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Market Survey of Municipal Solid Waste Gasification Technologies and Projects

April 2016

WM Warwick
AE Solana

U.S. DEPARTMENT OF ENERGY

Prepared for the U.S. Department of Energy
under Contract DE-AC05-76RL01830

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Executive Summary

The U.S. Air Force (AF) is interested in renewable energy projects that can provide continuous power to enhance installation reliability and security. Waste-to-energy (WTE) projects using municipal solid waste (MSW) as a feedstock are an example of baseload generation. Energy from MSW is produced in one of three ways: open combustion, gasification, or pyrolysis using a plasma torch. Open combustion is the most common process. The AF favors gasification technology based on assumed public opposition to "mass burn" of MSW in open combustion plants and the more favorable environmental reputation of gasification technologies. In light of interest in renewable baseload generation options, Pacific Northwest National Laboratory (PNNL) was tasked to provide the AF with a brief, high-level survey of gasification technologies and comparison to mass-burn technologies, as well as perspectives on the future for gasification technologies as an affordable WTE option. Assuming favorable findings, PNNL was also to conduct an in-depth review of commercial technologies and vendors to provide the foundation for future WTE project procurements.

PNNL conducted a literature survey of operating commercial gasification facilities using MSW. PNNL also reviewed several WTE technology surveys conducted by or for waste management authorities in the U.S. and overseas. Some of these surveys included operating plants overseas and technologies in the demonstration phase or using biomass but not MSW. To ensure competitive selection of a technology and vendor by the AF, multiple vendors of technologies with commercial operations in the U.S. are necessary. Otherwise, the AF may find itself with a power supply option from a single source or a technology that is unreliable or untested with MSW. No commercial WTE plants using gasification technology are currently operating in the U.S. Consequently, PNNL concludes gasification technologies using MSW are not sufficiently mature to provide the AF with WTE options competitive with current mass-burn plants. Based on this finding, PNNL has provided a third-party summary of gasification technologies in lieu of a further in-depth technology review.

Bottom Line Up Front

At the request of the Air Force, Pacific Northwest National Laboratory (PNNL) surveyed available information on state-of-the-art waste-to-energy (WTE) technologies. It found that the Air Force is not alone in its interest in advanced WTE technologies. Waste management authorities around the globe face challenges to landfilling municipal solid waste (MSW). Some of these organizations have conducted very thorough analyses of commercial and emerging technical options. Review of their research led PNNL to conclude that advanced WTE technologies are not sufficiently mature in the U.S. to provide a feasible, commercial WTE option for the Air Force. Equally important, this research suggests that a growing movement toward waste minimization may make future MSW supplies uncertain and transportation costs infeasible.

Acronyms and Abbreviations

AD	anaerobic digestion
AF	Air Force
AFB	Air Force Base
EPA	U.S. Environmental Protection Agency
MES	Mitsui Engineering & Shipbuilding
MSW	municipal solid waste
PNNL	Pacific Northwest National Laboratory
RDF	refuse-derived fuel
tpd	tons per day
WTE	waste-to-energy

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1.0 Introduction

Municipal solid waste (MSW) is used for commercial power production in the U.S. and elsewhere using a process called waste-to-energy (WTE). Energy from MSW is derived through one of three processes: (1) atmospheric combustion, (2) gasification, or (3) pyrolysis using a plasma torch. Open combustion is the most common process. All organic materials, including MSW, can produce a combustible gas when they are heated in a reduced oxygen environment, a thermo-chemical process called gasification. WTE can also be converted to a combustible gas using a plasma torch, an exotic and expensive process that uses ionization rather than heat. At the request of the U.S. Air Force (AF), Pacific Northwest National Laboratory (PNNL) recently evaluated options for locating a WTE plant using MSW on or near Andrews Air Force Base (AFB) (Warwick and Orrell 2015).

PNNL's WTE evaluation for Andrews AFB had two primary objectives: (1) identify sufficient MSW feedstocks to fuel a plant and (2) assess the commercial feasibility of a plant using gasification rather than atmospheric combustion of MSW. The AF favors gasification technology because of public concerns regarding air emissions, which can be significantly reduced through gasification processes. The PNNL assessment for Andrews identified sufficient MSW feedstock in the region; however, the research was unable to identify examples of commercial gasification plants using MSW in the U.S. at the scale needed to provide affordable power for Andrews AFB. The PNNL survey of gasification plants did identify small-scale plants and promising technology developments, but it left many questions unanswered regarding the state of gasification technology for WTE in the U.S., and therefore, as a practical option for WTE for AF installations. This finding led to a follow-on request for PNNL to further research gasification technologies to clarify expectations about their future use for WTE projects on AF bases. PNNL proposed to follow this survey with an in-depth analysis of promising technologies, assuming the initial technology survey produced favorable results. This report provides the results of the gasification technology survey and PNNL's response regarding the additional in-depth technology review.

2.0 Context for Air Force's Interest in WTE

The AF and other Services are interested in increased energy security and resilience for critical installations. Conventionally fueled boilers and generators have served this purpose in the past, and will continue to do so in the future; however, renewable energy sources provide an alternative that does not have as long or vulnerable a logistical tail, produces fewer or no emissions, and increasingly is price competitive. Reducing vulnerability requires reliance on readily available renewable energy sources. Of those renewable resources that may be available, some are intermittent and require energy to be stored to ensure reliability. Others are always available and/or use feedstocks that can be stockpiled. These are called "baseload" resources. Baseload resources operate most efficiently and produce energy at the lowest unit cost when operated continuously, although they can be cycled to follow variations in demand. Examples of renewable resources for baseload use include geothermal sources, hydropower, and biomass, including the use of MSW as a feedstock.

Renewable energy projects traditionally trade high upfront development costs for a lifetime of low operating costs. The electricity-generating technology used for baseload plants using renewable resources is similar or identical to that of conventional power plants, although the size of plants is constrained by available resources. That generally means they are much smaller. Utility power plants benefit from economies of scale; larger plants cost less to build per unit of capacity and produce power for less per unit of output. As a result, smaller-scale baseload renewable plants are only competitive if conventional power costs are high and/or volatile, if feedstocks are lower cost than conventional fuels, and/or if the renewable attributes of the feedstock are monetized as renewable energy credits or otherwise valued. Despite their smaller size, WTE projects may be competitive because the feedstock used is slated for disposal for a "tipping" fee at the landfill and the cost of hauling. WTE can be competitive with power from conventional and other biomass fuels if tipping and/or hauling fees are sufficiently high and are transferred to the WTE project.

WTE projects are attractive to the AF because they are baseload plants that increase reliability and resilience when sited on or near an installation. In addition, MSW is considered a "renewable" resource by the federal government and many states. As a renewable energy project, WTE may benefit from incentives that reduce plant and/or operating costs. In some cases, the ability to dispose of the site's solid waste onsite is also a benefit. WTE is an established generating technology with over 80 U.S. plants (Michaels 2010). The WTE industry has addressed historical emissions issues with state-of-the-art emissions control technologies; however, environmental and social concerns remain in some locations. The AF is interested in gasification technologies that may not carry the same stigma.

2.1 MSW 101

The composition of MSW is critical for evaluating WTE potential, both total generation and total landfilled after material recovery (i.e., recycling). The U.S. Environmental Protection Agency (EPA) provides an estimate shown in Table 1.

Table 1. Generation, Recovery, and Discards of Materials in 2013 (millions of tons) (EPA 2015)

Material	Weight Generated	Weight Recovered	Recovery Percentage	Weight Discarded
Paper/Paperboard	68.60	43.40	63.30	25.20
Glass	11.54	3.15	27.30	8.39
Metals	23.06	7.87	34.10	15.19
Steel	17.55	5.80	33.00	11.75
Aluminum	3.50	0.70	20.00	2.80
Other Nonferrous	2.01	1.37	68.20	0.64
Plastics	32.52	3.00	9.20	29.52
Food	37.06	1.84	5.00	35.22
Rubber/Leather	7.72	1.24	16.10	6.48
Textiles	15.13	2.30	15.20	12.83
Wood	15.77	2.47	15.70	13.30
Yard Trimmings	34.20	20.60	60.20	13.60
Misc. Inorganic	3.93	0.00	0.00	3.93
Other Materials	4.58	1.31	28.60	3.27
Total MSW	**254.11**	**87.18**	**34.30**	**166.93**

MSW has value as an energy resource because it contains organic materials. By definition, organic materials contain carbon, which is a building block for all conventional fuel sources. In addition to natural organic materials, MSW can include processed organic materials, such as plastics. However, many plastic compounds include elemental chlorine, which is hazardous when burned. MSW may also contain inorganic materials, such as metal cans and glass bottles that are not useful as feedstocks. As Table 1 indicates, a significant fraction of materials is diverted from disposal through recycling and composting. This fraction is increasing over time; increasing it further is a goal for EPA and many state, county, and municipal waste management authorities, many of which have adopted net zero waste programs. Nevertheless, a significant fraction of materials appropriate for WTE remains in the MSW stream, even with recycling.

The EPA estimated that in 2005 MSW in the U.S. had an energy content of 11.73 MMBtu/ton (EIA 2007). For comparison, coal has an average energy content of about 20 MMBtu/ton (EIA n.d.). The estimated fraction of biogenic materials in MSW decreased from 67% in 1989 to 56% in 2005 (EIA 2007), presumably from composting programs. Non-biogenic wastes include inorganics as well as plastics and other processed organic materials. Although non-biogenic materials have value for WTE processes, that component of the MSW waste supply may not be considered renewable for some state Renewable Portfolio Standard programs. At present, all WTE output is considered renewable by most states with WTE facilities and for meeting federal agency *renewable energy* goals. EPA and federal executive orders distinguish between biogenic and non-biogenic feedstocks for estimating *greenhouse gas* reductions.

An estimated 50% of biogenic material in landfills does not decompose or does so very slowly, thereby removing its inherent energy content for use as landfill gas. As a result, using MSW as a feedstock makes more effective use of the inherent energy content of MSW. In addition, there is a tradeoff between WTE air emissions and fugitive methane emissions, even from state-of-the-art landfills. Air emissions from WTE include CO_2; however, CO_2 is also produced when landfill gas is either flared or used for power generation. Equivalent CO_2 emissions from methane captured from landfills to generate electricity are over five times greater than those from direct combustion of MSW for WTE (Kaplan et al. 2009). This is partly because methane collection from landfills is incomplete and fugitive methane releases are more potent greenhouse gases than CO_2 by a factor of 20. In contrast, WTE facilities convert potential methane-producing components of MSW to energy immediately. Consequently, WTE is a more environmentally friendly alternative to (1) the maintenance of small landfills that cannot afford gas recovery, (2) incomplete methane recovery from existing methane collection systems, (3) the use of landfill gas for power generation at large landfills, and (4) the development of wholly new landfills (Sullivan 2010).

3.0 Thermal Gasification Overview

Gasification technologies decompose the organic elements in MSW into gaseous components, principally carbon monoxide, hydrogen, and carbon dioxide, that can be captured for further processing. Limiting oxygen prevents the otherwise combustible gases from igniting so they can be refined into a synthetic gas (syngas) with higher heat content than raw MSW and burned with fewer problematic emissions. Syngas is cleaned to remove impurities, and then is used to generate electricity or to produce liquid fuels and/or commercially valuable chemicals. After processing, inorganic materials are discharged as inert solids that can be used for construction, road building, or other purposes. Attachment 1 summarizes the chemical process in the conversion of MSW via gasification and provides a simplified block diagram representative of the process (pp. 12 and 13, respectively).

There are many types of gasification designs that use different amounts of oxygen and steam at different stages and temperatures, producing different amounts of waste heat, syngas, and solids. Although gasification processes may require external energy inputs, the higher heat content of the syngas results in more efficient conversion of MSW to useful energy. Some standard designs include updraft and downdraft fixed beds, bubbling and circulating fluidized beds, and entrained flow. Fixed bed systems are smaller scale, while fluidized bed and entrained flow systems are typically larger scale. Some standard gasification technologies are listed in Table 2, along with general system characteristics.

Table 2. Biomass Gasification Technologies (Source: Roos 2010)

Gasifier Type	Scale	Typical Temperatures		Fuel Requirements		Efficiency	Gas Characteristics	Other Notes
		Reaction	Operating	Moisture Content (%)	Flexibility			
Downdraft Fixed Bed	5 kW_{th} to 2 MW_{th}	1000°C (1800°F)	800°C (1450°F)	<20%	• Less tolerant of fuel switching • Requires uniform particle size • Large particles	Very good	• Very low tar • Moderate particulates	• Small Scale • Easy to control • Produces biochar at low temperatures • Low throughput • Higher maintenance costs
Updraft Fixed Bed	<10 MW_{th}	1000°C (1800°F)	250°C (480°F)	up to 50% - 55%	• More tolerant of fuel switching than downdraft	Excellent	• Very high tar (10% to 20%) • Low particulates • High Methane	• Small- and Medium-Scale • Easy to control • Can handle high moisture content • Low throughput
Bubbling Fluidized Bed	<25 MW_{th}	850°C (1550°F)	800°C (1450°F)	<5 to 10%	• Very fuel flexible • Can tolerate high ash feedstocks • Requires small particle size	Good	• Moderate tar • Very high in particulates	• Medium Scale • Higher throughput • Reduced char • Ash does not melt • Simpler than circulating bed
Circulating Fluidized Bed	A few MW_{th} up to 100 MW_{th}	850°C (1550°F)	850°C (1550°F)	<5 to 10%	• Very fuel flexible • Can tolerate high ash feedstocks • Requires small particle size	Very Good	• Low tar • Very high in particulates	• Medium to Large Scale • Higher throughput • Reduced char • Ash does not melt • Excellent fuel flexibility • Smaller size than bubbling fluidized bed
Indirectly Heated Steam Gasification	Large scale	850°C (1550°F)	800°C (1450°F)	Flexible	• Very flexible, does not require sizing, pelletizing or drying	Excellent	• High methane yield	• Very high throughput • Low emissions, even with high chlorine feedstocks such as MSW • High capital cost

Circulating fluidized beds typically generate a low-quality gas that is best for direct thermal use in a boiler or industrial application. Bubbling fluidized beds and fixed beds tend to produce a cleaner gas that can be used in a reciprocating gas engine.

Syngas can be used for thermal energy production with minimal gas cleaning. Electricity can be generated with syngas using a combustion turbine, gas reciprocating engine, or fuel cell, although each of these technologies requires a progressively greater amount of gas cleaning. Electricity generation using syngas is typically between about 30% and 40% efficient. Combustion turbines may be combined with a heat recovery steam generator in the turbine exhaust stream to recover thermal energy for use in a steam turbine, steam heating application, or both. Waste heat can be similarly captured from a reciprocating engine's cooling water and exhaust gas. The higher steam pressure for electricity generating systems and additional personnel to operate turbines results in higher operations and maintenance costs for electricity generation compared to thermal uses.

Gasification technology has been demonstrated as an effective and efficient alternative to combustion technologies for fossil fuels, but has been slow to be adopted on a large scale for WTE. As it was for coal, the adoption of non-combustion technologies will be driven by economic factors, because it allows for more efficient conversion of fuel to energy, or it will be driven by environmental requirements for improved management of pollutant streams.

3.1 Feedstock Preparation

Required preprocessing of feedstock for gasification can be more extensive than for combustion because gasification is more sensitive to feedstock variations. Advanced MSW diversion processes, such as aggressive waste reduction, composting, and recycling, are preconditions for the use of non-combustion WTE technologies because a uniform feedstock is required. This is essential because heterogeneous feedstocks reduce the efficiency of the process, resulting in a lower Btu syngas and increased emission cleanup costs.

In addition to source separation, MSW can be further processed into more uniform feedstock, or refuse-derived fuel (RDF). Production of RDF for gasification takes several forms, often tailored to the proprietary gasification technology used. Processing by grinding creates a more uniform feedstock that is easier to process, which increases conversion efficiency and syngas production. Shredded MSW may be pelletized as well. Pelletization creates a feedstock that has a more uniform size and moisture content that is easier to feed into a gasifier. The pressure and heat inherent in the pelletization process also produce a feedstock with lower moisture content. Pelletized fuels are easier and safer to store than raw or even shredded MSW because they are more compact, less likely to self-ignite, and less attractive to birds and rodents.

Processing RDF adds another step to the WTE process. Material processing for RDF and storage of the new feedstock can double the area required for a WTE facility and add roughly between $8 and $34/ton to feedstock cost (Caputo and Pelagagge 2002; DEFRA 2014), based on European costs and assuming an exchange rate of $1.13 per Euro. However, it is not necessary for RDF to be processed at or by the WTE facility. Another contractor may be tasked with material recovery and RDF production by the waste management authority.

4.0 Other WTE Technologies

The inherent energy in MSW can also be captured through combustion, gasification using an electric plasma torch, and anaerobic digestion (AD).

