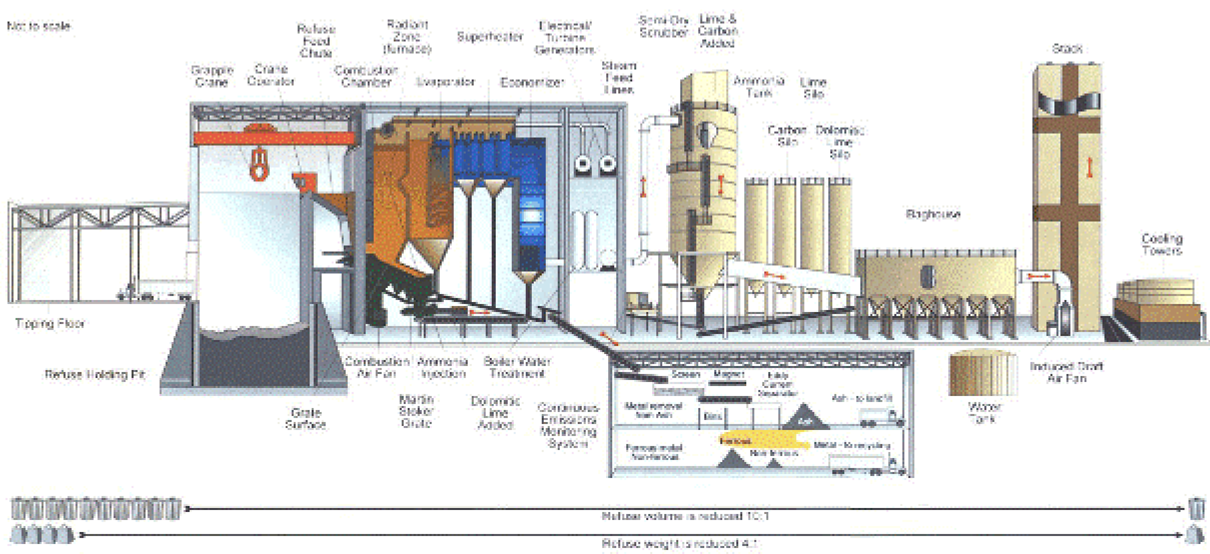
Garbage has been burned for centuries in communal open piles and dumps, as well as in backyard pits and metal drums. While uncontrolled burning reduces the volume of MSW and reduces pathogens, it causes air pollution, including significant emissions of particulate matter and dioxin. Most developed countries have phased out open burning of MSW over the past four decades. However, open burning continues in most developing countries of the world and persists in the rural areas of some developed countries including the U.S.

Starting in Europe in the 1970's, advanced technologies emerged for efficient combustion of MSW in boilers, with recovery of energy. These evolving waste-to-energy (WTE) technologies provided high combustion efficiency, and hence, lower generation of air pollutants than open burning. Modern WTE technology reduces the volume and weight of the MSW combusted by approximately 90% and 75%, respectively, while eliminating pathogens and recovering energy from the MSW. While the early WTE technology was a vast improvement over open dumping of MSW, public concerns arose worldwide in the 1980's regarding WTE emissions of specifically dioxins/furans and mercury. In response, effective new emission control methods for dioxins/furans and mercury were adopted in the developed countries, and these have dramatically reduced emission levels.

With WTE combustion technology, the MSW fuel must have a sufficient heat content or "calorific value" to ensure efficient combustion and economically-viable energy generation. The calorific value of MSW in developed countries is sufficient for WTE combustion technology, but is sometimes not sufficient in developing countries, owing to differences in waste composition.



Simple Process Schematic of a Waste-to-Energy Facility



Detailed Process Schematic of a Typical Waste-to-Energy Facility
(Source: Website of Fairfax County, Virginia, USA, accessed 13 April 2011)

The MSW treatment process in a typical, modern WTE facility is depicted in the figures above and can be summarized as follows:

- Waste continuously enters the enclosed furnace on a moving grate.
- As the waste moves along in the furnace, it undergoes complete combustion at high temperature.
- Via adjusting the combustion air supply and the grate speed, the burning is controlled to ensure that complete combustion occurs.
- Ash resulting from waste combustion is removed from the boiler grate (boiler ash), as well as being filtered from the flue gas (fly ash). Boiler ash comprises about 85% of the total ash.
- Air pollutant emissions are controlled using a combination of good combustion techniques plus add-on emission control technology.
- The heat from combustion is used to produce steam in a boiler. The steam is then used to turn a steam-turbine generator to produce electric power. Alternatively, the steam is piped to a municipal, institutional, or industrial user of thermal energy (steam). Some WTE facilities produce both electric and thermal energy (combined heat and power).

While there are a number of WTE technologies in use, the most common are mass-burn, modular, and RDF technologies:

- Mass-burn WTE technologies use large-capacity furnaces that are field-erected, and can combust mixed MSW without requirement for any mechanical pre-processing or refinement of the MSW.
- Modular technologies accept unprocessed MSW as do mass-burn types, but are of much smaller capacity, so are typically factory-assembled and brought to the site.
- WDF combustion technologies, also known as RDF technologies, are somewhat similar to mass-burn technologies, but require that the MSW be mechanically pre-processed into a more homogeneous fuel prior to combustion. That processed MSW is called Waste Derived Fuel (WDF) or Refuse Derived Fuel (RDF). MSW is processed into WDF via mechanical processing using equipment such as grinders, shredders, trommels and screens. This results in removal of some recyclable materials and inert reject materials, and yields a fuel product of more uniform composition and particle size. Typically, the WDF product is a shredded material. However, in the most advanced WDF processes, the WDF is further processed into dense fuel pellets. Most WDF combustion technologies are large in capacity and are field-erected. The most common WDF technology is a stoker boiler, which uses a grate combustion system. Besides WDF stoker technology, there is also WDF fluid bed technology, which has found some application in Europe.

With fluid bed technology, the waste is not burned on a grate; rather, it burns in suspension within the combustion chamber, entrained in an updraft of combustion air and extremely hot inert particles (e.g., heated sand). There are two varieties of fluid bed technology, bubbling fluid bed and circulating fluid bed. The latter is distinctive as it separates the combustion process into two zones within the combustion chamber and also recirculates the hot inert material for re-use in the furnace.

Waste Types Processed

WTE technology is intended principally for combustion of MSW and WDF. It is not suitable for combustion of certain components of MSW individually, such as yard leaves or source-separated food waste. WTE technology is suitable for co-combustion of certain other wastes such as medical waste, demolition wood, auto shredder residue, dried sewage sludge, and some industrial solid wastes.

Operating Scale

The size (capacity) of modern WTE facilities is typically expressed as the number of tons per day (TPD) of MSW or WDF that can be processed by a combustion unit. WTE combustion units are available worldwide in capacities ranging from ~ 5 TPD to over 1,000 TPD. The economic viability of WTE technology depends on economies of scale in most locales. Accordingly, WTE units in the U.S. are rarely less than 100TPD in capacity, and units in the 200 to 700 TPD range are most common. Smaller capacity units have been economic in regions of Europe.

Commercial Experience and Viability

WTE is a mature processing technology with decades of successful commercial application worldwide, from small scale to large scale in processing capacity. Well-operated WTE facilities are reliable, typically achieving an annual operational availability exceeding 90% of all hours in a year. There are over 700 WTE facilities operating in 37 nations worldwide, including some small island nations[†]. Most of the WTE facilities operating worldwide are of the traditional combustion type; however; a number of advanced technology (gasification) WTE facilities are also reflected in the total.

The distribution of commercially operating WTE facilities in Europe, the Americas, and Asia is summarized in the tables that follow. In 2005, 431 WTE facilities operated in Europe, while in 2010 there were 87 WTE facilities operating in the U.S. In Europe, France, Germany, Italy, and Denmark have the most WTE plants. Clearly, with WTE in Europe, the production of thermal energy (heat) for

† Columbia University (U.S.), Waste-to-Energy Research & Technology Council (WTERT), http://www.seas.columbia.edu/earth/wtert/, accessed 12 April 2011.

municipal district heating systems (steam or hot water) predominates over electricity generation. By contrast, the generation of electricity dominates almost exclusively over heat production at WTE facilities in the U.S. Elsewhere in the Americas, there are eight WTE facilities operating in Canada; none are known to operate yet in Latin American countries; but WTE facilities operate on two Caribbean islands (Martinique, St. Barthelemy). In Asia, Japan depends entirely on WTE for MSW management, rather than on landfills.

WTE Facilities Operating in Europe		
Country	**WTE Plants* (2005)**	**Predominantly Electric or Heat Energy?**
Austria	9	Heat
Belgium	18	Electricity
Czech Rep.	3	Heat
Denmark	34	Heat
Finland	1	Heat
France	127	Heat
Germany	68	Heat
Great Britain	22	Electricity
Hungary	1	Heat
Italy	51	Electricity
Netherlands	11	Electricity
Norway	13	Heat
Portugal	3	Electricity
Spain	10	Electricity
Sweden	30	Heat
Switzerland	30	Heat
Total	431	Heat Predominates Overall

* List includes all types of WTE technology. Most are traditional combustion WTE technology; however, there are a number of advanced technologies (gasification) represented as well.
Source: International Solid Waste Association (ISWA), http://www.wte.org/userfiles/file/ERC_2010_Directory.pdf, accessed 13 April 2011

WTE Facilities Operating in the North America		
Country	**WTE Plants**	**Predominantly Electric or Heat Energy?**
U.S.	87[1]	85% Electric and 15% Heat or Heat + Electric
Canada	8[2]	Mostly electric

[1] Source: Energy Recovery Council (U.S.), http://www.wte.org/userfiles/file/ERC_2010_Directory.pdf, accessed 13 April 2011
[2] Source: Candadian Energy from Waste Coalition, http://www.energyfromwaste.ca/resources/EFW-Worldwide, accessed 14 April 2011

WTE Facilities Operating in Asia and Australia		
Country	**WTE Plants**	**Predominantly Electric or Heat Energy?**
Japan	46* [1]	Heat
Taiwan	8[2]	Electric
Singapore	5[2]	Electricity
China	4[2]	Electricity
Malasia	1[2]	Electricity
India	1[2]	Electricity
Australia	0[2]	-

* Includes all types of WTE technology, that is, a mix of traditional combustion WTE technology and advanced technologies (gasification).
[1] Source: Columbia University (U.S.), Waste-to-Energy Research & Technology Council (WTERT), http://www.seas.columbia.edu/earth/wtert/, accessed 12 April 2011
[2] Source: http://www.industcards.com/ppworld.htm, accessed 13 April 2011

WTE Facilities Operating in Small Island Countries		
Country	**WTE Plants**	**Predominantly Electric or Heat Energy?**
Caribbean (Martinique)	1[1]	Electricity
Caribbean (St. Barthelemy)	1[1]	Heat for desalination
Bermuda	1[2]	Electricity

[1] Source: http://www.industcards.com/ppworld.htm, accessed 13 April 2011
[2] Source: Government of Bermuda, http://www.rossgo.com/Tynes%20Bay/Incinerator.html, accessed 13 April 2011

Large WTE Facility in the U.S. (Huntington, NY)

Small WTE Facility in Martinique

Technology Suppliers

Listed below are many of the experienced suppliers of WTE combustion technology worldwide that have been active in the past decade. The leading suppliers are based primarily in Europe and the U.S. Most of the listed suppliers provide WTE boiler technology; however, some listed companies provide complete WTE systems (e.g., Alstom, AE&E, CNIM, Covanta, Energy Answers, Lurgi, SITA, Wheelabrator, and others).

Traditional WTE Technology Suppliers Worldwide			
AE&E/Von Roll	CTC	Inova	Onyx
ABAY	DBA	JFE	Seghers
ABB	Energy Answers	Kvaerner	SITA
Alstom	EPI	Lentje	Steinmuller
AVR	Fire Power	Lurgi	SUEM
Anseldo	FLS	Leroux	Techtue
Babcock	Foster Wheeler	Martin	Veolia
Baumjarte	Gotaverken	Mitusubishi	Wehrle
CNIM	HERA	Mucchi	Wheelabrator
Covanta			Volund

Sustainability

Resource Recovery

The principal form of resource recovery with WTE technology is energy, either in the form of electric power, thermal energy (steam or hot water), or both electric and thermal energy. WDF WTE energy facilities may also recover small quantities of traditional recyclable materials in conjunction with the mechanical processing of MSW into WDF. Most WTE facilities also recover modest amounts of ferrous metal from the ash.

Energy Conversion Efficiency

With WTE combustion technology, the MSW fuel must have a sufficient heat content or "calorific value" to ensure efficient combustion and economically-viable energy generation. In Europe, the calorific value of fuel is expressed as the Lower Heating Value (LHV), which is the heat content of the fuel, net of the amount of that heat content required to evaporate the water present in the fuel. The LHV is expressed in units of MJ/Kg. In the U.S., the heat content of fuel is expressed as the Higher Heating Value (HHV), which is the gross heat content, expressed in units of Btu/lb. In highly developed countries, the heat content of mixed MSW has HHV values ranging from 3,800 to 5,500 BTU/lb, and a typical value is 4,500 to 4,900 BTU/lb. For WDF, the heat content is higher than for mixed MSW and can range typically from 5,000 to 6,000 Btu/lb. The LHV of MSW in highly developed countries ranges from 6.3 to 12.6 MJ/Kg, and is typically 9.0 to 10.4 MJ/Kg[‡]. Generally, to be viable for WTE combustion technology, the gross calorific value (HHV) of the MSW must average above 4,000 Btu/lb. The net calorific value (LLV) must on average be at least 7 MJ/kg, and must never fall below 6 MJ/kg in any season[§].

WTE facilities are not as efficient as fossil fuel power plants at converting the energy content of the fuel into useful electric or thermal energy. Traditional power plants have a singular purpose, to generate electric power as efficiently as possible. WTE facilities are less efficient at energy generation because, they have to achieve two objectives: to reduce the volume of waste requiring disposal and to recovery of energy. Waste contains less fuel value per pound or kilogram than do the fossil fuels used at traditional power plants.

‡ European Commission, August 2006, Reference Document on the Best Available Techniques for Waste Incineration.

§ World Bank, June 2000, Municipal Solid Waste Incineration – A Decision Maker's Guide]

With WTE technology, the energy conversion efficiency is greater for generating thermal energy such as steam or hot water for district heating systems, than it is for generating electric power. As summarized by WTE experts at Columbia University in the U.S., WTE technology typically generates a net output of electric power of 500 to 600 kW-hour per ton of MSW or WDF combusted (500-600 kW h/ton); however, the net energy output for producing thermal energy (steam) is typically 1000 kW h/ton[**]. A study by US EPA scientists reported the net energy output for WTE to be typically 590 kW h/ton, and the range to be 470 to 930 kW h/ton[††]. Based on this information, the range of energy conversion efficiencies for combustion WTE to generate electric power is 500 to 600 kW h/ton, and the net energy efficiency for producing thermal energy is typically 1000 kW h/ton.

Whereas production of electric energy is the norm for WTE facilities in North America, the production of thermal energy, steam and hot water, is common in Europe. For example, 35% of Denmark's municipal district heating is provided by the 28 WTE plants operating in Denmark.

Carbon Profile and Renewable Energy

Renewable energy is often defined as energy that is derived from renewable sources and does not contribute to global warming. Only part of the energy produced by a WTE facility is considered renewable energy. Specifically, the energy produced by a WTE facility is renewable in proportion to the biogenic content of the MSW fuel that is combusted. Generally, approximately half of the total energy generation from WTE is renewable energy and half is not. This is because about half the content of MSW is comprised of biogenic materials derived originally from plants that were recently alive (e.g., paper, food waste, wood). The greenhouse gas, carbon dioxide (CO2), emitted from combusting the biogenic fraction of MSW is carbon that was previously circulating in the environment, and accordingly, that CO2 emission is “carbon-neutral,” not contributing to climate change. However, the other half of the MSW content is comprised of materials derived from fossil fuels (e.g., plastics, rubber). The combustion of the non-biogenic fraction of MSW generates emissions of CO2 that are a “new” injection of carbon into the atmosphere, which increases the potential for climate change, just as with fossil fuel combustion. To summarize, approximately half the CO2 emissions from MSW combustion are biogenic and carbon-neutral; hence, about half the energy produced by a WTE facility is renewable energy.

** Columbia University (U.S.), Waste-to-Energy Research & Technology Council (WTERT), http://www.seas.columbia.edu/earth/wtert/, accessed 12 April 2011.

†† Kaplan J, Decarolis, and Thorneloe, US EPA, Is It Better to Burn or Bury Waste for Clean Energy Generation?, Environmental Science & Technology, Volume 43, 2009.

- US EPA AP-42 emission factor compilation at http://www.epa.gov/ttn/chief/ap42/ch02/final/c02s01.pdf.

While the CO2 emissions from combustion of the biogenic fraction of MSW are carbon-neutral for WTE technology, a WTE facility can cause a net reduction in greenhouse gas emissions, if the energy generated by the WTE facility displaces existing fossil-fuel energy generation.

Water Resource Use

WTE facilities require process water. The most significant process uses include water needed by the boiler to make steam, as well as water for use in the boiler's cooling tower. Significant water use is also required by some types of emission control equipment, notably, wet and semi-dry scrubbers. Much of the water used by these processes is recycled and re-used.

Waste Diversion from Landfill

As noted above, the ash produced by WTE technology is about 15% to 25% of the weight of the MSW or WDF that is combusted. Accordingly, WTE technology diverts approximately 75% to 85% of the MSW by weight from being landfilled.

In addition, where the bottom ash is used beneficially in construction applications, rather than being landfilled, then the diversion rate from landfilling could exceed 90%.

While the mass-burn and WDF types of WTE technology each claims unique advantages and disadvantages, the WDF technology has a sustainability advantage from the standpoint of materials recovery. With RDF technology, mixed MSW is pre-processed mechanically into a more homogeneous fuel (WDF) prior to combustion and the pre-processing system is often designed to also separate significant quantities of metals, glass, plastics, and cardboard for traditional recycling. Mass-burn WTE facilities do not require preprocessing of the MSW, so normally this additional opportunity to divert materials to recycling is forgone. Mass-burn WTE facilities, however, do typically recover ferrous metals from the ash for recycling.

Land Resource Use

WTE energy facilities require adequate land for the facility structures that house the processing equipment and fuel storage, and to enable efficient onsite flow of MSW delivery trucks. In addition, the landfill where the WTE combustion ash is disposed consumes land resources.

The land area required for a WTE facility is much smaller than the land required for a landfill of similar capacity. Accordingly, from the standpoint of land resources, WTE facilities are best suited to serve regions where adequate land for a landfill is unavailable or too expensive, or the attributes of the available land resource are incompatible with landfills (ground water is near surface, karst geology).

