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Alternative Technologies

Technical Memorandum

Cedar Rapids Linn County
Solid Waste Agency

Cedar Rapids, Iowa

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Acronyms/Abbreviations:

ACI = activated carbon injection
AD = anaerobic digestion
APC = air pollution control
CH_4 = methane
C&D = construction and demolition
CNG = compressed natural gas
CO = carbon monoxide
CO_2 = carbon dioxide
CRLCSWA = Cedar Rapids Linn County Solid Waste Agency
DWRF = Drake Water Reclamation Facility
ECS = eddy current separators
EU = European Union
FB = filter baghouse
FT = Fischer-Tropsch
H_2 = hydrogen
HCl = hydrogen chloride
HDPE = high density polyethylene
HRSG = heat recovery steam generator
H_2S = hydrogen sulfide
IGCC = integrated gasification combined cycle
IRBF = Indian River Biofuels Facility
IW = industrial waste
MBT = mechanical biological treatment
MRF = materials recovery facility
MSW = municipal solid waste
MWPF = Mixed Waste Processing Facility
N_2 = nitrogen
NHSM = Non-Hazardous Secondary Material
NO_x = nitrogen oxide
PAG = plasma arc gasification
PET = polyethylene terephthalate
PVC = polyvinyl chloride
RDF = refuse-derived fuel
Region = Linn County and the regional area
SCR = selective catalytic reduction
SDA = spray dryer absorbers
SNCR = selective non-catalytic reduction
SRF = solid recovered fuel
SO_x = sulfur oxide
tpd = tons per-day
WTE = waste-to-energy
WWTP = wastewater treatment plant

1 Introduction & Purpose

The Cedar Rapids and Linn County Solid Waste Agency (CRLCSWA) is researching relevant existing information to form the basis for evaluating infrastructure related options to address current and future solid waste demands within Linn County and the regional area (Region). This technical memorandum addresses Task 1, Alternative Technologies, Management Practices, and Industry Trends. CRLCSWA will review alternative technologies, often called conversion technologies, that may use waste generated within the Region as an acceptable and achievable resource. HDR has prepared this report based on our recent, relevant experience and research into these technologies. This includes site tours and inspections where some of these technologies are in use around North America and the world, specifically Europe, Asia (Japan), the Middle East, and Australia. Conversion technologies are a rapidly developing and evolving industry. HDR provides an overview of these technologies and current applications at the time of this report; however, this report does not represent or cover all the technologies that may be in development now or in the near future.

The technology development process can provide improved waste utilization instead of simply landfilling what cannot be recycled. The process may be completed in multiple ways, by more than one development team, using varying technologies at various stages of development. Broadly, a technology goes through three developmental stages: laboratory or emerging, pilot or demonstration, and commercial. Passing from one developmental stage in the process to the next is often hard to define as development may be on a continuum or have various sub-steps along the way.

Technologies begin the emerging process often as a small-scale operation of a technology concept. Initial development is completed in a laboratory setting and does not have demonstrated facilities that have been operated on a commercial basis as a full-scale, complete process. The technology may work well in a laboratory setting or for a select waste material, but it has not been demonstrated with mixed waste or even select portions of municipal solid waste (MSW) that can be separated readily from the remaining waste. It is likely the laboratory model will not have a fuel preparation or energy recovery process, even if these technologies are off the shelf systems.

Pilot scale or demonstration level technologies have advanced far enough that they may have a test facility where the development team will make test runs of varying and increasingly more complex waste mixtures. Initially, the pilot facility may not have all the waste preparation, energy recovery, and pollution control equipment fully integrated, but the process begins to gradually look and perform as a complete system. The development may go through several stages and increase in size and complexity as the technology advances. The demonstration facility will look very similar to a commercial facility toward the end of this stage.

The commercial stage means at least one fully integrated facility has been built and has been in continuous operation for long enough to have gone through several operation cycles and proven it can reliably achieve the anticipated level of performance. It often takes several years for a technology to be considered commercial. This allows time for planned and unplanned outages to occur, waste materials to pass through short term and seasonal changes, and a better understanding of the operational and maintenance costs and limitations to develop. Sometimes other innovators will have similar processes along the development curve, but not all related technologies will become commercial at the same time. While development risk is never fully eliminated, risk of technology failure drops substantially once commercial operation is reached.

The alternative technologies CRLCSWA considered for this analysis needed to be economically viable and technically commercial for operation in Linn County. In support of this technical memorandum, HDR looked at the full spectrum of potential technologies. From this list of technologies, those that were not developed commercially were screened out leaving those that are developed and, ultimately, those that could be implemented given reasonable conditions with the waste streams in Linn County, Iowa.

General Description

Waste processing and conversion technology options can be grouped into the following technology classes:

- Thermal technologies
    - Direct combustion (various forms of traditional waste-to-energy [WTE])
    - Gasification
    - Plasma arc gasification (PAG)
    - Pyrolysis
- Biological technologies
    - Aerobic composting
    - Anaerobic digestion with biogas production for electricity or fuel generation
- Chemical technologies
    - Hydrolysis
    - Catalytic and thermal depolymerization
- Mechanical technologies
    - Autoclave/Steam classification
    - Mixed waste processing
    - Refuse-derived fuel (RDF) production

It is important to note that there are waste conversion technologies that are a combination of two or more technology classes. For example, mechanical biological treatment (MBT) technologies combine mechanical separation and treatment with biological processing, while waste-to-fuel technologies combine mechanical pre-processing with thermal and chemical conversion processes, sometimes including a biological component like anaerobic digestion. Each vendor promoting their technology will have unique features and approaches that may differ slightly from the descriptions provided below. For example, gasification may employ a two-stage gasification process or a single chamber where the waste fuel is gasified, and one technology may require more or less fuel preparation than another gasification technology.

2 Conversion Technology Processes and Methodologies

Thermal Technologies

Thermal technologies are designed to use high temperatures from combustion, gasification, or pyrolysis to convert the carbonaceous combustible materials in MSW feedstocks into a gas and other solid by-products (ash/char). The caloric energy contained in the waste may be recovered to produce an energy product, or the gases produced from the exothermic reaction that breaks down the waste may be further refined into a synthesis gas (syngas) or chemical. Traditional thermal processes, such as incineration or WTE technologies, produce electrical power or steam by using a boiler to recover the latent heat in the exhaust gas formed from combusting the waste. The steam produced is then sent to a turbine generator to generate electricity. Some thermal facilities may also sell the steam or hot water directly to a commercial/industrial user or send it to a district energy system.

Thermal processes that convert waste to a liquid fuel and/or syngas (i.e. gasification, PAG, and pyrolysis) may be designed to either combust that gas and/or liquid directly in a boiler to make steam and electricity (similar to a traditional WTE technology), or the process may be designed to clean and refine the gas and/or liquid to be combusted in an engine or gas turbine to make electricity. In addition, there are technologies designed to use gasification or pyrolysis to produce a syngas and/or liquid that is cleaned and further refined through a chemical or catalytic process to produce commercial grade chemicals or liquid synthetic fuel for fixed or mobile internal combustion engines, fixed turbines, or commercial airliners. The gas produced by gasification technologies is composed mostly of hydrogen (H_2) and carbon monoxide (CO), and there are some technologies that attempt to further refine and capture the H_2 gas for reuse. Gasification and other similar technologies can be highly complex, may only be effective on a limited fraction of the waste stream, and are generally less commercially developed than traditional WTE technologies.

Regardless of the specific thermal process used, direct waste combustion or gasification produces certain types of impurities and constituent air emissions. The quantities vary depending on the type of technology and must be controlled or removed through refining or cleaning. In theory, the emissions from gasification and pyrolysis technologies are lower than traditional WTE technologies that directly combust the waste with an oxygen-rich environment; however, modern emission control systems are required to reduce emissions from both types of technologies below any regulatory emission standards.

Thermal technologies can yield gases such as carbon dioxide (CO_2), water vapor, nitrogen oxide (NO_x), sulfur oxide (SO_x); hydrogen chloride (HCl); particulate and particulate-related emissions (such as heavy metals); and trace amounts of products of incomplete combustion, such as CO, dioxins and furans. New thermal technologies are expected to use modern air pollution control (APC) devices for emissions clean-up. The array of APC equipment available for use in minimizing air emissions is quite diverse and includes but may not be limited to: selective catalytic reduction (SCR) or selective non-catalytic reduction (SNCR) for NO_x emissions reduction; spray dryer absorbers (SDA), wet scrubbers, and sorbent injection for acid gas reduction; activated carbon injection (ACI) for mercury and dioxins reduction; and a fabric filter baghouse (FB) for particulate and heavy metals removal. Combustion control techniques are used to control CO and optimize the other APC equipment. Continuous emission monitoring systems, specific operating parameters, and periodic compliance testing are used to demonstrate emission compliance. The complexity of the optimal APC and gas cleanup systems may vary depending on the thermal technology used and the desired end use of the gases and/or liquids produced by the process.

Direct Combustion

Direct combustion technologies with energy recovery, such as mass burn technology and RDF combustion, have been used since the 1950s and continue to be constructed and operated around the world. This technology was first introduced in the US in the early to mid-1970s and many of the facilities operating currently have been on-line for 25 to 40 years. Direct combustion, referred to herein as traditional WTE or Energy from Waste, is the most widely demonstrated and commercially viable of the thermal conversion technologies available with approximately 4,000 installations worldwide.

The majority of the 70+ thermal waste conversion facilities operating in North America use direct combustion technology. Significant construction of traditional WTE facilities in North America stopped in the mid-1990s, but several existing WTE facilities in Minnesota, Florida, and Hawaii have undergone recent expansions. Two new greenfield facilities have been constructed using modern WTE combustion technology. These include a 3,000 tons per day (tpd) mass burn facility in West Palm Beach, Florida (2015) and a 480 tpd mass burn facility in Clarington, Ontario, Canada (Durham York Region), shown in Figure 1. The Hennepin County Facility in Minneapolis offers a representative WTE facility that could be visited to see firsthand how the technology works. There are several other waste facilities in the Midwest region as well. Additional exploratory expansion work is also underway at a number of facilities in the US and the early siting study and funding are being prepared for a greenfield facility in Canada.

Figure 1: Durham York Energy Centre (Ontario, Canada)

Direct combustion of waste involves the complete oxidation of a fuel by combustion under controlled conditions using more than stoichiometric levels of oxygen (also known as excess air combustion). The latent heat generated from the combustion process is recovered in a boiler to generate steam, which can be used directly for heating/industrial purposes or passed through a steam turbine-generator to create electricity. There are several types of direct combustion technologies used on a commercial scale in North America, Europe, and Asia. The most common include:

1) Mass burn with a grate system,
2) RDF stoker-fired boilers,
3) Modular starved air systems, and
4) RDF fluidized bed combustion.

RDF processing is further discussed below. Mass burn combustion technology can be divided into two main types:

1) Grate-based, waterwall boiler field erected installations, and
2) Modular, shop-fabricated combustion units with waste heat recovery boilers.

The modular units are typically limited to less than 200 tpd and were historically used in facilities where the total throughput is under 500 tpd. All direct combustion technologies require advanced APC to reduce or remove air emissions before the flue gas is discharged to the atmosphere. The most common examples of APC equipment used at traditional WTE facilities include SCR, or SNCR for NO_x emissions reduction, SDA, or dry sorbent scrubbers for acid gas reduction, ACI for mercury and dioxins reduction, and a fabric FB for particulate and heavy metals removal.

The larger mass burn combustion units with waterwall boilers are generally sized at 200 tpd up to as large as 1,000 tpd with facilities generally sized at 400 tpd to 3,000 tpd or more. MSW is fed directly into a boiler system with little to no pre-processing, other than the removal of large bulky items such as furniture and white goods. The MSW is typically pushed onto a grate by a ram connected to hydraulic cylinders where it is combusted. Air is admitted under the grates, into the bed of material, and additional air is supplied above the grates to thoroughly complete MSW combustion. The resulting flue gases pass through the boiler and the heat energy is recovered in the boiler tubes to generate steam. This creates three streams of material: steam, flue gases, and ash.

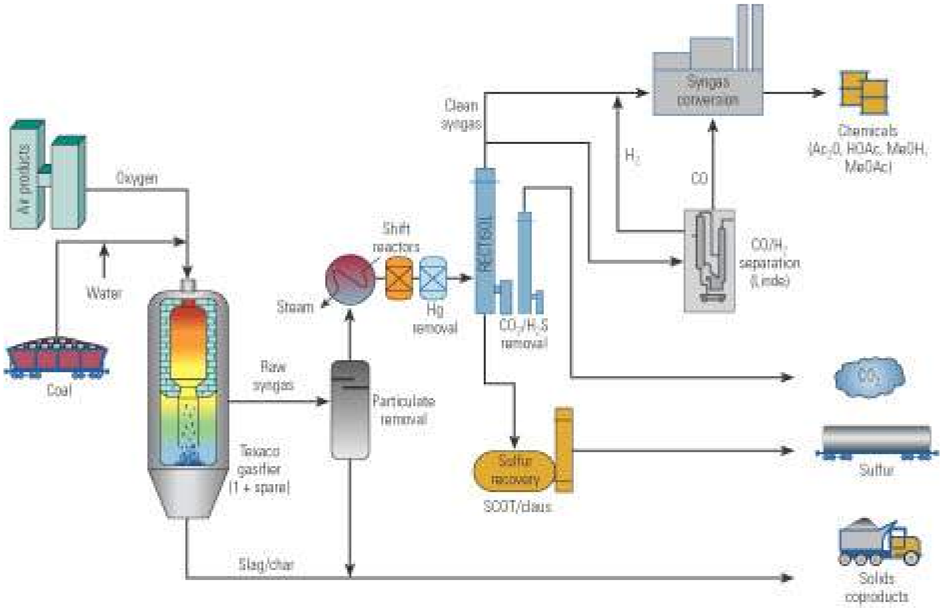
In the smaller modular mass burn systems, MSW is fed into a refractory lined combustor where the waste is combusted on refractory lined hearths or within a refractory lined oscillating combustor. Typically, there is no heat recovery in the refractory combustors. Instead, the flue gases exit the combustors and enter a heat recovery steam generator (HRSG), or waste heat boiler, where steam is generated by the heat in the flue gas, resulting again in steam, flue gases, and ash.