4.1 Combustion

WTE projects that burn or combust waste in an aerobic, or open air, environment are the dominant type of WTE project in the U.S. Combustion systems burn MSW feedstock to produce steam in a boiler, which can be used directly as thermal energy or to turn a turbine connected to a steam-driven generator to produce electricity. This method of producing electricity has an efficiency of between 20% and 30%. Typical combustion system designs include moving-grate and fixed-grate stoker boilers and stationary and circulating fluidized beds; designs and equipment are primarily derived from coal-fired power plants and are based on proprietary designs for MSW from Von Roll (based in Switzerland) or Martin (based in Germany). Attachment 1 summarizes of the chemical process in conversion of MSW via combustion and provides a simplified block diagram representative of the process (pp. 8 and 10, respectively).

In general, these designs require large quantities of material so that a core of burning waste is available as a self-sustaining heat source to both dry and ignite the incoming waste material. There are economies of scale for WTE plants using these technologies because of the amount of heat needed to dry incoming waste; larger projects produce more excess heat during waste combustion for that purpose. Small-scale combustion plants (<100 tons of MSW/day) typically use stationary mass-burn technologies (fixed or moving-grate) and are often used for direct heating applications. Large-scale plants are necessary to use fluidized beds and generate electricity because of the higher cost of the technology and scale required for thermal efficiency. The tradeoff between designs is first cost versus higher efficiency; higher efficiency plants may have somewhat lower native (pretreatment) air emissions.

There are a variety of mass-burn plant designs, many of which are proprietary. Some standard combustion technologies are listed in Table 3, along with general system characteristics (APO 2009; Bungert 2012; IEA Bioenergy n.d.; ODOE 2003).

Table 3. Comparison of Selected WTE Combustion Technologies

Combustor Type	Typical Scale	Typical Reaction Temp (°C)	Fuel Requirements: Moisture Content (%)	Fuel Requirements: Flexibility	Efficiency (%)	Other Notes
Fixed-Grate Stoker Furnace	40,000 to 700,000 lb/hr; <20 MW_{th}	1000 to 1200	5 to 50	Tolerant of varying particle sizes, high ash content, and wood fuel mixing	65 to 75 boiler, 20 to 25 electrical; relatively inefficient	Can follow varying loads but high maintenance and has higher emissions
Moving-Grate Stoker Furnace	40,000 to 700,000 lb/hr; <20 MW_{th}	1000 to 1200	5 to 50	Tolerant of varying particle sizes, high ash content, and wood fuel mixing	65 to 75 boiler, 20 to 25 electrical; relatively inefficient	Can follow varying loads but high maintenance and has higher emissions
Underfeed Stoker	< 6 MW_{th}	1000 to 1200	5 to 50	Low ash content Small particle size (<50 mm)	80 to 85 boiler efficiency	Operationally safe, inexpensive, and can follow varying loads. Has higher emissions
Bubbling Fluidized Bed	>20 MW_{th}; 25,000 lb/hr up to 600,000 lb/hr	800 to 900	High	Tolerant of fuel switching and diversity, small particle size, although less tolerant of impurities	80 to 82 boiler efficiency	--
Circulating Fluidized Bed	>30 MW_{th}	800 to 900	Low but tolerant of some higher moisture content	Tolerant of fuel switching and co-firing, small particle size, and accepts tires and petroleum coke	80 to 82 boiler efficiency	Reduced SO_x and NO_x emissions and no loss of efficiency with fuel switching, although not suited for cogeneration. Highest cost

No new commercial combustion projects using MSW have been constructed in the U.S. since the 1990s, although several have been proposed and may yet be completed.

4.2 Plasma Arc Gasification

Gasification using a plasma torch is an emerging WTE technology. Most project designs are proprietary; however, they typically use an electric plasma arc through which MSW flows. The plasma torch requires an external power source, although that power can be produced using the synthetic gas the process produces once it is self-sustaining. Plasma temperatures above 5000°C ionize incoming feedstock into its elemental components. The reaction is contained in a closed vessel so gases can be exhausted for scrubbing and further processing. A closed vessel is also required to maintain a low oxygen environment to prevent combustion of ionized gases. The resulting syngas can be manipulated using well-known chemical refining processes. Non-gaseous metals and inert materials flow to the bottom of the plasma reactor vessel. The resulting metallic slag can be refined into component metals and the remaining granular material can be used for construction projects. Plasma gasification produces syngas that is cleaner and has higher organic content, which can facilitate capture of materials that would be hazardous air, water, or ash discharges in other WTE plants. The richer syngas can be more readily converted into a liquid fuel using the Fischer-Tropsch process if desired.

Plasma torches have a narrow beam width, which necessitates preprocessing of MSW to provide a uniform feedstock to inject into the plasma arc. Source separation of MSW feedstock is not mandatory because any material that passes through the arc will be ionized; however, source-separated RDF allows the process to operate more efficiently. Otherwise, the plasma energy is used for slag production of metals and other contaminants instead of syngas production. The ability to destroy any material makes plasma gasification an ideal technology for hazardous and sensitive wastes, such as medical waste, cadavers, and business sensitive and classified materials. In fact, its primary use currently is for processing these specific waste materials. It is also favored where near-complete waste reduction is desired because the process reduces waste volume by between 95% and 99% and residual materials are fundamentally inert so they can be used as an aggregate in construction rather than landfilled.

A significant amount of electricity is required to provide the plasma arc and operate the material handling and gas processing infrastructure. This has limited deployment of this technology to applications where waste disposal costs are very high, complete conversion of wastes is essential, the resulting gases are highly valued, and/or conventional waste management options are unacceptable. Management of battlefield wastes using plasma technologies has been demonstrated as have shipboard applications; however, further development for either has been limited.

4.3 Anaerobic Digestion

AD is a biological process that can be used to process raw liquid sludge or as an alternative method to dispose of food and landscape waste. It is widely used in wastewater treatment systems and certain agricultural situations, such as dairy farms and industrial hog operations. AD technology is common in Europe because of limited landfill space and bans on disposing of organic wastes in landfills. *Anaerobic* digestion of MSW is not prevalent in the U.S. at present, although the *aerobic* process of composting food waste is common (Clark 2015; Rapport 2008).

AD is a bacterial fermentation process that uses naturally occurring microorganisms in a series of biochemical reactions to decompose the organic fraction of waste in an oxygen-free or oxygen-reduced environment (Clark 2015). The two byproducts of the process are biogas with high methane content (which can be used to produce thermal or electrical energy) and low-solids digested sludge. This liquid-based ("wet") AD technology has been adapted to process "dry" feedstock, such as food waste. The application of this technology is expanding in the U.S. as European companies are bringing their expertise to the U.S. and public policies are shifting to encourage a reduction in organic solid waste disposal, primarily food waste and yard debris. Composting of organic waste is still the preferred diversion solution; however, composting facilities require a large site and the potential for odor dictates locations away from the urban areas where most of the waste is produced.

5.0 WTE Environmental Impacts and Operations and Maintenance

The flue gas from waste processing includes air emissions that have to be captured and neutralized. These emissions are currently subject to stringent controls. That was not always the case, and WTE projects still suffer from their past record. In 1990, almost 300 MSW incinerators were operating, many of which did not include power generators. By 2007, that number was fewer than 100, all of which had to comply with the EPA best available control technology (see Attachment 1, p. 9). The cost to comply with EPA regulations made the other 200-plus plants impractical to operate. All remaining plants are combustion plants using various pollution control technologies to meet emissions limits. Gasification and other syngas-producing processes release fewer emissions during waste conversion because of the lower processing temperatures. The resulting syngas can be cleaned prior to combustion, which reduces the overall emissions profile and allows the use of additional, less expensive, control technologies. Oxygen restriction during the gasification process also helps to capture gases with higher energy content for reforming into better fuels for heat or power production. This is illustrated in Figure 1.

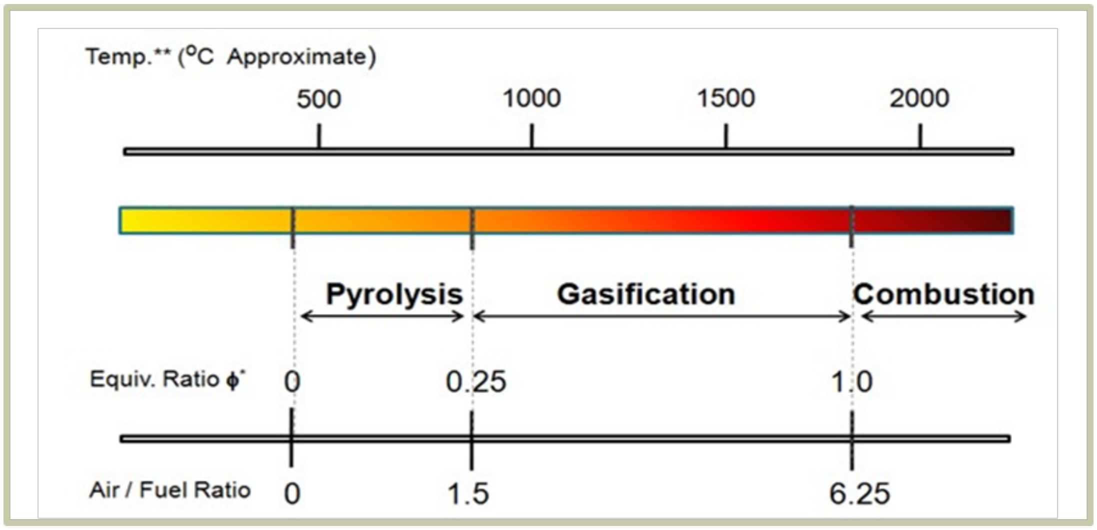

Figure 1. Relative Temperatures and Fuel/Air Ratio for Three WTE Technologies (Source: Attachment 1, p. 11.)

The synthesis gas produced through gasification is generated without the formation of impurities associated with incinerator flue gas as a result of the lower temperature and fuel/air ratio. Gasification emissions are generally an order of magnitude lower than the emissions from an incinerator, and the syngas that is produced has higher energy content than raw MSW and can be used directly (after cleaning) for power generation, as well as to fire boilers for traditional steam generation. In addition, the chemical reforming process can continue to produce liquid fuel substitutes using the Fischer-Tropsch process. See pp. 32 to 35 of Attachment 1 for more details on emissions from combustion, gasification, and landfilling.

Some components of MSW feedstock are known to form deposits on heat transfer surfaces, resulting in corrosion, increased maintenance requirements, and decreased lifetime for these surfaces. Ash (both fly ash in the exhaust and bottom ash in the bed) has to be collected and removed from the system. Excessive ash and corrosion are problems within MSW projects because of the variability of the incoming feedstock in terms of its composition and moisture content. These contaminants are present in both landfill gas and syngas from gasification systems; therefore, the resulting gas cannot be used without further processing in some generating technologies, such as gas turbines and fuel cells, and special maintenance procedures are required for other technologies, including internal combustion engine generators. WTE systems that use a homogeneous feedstock benefit from more complete conversion of MSW, thereby increasing efficiency and plant availability and reducing combustion waste products and emissions.

6.0 Current Waste Management Trends and Research

AF interest in new WTE technologies is similar to that of waste management authorities internationally who are seeking alternatives to landfills. Concurrently, there is a movement toward "net zero waste" that aims to significantly reduce waste disposal by reducing waste generation at the source (such as eliminating unnecessary packaging), recycling, and composting. Within the net zero waste movement, some political jurisdictions include WTE technologies as recycling or as an acceptable option to convert waste that remains after reduction and recycling.

The growing movement toward net zero waste is expected to reduce waste disposal volume significantly. This movement envisions reduction of waste volume, aggressive recycling, and conversion of remaining wastes into energy or other useful materials through WTE, AD, and composting. Composting and AD appear to be favored over WTE for conversion of non-recyclable wastes, although that varies by political jurisdiction. An example is provided by the State of California, as described below. A few potential trends emerge from this movement. First, increasing waste diversion/conversion will require investment in new facilities to recycle and compost, which will increase the overall cost of waste management. This will require additional funding for waste management, either from tipping fees or other sources, such as taxes. Second, remaining waste materials will have a different composition than they do today, with higher concentrations of noncombustible wastes. Third, reducing the volume of combustible wastes will increase hauling distances to accumulate sufficient feedstock for WTE, making hauling for WTE uneconomical without a commensurate increase in tipping fees that can be offset by diversion to a WTE facility.

The State of California provides a useful example of the waste reduction movement that other states or municipalities may soon follow. The state legislature started taking an active interest in reducing landfill disposal of waste in the 1970s by initiating waste planning by waste management authorities and paper and container recycling. By 2011, it had progressed to the point of mandating a 75% waste reduction goal for 2020 through a combination of source reduction, recycling, and composting. New conventional mass-burn WTE facilities continue to be allowed, but waste diverted through them is not credited toward the 75% reduction goal. New WTE projects using AD, gasification, and pyrolysis may receive credit. The state recently claimed to have achieved 50% waste reduction and expects to meet the 75% goal as recycling and composting facilities expand. If recyclable and compostable wastes are in the same waste collection stream as other wastes, the required investment funds could come from higher tipping fees (CalRecycle 2015). Higher tipping fees tend to favor WTE options. If higher tipping fees are not an option, another funding source, such as property taxes, could be used, resulting in a loss of the incentive provided by tipping fees. Reduced waste volume also means less waste is available to fuel WTE plants.

While the regulatory environments in Europe and Canada make gasification WTE more cost effective through incentives and disposal restrictions, for now the U.S. relies primarily on landfills because they are the most cost-effective alternative for waste disposal. This is the case even in California, despite its high waste reduction goal.

7.0 Commercialization of MSW Gasification Technologies

Based on a review of relevant literature, PNNL was unable to identify any currently operating commercial gasification projects in the U.S. using MSW at a 15- to 20-MW scale. Selections from that survey are summarized in Table 4, and some highlights are discussed in this section. Waste disposal costs in the U.S. are significantly lower than in other industrialized nations, which contributes to the difference in use of WTE compared to those other nations.

The closest example in the U.S. is a "pilot" plant that was operated by Covanta in Tulsa, Oklahoma, for a limited test period. That plant was originally constructed as a mass-burn WTE plant with three boilers and associated MSW combustion lines using conventional stoker grate combustion technology. Most of the steam from the plant is sold to an adjacent oil refinery instead of being used for power generation. Covanta purchased the facility from the previous owner and modified one of the processing lines to gasify MSW in two stages using a process it trademarked as CLEERGAS. The CLEERGAS module can process 300 tons of MSW per day to produce 6 to 8 MW of electricity. The pilot plant operated for roughly 1 year to demonstrate and prove the technology. Covanta tried to market the CLEERGAS gasification technology for WTE, but was not successful and has discontinued that effort. Covanta owns or operates over half of all U.S. WTE facilities. Converting those plants to the CLEERGAS process is not cost effective due to the underlying contracts, which typically have set terms for payment of electricity production that will not allow for new capital investment.

The Los Angeles County Department of Public Works addressed the question of alternatives to landfilling MSW through a review of waste conversion processes, as did the City of Perth, Australia, both of which are discussed further. Other documents found during the study provided similar surveys and similar results; namely, there are no currently operating commercial gasification WTE projects in the U.S. (Lombardi et al. 2015; Thorin et al. 2012; Wilson et al. 2013).

The Los Angeles County Department of Public Works commissioned an evaluation of MSW conversion technologies in anticipation of pending landfill closures. The resulting report included a survey of multiple commercial or near-commercial technology providers, including Covanta (URS Corp 2005a, b). Covanta did not respond to the final battery of survey questions regarding its CLEERGAS process, which Covanta was no longer marketing by 2005. The final listing of leading thermal conversion technologies consisted of four firms, only one of which had a U.S. plant; that plant used agricultural waste, not MSW. Each of the ranked firms had operating plants in Europe or Japan. The report concluded that "advanced" thermal conversion using combustion technology was the preferred option, followed by gasification. Modeling of project economics using vendor inputs suggested some of the proposed advanced thermal conversion technologies could be cost effective with tipping fees in the $40 to $50 range. However, most of the proposals LA County received were not based on operating plants and many of the firms that submitted proposals are no longer in business. Ultimately, the county abandoned plans to increase landfill capacity and now relies on an effort to reduce waste by at least 50%. This will allow existing landfills to accommodate remaining waste volumes for several decades (LA County 2014).

The City of Perth conducted a survey similar to that of LA County, which resulted in reports that were published in 2013 (WSP 2013a, b). The technologies that Perth selected for case studies highlighted innovative solutions to various performance challenges. A few of these effective MSW gasification systems are described below; all are large-scale plants operating in Europe or Japan.

Energos supplied gasifiers for eight plants in Norway, the UK, and Germany. The system is close-coupled gasification, meaning the syngas produced is immediately combusted to generate steam. The plants have operated successfully to date. Issues at one Norwegian plant have all been related to feedstock quality: "High levels of plasterboard from demolition waste have resulted in relatively high SO2 levels in the flue gas. The volumes of ash are also relatively high compared to plants operating on MSW, again due to the feedstock composition" (WSP 2013b, p. 101).