Environmental Impacts

Air Pollutant Emissions

The combustion of MSW in a WTE facility produces air pollutants, including the common, combustion-related pollutants, nitrogen oxides (NOx), carbon dioxide (CO), and particulate matter (PM). In addition, because constituents of MSW contain levels of sulfur and chlorine, combustion of MSW results in emissions of the acid gases, sulfur dioxide (SO2) and hydrogen chloride (HCl). Further, combustion of MSW results in trace emissions of mercury and other toxic heavy metals, as well as trace emissions of toxic organic compounds, notably, dioxins and furans. Modern WTE technology includes emission control techniques that are well-demonstrated to control these emissions to levels considered acceptable by environmental regulatory agencies worldwide. Control techniques commonly used at modern WTE facilities include:

Control Technique	Pollutants Controlled
Good combustion practices	PM, NOx, CO, dioxin
Fabric filters and electrostatic precipitators (ESP)	PM, heavy metals, dioxin
Scrubbers (dry, semi-dry, wet, ionizing types)	SO2, HCl,
Ammonia reagent injection (catalytic, non-catalytic)	NOx
Carbon injection	Mercury, dioxin

Emissions of Dioxin/Furans and Mercury

With any high-temperature treatment process for MSW, there is a potential concern over the formation of dioxins and furans. In addition, with *any* treatment process for MSW, there is also a concern over the environmental fate of the mercury that is present in MSW.

Public concern arose in the 1980's regarding the potential risks to public health associated with the emission of dioxins/furnas and mercury from WTE facilities. In response, WTE combustion efficiency was further enhanced to reduce the formation of dioxins/furans, and an additional add-on control technique was implemented to ensure stringent control of both dioxins/furans and mercury, namely, the injection of carbon into the flue gas. These additional control measures have been very effective. For example, the US EPA has determined that these emission controls successfully reduced WTE emissions of dioxins/furans in the U.S. by over 99%, and mercury emissions by 96%, between 1990 and 2005[‡‡]. While modern WTE facilities still emit quantities of dioxins/furans and mercury, the emission levels are so small today that they are no longer a significant issue with most environmental regulatory bodies worldwide.

Odor

Modern WTE facilities normally do not cause odor nuisances offsite, because of mitigation methods that are proven effective. MSW storage and process are performed entirely within enclosed structures. Interior ventilation air is used as combustion air by the boiler, hence destroying odors present in that air.

Wastewater Discharges

While much of the process water used by WTE facilities is recycled and re-used, a quantity of wastewater is generated. Contaminants build up in the process water used in the boiler and in the cooling system, so a portion of the contaminated process water must be constantly withdrawn as a wastewater, and replaced with fresh water. The process wastewater is treated and discharged to the sewer or to an adequate, receiving water body. Many WTE facilities are "zero discharge" for process wastewater, with no process wastewater discharge to the environment. This is the norm for WTE facilities in North America. Instead of discharging process wastewater, those facilities use the wastewater to quench and moisten the ash, which facilitates ash handling.

‡‡ US EPA, 10 August 2007, Memorandum from W. Stevenson to docket file, "Emissions from Large and Small MWC Units at MACT Compliance."

Regarding storm water, there is little potential for a contaminated storm-water discharge to the environment from a modern WTE facility. This is because modern WTE facilities are totally enclosed, including MSW delivery and storage operations, and ash handling and storage. Accordingly, the environment is not exposed to the MSW and ash.

Solid Waste Generation

The principal generation of solid waste by WTE technology is the combustion ash, which comprises about 15% to 25% of the incoming MSW or WDF by weight, and about 10% by volume. Small quantities of waste sludge can be generated when waste water from emission control scrubbers is treated. With WDF WTE facilities, the mechanical processing of MSW into WDF results in quantities of solid waste in the form of inert unprocessible material such as grit.

Ash management at WTE facilities is different in Europe and Japan from North America. In Europe and Japan, the ash removed from the boiler grate (boiler ash) is managed separately from the ash filtered from the flue gas by the emission control equipment (fly ash). Rather than landfilling the bottom ash, it is typically beneficially used, principally in road construction. The fly ash, which is contaminated with heavy metals, is normally disposed in a landfill. In North America, however, the boiler ash and fly ash are normally combined at the WTE facility, not managed separately, for economic reasons. As a consequence, this discourages beneficial use of the ash, and most ash is landfilled. Except for some use as daily cover material at landfills, instead of using soil, there is very little beneficial use of WTE ash in North America. Because of the heavy metals present in fly ash, toxicity testing of WTE ash is required in North America to determine suitable disposal.

The generation of solid waste by WTE technology varies from 15% to 25% of the weight of the input MSW in the U.S. where the ash is landfilled, to as little as 10% in Europe, where the fly ash is also landfilled, but the bottom ash component of total ash is beneficially used.

Safety Hazards

The safety hazards specific to WTE facilities would include the following:

- Fires on waste delivery trucks and during waste storage
- Exposure to waste-borne pathogens and toxic substances
- Increased traffic hazard from waste delivery trucks

- For WDF WTE technology, there is an explosion risk if explosive materials (e.g., gas tank) are mixed with the waste that is being mechanically processed into WDF.
- Injury, potentially fatal, from rare boiler-related explosions.

While these are all safety hazards for workers at a WTE facility, only the truck-related safety hazard would likely extend significantly to the public offsite.

Economics/ Institutional

Economics

Thermal technologies for MSW processing such as combustion WTE, gasification, and pyrolysis, are typically the most costly options for MSW processing. WTE technology requires high capital cost as well as high operating and maintenance costs. Accordingly, the implementation of WTE technology worldwide has been confined mostly to developed countries. While the high cost of WTE has kept it beyond the reach of most developing countries to date, there are circumstances under which WTE is potentially viable in developing countries:

- Locations in major urban centers with a robust industrial/commercial economy and adequate municipal financial/investment capacity, as well as a skilled work force
- Other urban centers where non-economic factors control, making modern landfills infeasible. For example, locations with unsuitable subsurface conditions (e.g., ground water near surface, karst) or lack of land resource (island nations or mountainous areas).
- Project locations where the high cost for WTE can be adequately defrayed by using international financing mechanisms.

The capital and operating costs for WTE technology will vary with the type of WTE combustion technology, the facility size, the nature of the country's economy, taxation laws, market competition, and other factors. The capital cost for modern WTE technology in developed countries has risen substantially over the past 15 years, owing to the cost of improved emission controls. Based on review of the literature, the capital cost for modern WTE technology today is in the general range of US $450 to $750 for each ton of annual processing capacity. Stated in another common form, the capital cost is approximately US $150,000 to $250,000 for each ton-per-day (TPD) of processing capacity, assuming a modern plant operates 90% of the days in a year (~330 days). For example, a WTE facility processing 100,000 tons per year of MSW (~ 300 TPD) would have a typical total capital cost in a developed country of US $45,000,000 to $75,000,000.

The typical operating cost for a WTE facility in developed countries can vary significantly, but based on review of the literature, a typical cost is US $40 to $50 per ton of waste processed.

Summarized below are literature sources consulted in estimating the capital and operating costs for WTE technology:

- The capital cost in Europe in 2001 for a hypothetical WTE facility combusting 250,000 tonnes per year of MSW was estimated to be 140,000,000 euros, and the operating cost was estimated at 29 million euros per year[§§].
- A representative capital cost for WTE is given presently as US $650/annual ton (500 euros) by waste management specialists at Columbia University (U.S.), which for an operation of 330 days per year converts to $215,000/TPD[***].
- A comprehensive study in 2004 of thermal treatment technologies for MSW estimated the capital cost for WTE technology to be US $150,000/TPD for a 500 ton per day facility, and the operating cost to be $44/ton[†††].

Operational Complexity

WTE combustion technology is technically complex and requires skillful operation and careful maintenance. This requires facility operating personnel who possess specialized skills and who are highly trained. While qualified personnel are readily available in developed countries, this is not the case in most developing countries, except in some major urban centers.

Public Acceptance

Public acceptance of combustion WTE technology varies around the world in the countries where it has been deployed. WTE technology has generally been supported in European countries and Japan. In the U.S. and Canada, WTE has been much more controversial, with some regions of those countries supporting WTE development and others prohibiting it. While there has been only limited implementation of WTE in developing countries to date, the initial WTE projects proposed to date appear to be publicly supported.

§§ European Commission, August 2006, Reference Document on the Best Available Techniques for Waste Incineration, P.14.

*** Columbia University (U.S.), Waste-to-Energy Research & Technology Council (WTERT), http://www.seas.columbia.edu/earth/wtert/, accessed 16 April 2011.

††† Alternative Resources Inc., September 2004, Phase-I, Evaluation of New and Emerging Solid Waste Management Technologies, P.90, prepared for the Economic Development Corp. of the City of New York.]

Annex 3:

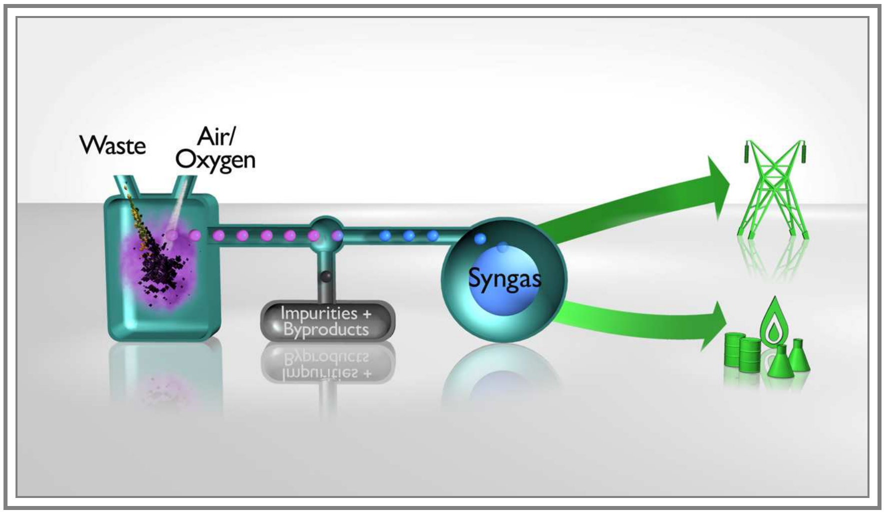
Gasification and Pyrolysis

Technology Description and Operating Scale

Technology Description

Thermal gasification, in general, is a centuries-old technology, with a long history of commercial application. Pyrolysis-type gasification (defined below) has been in continuous use for several hundred years to produce charcoal from wood. Modern gasification got its start in the 1800's when coal was gasified to produce "town gas" for street lights and cooking stoves. Gasification to produce liquid chemicals and liquid fuels from coal started in the 1920's. Gasification of coal, woody biomass, and industrial scrap/wastes has been accomplished successfully at commercial scale, principally in Europe and Asia. Application of gasification technology specifically to MSW has gained commercial viability over the past 20 years, again, principally in Asia and Europe.

Thermal gasifiers use high heat to convert solid feedstocks into a synthetic gas for use as a fuel, which is then combusted in a boiler to generate electricity or thermal energy (steam), or is combusted in an engine-generator set to produce electricity. Alternatively, the synthetic gas can be converted in a chemical process to liquid transportation fuels (ethanol, synthetic diesel) or chemicals. The basic process for gasification of MSW is shown in the diagram below. MSW is normally pre-processed with mechanical equipment that reduces the MSW to particles of a uniform small size, and in some processes, densifies this waste-derived fuel (WDF) into pellets. The WDF is then introduced to the gasifier unit. There, the MSW is converted at high temperature to a synthesis gas. The synthesis gas is cleaned of impurities, then used as a fuel to generate energy or as a feedstock to make synthetic liquid fuel or chemicals. Gasification produces a solid residue in the form of ash, slag, or char that is normally disposed, but can be beneficially used in some cases.



Gasification of Solid Waste to Produce Energy or Liquid Fuels
(Source: Gasification Technologies Counsel)

Modern gasifiers are of three types. *Conventional thermal gasifiers* use a limited amount of air, steam, or oxygen to initiate heating and gasification reactions. *Pyrolysis gasifiers* use an external heat source and accomplish gasification in the absence of oxygen. *Plasma gasifiers* use an electric arc to generate the heat needed for gasification or pyrolysis. The three gasifier types are further described below.

Thermal Gasification – Converts organic feedstock materials (i.e., carbon-containing materials such as MSW, coal, plastics, wood, manures) into a synthetic gas via a thermo-chemical reaction in the presence of a limited amount of oxygen. Enough air, steam, or oxygen is used to promote partial oxidation (partial combustion) of the feedstock materials, but not enough to enable full combustion. Hence, MSW gasification is different from MSW combustion. The partial oxidation in the gasifier produces hydrogen, carbon monoxide and heat energy. The heat energy from partial oxidation in the gasifier releases volatile compounds from the feedstock material (the process of pyrolysis) and leaves a char. The heat energy also enables a second reaction to occur rapidly ("water-gas shift"), in which some of the carbon monoxide reacts with water vapor to yield hydrogen. Conventional thermal gasification yields a synthesis gas (syngas) that is rich in carbon monoxide and hydrogen, and also contains varying amounts of methane, other gases, tars, and water vapor. The hydrogen and carbon monoxide provide the principal fuel value of the syngas. The syngas is typically treated to remove impurities, and can then be used as a fuel in a boiler to generate electricity or thermal energy (steam). The syngas can also be used to fuel a reciprocating-engine/generator set to generate electric power. Gasification results in an ash-like solid residue that must be disposed, if not suitable for beneficial uses.

While MSW is not combusted in a gasification process, the syngas resulting from gasification is combusted in the boilers and engine-generators used to recover energy. Those boilers and engines need to employ standard, air-pollutant emission controls. Another use for the syngas is to subject it to a process that converts the syngas to a synthetic liquid fuel (e.g., ethanol, diesel fuel) or a chemical product. The conversion of the syngas to liquid fuel often uses a metal catalyst in a long-established chemical process referred to as the Fischer-Tropsch process.

There are variations of thermal gasifier design (fixed bed, fluid bed, downdraft, updraft, others) and each has advantages and disadvantages, depending on the particular application.

Pyrolysis – In this type of gasification, the MSW is placed in a closed vessel and heated from the outside to a high temperature, with no oxygen or air present. No combustion of the MSW occurs. With pyrolysis, the source of heat for heating the vessel can be fossil fuel combustion, fuel gas recovered from downstream in the process, or plasma (described next below). The heating converts the carbon present in the MSW to gases and oils composed of hydrocarbons and hydrogen gas. High-temperature pyrolysis produces more gases than oils, and the gas produced is characterized as a synthetic gas ("syngas"). Lower temperature pyrolysis processes produce more volatilized oils than gas, and the resulting gaseous product is called a "fuel gas," and the resulting liquid fuel oil is called "pyrolysis oil." Pyrolysis oil can be used as a lower-grade fuel, or refined into higher-grade fuels and chemicals. Following treatment to remove impurities, the syngas or fuel gas can be used in boilers to generate electricity and/or steam, or in an engine-generator set to generate electricity. Pyrolysis gas can contain significant concentrations of methane and high tar levels, making conversion of the gas to high-grade liquid fuels challenging. The solid residue resulting from pyrolysis, the char, can potentially have beneficial uses, but is also simply disposed.

Plasma-Arc Gasification – Plasma is used as the source of heat for gasification or pyrolysis of the feedstock materials, including MSW. Plasma is an extremely hot (7,000^{o} F) flow of ionized gas, produced by passing electricity through electrodes to create an electric arc torch. The high operating temperature results in almost complete conversion of the carbon in the MSW to energy, the virtual destruction of organic pollutants, and the conversion of the process residue into an inert glassy slag. The high-quality synthesis gas can be used directly as a fuel for electricity or steam generation, or be converted in a subsequent process to a high-grade liquid fuel. Plasma gasifiers, however, generally can't operate efficiently at partial load conditions, which could be a problem if the amount of available MSW were to vary from day to day. The economics of plasma-arc gasification can be very challenging. Plasma gasification has the important advantage of converting the energy value of the feedstock material into useful energy with the highest efficiency of all of the gasifier types; however, a related disadvantage is that a large fraction of the energy generated is offset by the high electric power consumption inherent to the operation of a plasma arc torch. Finally, the ability of plasma gasification to render the most toxic pollutants inert makes it ideal for co-disposal of multiple types of waste: MSW, medical waste, hazardous waste, and nuclear waste.

With gasification technology, the MSW fuel must have a sufficient heat content or "calorific value" to ensure efficient and economically-viable energy generation. The calorific value of MSW in developed countries is sufficient for gasification technology, but may not be in the least developed countries and in rural sub-regions of many developing countries, owing to differences in waste composition.

Waste Types Processed

While gasification technology is suitable for MSW and WDF, it is generally not suitable for processing of certain components of MSW individually, such as yard leaves or source-separated food waste. The technology is suitable for co-gasification of virtually any other type of waste, including medical waste, hazardous waste, demolition wood, auto shredder residue, dried sewage sludge, industrial solid wastes, and radioactive waste

Operating Scale

The size (capacity) of MSW gasification technology is typically expressed as the number of tons per day (TPD) of MSW or WDF that can be processed by a gasification unit. MSW gasification units are available worldwide in capacities ranging from ~ 40 TPD to 900 TPD. The economic viability of MSW gasification depends on economies of scale in most locales. Accordingly, MSW gasification units operating worldwide are most commonly in the 150 to 600 TPD.

Commercial Experience and Viability

As noted above, gasification technology in general is a centuries-old technology, with a long history of commercial application. Many advancements in gasification technology have been made since the 1940's, principally in Europe and Japan. Gasification of coal, woody biomass, industrial scrap/wastes, and, notably MSW, has been accomplished successfully at commercial scale, again principally in Europe and Asia. In most of the world, the syngas from gasification of all feedstocks, MSW included, has been used for energy generation. Since the 1950's, however, South Africa has been a pioneer and world leader in the gasification of solid feedstocks (coal, and recently, wood), with conversion of the syngas to liquid transportation fuel. Gasification of MSW for conversion to liquid fuels is still an emerging technology, and is evolving most rapidly in North America.

While gasification of MSW has not yet been commercialized in the in the Americas, there is a substantial commercial track record in Asia and Europe for successful gasification of MSW, established over the past two decades. There are over 60 MSW gasification facilities operating worldwide. In Japan, there is an extensive commercial track record for MSW gasification – nearly three dozen facilities using various types of gasifiers (conventional thermal, pyrolysis, plasma arc). MSW gasifiers became commercially common in Japan first, because Japan is a small island nation, has no landfill capacity and is thus accustomed to high waste management costs. In addition, the cost for electric power generated from fossil fuels is high in Japan. These factors make advanced MSW treatment technologies such as gasification cost-effective in Japan. Most of the MSW gasification facilities in Japan became operational since 2000, and all convert waste materials into electricity and steam. Those waste materials include MSW; components of MSW such as waste wood, plastics residue, auto shredder residue, and old tires; biosolids; and even hazardous waste co-gasified with MSW. All types of MSW gasification technology have been commercially demonstrated in Japan – thermal gasification, pyrolysis, and plasma arc.

There has been significant commercial experience in Europe as well with MSW gasification (Denmark, Finland, Germany, Italy, Norway, Sweden and the U.K.), and at least 15 commercial facilities for gasification of MSW have operated there. In Europe, the commercial experience is significant for both thermal gasification and pyrolysis gasification. No plasma gasifiers for MSW have operated in Europe.

There has been increased interest in MSW gasification in the Americas since the late 1990s. Gasification technology vendors have operated demonstration-scale facilities for MSW gasification in the U.S. and Canada, and a number of commercial project developments are in various stages of planning and implementation. To date, however, MSW gasification has not been demonstrated at commercial scale in the Americas.