RDF combustion technologies prepare MSW by shredding, screening, and removing non-combustible materials prior to thermal conversion. The goal of this technology is to derive a better, more homogenous fuel (uniform in size and composition) that can be used in a more conventional solid-fuel boiler as compared to a mass-burn combustion waterwall boiler. RDF is blown or fed into a boiler for semi-suspension firing. Combustion is completed on a traveling grate. Thermal recovery occurs in an integral boiler. The APC equipment arrangement for an RDF facility would be similar to a mass-burn combustion system.

Gasification

Gasification has been used for over two hundred years. In the 1790s “coal gas” was used for factory lighting. In the 1940s, during World War II, Germany used wood and coal gasification to synthesize fuels for vehicles and aircraft. Starting in the 1970s and continuing to the present-day, the fuel gas produced from the gasification of coal (shown in Figure 2) and various types of biomass (e.g. wood and woody wastes) has been used on a smaller scale to fire stationary internal combustion engines or as a building block to produce liquid fuels.

Figure 2: Typical Gasification Process Utilizing Coal



The gasification process is similar for waste facilities and involves the conversion of carbonaceous material (such as MSW) into a raw gas, often called a producer gas, that contains principally CO, H_2, methane (CH_4), other light hydrocarbons, water, CO_2, and nitrogen (N_2), depending on the specific process. The conversion of the feedstock using gasification typically occurs in a reducing environment (i.e. in the presence of limited or substoichiometric amounts of oxygen) under high temperatures. In some cases, steam is added to the process to alter the ratio of the combustible gases. The relative concentration of producer gas components depends upon the composition of the feedstock and process operating conditions.

Gasification is a thermochemical process that performs more consistently when converting homogenous or uniform feedstock. As a result, the feedstock for most gasification technologies must be prepared from the incoming MSW through shredding and pre-sorting to pull out bulky materials, hazardous household waste, as well as recyclables and inert materials such as dirt, glass/grit, and metals. These materials must be separated and removed to prevent slag formations that can cause process upsets or potential operating issues.

Syngas can be derived from the producer gas by removing impurities and contaminants through appropriate cleaning and reforming processes to produce a gas composed primarily of CO and H_2. The relative concentration of syngas components depends on the composition of the feedstock and process operating conditions (temperature, air, oxygen, or steam injection, pressure, etc.). The typical breakdown of syngas components for gasification technologies that process MSW streams is provided in Table 1. Many gasification technologies are sensitive to the composition of materials they process and will adapt the fuel preparation steps based on their experience. The outputs provided in Table 1 are heavily dependent on the waste being used as feedstock.

Table 1: Typical Syngas Composition

Constituents	Output by % Volume	Output in m^3/kg-waste processed	Energy output in Btu/lb-waste processed
Hydrogen (H_2)	30%-50%	0.25-0.50	1,360
Carbon Monoxide (CO)	25%-70%	0.25-0.60	1,940
Carbon Dioxide (CO_2)	0%-35%	0.05-0.25	0.00
Methane (CH_4)	0%-10%	0.00-0.15	425
Note: Syngas composition data based on available data from technology vendors including, but not limited to, Thermoselect, Ebara, Taylor, and Sierra Energy. Data is provided as dry percentages.			

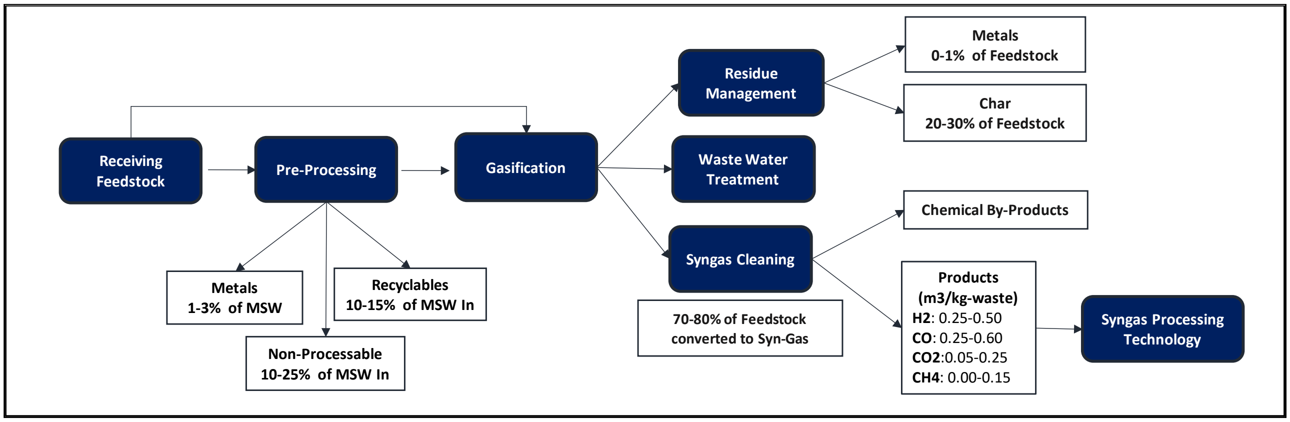
The latent heat in the raw producer gas or syngas could be recovered in a boiler or HRSG to create steam that can be used to generate electricity through a steam condensing turbine (similar to the traditional WTE technology described above). Some systems could be designed to use the syngas as a fuel to generate electricity directly in a combustion turbine or internal combustion engine (similar to a landfill gas-to-energy system). The generated syngas could also be used as a chemical building block in a catalytic or Fischer-Tropsch (FT) process for the synthesis of chemicals and liquid fuels (e.g. methanol, ethanol) but only after considerable gas cleanup.

Gasification with waste fuels has had a long developmental run but remains in the developmental pilot phase, at least in the US. There are a wide variety of technology designs that can be defined as gasification, but these facilities have generally been smaller than most direct combustion facilities. Figure 3 shows a representative facility in Japan. Some modular combustors operate on the principles of gasification through a two-stage combustion process in which the first (primary) chamber operates in a low-oxygen or starved air reducing environment and burnout of the combustion gases produced is completed in a secondary chamber before passing on to a waste heat boiler. Some systems are designed to vitrify the ash into slag that can be recovered as road base material or certain other aggregate products, potentially reducing waste volume by more than 95 percent.

Figure 3: Homan Gasification Plant (Fukuoka, Japan)

Figure 4 provides a gasification technology schematic with a range of values for the typical reported outputs.

Figure 4: Schematic of Typical Reported Gasification Technologies



Note:
Projected syngas products are equivalent to those indicated in Table 1 above.

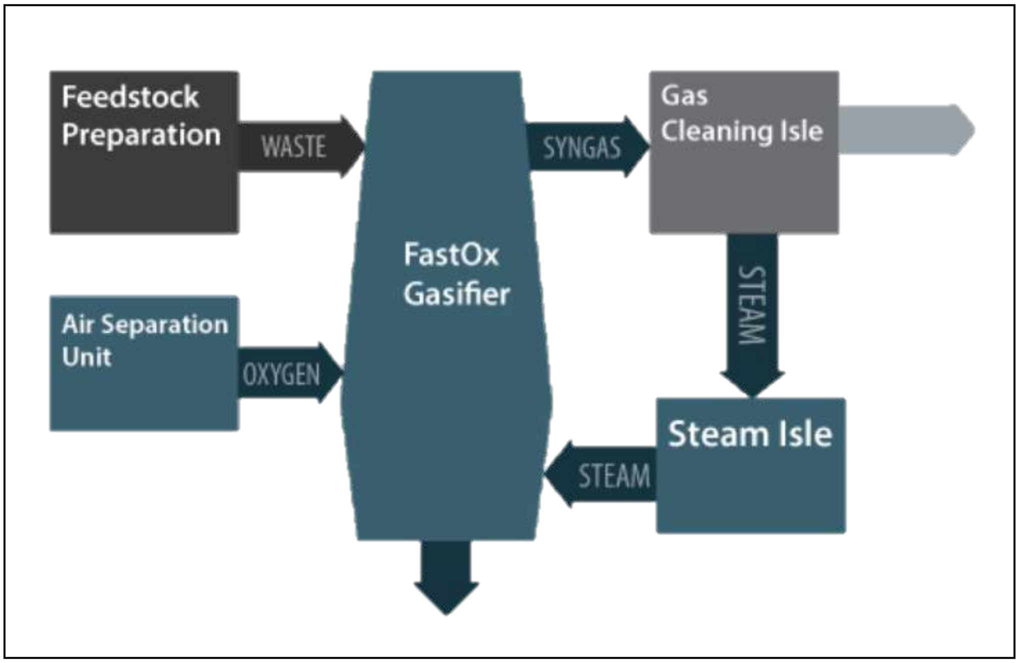
Gasification facilities that combust the syngas generated by the process will have similar air emissions as traditional WTE facilities. However, the volume and concentration of these air pollutants should theoretically be lower. If the syngas is conditioned for use elsewhere (e.g. as part of a catalytic process to generate a liquid fuel), then additional gas cleaning and conditioning equipment is required. These technologies also produce char or ash in quantities similar to or less than tradition WTE technologies (less than 90 percent by volume and less than 20 percent by weight). Other metals and inert materials can remain with the char and ash and may be recovered after processing.

There are several commercial-scale gasification facilities in operation overseas, some of which have been operating for several decades. Most of these facilities are located in Asia, particularly in Japan, and a few in the European Union (EU). The facilities generally process feedstock materials using units sized from approximately 100 tpd to 275 tpd. Some gasification facilities in Japan utilize feedstocks with high energy content, such as select industrial waste (IW) or a combination of these feedstocks and MSW. The drivers for the use of gasification in Japan are largely related to the lack of available landfill capacity and very stringent emission standards, which favor the use of this technology. In addition, it is important to understand that waste tipping fees in Japan are much higher compared to the US (more than $250/ton USD), which makes these facilities more financially viable. In addition, one goal of the process is to generate a stabilized, and in some cases vitrified, ash product that can be reused beneficially as an aggregate in the construction industry to limit the amount of material being diverted to scarce landfills. However, the use and marketability of this material in the US is not demonstrated.

Thermal MSW and IW gasification has been attempted for many years, particularly in North America, but many of these facilities experienced difficulties scaling-up to commercial operations. Currently, gasification technologies in North America are mostly limited to demonstration or pilot scale operations with limited operational history. This is due partially to economics driven by low electricity prices and lower landfill tipping fees in the United States. It is also due to the costs and difficulty associated with front-end MSW processing to achieve a homogenized and higher Btu-content MSW feedstock suitable for some gasification technologies. In addition, many of the gasification facilities are having issues consistently meeting the gas quality and energy content of the syngas to allow the engines or other power operating equipment to efficiently produce electricity.

More recent projects in North America are currently under development. Ways2H is a Japanese technology that claims to produce H_2 gas as a transportation fuel from MSW using their gasification technology. The technology has been tested in Japan on a small scale and a project in Kern County, California is under development. The Sierra Energy FastOx technology—Monterey, California—is a fixed-bed gasification system that feeds MSW into the top of the gasifier vessel through an airlock chamber and purified oxygen and steam are injected into the base of the vessel. As the waste travels down the reaction vessel, it passes through several reaction zones reaching the hottest area at the base of the vessel where the gasification reaction is designed to occur at temperatures of approximately 2,200°C (4,000°F). The FastOx system includes equipment for feedstock preparation, gasification, syngas conditioning, and final product conversion to fuels or energy. Figure 1 provides a schematic of the FastOx process. Sierra Energy claims that the FastOx gasification system can accept most wastes, with the exception of radioactive and explosive materials. This includes MSW and IW (including hazardous wastes), as well as biomass, construction and demolition waste, and medical wastes. The syngas produced via FastOx gasification is designed to be converted into a wide range of sustainable and marketable energy products, including electricity, diesel, H_2, and ammonia. Sierra Energy is currently operating a small, 20-tpd unit for the US Army and Department of Defense at Fort Hunter Liggett in California. The facility is designed to process MSW and biomass to produce electricity and biodiesel. They are currently developing a commercial-scale version of the FastOx gasifier, called the Pathfinder, which will be designed to process 50-tpd per unit.

Figure 5: Sierra Energy FastOx Process Schematic



Source: Sierra Energy.

Plasma Arc Gasification

PAG is considered a subset of thermal gasification. Plasma arc melting technology has been used in the metal industry since the late 19th century. PAG technology has been used more recently, mostly overseas, as a disposal option for a range of industrial and other disposal applications, such as the gasification of hazardous waste, auto shredder fluff, and other types of homogeneous wastes and ash treatment. This technology has only been considered a possible source of MSW feed stock disposal and conversion at demonstration and pilot-scale level applications within the last 15 to 20 years.

Plasma arc technology uses carbon electrodes to produce a very-high-temperature arc ranging between 5,000 and 12,000-degrees Fahrenheit that “vaporizes” the feedstock. The high-energy electric arc that is struck between the two carbon electrodes creates a high temperature ionized gas (or plasma). The intense heat of the plasma breaks MSW and other organic materials fed to the reaction chamber into basic elemental compounds. As the feedstock gasifies, a low-Btu syngas is generated, similar to other gasification technologies, that could be suitable for combustion, and the heat is recovered in a boiler. In theory, the high temperatures produced by a PAG technology produces a cleaner (i.e. lower in tars or other impurities) and higher quality syngas than other technologies that can be more easily cleaned and combusted directly in an internal combustion engine or gas turbine to produce electricity and/or thermal energy (i.e. steam, hot water). The gas can also be cleaned and used for a chemical process. The inorganic fractions (glass, metals, etc.) of the MSW stream in a PAG system are melted to form a liquid slag material that vitrifies to encapsulate toxic metals when cooled. The systems may be designed to recover recyclable and other materials through a pre-processing system. Metals may be recovered from both feedstock pre-processing and from post-processing the solid slag material.