Metso Power supplied an MSW cogeneration gasifier to a plant in Finland in 2012, the world's largest MSW gasifier at that time. The plant has operated successfully to date, at 31% net conversion efficiency, with only a few minor problems in the first year, all of which have been resolved:

- Oversized metals in the feedstock blocked rotary valves in the fuel feeding system, requiring modification to the pre-processing as well as the mechanical fuel feeding system.
- Hot gas cleanup filters malfunctioned.
- Tar condensation required additional insulation (WSP 2013b).

As of 2012, there were 122 operational MSW gasification plants and 9 under construction in Japan. The main technology used in Japan is slagging gasification, which helps achieve the primary goal of minimizing landfill waste. The largest supplier, Nippon Steel, supplied 35 of the operational plants and 5 of the plants under construction. Other suppliers include Kobelco, JFE, Hitachi Zosen, Ebara, and Mitsui Engineering & Shipbuilding (MES). The plants are "very reliable;" the most vulnerable parts are those supporting the molten slag pool. One technology, Thermoselect, is used in 7 plants but is no longer offered because of its expense. The MES process originally had issues related to the material feeding method with variable waste feedstock, but pretreatment has been modified and 8 MES plants are "operating satisfactorily" in Japan (WSP 2013b).

Table 4. Selected WTE Gasification Technologies Identified in the PNNL Literature Survey

Vendor/Technology	Currently Operating?	Located in U.S.?	Capacity	Feedstock
Covanta/CLEERGAS	No	Yes	6-8 MW	MSW
Energos	Yes	No	215 tpd	MSW
Metso	Yes	No	750 tpd, 160 MW_{th}	RDF
Nippon Steel/Direct Melting Furnace	Yes	No	65 to 720 metric tpd	MSW
Kobelco	Yes	No	60 to 525 metric tpd	MSW or RDF
JFE/Thermoselect	Yes	No	38 to 314 tpd	MSW, including mined from landfills
Hitachi Zosen	Yes	No	50 to 405 tpd	MSW
Ebara	Yes	No	48 to 550 tpd	MSW or industrial waste
Mitsui Engineering & Shipbuilding	Yes	No	140 to 450 tpd	MSW
Interstate Waste Technologies/Thermoselect	Yes	No, but 2 planned	1700 tpd planned; generate ethanol	MSW
PRM Energy Systems, Inc.	Yes	No	118 MMBtu/hr	RDF
Entech Renewable Energy Solutions	Yes	No	1.6 to 14.2 MW_{th}	MSW RDF or industrial RDF
Conrad Industries: Advanced Recycling Technology	No, demo only	Yes	12 MW modules	Plastic, tires, etc., but not mixed MSW
SilvaGas	No, demo only	Yes	9.1 tpd	RDF
Alter NRG (plasma)	Yes	No	220 tpd	MSW
InEnTec/Plasma Enhanced Melter (PEM)	No	Yes	Demonstration	MSW
TPS Termiska	No	No	6.7 MW	Pelletized RDF

8.0 Summary and Conclusion

PNNL's survey of the current state of gasification for WTE found that although it may provide superior conversion efficiency, deliver excellent air emissions reduction, and reduce the volume and disposal costs of residues, the commercial market for these plants in the U.S. is not sufficiently mature to provide the AF with competitive vendors to ensure power production at affordable rates. As a practical matter, were the AF to solicit offers for WTE facilities using gasification, it is unlikely it would receive multiple bids from vendors with commercial plants and it would likely receive none from vendors with commercial plants in the U.S. More importantly, pressure to reduce an increasing fraction of MSW and retrofit of existing landfills for landfill gas collection provides competitive alternatives to WTE in general, and the higher capital cost of gasification technologies in particular.

The future competitiveness of WTE as a resource is unclear in the face of the growing net zero waste movement. Significantly greater fractions of current waste streams can be diverted through recycling and composting; however, this will increase the overall cost of waste management. If tipping fees are significantly increased as a consequence, it may favor gasification for WTE. On the other hand, significant reduction in waste volume, changes in waste composition, and longer hauling distances may counter the benefit of higher tipping fees. Regardless, this movement increases uncertainty of future MSW volume and cost, making investment in new WTE capacity *of any sort* more risky than it was previously. In light of this conclusion, PNNL does not recommend further in-depth analysis of gasification technologies and WTE plants. In lieu of that study, a comparable technology assessment (Wilson et al. 2013) is included as an attachment to this report.

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Attachment 1

A Comparative Assessment of Commercial Technologies for Conversion of Solid Waste to Energy

A Comparative Assessment of Commercial Technologies for Conversion of Solid Waste to Energy

Bary Wilson, Ph.D.

Neil Williams, Ph.D., P.E.

Barry Liss, Ph.D., P.E.

Brandon Wilson, Ph.D.

Prepared for

EnviroPower Renewable, Inc.

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1. Executive Summary

This document describes and compares biomass and municipal solid waste to energy conversion technologies in terms of their design, operation, waste treatment capability, conversion efficiency, economic performance, and environmental impact. The focus is on commercial, or near commercial, scale technologies that are available for converting various types of municipal solid waste and biomass to electrical energy, or for generating combined heat and power on a commercial scale. For thermal processes, both refuse derived fuel (RDF) and mass burn firing options are discussed, as are various approaches to convert the wide variety of fuels that comprise the solid waste streams that would otherwise go to compost or landfill.

Waste streams considered in this assessment include wet agricultural biomass and sorted municipal solid waste from which recyclable materials, inert inorganic materials, and hazardous waste have been removed; source separated commercial waste; light construction and demolition waste; used tires; and relatively wet organic materials such as sewage sludge, food waste and green waste (wet organic waste). In general, these materials are either sorted, and blended to form a refuse derived fuel (RDF) or in the case of incineration, simply mass burned, essentially as received, after removal of hazardous materials.

Technologies considered in this assessment include thermal processes including RDF and mass burn incineration, fast and slow pyrolysis, plasma arc gasification and air fed gasification. Air fed gasification of RDF in both updraft fluidized bed and smaller rotary kiln units is described. Non-thermal processes such as anaerobic digestion (methanogenic microbial conversion), and aerobic digestion, or composting, are also discussed. The latter technologies, although highly inefficient in recovering energy, are often used for conversion of wet organic materials such as wet agricultural biomass, food waste and green waste.

While incineration is currently the most widely deployed among these conversion technologies, this assessment shows that air fed gasification, the technology identified by the USEPA and the US Department of Energy as the technology best suited for conversion of municipal solid waste, ranked highest overall when considering the combined characteristics of conversion efficiency, cost per unit of power generated, and environmental impact.

Air fed gasification was ranked as superior in terms of construction costs, net operating costs, and environmental impact, to pyrolysis, plasma arc gasification, and both RDF and mass burn incineration, whether or not combined with anaerobic digestion. Air fed RDF gasification with steam turbine power generation, or district heating, was also found to be preferable to disposal in landfills as a means of treating municipal solid waste in terms of both long term cost and environmental impact.

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GLOSSARY

APC / APC residues : Air Pollution Control / APC residues comprise: (i) dry and semi-dry scrubber systems involving the injection of an alkaline powder or slurry to remove acid gases and particulates and flue gas condensation/reaction products (scrubber residue); (ii) fabric filters in bag houses may be used downstream of the scrubber systems to remove the fine particulates (bag house filter dust); and (iii) the solid phase generated by wet scrubber systems (scrubber sludge). APC residues are often combined with fly ash.

Bottom Ash : Comprises heterogeneous material discharged from the burning grate of the incinerator (grate ash) and material that falls through the burning grate to be collected in hoppers below the furnace (grate riddlings).

CHP : Combined Heat and Power produces electricity and heat in the same process.

CO : Carbon Monoxide

CO_2 : Carbon Dioxide

Co-disposal : Co-disposal is the practice of mixing wastes of different origins in the same landfill or other disposal facility.

Dryer: Device used for drying high moisture waste materials or biomass by use of heat extracted from steam or from hot flue gasses.

ESP : Electrostatic Precipitator is a particulate collection device that uses the force of an induced electrostatic charge to remove particles from a flowing gas.

FGT : Flue Gas Treatment

Fly Ash: Finely divided particles of ash which are normally entrained in the combustion gases. Fly ash is recovered from the gas stream by a combination of precipitators and cyclones.

GHG: Greenhouse Gases including, and normally referring to, mainly carbon dioxide and methane

HCl : Hydrochloric Acid

HHV: Higher Heating Value is the *gross energy* or *upper heating value* or *gross calorific value* of a material (fuel) and is determined by bringing all the products of combustion back to the original pre-combustion temperature, and in particular condensing any vapor produced.

Hg: Mercury, a toxic heavy metal with a high vapor pressure that can be found in exceedingly low concentrations in the flue gas from combustion of coal an and other fuels

kW: Kilowatt, equal to one thousand watts

kWh: Kilowatt hour, a measure of electrical energy equal to 1000 watts expended for 1 hour.

LHV: Lower Heating Value is the *net calorific value* of a material or fuel and is determined by subtracting the heat of vaporization of the water vapor from the higher heating value.

MAF: Moisture and ash free,

Mass-Burn Incineration : The incineration of waste in a grate combustion system with little or no pre-sorting of the waste material

MSW : Municipal Solid Waste is waste which is collected for treatment and disposal by a local authority. MSW generally comprise waste from households, civic amenity sites, street-sweepings, local authority collected commercial waste, and some non-hazardous industrial waste.

MW :Megawatts (10 exp 6 Watts) is a unit of power equal to one million watts

NOx : Mono-nitrogen oxides (NO and NO_2) produced mainly from fuel bound nitrogen during combustion.

RDF : Refuse Derived Fuel is a fuel product recovered from the combustible fraction of household waste.

Rotary Kiln: A rotating cylinder lined with refractory and slightly inclined axially used for pyro processing in manufacture of materials such as cement as well as the main thermal reactor in incineration and gasification systems.

SOx : Oxides of Sulphur

Slagging Kiln or Slagger: A rotary kiln operated at temperatures between approximately 1400 and 1460 degrees C used for the purpose of further processing combustion bottom ash by removing the remaining carbon and melting, or partially melting, the remaining inorganic oxides to produce an inert slag or vitreous frit.

Syngas : a clean burning mixture of gases evolved from the heating of carbonaceous waste materials in an oxygen starved environment and comprised mainly of CO, CO_2 ,H_2 water vapor and (when produced by an air fed gasification) N_2.

TWh : Terawatt hours (10 exp 12 Watt hours)

VOC: Volatile Organic Compounds are organic substances of concern (carbon chains or rings that also contain hydrogen) that have high enough vapor pressures under normal conditions to significantly vaporize and enter the atmosphere (i.e., with a vapor pressure greater than 2mm of mercury (0.27 kPa) at 250oC or a boiling range of between 60 and 250oC) excluding methane.

WTE: Waste to Energy, also known as Energy from Waste (EFW) is the conversion of waste into a useable form of energy, e.g., heat or electricity. A common conversion process is waste combustion.

2. Introduction

Total global energy consumption in 2010 was estimated to be on the order of 400 quadrillion BTU (400 quads), with the US accounting for 98 quads of that amount. In spite of stated policies to increase renewable energy production in the US in recent years, the renewable energy contribution remains at about 8 quads[1]. In 2010 about 1.2 quads of recoverable renewable energy was sent to landfills, much of which could be converted electrical power or usable heat energy through thermal or biological processes. A recent survey[2] found 87 operating thermal waste to energy plants in the US, while Europe has more than 400 such plants and Japan has 190.

Because of a relative scarcity of landfill airspace and a greater political emphasis on environmental sustainability, Japan and several countries in Europe have deployed thermal treatment of municipal and solid wastes as a means of volume reduction as well as for the generation of electrical power or combined heat and power. Denmark, Germany, and other European countries have developed policies that encourage the recovery of energy from municipal solid waste, certain industrial solid waste streams, and agricultural biomass. Denmark is an outstanding example of what can be done in terms of reducing the amount of solid waste going to landfill, with approximately one fourth of the waste produced in 2005 being incinerated for heat and power production, approximately two thirds being recycled, and only 8 percent going to landfill. In 2006, waste supplied fuel for 5 percent of the Danish electricity production and just under a quarter of district heat production[3].

Conversion technologies described herein were evaluated according to the overall objective of diverting MSW that is not currently recycled from landfill disposal by converting the non-recycled material into energy or other beneficial products. Waste to energy projects should be implemented as a supplement to, not a replacement for, recycling efforts. In addition to the quantitative comparison, the following overall criteria [4] were used in determining the best available conversion technologies.

- Increase Diversion of Post-Recycled MSW from landfills:
- Reduce Environmental Impacts including water quality and greenhouse gas emissions
- Provide Financial Feasibility and Sustainability with capital and operating costs that result in feasible, cost-competitive tipping fees and energy, and long-term financial stability
- Produce Green Energy and Other Marketable Products.
- Provide a Safe Work Environment
- Enable a Sustainable and Long-Term Waste Disposal Plan

Following are brief descriptions and quantitative performance comparisons of commercial or near commercial scale thermal and biological waste to energy technologies as described above.

3. Incineration

Incineration is a thermal process wherein the combustible components of a solid waste stream are thermally oxidized to produce heat energy that can be used to create steam for generating electrical power, for industrial process, or for district heating. In addition to thermal energy, products of the incinerations process include bottom ash, fly ash, and flue gas, in which are found a number of regulated pollutants[5]. The combustion of carbonaceous materials can be characterized by the following well know chemical reactions shown in **Figure 1.** Not shown are reactions involving chlorine, which are of significance in incineration processes for environmental reasons. .

$C + O_2 \longleftrightarrow CO_2$	Oxidation of carbon
$\frac{1}{2} O2 + H_2 \longleftrightarrow H_2O$	Oxidation of hydrogen
$N + O_2 \longleftrightarrow NO_2\ (NOx)$	Oxidation of Nitrogen
$S + O_2 \longleftrightarrow SO_2\ (SOx)$	Oxidation of Sulfur

Fig. 1. Basic combustion (oxidation) reactions

Bottom ash is that component of the fuel that is not converted to gas. This material is comprised mainly of inorganic materials including metal oxides and unburned carbon and remains in the char bed until it is removed from the bottom of the combustor.

Smaller ash particles may become entrained in the flue gas and must be removed along with volatile organic compounds (VOCs) as well as semi-volatile organic compounds (SVOCs) and acid gas constituents that were not fully oxidized in the combustion process or may have reformed upon cooling of the flue gas.

Several processes are in current use for removal of particulates from the flue gas before it is released into the atmosphere[6]. Flue gas clean-up units commonly found in MSW incineration plants include either a dry or wet acid gas removal unit or scrubber, and a bag house. For additional clean-up of the flue gas, carbon and/or lime can be injected into the gas stream in the bag house. Since flue gas clean up systems can be used as a component of several of the thermal processes described here, they will be described and discussed in a separate section (**See Section 11**).

Waste combustion is particularly popular in countries such as Japan where land is a scarce resource. Denmark and Sweden have been leaders in using the energy generated from incineration for more than a century. This is due to land resource issues and higher overall thermal efficiencies where heat rejected in the power cycle can be used and not just transferred to the environment (atmosphere or water). In 2005, for example, waste incineration produced nearly 5 percent of the electricity consumption and almost 14 percent of the total domestic heat consumption in Denmark [3]. A number of other European countries including Luxembourg, the Netherlands, Germany and France, rely heavily on incineration for handling municipal waste, in particular.

In terms of conversion efficiency to electricity, between approximately 0.4 and 0.7 MWh of electrical energy can be generated from a ton of MSW through incineration. Thermal efficiency is somewhat higher, with a ton of MSW producing approximately 2 MWh in steam for district heating applications. Incineration of 1000 short tons per day of waste will produce about 650 MWh of electrical energy per day (27 MW of electrical power continuously for 24 hours) or approximately 2,000 MWh of district heating energy each day.

Environmental Impacts of Incineration and Closing of MSW Incineration Plants

Like coal combustion, incineration of MSW produces carbon dioxide, as well as nitrogen and sulfur oxides and a range of other gas phase organic and inorganic air emissions[6]. Fly ash and bottom ash are also generated, just as in the case of coal combustion. The total amount of ash produced by municipal solid waste incineration ranges from 4 to 10 percent by volume and 15-20 percent by weight of the original quantity of waste, and the fly ash amounts to about 10-20 percent of the total ash. By far, fly ash constitutes more of a potential health hazard than does the bottom ash, because the fly ash often contains high concentrations of heavy metals such as lead, cadmium, copper, and zinc, as well as small amounts of dioxins and furans. Exposure to toxic metals in fly ash is via inhalation, while exposure toxic metals in bottom ash[7] in primarily through groundwater contaminated by leachate.

The relative environmental impacts of incineration, as compared to other thermal and biological waste to energy conversion technologies, are discussed in more detail in **Section 10**. Environmental impact concerns related to incineration are mentioned herein because these have been a factor in the recent closure of a number of WTE incinerators in the US.