Detailed information is summarized in the tables below on the worldwide, commercial implementation of MSW gasification technology. Again, this experience is presently confined to Asia and Europe. As these compilations were performed by third parties, there are differences between the tables in the type of information provided, and there is some overlap between the tables in the gasification facilities listed. These tables summarize the commercial implementation of MSW gasification worldwide through 2005, and there have been a number of additional MSW gasification facilities that have begun commercial operation after 2005, for example, the Skive Plant in Denmark (2008) that gasifies both biomass and MSW to produce electric power using the GTI U-GAS gasification process. It is noteworthy that all three types of gasifier technology (thermal gasification, pyrolysis, and plasma arc) have had significant commercial implementation worldwide processing MSW.

Commercially Operating Facilities Worldwide for MSW Gasification as of 2003[1]			
Location	**Company**	**Began Operation**	**MSW Capacity**
Toyohashi City, Japan Aichi Prefecture	Mitsui Babcock	March 2002	2 x 220 TPD
Hamm, Germany	Techtrade	2002	353 TPD
Koga Seibu, Japan Fukuoka Prefecture	Mitsui Babcock	January 2003	2 x 143 TPD
Yame Seibu, Japan Fukuoka Prefecture	Mitsui Babcock	March 2000	2 x 121TPD
Izumo, Japan	Thidde/Hitachi	2003	70,000 TPY
Nishi Iburi, Japan Hokkaido Prefecture	Mitsui Babcock	March 2003	2 x 115 TPD
Kokubu, Japan	Takuma	2003	2 x 89 TPD
Kyouhoku, Japan Prefecture	Mitsui Babcock	2003	2 x 88 TPD
Ebetsu City, Japan Hokkaido Prefecture	Mitsui Babcock	2002	2 x 77 TPD
Oshima, Hokkaido Is., Japan	Takuma	unknown	2 x 66 TPD
Burgau, Germany	Technip/Waste Gen	1987	40,000 TPY
Itoigawa, Japan	Thidde/Hitachi	2002	25,000 TPY
SVZ, Germany	Envirotherm	2001	275,000 tpy
Karlsuhe, 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

Commercially Operating Facilities Worldwide for MSW Gasification as of 2003[1]			
Location	**Company**	**Began Operation**	**MSW Capacity**
Utashinai City, Japan	Hitachi Metals	unknown	300 tpd
Kagawa, Japan	Hitachi Zosen	2004	unknown
Nagareyama, Japan	Ebara	2004	229 tpd
Narashino City, Japan	Nippon Steel	2002	222 tpd
Itoshima-Kumiai, Japan	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, Japan	Nippon Steel	1997	216 tpd
Lizuka City, Japan	Nippon Steel	1998	198 tpd
Tajimi City, Japan	Nippon Steel	2003	188 tpd
Chuno Union, Japan	Ebara	2003	186 tpd
Genkai Envir. Union, Japan	Nippon Steel	2003	176 tpd
Iabarki #3, Japan	Nippon Steel	1999	166 tpd
Ishikawa, Japan	Hitachi-Zosen	2003	160 tpd
Kocki West Envir., Japan	Nippon Steel	2002	154 tpd
Nara, Japan	Hitachi-Zosen	2001	150 tpd
Toyokama Union, Japan	Nippon Steel	2003	144 tpd

[1] "Conversion Technologies Report to Legislature (Draft)," Integrated Waste Management Board, Sacramento, CA, February 2005.

Commercial Facilities in Europe for MSW Gasification as of 2005[1]

Manufacturer	Primary Technology	Country	Operational	Capacity, tpa	Feed
Compact Power	Tube Pyrolysis	UK - Avonmouth	2001	8,000	Clinical Waste
Energos	Grate Gasification	Norway	1997	10,000	Industrial & Paper Wastes
Energos	Grate Gasification	Norway	2000	34,000	MSW
Energos	Grate Gasification	Norway	2001	36,000	MSW & industrial waste
Energos	Grate Gasification	Norway	2002	70,000	MSW & industrial waste
Energos	Grate Gasification	Norway	2002	37,000	MSW
Energos	Grate Gasification	Germany	2002	37,000	MSW & industrial waste
Energos	Grate Gasification	Germany	2005	80,000	MSW, Commercial, Industrial
Energos	Grate Gasification	Sweden	2005	80,000	Municipal & Industrial Waste
Enerkem/Novera	Fluidised Bed Gasification	Spain	2002	25,000	Plastics
FERCO	Fluidised Bed Gasification	USA	1997	165,000	Biomass
Foster Wheeler	Fast (ablative) Pyrolysis	Finland	1998	80,000	Mix waste
Mitsui Babcock	Rotary Kiln Pyrolysis	Japan	2000	80,000	MSW
Mitsui Babcock	Rotary Kiln Pyrolysis	Japan	2002	150,000	MSW
Mitsui Babcock	Rotary Kiln Pyrolysis	Japan	2002	50,000	MSW
Mitsui Babcock	Rotary Kiln Pyrolysis	Japan	2003	95,000	MSW
Mitsui Babcock	Rotary Kiln Pyrolysis	Japan	2003	75,000	MSW
Mitsui Babcock	Rotary Kiln Pyrolysis	Japan	2003	60,000	MSW
Thermoselect	Tube Pyrolysis	Germany	1999	225,000	Domestic & Industrial Wastes
Thermoselect	Tube Pyrolysis	Japan	1999	100,000	Domestic & Industrial Wastes
Thermoselect	Tube Pyrolysis	Japan	2003	50,000	Industrial Wastes
Techtrade/ Wastegen	Rotary Kiln Pyrolysis	Germany	1984	35,000	RDF
Techtrade/ Wastegen	Rotary Kiln Pyrolysis	Germany	2002	100,000	Domestic & Industrial Wastes

[1] Source: U.K. Department for Environment, Food and Rural Affairs (DEFRA), 2007, Advanced Thermal Treatment of Municipal Solid Waste, http://archive.defra.gov.uk/environment/waste/residual/newtech/documents/att.pdf

Regarding gasification of MSW to produce liquid fuels and chemicals, there are no commercial facilities operating anywhere in the world as yet. However, in North America, companies such as Enerkem, Rentech, and Plasco have demonstration scale facilities. Enerkem has a large commercial scale facility in construction in Edmonton, Canada. In addition, Coskata and Fulcrum Bioenergy have recently announced planned project developments in the U.S.

MSW Gasification at Small Scale (30,000 TPY), U.K.
(Source: Energos. Note that World Bank does not make commercial endorsements.)

MSW Gasification at Large Scale (260,000 TPY), Germany
(Source: Thermoselect. Note that World Bank does not make commercial endorsements.)

Technology Suppliers

Listed below are many of the suppliers of gasification technology worldwide that have been active in the past decade. The leading suppliers are based primarily in Europe and North America. Most of the listed suppliers provide the gasification technology; however, some listed companies provide complete systems for conversion of MSW to energy via gasification.

Suppliers of MSW Gasification Technology Worldwide			
AE&E	Envirotherm	IES	Taylor Recycling
AlterNRG	EPI	Lurgi	Techtrade/Wastengen
Coskata	Foster Wheeler	Mitsui Babcock	Thermoselect/IWT/JFE
Dynecology	Fulcrum Bioenergy	Nippon Steel	Thidde/Hitachi
Ebarra	GEM	Primenergy	Hued Prenflo
Energos	Geoplasma	Remtech	Wastegen
Envirotherm	GTI U-Gas	Rigel	Westinghouse
EPI	Gentech	Plasco	
Energos	Hitachi	Takuma	

The suppliers of gasification technology who have been actively pursuing the market specifically in the Americas for MSW gasification include the following:

- AlterNRG (Westinghouse-plasma gasification)
- Ebara (conventional gasification)
- Geoplasma (plasma gasification)
- Enerkem (gasification for ethanol production)
- Interstate Waste Technologies/Thermoselect (integrated pyrolysis and conventional gasification)
- IES - International Environmental Solutions (pyrolysis gasification)
- NTech Environmental (conventional gasification)
- Primenergy (conventional gasification)
- Rigel Resource Recovery and Conversion (Westinghouse-plasma gasification process)
- WasteGen (pyrolysis gasification)

Note that all three types of gasification technology (thermal, pyrolysis, plasma) are represented among the vendors of commercially-demonstrated gasifiers pursuing the market in the Americas for MSW gasification.

For a number of the MSW gasification technologies being marketed in the Americas, information is summarized below regarding the U.S. sponsor for each technology and the commercial reference plant for each technology.

Gasification Technology and US Sponsor Company		Type of Gasification Technology	Commercial Reference Plants for Gasification of MSW
Technology Vendor (Country)	US Sponsor		
Twin-Rec (Japan)	Ebara (Japan)	Conventional	Kawaguchi, Japan (379 TPD)
GEM (UK)	GEM America (US)	Pyrolysis	South Wales, UK (40 TPD)
JFE Thermoselect (Japan)	IWT -- Interstate Waste Technologies (US)	Conventional	Kurashiki, Japan (610 TPD) Chiba, Japan (330 TPD) Karlsruhe, Germany (678 TPD)
Westinghouse (US)	Rigel (US and Others)	Plasma-Arc	Utashinai, Japan (247 TPD)
IES – International Environmental Solutions (US)	IES (US)	Pyrolysis	Romoland, California (50 TPD)
Entech (Australia)	NTech Environmental	Conventional	Genting, Malaysia (67 TPD)

Data Sources:
New York City Economic Development Corporation, "Focused Verification and Validation of Advanced Solid Waste Management Conversion Technologies: Phase 2 Study," prepared by Alternative Resources, Inc. (ARI), Concord, MA, March 2006

County of Los Angeles (California) Department of Public Works and County Solid Waste Management Committee, "Los Angeles County Conversion Technology Evaluation Report – Phase II," prepared by Alternative Resources, Inc. (ARI), Concord, MA, October 2007.

Finally, again, although there are no commercial scale facilities operating in the world as yet for conversion of MSW to liquid transportation fuels, companies actively pursuing the market in the Americas include Enerkem, Plasco, Remtech, Coskata, Fulcrum Bioenergy, and others.

Sustainability

Resource Recovery

The principal form of resource recovery with MSW gasification technology is energy, either in the form of electric power, thermal energy (steam or hot water), or both electric and thermal energy. However, technology is emerging rapidly towards commercialization of processes that gasify MSW and convert the resulting syngas to liquid fuels such as ethanol or synthetic diesel, or to industrial chemicals such as methanol.

While the solid residue produced by most gasifiers is likely to be disposed as a solid waste, the residue from plasma-type gasification of MSW is an inert, glassy slag having market value as aggregate. Beneficial use of the solid residue is another opportunity for resource recovery.

Energy Conversion Efficiency

As with combustion WTE technology, MSW gasification is generally not as efficient as fossil fuel power plants at converting the energy content of the fuel into useful electric or thermal energy. Traditional power plants have a singular purpose, to generate electric power as efficiently as possible. MSW gasification facilities are less efficient at energy generation because, they have two objectives: to reduce the volume of waste requiring disposal and to recovery energy and other products. The energy content of waste per pound or kilogram is much less than with fossil fuels used by traditional power plants. With MSW gasification technology, the energy conversion efficiency is greater for generating thermal energy such as steam or hot water for district heating systems, than it is for generating electric power.

The energy conversion efficiency is measured as the amount of net energy output generated per ton of MSW or WDF gasified, expressed in units of kW-h per ton. In studies performed in the U.S. for the City of New York and Los Angeles County, California, the energy conversion efficiency of MSW gasification was evaluated for a number of individual vendors'gasification systems being marketed for MSW gasification in the U.S. The energy conversion efficiencies are summarized below:

Energy Conversion Efficiency Determined for a Number of MSW Gasification Systems			
MSW Gasifier Supplier	**Gasifier Type**	**Energy Conversion Efficiency – Net Electric Energy Output per Ton of MSW Processed (kW h/ton)**	**Reference**
Ebara	Thermal gasification	383, <455	1,2
GEM America	Thermal gasification	583	2
IES	Pyrolysis	489	3
IWT/Thermselect	Thermal gasification	476, 493, and 851 (combined cycle)	1,2,3
NTech	Thermal gasification	573	3
Rigel	Plasma gasification	684	1

References:

[1]Alternative Resources Inc., September 2004, Phase-I - Evaluation of New and Emerging Solid Waste Management Technologies, prepared for the Economic Development Corp. of the City of New York.

[2]Alternative Resources Inc., March 2006, Phase 2 - Advanced Solid Waste Management Conversion Technologies, prepared for the Economic Development Corp. of the City of New York.

[3]Alternative Resources, Inc., 2007. "Los Angeles County Conversion Technology Evaluation Report – Phase II," prepared for the Los Angeles County Dept. of Public Works, October 2007.

Another assessment of available data compiled the following ranges of energy conversion efficiencies for electric power production using MSW gasification[1]:

Thermal gasification:	400 – 650 kW h/ton
Pyrolysis gasification:	450 – 530 kW h/ton
Plasma Arc gasification:	400 – 1,250 kW h/ton

The anomalously high-end value for plasma gasification may represent the gross energy generation, rather than net, that is, the energy output before subtracting the considerable fraction of the energy generated that is required to operate the plasma equipment.

[1] Environmental and Energy Study Institute (EESI), July 2009, Reconsidering Municipal Solid Waste as a Renewable Energy Feedstock.

From the data bases above, typical values are presented below for the efficiencies with which the energy content of MSW is converted to net electric output via MSW gasification:

Typical Energy Conversion Efficiency for MSW Gasification to Generate Electricity	
Thermal Gasification	400 to 600 kW h/Ton of MSW
Pyrolysis Gasification	450 to 530 kW h/Ton of MSW
Plasma Arc Gasifaction	400 to 700 kW h/Ton of MSW
Benchmark: Combustion WTE	500 to 600 kW h/Ton of MSW

It is important to recognize that the energy conversion efficiencies shown above for MSW gasification to generate electricity could be substantially higher if the energy product is thermal energy (steam, hot water), rather than electricity. In addition, if electric power is generated using a combustion turbine with waste-heat recovery, rather than a conventional steam boiler, then the energy conversion efficiency would also be much higher than indicated above. Such efficient "combined cycle" electric generation is technically feasible with MSW gasification, but not with combustion WTE technology. The energy conversion efficiencies for MSW gasification to generate thermal energy, rather than electricity, or to generate electric power using combined-cycle technology, is estimated to be in the range of 800 to 1,000 kW h/ton.

Finally, the energy conversion efficiency is also likely higher for gasification to convert MSW to liquid transportation fuels than it is for conversion to electric power.

Carbon Profile and Renewable Energy

Renewable energy is often defined as energy that is derived from renewable sources and does not contribute to global warming. Only part of the energy produced by a MSW gasification facility is considered renewable energy. Specifically, the energy produced by a MSW gasification facility is renewable in proportion to the biogenic content of the MSW fuel that is gasified. Generally, approximately half of the total energy generation from a MSW gasification facility is renewable energy and half is not. This is because about half the content of MSW is comprised of biogenic materials derived originally from plants that were recently alive (e.g., paper, food waste, wood)[2]. The greenhouse gas, carbon

2 US EPA AP-42 emission factor compilationhttp://www.epa.gov/ttn/chief/ap42/ch02/final/c02s01.pdf.

dioxide (CO_2), emitted from gasifying the biogenic fraction of MSW is carbon that was previously circulating in the environment, and accordingly, that CO_2 emission is "carbon-neutral," not contributing to climate change. However, the other half of the MSW content is comprised of materials derived from fossil fuels (e.g., plastics, rubber). The gasification of the non-biogenic fraction of MSW generates emissions of CO_2 that are a "new" injection of carbon into the atmosphere, which increases the potential for climate change, just as with fossil fuel gasification. To summarize, approximately half the CO_2 emissions from MSW gasification are biogenic and carbon-neutral; hence, about half the energy produced by a MSW gasification facility is renewable energy.

While the CO_2 emissions from gasification of the biogenic fraction of MSW are carbon-neutral for MSW gasification technology, a MSW gasification facility can cause a net reduction in greenhouse gas emissions, if the energy generated by the MSW gasification facility displaces existing fossil-fuel energy generation. Since the net energy conversion efficiency for producing electric energy from gasification of MSW is similar to that of combustion WTE, they would typically have similar carbon profiles. However, unlike with combustion WTE, there is the potential with MSW gasification to use highly efficient "combined-cycle" technology for generating energy. If used, then the carbon profile for MSW gasification would be better than that of combustion WTE. Similarly, if the syngas resulting from MSW gasification is efficiently converted to liquid fuels, the carbon profile is likely more favorable than that of combustion WTE.

Conversely, if fossil fuel were used continuously as the heat source in a pyrolysis-type MSW gasifer, then the carbon profile could be less favorable than with combustion WTE. The same is potentially true for plasma arc gasification of MSW if the electricity needed to run the plasma technology is derived from fossil fuel generation.

<u>Water Resource Use</u>

MSW gasification facilities can require process water to various degrees, depending on a number of factors. Steam is injected into some gasifiers as part of the process and that requires water. Process water is needed for the scrubbing systems used by some gasifiers to clean the syngas of impurities. If energy is produced by combusting syngas using a boiler, significant process water would be needed by the boiler to make steam, and water would also be needed for use in the boiler's cooling tower. Significant water use is also required by some types of emission control equipment, notably, wet and semi-dry scrubbers, if used to clean the boiler exhaust. Much of the water used by these processes is recycled and re-used.

Notably, some gasification processes actually produce more water than they use. This is especially so for MSW gasification when the product is liquid fuels. In comparison with combustion WTE, gasification of MSW would use process water in amounts varying from similar to substantially lower, depending on the type of gasification technology and the type of energy product produced.

Waste Diversion from Landfill

All technologies that process MSW thermally at high temperature (combustion, gasification, pyrolysis) generate a solid residue that, if not beneficially used, must be disposed. As discussed elsewhere in this report, the diversion of waste from landfilling achieved using combustion WTE ranges from about 75% where the combustion ash is simply landfilled, to 90% or more where most of the ash is beneficially used. Waste diversion for gasification has been estimated based on literature data[3],[4]. With pyrolysis gasification, the waste diversion ranges similarly from 72% to 95%, depending on the fraction of the solid residue (char) that is landfilled versus beneficially used. With thermal gasification there appears to be a greater potential for beneficial use of the solid residue (ash/slag), and waste diversion from landfill ranges from 94% to nearly 100%. Finally, with plasma gasification which operates at extremely high temperature, the solid residue takes the form of an inert, glassy slag that has market value as construction aggregate. Accordingly, little of the residue needs be landfilled and the waste diversion rate from landfill is 95% to 100%.

Land Resource Use

MSW gasification requires adequate land for the facility structures that house the processing equipment and fuel storage, and to enable efficient onsite flow of MSW delivery trucks. In addition, if solid residue is landfilled, the landfill where that ash/char/slag is disposed consumes land resources.