Similar to other gasification processes, the MSW feedstock requires pre-processing to shred and homogenize the size of the feedstocks, as well as to remove materials that may cause potential operating issues. Vendors of this technology claim the energy efficiencies capable with PAG systems are higher than direct combustion and other gasification technologies. These higher efficiencies are theoretically possible if an integrated gasification combined cycle (IGCC) power system is incorporated to harness the energy in the syngas; however, this has not been proven for PAG systems on a commercial scale.

Vendors of this technology claim to achieve lower emission concentrations than more conventional technologies like direct combustion. However, air pollution control equipment is still required to clean the gas from the syngas combustion as these facilities generally have similar air emissions issues as other gasification, pyrolysis, and direct combustion facilities. Mercury and other, more volatile metals are expected be driven off with the gas and will need to be removed from the gas combustion device's exhaust.

Individual units in Japan and around the world are sized anywhere from approximately 20 tpd to 200 tpd and are sometimes combined in multi-unit configurations when developing a facility to create an overall capacity of 400 tpd or greater. Although Japan has approximately 10 to 15 years of operating experience, their facilities are mainly used for ash melting (as described below), IW, or MSW with high plastics content that increases the Btu value. Several facilities operate in Japan, most notably three developed by Hitachi Metals, in Yoshii, Utashinai, and Mihama-Mikata. These facilities are referred to as plasma direct melting reactors. The name is significant due to the desire in Japan to vitrify ash from mass burn WTE facilities.

Many gasification facilities in Japan also accept ash from conventional WTE facilities for vitrification. In many cases, the primary function of these facilities is ash vitrification rather than energy recovery. The benefit of the vitrified ash is it binds potentially hazardous elements thereby rendering the ash inert. Most facilities in Japan use this vitrified ash as an aggregate product. Because of the high MSW tipping fees and other economic drivers in Japan, and the fact that the PAG facilities operate only about 9 months per year, any data from these facilities is difficult to correlate to conditions in the United States.

There are few commercial PAG facilities around the world, but none are currently processing MSW in the US. There have been some recent attempts at applying PAG technology commercially in North America and in the UK. However, these attempts have met financial hurdles. In April 2012, after 5 years of planning, construction of a large scale PAG facility in Saint Lucie County, Florida was cancelled. An NRG/Adaptive Arc was in the permitting/approvals phase for a facility in Atlantic County, NJ, but was eventually canceled. A demonstration project located in Ottawa, Ontario, Canada (i.e. the 110-tpd Plasco Trail Road Facility) also utilized PAG principles on a mixed MSW waste stream. However, after almost 8 years of sporadic operations and design issues, the facility ultimately closed due to funding issues. The 1,000 tpd Tees Valley 1 and 2 projects in the United Kingdom are shown in Figure 6. However, both projects ran into technical issues and also failed to achieve commercial operation. The project was canceled at a loss of almost $1 billion USD for the project sponsor, Air Products.

Figure 6: Alter NRG 1,000-TPD Plasma Gasification Reactor Tees Valley, England, UK

There were some demonstration facilities in North America that utilized PAG technology, which included a 10-tpd demonstration PAG unit (manufactured by Pyrogenesis based out of Quebec, Canada). This facility processed small amounts of a manually separated MSW from the Hurlburt Field Air Force Base in Florida. That demonstration facility has since been shut down. However, Pyrogenesis continues to manufacturer their plasma torches and has constructed PAG waste processing systems for onboard sailor waste for the US Navy, specifically the U.S.S. Gerald Ford, and for commercial cruise lines.

Pyrolysis

Pyrolysis technologies are closely related to gasification and some facilities could fall into either technology category depending on how they are operated. Pyrolysis is the process of heating material to high temperatures (700 to 1500°F) in an oxygen-free environment and driving off the volatile hydrocarbons to produce a combustible gas and liquid product (i.e. pyrolytic oils). The remaining fixed carbon forms a carbon-rich solid residue with the remaining ash and metals materials. This is similar to the process to produce coke from coal or charcoal from wood. The feedstock used in pyrolysis technologies has typically been more homogeneous than mixed municipal waste, using materials such as coal, biomass (woody wastes), or even waste tires. Torrefaction is a similar pyrolytic process, most often used with wood or biomass, that has been proposed for some facility designs. In some pyrolysis operations, pre-processing mixed MSW has been used to obtain RDF, which is a relatively more homogeneous feedstock, as the primary or another feedstock for the pyrolysis facility.

Similar to gasification, the pyrolysis process can be designed to optimize the production of gases or liquids. A pilot project, shown in Figure 7, is under development by Ways2H in Kern County, CA. This is sometimes classified as gasification and is a waste-to-fuel technology. It uses a pyrolysis technology to generate a syngas that is then further refined in a waste-to-fuels project (discussed below) to generate H_2. For other pyrolysis facilities, syngas can be produced and used as fuel in boilers or, theoretically, in internal combustion units or gas turbines, provided that the gas is adequately cleaned. As discussed, the pyrolysis process is performed in an air- or oxygen-free environment. Therefore, the system must usually have a complex design and control system to prevent air or oxygen from intruding into the process, or a provision must be incorporated into the design to purge air from the reaction chamber. However, some pyrolysis processes allow very small amounts of air/oxygen into the system. This allows the feedstock to combust partially and supplement the heating process. Other designs may use some or all of the volatile gases to heat the feedstock. This would drive off more gases and liquids and produce the fixed carbon char.

Figure 7: Ways2H Pyrolysis Facility Kern County, CA

Photo courtesy of Ways2H

Air emissions from pyrolysis systems are primarily those discharged from combustion of the producer gas or syngas (and possibly char). The treatment of syngas produced from MSW pyrolytic processing for use in energy conversion equipment and emissions control of syngas constituents has little history but is similar to the gasification process described above. Facilities using the pyrolytic oil and other products as fuel could have some of the same air emissions issues as direct combustion. Less SO_x might be generated in the gas or oil, because most of the sulfur is expected to stay with the char. However, the sulfur could be released to form SO_x if the char is combusted. HCl will also need to be addressed in the exhaust gases. Units that heat the feedstock in an oxygen-deficient environment would produce fewer emissions. Mercury would be expected to be largely driven off with the gas and the gas combustion device exhaust would have to be addressed. Other metals and particulate could remain with the char and could be largely separated from the char prior to combustion with a suitable processing system. These emissions can theoretically be controlled using modern air pollution control devices to meet local, state, and national regulatory standards.

Biological Technologies

Biological technologies are designed to use bacteria as part of the technology employed to consume the putrescible content of the feedstock. This typically occurs in low temperature environments employing either aerobic bacteria or anaerobic bacteria. The volatile solids contained in the waste are consumed by the bacteria and converted to CO_2 (for aerobic processes) or a blend of CH_4, alcohols, CO_2, and other gases (for anaerobic processes). Aerobic processes are exothermic and, if managed properly, produce enough excess heat to kill pathogens contained in the feedstock. Anaerobic process typically require heat and may require subsequent processes to kill pathogens contained in the feedstock.

Aerobic Composting

Aerobic composting has been employed successfully on source separated organics such as food waste, yard/agricultural waste, and wastewater biosolids. Some facilities are permitted and designed to accept compostable paper and plastic and some operations have attempted to process other compostable solid waste. Aerobic composting can include a number of different processes. The two most common are aerobic windrow composting, also called turned windrow composting (see Figure 8) and forced aerated static pile composting. Windrow style composting is the most commonly used in the US, treating predominantly yard/agricultural waste, and is usually conducted outdoors. Forced aerated static pile composting is typically constrained to higher quantities of putrescible material, such as food waste or biosolids, and is often covered or indoors. However, some forced aerated static pile composting is conducted outdoors and employs the use of biofiltration to minimize odor emissions. Aerated static pile composting can also include a variety of cover systems, including specially designed tarps or fabric covers, organic covers such as finished compost, or a specially-equipped bag system to contain the materials.

Figure 8: Example of a Windrow Aerobic Composting Facility

In windrow composting, the materials (generally green material) are placed in elongated piles called windrows. The windrows are aerated naturally through a “chimney effect” or by mechanically turning the piles with a machine or forced aeration, which improves porosity. Usually, a bulking agent such as wood chips or other green waste is used to allow proper air flow through the pile to help prevent pockets of the material from becoming oxygen deficient and the composting process from becoming a localized, odiferous, anaerobic process. Frequent pile turning introduces oxygen, accelerates physical degradation of feedstocks, and provides an opportunity to adjust the moisture content and temperature to optimum levels. This technology can be particularly odorous if food waste or other MSW is included in the feedstock. The average time required for active composting is 8 to 12 weeks for windrowing, but bag and static pile composting (see Figure 9) can achieve faster composting if managed carefully.

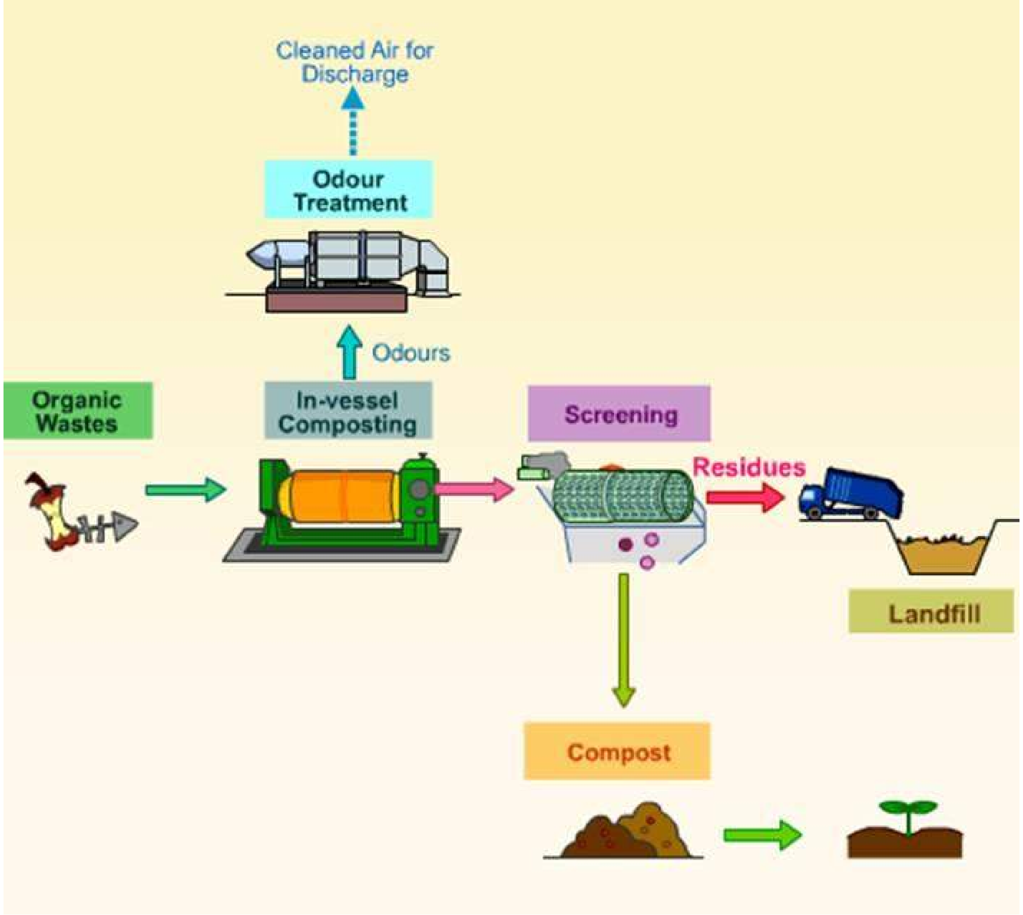
Figure 9: Example of a Fabric Covered Aerobic Static Composting Facility, Issaquah, WA

The aerated composting process refers to any of several systems used to biodegrade organic material without physical manipulation during primary composting. It may be in windrows, bunkers, or mass beds and be open, covered, or in closed containers (in-vessel). Figure 10 shows an aerated static pile operation located in a covered setting and Figure 11 shows a bunker arrangement. Figure 12 shows a schematic flow diagram for an in-vessel composting system. The steps required for in-vessel composting are similar to other processes. In an aerated static pile composting technology, fresh air is either forced into the pile or drawn from the pile to maintain high levels of oxygen. This process accelerates the bacterial consumption of the organic material. Without the added fresh air, the denser putrescible material would naturally default to an anaerobic condition and lose aerobic bacteria. This method is suited to producing large volumes of compost in relatively smaller areas. This technology can be particularly odorous if the composting pile is allowed to have pockets of anaerobic activity. The blended mixture is usually placed on perforated piping or trenches, providing air circulation for controlled aeration. Moisture levels are managed, and material temperatures are monitored for best operation.

Figure 10: Example of a Covered Aerobic Static Composting Facility, Olympia, WA

Figure 11: Example of a Bunker Aerobic Static Composting Facility, Stanwood, WA

Figure 12: Example of a Windrow Aerobic Composting Facility



In negatively aerated types of aerated compost processes, a series of perforated pipes draws air down through the windrows to an air collection manifold that runs under the windrows. The compost air can be drawn through the compost using a blower system that then pushes the air through a biofilter that acts as an emission and odor control system. Alternatively, in positive aerated systems, air can be injected into the windrows to maintain proper oxygen levels. The key in either of these systems is the appropriate use of best management practices that include the initial mix of putrescible material and bulking material (typically mulch or chipped wood) in the correct proportions to assure the porosity and moisture content needed to maintain proper aerobic bacterial health throughout the process.