Of the 186 MSW incinerators in 1990, only 89 remained in 2007. Of the 6,200 medical waste incinerators in 1988, only 115 remained in 2003. Permitting and construction of new MSW incinerators in the US today is essentially at a standstill, with some expansion and upgrading of current facilities. One reason for lack of activity has been the increase in the number of large and relatively inexpensive regional landfills. These super facilities, exemplified by the Apex Landfill in Las Vegas, tend to be large in land area, located far from urban areas and are designed, constructed, and operated in accordance with current best practices.

Other reasons for incinerator closures include the relatively low price of electricity in many regions of the US, and changes in regulations and federal tax laws that no longer give incinerator operators the economic incentives they once enjoyed. On a local level in the US, flow control legislation requiring that certain types of MSW be incinerated, regardless of cost relative to landfillibg, has largely been rescinded. Without the economic advantages afforded to incinerators by this legislation, and in view of the changes in applicable US federal tax laws, many incinerators were no longer profitable and were closed.

RDF Burn vs. Mass Burn Incineration

Mass burn incineration is the term used to designate a system wherein solid waste is burned, as received, after removal of hazardous waste, some metals, and items that will not physically pass into the incinerator. This approach requires essentially no labor for sorting and is cost effective when electrical rates are low and volume reduction is a main objective.

Figure 2 is a depiction of an MSW incinerator used for mass burn operation. To generate power, thermal energy from the furnace flue gas would be recovered in by a steam boiler and use to produce steam that would drive a steam turbine generator. The flue gas clean-up train in this mass burn system comprises a dry scrubber and a baghouse. Not shown are the lime injection into the dry scrubber and an ammonia injection system into the boiler to decrease NOx emissions.

RDF burn, as the name implies, refers to the practice of sorting the incoming waste stream by removal of recyclables and hazardous materials and non-combustibles such as metals, glass, rock, concrete, and sheet rock. In RDF facilities, wet and low BTU materials such as green waste are processed separately. With this minimal sorting, the average calorific values of the RDF is still higher and the ash production lower than in mass burn mode, all other factors being equal. At a 3,000 TPD incinerator[8] in South Florida, for example, the average calorific value of the RDF is 6,500 BTU per pound with some seasonal variation in moisture content.

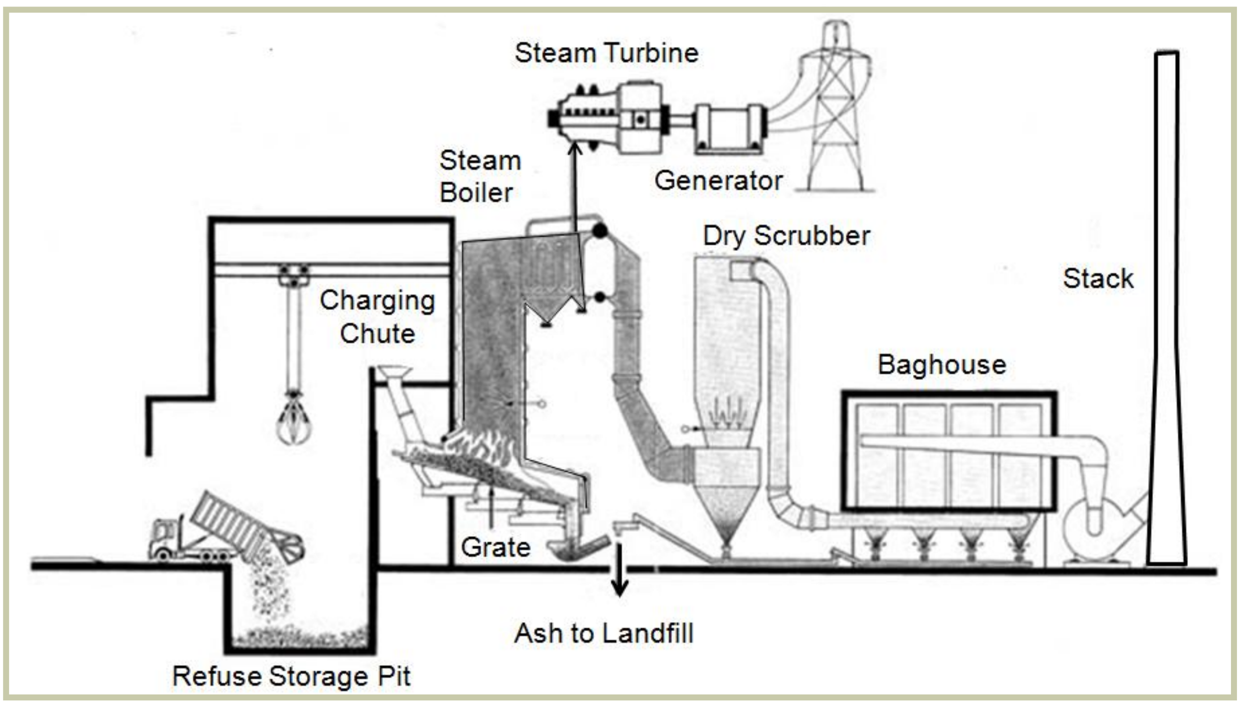


Fig. 2 . Schematic diagram of an MSW incinerator facility showing refuse storage pit, charging chute, furnace, grate, boiler, and turbine generator, with dry scrubber and baghouse in the flue gas clean-up train.

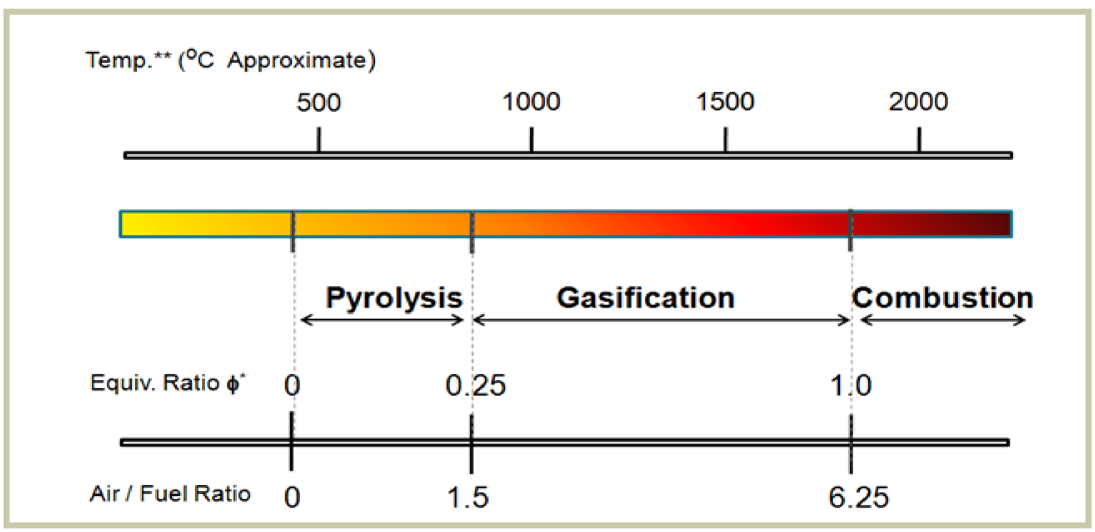
4. Gasification

Gasification is a process wherein organic carbonaceous materials are dissociated at high temperatures in an oxygen-starved thermal reactor to form a gas known as synthesis gas (also designated as syngas, or producer gas)[4]. The syngas is composed of mainly carbon dioxide, carbon monoxide, hydrogen, methane, and water vapor. If the thermal reactor is air fed (as opposed to oxygen fed only), the syngas stream also contains nitrogen gas. This latter form of syngas, which includes di-molecular nitrogen in relatively large quantities, is more correctly referred to as producer gas, but in accordance with common usage, will be referred to as syngas in this document.

Gasification has been used to convert mixed solid waste materials for more than 30 years, and for the purpose of this assessment will be divided into three primary categories:

- Pyrolysis, which is carried out a low to nil oxygen partial pressure operating at temperatures between approximately 600 and 800 °C;
- Air Fed gasification systems, which typically operate at temperatures ranging between approximately 800 and 1,800 °C; and
- Plasma or plasma arc systems, which operate at 2,000 to 2,800 °C with higher local temperatures.

The relative operating temperatures and air supply associated with these three technologies are shown in **Figure 3** below. Plasma arc normally operates at temperatures above 2000^{O}C at low air to fuel ratios.



* Phi is the actual fuel ratio / air to fuel ratio required for complete combustions of: $C_1 H_{1.4}O_{0.}$
** Combustion temperatures shown are adiabatic flame temperatures.

Fig. 3 Relative temperatures and air fuel ratios for pyrolysis, gasification and combustion (plasma arc normally operates above 2,000^{O}C, but at an air fuel equivalence ratio of less than 1).

Air fed gasification technology was originally developed in the early 1800s to produce coal gas, or town gas, which was used for lighting. The coal gas was later used for industrial energy applications and still later for the production of electricity. Gasification of wood or woody biomass was used extensively by Japan and Germany during the Second World War to produce liquid fuels, and gasification of coal in a process known as Fischer Tropsch[9] is still animportant process by which SASOL of South Africa produces liquid fuel as well as some lubricants and waxes.

While gasification processes vary considerably, typical air fed gasifier reactors operate at temperatures between approximately 700° and 1,000° C. The initial step, devolatilization, is similar to the initial step in the pyrolysis reaction (**see Section 7**). Depending on the gasification process, the devolatilization step can take place in a separate reactor upstream of the gasification reaction or simultaneously with the gasification reaction. Because of the higher temperatures involved, thermochemical reactions associated with air fed gasification are more energetic than those associated with pyrolysis. Air fed gasification involves the use of air, oxygen (O_2), and hydrogen (H_2), or steam as reactants.

Chemical reactions involved in gasification vary in rate and relative importance, depending on the process conditions and the gasification agent (air, oxygen, steam, carbon dioxide, or hydrogen). A listing of some of the more important gasification reactions for MSW, and in particular the carbonaceous char that remains after the volatilization step in the process, are shown in equations 1–9 below[4]. The "ΔH°" (delta H degree) or enthalpy of formation numbers are provided for each reaction. Enthalpy of formation is a positive number for reactions requiring heat (endothermic) and is a negative number for reactions that release heat (exothermic).

1. $C + CO_2 = 2CO$ — $\Delta H° = +172$ kJ — Gasification with Carbon Dioxide
2. $C + H_2O\ (g) = CO + H_2$ — $\Delta H° = +130$ kJ — Gasification with Steam
3. $C + 2H_2O\ (g) = CO_2 + 2H_2$ — $\Delta H° = +88$ kJ — Gasification with Steam
4. $C + 2H_2 = CH_4$ — $\Delta H° = -71$ kJ — Gasification with Hydrogen
5. $CO + H_2O\ (g) = CO_2 + H_2$ — $\Delta H° = -42$ kJ — Water Gas Shift Reaction
6. $C + 1/2\ O_2 = CO$ — $\Delta H° = -109$ kJ — Gasification with Oxygen
7. $CO + 3H_2 = CH_4 + H_2O\ (g)$ — $\Delta H° = -205$ kJ — Gasification with Hydrogen
8. $S + H_2 = H_2S$ — $\Delta H° = -21$ kJ — Gasification with Hydrogen
9. $C + O_2 = CO_2$ — $\Delta H° = -390$ kJ — Gasification with Oxygen

Note that, according to equation # 8 fuel bound sulfur is converted to hydrogen sulfide in an exothermic reaction instead of SO_x as in combustion. Likewise, chlorine can be converted to hydrochloric acid ($H + Cl = HCl$). Both hydrogen sulfide and hydrochloric acid are a strongly acidic and react readily with alkaline materials in the acid gas removal units or scrubbers (**See Section 11),** which are very effective in removing acidic compounds from the flue gas stream.

The energy required to drive reactions 1 through 3 is commonly provided through partial oxidation, as shown in equations 6 and 9. The high rates of heat transfer achievable during the partial oxidation process within the gasifier are such that this process is often considered an autothermal method of gasification. Often, between 20 and 30 percent of the feed mass flow is consumed to provide the energy needed to pyrolyze the feed and complete the gasification of the pyrolytic products.

These reactions will not be discussed in further detail, but it is important to note that the range of reactions present provides the opportunity, through additional process controls, to produce products that can be made for specific uses. This carbon monoxide/hydrogen ratio can be varied under different reaction conditions.

While not significant when considering gasification of MSW, the reactions involved in gasification are useful in understanding the distinction between air fed gasification and pyrolysis. Pyrolysis does not have such a reactive step; hence its gaseous yield is produced in a smaller range and typically cannot be used for anything other than direct combustion.

Air fed gasification systems can provide clean, reliable power and while meeting the emission requirements to qualify as a green energy source when fired with properly prepared and formulated renewable fuels[10, 11, 12]. The process by which this standard of operation can be accomplished is comprised of 5 stages, as described below and shown in **Figure 4.**

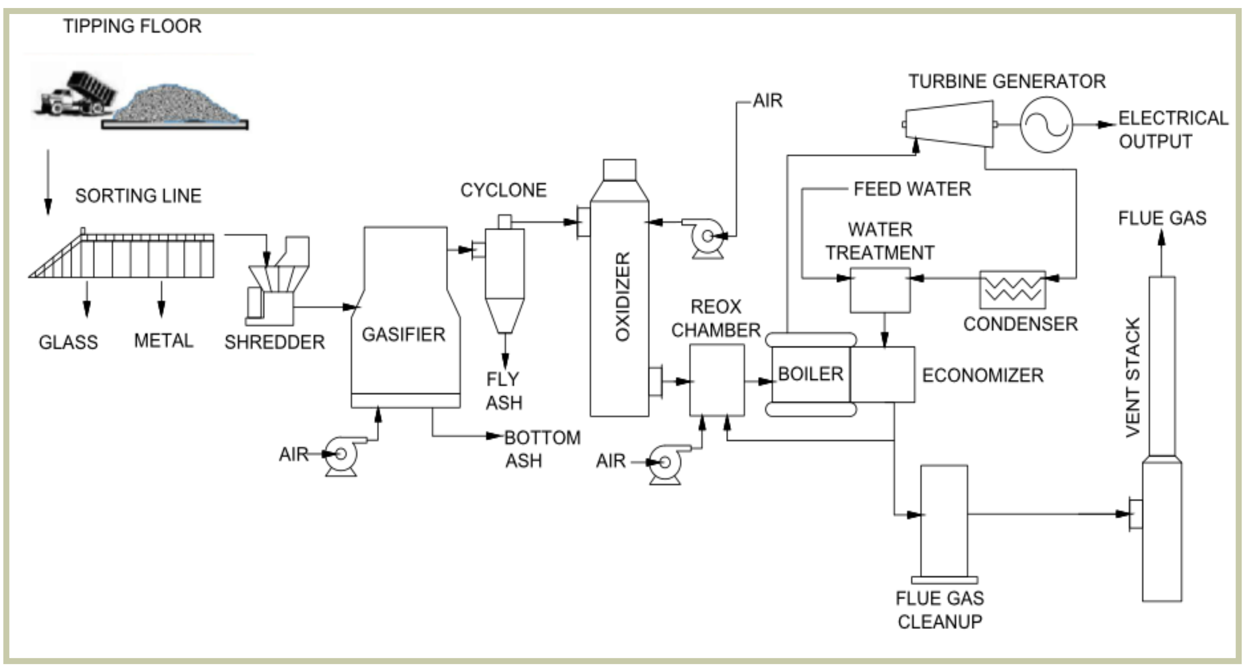


Fig. 4 Process diagram for an air fed RDF gasification power plant using a heat recovery boiler and steam turbine to generate electrical power.

These treatment stages are essential to the efficient and clean operation of any gasification system, and are designed to minimize the quantity of ash generated by the system, minimize the quantity of heavy metals and hazardous constituents in the flue gas, improve the energy efficiency, and provide the highest level of performance and protection for human health and the environment available in the market place. These five treatment stages are summarized as follows:

- Stage 1: Sorting and processing of waste to make into Refuse Derived Fuel;
- Stage 2: Gasification of the Refuse Derived Fuel;
- Stage 3: Combustion of the Syngas in a Heat Recovery Boiler to make steam;
- Stage 4: Production of electricity from one or more Steam Turbine Generators; and
- Stage 5: Treatment of flue gas from the Heat Recovery Boilers.

RDF is introduced into the gasifier by a water-cooled screw conveyor that discharges into the drying and heating zone of the gasifier. The gasification process is controlled by the proportioned application of air in a manner that auto-genetically supports efficient gasification. Residence time in the gasifier is varied by a residence time control system that is adjusted to achieve the desired carbon content of the ash discharged from the gasifier. The use of precise gasification air control and zoning produces a calorific syngas that is directed to the gas combustion assembly. The syngas is continuously evolved from the gasifier at temperatures approaching 1,000 ºC.