The land area required for a MSW gasification facility is much smaller than the land required for a landfill of similar capacity. The land area requirements for MSW gasification and combustion WTE are approximately similar. Accordingly, from the standpoint of land resources, MSW gasification technology and combustion WTE facilities are best suited to serve regions where adequate land for a landfill is unavailable or too expensive, or the attributes of the available land resource are incompatible with landfills (ground water is near surface, karst geology).

[3] Environmental and Energy Study Institute (EESI), July 2009, Reconsidering Municipal Solid Waste as a Renewable Energy Feedstock.
[4] Alternative Resources Inc., September 2004, Phase-I, Evaluation of New and Emerging Solid Waste Management Technologies, prepared for the Economic Development Corp. of the City of New York.

Environmental Impacts

Air Pollutant Emissions

Gasification processes, including gasification of MSW, are "closed processes," and as such do not generally have emissions to the air. Whereas combustion processes produce an exhaust gas containing air pollutants, gasification creates a syngas that is beneficially used, not exhausted to the atmosphere. While the gasification process does not emit air pollutants, the combustion of the syngas to produce energy does result in an exhaust gas and air pollutant emissions. Accordingly, there will be air pollutant emissions from the boiler, combustion turbine, or engine-generator set in which the syngas is combusted to produce energy.

With gasification, air pollutants can be removed from the syngas before the syngas is combusted as a fuel, or the pollutants can be removed using controls placed on the exhaust of the syngas combustion devices, as is done with combustion WTE. Combustion of syngas to generate energy would result in emissions of the standard combustion pollutants, carbon monoxide, nitrogen oxides, and particulate matter. Those emissions would be controlled using a combination of good combustion efficiency and add-on control methods, as required. Generally, the formation and emission of those pollutants would be less for MSW gasification than with combustion WTE, as combustion of a gaseous fuel is more efficient than combustion of a solid fuel. The potential for emissions of acid gases such as sulfur dioxide and hydrogen chloride would be similar for MSW gasification and combustion WTE. With gasification, the sulfur and chlorine responsible for those emissions are typically cleaned from the syngas, prior to combustion using conventional scrubbing techniques. Potential emissions of dioxins/furans for MSW gasification are addressed subsequently below.

Emissions of Dioxin/Furans and Mercury

With any high-temperature treatment process for MSW, there is a potential concern over the formation of dioxins and furans. In addition, with *any* treatment process for MSW, there is also a concern over the environmental fate of the mercury that is present in MSW.

Emissions of dioxins/furans and mercury from waste-to-energy (WTE) facilities became very controversial in the 1980's; however, stringent control requirements imposed since have been effective in reducing the emissions to minor levels. Regarding dioxins/furans, because with gasification, the MSW gasification process takes place with little to no oxygen present, the potential for formation of dioxins/furans is lower than with combustion WTE.

Comprehensive summaries of data on actual emissions of dioxins/furans from MSW gasification facilities were not found. However, dioxins/furans emissions data supplied by the vendors for three specific gasification technologies are summarized in the table below. As a benchmark, the emission rates for the MSW gasifiers are compared there with the typical emission rate of dioxins/furans for combustion WTE. While the emissions are very low for both MSW combustion and gasification, the MSW gasifiers have typical dioxins/furans emission levels that are lower than for combustion WTE.

Emission of Dioxins/Furans for MSW Gasification		
MSW Gasifier	**Gasifier Type**	**Typical Emission of Dioxins/Furans – ITEQ (Billionth of a Pound Emitted per Ton MSW Processed)**
Ebara	Thermal gasification	0.001
IWT	Thermal gasification	0.0001
Rigel	Plasma gasification	0.01
Benchmark: Combustion WTE	Combustion Benchmark	0.1 to 1

ITEQ = Toxic Equivalent Emissions of Dioxins/Furans, International Protocol

Reference::
Alternative Resources Inc., March 2006, Phase 2 - Advanced Solid Waste Management Conversion Technologies, prepared for the Economic Development Corp. of the City of New York.

Mercury present in MSW will be volatilized during thermal treatment of the MSW (combustion, gasification) and, unless controlled, will be emitted to the environment, where it can pose a health risk. The potential emissions of mercury for MSW gasification are the same as with combustion MSW, and the control technique, carbon adsorption, is the same. Use of carbon to adsorb mercury from the flue gas of a WTE facility or the syngas produced by a MSW gasifier is highly effective and reduces mercury emissions to minor levels.

Odor

MSW gasification facilities would not be expected to cause waste-related odors offsite, if effective mitigation measures are used. As the first step in effective odor control, MSW storage and processing are performed entirely within enclosed structures. If there is a boiler combusting the syngas, the interior ventilation air would be used as combustion air for the boiler, hence destroying odors present in that air. If a boiler is not used for energy recovery, then alternative emission control methods may be needed to remove odorants from the ventilation air, such as an odor control scrubber.

The syngas resulting from MSW gasification contains hydrogen sulfide and is very odorous. Normally, the odorant present in the syngas would be destroyed when the syngas is combusted as a fuel. However, any leaks of syngas could cause an odor nuisance. Any release of raw syngas during facility testing or in an emergency could cause a significant odor nuisance offsite.

Wastewater Discharges

While much of the process water used by MSW gasification facilities is recycled and re-used, a quantity of wastewater is generated. Water use by MSW gasification technologies varies with many factors, as discussed above. Hence, the amount of wastewater discharge will similarly vary. Wastewater generation for MSW gasification would be typically similar too or less than with combustion WTE technology. The process in which MSW is gasified and the syngas is converted to liquid transportation fuels can actually produce more water than it consumes. Its wastewater discharge could be minimal.

Regarding storm water, there is little potential for a contaminated storm-water discharge to the environment from a modern MSW gasification facility. This is because modern MSW gasification facilities are totally enclosed, including MSW delivery and storage operations, and ash handling and storage. Accordingly, the environment is not exposed to the MSW and solid residue.

Solid Waste Generation

All technologies that process MSW thermally at high temperature (combustion, gasification, pyrolysis) generate a solid residue that, if not beneficially used, must be disposed in a landfill. Gasification produces a solid residue in the form of ash/slag, or char, or glassy slag, depending on the type of gasifier – thermal, pyrolysis, or plasma, respectively. As noted elsewhere in this report, the solid residue (ash) generated by combustion WTE technology is typically 25% of the weight of MSW processed. Depending how the ash is managed at a WTE facility, all of the ash produced may be landfilled, or the majority of it may be beneficially used in construction. For thermal gasification, it appears that the potential for beneficial use of the solid residue is high, as discussed previously above. With thermal gasification, the amount of solid residue landfilled is about 6% of the weight of the MSW processed, on average. With pyrolysis gasification, the potential for beneficial use of its solid residue varies considerably, with the amount landfilled being about 5% to 28% of the weight of the MSW processed. With plasma gasification, the extremely high temperatures involved result in a slag residue that is glass-like and inert and can not contaminate the environment. Accordingly, the residue has value as a construction material and it is unlikely that it would be disposed. Accordingly, essentially none of the solid residue produced via plasma gasification is expected to be landfilled.

Safety Hazards

The safety hazards specific to MSW gasification facilities would include the following:

- Fires on waste delivery trucks and during waste storage
- Exposure to waste-borne pathogens and toxic substances
- Increased traffic hazard from waste delivery trucks
- If WDF is produced onsite, there is an explosion risk if explosive materials (e.g., gas tank) are mixed with the waste that is being mechanically processed into WDF.
- Risk of injury/death from explosion of leaking syngas
- Risk of asphyxia from exposure to leaking syngas that builds up in confined spaces
- With conversion of MSW to liquid fuel, there is risk of fuel-related fires
- Injury, potentially fatal, from rare boiler-related explosions, if a boiler is used.

While these are all safety hazards for workers at a MSW gasification facility, only the truck-related safety hazard would likely extend significantly to the public offsite.

Economics/ Institutional

Economics

Thermal technologies for MSW processing such as combustion WTE and MSW gasification are typically the most costly options for MSW processing. These technically-sophisticated thermal technologies require high capital cost as well as high operating and maintenance costs. Accordingly, the implementation of both combustion WTE and MSW gasification technologies worldwide has been confined mostly to developed countries. While the high cost has kept these technologies beyond the reach of most developing countries to date, there are circumstances under which combustion WTE and MSW gasification are potentially viable in developing countries:

- Locations in major urban centers with a robust industrial/commercial economy, an adequate municipal financial/investment capacity, as well as a skilled work force
- Other urban centers where non-economic factors control, making modern landfills infeasible. For example, locations with unsuitable subsurface conditions (e.g., ground water near surface, karst) or lack of land resource (island nations or mountainous areas).
- Project locations where the high cost for the technology can be adequately defrayed by using international financing mechanisms.

The capital and operating costs for MSW gasification technology will vary with the type of gasification technology, the facility size, the nature of the country's economy, taxation laws, market competition, and other factors. Reliable information on the capital and operating costs for MSW gasification technology remains difficult to obtain. Detailed cost estimates, however, were developed for a potential, very large MSW gasification facility in New York City and are summarized in the table that follows.

Capital and Operating Cost Estimates for MSW Gasification				
Technology Sponsor in the US (Technology Origin)	Type of Gasification Technology	Planned Facility Processing Capacity for MSW	Projected Construction Cost (US Dollars, 2005 to 2007)	Projected Operating Cost in First Year
Ebara (Japan)	Conventional	3,000 TPD	$763 million $258, 000/TPD capacity	$32 million/year $29/ton processed
GEM (UK)	Pyrolysis	2,800 TPD	$468 million $170, 000/TPD capacity	$52 million/year $52/ton processed
IWT (Japan)	Conventional	2,600 TPD	$406 million $155, 000/TPD capacity	$51 million/year $54/ton processed
Rigel (US)	Plasma-Arc	2,700 TPD	$877 million $321, 000/TPD capacity	$167 million/year $167/ton processed

Note:
Costs were estimated for a planned, full-scale facility in New York City, requiring very large processing capacity. Projected costs for smaller-scale plants would likely be higher, due to lose of economies of scale. Projected construction costs do not include land cost or cost of financing.

Reference:
New York City Economic Development Corporation, "Focused Verification and Validation of Advanced Solid Waste Management Conversion Technologies: Phase 2 Study," prepared by Alternative Resources, Inc. (ARI), Concord, MA, March 2006.

Based on this limited available information, the following cost estimates for MSW gasification technology are presented:

Capital cost is expressed in units of US dollar cost for each ton per day (TPD) of MSW processing capacity. The capital cost for MSW gasification technology appears to be in the approximate range of US $160,000/TPD of MSW to $320,000/TPD. Assuming a modern plant operates 90% of the days in a year (~330 days), this would equate to a capital cost of $485/annual ton to $800/annual ton. Plasma arc gasification has higher capital cost at $970/annual ton than thermal gasification or pyrolysis. The range of capital cost for MSW gasification ($485 to $970 per short ton) is generally higher than the range of cost presented elsewhere in this report for combustion WTE ($450 to $750 per ton).

A typical operating cost for thermal and pyrolysis gasification appears to be ~ $50/ton of MSW processed; however, the operating cost for plasma arc gasification could exceed $150/ton, owing to the technology's unique complexity. The operating cost for thermal and pyrolysis gasification ($50/ton) is similar to or slightly higher than the operating cost presented elsewhere in this report for combustion WTE ($40/ton). The operating cost for plasma arc gasfication is likely much higher than for combustion WTE.

The range of operating costs represented by the limited data base is large, from $29 to $167 per ton of MSW processed, with two of the four values being in the $50+/ton range. This indicates that the typical operating cost for MSW gasification may be higher than the typical operating cost for combustion WTE of $40-$50/ton given elsewhere in this report

<u>Operational Complexity</u>

MSW gasification technology is technically complex and efficient, economic operation requires facility operating personnel who possess specialized skills and who are highly trained. While qualified personnel are readily available in developed countries, this is not the case in most developing countries, except in some major urban centers.

<u>Public Acceptance</u>

Conventional combustion waste-to-energy (WTE) is controversial in the U.S. and Canada, less so in Europe, and even less so in Asia. Where combustion WTE is controversial, gasification is an alternative that may more easily gain public acceptance, as gasification does not entail waste combustion.

Annex 4:

Anaerobic Digestion

Technical Description and Operating Scale

Technology Description

Anaerobic digestion (AD) is a biological process. AD reduces the volume of the input material, which is important in the management of MSW. Typically, waste materials to be digested are mechanically preprocessed as necessary to reduce the material to a uniform particle size, and to isolate the organic biodegradable fraction by removing inert or undesirable material such as glass shards and metals. In the AD process, the organic biodegradable materials are placed in a closed vessel and allowed to digest (ferment) without oxygen present. Materials suitable as feedstocks for anaerobic digestion in general include sewage sludge and animal manures; biomass (leaves, wood, agricultural residue); and the biodegradable components of municipal solid waste (MSW) such as paper, food waste, used fats/oils, slaughterhouse waste, leaves, and tree prunings. When the organic feedstock material is digested, a portion of the carbon present in the feedstock is converted to a methane-rich gas (biogas) which has use as a low grade fuel. When the process of digestion is complete, a solid residue remains called "digestate" that is similar to compost. Water is mechanically removed from the digestate. The de-watered digestate must undergo a period of "curing" via aeration in composting piles before it is marketed for use as a fertilizer or soil amendment. If a market can not be found for the digestate product, then it must be landfilled.

With AD, the biological processing of the input material occurs in two phases. In the first phase, a group of microorganisms referred to as "acid formers" breaks down complex organic materials in an acidic environment. In the second phase, a different variety of microorganisms, referred to as "methane formers," breaks down the output from the first phase and consumes the organic material to form methane-rich biogas.

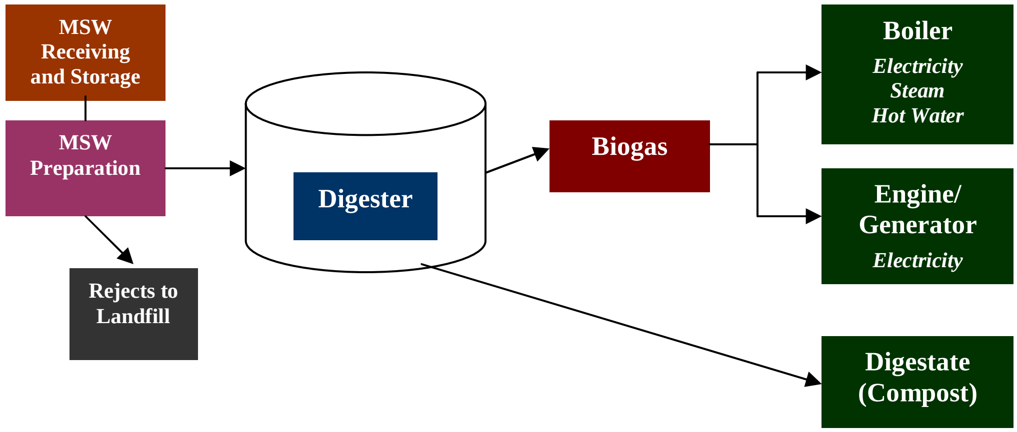
While the basic process of AD is straightforward, there are variations among specific process designs for AD, related to the following factors:

- Retention time of the feedstock material in the digester (which varies from 10 to 25 days generally);
- Moisture content of the digesting material in the digesters (dry vs. wet designs);
- Operating temperature during digestion (two operating regimes can be used: higher-temperature thermophilic or lower-temperature mesophilic); and

- Number of digestion stages (one or two).

Aspects of these design variations are normally considered in selecting AD technology for processing of various organic feedstocks, including components of MSW. The design variations are further explained below.

- *Wet vs. Dry*: Wet digestion means operating at a higher moisture content than dry digestion. Moisture is added to the incoming waste material. Digesting the material in a wet slurry has the advantage of enabling removal by floatation of any plastic materials that have been commingled with the organic feedstock. However, wet digestion typically results in a loss of volatile solids from the incoming waste stream, important because it means lower biogas yields. Wet digestion also consumes more of the energy generated from biogas (up to 50 percent) to meet greater in-plant energy needs (water pumping, dewatering) than dry digestion technologies (20 to 30 percent of energy is typically required for in-plant needs).
- *Mesophilic vs. Thermophilic*: Mesophilic bacteria thrive at relatively lower temperatures than thermophilic bacteria. As mesophilic digesters operate at a lower temperature, the required retention time for complete digestion is longer (15 to 30 days) to generate the same level of organic breakdown. Gas production is reported to be lower in mesophilic digesters, although the biological process is considered more stable (more complete). The longer retention time results in more space requirements and higher costs. Thermophilic digestion has a higher gas yield and a shorter retention time (12 to 14 days), lower space and equipment-volume requirements, but higher maintenance requirements and costs.
- *One Stage vs. Two Stage*: The process of anaerobic digestion proceeds in a series of biochemical reaction steps. Some AD systems are designed to accomplish all the reaction steps in a single digestion vessel. Other systems apportion the biochemical reaction steps into two stages in two separate vessels. Single stage digestion is a simple design with a longer track record, and has lower capital costs and technical problems. Two stage systems have lower digestion retention times as each stage design is optimized. There is a potentially higher gas yield with two stage systems, but higher capital costs.



Process Flow for Anaerobic Digestion of MSW
Source: ERM

Waste Types Processed

Anaerobic digestion is most efficient at processing waste types that are highly biodegradeable. With regard to MSW, the degradeable components most suitable for AD include food waste, fats/oils/greases, paper, slaughterhouse renderings, yard leaves and tree prunings. Any or all of those organic components, if collected separately from the general MSW collection, could be digested very efficiently. Mixed MSW could also be digested, however, the process would likely not be as efficient since mixed MSW contains waste components (plastic, glass, metals, grit) that are not biodegradable. Finally, there can be both technical and economic incentives for co-digestion of the organic components of MSW with other highly suitable wastes such as sewage sludge or animal manure.

Operating Scale

Based on industry data presented subsequently below, MSW anaerobic digestion technology has been demonstrated worldwide in processing ranging from 20,000 tons per year (TPY) to 240,000 TPY. This is for digestion of source-separated organic components of MSW. If one assumes that a facility operates 90% of the days of the year (~ 330 days per year), the processing capacity range is about 60 tons per day (TPD) to 700 TPD for source-separated organic components. The one known facility that digests mixed MSW (in Israel) has a capacity of 230 TPD.

Commercial Experience and Viability

There is extensive commercial experience in Europe with anaerobic digestion of the organic components of MSW, and very limited experience with digestion of mixed MSW. The only known, large-scale AD facility for mixed MSW operates in Israel. There have been only limited attempts to date to commercialize MSW anaerobic digestion in North America. Information was not found to be readily available summarizing the extent to which MSW anaerobic digestion has been implemented in Latin America and in Asia. It does not appear that AD has had commercial application as yet in Latin America.

In Europe, there is a specific impetus for biological treatment of MSW, either via composting or anaerobic digestion. This is because European legislation has imposed the "Landfill Directive," (Directive 1999/31/EC of 26 April 1999) that restricts the landfilling of the organic fraction of MSW unless processed first. The number of commercial facilities in Europe for digestion of MSW has grown rapidly since 2000. As shown in the table that follows, there were 127 facilities for digestion of the organic fraction of MSW operating in 13 European countries in 2006, processing a total of 4.6 million tonnes per year of MSW. The leading countries in Europe are Germany, Spain, and Switzerland.