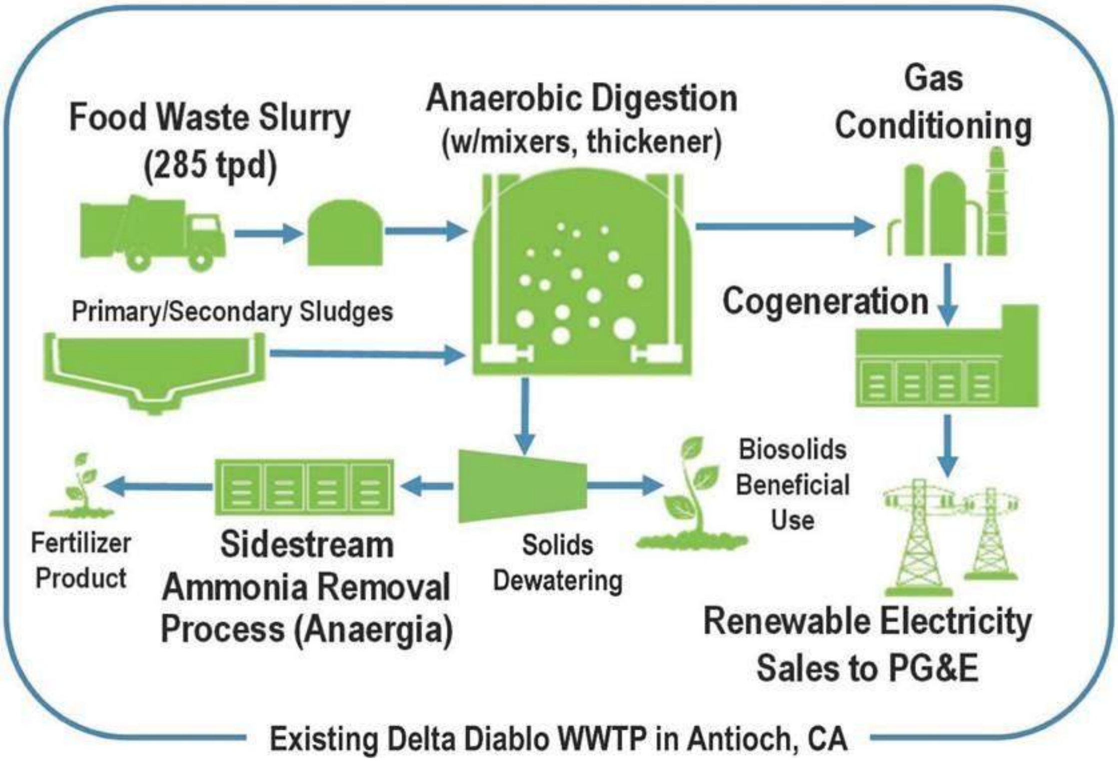
In-vessel food waste aerobic composting can also take place in highly controlled, automated equipment using a combination of agitation and temperature/moisture control to convert food scraps into compost in just a few days. Current models on the market have modest capacity. Larger units are able to process up to 1.5 tpd. This technology is most efficient for use with small food waste generators such as schools, hotels/conference centers, malls/food courts, cruise ships, hospitals, amusement parks, and sports stadiums. Some larger facilities use bags or other enclosures. Managing odors is a key concern.

Compostable paper and compostable plastic materials in the compost are often a challenge. While many of materials can eventually break down under ideal time and temperature conditions, most commercial compost facilities do not successfully accomplish this in a single process. Often these materials require additional screening processes to remove them from the final compost and either return them to the compost system for additional biological degradation or dispose of them as a residue. Also, it is difficult to differentiate between compostable and non-compostable plastics. This results in an abundance of non-compostable materials at the end of the compost process. Facilities that have accepted post-consumer food waste with compostable service ware, or other MSW materials, have had to install robust screening/cleanup measures to remove glass, plastic, metal, and other foreign materials from the compost products. These facilities often have operational issues, such as odor generation, and have had difficulty producing marketable products. Finally, composters attempt to produce the highest quality compost possible to secure the best price for their compost. The highest quality compost is a certified organic compost. However, the presence of foreign materials that derive from non-compostable feedstocks will prevent the compost from obtaining certified organic compost grades.

Anaerobic Digestion

Anaerobic digestion (AD) is commonly used to treat wastewater biosolids and industrial/agricultural wastewater. It has also been used to treat the organic fraction of the MSW waste stream, such as food wastes and, in a few cases, additional portions of the MSW waste stream. A representative flow diagram for the Delta Diablo wastewater treatment plant (WWTP) AD system in Antioch, California, is shown in Figure 13. The processes that mechanically separate the organic fraction of MSW for use in an AD process were first employed in the 1980s under the term MBT. A few facilities were developed in the US using these AD and MBT technologies, but they ceased to operate years ago due mostly to a variety of technical and financial issues. However, evolution of the technology in parts of Europe, particularly in Germany, Spain, France, Italy, and the UK, has renewed interest in this technology in North America. AD facilities using source separated organics, and even in a few cases mixed MSW, are successfully operating in Europe due to landfill ban policies, high tipping fees, and high prices paid for energy. In parts of California, Canada, and more recently in other parts of the US, processing food and source separated organic waste streams with the use of AD in combination with aerobic composting to bio-stabilize the process residue has been developed on a commercial scale. These systems require separate collection of the targeted organic waste streams with high purity, increasing collection costs.

Figure 13: Typical Flow Diagram for an AD Plant, Delta Diablo WWTP, CA



Curtesy of Delta Diablo WWTP

The attraction to use an AD process is that the anaerobic digestion of material produces a CH_4 rich biogas that can be refined into a variety of beneficial fuels including renewable natural gas and compressed natural gas (CNG). It can also be used in low-grade conditions to fuel an engine generator. The AD process occurs when organic matter is decomposed using bacteria in the absence of oxygen. By consuming the organic materials, the bacteria produce a biogas (primarily CH_4 and CO_2). Feedstocks for AD vary according to the type of technology but, in broad terms, could include MSW-derived organics, manure, food waste, grass clippings, yard waste, brush, and wastewater treatment plant biosolids. Biologically inert materials that might be contained in the digestion feedstock, such as metals, glass, and plastics, are undesirable and considered contamination and either must be removed prior to digestion (for wet type systems) or be screened out during or after digestion (for dry type systems). If not managed properly, the gases produced by an AD system are highly odorous and explosive. Since the AD process occurs inside a vessel, odors from these types of facilities are typically attributed to mismanagement of either the arriving feedstock or the residual digestate that has not been returned to an aerobic phase. Both of these systems should be included in a properly designed and operating AD facility. Also, with the high levels of proteins in food waste, the formation of odorous trace gases, such as hydrogen sulfide (H_2S), have been problematic for mixed MSW systems. Again, these gases can and should be managed within the gas management system of a properly designed AD facility.

There are several factors that influence AD system design and performance. Some of these factors include: the concentration and composition of nutrients in the feedstock, temperature of the digesting mass, retention time of the material in the reactor, pH, acid concentration, and oxygen level.

Three basic approaches are used for AD systems based largely on the nature of the feedstocks:

- Wet low solids for dilute feedstock materials with very little to no contamination
- High solids for thick but pumpable materials that contain some contamination
- Dry or stacked for stackable feedstock blends with higher levels of contamination

Wet low solids AD systems, as shown in Figure 14 and Figure 15, have a more dilute process that requires careful pre-processing of food waste and other feedstocks to remove any grit and other contaminants. The wet low solids systems can include a WWTP type, in which case it could be a co-digestion system that includes both biosolids and dilute putrescible (food waste or similar) material. Generally, this is a large, tank-based system with a mixing system included in the process.

Figure 14: Low Solids AD Plant, Sacramento, CA

Figure 15: Low Solids (POTW) AD Plant, Renton, WA

High solids AD systems use a vessel designed for higher viscosity, or thicker material, using a plug flow or similar process. They may be horizontal, as shown in Figure 16, or vertical tank arrangements, as shown in Figure 17 and Figure 18, and can accept a more diverse feedstock including some level of contamination. However, they typically require some level of pre-processing to manage the material. Further compost post-processing is required for this design.

Figure 16: High Solids Horizontal AD Plant, San Luis Obispo, CA

Photo courtesy of Hitachi Zosen Inova

Figure 17: High Solids AD Plant, Perris, CA

Photo courtesy of CRR

Figure 18: Vertical High Solids AD Plant, Perris, CA

Photo courtesy of CRR

Dry or stackable AD systems are designed to treat material that remains stationary throughout the digestion process. These systems use enclosed tunnels or bunkers where the feedstock is placed for several weeks or they use percolate bunkers to stack and store drier feedstock for fermentation, as shown in Figure 19 and Figure 20. The feedstock must be somewhat porous and have a higher solids content so it can be stacked and enable the percolate to drain through the media. Consequently, yard/greenwaste is often included as a feedstock in this type of system. The tunnel or bunker is oriented horizontally. Biologically rich water is sprayed on the material and, after percolating through the material, is collected and recycled through the feedstock controlling moisture levels. The resultant digestate requires post-processing to convert from an anaerobic to an aerobic condition.

Figure 19: Zero Waste Energy Development Co. AD Plant, San Jose, CA

Photo courtesy of ZWED, San Jose CA

Figure 20: Interior of Zero Waste Energy Development Co. AD Plant, San Jose, CA

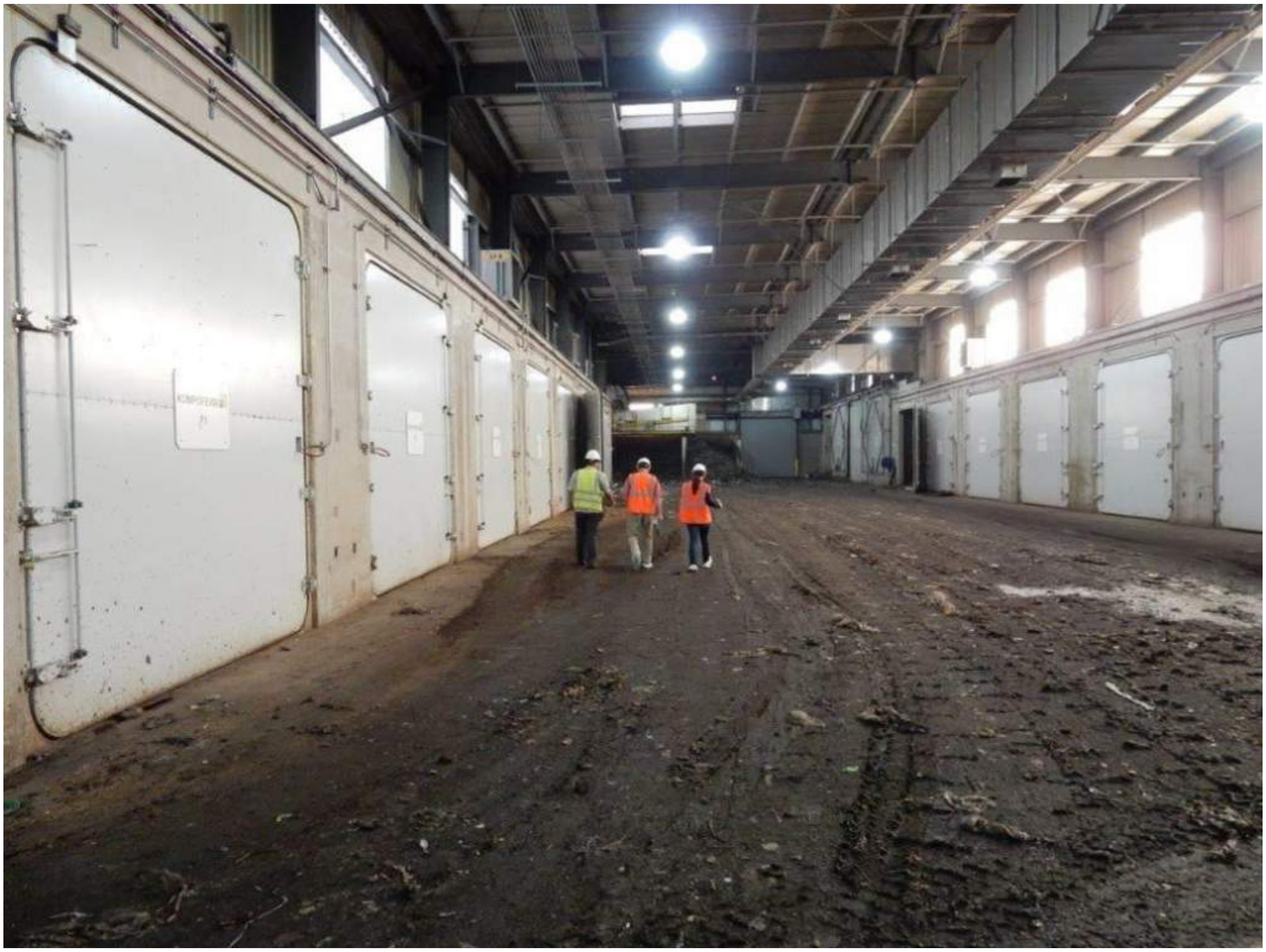


Photo courtesy of ZWED, San Jose CA

The Drake Water Reclamation Facility (DWRF) in the City of Fort Collins, Colorado currently uses AD to convert volatile organic solids from wastewater into a biogas that is used to heat the facility. A multi-year pilot project experimented with introducing source separated organics directly into its biodigesters to increase biogas output. DWRF has designed and partially funded a co-generation system that will convert biogas into electricity – dependent on increased throughput of food scraps as feedstock. There are other municipal wastewater treatment plants in the county that may be a resource in developing similar AD facilities that convert diverted food waste organics to energy.

Mechanical Biological Treatment

As described above, MBT is a composting and materials recovery variation that incorporates a multi-stage mechanical and biological treatment process. In North America, MBT is sometimes referred to as mixed waste processing with organics recovery, but the approach and desired end products are generally the same. This technology is designed to process a fully mixed MSW stream. It is an effective waste-management method and can be built in various sizes. While there are a number of facilities in the EU, the technology has not established itself in the US. There is only one commercial scale facility–discussed below–that has been in operation in the US for approximately one year. If this facility remains in operation and other potential applications develop, this technology may be considered commercial.

The order of mechanical separating, shredding, and composting can vary. Different system suppliers offer unique arrangements, but the processes generally use the following steps. During the mechanical stages, the entire feedstock is sorted to recover recyclables and remove bulky objects, non-processible items, and other contaminants. Then shredding or grinding takes place to reduce the size of the materials prior to the biological stage. Materials derived from the process usually include marketable metals, glass, containers, and other recyclables. Some processes may have the ability to recover select paper products when economics favor recycling.