Upon exiting the gasifier, the hot gases are first cleansed of entrained ash in a high temperature cyclone. The evolved gases are then oxidized in a series of stages for the proactive control of nitrogen oxides. The staged combustion of synthesis gas takes full advantage of the gasification of the solid feed by converting the fuel bound nitrogen into diatomic nitrogen (atmospheric N_2) instead of oxides of nitrogen (NO_x). It also operates in a starved air mode such that there is always a reducing gas atmosphere preventing NOx formation. The final stage of the combustor system operates with excess air and sufficient residence time such that the temperature is kept at 1800 ^{o}F to simultaneously limit thermal NOx formation and also destroy polycyclic organic compounds such as dioxins, furans and other VOCs.

The reducing gas atmosphere section of the combustion chamber is vertically oriented, constructed of refractory lined carbon steel, designed to resist operating temperatures and mechanically designed to resist wind and earthquake loadings. The final stage in which the lean reducing gas from the vertical combustion stage is combusted to extinction is a horizontal REOX section. The temperature of the combusted synthesis gas at the discharge point from the combustor is limited to about 980 ^{o}C by flue gas recycle from the boiler exit.

Syngas produced by the gasifier and oxidized in the combustion chamber and re-ox units is directed to a water tube type heat recovery boiler, which is equipped with both economizer and superheater sections. Water in the tubes is converted to steam at a pressure and temperature sufficient to drive a high-efficiency steam turbine to generate electricity. Additional recycled flue gas is added at the combustor discharge to further reduce the hot gases to about 760 ºC prior to entry into the heat recovery boiler. This temperature reduction helps to prevent fouling by trace quantities of molten mineral matter condensing on the boiler tubes, and prevents chloride corrosion of the boiler tubes.

The entire gasification process is operated at a slightly negative pressure. The negative pressure is provided by the induced draft (ID) fan. The ID fan is located after the heat recovery boiler and particulate removal system and is sized for the mass flow and static pressures. Negative pressure operation, in addition to superior process control, provides the added safety benefit of preventing leakage of synthesis gas and flue gas. Any leakage of gas is in-leakage of ambient air into the controlled process conditions, and not out-leakage of gases to the uncontrolled atmosphere. Flow through the ID fan is controlled by a signal from the gasifier pressure controller. A dual reactor gasification system of the type described above is shown in **Figure 5** below. The flue gas clean up train for this system is comprised of a baghouse, which provide more than adequate flue gas clean-up.

Fig. 5. Dual reactor air fed gasifier of the general design as that depicted in Fig 4. (From left to right: bucket elevator for RDF feed, gasifier reactor(s), combustion tube, heat recovery boiler, baghouse and stack.)

In addition to the fluidized bed air fed gasifiers described so far, which are generally best used at waste capacities of approximately 200 tons per day or more, another commercially deployed gasifier is the rotary kiln. This type of gasifier, while generally not suited for processing waste than approximately 50 tons of waste or so per day for a single kiln, do have a number of advantages. They can achieve higher operating temperatures and are capable of handling a wide variety of wastes including low BTU materials and wastes with higher inorganic content. Rotary kilns can be deployed as parallel reactor systems such as the one shown in **Figure 6L** below. **Figure 6R** shows a single kiln system installed inside a building.

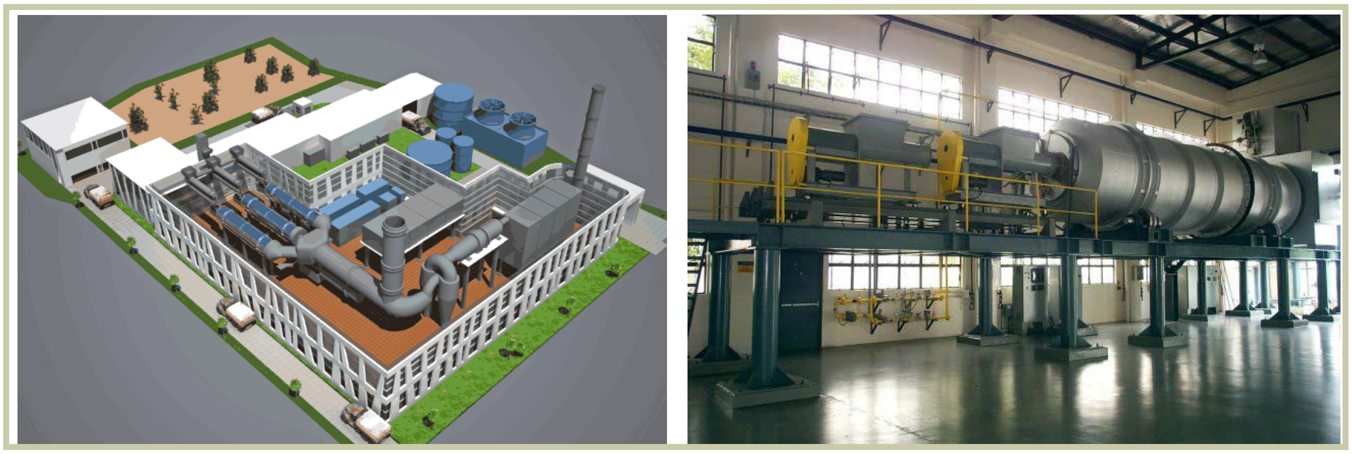


Fig. 6. Left) Three reactor rotary kiln system with waste dryers and a slagging kiln for conversion of high moisture MSW to energy; **Right**) Rotary kiln gasification reactor installation (flue gas clean up systems are exterior to the building).

The rotary kiln system shown in **Figure 6L** above features a waste dryer system that removes moisture from wet organic waste before it enters the kiln. Depending on local requirements, these dryers can use heat recovered from flue gas or steam to remove moisture from the waste. Moisture from the waste can be condensed and recovered for process water or simply vented to the atmosphere.

Small rotary kilns operating at temperatures in the range of 1450 degrees C can be used in series to produce syngas from the fixed carbon remaining in the ash from fluidized bed or larger rotary kiln primary gasifiers that operate at lower temperatures. These smaller units are variously referred to as slagging kilns, carbon burn out units, or simply slaggers. They operate at a sufficiently high temperature so as to melt, or partially melt, the remaining inorganic oxides in the bottom ash to produce an inert slag or vitreous frit.

Gasification systems have also been developed to operate in quasi-mass burn mode, wherein only minimal sorting of the fuel is done prior to firing. Because of less precise fuel formulation, these systems typically produce more solid residual materials, which, as shown in **Figure 7** below, are generally slagged prior to release. Such designs require more expensive flue gas clean-up equipment to achieve regulatory air emission standards and are not as efficient or reliable as a non-slagging air fed systems.

Their advantage is reduced cost due to lack of sorting. In the unit shown in **Figure 7**, the gasifier operates as a fluidized bed with sand as a heat transfer medium. Particles entrained in the syngas from the first reaction chamber are melted in a region of the second combustion chamber and recovered from the process as a vitreous frit. This process employs little or no on-site sorting and simply recovers incombustibles and metals in the form of a slag, mainly from the initial reactor.

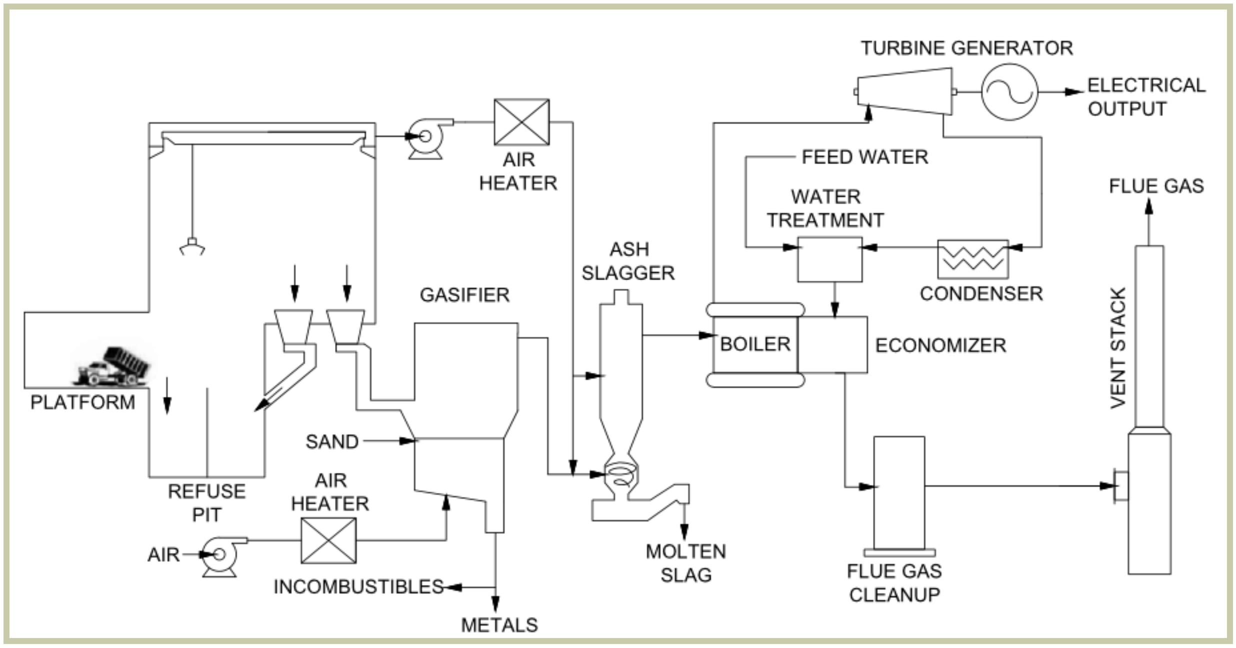


Fig. 7. Fluidized bed two chamber gasification system designed for generating steam for electrical power while performing minimal sorting on the incoming MSW.

In general, the advantages of air fed gasification over other thermal conversion processes include:

- Ability to process a wide variety of gaseous, liquid, and solid state feed stocks;
- SO_x and NO_x are substantially lower in gasification compared to incineration;
- Entrainment of particulates is significantly lower due to much lower gasifier air flow per unit waste processed compared to incineration;
- Hydrocarbon pollutants are either not formed or destroyed in the gas clean-up process, and
- Equipment is robust and reliable

Perhaps most importantly, a number of studies on the issue of thermal waste to energy processes including those done by the US Department of Energy[11], the US Environmental Protection Agency (USEPA) , and Alameda Power & Telecom[10] have concluded that conventional, air fed gasification systems provided the most cost-effective and clean form of waste to energy systems.

The studies further concluded that pyrolysis systems did not provide high enough temperatures to prevent the formation of dioxins, furans, and tars, and that plasma and plasma arc systems were not cost-effective for municipal solid waste.

5. Plasma Arc Gasification

Plasma arc gasification is a waste treatment technology that uses an electric arc to produce high temperatures within the reactor to convert organic fuel material to synthesis gas and melt the residual inorganic materials, which form a vitreous solid upon cooling[13]. The electric arc is maintained between electrodes in a firing device designated as a torch, or in some cases, between the torch electrodes and the walls of the reactor (transfer arc mode).

Plasma arc gasification processes are characterized by:

- High reaction temperatures and energy densities in the reactor (temperatures up to 7,000 °C or more with plasma torches that can generate energy densities up to 100 MW/m^3);

- Capability to safely dispose of hazardous wastes including asbestos, munitions, medical waste, toxic chemical agents, etc.;

- High parasitic power loads required operate the torches;

- Production of inert vitrified solid (after cooling) from inorganic components in the fuel;

- Requirement for a low moisture fuel that is consistent in composition.

In conventional plasma arc gasification reactor designs, the plasma torches are installed a copula and heat incoming waste as shown in **Figure 8**. As in a conventional updraft gasification reactor, the syngas exits the reactor at a point above the fuel bed. Unconverted material exits the process as a molten slag through a port at the bottom of the reactor vessel. In the conventional design the syngas is combusted and the hot gases are directed to a heat recovery boiler to produce steam, which is used to generate electricity.

Plasma arc systems of this type were originally intended for use in mass burn mode after removal of recyclables from the waste stream. Because of the extremely high temperatures achievable in plasma arc, it was believed that little or no waste sorting would be required because all components of the municipal solid waste stream would eventually leave the reactor as gas or as a molten slag,

As has been shown by the operation of small specialty facilities and demonstration MSW plants, the consistency of the waste has a direct impact on performance of a plasma facility. Waste streams that include large amounts of inorganic materials such as poorly sorted construction waste, metals, and glass, result in increased slag production and decreased syngas production. The heat energy that is required to melt these inorganics is lost since the molten slag does not contribute to syngas production. A conventional plasma arc gasifier design is shown in **Figure 8**.

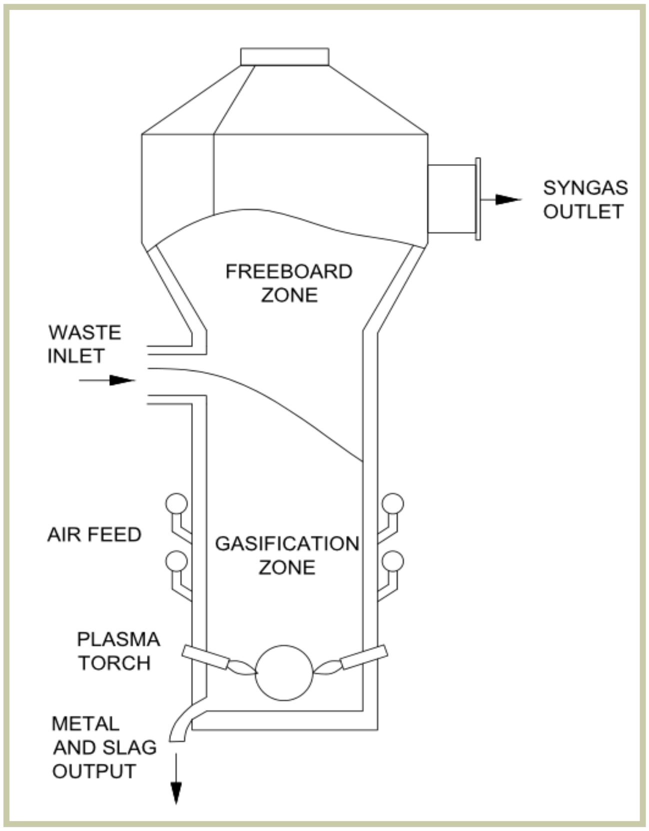


Fig. 8. Plasma arc gasification system.

Most plasma arc facilities in Japan and North America are used for disposal of special industrial waste or hazardous waste. Some of these facilities do provide thermal energy for district heating or generating small amounts of electricity. Due to the high temperatures generated by the plasma arc torches, these plants are used to dispose of such waste as asbestos, munitions, catalytic converters, aluminum dross, and fly ash. These system range in capacity from 1 TPD to 200 TPD, with most in the 10-20 TPD range[14].

These plasma arc disposal facilities described above operate successfully on a single, low moisture feedstock, the composition and characteristics of which are well understood and do not vary over time.

Municipal solid waste, on the other hand, has a high moisture content and is not constant in composition. Attempts to use plasma arc gasification to treat municipal solid waste have not been successful for this and other reasons.

While several commercial scale plants using plasma arc technology for disposal of municipal solid waste have been proposed in the US, none have yet been built. Citizens in Florida, for example, recently rejected proposals for two large commercial scale plants citing environmental concerns and a lack of trust in the technology.

Plasma arc gasification of MSW on a demonstration scale has been carried out. One instructive example is the 90 TPD facility[15] in Ontario, Canada as shown in **Figure 9.** Interestingly, this plant uses a more or less conventional reactor for the initial gasification of the solid waste. Final gasification of the residual char material and vitrification of the bottom ash is carried out by treatments with a plasma torch. Plasma torches are also used to clean the raw syngas as it exits the reactor chamber and enters the cyclone. In the Ontario plant design, the syngas is cooled and used to fire a reciprocating engine powered electrical generator. Heat recovered from the exhaust of the reciprocating engine, combined with that recovered from the cooling of the syngas and can be used to generate low quality steam for district heating or bottom cycle power generation.