Commercial Facilities in Europe for Anaerobic Digestion of MSW

Country	Number of Plants	Country Capacity (tonnes/year)
Germany	55	1,250,000
Spain	23	1,800,000
Switzerland	13	130,000
France	6	400,000
Netherlands	5	300,000
Belgium	5	200,000
Italy	5	160,000
Austria	4	70,000
Sweden	3	35,000
Portugal	3	100,000
United Kingdom	2	100,000
Denmark	2	40,000
Poland	1	20,000
Total	**127**	**4,605,000**

Reference:

Arsova, L, Anaerobic digestion of food waste: Current status, problems and an alternative product, Thesis, Columbia University, New York City, May 2010. http://www.seas.columbia.edu/earth/wtert/sofos/arsova_thesis.pdf

Plant-specific information was found for the MSW anaerobic digestion facilities operating in Spain, again a world leader in AD for MSW. That information summarized in the table below, shows an even mix of wet-type versus dry AD processing in use, with operating capacities ranging from 20,000 tonnes per year to 240,000 tonnes per year. Many of the leading AD technology suppliers have installed facilities in Spain.

Commercial Facilities in Spain for Anaerobic Digestion of MSW (2008)					
Location	**Feedstock**	**Technology Supplier**	**Capacity (tonne/year)**	**Date**	**Process**
Alicante	MSW	Dranco	30,000	2002	dry
Avila	MSW	Ros Roca	36,500	2004	wet
Barcelona Ecoparc	MSW	Linde/ Strabag	150,000	2002	wet
Barcelona Ecoparc	MSW	Ros Roca	90,000	2005	wet
Barcelona Ecoparc	MSW, Biowaste	Valorga	240,000	2004	
Burgos	MSW	STRABAG	40,000	2005	wet
Cadiz	MSW	Valorga	115,000	2001	dry
Gran Canaria	MSW	Ros Roca	60,000	2004	
Jaen	MSW	Ros Roca	20,000	2004	
La Coruña	MSW	Valorga	182,000	2001	dry
Lanzarote	MSW	Ros Roca	36,000	2004	
Las Dehesas	MSW	Valorga	195,200	2007	
Palma de Mallorca	MSW, SS	Ros Roca	32,000	2004	wet
Rioja	Biowaste	Kompogas	75,000	2005	dry

Reference:

IEA Bioenergy Agreement, http://www.iea-biogas.net/_content/plant-list/plant-list.html, accessed 15 April 2011.

In North America, two AD facilities processing organic components of MSW operate in Canada, as shown in the table that follows. There are no known AD facilities for MSW operating in the U.S.; however one sewage sludge digester at a wastewater treatment plant in the State of California co-digests organic components of MSW.

Commercial Facilities in North America for Anaerobic Digestion of MSW (2010)					
Facility	**Technology**	**Year**	**Feedstock**	**Capacity**	**Process**
Defferin Plant Toronto, Canada	BTA	2002	Source-separated organic MSW	45,000 ton/year	Wet
Newmarket Plant Toronto, Canada	Canada Composting	2000	Source-separated organic MSW	150,000 ton/year	Wet
EBMUD Oakland California, U.S.	Not Applicable	2005	Co-digestion of source-separated organic MSW in existing sewage-sludge digester	22,000 ton/year	Wet

Reference:

Arsova, L, Anaerobic digestion of food waste: Current status, problems and an alternative product, Thesis, Columbia University, New York City, May 2010.
http://www.seas.columbia.edu/earth/wtert/sofos/arsova_thesis.pdf

Finally, only one commercial facility has been identified worldwide that anaerobically digests mixed MSW, as opposed to pre-sorted organic components[1]. This is the Arrow Bio facility that has operated in Hiriya, Israel since 2003, processing 77,000 tons per year of mixed MSW and generating electric energy from the biogas. The Arrow Bio process uniquely starts by placing shredded, mixed MSW into slurry, which facilitates removal of recyclable plastics and metals. The remainder is then anaerobically digested. The digestate is composted and intended for use as a soil amendment.

MSW Anaerobic Digester and Biogas Energy, Barcelona, Spain
Photo credit: L. Arsova

[1] Alternative Resources Inc., September 2004, Phase-I - Evaluation of New and Emerging Solid Waste Management Technologies, prepared for the Economic Development Corp. of the City of New York.

Technology Suppliers

According to a recent survey, referenced in the table below, there were approximately 15 anaerobic digestion technology vendors of significance in the global market in 2006. Most of the AD technology vendors are Europe-based; however, one (APS) is based in the U.S. The seven vendors listed in the table below collectively account for about 70 percent of the AD capacity in Europe and 80 percent of the operating facilities there. Some of the AD technology companies participating in the market include: Kompogas (Swiss); Dranco (Belgian, now OWS); Linde (German, now Strabag); Biopercolat (German); ISKA (German, now CITEC); Valorga (French); APS (US); Bioconverter (US); Arrowbio (Israel); BTA (German); Waasa (Finland, now Citec); Linde (German); Entec (Austria) RosRoca (German); and Hasse.

Market Leaders Worldwide for MSW Anaerobic Digestion Technology (2008)		
AD Technology Supplier	Number of plants	Installed capacity (tonne/year)
Kompogas	26	533,500
Valorga	19	2,197,000
Ros Roca	17	541,000
BTA	17	300,500
OWS / DRANCO	15	627,000
Citec / Waasa	13	469,500
Linde / Strabag	11	459,000
Sum total	**118**	**5,127,500**

Reference:

Arsova, L, Anaerobic digestion of food waste: Current status, problems and an alternative product, Thesis, Columbia University, New York City, May 2010.
http://www.seas.columbia.edu/earth/wtert/sofos/arsova_thesis.pdf

There is only one, known commercially experienced vendor of AD technology for processing specifically mixed MSW, rather than pre-separated organic components. That firm is Arrow Ecology & Engineering, based in Israel, which offers the Arrow Bio technology.

In many developing countries, particularly in Asia and Latin America, the engineering-construction expertise for developing an MSW anaerobic digestion project exists within the country's principal urban center, and development of a project would be feasible, if the AD technology of an experienced vendor is used. However, in the least developed countries of the world, the required skills may not yet exist and the expertise would need to be imported.

Sustainability

Resource Recovery

Anaerobic digestion of MSW provides an opportunity for substantial resource recovery. The biogas produced by AD is used as a renewable-energy fuel to produce electric energy or thermal energy (steam, hot water). The solid residue – the composted digestate, is marketed as an organic fertilizer or soil amendment product, substituting for inorganic commercial fertilizer products.

A key issue for the economic and environmental viability of AD is the ability to market the digestate compost product. Once digestion is complete, the digestate product remaining is typically 13% to 35% of the weight of the MSW received for processing[2, 3]. If the compost can not be marketed, it must be landfilled. There has been difficulty with marketability of the compost product at some AD facilities[4]. The presence of glass shards and metal fragments mixed within the compost significantly reduces market value. In addition, concerns over pathogens potentially being present in the compost (e.g., prions) can be a barrier to marketability. Finally, concerns over toxic pollutants being present in the compost can discourage potential purchasers of the compost. This would include pesticides, defoliants, PCBs, and heavy metals. Mixed MSW contains mercury and the mercury is not destroyed in the AD process. With mixed MSW as the feedstock, the fate of that mercury is a legitimate question. There would not be a mercury concern for digestion of source-separated components of MSW such as food waste, fats/greases, yard leaves and prunings, as they do not contain elevated levels of mercury.

The key to producing a marketable compost is to monitor the types and sources of MSW to be digested to make sure they are not contaminated with pathogens or toxic contaminants. In addition, the MSW must be processed sufficiently prior to digestion to remove glass, metal, and plastic shards that interfere with the digestion process and reduce the marketability of the compost.

[2] Arsova, L, Anaerobic digestion of food waste: Current status, problems and an alternative product, Thesis, Columbia University, New York City, May 2010. http://www.seas.columbia.edu/earth/wtert/sofos/arsova_thesis.pdf.

[3] Alternative Resources Inc., March 2006, Phase 2 - Advanced Solid Waste Management Conversion Technologies, prepared for the Economic Development Corp. of the City of New York.

[4] Arsova, L, Anaerobic digestion of food waste: Current status, problems and an alternative product, Thesis, Columbia University, New York City, May 2010. http://www.seas.columbia.edu/earth/wtert/sofos/arsova_thesis.pdf.

Energy Conversion Efficiency

The process of anaerobic digestion of MSW results in the production of a biogas comprised of 50% to 60% methane. The biogas has value as a fuel due to its methane content; however, the biogas has only about half the calorific value (heat content) of natural gas, which is mostly methane. Biogass from AD is typically used to fuel a boiler or engine-generator set to generate electric power. It can also be used to generate thermal energy (steam or hot water).

The energy conversion efficiency for AD is estimated to be in the range of 100 to 245 kW h of electricity generated for each ton of MSW input to the AD process, or 100 to 245 kW h/ton. This estimate is based on the following data:

- A typical range of 165 to 245 kW h/ton reported in the literature[5]
- Values of 230 kW h/ton and 124 kW h/ton determined for two specific AD technologies for processing mixed MSW, Arrow Bio and WRS, respectively[6]; and
- Values of 130, 130, and 63 kW h/ton given, respectively, for AD facilities digesting organic components of MSW at a facility in Canada and two in Spain[7].

The energy conversion efficiency for AD at 100 to 245 kW h/ton is greater than the energy conversion efficiency for landfill gas energy recovery at 65 kW h/ton. But, the energy conversion efficiency for AD is much less than for the thermal technologies, combustion WTE and gasification, which have energy conversion efficiencies typically in the range of 400 to 600 kW h/ton. The greater energy conversion efficiency for the thermal technologies is explained by the fact that AD converts only the biodegradeable fraction of MSW into energy, while with WTE and gasfication, all components of MSW having fuel value are converted to energy.

[5] Bohn, J., May 2010. Food Waste Diversion and Utilization in Humboldt County – Thesis, Humboldt State University, California

[6] Alternative Resources Inc., March 2006, Phase 2 - Advanced Solid Waste Management Conversion Technologies, prepared for the Economic Development Corp. of the City of New York.

[7] Arsova, L, Anaerobic digestion of food waste: Current status, problems and an alternative product, Thesis, Columbia University, New York City, May 2010. http://www.seas.columbia.edu/earth/wtert/sofos/arsova_thesis.pdf.

Carbon Profile and Renewable Energy

As noted previously, the process of anaerobic digestion generates a biogas comprised of 50% to 60% methane and the rest mostly carbon dioxide, both greenhouse gases. However, presuming that the biogas resulting from AD is combusted for energy recovery, the methane is destroyed. The carbon dioxide present in the biogas is carbon-neutral when emitted from the combustion process, as it is biogenic in origin (derived originally from plants that were recently living).

The process of AD with energy recovery can result in a significant net reduction in greenhouse gas emissions. The carbon benefit for AD results from multiple factors (1) avoiding methane emissions that would result if the MSW were landfilled, (2) the generation of renewable energy that displaces energy generated with fossil fuels, (3) replacing commercial fertilizer with compost fertilizer (greenhouse gas emissions result from mining and manufacturing activities associated with making commercial fertilizer), and (4) the land application of the compost product resulting in long-term storage of carbon in the soil (sequestration).

Importantly, a fundamental concern with the economic and environmental viability of AD is the ability to market the digestate compost product for beneficial use. This has been a problem at some commercial AD facilities, as noted above and as is further discussed in a subsequent section. If the compost product can not be marketed, it must be landfilled. In that event, there would likely still be a net greenhouse benefit for AD owing to the generation of renewable energy that displaces fossil-fuel energy generation, but the benefit would be reduced.

The greenhouse gas benefit for AD is generally greater than for landfills with energy recovery because landfills leak methane emissions. This is true for the digestion of highly biodegradable components of MSW such as food waste. The greenhouse gas advantage for AD over landfills is less certain, however, for the digestion of woody feedstocks that are less biodegradable.

The greenhouse gas benefit for AD is also likely greater than for MSW composting, as composting does not generate renewable energy that displaces fossil-fuel energy generation[8]. However, the greenhouse gas benefit for AD is likely less than with combustion WTE and gasification of MSW, because the latter technologies convert all of the organic content of MSW to renewable

[8] Haight, M., 2005. Assessing the environmental burdens of anaerobic digestion in comparison to alternative options for managing the biodegradable fraction of municipal solid wastes, Water Science & Technology Vol 52 No 1-2 pp 553–559.

energy that displaces fossil-fuel energy generation, whereas AD converts only the fraction that biodegrades rapidly.

Water Resource Use

The organic fraction of MSW contains 15% to 70% water by weight[9], and much of that water leaves the MSW during the process of digestion. Accordingly, AD processes can yield more water than they consume. Anaerobic digestion processes of the dry type are a net producer of water. AD processes of the wet type require process water, but that water, with treatment as necessary, can be re-used. If not reused, however, it would become a wastewater discharge to the environment.

Waste Diversion from Landfill

The goal of many solid waste managers is to divert as high a fraction of the MSW from landfill disposal as possible. Landfills are always the final repository of residual MSW after implementing waste diversion measures: waste minimization, recycling, and various forms of resource recovery.

Prior to digestion, MSW must be pre-processed mechanically to remove components that would interfere with the digestion process, or would degrade the quality of the digestate compost product. Such materials removed would include glass, metals, plastics, and grit. If suitable, the materials removed would be recycled, and the recycled fraction is diverted from landfilling. The remainder, normally a substantial fraction, would be disposed by landfilling and not diverted. Generally, the fraction of the MSW received for processing that ends up requiring disposal is 25% to 40% by weight; however, disposal percentages as high has 70% are reported[10]. The variation in the reject rate is explained principally by variation in the purity of the MSW received for processing. Following pre-processing, the amount of MSW then input to the digestion process is diverted from landfilling, as it is converted to biogas and digestate compost product.

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[9] Arsova, L, Anaerobic digestion of food waste: Current status, problems and an alternative product, Thesis, Columbia University, New York City, May 2010. http://www.seas.columbia.edu/earth/wtert/sofos/arsova_thesis.pdf.

[10] Arsova, L, Anaerobic digestion of food waste: Current status, problems and an alternative product, Thesis, Columbia University, New York City, May 2010. http://www.seas.columbia.edu/earth/wtert/sofos/arsova_thesis.pdf.

If it is mixed MSW that is being anaerobically digested, then the overall diversion rate from landfilling for AD is 60% to 75%, since as noted above, 25% to 40% of the MSW received for processing is residual material that must be landfilled. However, when the material input for digestion is not mixed MSW, but only specific separated components such as food waste, then the overall diversion rate of MSW from landfilling is difficult to estimate, since in that scenario, AD is not being used to manage the entire amount of post-recycling MSW. Accordingly, the overall diversion rate would depend on whether companion methods for further resource recovery from the mixed MSW are being employed, rather than just landfilling. With AD for specific components of MSW, the overall diversion rate could range from being an estimated 10% to 25%, to being similar to combustion WTE and gasification (75% to > 90%).

Land Resource Use

The MSW anaerobic digestion process itself requires only 25% to 50% of the land area of a thermal technology (combustion WTE or gasification)[11] and far less than a landfill. However, the digestate must be composted in piles or rows prior to marketing, and that requires substantial additional land area. Overall, an AD facility and its compost area would likely require about the same or more land as a combustion WTE or gasification facility, but still less than a landfill.

Environmental Impacts

Air Pollutant Emissions

Air pollutant emissions from AD are associated primarily with emissions from the combustion of the biogas in a boiler or engine-generator set to produce energy. The air pollutants emitted include the standard combustion pollutants, nitrogen oxides, carbon dioxide, sulfur dioxide, and particulate matter. Standard emission control techniques are applied, as needed, to achieve emission levels that meet regulatory requirements. In general, the emission levels of most combustion pollutants, especially carbon dioxide, nitrogen oxides, and particulate matter, are less for combustion of a gaseous fuel (including biogas), than with combustion of a solid fuel, including MSW. Potential emissions of mercury are a concern, but emissions of dioxins/furans are not, as discussed next.

[11] Alternative Resources Inc., March 2006, Phase 2 - Advanced Solid Waste Management Conversion Technologies, prepared for the Economic Development Corp. of the City of New York].

Emissions of Dioxin/Furans and Mercury

As with most combustion processes, the combustion of biogas produced by anaerobic digestion of MSW results in trace emissions of dioxins/furans. Significant emissions of dioxins/furans are not expected with combustion of the biogas as the precursor compounds necessary for formation of dioxins/furans are not prevalent in the biogas. Emissions of dioxins/furans from AD biogas combustion are likely similar to emissions from landfill gas combustion. Emissions of dioxins/furans from AD biogas combustion are likely to be at levels much lower than the uncontrolled emissions from combustion WTE technology, and likely lower than the controlled emissions from WTE technology. The emissions of dioxins/furans from combustion of AD biogas are likely similar to or lower than the controlled emissions from thermal gasification or pyrolysis of MSW.

As noted above, mixed MSW contains mercury and the mercury is not destroyed in the AD process. If mixed MSW is the feedstock for digestion, the fate of that mercury in the mixed MSW is a legitimate question. There would not be a mercury concern for digestion of source-separated components of MSW such as food waste, fats/greases, yard leaves and prunings, as they normally do not contain elevated levels of mercury. When mixed MSW is being digested, if the mercury present in the MSW were to volatilize during the digestion process and enter the biogas, then mercury emissions to the atmosphere would result when the biogas is combusted. If, however, most of the mercury present in the MSW ends up in the digestate, not the biogas, there would not be a significant emission of mercury to the air when the biogas is combusted, but the mercury could become a potential contamination issue for use of the digestate as a compost product. It is also possible that the mercury present in MSW ends up in the process water. If the process water from the digestion process and from the de-watering of digestate were discharged, that discharge may contain mercury. No information was found in this study addressing the fate of mercury present in MSW when mixed MSW is digested, and specifically, whether there is significant mercury emitted during biogas combustion or present in digestate compost. The fate of mercury during digestion of mixed MSW appears to be an open question that merits research.

Odor

There is a potential for odor nuisance with anaerobic digestion of MSW and odor problems have resulted in the curtailment of operations at some operating facilities[12]. The principal sources of odor with digestion of MSW are the mechanical pre-processing of the MSW prior to digestion, and at the other end of the process, the open-air composting of digestate in rows or piles. While the biogas produced by digestion contains the strong odorant, hydrogen sulfide, the digestion takes place in a closed vessel. As long as there are no significant leaks of biogas, then the biogas would not be a significant odor source.

Odors associated with pre-processing the MSW can be effectively controlled by storing and pre-processing the MSW within enclosed structures, and applying odor control equipment to the building's ventilation air exhaust.

Odor control during composting of the digestate can be very challenging as the composting operation is usually open-air and is spread out over a large land area. Most important in preventing odors during composting is to prevent biodegradation of the compost in the absence of oxygen; i.e., anaerobic degradation, which forms strong odorants. Prevention of anaerobic conditions is achieved by turning the compost piles periodically to introduce air and by preventing the pooling of storm water under or near the compost piles. As there is a significant potential for odor generation with AD, the most effective mitigation strategy is to allow an adequate buffer distance between the AD facility and the nearest odor-sensitive land uses.