The biological stage includes a digestion step in an enclosed vessel. This digestion generates a biogas that may be used to produce energy. In addition, the heat produced dries the feedstock thereby making it ready for processing into an RDF product. Limited composting is used to break down MSW and dry the fuel. The biological process also generates heat, which naturally reduces moisture. Moisture level controls may be used to manage this stage. In most cases, the digestion step is not allowed to progress as long or complete as an AD system but rather allows for easier feedstock break down. As with other composting and digestion systems, the process must be designed to manage potential odor issues.

RDF produced by an MBT process can either be landfilled or converted into energy via a thermal conversion process. RDF is then available as a solid fuel substitute for coal, wood, or other fuels at cement kilns or other industrial solid fuel facilities. In Europe, it is common for RDF and the residue produced by an MBT process to be fired directly in a boiler at a traditional WTE combustion facility or sold directly to a third party (e.g. cement kiln). If no fuel markets are available, the product could be further composted to render the material inert for landfilling. Consequently, similar to RDF, the MBT process produces compost and fuel products that are dependent on the sale of that product for economic viability. Since the compost is produced from mixed waste, the quality is low, the potential for beneficial use is limited, and it usually must be landfilled. One facility is reported to be in operation in Martinsburg, West Virginia. It is reported to provide its fuel product to a cement kiln, but limited information is available regarding the facility's operational performance.

In 2019, Entsorga, an Italy-based provider of MBT technology, started commercial operations of the HEBioT MBT Facility in Martinsburg, West Virginia. The facility is claimed to be able to recover biomass, plastics, and other carbon-based materials from MSW, compost the materials, and then convert them into a solid recovered fuel (SRF) that is used by a nearby cement manufacturer. Other recyclable commodities found in the MSW stream, such as metals and glass, are placed in the local municipality recycling stream to be recycled properly.

Chemical Technologies

Chemical technologies are designed to use physical chemistry processes as part of the technology employed to break down or transform various components of the processed waste infeed into building blocks that can be used for chemical feedstock, transportation fuels, or thermal energy. The potential value in these technologies is the possibility of producing transportation fuels such as diesel fuel, ethanol, or kerosene and industrial chemicals, which are usually much more valuable than the thermal energy produced that can only be turned into electricity or steam. In some cases, oil refineries may be willing to buy the fuels to blend with their fuels. Solvents (including water or potentially other solvents such as alcohol, acids, and caustic solutions), catalysts, and heat may be used as part of the chemical process to break down wastes into usable materials. Thermal depolymerization uses heat and pressure to break down hydrocarbon molecules. These processes may require emission controls for certain pollutants or have certain process residual wastes that may require management.

The feedstock for these processes usually requires extensive presorting and preparation to minimize undesirable materials and contamination. In many cases, chemical technologies are combined with mechanical, thermal, and/or biological technologies to begin the transformation process to the desired products. The other technologies are used to clean, size, sort, produce, or otherwise provide the input materials for the final chemical process to produce the desired products. Chemical technologies may only address certain types of waste materials, such as cellulosic wastes or plastics, oils, and grease, and the other technologies may be used to make the feedstock for the chemical process. Some processes may only use certain types of plastics because other types, such as polyvinyl chloride (PVC) or polyethylene terephthalate (PET), may not be suitable for the process. Sometimes multiple chemical processing steps may be necessary to produce the desired products. Long chain molecules, such as waxes or a synthetic crude oil, formed first as an intermediate product may then crack or break additional chemical bonds into shorter molecules to form products such as diesel fuel or alcohols that are more valuable. Alternatively, desired chemicals such as methanol or ethanol may be built up from syngas first produced by a thermal reaction or other process.

Hydrolysis

There is much interest and development in cellulosic ethanol technology, which aims to move from corn-based ethanol production to the use of more abundant cellulosic materials. However, there are no facilities in the US or elsewhere that are considered commercial at this time. Hydrolysis is part of that development. Hydrolysis is a solvolytic reaction. Solvolysis is a chemical reaction that uses a solvent such as alcohol or water. The solvent breaks down material at elevated temperatures or in association with strong acids or bases. The hydrolysis process involves the reaction of water and cellulose fractions in a feedstock (e.g., paper, yard waste, etc.) with a strong acid (e.g., sulfuric acid) to produce sugars. Next, these sugars are fermented to produce an organic alcohol. This alcohol is then distilled to produce a fuel-grade ethanol solution that can be burned in energy conversion devices such as heaters and engines.

Hydrolysis is a multi-step process that includes four major steps: pre-treatment, hydrolysis, fermentation, and distillation. The pre-treatment step for MSW includes separating the feedstock stream as necessary to remove any inorganic/inert materials (glass, plastic, metal, rock, etc.) from the organic materials (yard waste, food waste, paper, etc.). Feedstock materials that are appropriate for hydrolysis/fermentation of the MSW cellulosic components include wood, green waste, and paper. This process does not handle or convert mixed MSW directly and is best suited for clean source-separated cellulosic waste components. The organic material is shredded to reduce the size and to make the feedstock more homogenous. The shredded organic material is placed into a reactor where it is introduced to the acid catalyst and the cellulose in the organic material is converted into simple sugars. These sugars are fermented and converted into an organic alcohol. The organic alcohol is then distilled into fuel-grade ethanol. The by-products from this process are CO_2 (from the fermentation step), gypsum (from the hydrolysis step) and lignin (non-cellulose material from the hydrolysis step). Since the acid acts only as a catalyst, it can usually be extracted and recycled back into the process.

Catalytic and Thermal Depolymerization

As for hydrolysis, while there is much interest in developing catalytic and thermal depolymerization processes, there are no current facilities fully advanced to a commercial level. The depolymerization, or cracking, process converts long-chain hydrocarbon polymers present in some waste materials into intermediate products that can be processed into fuels such as diesel and gasoline. Pressure and heat are used to decompose long-chain H_2, oxygen, and carbon polymers into shorter chains of petroleum-like feedstock. This process is somewhat similar to the process used to convert crude oil into usable products, including the use of distillation to segregate the desired hydrocarbon liquids (such as diesel fuel). The typical feedstocks proposed for depolymerization are plastics, waste oils, grease, and offal (i.e., processed animal soft tissue), although some of the technology vendors are claiming that this technology can theoretically use MSW and biomass as feedstocks.

In some cases, plastics may be divided by classification. This will separate certain types of plastics that are not as useful with an economic decision regarding which materials are used as feedstock and which may be sold in traditional recycling markets. Generally, PET (or plastic type No. 1) is less useful and PVC (or plastic type No. 3) is generally not suitable for the depolymerization processes and must be separated from suitable feedstock. High density polyethylene (HDPE or plastic type No. 2) is suitable for depolymerization. However, it may be more valuable recycled as a No. 2 plastic and not mixed with other types of plastics for fuel production. These depolymerization technologies have not been shown to be feasible except at small scale.

There are two depolymerization methods that can be used to convert organic materials into fuel: thermal and catalytic. Thermal depolymerization utilizes temperature (temperature ranges from 1,000 to 1,400°F) and pressure to crack the large hydrocarbon molecules within the feedstock. These processes are similar to pyrolytic processes but are usually applied to a more refined or pure plastic feedstock and not mixed waste. The plastics must be adequately cleaned and purified to reduce contamination rates from higher levels found in plastic feedstocks (approximately 10 to 25 percent contamination) to levels suitable for processing (sometimes less than 5 percent contamination). Once the hydrocarbon molecules are broken into shorter chains, additional refining steps are required to separate fixed carbon and lighter molecules to convert the heavier molecules into commercial grade diesel. The high temperature and additional refining steps in the thermal process require a significant amount of energy compared to the catalytic depolymerization approach. There are some thermal pilot-scale plants in development that are using pyrolytic or gasification processes on plastic wastes to produce a fuel or H_2. However, the energy balance data for thermal depolymerization of waste-derived organic materials are lacking and are not fully developed regarding commercial scale processing.

The catalytic depolymerization process uses lower temperatures (ranging from 500 to 700°F) and lower pressures than thermal depolymerization. In order to achieve adequate product yields and qualities at the lower temperatures and pressures, a catalyst is employed to aid in breaking down or cracking the large molecules efficiently. Zeolite, silica-alumina, and bauxite are common catalysts used in the process. In a catalytic depolymerization process, the plastics, synthetic-fiber components, and water in the feedstock react with a catalyst under pressure and heat to produce a crude oil. This crude oil can then be distilled to produce a synthetic gasoline or fuel-grade diesel. Some technology vendors claim to meet diesel fuel or other fuel standards suitable for use in commercial vehicles, as discussed below.

Waste-to-Fuel Technologies

Waste-to-Fuel technologies typically involve four main steps:

1) Pre-processing and preparation of the feedstock material (e.g. woody biomass or MSW),
2) Converting the feedstock to generate a syngas through a thermal conversion process (e.g. gasification or another technology),
3) Cleaning and conditioning the syngas of impurities and other contaminants, and
4) Passing the syngas through a catalytic process, such as an FT process to synthesize a liquid fuel.

Refer to Figure 7 above for an example of a Ways2H's pyrolytic waste to H_2 pilot project. The use of woody biomass and some agricultural wastes as feedstock for these technologies has some long-term operating track record. There are also some demonstration/pilot projects that are attempting to use MSW or other feedstocks, which are described in more detail below. However, the long-term operating and financial viability of using an MSW feedstock to produce a liquid fuel is still unknown.

The waste-to-fuel process for mixed MSW starts with a sophisticated processing system. Generally, the MSW is sorted to remove and recover the metals, glass, inorganic materials, other undesirable materials, and select traditional recyclables. Depending on the downstream processing system needs, the sorting process may selectively separate paper and cellulose containing materials and select plastics, as shown in Figure 21, or may use both types of materials. The selected fuel material is generally shredded for easier handling and to develop a more uniform feedstock. The more uniform feedstock simplifies downstream processing issues.

Figure 21: Plastics to Fuels Demonstration Project

Once a relatively uniform feedstock is produced, there are several proposed methodologies to convert MSW into fuels. First, the majority of MSW-to-fuel technologies require a process that generates a syngas, typically a thermal conversion process such as gasification or pyrolysis. The next and most important step in this process is to take the syngas produced and clean it to remove impurities (tars, hydrocarbons, contaminants, etc.) that can impact the catalytic process. The syngas has a lower Btu (energy) content compared to natural gas, and the downstream process may require water removal to concentrate the H_2 and CO.

The next step involves a catalytic process, such as an FT-type process, that converts the syngas into a liquid fuel. The FT process is defined as a series of chemical reactions that use a metal-based catalyst (cobalt, iron, or others) to convert a mixture of CO, H_2, and sometimes steam into liquid hydrocarbons under elevated and controlled temperature and pressure conditions. The FT process has been around for almost 100-years and is used most to convert coal, biomass, or even CH_4 into synthetic liquid fuels. The purity of the syngas used can be critical to the success of the FT process, which makes syngas produced from MSW gasification challenging because of the contaminants present in the MSW feedstock and the relatively low ratios of H_2 to CO. The chemical reactions produce a variety of hydrocarbon molecules with the more useful reactions producing alkanes. Most of the alkanes produced tend to be straight chain, which are suitable as diesel fuel. Use of the proper catalyst in the FT process is essential to garner the highest quality fuel while not deteriorating the catalyst. In this technical industry there are many forms of catalyst including cobalt and ferrous based. Syngas from MSW gasification is having the greatest issues in this area because of the contaminants in the MSW syngas and the low of ratios of H_2 to CO. Even with the extensive waste processing, the small variations in the gases produced during the FT process may cause disruptions.

The FT process is usually followed by a hydrocracking process. Hydrocracking is required to break up the long-chained hydrocarbons. The long-chained hydrocarbons are waxes, which are solid at room temperature. Therefore, to produce liquid transportation fuels it is usually necessary to crack some of the FT products.

As mentioned, FT is one of the most popular types of chemical catalytic processes used to synthesize syngas into a liquid fuel. In addition to FT synthesis, there is methanol synthesis, mixed alcohol synthesis, or syngas fermentation. Each process features different reaction pressures and temperatures, requires different syngas compositions, and uses different catalysts. Alternatives to the FT process include a bio-catalytic process where biological organisms are used to break down the elemental components in the syngas into a biofuel. The Indian River Biofules Facility (IRBF) in Vero Beach, Florida employed this technology to convert mostly agricultural wastes into ethanol, but this facility is no longer operating.

Feedstock preparation, gasification, syngas clean-up, and fuel synthesis are commercially viable using select feedstock materials such as biomass, coal, or petroleum-based materials. However, the catalysts and FT process used to produce the biofuels are very sensitive to the quality and composition of the syngas produced by the thermal/gasification component of these technologies. Using MSW or other heterogenous and mixed feedstocks in these systems is still in the development or demonstration stage.

Generating liquid fuels from wastes is an evolving technology. The use of biomass, organic wastes, and plastics as feedstocks appear to be advancing in demonstration/pilot projects with a couple projects moving toward commercialization. However, the use of a mixed MSW feedstock is still being tested in laboratories and demonstration/pilot projects. Some examples of commercial-scale waste-to-fuel technologies that are in commercial development include the Enerkem, Fulcrum Bioenergy, and INEOS Biofuel technologies. In June 2014, Enerkem Alberta Biofuels in Edmonton, Alberta, Canada opened a 10 million gallons per year methanol facility designed to help Edmonton reach a 90 percent MSW diversion goal by accepting up to 100,000 metric tons of MSW (the city already diverts 60 percent of the MSW stream). The Enerkem facility, shown in Figure 22, is a commercial-scale waste-to-fuel facility. The Enerkem facility is currently in operation and utilizes an MSW gasification-to-liquid fuels technology that uses an FT-type catalytic process to generate liquid methanol. Enerkem hopes to ultimately use the methanol to produce ethanol on a commercial scale. Information on the performance of the Enerkem facility’s ethanol production is not readily available. Therefore, the facility is not considered fully commercial at this time.

In addition, Fulcrum Bioenergy is developing the Sierra Biofuels Facility in Storey County, Nevada. This facility will use a combination of gasification and FT. Fulcrum Bioenergy is also planning another, similar facility in the United Kingdom. Neither of these facilities are operating on a commercial scale at the present time.