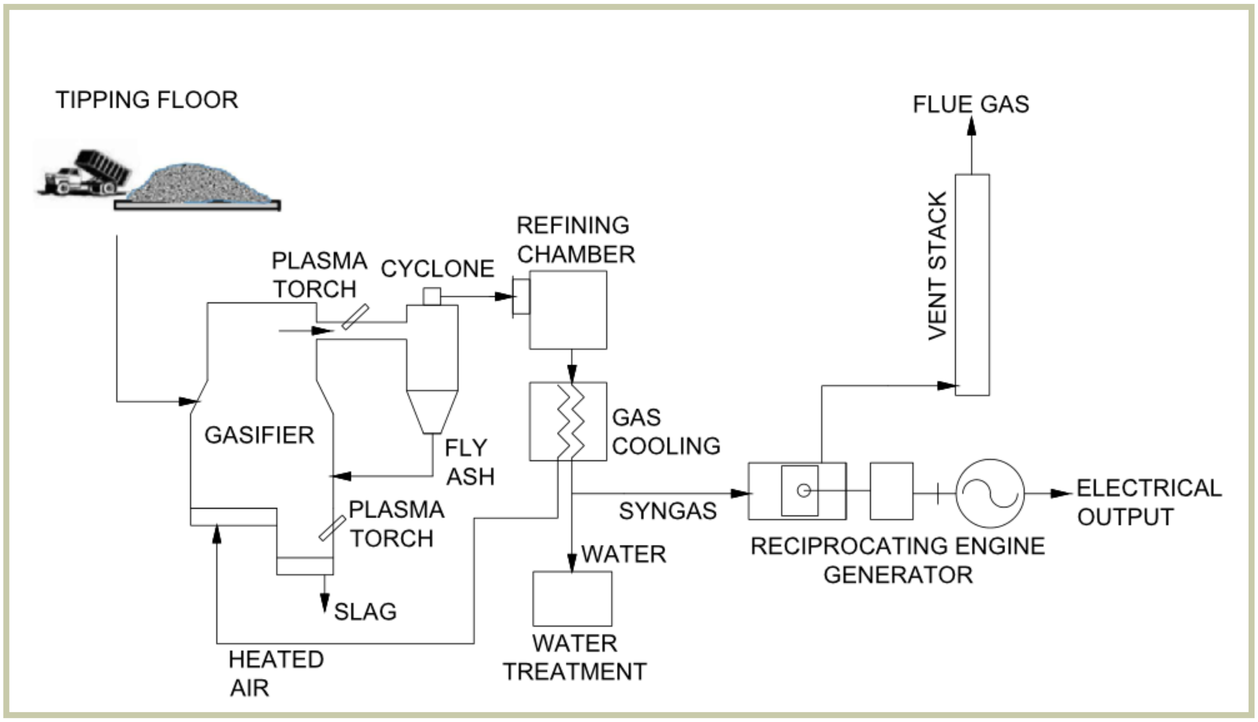


Fig. 9 MSW gasification system employing plasma torches for slagging of the bottom ash and thermal cleaning of the syngas prior to entry into the cyclone and refining chamber.

This particular system experienced a number of operational problems including the requirement to build a waste water treatment plant onsite to treat the condensate recovered from the cooling of the syngas. The overall performance of the facility since put into operation is indicated by the fact that, although rated at 90 TPD, it processed on average less than 10 TPD in its first three years of commercial demonstration.

Because of the high temperatures involved in plasma arc gasification, the stability and service life of the refractory linings in the reactor have been a problem in some designs. Variability in temperatures leading to thermal shock and attack of the liner material by highly reactive hot chlorine gas evolved from poorly sorted solid waste can severely reduce refractory life. Another issue in the reliability and availability of some plasma arc system designs is the need to periodically change out expensive plasma torches or torch components due to discharge ablation of electrodes during operation. Plasma torch assemblies can cost up to $50,000 or more. In some systems, the service life of these torches is on the order of 30 days between major component replacement.

Several independent consulting groups that have evaluated plasma arc gasification proposed for MSW treatment have recommended against this technology, mainly on economic grounds [14, 16].

6. Pyrolysis

Pyrolysis is thermal decomposition occurring in the absence of oxygen. It is also the first step in combustion and gasification processes where it is followed by total or partial oxidation of the heated material [17]. In pyrolysis, lower process temperatures and longer vapor residence times favor the production of charcoal. High temperature and longer residence time increase the biomass conversion to gas and moderate temperature and short vapor residence time are optimum for producing liquids. **Table 1** indicates the product distribution obtained from different pyrolysis conditions of temperature and residence time.

Table 1. Liquid, char and gas production s a function of pyrolysis temperature and residence time [17] .

Process	Conditions	Liquid	Char	Gas
Fast Pyrolysis	Moderate temperature, short residence time, especially for the vapor	**75%**	**12%**	**13%**
Carbonization	Low temperature, very long residence time	**30%**	**35%**	**35%**
Gasification	High Temperature, long residence times	**5%**	**10%**	**85%**

Pyrolysis of biomass or dried combustible components of MSW is carried out in a low or nil oxygen environment at relatively low temperatures (approximately 400 to 800 °F), depending on the fuel material. The pyrolysis of wood, a common feed stock for this process, for example, starts at 390–570 °F (200–300 °C). At these reaction temperatures, the thermal energy available is not sufficient to completely break down the constituents to carbon monoxide and hydrogen fuel gas. Upon cooling, much of the material that leaves the reactor in the gas phase condenses to form a liquid. Lighter gas phase components that do not re-condense such as H_2, CO, CH_4 and C_2H_5 are combusted to provide heat to the main reaction chamber. At pyrolysis temperatures much of the carbon in the fuel does not react and leaves the process as a char material.

As shown in **Table 1**, a variant known as fast pyrolysis is a thermal decomposition process that occurs at moderate temperatures with a high heat transfer rate to the biomass particles and a short hot vapor residence time in the reaction zone. Several reactor configurations have been used to accomplish fast pyrolysis, which can yield of liquid product with efficiency as high as 75 percent based on the mass of liquid fuel compared to the mass of the fuel material (dry weight). Fast pyrolyis reactor types include bubbling fluid beds, circulating and transported beds, and cyclonic reactors.

In the fast pyrolysis process[17, 18], up to 75 wt. percent pyrolysis oil and only 25 wt. percent char and gas are produced as primary products. Since no "inert" carrier gas is used the pyrolysis products are undiluted. This undiluted and hence small vapor flow requires less fuel gas and flue gas cleaning equipment. As shown in **Figure 9**, the vapor from the reaction chamber is rapidly cooled yielding the oil product and the fuel gas that is used to heat the main reactor. Elemental composition and physical characteristics of an oil recovered from fast pyrolysis of wood is shown below in **Table 2.**

Table 2. Characteristics of pyrolysis oil derived from wood.

Elemental Composition	$C_2 H_5 O_2$
Density	1,150 - 1,250 kg/m^3
Higher Heating Value	17-20 GJ/m^3
Water Content	15-30wt.%
Viscosity	25-1000 cP
pH	2.5 - 3
Ash Content	< 0.1%

Fast pyrolysis technologies reached near-commercial status in the last decade of the 20th century. Several circulating fluidized bed plants were built, with the largest having a nominal capacity of 50 TPD. A 12 TPD fast pyrolysis pilot plant is in operation in Finland and a bubbling fluidized bed process operating at 10 TPD and a rotary cone reactor system capable of treating 5 TPD have been built and are operational.

The latter fast pyrolysis technology uses sand as a heat transfer medium. Charcoal and sand are recycled to a combustor, where charcoal is burned to reheat the sand. The fuel gases can be used in a gas engine to generate electricity or simply flared off. Normally, no external utilities are required for this process when used with biomass such as wood. Properties of the liquid product vary widely depending on the feedstock, the process type and conditions, and the product collection efficiency. While the yields from these fast pyrolysis demonstration plants vary, none have reached commercial scale for the conversion of MSW.

A wide variety of different waste and biomass feedstocks can be converted by pyrolysis processes. Solid fuel must be shredded or otherwise sized to less than approximately 6 - 10 mm before being introduced into the pyrolysis reactor. For fast pyrolysis fuel moisture content below 10 wt. percent is required. Pyrolyis produces sufficient excess heat to dry common fuels such as biomass must be reduced to 10 percent moisture or below. However for the wide variety of components and moisture content found in MSW-derived waste streams, reduction of moisture content of hundreds of tons per day on MSW to below 10% has proven impractical. As received MSW can have moisture content of between 40% and 50%. This means that, for a small 300 TPD commercial plant, more than 150 tons of water per day would have to be removed from the fuel stream. This is one of the reasons that fast pyrolysis plants for the conversion of MSW have not been successfully scaled to more than about 50 TPD.

A general process schematic for a pyrolysis unit is shown in **Figure 10** below, in which char particles are entrained in the off gas flow and are collected in the cyclone while the gas continues on to be rapidly cooled to recover a fuel oil. Permanent gases can be recycled to the reactor.

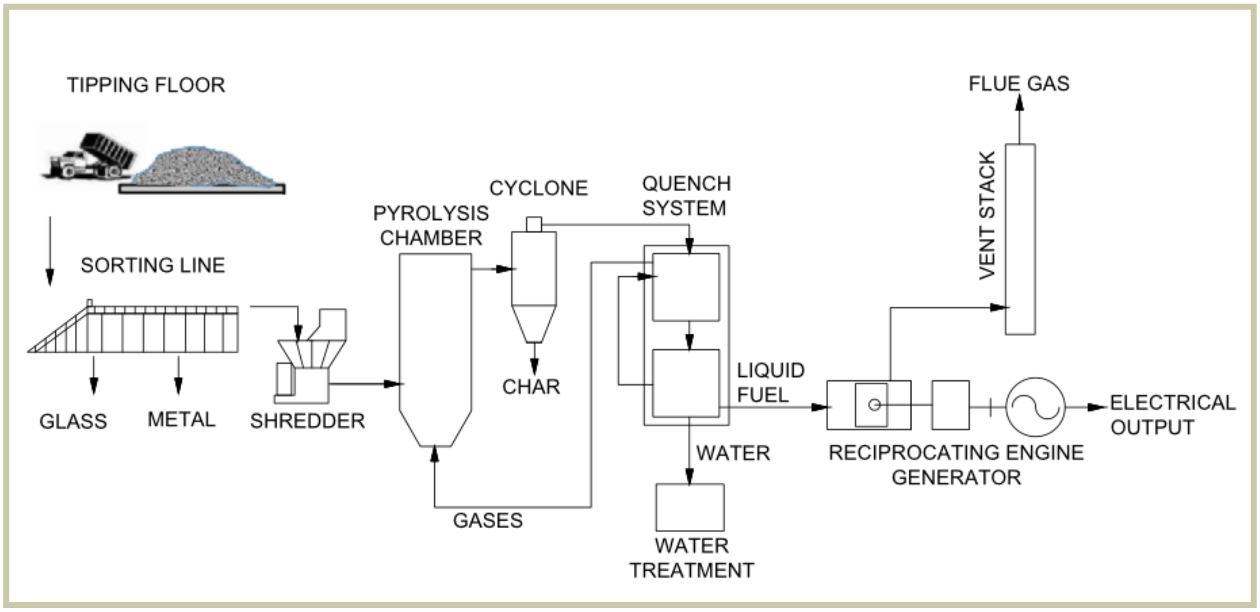


Fig. 10. Process diagram for a fast pyrolysis system in which the char is entrained in the flow from the first reactor and recovered from the second chamber. A reciprocating engine powered generator is fired by liquid fuel recovered from the cooled gas.

While pyrolysis of biomass continues to be developed on a relatively small scale, no commercial plants for the pyrolysis of MSW are operating in the United States today. Attempts to apply these technologies to MSW were made in the 1970s, but the plants failed to achieve acceptable technical or economic performance, and all have been shut down.

Authors of a recent technology review of the economic viability of pyrolysis processes in general[19] concluded that large scale pyrolysis processes still faced daunting problems, not the least of which was the refining of the various pyrolysis bio-oils for commercial use. Among the outstanding issues regarding pyrolysis of biomass, they noted the following:

- No universally accepted specification or standards for bio oil;
- Insufficient studies on the biological and environmental effects of large scale bio-oil production by pyrolysis;
- Lack of sufficient supplies of bio-oil for the required long term testing to determine effects of use in burners and prime movers;
- Strong potential for lack of public acceptance of bio-oils, which have distinct, strong odors.

7. Anaerobic Digestion

Anaerobic digestion is a biological process wherein microorganisms break down biodegradable organic material in an oxygen poor environment [20]. Anaerobic digestion can be used to reduce moisture content in organic waste and to convert a portion of the organic waste into a digester gas comprised mainly of methane and carbon dioxide. The nutrient-rich digestate also produced can be used as fertilizer. The anaerobic digestion of organic material is accomplished by a consortium of microorganisms working synergistically. Digestion occurs in a four-step process: hydrolysis, acidogenesis, acetogenesis, and methanogenesis as shown in **Figure 11** below [22].

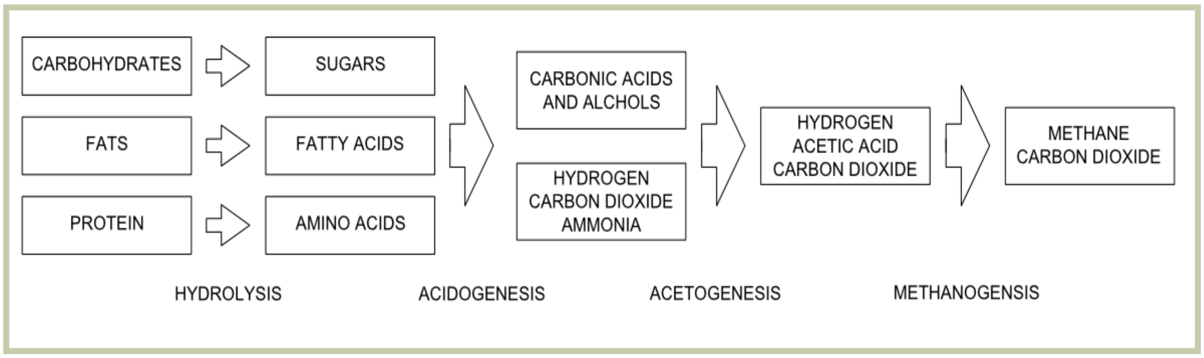


Fig. 11. Scheme for the production of methane from various wet organic components of MSW.

Given the assumption that the feedstocks to biological processes are primarily biogenic and consist of protein, fats, and carbohydrates, including plant derived organics such as cellulose, lignin and associated polysaccharides, the anaerobic methanization process shown in **Figure 11** proceeds as follows:

1. Large protein macromolecules, fats and carbohydrate polymers (such as cellulose and starch) are broken down through hydrolysis to amino acids, long-chain fatty acids, and sugars.
2. These products are then fermented during acidogenesis to form three, four, and five-carbon volatile fatty acids, such as lactic, butyric, propionic, and valeric acid.
3. In acetogenesis, bacteria consume these fermentation products and generate acetic acid, carbon dioxide, and hydrogen.
4. Finally, methanogenic organisms consume the acetate, hydrogen, and some of the carbon dioxide to produce methane. Three biochemical pathways are used by methanogens to produce methane gas. The pathways along with the stoichiometries of the overall chemical reactions are:
    a. Acetotrophic methanogenesis: $4\ CH_3COOH \rightarrow 4\ CO_2 + 4\ CH_4$
    b. Hydrogenotrophic methanogenesis: $CO_2 + 4\ H_2 \rightarrow CH_4 + 2\ H_2O$
    c. Methylotrophic methanogenesis: $4\ CH_3OH + 6\ H_2 \rightarrow 3\ CH_4 + 2\ H_2O$

Anaerobic digestion is best suited to the treatment of wet organic feed stocks such as high moisture agricultural biomass, food waste, and animal wastes including manure and domestic sewage. A prepared feedstock stream with less than 15 percent TS is considered wet and feedstocks with TS greater than 15-20 percent are considered dry (although there is no established standard for the cutoff point). Feedstock is typically diluted with process water to achieve the desirable solids content during the preparation stages. Biological processes are best applied to the disposal of municipal solid waste in concert with a thermal process in a scheme wherein the high moisture organic components are treated biologically while the dry high BTU components are converted thermally.

Single-stage digesters are simple to design, build, and operate and are generally less expensive. The organic loading rate of single-stage digesters is limited by the ability of methanogenic organisms to tolerate the sudden decline in pH that results from rapid acid production during hydrolysis. Two-stage digesters separate the initial hydrolysis and acid-producing fermentation from methanogenesis, which allows for higher loading rates but requires additional reactors and handling systems. In Europe, about 90 percent of the installed anaerobic digestion capacity is from single-stage systems and about 10 percent is from two-stage systems (see **Figure 12**).