Wastewater Discharges

As noted above, some AD processes are a net producer of water. Other types of AD processes use water in the process, but much of that water would be recycled and reused. To the extent the process water is not reused, it could become a wastewater discharge. Normally, AD processes would find beneficial uses for the water produced, and there would be little process water discharge.

The process of curing (composting) the digestate in open rows or piles creates a potential for contaminated storm water runoff. Accordingly, storm water runoff may require treatment to remove particulate matter and biological oxygen demand (BOD) prior to discharge to the environment.

[12] Arsova, L, Anaerobic digestion of food waste: Current status, problems and an alternative product, Thesis, Columbia University, New York City, May 2010. http://www.seas.columbia.edu/earth/wtert/sofos/arsova_thesis.pdf.

Solid Waste Generation

As noted above, with mixed MSW digestion, AD generates a solid residue requiring landfilling that is 25% to 40% of the weight of the MSW received for processing. This is about the same as for composting, but greater than the solid waste generation rates for thermal treatment (WTE and gasification).

Safety Hazards

The safety hazards of potential concern for AD facilities would include the following:

- Fires on waste delivery trucks and within the waste storage area.
- Fires in the digestate piles or rows during composting of the digestate outdoors.
- Risks of potentially-fatal fires and explosions from biogas leaks, especially in confined spaces
- Risk of asphyxia from exposure to leaking biogas in confined spaces
- Exposure to waste-borne and leachate-borne pathogens and toxic substances
- Risk of exposure to molds that can grow in the digestate during composting, such as *Aspergillus fumigatus*, which causes respiratory disease in susceptible individuals.
- Increased traffic hazard from waste delivery trucks

While these are all safety hazards for workers at an AD facility, the truck-related safety hazard would likely extend significantly to the public offsite.

Economics/ Institutional

Anaerobic digestion technology for MSW has a high capital cost, expressed as cost per ton of MSW processed. Capital cost data for AD is available, based on a survey of capital costs compiled for some 20 MSW digestion facilities[13]. The capital cost for AD is in the range of $200 to $600 per ton of MSW processed, for a corresponding range of facility capacities of 22,000 to 110,000 tons per year. For a facility operating 90% of the days in a year (~330 days), this corresponds to a range of $66,000 to $198,000 per ton per day (TPD) of processing capacity, or $66,000 to $198,000/TPD of MSW input. This suggests that AD, especially at

[13] California Integrated Waste Management Board, March 2008. Current Anaerobic Digestion Technologies Used for Treatment of Municipal Organic Solid Waste, prepared by Rapport J. et al., University of California, Davis.

small scale, can have a capital cost per ton of MSW processed that is comparable to combustion WTE or gasification.

The same survey cited above found operating costs for AD to be in the range of $20/ton of MSW processed to $50/ton, again with the higher costs being associated with smaller-scale facilities. The smaller-scale AD facilities can have an operating cost per ton of MSW processed similar to that of combustion WTE (~ $40/ton).

Operational Complexity

Operation of the MSW pre-processing equipment to achieve a quality feedstock for digestion requires properly trained personnel, as it is crucial to produce a feedstock of adequate purity for digestion. In addition, specially trained personnel are required for operating the digestion and energy generation equipment. Adequately trained personnel are available in many developing countries, including the large cities of Latin America and Asia. In lesser developed countries of the world, however, and in very rural areas of more developed countries, adequately trained personnel for proper operation may not exist.

Public Acceptance

Anaerobic digestion of MSW is a biological process and is not "waste combustion." Opponents of thermal processes such as combustion WTE and gasification are likely to be more accepting of a biological process such as AD or composting. In addition, AD does not have the stigma historically associated with landfills, another type of biological process.

While the concept of AD should find public support, that initial support for an AD project can rapidly turn to determined opposition over the issue of odor. As noted above, AD technology has a significant potential to create offsite odor impacts. Also as noted above, repeated incidents of odor nuisance have resulted in curtailment of operations at MSW digestion facilities. Although odor control methods are essential at AD facilities, the best means for ensuring continued public support is to site the AD facility a substantial distance from the nearest odor-sensitive land uses.

Annex 5:

Composting

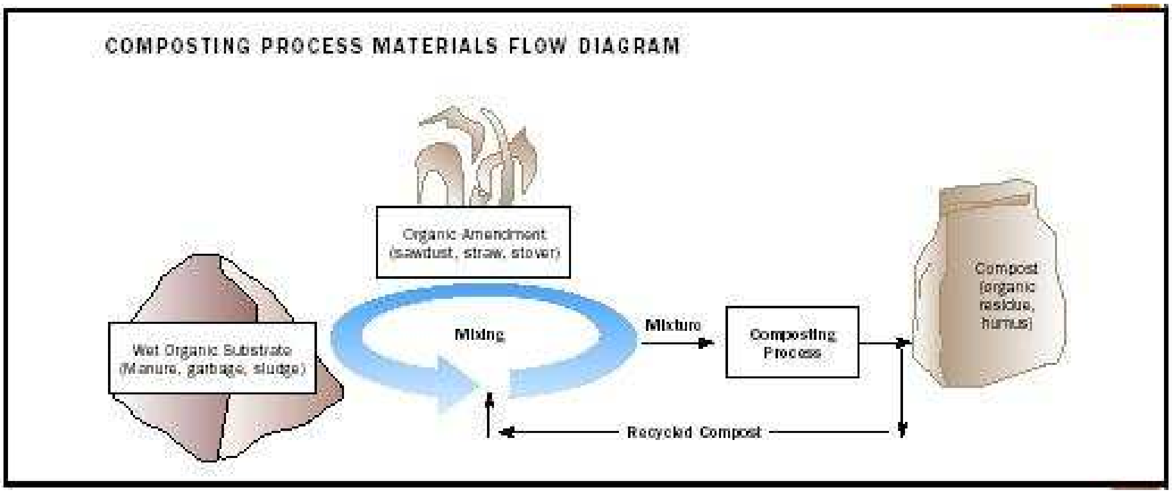
Technical Description and Operating Scale

Technology Description

Composting is an aerobic biological process in which organic wastes are metabolized by microorganisms that thrive in the presence of air (oxygen). During the process of composting, the temperature and pH of the material increase, destroying most common pathogens, and carbon dioxide and water are liberated to the air. The resulting compost (humus) can be used as a soil amendment or a fertilizer. A variation of composting is the addition of worms to the material during the composting process (vermiculture), to aid in digestion of the material. Vermiculture produces a high quality compost. Regarding methane emissions, composting, an aerobic process, does not emit methane, whereas anaerobic digestion does.

Modern systems for MSW composting include windrow and static-pile designs which require large tracts of land. There are vertical systems that require less land. The types of composting technologies are further described below; however, the basic steps of a modern composting process are as follow:

1. MSW is received. Mechanical equipment as well as hand-picking are used to separate inert materials – glass, plastic, metal, grit, from the compostable organic components of MSW. Inert materials are either recycled or landfilled, as appropriate.
2. Magnets and screens remove additional non-compostable materials.
3. The remaining compostable material enters the composting process where temperature, moisture and oxygen are carefully controlled to maximize the rate of decomposition.
4. The composted material is then screened one more time.
5. The final step is curing (further composting) in piles or rows, which takes from one to six months, and produces a nutrient-rich compost product.



Source Credit: Pollution Issues, accessed 23 April 2011 at http://webcache.googleusercontent.com/search?q=cache:YHFf7-8ItHIJ:www.pollutionissues.com/CoEa/Composting.html+flow+diagram+composting&cd=2&hl=en&ct=clnk&gl=us&source=www.google.com

There are three basic types of composting systems used to compost MSW: windrow, aerated static-pile, and in-vessel. These are described below.

Windrow Composting – The MSW is piled into long rows, either outdoors, under roof, or indoors. The rows are periodically turned to inject air and to adjust the moisture content and temperature. To maintain the proper ratio of carbon to nitrogen in the material needed for efficient composting, a bulking agent such as wood chips is sometimes added. Windrow composting is intended for large-volume operations and requires a substantial amount of land.

Aerated Static Pile Composting – The MSW is placed in windrows or piles atop a system of perforated piping used to inject air into the material in a controlled manner. The material is not physically turned. The windrows/piles can be outdoors, under roof or indoors. Some systems place the material in closed vessels for aeration, often called tunnel composting. Aerated Static Pile systems can achieve rapid biodegradation and are used for large-volume operations, but have also been applied to smaller scale composting operations.

In-Vessel Composting – This type of composting is highly engineered, "industrial" composting, applied to high-volume operations, particularly when odorous materials such as manures and sewage sludge (biosolids) are composted. These systems are ideal for co-composting MSW with biosolids. With this type of system, the materials are placed in an enclosed reactor vessel (e.g., tank), and air injection is constantly optimized. Temperature and moisture conditions are monitored and adjusted. If the vessel systems described above as aerated static pile systems are well-covered, they effectively become in-vessel composting.

Finally, vermiculture, the addition of worms to the composting material to aid digestion, produces an aesthetically desirable compost product. However, the incoming MSW must be relatively pure as the worms can not endure significant exposure to contaminants. Vermiculture is labor-intensive, so it is normally only economic on the small, local-community scale of up to several tons per day.

Waste Types Processed

Composting is most efficient at processing waste types that are highly biodegradeable. With regard to MSW, the degradeable components most suitable for composting include food waste, fats/oils/greases, paper, slaughterhouse renderings, yard leaves, and garden waste. Any or all of those organic components, if collected separately from the general MSW collection, could be composted very efficiently. Mixed MSW can also be composted however, the process is likely not as efficient since mixed MSW contains waste components (plastic, glass, metals, grit) that are not biodegradable. Finally, there can be both technical and economic incentives for co-composting the organic components of MSW with other highly suitable wastes such as sewage sludge or animal manure.

Operating Scale

The commercial implementation of MSW composting worldwide is addressed in a subsequent section below. From that assessment, the smallest scale MSW composting is backyard composting of food waste and yard waste. Municipal scale systems for mixed MSW composting have been commercially demonstrated for processing capacities from 2,000 to 90,000 tons per year, with one at 260,000 tons. The demonstrated operating capacities are approximately similar for systems that compost source-separated components of MSW such as food waste. If one assumes that a facility operates 90% of the days of the year (~ 330 days per year), the processing capacity range is from 6 tons per day (TPD) to over 270TPD, but have been as large as 790 TPD.

MSW Composting in the State of California, U.S.
Source: City of San Jose, California (U.S.), November 2008, Final Report - Appendix E: Conversion Technologies and Facilities for the Integrated Waste Management Zero Waste Strategic Plan Development, prepared by HDR Engineering, Inc.

Commercial Experience and Viability

MSW composting is commercially demonstrated in Europe, the U.S. and Canada, and in a number of countries in Latin America.

In Europe, there is a specific impetus for biological treatment of MSW, either via composting or anaerobic digestion. This is because European legislation has imposed the "Landfill Directive," (Directive 1999/31/EC of 26 April 1999) that restricts the landfilling of the organic fraction of MSW unless processed first. Composting is now commercially established in some European countries. Italy and Austria are the leaders, with 20 and 15 facilities, respectively[1]. In some regions, the MSW is composted prior to landfilling, simply to comply with the legislation. In other regions, however, the compost is land applied or used as a fuel for energy recovery.

In the U.S., it is reported[2] that there are thousands of municipal composting facilities for composting leaves and lawn/garden waste. These range in scale from very small to 50,000 tons per year. There are approximately 16 facilities

[1] Steiner, M., 2011. MBT in Europe, published in Waste Management World

[2] Environmental Business International (EBI), 2006. "Report 214 - Solid Waste Management and Resource Recovery, EBI, San Diego, California, U.S.

that compost mixed MSW, and there are likely 200 composting facilities nationally for composting food waste, often co-composting with yard waste added as a bulking agent.

The table below shows twelve composting facilities in the U.S. that process (or did process) mixed MSW. Some of the facilities co-composted waste water treatment sludge (biosolids). The processing capacities range from 3,000 to 94,000 tons per year. MSW composting facilities use different composting systems, with many using a rotary drum processor at the front of the process.

Mixed MSW Composting Facilities in the United States

Location	State	Ownership/ Operator	System	Capacity (tons MSW/year)
Gilroy	CA	Private/Z-Best	Enclosed ASP (Ag Bag)	92,400
Mariposa County	CA	Municipal	In vessel (SV Composter/ECS)	19,800
Cobb County	GA	Municipal	Rotating drum/aerated windrow (Bedminster)	66,000
Marlborough	MA	Municipal/WeCare Environmental	Rotating drum/aerated windrow (Bedminster with Allu turner)	34,000
Nantucket	MA	Municipal	Rotating drum/aerated windrow (Bedminster)	25,575
Truman	MN	Municipal	In-vessel (OTVD)	21,450
West Yellowstone	MT	Municipal	In-vessel (SV Composter-ECS)	3,000
West Wendover	NV	Municipal	Rotating drum/aerated windrow	8,250
Delaware County	NY	Municipal	Rotating drum w/agitated bays (Conporec/IPS-Siemens)	24,000
Medina	OH	Municipal/Norton Environmental	Windrow	14,850
Rapid City	SD	Municipal	Rotating drum/agitated bays (Daro/IPS-Siemens	59,400
Columbia County	WI	Municipal	Rotating drum/windrows	24,750

Reference:

Ulloa, P, 2008. "Overview of Food Waste Composting in the U.S." Internal Report, Earth Engineering Center, Columbia University, July 2008.

In the U.S., there were 30 municipalities reported in 2008 to havecomposting facilities that process source-separated components of MSW organics (SSO) such as food waste, many co-composting with yard waste[3]. Information on twelve of the facilities is presented in the table that follows. Their capacities range from 17,000 to 264,000 tons of source-separated organic MSW (including yard trimmings) processed annually.

Composting Facilities in the United States for Source-Separated Components of MSW				
Facility	**Location**	**State**	**System**	**Capacity (tons MSW/year)**
Z-Best Composting	Gilroy	CA	Versa aerated bags; windrow	74,2501
Allied Newby Island	San Jose	CA	Green Mountain Tech in-vessel	16,5001
Community Recycling & Resource Recovery	Lamont	CA	Windrow	264,0002
Grover Environmental	Modesto	CA	Windrow	69,0003
Jepson Prairie Composting Facility	Vacaville	CA	Ag-Bag; windrow	45,0003
Mackinac Island Facility	Mackinac Island	MI	Aerated static pile	8364
Resource Recovery Technologies	Empire Township	MN	Versa aerated bags; windrow	6305
Creekside Organic Materials Processing Facility	Hutchinson	MN	Green Mountain Tech in-vessel; windrow	6135
Swift County	Benson	MN	Windrow	2,0005
Western Lake Superior Sanitary District	Duluth	MN	Windrow	245
Cedar Grove Composting	Maple Valley	WA	Gore Cover System/ Aerated static pile	40,0006
Cedar Grove Composting	Everett	WA	Gore Cover System/ Aerated static pile	50,0007

Reference:

Ulloa, P, 2008. "Overview of Food Waste Composting in the U.S." Internal Report, Earth Engineering Center, Columbia University, July 2008

[3] Ulloa, P, 2008. "Overview of Food Waste Composting in the U.S." Internal Report, Earth Engineering Center, Columbia University, July 2008.

In Latin America, composting of the organic components of MSW has been demonstrated commercially in a number of countries. That experience, however, has been limited mostly to small scale facilities. Interestingly, composting using worms (vermiculture) has been carried out at many small-scale facilities.

It is reported that composting in Latin America in general has been hampered by high costs and difficulties in marketing the compost product[4].

While information on organic MSW composting was not available for most Latin American countries, information was found for three countries, Columbia, Ecuador, and Mexico, as summarized in the table that follows:

MSW Composting in Columbia, Ecuador, and Mexico

Country	Number of Facilities	Capacity (tons/year)	Composting Type(s)	Reference
Columbia	30	28 – 2,300	Standard Composting, Worms, Both	1
Ecuador	12	Small scale, but one at 1,500	Standard Composting	2
Mexico	60	24 – 3,300	Standard Composting, Worms, Both	3

[1]Aprovechamiento De Los Residuos Sólidos Orgánicos En Colombia, Gladys Jaramillo Henao, Liliana María Zapata Márquez, silvia maría puerta echeverri,Universidad de Antioquia, Tesis 2008.

[2] Compost Projects Evaluation in Ecuador, Fundación Natura - REPAMAR - CEPIS - G.T.Z., Quito, Marzo de 1998, Coordinación General: Margarita Campos, Realización: Saskya Lugo, Colaboración: Udo Gitscher, http://www.bvsde.paho.org/eswww/repamar/gtzproye/compost/compost.html

[3]Manual de Compostaje Municipal,Tratamiento de residuos sólidos urbanos, Marcos A. Rodríguez y Ana Córdova, Secretaria de Medio Ambiente y Recursos Naturales, Septiembre de 2006, México

Technology Suppliers

Some of the leading vendors of MSW composting systems serving the market in the Americas include Bedminster, Christiaens Group, Conporec, Engineered Compost Systems, Herhof, and Z-Best, as well as Engineered Compost Systems, Gore Cover Systems, Green Mountain Technologies, Natur-Tech, Polyflex, Transform, VCU, and Versa.

[4] Pan American Health Organization, 2005. Report on the Evaluation of Municipal Solid Waste Management Services in Latin America and the Caribbean.

Sufficient capability exists within most developing countries to implement MSW composting; however, in the least developed countries, specialized assistance from outside specialists in composting may be needed to ensure proper design and construction of the composting facility.

Sustainability

Resource Recovery

Composting of MSW provides an opportunity for resource recovery, because the compost product is marketed as an organic fertilizer or soil amendment product, substituting for inorganic commercial fertilizer products.

A key issue for the economic and environmental viability of MSW composting is the ability to market the compost product. If the compost can not be marketed, it must be landfilled. There has been difficulty with marketability of the compost product at some composting facilities, especially for mixed MSW, owing to lack of markets. The presence of glass shards and metal fragments mixed within the compost significantly reduce market value. In addition, concerns over pathogens potentially being present in the compost (e.g., prions) can be a barrier to marketability. Finally, concerns over toxic pollutants being present in the compost can discourage potential purchasers of the compost. This would include pesticides, defoliants, PCBs, and heavy metals. Mixed MSW contains mercury and the mercury is not destroyed in the compost process. With mixed MSW as the feedstock, the fate of that mercury is a legitimate question. There would not be a mercury concern for composting of source-separated components of MSW such as food waste, fats/greases, yard leaves and prunings, as they do not contain elevated levels of mercury.

The key to producing a marketable compost is to monitor the types and sources of MSW to be digested to make sure they are not contaminated with pathogens or toxic contaminants. In addition, mixed MSW must be processed sufficiently prior to digestion to remove glass, metal, and plastic shards that interfere with the digestion process and reduce the marketability of the compost.

Energy Conversion Efficiency

Composting does not generate energy.

Carbon Profile and Renewable Energy

Although the biological process of composting results in emissions of carbon dioxide, a greenhouse gas, that emission is carbon-neutral because it is biogenic in origin (derived originally from plants). The process of composting MSW can result in a net reduction in greenhouse gas emissions. The carbon benefit for composting results from two principal factors (1) reducing landfilling and associated methane emissions and (2) the land application of the compost product resulting in long-term storage of carbon in the soil (sequestration).