Figure 22: Enerkem Alberta Biofuels Facility, Edmonton, Alberta, Canada

Photo Curtesy of Enerkem

Fulcrum Bioenergy is also developing another commercial-scale project in Nevada. An MSW processing facility has been in operation processing mixed waste to recover recyclables and generate a waste fuel feedstock from suitable materials for a separate biorefinery. Construction of the biorefinery is anticipated to be complete in 2021 and the facility will proceed into a commissioning phase. The anticipated fuel product will be jet fuel suitable for commercial applications. The fuel may be blended with conventionally refined jet fuel.

Ineos Biofuels developed the IRBF, a waste-to-fuel technology facility located in Vero Beach, Florida (see Figure 23). This 300-tpd IRBF (2 units producing 150 tpd each) facility cost approximately $130-million and started operations in late 2012 using woody biomass wastes as a feedstock. The technology was designed to use a thermal gasification process to generate a syngas that was then passed through a fermentation reactor where biological organisms converted the H_2 and CO in the syngas directly to ethanol. IRBF is permitted to receive waste, but to HDR’s knowledge it never processed any MSW feedstocks. IBRF had some operational issues and challenges since startup, particularly with certain contaminants in the syngas that affected or killed off the biological organisms and eventually resulted in the facility being taken offline.

Figure 23: Indian River Biofuels Facility in Vero Beach, Florida

Mechanical Technologies

Mechanical technologies use equipment and external heat from steam or hot air (not heat produced from combustion or partial oxidation of the waste feedstock) to divide waste into usable products and residue. Most processes produce ancillary products, including recyclables, that can be marketed like those produced from a materials recovery facility (MRF) or the process may start with MRF residual materials as the feedstock. The arrangement of the equipment and overall separation processes can vary widely by facility and produce a wide range of output products. Wastes may be subdivided into plastics, paper (fiber), metals, glass, and other inert materials. Some processes may produce a low-grade cellulose product that can be used for cardboard production or for thermal, certain chemical, and biological processes. Feedstock may be cleaned to reduce chlorine content and otherwise processed to improve its fuel properties. Usually a fuel or feedstock is produced that is designed to be used by another process or another facility, potentially to offset other solid fossil fuels. Often the ultimate fuel use facility is not part of the fuel production facility and may likely be an existing cement kiln or solid fuel boiler that is willing to contract for the fuel produced to offset coal or other fossil fuels. If a suitable use for the waste fuel is not identified, the fuel may require landfilling so a long-term fuel supply contract is usually necessary for a viable operation that pays for the fuel production operating and maintenance costs. Process residues are generally produced that, in most cases, must be landfilled.

Autoclave/Steam Classification

Autoclaving is classified as a mechanical process that uses heat and pressure in a mechanical, rotating cylinder that can be used to separate cellulosic and organic material from other portions of the MSW stream. As an example, basic autoclave technology has been used to sterilize hospital wastes and equipment for many years. Autoclaves are generally anticipated to be applied as a step in the management of waste materials; however, HDR is not aware of commercially operating facilities using autoclaving or steam classification.

Autoclaves used for MSW processing are large rotating vessels that have steam injected and kept at a certain temperature and pressure over a controlled period, up to 2–4 hours, to convert the MSW. Most autoclaves are currently operating in batch mode accepting between approximately 1 and 25 tons per batch (2-3 hour), although at least one facility was designed for continuous feeding. The autoclave process has the potential for a 40 to 60 percent reduction in waste volume with the cellulose recovery having the potential to be used as feedstock for paper production, ethanol production feedstock, compost feedstock, or digester feedstock for CH_4 production.

Like AD and chemical technologies, autoclaving may be best applied when it addresses only a portion of the waste stream, namely the cellulose-fiber-containing portion, which is usually 40 to 60 percent of the total MSW input stream. However, this technology can accept mixed MSW that contains a large organic fraction to be used as a front-end separation system for many of the other alternative technologies such as hydrolysis for fuel product production, gasification or pyrolysis for energy generation, anaerobic digestion for energy and compost production, or fiber recovery for the pulp/paper industry. A trommel screen is usually used after the autoclave to separate the fibrous organic materials produced from autoclaving and other materials (inorganic materials, plastics, and recyclables such as glass and metals). If the goal for the autoclaving technology is recovery for paper production, because the fibers are a mixed grade, the main product that can be produced is a lower-grade cardboard. Plastics generally will melt and form small balls of material. While the fiber and plastic portions of the MSW are lower quality, mixed grade materials with fines are often very clean. Fines usually consist of material two inches in diameter or smaller that include organic material such as paper, dirt, and food particles as well as inorganics such as glass, plastics, and metals. Labels, paint, and other coatings are generally removed.

Mixed Waste Processing

There are several types of MRFs in operation in the US and around the world. Most can be classified into two groups: those that accept and process source separated recyclables, sometimes referred to clean MRFs, and those that take a mixed MSW stream, referred to as a Mixed Waste Processing Facility (MWPF), a dirty MRF, or an advanced materials recovery system. The purpose of this section is to describe MWPFs and their potential commercial applications. These facilities are often used to capture select materials, depending on the feedstock and established markets, and may not recover all the materials noted below. MWPF yields are usually much lower than conventional MRFs due to the nature of the feedstock, but they can provide significant landfill diversion.

A MWPF begins with mixed solid waste from residential and/or commercial collection vehicles being off-loaded onto a tipping floor. Materials are first sorted on the floor using mobile and fixed equipment with some manual labor to remove or break up larger or bulky items such as appliances, dimensional wood, metal, or large pieces of plastics that might clog or interrupt processing system operations. Loaders or grapples then load a conveyor or surge hopper to convey the material to the sort lines and mechanical equipment for separation. In most cases, either a mechanical device or manual labor is used to open bags and containers prior to screening and sorting. Systems can be adapted to construction and demolition (C&D) wastes or certain other mixed waste materials.

Material is usually processed through multi-stage screens to separate fiber (cardboard, newspaper, and mixed paper), plastic, metal and glass containers, and small contaminants. This is usually accomplished using mechanical, optical, or pneumatic screening equipment and/or labor to separate materials into size classifications and/or lighter versus heavier materials. Fiber is usually sorted optically or by hand off elevated conveyor platforms into commodities and dropped into bunkers. Containers are processed through ferrous magnets, optical sorters, robotic sorters, hand sorting, and eddy current separators (ECS). The fines, usually less than two inches and consisting of dirt, rocks, broken glass, ceramics, bottle caps, etc., may be further processed by magnets, ECS, and pneumatic sorting steps to recover metals, fiber, and a glass-rich stream.

Sorted material is moved from bunkers and baled (fiber, plastic, metal) or loaded directly into roll-off bins (glass, wood, scrap metal). Some MWPFs also isolate the organic fraction of the MSW stream to be used in a composting or AD process. The remaining residue material from a MWPF is shipped to a local landfill or used for another appropriate waste reduction application. The main purpose of this type of MWPF is to remove recyclable materials and organics from the mixed MSW. These types of facilities usually recover about 10 to 25 percent, although some facilities have reported recovery of up to 50 percent or more. There is a wide range of MWPF capacities operating throughout the world. The optimal capacity is between 200 tpd and 1,500 tpd using multiple sort lines and operating additional shifts. MWPFs can have a useful operating life of 20 to 30 years if proper maintenance is provided. Many MWPFs are retrofitted throughout their life with new processing equipment, as applicable.

There have been several commercial scale MWPFs implemented in North America. The most notable examples are in Montgomery County, Alabama; San Jose, California; and Edmonton, Alberta, Canada. It should be noted that the current downward trend in commodity pricing and acceptance of the processing approach has impacted the financial viability of some of these projects. The Montgomery County Facility went through an ownership change with the County acquiring the facility and hiring a new operator. Numerous upgrades and modifications were made to the facility with the current facility accepting more tradition single stream materials but is capable of handling other types of feedstock such as mixed fiber, commercial, and industrial materials and has the potential to produce a fuel material. The Newby Island Resource Recovery Park in San Jose, shown in Figure 24, has infeed lines for residential single stream, commercial single stream, commercial wet recyclables, and a common container line that accepts materials from all of the other streams. Incoming material can be characterized in this manner and routed to the appropriate processing system.

Figure 24: Newby Island Resource Recovery Park, California

Refuse Derived Fuel Production

An RDF processing system prepares MSW using separation, shredding, screening, air classifying, and other equipment to produce a fuel product, such as coarse shred, fluff, or pellets, for either on-site thermal processing, off-site thermal processing, or use in another conversion technology that requires a prepared feedstock. The goal of this technology is to derive a more homogeneous fuel product that can be used in specified thermal equipment or as a supplement to coal-fired power generating facilities, and even cement kilns in some cases. The fuel goes by various names but is generally categorized as RDF.

The RDF process typically results in a fuel yield in the 80 to 90 percent range (i.e., 80 to 90 percent of the incoming MSW is converted to RDF). The remaining 10 to 20 percent of the incoming waste that is not converted to RDF is composed of either recovered ferrous and nonferrous metals (1 to 5 percent) which can be sold to market, or process residue (15 to 19 percent) that must be disposed of in a landfill. In most cases, the fuel is used at the same facility where it is processed, although this does not have to be the case.

Non-recovered discards from an MRF can be processed using this technology. Facilities can range in size from several hundred tpd to more than 3,000 tpd. Recycling processes can also be built into an RDF facility, such as in a MRF or MWPF. Metals can usually be sorted and removed by magnets and ECS. In some cases, other recyclables such as cardboard, glass, or even plastic containers may be recycled. An RDF facility strives to develop a consistently sized fuel with a relatively constant heating value for thermal technologies. These facilities can employ multiple shredding stages, large trommel screens or other types of screens for sizing, several magnet stages, and possibly air separation, optical sorters, and ECS. The product would typically have a nominal particle size of 3 to 4 inches (although the sizing of final product RDF can be controlled for a specific technology), have the grit and metals largely removed, and be ready to market.

EPA has encouraged processors to produce a Non-Hazardous Secondary Material (NHSM) for use in industrial boilers or other applications that are subject to Section 112 of the Clean Air Act as opposed to Section 129, which waste combustors must follow. The fuel must meet the requirements for NHSM as defined by the US EPA in 40 CFR Section 241.3 of the Clean Air Act. These processing facilities require more processing and ongoing sampling to meet more restrictive requirements for residual chlorine content, chlorine to sulfur ratio, heating value, moisture, and ash content in the resultant fuel than are required for combustion of waste or RDF in a waste boiler. Refer to Section 5 for additional discussion of the NHSM program.

Many of the existing RDF combustion facilities in the US (e.g. Miami-Dade, FL; West Palm Beach, FL; Detroit, MI; Honolulu, HI; Norfolk, VA; Ames, IA; etc.) employ these practices to process the fuel. Some RDF facilities can be classified as shred and burn style facilities. These facilities shred the material and magnetically remove ferrous metals without removing fines. Some RDF facilities have converted to shred and burn through blanking the small holes in trommels. The purpose for this change is to reduce the overall amount of residue (fines) landfilled and simplify the fuel production process. An example of a shred and burn facility is the SEMASS facility in West Wareham, Massachusetts. This facility has recently replaced its high-speed hammermill shredders with high torque shredders for safety and operational reasons.

There are also RDF technologies that, after removal of recyclable, bulky, and inert materials, form the remaining MSW stream into a pellet or briquette. The intended use of these pellets or briquettes varies by technology developer and regulation, but some examples include use as a supplement to coal at a conventional fossil fuel power plant or cement kiln. Some technology providers also offer the pellets for use as a soil amendment in greenhouses. However, the quality and integrity of the pellets or briquettes produced, and the willingness of the local market to accept this product, factor significantly into the economic viability of the project. A commercial-scale MSW pelletizer facility in York Region, Ontario, Canada (just north of the City of Toronto) was constructed in 2008 but was later shutdown due to operating issues and limited available markets for the pellets. The WastAway facility in Morrison, TN may produce either an RDF fluff material or compress the fluff into pellets depending on the target market.

3 Comparison of Technology Options

The following table presents a comparison of direct combustion, gasification, and PAG. It shows criteria including commercial viability, capability of processing feedstock, technology capacity level, diversion potential, marketability of end products and bi-products, useful operating life, environmental benefits and drawbacks, local economic benefits, range of operating and capital costs (high, medium, low), and any necessary support facilities for the technology for complete waste management.