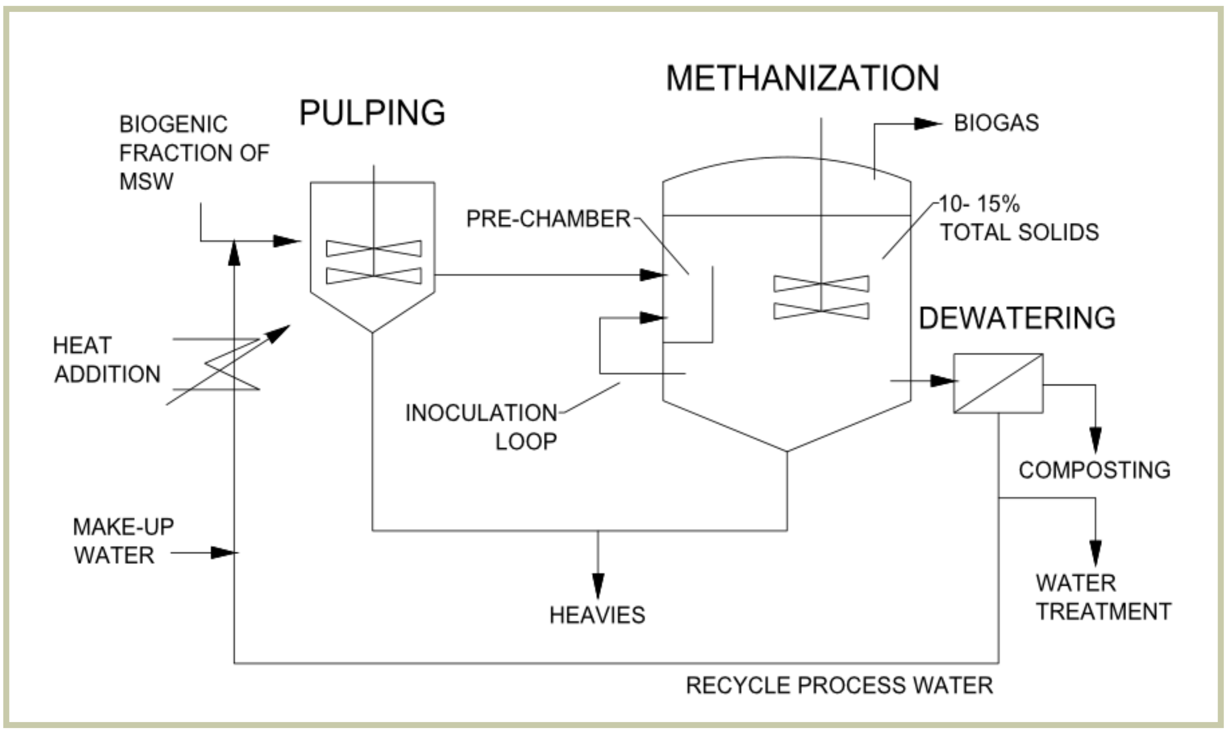


Fig. 12. Process diagram for a wet single stage anaerobic digester.

A number of factors affect biogas production efficiency including pH, temperature, inhibitory factors such as high organic loading, formation of volatile fatty acids, inadequate alkalinity, etc. Volatile solids input, digester temperature and retention time are also operational parameter that have a strong effect on digester performance. MSW tends to contain relatively larger amounts of materials that are toxic and inhibitory to the multi-step methanogenesis process. As in other conversion processes, this issue can be addressed by careful sorting of the MSW waste stream prior to treatment.

It is used as part of the process to treat biodegradable waste and sewage sludge. As part of an integrated waste management system, anaerobic digestion reduces the emission of landfill gas into the atmosphere.

Another important design parameter is the total solids concentration in the reactor, expressed as a fraction of the wet mass of the prepared feedstock. The remainder of the wet mass is water by definition. The classification scheme for solids content is usually described as being either high-solids or low-solids.

Before anaerobic digestion became an accepted technology for treating MSW, single-stage wet digesters, such as the one depicted above, were used for treating agricultural and municipal wastewater. However, MSW slurry behaves differently than wastewater sludge. Because of the heterogeneous nature of MSW, the slurry tends to separate and form a scum layer which prevents the bacteria from degrading these organics. The scum layer tends to evade the pump outlets and can clog pumps and pipes when it is removed from the reactors. To prevent this, pretreatment to remove inert solids and homogenize the waste is required. Solids can also short circuit to the effluent pipe before they have broken down completely, therefore design modifications were made to allow longer contact time between bacteria and dense, recalcitrant material.

The technical expertise required to maintain industrial-scale anaerobic digesters, coupled with high capital costs and low process efficiencies, has so far been a limiting factor in its deployment as a waste treatment technology.

Anaerobic digestion has been proposed for the conversion of biodegradable components of MSW [22]. Nonetheless, while anaerobic digestion has long been used in the US for treating agricultural waste and municipal wastewater with anaerobic digestion, no commercial scale facilities for digesters for the wet organic fraction of municipal solid waste were operating in the US as of 2008 [23] .

8. Aerobic Digestion and Composting

Aerobic digestion involves the breakdown of biogenic organic materials by aerobic microorganisms in the presence of sufficient oxygen to support reaction rates required to reach temperatures sufficient to kill pathogens, reduce moisture content, and produce a type of compost material. Composting is defined by Haug [21] as “the biological decomposition and stabilization of organic substrates, under conditions that allow development of thermophilic temperatures as a result of biologically produced heat, to produce a final product that is stable, free of pathogens and plant seeds, and can be beneficially applied to land.”

Composting is a waste stabilization process that requires specific moisture and temperature conditions. Pathogen inactivation and seed destruction occur when temperatures are maintained above about 45°C for a minimum of 21 days. The primary objectives of composting are:

- biologically convert putrescible organic wastes into a stabilized form;
- destroy or inactivate pathogens harmful to humans;
- destroy plant diseases, weed seeds, insects, and insect eggs;
- produce an organic compost that is a good fertilizer and soil amendment; and
- reduce the potential for malodors.

The desired result of the composting process is the production of high quality compost, where compost is defined as “an organic soil conditioner that has been stabilized to a humus-like product, that is free of viable human and plant pathogens and plant seeds, that does not attract insects or vectors, that can be handled and stored without nuisance, and that is beneficial to the growth of plants.”

There are many different technologies that can be used to produce compost. The quality of the compost produced by any technology depends primarily on the properties of the organic feedstock, the quantities of impurities, the moisture content, the oxygen content, and the carbon to nitrogen ratio. Both aerobic and anaerobic processes can be involved in the overall composting process.

As best practiced for waste to energy conversion, aerobic digestion can be used as a means of economically reducing the moisture content of wet biogenic organic materials including green waste and food waste.

9. Combined Thermal and Biological Treatment Technologies for Comprehensive Municipal Solid Waste Disposal

Biological waste treatment processes can be used in concert with thermal processes and landfill to provide a environmentally responsible and more sustainable solution to the efficient energy conversion and safe disposal of all MSW components.

To the extent that anaerobic processes proceed in landfills, incineration has been used with anaerobic digestion to dispose of solid waste streams. Many incinerators located on or near landfill property also pipe the methane gas produced by the landfill for use in firing small gas turbines or reciprocating engines for the generation of electricity.

Fig. 13. Indoor aerobic digestion facility.

Both "wet" and "dry" anaerobic digesters are being designed and built to recover energy from biogenic wet waste in the form of methane rich digester gas. These digesters are relatively expensive and inefficient when compared to an alternative process of aerobic digestion or partial composting of the food waste and green waste. In the latter process, the biogenic waste is dispersed in cribs in an indoor facility as described above and allowed to go through the fermentation stage of the composting process.

During this stage in the process, normally carried out inside a facility such as depicted in **Figure 12**, the bulk materials are turned on a near daily basis to ensure even drying and the availability of oxygen to promote the autothermal processes of the anaerobic bacteria breaking down the substrate materials. As with anaerobic digestion, important metabolic products of this bacterial action include acetates and propionates. Because of the availability of atmospheric oxygen, methane is not produced by aerobic digestion.

This indoor process naturally reduces the moisture content of the waste materials by as much as 80%, and renders them suitable for inclusion in the fuel mixture for an air fed gasifier. Thus aerobic digestion coupled with air fed gasification and landfill of the gasifier bottom ash is an optimal and cost effective approach to the safe, efficient, and environmentally responsible energy conversion and disposal of all of the components of the MSW waste streams.

10. Characteristics and Calorific Values of Solid Waste Materials

Municipal Solid waste represents a variety of waste streams containing multiple components, each with different value as a fuel. Selection of the most suitable waste to energy conversion technology depends largely on the characteristics and quantity of readily available waste materials. Components of solid waste streams vary by region and local economics, populations and environmental factors, as does the designation or classification of these streams. One such classification is shown in **Table 3** below, along with the moisture content and average heating value of the various classifications of waste. An exhaustive list of various MSW components and their calorific values can be found in Reference UFC 3-240-05A[24].

Table 3. General classification of solid waste streams with approximate calorific values for each[24].

Waste Classification	Principal Components	Average Moisture (%)	Inorganic Ash (%)	As-Fired Heating Value (BTU/lb)	Avg. Density (lb/cu. ft.)
Trash	Paper, plastic, cardboard rubber	10%	5%	8,500	8-10
Rubbish	Paper cartons, rags, floor sweepings	25%	10	6,500	8-10
Refuse	Residential Rubbish and Garbage	50%	7%	4,300	15-20
Garbage	Food waste (animal and vegetable)	70%	5%	2,500	30 - 35
Animal Solids and Organic Waste	Carcasses organs hospital waste,	85%	5%	1,000	45- 55

While mass burn without much regard for fuel content is still practiced in the incineration of solid waste, proper waste sorting and fuel component selection and blending is critical to the efficient operation of gasifiers, pyrolysis systems and biological conversion technologies. From a refuse derived fuel design standpoint, it is useful to consider available waste streams according to their source. In urban areas, available solid waste stream designations may include relatively dry and high BTU waste streams such as:

- Source Separated Commercial Waste (plastic packaging materials light wood paper);
- Light Construction and Demolition Waste (wood, plastic, cardboard, carpet, roofing);
- Used Tires (de-beaded tires: removal of the steel beads increases the avg. calorific value;
- High BTU Industrial Wastes (auto fluff, carpet scraps, waste oils and lubricants, etc.);
- Residential MSW that has been sorted in a materials recovery facility to remove hazardous wastes, recyclables, non-combustibles and putrecible materials.

Low BTU, high moisture content wastes that are best suited for biological treatment, or biological pre-treatment, include food waste, green waste, and sewage sludge.

In comparing waste derived fuels, the designation of Higher Heating Value, or HHV, refers to the calorific value of the waste material on a moisture and ash free basis. Lower heating value, or LHV, refers to the calorific value of the waste or fuel material as normally received, or as-fired if no drying or sorting is carried out. **Table 4** below shows the bulk elemental composition of MSW streams collected in two US cities as well as the Higher Heating Value (HHV) for these bulk waste streams. Elemental analysis data such as this helps to predict the energy that will be available from given waste stream components and is very useful in the design of waste to energy conversion facilities.

Table 4. Elemental analysis of residential commercial and mixed waste streams from two cities.

	Portland, OR			Broward Co. FL
Analysis	**Residential**	**Commercial**	**Mixed**	**Mixed**
Carbon	29.5%	40%	34.7%	41%
Hydrogen	6.7%	6.5	6.6	5.8
Oxygen	28	31	29.9	21.6
Sulfur	1.3	2.5	1.86	0.09
Chlorine	0.19	0.31	0.25	0.41
Nitrogen	1.5	0.5	1.0	.50
Moisture	25	11.24	19	24.58
Ash	6.1	7.5	6.8	6/07
HHV As Received	6,280	7,110	6,690	6,760
HHV Dry	9,940	8,050	9,000	8,960
HHV MAF	10,640	8,720	9,860	10,290

Higher heating values are shown for the various waste components as is their percent composition of the as-fired waste material. For calorific value calculations purposes, the bulk elemental composition for this RDF blend is $C_{1.000}$ $H_{1.514}$ $O_{0.380}$. As can be seen, the MAF heating value of the blended RDF material, including approximately 3% sewage sludge, is 10,500 BTU/lb at an overall moisture content of 20 percent.

Table 5. Components of an RDF mix for an air fed gasifier

Waste Material	**Blended Fuel Composition in RDF**	**HHV of Waste (BTU/lb)**	**HHV of RDF (BTU/lb)**
Wood	0.3258	5,000.0	1,629.2
Paper and Cardboard	0.0170	7,712.0	130.8
Plastics	0.3469	15,161.0	5,259.3
Sewage Sludge	0.0286	5,000.0	142.9
Waste Tires	0.0569	17,178.0	977.1
Ash	0.0215	0.0	0.0
Water	0.2034	0.0	0.0
Total for RDF	**1.0000**		**8,139**
MAF HHV (Estimate)			10,500

High BTU fuels such as tire shreds, as shown below in **Figure 14** can be use as a "trimming fuel" with more or less being blended into the fuel stream to help hold the blended fuel calorific value constant. This RDF is comprised mainly of source separated commercial waste, light construction and demolition waste and used tires, with a small amount of sewage sludge added for moisture and because the tipping fee for this material makes it economical to process in a gasifier. **Table 5** below shows the composition of an RDF designed and blended for an air fed gasifier.

Fig. 14 (a, b, c, d, e, f, g) Various components of RDF for an air fed gasifier

11. Process Environmental Impact: Comparison of Gas Phase and Solid Phase Emissions

Environmental impact is an important criteria in the assessment of waste to energy conversion technologies, which should be compared not only to burning fossil fuel, but also to the alternative of landfill for the disposal of municipal solid waste.

Gas Phase Emissions: Carbon dioxide, sulfur dioxide, nitrogen oxides, and mercury compounds are among the regulated emissions that are released into the environment from the mining and burning of coal. The average emission rates in the United States from coal-fired generation are: 2,249 lbs/MWh of carbon dioxide, 13 lbs/MWh of sulfur dioxide, and 6 lbs/MWh of nitrogen oxides.

Mining, cleaning, and transporting coal to the power plant generate additional emissions. For example, methane, a potent greenhouse gas that is trapped in the coal, is often vented during these processes to increase safety.

The average air emission rates in the United States from municipal solid waste-fired generation are: 2988 lbs/MWh of carbon dioxide, (it is estimated that the fossil fuel-derived portion of carbon dioxide emissions represent approximately one-third of the total carbon dioxide emissions) 0.8 lbs/MWh of sulfur dioxide, and 5.4 lbs/MWh of nitrogen oxides.

Incineration of municipal solid waste, especially in mass burn mode, generates many of the same regulated constituents as combustion of coal[2, 26], including carbon dioxide, sulfur and nitrogen oxides, hydrochloric acid and to a much lesser extent than coal, toxic metals such as mercury. In addition, any chlorine in the fuel is more likely to form chlorinated polycyclic compounds such as dioxins in the oxidizing environment of the incinerator than in the reducing environment of a gasifier.

The most prevalent processes for MSW applications utilize post-combustion of gaseous and solid products on-site for heat and/or electricity production. Post-combustion processes associated with gasification technologies still differ dramatically from incineration in several key respects:

- The volume of output gases from a gasifcation or pyrolysis reactor is much smaller per ton of feedstock processed than an equivalent incineration process. While these output gases may be eventually combusted, the alternative processes provide an intermediate step where gas cleanup can occur. Mass burn incineration is limited by application of air pollution control equipment to the fully combusted exhaust only.

• Output gases from pyrolysis reactors or gasifiers are typically in a reducing environment, and can be treated with different technologies compared with a fully combusted (oxidative) exhaust. Reactant media can also be hydrogen or steam.

• Gasification and pyrolysis produce intermediate synthesis gases composed of lower molecular weight species such as natural gas, which are cleaner to combust than raw MSW

• Pyrolysis and gasification processes use very little air/oxygen or none at all. These factors make control of air emissions less costly and less complex than that required for incineration.

Particulate Emissions: In addition to these gas phase emissions, particulates from MSW incineration are also of concern[25]. Smoke and fly ash are fine airborne particles that can be hazardous to human health when inhaled, and deposited in the lungs. To reduce particulate and gas phase pollutant emissions, coal and MSW fired power plants can be fitted with a variety of process units to clean the flue gas stream before it is released from the stacks.

As shown in **Figure 15**, these devices include cyclones, scrubbers, fabric filters (bag houses) and electrostatic precipitators. These same devices can be used to clean the flue gas from thermal treatment of municipal solid waste. The basic design and operating principals of each of these devices is shown below.

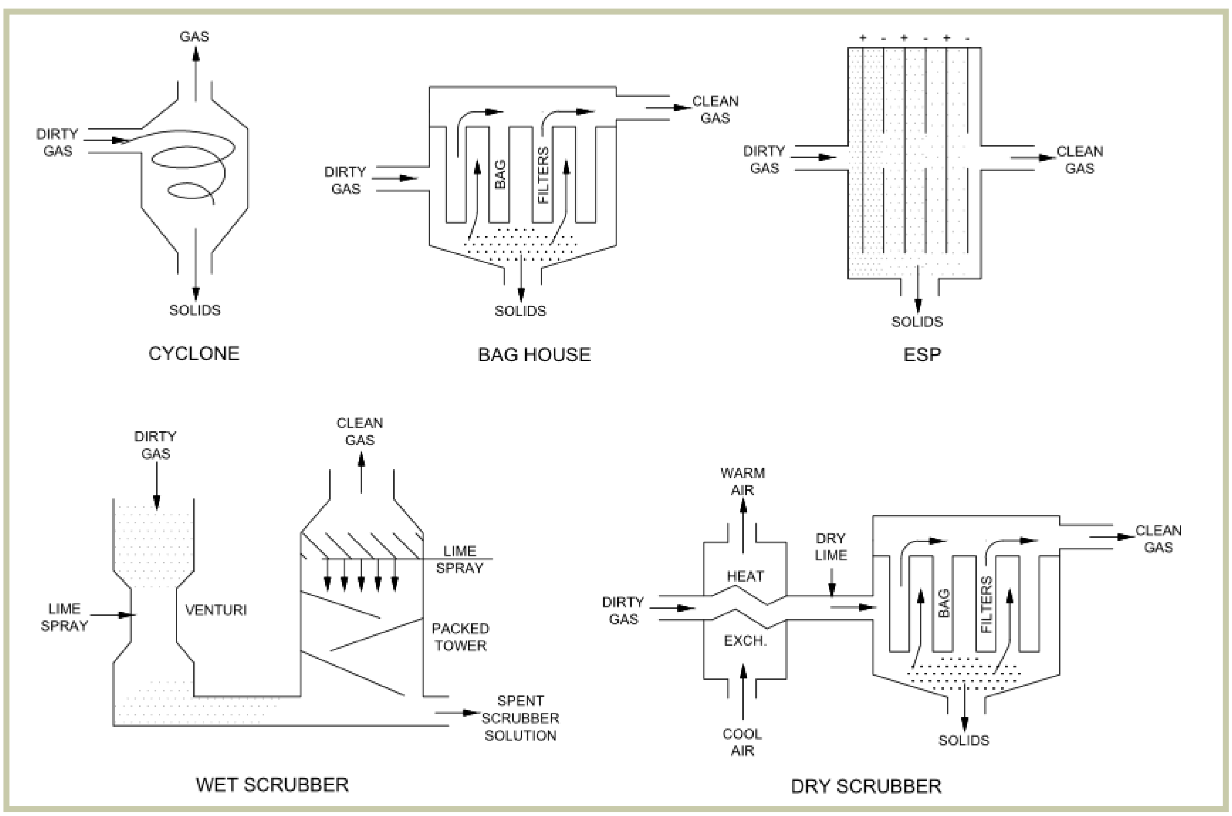


Fig. 15 Devices for removal of particulates, acids, and organics from a flue gas streams.