Importantly, a fundamental concern with the economic and environmental viability of composting is the ability to market the compost product for beneficial use. As noted previously, this has been a problem at some commercial compost facilities. If the compost product can not be marketed, then it must be landfilled. In addition, in some European countries, MSW is composted, simply as a required biological stabilization step prior to landfilling, and there is not an intent to market the compost. In any event, if the compost is landfilled rather than land-applied, then the greenhouse gas benefits for composting are only partially realized.

Comparing the greenhouse gas profiles for composting versus landfilling, anaerobic digestion, and the thermal processing technologies (combustion WTE and gasification) is not straightforward, as the results can be very sensitive to case-specific circumstances in which the technologies are applied. The greenhouse gas benefit for composting is intuitively greater than for landfills, likely even if the landfill recovers energy, because even the best controlled landfills leak substantial methane emissions. However, the greenhouse gas benefit for composting is likely less than for anaerobic digestion of MSW, because composting, unlike AD, does not generate renewable energy that displaces fossil-fuel energy generation[5].

Similarly, the greenhouse gas benefit for composting of MSW is intuitively likely to be less than with combustion WTE and gasification of MSW, because the latter technologies convert all of the organic content of MSW to renewable energy that displaces fossil-fuel energy generation, whereas digestion converts only the fraction that biodegrades rapidly. However, these intuitive assessments may or may not be true. An assessment by US Environmental Protection Agency (US EPA) reported that, within the significant uncertainties in comparing the greenhouse gas profiles for composting and combustion WTE, the profiles are similar. US EPA also stated that the greenhouse gas profile for composting is

[5] Haight, M., 2005. Assessing the environmental burdens of anaerobic digestion in comparison to alternative options for managing the biodegradable fraction of municipal solid wastes, Water Science & Technology Vol 52 No 1-2 pp 553–559.

better than for landfilling when food waste is composted, but worse than for landfilling for composting of woody materials[6].

Clearly, there is considerable uncertainty regarding how the greenhouse gas profile for MSW composting compares with any and all of the alternative methods for MSW processing.

Water Resource Use

MSW composting facilities do not require use of water in significant quantities.

Waste Diversion from Landfill

The goal of many solid waste managers is to divert as high a fraction of the MSW from landfill disposal as possible. Landfills are always the final repository of residual MSW after implementing waste diversion measures: waste minimization, recycling, and various forms of resource recovery.

Prior to composting, MSW must be pre-processed to remove components that would interfere with the composting process, or would degrade the quality of the compost product. Such materials removed would include glass, metals, plastics, and grit. If suitable, the materials removed would be recycled, and the recycled fraction is diverted from landfilling. The remainder, normally a substantial fraction, would be disposed by landfilling and not diverted. In the course of preparing the present study, little reliable information was found for mixed MSW composting on the waste diversion rate from landfilling. Accordingly, the diversion rate determined elsewhere in this study for anaerobic digestion of MSW is considered representative, as similar pre-processing of the MSW received is required. On this basis, with mixed MSW composting, the fraction of the MSW received for processing that ends up requiring disposal is 25% to 40% by weight; however, much higher disposal percentages are sometimes experienced. The variation in the reject rate is explained principally by variation in the purity of the MSW received for processing. Following pre-processing, the amount of MSW input to the composting process is diverted from landfilling, as it is converted to compost product.

If it is mixed MSW that is being composted, then the overall diversion rate from landfilling for MSW composting is 60% to 75%, since as noted above, 25% to 40% of the MSW received for processing is residual material that must be landfilled. In some cases, the diversion rate can be substantially less than this range.

[6] U S Environmental Protection Agency (EPA), 2006. Solid Waste Management And Greenhouse Gases -- A Life-Cycle Assessment of Emissions and Sinks (3rd Edition), September 2006.

When the material input for composting is not mixed MSW, but only specific separated components such as food waste and yard leaves/prunings, then the overall diversion rate of MSW from landfilling is difficult to estimate, since in that scenario, composting is not being used to manage the entire amount of post-recycling MSW. Accordingly, the overall diversion rate would depend on whether or not companion methods for further resource recovery from mixed MSW are being employed. With composting for specific components of MSW, the overall diversion rate could range from an estimated 10% to 25% with no companion resource recovery, to being 75% to >90% if companion techniques such as WTE and gasification are also used.

Land Resource Use

An MSW compost facility would likely require about the same land as a combustion WTE or gasification facility if in-vessel composting, more land otherwise, and about the same amount of land as an MSW anaerobic digestion facility, but less than a landfill.

Environmental Impacts

Air Pollutant Emissions

There are no air pollutant emissions associated with the composting of MSW, except for emissions of dust during the handling of input MSW and the compost product.

Emissions of Dioxin/Furans and Mercury

Composting does not have emissions of dioxins/furans, as there is no combustion involved.

As noted above, mixed MSW contains mercury and the mercury is not destroyed in the composting process. If mixed MSW is the feedstock for composting, the fate of that mercury is a legitimate question. There would not be a mercury concern for composting of source-separated components of MSW such as food waste, fats/greases, yard leaves and prunings, as they do not contain elevated levels of mercury. When mixed MSW is being composted, some of the mercury present in the MSW may volatilize to the air during the composting process. However, mercury present in the input MSW may end up in the compost and could become a potential contamination issue for marketing and use of the compost. Mercury contamination of MSW compost has been the subject of a number of studies and compost quality standards have been set in some countries to limit the permissible levels of mercury and other contaminants in the compost. The fate of mercury during composting of mixed MSW does not yet appear to be a settled issue, and accordingly, merits continued further research.

Odor

The principal sources of odor with composting of MSW are the mechanical pre-processing of the MSW prior to composting, and at the other end of the process, the open-air composting of compost in rows or piles. Odors associated with pre-processing the MSW can be effectively controlled by storing and pre-processing the MSW within enclosed structures, and applying odor control equipment to the building's ventilation air exhaust.

Odor control during composting operations can be very challenging if the composting operation is open-air and spread out over a large land area. Conducting composting within an enclosed vessel or structure is effective in containing odors, especially if odor controls are applied to the ventilation air exhaust. Most important in preventing odors during composting is to prevent pockets of biodegradation from occurring in the absence of oxygen; i.e., anaerobic degradation, which forms strong odorants. Prevention of anaerobic conditions is achieved by keeping the compost well-aerated, and if outdoors, by preventing the pooling of storm water under or near the compost piles. As there is a significant potential for odor generation with composting, the most effective mitigation strategy is to allow an adequate buffer distance between the composting facility and the nearest odor-sensitive land uses.

Wastewater Discharges

MSW composting processes typically do not use significant process water; hence, there would be not process waste water discharge.

If aspects of the composting process take place outdoors, this creates a potential for contaminated storm water runoff. Accordingly, storm water runoff may require treatment to remove particulate matter and biological oxygen demand (BOD) prior to discharge to the environment.

Solid Waste Generation

As noted above, with mixed MSW composting, this generates a solid residue requiring landfilling that is estimated to be 25% to 40% of the weight of the MSW received for processing. This solid waste generation is about the same as for anaerobic digestion, but greater than the solid waste generation rates for thermal treatment (WTE and gasification).

Safety Hazards

The safety hazards of potential concern for compost facilities would include the following:

- Fires on waste delivery trucks and within the waste storage area.
- Compost fires in compost piles or rows. For example, an MSW composting facility in the U.S. processing 250 TPD of MSW in Sevierville, Tennessee burned to the ground in 2007[7].
- Exposure to waste-borne and leachate-borne pathogens and toxic substances
- Risk of exposure to molds that can grow in the compost, such as *Aspergillus fumigatus*, which causes respiratory disease in susceptible individuals.
- Increased traffic hazard from waste delivery trucks and compost trucks

While these are all safety hazards for workers at an composting facility, the truck-related safety hazard would likely extend significantly to the public offsite.

Economics/ Institutional

This study found no comprehensive compilations of cost information for MSW composting technology. The City of New York surveyed the economics of four MSW composting facilities operating in the U.S. and Canada, as reference facilities for planning a potential facility in New York City[8].

The reference facilities composted principally MSW, but three co-composted smaller quantities of waste water sewage sludge (biosolids). The MSW processing capacities of three facilities ranged from 150 to 300 tons per day (TPD) of combined input material, and the fourth can process 825 TPD of MSW plus 380 TPD of biosolids. Based on data in that survey, capital costs for these four MSW composting facilities have been calculated here to be in the approximate range of $200 to $300 per ton of MSW/biosolids processed, which presuming the facilities operate 90% of the days of a year (~330 days), corresponds to a range of $70,000 to $110,000 per TPD of design capacity. This is believed to be representative of capital costs for MSW composting in the U.S.

[7] BioCycle Magazine, November 2007. Vol. 48, No. 11, p. 22
[8] NYC MSW Composting Report, January 2004. Department of Sanitation, City of New York, U.S.

In the New York City survey above, the operating costs for three of the four facilities ranged from $70 to $90 per ton, and the cost for the fourth facility was reported at $27 per ton. An academic study of MSW composting in 1996[9] reported operating costs to be $23 to $30 per ton for five MSW composting facilities in the U.S. and ~ $50 per ton for two facilities. Those costs today would be somewhat higher.

An MSW composting facility in the U.S. (Sevierville, Tennessee) processing 250 TPD of MSW and 50 TPD of municipal waste water sludge (biosolids) had reported operating costs of $25 per ton in 2007[10].

The limited data above on operating costs for MSW composting show disparity, ranging from $25 per ton to $90 per ton; however, most are in the $20 to $50 per ton range. It is possible that the $90 per ton costs included debt service as well as actual operating costs. Based on a more robust economics data base available for anaerobic digestion of MSW, operating costs for that technology were determined elsewhere in this study to be in the range of $20 to $50 per ton of MSW processed. It is doubtful that operating costs for composting of MSW would be greater than for digestion of MSW. For the present study, operating costs in the range of $20 to $50 per ton are considered representative for MSW composting.

Operational Complexity

Proper operation of an MSW composting facility requires training; however, because operating requirements are not complex, trainable personnel can likely be found in all locations of a developing country. Composting facilities operating in Latin America have had operating difficulties (e.g., poor compost quality) owing to lack of adequate operator training.

Public Acceptance

Composting is a "low-technology" biological process that entails no combustion. Opponents of thermal processes such as combustion WTE and gasification are likely to be more accepting of a biological process such as composting or anaerobic digestion. In addition, composting does not have the stigma historically associated with landfills, another type of biological process.

[9] Renkow, M. et al., 1996. Municipal Solid Waste Composting: Does It Make Economic Sense?, North Carolina State University, North Carolina, U.S.
[10] BioCycle Magazine, November 2007. Vol. 48, No. 11, p. 22

While the concept of composting should find public support, that initial support for a composting project can rapidly turn to determined opposition over the issue of odor. As noted above, composting technology has the potential to create offsite odor impacts. Although proper composting techniques can be effective at preventing odorous emissions, the best means for ensuring continued public support is to site the composting facility a substantial distance from the nearest odor-sensitive land uses.

Annex 6:

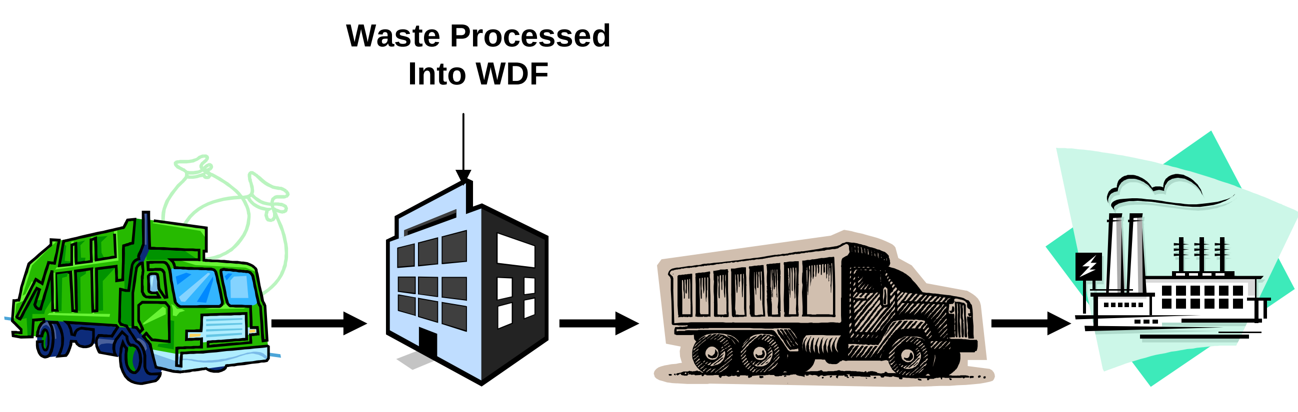
Waste-Derived-Fuel Production, an Alternative Technology

ANNEX 6 — WASTE-DERIVED-FUEL (WDF) PRODUCTION, AN ALTERNATIVE TECHNOLOGY

In this annex, a demonstrated alternative to traditional waste-to-energy (WTE) is profiled, as it has potential economic advantages for application in Latin American countries. This alternative technology will be referred to here as Waste-Derived-Fuel (WDF) Production.

Technical Description and Operating Scale

This technology is similar to traditional combustion WTE described in Annex 2, except that there is a decoupling of the main processing steps, as illustrated in the graphic below. With this alternative approach, mixed MSW is mechanically processed into WDF under municipal auspices, then the WDF is transported to a third party's facility in the same region for combustion and conversion into energy. So, the municipality produces the WDF and a third party then accomplishes the waste-to-energy conversion.



WDF Production (Municipality) and WTE Combustion (Third-Party Facility)

Source: ERM

This two step process is further described below.

Step 1: WDF Production (Municipal Responsibility)

- Mixed solid waste is mechanically processed into a refined, shredded or pelletized, waste-derived fuel ("WDF"), using shredders, grinders, trommels, and screens, as was described for combustion WTE technology in Annex 2. In these standard mechanical processing systems, the MSW is processed dry, as received. An alternative technology for converting MSW into WDF is Mechanical Heat Treatment (MHT). This process subjects the MSW to moisture and heat, as well as to the mechanical processing steps. The moist heat treatment is similar to the autoclaving process commonly used to treat medical waste. The moist heat treatment of MSW increases the efficiency with which MSW components can be separated from the MSW for recycling or use as WDF. MHT processes, however, are more costly and are more complex to operate. Only a few MHT systems operate commercially worldwide to process MSW.

Step 2: WDF Co-Combustion (Third-Party Responsibility)

- The WDF is taken by truck or rail to an existing coal-fueled power plant, cement kiln, or waste-fueled industrial boiler. The WDF can replace up to 10% to 15% of the coal normally used as fuel at a coal-fueled power plant or industrial boiler. It can displace a portion of the coal used at a cement kiln. It is also possible that a local industrial facility may consider installing a dedicated, WDF-fueled boiler to save on fuel costs.
- The coal power plant, cement kiln, or industrial boiler must be located in the local area, because longer-distance transport of the WDF is normally not economic.
- A crucial feasibility issue, the coal power plant, cement kiln, or industrial boiler must have modern emissions control equipment, similar to that used by modern, traditional WTE facilities, as described in Annex 2.

For WDF production facilities, the commercially-feasible size (capacity) range would be consistent with the feasible capacities of traditional combustion WTE facilities in commercial operation around the world. As detailed in Annex 2, the economic viability of WTE depends on economies of scale in most locales. Accordingly, WTE units in the U.S. are rarely less than 100TPD in capacity, and units in the 200 to 700 TPD range are most common. Smaller capacity units have been economic in regions of Europe.

Commercial Experience and Viability

The production of WDF under municipal auspices and its subsequent combustion for energy recovery by third parties has been practiced in the U.S. and Europe for about 30 years, and is well demonstrated to be commercially viable. That said, most WTE facilities operating in the U.S. today do not use this model, but rather, are stand-alone, self-contained WTE facilities.

Technology Suppliers

There are numerous suppliers of traditional Materials Recovery Facility (MRF) systems for processing MSW in order to simultaneously recover recyclable materials and produce WDF. Many of these suppliers are summarized in the following table for the traditional, dry systems.

Companies that Supply Systems and Equipment for Production of WDF			
Company	**Company Location**	**Turnkey Systems Offered**	**Commercial Experience Claimed by Company**
CP Manufacturing, Inc. (Subsidiary of IMS Group)	Based in U.S. (California)	• Mixed-waste MRF for WDF production • Materials separation from C&D waste	• 300 MRFs supplied worldwide • 40 MRFs supplied in U.S., including in the Northeast U.S. • MRFs supplied in Puerto Rico and Bermuda
BHS – Bulk Handling Systems	Based in U.S.(Oregon)	• Mixed-waste MRF for WDF production; advanced system • Materials separation from C&D waste	• Advanced MRFs in U.S. in states of CA, WI, and TX
RRT Design & Construction (RRT)	Based in U.S. (New York)	• Mixed-waste MRF for WDF production; advanced system • Materials separation from C&D waste	• Not an equipment manufacturer; rather, a system integrator, working like an EPC contractor. • 60 MRFs in 20 U.S. states, including in the Northeast U.S. • Developed some of the first MRFs built in the U.S. • Was the leading turnkey MRF supplier in the U.S. during the 1990's. Only limited market participation since, however. Current viability of RRT would need to be determined. Nat Egosi, President, is the Principal to speak with.
Sherbrook OEM	Based in Canada (Quebec)	• Mixed-waste MRF for WDF production; advanced system	• Company claims an operating MRF, but does not state location or details.
Bollegraff	Based in Netherlands	• Known principally for	• Has extensive clean-MRF

Companies that Supply Systems and Equipment for Production of WDF			
Company	**Company Location**	**Turnkey Systems Offered**	**Commercial Experience Claimed by Company**
	(Sells their equipment in the U.S. through Van Dyke Baler, a prominent U.S. vendor of baling equipment.)	"clean MRF' systems • Claims to sell mixed-waste MRF systems	commercial experience in Europe; has supplied equipment in U.S. for MRFs. But, little publicly available information on extent of commercial experience with mixed-waste MRFs in Europe or U.S.
Machinex	Based in Canada (Quebec)	• Mixed-waste MRF for WDF production; advanced system	• Not an equipment manufacturer; rather, a system integrator, working like an EPC contractor. • Claims MRFs in U.S. states of IA and CA
Enterprise Company	Based in U.S. (California)	• Mixed-waste MRF for WDF production; advanced system	• Commercial experience not readily available.

While the MHT systems (moist heat plus mechanical) for processing MSW have had little deployment to date worldwide, some of the suppliers of MHT systems are summarized in the table that follows.