	Criteria	Direct Combustion	Gasification	Plasma Arc Gasification
1. Commercial Viability (Development Stage)				
a	Status of technology in North America	Commercial	Demo/Pilot on MSW. Example commercial facilities in development: Ways2H, Kern County, CA Sierra Energy, Monterey, CA	Demo/Pilot on MSW. Some facilities were shutdown:: Geoplasma, St. Lucie County, Fl NRG, Atlantic County, NJ Plasco, Ottawa, Ontario
b	Years of commercial operating history in North America	30 plus years	Limited to none on MSW	Limited to none on MSW
c	Number of commercial continuously operating facilities in North America	70 plus facilities	Limited on MSW No commercial facilities in North America	Limited on MSW No commercial facilities in North America
d	Status of technology worldwide	Commercial, hundreds of plants	Commercial (mostly in Asia <50)	Limited commercial on MSW in Asia (<6)
2. Capability of Processing Feedstock				
a	Type of MSW processed	Handle entire MSW stream	Handle entire MSW stream or select materials	Ideal for hazardous and high carbon fraction (e.g. plastics) of MSW stream
3. Technology Capacity Level				
a	Processing unit capacity (tpd)	200 to more than 1000 tpd Modular less than 500 tpd	Typically, 100-250 tpd and less than 500 tpd	50 to 1,000 tpd (claimed)

	Criteria	Direct Combustion	Gasification	Plasma Arc Gasification
4. Diversion Potential of Technology				
a	Potential landfill diversion (weight percent)	70%-90%	Claimed greater than 90%	Claimed greater than 90%
5. Marketability of End- and By-Products				
a	Availability and feasibility of markets for recovered materials	Good for metals and mixed ash for LF cover (as permitted); potential aggregate re-use	Unknown markets for chemicals and vitrified ash/slag for aggregate	Unknown for vitrified ash/slag for aggregate
b	Availability and feasibility of markets for energy produced	Good	Good	Good
c	Undesired by-products	Fly ash if not mixed with bottom ash	Ash/Slag if not sold/given away as aggregate	Ash/Slag if not sold/given away as aggregate
6. Useful Operating Life				
a	Facility life (yrs)	Greater than 25 years	Anticipated about 20 years	Anticipated about 10 to 15 years
7. Typical Environment Benefits/Drawbacks				
a	Benefits	Produces energy, metals for market and ash for cover (mixed), possible aggregates where permitted	Produces energy, possible aggregates from slag (need mkts)	Produces energy, possible aggregates from slag (need mkts)
b	Drawbacks	Air emissions to be mitigated by APC equipment	Air emissions to be mitigated by APC equipment	Air emissions to be mitigated by APC equipment
8. Local Economic Benefits				
a	Permanent full-time Jobs	40 to 80 permanent jobs	40 to 80 permanent jobs	40 to 80 permanent jobs

	Criteria	Direct Combustion	Gasification	Plasma Arc Gasification
9. Financial				
a	Range of capital and operating unit cost	Moderate to high Typically $80 - $120 per ton	Moderate to high Expected $100 - $180 per ton	High Expected $120 - $200 per ton
10. Necessity of Support Facilities for Complete Waste Management				
a	Front-end processing	Not required other than large bulky wastes	Generally necessary	Generally necessary
b	Supplemental facility	Included	Boiler, engine, or other fuel consumer required	Boiler, engine, or other fuel consumer required

The following table presents a comparison of pyrolysis, aerobic composting, and anaerobic digestion. Criteria include commercial viability, feedstock processing capability, technology capacity level, diversion potential, end product and bi-product marketability, useful operating life, environmental benefits and drawbacks, local economic benefits, range of operating and capital costs (high, medium, low), and any necessary support facilities for the technology for complete waste management.

	Criteria	Pyrolysis	Aerobic Composting	Anaerobic Digestion
1. Commercial Viability (Development Stage)				
a	Status of technology in North America	Demo/Pilot on MSW. Some commercial facilities in development on select waste streams: Ways2H, Kern County, CA	Commercial (particularly for source separated organic streams)	Commercial (particularly for source separated organic streams). Example: Delta Diablo, Antioch, CA ZWED, San Jose, CA Kompogas SLO, San Luis Obispo, CA No commercial facilities processing mixed MSW.
b	Years of commercial operating history in North America	Limited on MSW	More than 30 years on green/yard waste feedstock	More than ten years

	Criteria	Pyrolysis	Aerobic Composting	Anaerobic Digestion
c	Number of commercial operating facilities in North America	Limited on MSW No commercial facilities in North America	Thousands of operating facilities	More than 20 operating processing organic streams such as food waste (More under development)
d	Status of technology worldwide	Demo/Pilot on MSW; one commercial plant in Germany	Commercial	Commercial, >25
2. Feedstock Processing Capability				
a	Type of MSW processed	Handle entire MSW stream	Ideally suited to process green/yard waste and food waste portions of MSW	Can treat only organic portion of MSW typically food waste; green waste; fats, oils, and grease; sewage sludge; and manure
3. Technology Capacity Level				
a	Processing unit capacity (tpd)	Under development; Approximately 10 to 100 tpd	Can range from very small to over 3,000 tpd. Usually 200 to 400 tpd	Wide range from 5-10 tpd to 300 tpd
4. Diversion Potential of Technology				
a	Potential landfill diversion (weight percent)	Not known	Linn County's total organics is about 40% according to Wasteshed Study (2020)	For wet low solids and high solids AD food waste typically ranges from 15-20% of the overall waste system, Linn County's total organics is about 40% according to Wasteshed Study (2020)
5. Marketability of End- and By-Products				
a	Availability and feasibility of markets for recovered materials	Depends if gases, liquids, and char can be used	Properly processed compost is marketable to a wide range of customers (agricultural, commercial, residential)	Biogas from AD can be used to produce electricity or processed into renewable or pipeline grade natural gas or CNG. Digestate after process can sometimes be turned to compost

	Criteria	Pyrolysis	Aerobic Composting	Anaerobic Digestion
b	Availability and feasibility of markets for energy produced	Depends if gases, liquids and char can be combusted	N/A	Biogas can be used to create energy and/or fuels
c	Undesired by-products	Liquids, tars, chars, and other by-products	Screened overs, such as bottle caps, glass, and other small objects	Digestate must be assessed if compostable
6. Useful Operating Life				
a	Facility life (yrs)	One small facility operating in Germany since the 1980s	Life is 30+ years depending on equipment replacement	Operating internationally since the 1980s. Co-digestion using WWTPs in the US have been operating for decades
7. Typical Environment Benefits/Drawbacks				
a	Benefits	Potentially create energy and useful by-products	Create useable compost	Create renewable energy and/or fuels and potentially useable compost
b	Drawbacks	Air emissions to be mitigated by APC equipment	Can create odor, noise and dust	Designs must include proper management of feedstock and digestate to control odors
8. Local Economic Benefits				
a	Permanent full-time jobs	Not known	About 2 to 10 jobs, depending on the size of the operation	About 10 to 25 jobs, depending on the size of the operation. More jobs required if a MWPF is required for mixed MSW stream.
9. Financial				
a	Range of capital and operating unit cost	High Expected $120 - $180 per ton	Low Typically $30 - $75 per ton	Medium to high Typically $90 - $130 per ton
10. Necessity of Support Facilities for Complete Waste Management				

	Criteria	Pyrolysis	Aerobic Composting	Anaerobic Digestion
a	Front-end processing	Technology dependent	Shredder for greenwaste if not part of process	Generally necessary for de-packaging, removal of contaminants and for sizing/extraction
b	Supplemental facility	Boiler, engine or other fuel consumer required	Compost screening, cleanup if not part of process	Biogas refinement or boiler, engine generator

The following table presents a comparison between MBT, hydrolysis, catalytic and thermal depolymerization, and waste-to-fuels. Criteria include commercial viability, feedstock processing capability, technology capacity level, diversion potential, marketability of end products and bi-products, useful operating life, environmental benefits and drawbacks, local economic benefits, range of operating and capital costs (high, medium, low), and any necessary support facilities for the technology for complete waste management.

	Criteria	Mechanical Biological Treatment	Hydrolysis	Catalytic & Thermal Depolymerization	Waste-to-Fuels
1. Commercial Viability (Development Stage)					
a	Status of technology in North America	Commercial Scale[1] Example: Entsorga, Martinsburg, WV	Demo/Pilot No commercial facilities in North America	Demo/Pilot No commercial facilities in North America	One plant commercial. Enerkem, Edmonton Alberta, Can. Demo/Pilot on MSW: Ways2H, Kern County, CA FulcrumStorey County, NV
b	Years of commercial operating history in North America	More than one year	None commercialized	None commercialized	None fully commercialized
c	Number of commercial operating facilities in North America	At least one commercial scale	None commercialized	None commercialized	Several facilities in startup and commissioning

	Criteria	Mechanical Biological Treatment	Hydrolysis	Catalytic & Thermal Depolymerization	Waste-to-Fuels
					stages. One facility recently shutdown.
d	Status of technology worldwide	Commercial, >25	Demo/Pilot	Demo/Pilot; one facility claimed in Spain	R&D/pilot on MSW
2. Feedstock Processing Capability					
a	Type of MSW processed	Entire waste stream or select	Wood, green waste and paper	Plastics & oils	Entire or biomass portion of MSW
3. Technology Capacity Level					
a	Processing unit capacity (tpd)	Less than 250 tpd	Needs more research	Needs more research	Needs more research
4. Diversion Potential of Technology					
a	Potential landfill diversion (weight percent)	This is a feedstock pre-process; recover recyclables	Estimated 25%-30%	Estimated 10%-12%	If gasification is used, can be up to 90%
5. Marketability of End- and By-Products					
a	Availability and feasibility of markets for recovered materials	Markets for recyclables and possibly fuel product	Markets for gypsum & lignin will need to be established	Needs more information on the biodiesel created	Needs more information on the liquid fuel created
b	Availability and feasibility of markets for energy produced	There are markets for the potential biogas produced; possibly for solid fuel	A market for this fuel has not been established	A market for this fuel has not been established	A market for this fuel has not been established
c	Undesired by-products	None known if markets are available for fuel	Potentially the CO_2, gypsum, and lignin	Needs more research	Needs more research
6. Useful Operating Life					
a	Facility life (yrs)	Most probably 15 to 25 years	Needs more research	Needs more research	Needs more research

	Criteria	Mechanical Biological Treatment	Hydrolysis	Catalytic & Thermal Depolymerization	Waste-to-Fuels
7. Typical Environment Benefits/Drawbacks					
a	Benefits	Separates feedstock for recycling, digestion, and thermal	May be able to produce a fuel with more research	May be able to produce a fuel with more research	May be able to produce a fuel with more research
b	Drawbacks	Odors, dust & noise	Methane emissions and possible chemical spills	Hydrocarbons and fixed carbon could be emitted; catalysts or solvents needed	Hydrocarbons and fixed carbon could be emitted; catalysts or solvents needed
8. Local Economic Benefits					
a	Permanent full-time jobs	20 to 40 jobs	Not known	Not known	Not known
9. Financial					
a	Range of capital and operating unit cost	Medium Expected $45 - $100 per ton	Medium	Medium	Medium/High
10. Necessity of Support Facilities for Complete Waste Management					
a	Front-end processing	MRF and shredding system	Generally necessary to remove contaminants and for sizing/extraction	Generally necessary to remove contaminants and for sizing/extraction	Generally necessary to remove contaminants and for sizing/extraction
b	Supplemental facility	Boiler, cement kiln, or other fuel consumer required	Fuel consumer	Fuel consumer	Fuel consumer

Note:

[1] MBT is on the verge of being considered commercial. A number of commercial facilities exist in Europe. One commercial scale facility is known to exist in the US and is reported in operation. Within in a few years, particularly if more MBT facilities are brought into commercial operation, it will be an accepted technology in North America.

The following table presents a comparison between autoclave, mixed waste processing, and RDF processing, showing criteria including commercial viability, feedstock processing capability, technology capacity level, diversion potential, marketability of end products and bi-products, useful operating life, environmental benefits and drawbacks, local economic benefits, range of operating and capital costs (high, medium, low), and any necessary support facilities for the technology for complete waste management.

	Criteria	Autoclave	Mixed Waste Processing	RDF Processing
1. Commercial Viability (Development Stage)				
a	Status of technology in North America	Demo/Pilot on MSW components No commercial facilities in North America	Commercial Examples: Newby Island, San Jose, CA Edmonton, Alberta, Can. RePower, Montgomery, AL	Commercial Examples: Covanta, Miami-Dade County FL Wheelabrator SPSA, Norfolk, VA City of Ames, IA Covanta H-POWER, Honolulu, HI
b	Years of commercial operating history in North America	Limited on MSW components No commercial operations	30 + years	30 + years under MWC EPA requirements; about 5 + years under Boiler MACT EPA requirements[1]
c	Number of commercial operating facilities in North America	Limited on MSW components None active	Half dozen to a dozen	Approximately 20
d	Status of technology worldwide	Demo/Pilot on MSW components	Commercial, >25	Commercial, >50
2. Feedstock Processing Capability				
a	Type of MSW processed	System dependent but can process entire MSW stream	Handle entire MSW stream	MWC handle entire MSW stream; NHSM cannot handle chlorine containing materials
3. Technology Capacity Level				
a	Processing unit capacity (tpd)	At this time only smaller 100-300 tpd available	Approximately 200 to 1,500 tpd	Up to about 1,000 tpd
4. Diversion Potential of Technology				

	Criteria	Autoclave	Mixed Waste Processing	RDF Processing
a	Potential Landfill diversion (weight percent)	Approximately 35-40% of the MSW possibly more if combined with other technologies	Approximately 10-25% of the MSW possibly more if combined with fuel production	Approximately 60-90% of the MSW depending on the process
5. Marketability of End- and By-Products				
a	Availability and feasibility of markets for recovered materials	Metals and glass can be marketed. Fiber product may only be used for low grade cardboard. Market needs to be developed for plastics	Recyclables can be marketed; potentially fuel	Recyclables can be marketed. Markets are project specific if pellets or briquettes are produced. Possible use as soil amendment but no clear markets available.
b	Availability and feasibility of markets for energy produced	Market needs to be developed for fuel	N/A unless a fuel product is produced which needs a market developed	RDF can be converted to energy under either MWC or boiler rules or market need for fuel product.
c	Undesired by-products	Non-fiber unless a market can be developed for plastics	Grit/ fines, trash, low grade plastics and glass unless markets are available	Bulky items, grit/glass; for NHSM PVC and other chlorine containing materials
6. Useful Operating Life				
a	Facility life (yrs)	Not known at this time	20 to 30 years with periodic equipment upgrades	20 to 30 + years
7. Typical Environment Benefits/Drawbacks				
a	Benefits	Possibly create low grade fiber or fuel product; recover metals; output materials are sterilized	Recover recyclables; possibly produce fuel	Preparation of feedstock for other processes; NHSM can be processed in industrial boilers

	Criteria	Autoclave	Mixed Waste Processing	RDF Processing
b	Drawbacks	Risks of autoclaving are not known; fiber product is low quality	Odors, noise & dust to be mitigated	Odors, noise & dust to be mitigated; NHSM must meet strict fuel requirements and sampling
8. Local Economic Benefits				
a	Permanent Full-time Jobs	Not known at this time	20 to 60 jobs	20 to 100 jobs
9. Financial				
a	Range of Capital and Operating unit costs	Medium Insufficient data	Medium Typically $35-$75 per ton (Processing facility only)	Medium; NHSM produced for a boiler costs are higher than for RDF production for an MWC facility, however the boiler costs are lower. Expected $35 - $100 (Processing facility only)
10. Necessity of Support Facilities for Complete Waste Management				
a	Front-end Processing	May require material sizing and sorting	Technology is only a processing technology	Technology is only a processing technology
b	Supplemental Facility	Sorting and screening. Boiler, engine or other fuel consumer required	If fuel product boiler, engine or other fuel consumer required	Boiler, engine or other fuel consumer required

Note:

Solid Recovered Fuel (SRF) production as a NHSM where the fuel is combusted in an Industrial Boiler subject to 40 CFR Section 112 of the Clean Air Act has been completed commercially in the US only in the last few years. Refer to Section 5 for further discussion of SRF. Municipal Solid Waste (MWC) facilities combusting RDF are subject to 40 CFR Section 129.