Incineration of municipal solid waste as a source of energy has been opposed in many locations due to the level of pollutants created during the combustion process and emitted into the environment. Despite recent strengthening of emission standards for MSW incinerators, the process creates significant emissions, including trace amounts of hazardous air pollutants.

Incineration has a number of outputs such as the ash and the emission to the atmosphere of flue gas. Before the flue gas cleaning system, the flue gases may contain significant amounts of particulate matter, heavy metals, dioxins, furans, sulfur dioxide, and hydrochloric acid. The most publicized concerns from environmentalists about the incineration of municipal solid wastes (MSW) involve the fear that it produces significant amounts of dioxin and furan emissions.[15] Dioxins and furans are considered by many to be serious health hazards. According to the United States Environmental Protection Agency, incineration plants are no longer significant sources of dioxins and furans. In 1987, before the governmental regulations required the use of emission controls, there was a total of 10,000 grams (350 oz) of dioxin emissions from US incinerators. Today, the total emissions from the 87 plants are 10 grams (0.35 oz) annually, a reduction of 99.9 %.

Figure 16 below compares the collection efficiency of the devices depicted as a function of particle size. As can be seen, high efficiency electrostatic precipitators can be a powerful addition to a flue gas clean up train.

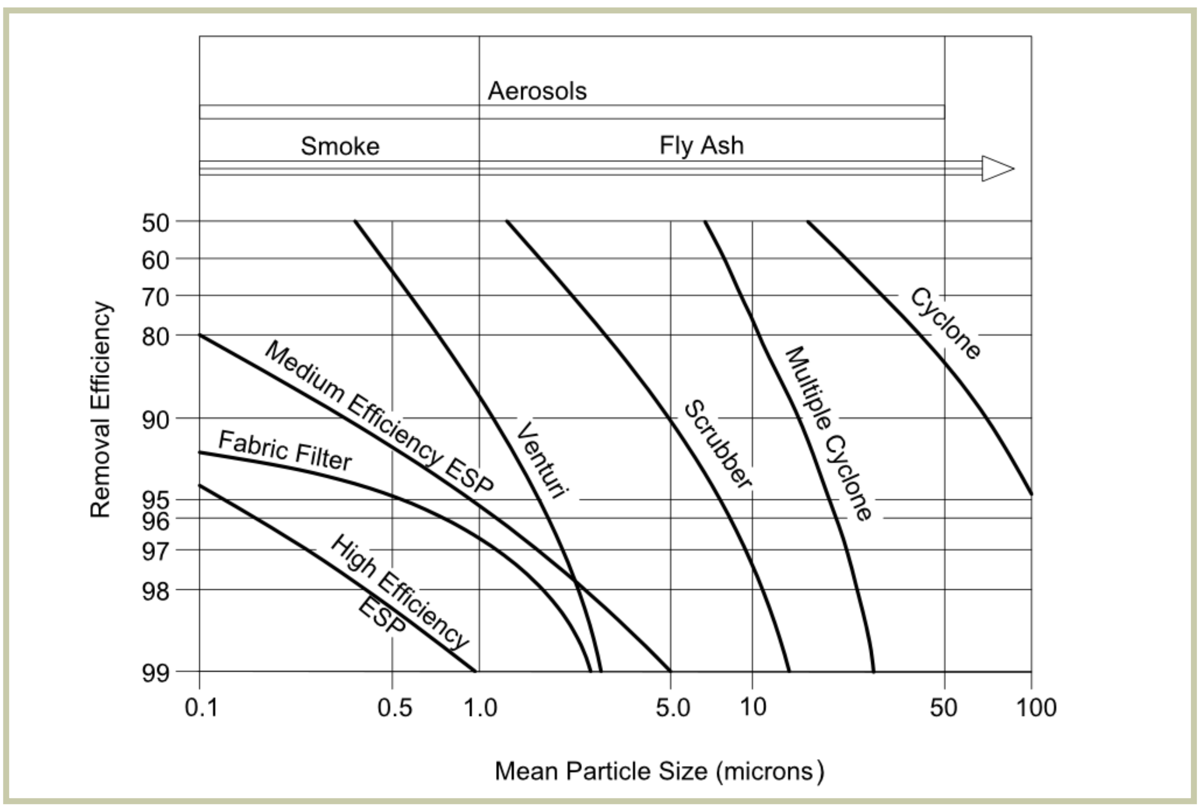


Fig. 16. Particulate removal efficiency of various flue gas cleaning devices as a function of particle size.

12. Environmental Impact of Thermal Disposal Technologies Compared to Landfill

Several studies have shown that air fed gasification of municipal solid waste produces less greenhouse gas as measured by carbon dioxide equivalents than either incineration or landfill. As shown in **Figure 17**, this comparative advantage of gasification is maintained when compared to landfills with gas capture systems, with gasification producing only about 1 kg of CO_2 equivalent per kWh of generated power, while landfill produces approximately 2.75 kg/kWh and incineration releases approximately 1.6 kg/kWh of power generated.

Gasification of MSW also releases substantially lower amounts of sulfur and nitrogen oxide criteria pollutants into the atmosphere from conversion of solid waste than does incineration or landfill. According to the studies cited, incineration releases more than 192 grams of NOx and more than 94 grams of SO_2 for every ton of waste burned. Landfill releases 68 and 53 grams per ton respectively, while gasification releases only 31 grams of NOx and 9 grams of SO_2 per ton of waste converted.

In terms of particulate matter, incineration emits about 17 grams per ton of waste burned, while landfill releases just over 5 grams per ton stored, and gasification releases just over 6 grams per ton converted. As indicated in the previous section, inclusion of an electrostatic precipitator in the flue gas clean-up system would reduce the amount of these criteria pollutants released for both gasifiers and incinerators.

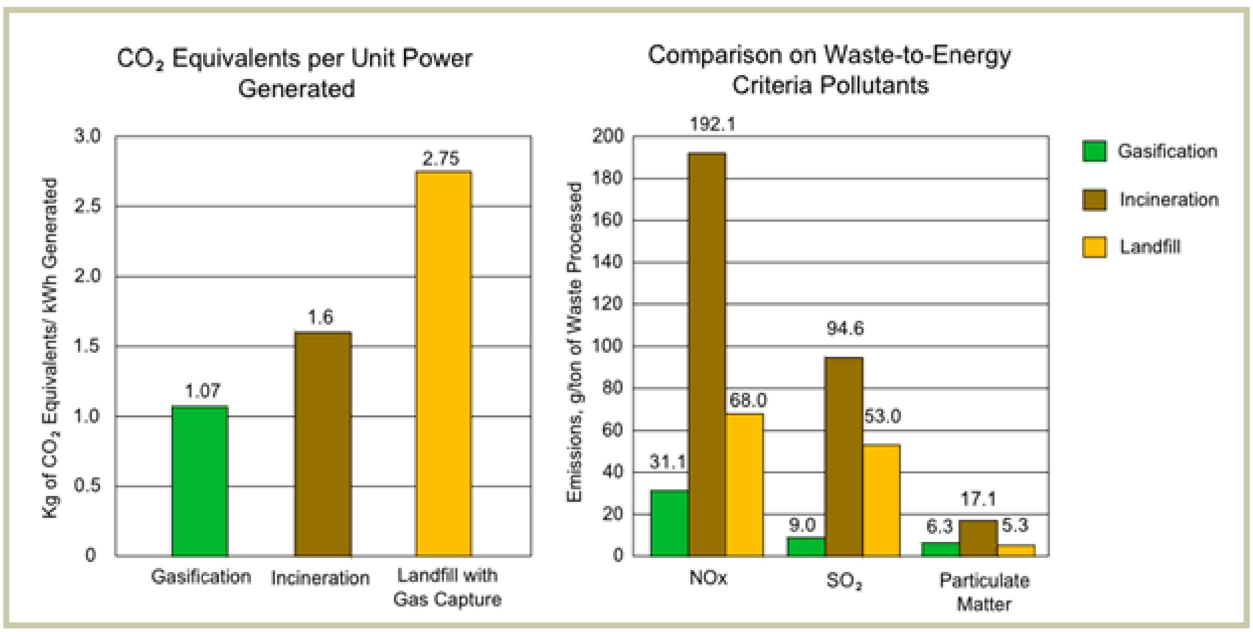


Fig. 17. Comparison of (left) carbon dioxide equivalents and (right) NOx, SOx and particulate emission. per kWh generated by landfill gas capture, incineration and gasification waste to energy conversion plants.

As shown in **Table 9** in the Conclusions Section, landfill and associated landfill gas collection is less than 10% as efficient in converting biodegradable solid waste to energy, as compared to direct thermal technologies.

13. Conclusions

As described at the outset, a goal of this assessment was to compare commercial waste to energy conversion technologies based on design, conversion efficiency, waste treatment capability, economic performance, and environmental impact.

Table 6 below summarizes cost and efficiency data for the thermal conversion technologies described above. Numbers for the air fed RDF gasification system are those for an air fed gasifier from a proven manufacturer coupled to a high performance steam generator and for which a fuel mix has an HHV of approximate 9,000 BTU /lb. The cost includes the associated MSW sorting and RDF preparation. Pyrolysis cost is based on a demonstration system[27] operating on wood and does not include the cost of a sorting facility. Incineration costs are based on a blend of several US facilities including a newly commissioned $600 million dollar build out of an existing waste incineration system in Palm Beach County, FL. Plasma arc gasification costs are based on a blend of a small MSW demonstration facility in the US[28], and one in Canada[15], neither of which is commercial scale.

Table 6. Overall cost and performance comparison for thermal waste to energy processes*.

Performance Parameter	Incineration	Pyrolysis	Plasma Arc Gasification*	Air Fed RDF Gasification**
Capacity in TPD	250	250	250	250
Conversion Efficiency (MWh/ton)	0.5	0.3	0.4	0.9
Cost of Construction ($MM)	70	40	100	28
Generating Capacity MWh / Day	160	180	108	224
Unit Cost /kWh Capacity	435	222	1,000	125
Unit Cost (US$ / Ton Capacity / day)	500	160	960	112

* Numbers are approximations and are derived from consideration of multiple facilities of each type.

In terms of cost per ton of waste processed as well as cost per kWh of electricity generated, air fed RDF gasification is the most cost effective, even when the cost of the sorting facility is included. Plasma arc is the least cost effective. Even in the case of a hybrid system that employs normal thermal gasification followed by plasma torch ash slagging and syngas cleaning, the cost of construction would be only about 15 percent less and still well above that for incineration and the other thermal processes.

Table 7 below compares fuel processing capability, service life and plant availability for both thermal and biological treatment technologies. Incineration numbers are from the literature [3], pyrolysis is based on small demonstration plants using wood. Plasma arc gasification is a generous estimate for a commercial scale plant given that the 90 TPD demonstration facility in Ontario has averaged less than 10 TPD during since being put into service[15] and given the requirement for torch electrode replacement in may systems. Air fed gasification estimates are based on the service records of some two dozen air fed systems in commercial service for up to 30 years operating on biomass. MSW fired systems may be slightly lower due to requirements to shut down because of service to ancillary equipment on the sorting line and the shredders. When ancillary system reliability is considered, air fed gasification availability is anticipated to be close to that of incineration.

Service life for incinerators and air fed gasification systems are based on demonstrated service life of multiple plants in commercial service. Others are based on design life from the literature. Maximum tolerated fuel moisture is from the literature cited for each process and is provided as an indication of the fuel range and multi-fuel capability of the various technologies.

Multi-fuel capability is an important criteria for technology selection, because fuel supply is a major factor in the long term economic viability of waste to energy facilities. A plant that can operate efficiently on multiple fuels of varying moisture content has a clear long-term advantage over technologies that are more fuel type or fuel moisture restricted. Overall, air fed gasification ranks highest overall, based on the criteria listed in **Table 7** .

Table 7. Fuel Processing capability , service life and availability

Performance Parameter	Incineration	Pyrolysis	Plasma Arc Gasification	Air Fed Gasification	Anaerobic Digestion / Co-Gen	Aerobic Digestion / Gasification
Availability (%) (est.)	92%	85%	80%	96%	85%	90%
Service Life / Design Life (yrs)	30	20	20	30	20	20-30
Max Fuel Moisture (%)	40-50	10	10	40 -50	Up to 97	Up to 85
Low BTU and Wet Waste	Limited	No	No	Limited	Yes	Yes
High BTU waste (incl. tires)	Up to 10%	Yes	Yes	Up to 50%	No	No

In summary, **Table 8** compares the environmental performance of the MSW treatment technologies considered in this document. As indicated in **Figure 3**, gasification and pyrolysis processes involve far less gas flow than does incineration, and thus tend to have less entrained particulate matter in their flue gas streams. Also, as described earlier, the relatively low oxygen partial pressure and reduced temperatures in the gasification reactor as compared to incineration greatly reduces to formation of sulfur, nitrogen, and sulfur oxides. In the overall gasification process, the fuel that is eventually combusted is a clean burning gas as opposed to mixed solid waste as is the case in incineration. Ash as a percentage of fuel mass is less with RFD gasification than with mass burn incineration. A major product of pyrolysis is the char material recovered from the gas stream.

Plasma arc emission numbers in **Table 8** are from the Ontario facility as reported in Bower 2009[14]. Pyrolysis emission numbers are for wood fuel as reported in Snow 2005[27]. Incineration emission numbers are from a Canadian Government Report[32]. Gasification emission numbers are from measurements on an MSW gasifier with standard factors for addition of a scrubber and ESP unit to the flue gas considered. These calculations were made based on the fuel mix shown in **Table 5** above.

Table 8. Comparison of particulate and gas phase emissions

Performance Parameter	Incineration	Pyrolysis	Plasma Arc Gasification	Air Fed Gasification (PRM)	Anaerobic Digestion / Co-Gen	Aerobic Digestion / Gasification
Environmental						
SOx Emission mg/m3	1-40	35	26	1.2		
NOx Emission mg/m3	40-100	77- 139	150	26		
VOC Emissions	1-20			1		
Particulate	1-20	5.75	12.8	0.018		
HCL	1-8		3.1	0.2		
Ash (% of fuel mass) RDF/Mass	5-/ 10	in Char	2-4	4-5		
Lifecycle CO_2 / kWh	14-35				11	11-14

As a further comparison between energy recovery from direct thermal conversion of solid waste and energy recovery from MSW in landfills, Table 9 presents the results of an extensive study[30] comparing the two. In general, landfill gas recovery and use for firing reciprocating or turbine engines, even in combines cycle, is only in the range of 5% to 10% as efficient as the thermal processes considered. These data are shown in **Table 9** below.

Table 9 Comparison of Electricity Generated by Direct Conversion vs Landfill of MSW [30] .

	Total Electricity Generated from 166 MM Tons of MSW in (TWh)	Total Power, GW	Electricity Generated from 1 ton of MSW (kWh/Ton)
Waste to Energy Conversion	78-160	9.7 - 19	470-930
Landfill Gas to Energy	7-14	.085- 1.8	41-85

Considering data available from commercial or near commercial scale thermal treatment technologies for MSW, conventional air fed gasification, fired with properly sorted and blended RDF materials and fitted with best available technologies for emission control, emerges as the most reliable, cost effective and environmentally friendly means of converting combustible MSW to electrical and/or thermal energy, while greatly reducing the volume of waste going to landfill. When combined with recycling, aerobic processes for drying high moisture food and green waste, and careful preparation and blending of RDF feed materials, air fed gasification can provide a highly flexible and cost effective "100% solution" to the broad spectrum of municipal solid waste.

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