Companies that Supply MHT Systems for Production of WDF			
Company	**Company Location**	**Turnkey Systems Offered**	**Commercial Experience Claimed by Company**
Enpure/Tempico (Enpure is the U.S. licensee for the Tempico process)	• Enpure based in U.S. (California) • Tempico based in U.S. (Alabama)	• Mixed-waste autoclave (Rotoclave) and MRF for recycling and WDF (biomass) production	• Pilot Tempico plant operated in U.S. (Birmingham, AL) • 350,000 TPY Tempico facility began operation in Jan 2010 at Gateshead, U.K. (Graphite Resources was project developer.)
Sterecycle (Sterecycle Process)	• Based in U.K.	• Mixed-waste autoclave and MRF for recycling and biomass fiber production for use in land regeneration	• Demonstration plant in U.S. in state of NV • 100,000 TPY commercial plant since 2008 in Rotherham, Yorkshire, U.K.; plans to expand to 240,000 TPY. • But, NOTE: In early January 2011, the pressurized autoclave exploded, killing a worker.
Cleantech Biofuels	• Based in U.S.	• Mixed-waste autoclave and MRF for recycling and WDF (biomass) production	• Website claims 600 TPD commercial facility in Australia since 2007, but U.S. SEC filing (Sep 2010) explicitly says no commercial facilities yet.
Bouldin Corp/WasteAway Services (WasteAway Process)	• Based in U.S.	• Mixed-waste autoclave and MRF for recycling and biomass fiber production for	• Demonstration plant in U.S. in state of NV • Commercial plant claimed in Aruba since 2009.

Companies that Supply MHT Systems for Production of WDF			
Company	**Company Location**	**Turnkey Systems Offered**	**Commercial Experience Claimed by Company**
		manufacture of extruded lumber	
CR3 – Comprehensive Resources Recovery and Reuse	• Based in U.S.	• Mixed-waste autoclave and MRF for recycling and biomass fuel production	• Demonstration plant in U.S. (Salinas, CA) • No commercial plants claimed
Vantage Waste Processor	• Based in U.S.	• Mixed-waste autoclave and MRF for recycling and fiber production for conversion to ethanol	• Permits obtained in 2010 to build plant in U.S. in state of TX
Estech (subsidiary of Babcock International)	• Based in U.S.	• Mixed-waste autoclave and MRF for recycling and biomass fuel production	• Selected for a project in Wakefield District of the U.K. Not constructed as of Dec 2010.
BioProducts International	• Based in U.S.	• Mixed-waste autoclave and MRF for recycling and biomass fuel production	• Operated a demonstration plant in U.S. (Anaheim, CA) in 2007-2008.
Prestige Thermal	• Based in South Africa	• Mixed-waste autoclave and MRF for recycling and biomass fuel production	• Claims a pilot plant at Bridgend, U.K.

Sustainability

For the overall system of WDF production (municipal) and waste-to-energy conversion (by a third-party), the sustainability profile with regard to resource recovery, energy efficiency, carbon profile, and waste diversion from landfill would be essentially the same as presented in Annex 2 for combustion WTE. The sustainability profile for land resource consumption and water use would be better, as the WDF production alternative entails using an existing, third-party facility to convert the WDF to energy, rather than new land development and new water use.

Environmental Impacts

For the overall system of WDF production (municipal) and WTE conversion (by third-party), the environmental impacts with regard to air quality, dioxin/mercury emissions, odor impacts, wastewater discharge, and solid waste production would be essentially the same as presented in Annex 2 for combustion WTE.

At a WDF production facility, odors associated with processing the MSW can be effectively controlled by storing and processing the MSW within enclosed structures, and applying odor control equipment to the building's ventilation air exhaust.

Safety hazards for the WDF production alternative would also be essentially the same as presented in Annex 2 for combustion WTE.

Economics/ Institutional

Economics

Regarding capital costs, the US Department of Energy recently estimated[1] an expected capital cost of US $105 million for a large WDF production facility (3,200 TPD capacity), which translates to ~$100 per ton of annual processing capacity, if one assumes the facility operates 90% of the hours in a year (~ 330 days). Due to economies of scale, the capital cost for WDF production is likely to be somewhat higher for facilities of smaller scale.

Material Recovery Facilities (MRF) that recover recyclable materials use processing equipment that is similar to that used by WDF production facilities. A recent national survey of MRFs operating nationally in the U.S.[2] reported capital costs in 2006 ranging from $36,000 to $42,000 for each ton-per-day of design processing capacity. This equates to a range of $110 to $130 per annual ton of processing capacity, presuming a facility operates 90% of the days in a year (~ 330 days).

Based on the above information, the capital cost for a WDF production facility is estimated to range from $100 per annual ton of processing capacity to $130/ton. ***Key point:*** the capital cost for WDF production of $100/ton to $130/ton *is dramatically less expensive* than the range of capital costs for a stand-alone WTE facility, noted in Annex 2 to be $450/ton to $750/ton. With the WDF production alternative, the third party that combusts the WDF to recover energy absorbs the high capital cost for the power production equipment.

The national survey cited above found typical operating costs for MRFs nationally in the U.S. to range from $46/ton to $56/ton for MRFs above 100 TPD in processing capacity, although the operating cost was much higher for the smallest of MRFs (6 TPD capacity) at over $200/ton.

[1] U.S. Department of Energy, March 2010. "Design Case Summary: Production of Mixed Alcohols from Municipal Solid Waste via Gasification."
[2] Pinellas County Utilities (Florida, U.S.), September 2009. Materials Recovery Feasibility Study.

Operational Complexity

Operating requirements for WDF production by a municipality are far less complex than for a complete WTE facility. Proper operation of a WDF production facility does require skills and training; however, at a level far less specialized than for operation of a WTE facility, which is technically complex power plant. With the WDF production alternative, the specialized skill sets needed to operate a WTE facility are not the responsibility of the municipality, but rather, are the responsibility of the third-party facility at which the WDF would be converted to energy.

Public Acceptance

In some parts of the U.S., combustion WTE generates public opposition, based on concerns about air emissions and WTE competing with recycling. While opposition to WTE is less in countries outside the U.S., some potential for opposition exists in any location. With the alternative of WDF production, the basis for public opposition is reduced, as the facility that would combust the WDF to recover energy would normally already exist.

Annex 7:

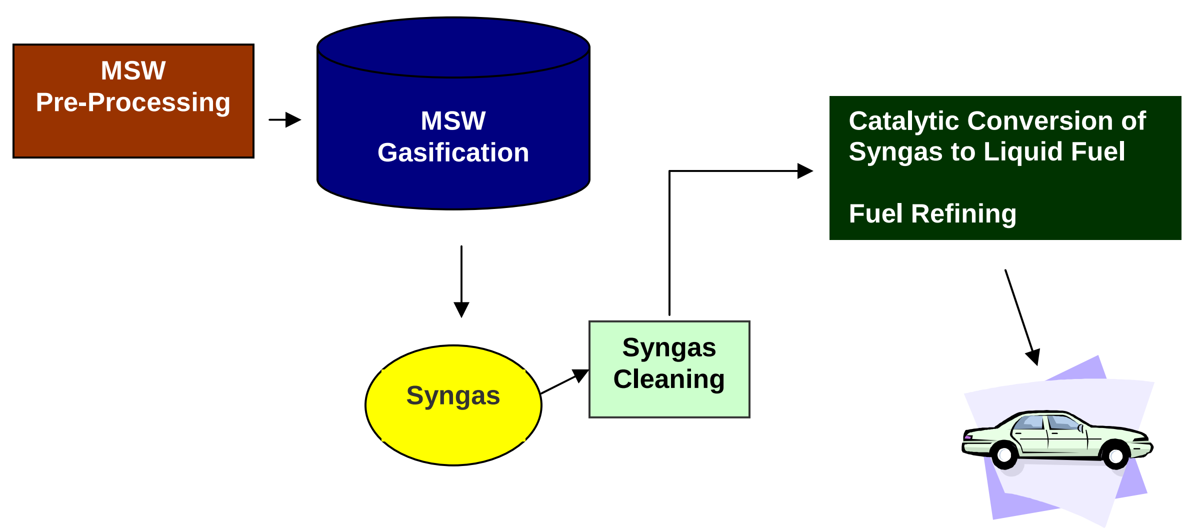
Waste-to-Liquid Fuel, an Emergency Technology

ANNEX 7 – WASTE-TO-LIQUID FUEL, AN EMERGING TECHNOLOGY

In this annex, an emerging technology is profiled that converts MSW into liquid transportation fuels or chemicals.

Technical Description and Operating Scale

An emerging technology for MSW processing is the conversion of MSW to liquid transportation fuels such as ethanol or synthetic diesel fuel, or to chemicals such as methanol or naptha. While there are as yet no waste-to-liquid fuels facilities operating commercially anywhere in the world, a number of developers have implemented plans to develop such commercial facilities in Canada and the U.S., and the first such commercial facility is under construction in Canada (Edmonton, Alberta). There are a number of different processes that could be used to convert MSW into liquid fuels/chemicals. These include processes such as acid hydrolysis and enzymatic hydrolysis, as well as thermal depolymerization, and thermal or plasma gasification combined with a chemical process. While all of these processes are undergoing development and testing for conversion of MSW to liquid fuels, the approach that appears to be farthest along towards general commercialization at this time entails thermal gasification of the MSW, followed by conversion of the gas to liquid fuel via a catalytic chemical process. Accordingly, the focus of this assessment will be on gasification-based processes for conversion of MSW to liquid fuels and chemicals. The basic process for gasification-based conversion of MSW to liquid fuels/chemicals is depicted in the figure that follows:



Simplified Process Schematic for Gasification Waste-to-Liquid Fuels

Source: ERM

As shown in the figure, the first step in the waste conversion process is to process the MSWinto a more refined, waste-derived feedstock. This is done using mechanical equipment that sorts, screens, and sizes the MSW to yield a feedstock material that is more homogeneous in composition, size, and density than the waste from which it is made. The feedstock is typically comprised principally of fiber (paper, wood, and food residues) and plastics residues. In some processes, this feedstock is formed into dense pellets.

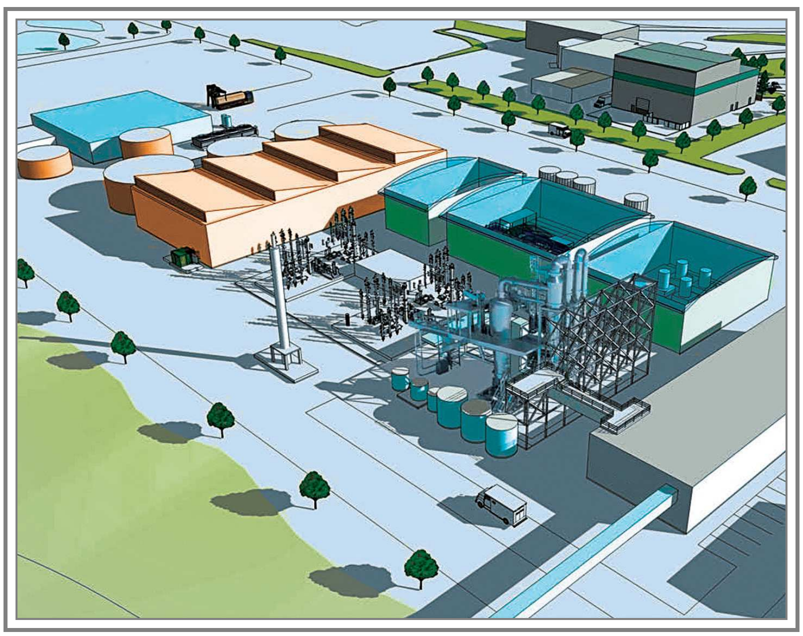
In the second step of the waste conversion process, the feedstock is fed to a gasifier, a closed vessel within which heat is generated that converts the feedstock into a synthetic gas. Typically, thermal or plasma-type gasifiers are used, of the types described more fully in Annex 3 for MSW gasification technologies. The feedstock does *not* combust in the gasification process. The synthetic gas (syngas) produced is rich in hydrogen and carbon (as carbon monoxide), which makes the syngas highly suitable for subsequent conversion to liquid hydrocarbon fuels. The syngas produced by the gasifier, however, also contains unwanted constituents. These include gases such water vapor that reduce the energy value of the syngas; constituents such as tars, ash, and sulfur that can inactivate the subsequent process for producing liquid fuels; and environmental contaminants such as sulfur and heavy metals. Accordingly, the gasification step of the process must be followed by effective syngas cleaning.

In the next step, the clean syngas undergoes a chemical reaction using the Fischer-Tropsch (F-T) Process. The F-T process is a long-established process that uses a metal catalyst, typically cobalt or iron, to meld the hydrogen and carbon present in the syngas into liquid hydrocarbon fuels (e.g., synthetic diesel fuel, ethanol, butanol) or chemicals (e.g., methanol, naptha). The F-T process was used extensively in Germany in the 1940's to produce liquid fuel from gasification of coal, and by South Africa to do the same from the 1950's to present. The liquid fuels produced by the F-T process are subjected to standard refinery processes (e.g., hydrocracking) to yield high-quality liquid fuels and chemicals. Again, it is essential for the syngas to be well-cleaned prior to its introduction to the F-T process for conversion to liquid fuels. For example, excessive tars and ash in the syngas can physically coat or plug the F-T catalyst, reducing its operating efficiency and service life, and even small amounts of sulfur and certain other elements can render the catalyst inactive.

The size (capacity) of waste-to-liquid fuels facilities is typically expressed as the number of tons per day (TPD) of MSW or WDF that can be processed, and also as the number of gallons per year of liquid-fuel production, expressed as millions of gallons per year (Mgy). As there are currently no commercial waste-to-liquid fuels facility operating anywhere in the world, the range of viable processing capacities is unknown. It is anticipated that the first commercial-scale facilities will have capacities similar to the small- to medium-capacity MSW gasification facilities that currently operate in Europe in Japan. That range is on the order of 80 to 600 tons per day (TPD) of MSW processing capacity, and likely 2 to 20 Mgy of fuel production.

Commercial Experience and Viability

As noted, there are no commercial-scale facilities operating anywhere in the world today that convert MSW to liquid fuels or chemicals. However, a number of developers have announced plans to develop commercial facilities in Canada and the U.S., and the first such commercial facility is under construction in Canada (Edmonton, Alberta). That $70 million facility will convert 100,000 TPY of post-recycling MSW to 10 Mgy of ethanol. Enerkem also recently began initial development activities for a $250 million waste-to-ethanol facility in the U.S. (Pontotoc, Mississippi) that would have twice the production capacity of the Edmonton plant.



Depiction of the 100,000-TPY Enerkem Waste-to-Ethanol Facility in Construction in Canada (Edmonton, Alberta)
Source: Enerkem

Technology Suppliers

Besides Enerkem, discussed above, there are other development companies, most based in North America, that have announced intent to enter the gasification waste-to-liquid fuels market, for example, Fulcrum Bioenergy and Cello Energy. There are also development companies working to commercialize the other types of processes for waste-to-liquid fuels, such as hydrolysis and thermal depolymerization.

Sustainability

For gasification waste-to-liquid fuels technology, the sustainability profiles with regard to resource recovery, energy efficiency, greenhouse gases, land resource requirements and waste diversion from landfill would be approximately similar to the profile presented in Annex 3 for gasification of MSW with energy recovery. Regarding water use, the gasification-based processes for waste-to-liquid fuels are typically net producers of water.

A key sustainabilty advantage for waste-to-liquid fuels technologies is that they produce a liquid transportation fuel or a chemical that replaces petroleum-based fuels and chemicals. Combustion of the liquid fuels in vehicle engines represents renewable energy, in proportion to the biogenic content of the MSW feedstock from which the fuel is made (typically, about 50% biogenic). Accordingly, use of the liquid fuel instead of petroleum-derived fuel results in an important reduction in greenhouse gas emissions.

Environmental Impacts

Regarding emissions to the air, there will be dust emissions from the MSW pre-processing equipment that will require control. The gasifier is a closed system, without emissions to the air. The syngas produced by the gasifier is not emitted or burned, but rather, is converted by the F-T process to liquid fuel or chemicals. Operation of the F-T process, however, can result in the production of a by-product fuel gas (tail gas) that would typically be used onsite as fuel for an engine-generator set, boiler, or process heater. Emissions of air pollutants will result from the combustion of the tail gas. The pollutants emitted and their control, including emissions of dioxin and mercury, would be similar to those described in Annex 3 for gasification of MSW with energy recovery. The liquid fuel, when combusted in vehicle engines, would produce tailpipe emissions. However, because the liquid fuel is very low in sulfur, the tailpipe emissions or sulfur dioxide, specifically, would be less than with use of conventional diesel fuel.

The scrubbing equipment used to clean the syngas in the waste-to-liquid fuels process can require substantial water. Normally, most of that scrubber water is recycled; however, there would be some wastewater discharge. The F-T catalytic process actually generates water, making the entire facility a net water producer.

The generation of disposable solid waste by the gasification waste-to-liquid fuels process would be similar to that described in Annex 3 for gasification of MSW with energy recovery.

Odor control during waste mechanical pre-processing is achieved using the same methods as described in Annex 6 for technology involving the production of waste-derived fuel (WDF). The remainder of the waste-to-liquid fuels process is a closed system, so there is little potential for odor emissions. Importantly, however, potential leaks of raw (pre-cleaning) syngas to the atmosphere could result in offsite odor nuisance, since the raw syngas contains the powerful odorant, hydrogen sulfide.

The safety hazards specific to gasification waste-to-liquid fuel facilities would include the following:

- Fires on waste delivery trucks and during waste storage
- Exposure to waste-borne pathogens and toxic substances
- Increased traffic hazard from waste delivery trucks
- During MSW pre-processing, there is an explosion risk if explosive materials (e.g., gas tank) are mixed with the waste that is being mechanically processed.
- Risk of injury/death from explosion of leaking syngas
- Risk of asphyxia from exposure to leaking syngas that builds up in confined spaces
- With conversion of MSW to liquid fuel, there is risk of fuel-related fires.

While these are all safety hazards for workers at a MSW gasification facility, only the truck-related safety hazard would likely extend significantly to the public off site.

Economics/ Institutional

<u>Economics</u>

As there are no waste-to-liquid fuels facilities in commercial operation as yet, there is no reliable information on the capital and operating costs for this technology. It is estimated that the capital and operating costs may be <u>very</u> approximately similar to the costs given in Annex 3 for MSW gasification with energy recovery.

Waste-to-liquid fuels is an emerging technology without a commercial track record as yet. In addition, it is a technologically complex process. Considering these factors, the technical and economic risks are very high for implementing the first commercial facilities, whether in developed or developing countries. Accordingly, if a waste-to-liquid fuels project is undertaken in Latin America, it would be highly advisable for the entire project development, ownership, and operation to be by the private sector. At this juncture, the economic and technical risks are too high for public-sector investment or operation.

Operational Complexity

Gasification of MSW and conversion of the syngas to liquid fuels or chemicals is a very complex process. Operation requires highly specialized skills and training. It is doubtful that the required specialized skills would be available in most regions of Latin America, except possibly in the capital cities of the most industrialized countries. Accordingly, a gasification waste-to-liquid fuels facility in Latin America would likely require specialized, private-sector operators.

Public Acceptance

In some parts of the U.S., combustion WTE generates public opposition, based on concerns about air emissions and WTE competing with recycling. While opposition to WTE is less in countries outside the U.S., some potential for opposition exists in any location. With the alternative of waste-to-liquid fuels technology, the basis for public opposition is reduced, as the there is no waste combustion involved and the focus is on producing liquid fuels, not onsite energy.