4 Benefits and Obstacles

Thermal Technologies

Direct Combustion

Direct combustion technologies have a long history of reliable commercial-scale operation and are flexible enough to handle a variety of feedstocks with little to no pre-processing requirements. Benefits of this technology are the local energy production and potential uses of the by-products, which include ferrous metals, nonferrous metals, and in some cases may include use of ash as landfill cover. Developing the technology can create a number of construction jobs over the one to three years of construction and 40 to 80 permanent jobs over the life of the project. This technology generally requires a large waste stream (200,000 tons per year or more) to be economically beneficial. Normally the feedstock is MSW, but most combustible wastes can be processed. In addition, although the technology recycles and re-uses water on-site, it also requires a moderate use of water. However, high capital and operating costs, particularly for smaller scale facilities, and strong opposition from environmental groups, due to a perception by the public that this technology is not environmentally friendly, make implementing projects very difficult. The current low pricing for electricity and natural gas makes the energy produced from these technologies (steam and/or electricity) of low value. This technology produces an ash residue stream of approximately 15 to 30 percent by weight of the incoming waste stream; however, development efforts are underway to utilize portions of the ash stream. Volume reduction of the ash residuals is approximately 90 percent before any ash reuse resulting in significant savings in landfill space.

Gasification

Gasification operators assert that one of the benefits of many gasification technologies is that very high diversion levels (above 90 percent) can be achieved because the slag is not leachable and can be sold as aggregate to industrial users. Other benefits include energy production, or a liquid fuel if the syngas produced is further cleaned and passed through a catalytic process (e.g. Fischer-Tropsch). Potential uses of ferrous metal and ash by-products are as landfill cover or as an aggregate in the construction industry. Local benefits include the creation of construction jobs over the one to three years of construction and 25 to 75 permanent jobs over the life of the project. The technology may be more suitable for small or medium sized plants than direct combustion and has been developed most frequently in Japan and South Korea. However, these benefits have not been reliably demonstrated as commercial facilities in the US.

Theoretically the emissions should be lower for most vendors than that from direct combustion, and the vendors of this technology claim this is true. However, to date, actual emissions from operating facilities have been difficult to obtain or verify due to the lack of commercial-scale facilities using mixed MSW in North America. In some cases, facilities that used to be defined as two-stage direct combustion may now identify as gasification processes since the primary chamber is intended to operate in a reducing environment and burnout of gases produced is completed in a secondary chamber. The technology may have some applicability processing a specific subset of waste materials (not just MSW) such as wood waste, tires, carpet, scrap plastic, or other waste streams.

A large number of equipment suppliers are working on gasification processes. Some technologies may require extensive pre-processing, shredding, and other fuel preparation, which increases capital and operating costs. This remains one of the most difficult tasks in the process. It involves significant mechanical processing and close supervision, which greatly impacts operating costs and can account for as much as 40 percent of the total plant capital costs. The capital cost of the 220 tpd Thermiska TPS plant in Italy was approximately $170m USD with the RDF plant making up about $63m (37 percent) of that cost. The current low pricing for electricity and natural gas makes the energy produced from these technologies (steam and/or electricity) of low value. Research and development by technology vendors, such as Sierra, may improve economics if production of H_2 and other useful by-products is successfully demonstrated.

Plasma Arc Gasification

Similar to the gasification and pyrolysis processes, no commercial PAG facilities are operating in the US. For plasma arc systems, the MSW feedstock will need to be pre-processed to remove the larger, bulky waste, household hazardous waste, dirt, glass/grit, and metals to prevent these materials from forming slag and causing potential operating issues. Benefits include a claimed over 95 percent diversion of waste from landfills, energy production, and potential use of ferrous metal by-products and the slag formed and marketed as aggregate (although no markets currently exist for this product). The slag that is produced is vitrified, locking up trace metals, and is not leachable. Vendors of this technology claim efficiencies that are higher than direct combustion and other gasification technologies. These higher efficiencies may be possible if a combined cycle power system is proposed; however, little operating experience and no commercial experience in North America are available for this technology. A local benefit is the creation of construction jobs over the one to three years of construction and 25 to 60 permanent jobs over the life of the project.

Vendors of this technology claim to achieve lower emissions concentrations than traditional mass burn technology. However, similar to other thermal technologies, APC equipment would still be required for the clean-up from the combustion of the syngas as these facilities generally have similar air emissions issues as other gasification, pyrolysis, and direct combustion facilities. Mercury and some other more volatile metals are expected be driven off with the gas and would have to be dealt with from the exhaust of the gas combustion device. It should be noted that although the technology recycles and re-uses water on-site, it requires a moderate amount of make-up water. Although there are some commercial scale facilities operating on sorted MSW in Europe and Asia, there has been very limited commercial application using mixed MSW in North America. In the past few years several significant setbacks occurred at facilities. In North America the shutdown or termination of development of a nearly commercial scale facility occurred and in England shutdown of the largest plasma arc facility constructed to date occurred due to design and operational difficulties and costs. The 1,000 tpd, 50MW, Tees Valley Westinghouse Plasma Gasification Facility units in the United Kingdom (efforts to commission and test have been discontinued) each had a total capital investment of $500,000,000. Annual potential operating costs are unknown but are assumed to be as high, if not higher, than other gasification technologies.

Pyrolysis

MSW pyrolysis has had limited operational history and no commercial success to date; therefore, there is little information regarding long-term operating experience. As there are not many pyrolysis units functioning at a high level of capacity using MSW as a feedstock, the industry needs more time developing this technology. Some development is underway for select waste streams, such as hard to recycle plastics.

Benefits include a claim of over 90 percent diversion of waste from landfills, energy production, and potential uses of the by-products, if marketable. The liquid fuels produced may be higher value and suitable for internal combustion engines and combustion turbines. Other local benefits include the creation of construction jobs over the one to three years of construction and a certain amount of permanent jobs over the life of the project. This figure cannot be estimated as the technology requires additional development.

Biological Technologies

Aerobic Composting

Benefits include diversion of yard/green waste, the possibility of including food waste from being landfilled, and the local production of beneficial use compost and mulch that can be used in the community. In addition, local benefits include the creation of construction jobs over the short period of construction and approximately 2-10 permanent jobs over the life of the project, depending on the size and complexity of the facility. The main drawback is the potential for creating odors, noise, and dust. This process also requires more land than AD. This can be mitigated with proper operations and facility siting (which is generally in agricultural lands away from urban development). Aerobic composting also only addresses certain segments of the waste stream. The technology can be used to manage storm debris, such as derecho wastes; however, those waste streams must be handled separately and kept free of miscellaneous trash and other contaminants.

Anaerobic Digestion

There are a number of anaerobic digestion systems of varying types in operation in the US. Generally, however, the systems are in operation where tipping fees are higher than in the Midwest or where other special circumstances exist. Potentially, the agribusiness firms in CRLCSWA's service area could be leveraged in a public-private partnership arrangement to develop a project. Benefits of this technology include diversion of putrescible waste (food, biosolids, wet organics) from landfill, the production of renewable energy and or renewable fuels, and potential uses of the by-products as compost. In addition, other local benefits include the creation of construction jobs over the year or so of construction and approximately 10 to 25 permanent jobs over the life of the project, depending on the size and complexity of the facility. The biogas produced can also be cleaned and compressed into CNG for vehicles or cleaned and sold directly to a natural gas pipeline. The drawbacks of AD technology include the limitation of the technology to process only the feedstock appropriate for the technology (putrescible organics), as well as the potential for creating odors, noise, and dust. Wet systems are most sensitive to the types of waste utilized with plug systems being somewhat more tolerable. Dry systems are able to accept a wide range of feedstocks that are generally similar to compost (stackable). All AD systems have the potential for odor problems. The management of odors, noise, and dust can be mitigated with proper operations and facility siting. However, they can be quite challenging for facilities that process a wider range of feedstock.

Mechanical Biological Treatment

A benefit is the post-collection separation of feedstocks to divert recyclables from landfill while preparing a feedstock for digestion and thermal consumption. Some processes may produce a fuel suitable for use in industrial boilers and cement kilns. Another benefit is the creation of construction jobs over the construction period and approximately 10 to 50 permanent jobs over the life of the project. The primary drawback is the necessity for the process to rely upon the sale of the fuel product for economic viability. As much as 40-50 percent of the incoming waste stream winds up as non-digestible residue that either requires processing from another thermal technology and/or landfilling. Without a firm contract for the fuel product, an MBT is economically viable and, in almost all cases, the cost of producing the fuel is more expensive than conventional fuels. Some facilities have high capital and/or operating costs. Other operating drawbacks include the potential for creating odors, noise, and dust. This can be mitigated with proper operations and facility siting. The opening of the Entsorga HEBioT MBT facility has helped demonstrate the potential for this technology to deliver a fuel product that is commercially viable.

Chemical Technologies

Hydrolysis

The process of chemical hydrolysis is well established for some organic feedstocks, such as in the conversion of wood to paper pulp, but has only been applied to MSW-derived organics on a conceptual basis or has been limited to laboratory- or pilot-scale. There has been no sustained commercial application of this technology using MSW as a feedstock in North America and little information is available from abroad.

Similarly, the environmental risks are not well defined. In addition to the environmental risks of any associated technology, there would be some emissions risks related to CH_4 emissions or issues dealing with potential chemical spills. It is also expected that significant quantities of water and significant wastewater capacity would be required.

Benefits include the diversion of organic waste from landfill, the production of a cellulosic ethanol that can be used as a fuel product, the creation of construction jobs over the construction period, and the creation of a certain number of permanent jobs over the life of the project. This figure cannot be estimated as the technology requires additional development.

Catalytic and Thermal Depolymerization

Benefits include the diversion of plastic and oil waste from landfill, the production of an oil or fuel product that can be used as fuel (possibly a transportation fuel), the creation of construction jobs over the construction period, and the creation of a certain amount of permanent jobs over the life of the project. This figure cannot be estimated as the technology requires additional development. A major drawback is that the environmental risks are not well defined. Catalytic cracking could emit some hydrocarbons from the process. There could also be some other risks resulting from the handling of the catalysts or solvents and related compounds that might be required for the process. Water and wastewater use are also not known.

Waste-to-Fuel Technologies

Given the emerging status of this technology with MSW, there is minimal information available on this technology. There are no commercial projects in operation in the US, although a few firms are trying to develop projects. This is a two-step process:

1) Producer gas will need to be generated through gasification or another technology, and
2) The producer gas will then need to be cleaned and conditioned with the proper chemical catalytic process used to synthesize the syngas into a liquid fuel.

Benefits include the potential production of an ethanol-based fuel, the creation of construction jobs over the construction period, and the creation of a certain amount of permanent jobs over the life of the project. Drawbacks include air emissions impacts associated with the thermal gasification and syngas conditioning processes and the potential for only being able to produce fuel from a biomass only feedstock. In addition, there are solid and liquid wastes associated with this technology. The current low oil pricing in the US also makes the sale of the liquid fuel less valuable and may impact the financial viability of the project.

Mechanical Technologies

Autoclave/Steam Classification

Benefits include the potential diversion of materials from landfill, the production of cellulose and plastic products that can be used as feedstock for many of the technologies, the creation of construction jobs over the construction period, and the creation of a certain amount of permanent jobs over the life of the project. This figure cannot be estimated as the technology requires additional development and no commercial projects exist in the US. A drawback is that the environmental risks of autoclaving are not known. This technology could be used primarily as a front-end system to prepare materials for other processes, such as fiber recovery and thermal technologies. However, it relies on additive technology for the most diversion potential and thus struggles economically. Water and wastewater use are also not known.

Mixed Waste Processing

Benefits include the diversion of recyclables from landfill; preparation of feedstock for thermal, chemical, or biological processes; the creation of construction jobs over the one to two year construction period; and the creation of approximately 20 to 60 permanent jobs, depending on the size and complexity of the project. A drawback is that certain environmental impacts must be mitigated, such as noise, dust, and odor. The diversion rate for this technology alone is lower unless coupled with another technology for management of the non-recyclable materials. Currently, onlay a few facilities in the US are used to pre-screen MSW before processing in another technology, such as direct combustion. In addition, some of the commodities recovered from a MRF of this type may be more contaminated than a “clean” MRF. Current commodity pricing also impacts the financial viability of these projects and some of the commodities that are readily recoverable, such as wood and concrete, are low value.

Refuse Derived Fuel Production

Benefits include the preparation of the MSW into a feedstock that is acceptable by other processes allowing them to be more effective and efficient, removal of recyclable and reusable materials for beneficial use; the creation of construction jobs over the one to two year construction period, and the creation of approximately 10 to 100 permanent jobs, depending on the size and complexity of the project. A drawback is that RDF facilities will have some air emissions directly from the processing (dust) as well as from the combustion of the RDF (discussed in the thermal technologies section). An economic drawback of RDF is that it produces a solid fuel similar to coal. An example may be partnership with an ethanol or agribusiness facility that can us the steam, hot water, and/or electricity produced from RDF processed in a solid fuel boiler. As a result, production of the RDF product presumes a local appetite for a coal-substitute to be economically viable. For most plants looking for a coal substitute, the fuel produced must also achieve the requirements for an NHSM if the plant wants to be regulated under Section 112 of the Clean Air Act. To distinguish this application from RDF production for a MWC combustion unit, processing required for a boiler subject to Section 112 is called SRF in this report. Refer to Section 5 for further discussion. Fugitive particulates from the process must be controlled. In addition, other environmental impacts, such as noise and odor, must be mitigated. Costs for this type of facility are based greatly on the amount of revenues garnered from sale of the RDF product.