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

**CO₂**: 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 gases.

**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 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\(^8\). 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.

![Chemical equations](image)

**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\(^9\). 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 landfilling, 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 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.

![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.](image)
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 at 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°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°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 is still an important 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 (O₂), and hydrogen (H₂), 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. \[ \text{C} + \text{CO}_2 = 2\text{CO} \quad \Delta H^\circ = +172 \text{ kJ} \quad \text{Gasification with Carbon Dioxide} \]
2. \[ \text{C} + \text{H}_2\text{O} (g) = \text{CO} + \text{H}_2 \quad \Delta H^\circ = +130 \text{ kJ} \quad \text{Gasification with Steam} \]
3. \[ \text{C} + 2\text{H}_2\text{O} (g) = \text{CO}_2 + 2\text{H}_2 \quad \Delta H^\circ = +88 \text{ kJ} \quad \text{Gasification with Steam} \]
4. \[ \text{C} + 2\text{H}_2 = \text{CH}_4 \quad \Delta H^\circ = -71 \text{ kJ} \quad \text{Gasification with Hydrogen} \]
5. \[ \text{CO} + \text{H}_2\text{O} (g) = \text{CO}_2 + \text{H}_2 \quad \Delta H^\circ = -42 \text{ kJ} \quad \text{Water Gas Shift Reaction} \]
6. \[ \text{C} + 1/2 \text{O}_2 = \text{CO} \quad \Delta H^\circ = -109 \text{ kJ} \quad \text{Gasification with Oxygen} \]
7. \[ \text{CO} + 3\text{H}_2 = \text{CH}_4 + \text{H}_2\text{O} (g) \quad \Delta H^\circ = -205 \text{ kJ} \quad \text{Gasification with Hydrogen} \]
8. \[ \text{S} + \text{H}_2 = \text{H}_2\text{S} \quad \Delta H^\circ = -21 \text{ kJ} \quad \text{Gasification with Hydrogen} \]
9. \[ \text{C} + \text{O}_2 = \text{CO}_2 \quad \Delta H^\circ = -390 \text{ kJ} \quad \text{Gasification with Oxygen} \]

Note that, according to equation # 8 fuel bound sulfur is converted to hydrogen sulfide in an exothermic reaction instead of SOₓ 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.](image)
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 °C.

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 N₂) instead of oxides of nitrogen (NOₓ). 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 °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 °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.
Comparative Assessment of Commercial Technologies for Conversion of Solid Waste to Energy

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

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\textsuperscript{11}, the US Environmental Protection Agency (USEPA), and Alameda Power & Telecom\textsuperscript{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.

Fig. 7. Fluidized bed two chamber gasification system designed for generating steam for electrical power while performing minimal sorting on the incoming MSW.
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\textsuperscript{[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\textsuperscript{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.
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 systems 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\(^ {19}\) 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 as a function of pyrolysis temperature and residence time [17].

<table>
<thead>
<tr>
<th>Process</th>
<th>Conditions</th>
<th>Liquid</th>
<th>Char</th>
<th>Gas</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fast Pyrolysis</td>
<td>Moderate temperature, short residence time, especially for the vapor</td>
<td>75%</td>
<td>12%</td>
<td>13%</td>
</tr>
<tr>
<td>Carbonization</td>
<td>Low temperature, very long residence time</td>
<td>30%</td>
<td>35%</td>
<td>35%</td>
</tr>
<tr>
<td>Gasification</td>
<td>High Temperature, long residence times</td>
<td>5%</td>
<td>10%</td>
<td>85%</td>
</tr>
</tbody>
</table>

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 H₂, CO, CH₄ and C₂H₆ 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 pyrolysis 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.

<table>
<thead>
<tr>
<th>Elemental Composition</th>
<th>C₂H₅O₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>1,150 - 1,250 kg/m³</td>
</tr>
<tr>
<td>Higher Heating Value</td>
<td>17-20 GJ/m³</td>
</tr>
<tr>
<td>Water Content</td>
<td>15-30wt.%</td>
</tr>
<tr>
<td>Viscosity</td>
<td>25-1000 cP</td>
</tr>
<tr>
<td>pH</td>
<td>2.5 - 3</td>
</tr>
<tr>
<td>Ash Content</td>
<td>&lt; 0.1%</td>
</tr>
</tbody>
</table>

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. Pyrolysis 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: $4 \text{CH}_3\text{COOH} \rightarrow 4 \text{CO}_2 + 4 \text{CH}_4$
   b. Hydrogenotrophic methanogenesis: $\text{CO}_2 + 4 \text{H}_2 \rightarrow \text{CH}_4 + 2 \text{H}_2\text{O}$
   c. Methylotrophic methanogenesis: $4 \text{CH}_3\text{OH} + 6 \text{H}_2 \rightarrow 3 \text{CH}_4 + 2 \text{H}_2\text{O}$
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 parameters 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.

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.

Fig. 13. Indoor aerobic digestion facility.

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].

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

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

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.

<table>
<thead>
<tr>
<th>Analysis</th>
<th>Residential</th>
<th>Portland, OR Commercial</th>
<th>Mixed</th>
<th>Broward Co., FL Mixed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon</td>
<td>29.5%</td>
<td>40%</td>
<td>34.7%</td>
<td>41%</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>6.7%</td>
<td>6.5</td>
<td>6.6</td>
<td>5.8</td>
</tr>
<tr>
<td>Oxygen</td>
<td>28</td>
<td>31</td>
<td>29.9</td>
<td>21.6</td>
</tr>
<tr>
<td>Sulfur</td>
<td>1.3</td>
<td>2.5</td>
<td>1.86</td>
<td>0.09</td>
</tr>
<tr>
<td>Chlorine</td>
<td>0.19</td>
<td>0.31</td>
<td>0.25</td>
<td>0.41</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>1.5</td>
<td>0.5</td>
<td>1.0</td>
<td>0.50</td>
</tr>
<tr>
<td>Moisture</td>
<td>25</td>
<td>11.24</td>
<td>19</td>
<td>24.58</td>
</tr>
<tr>
<td>Ash</td>
<td>6.1</td>
<td>7.5</td>
<td>6.8</td>
<td>6/07</td>
</tr>
<tr>
<td>HHV As Received</td>
<td>6,280</td>
<td>7,110</td>
<td>6,690</td>
<td>6,760</td>
</tr>
<tr>
<td>HHV Dry</td>
<td>9,940</td>
<td>8,050</td>
<td>9,000</td>
<td>8,960</td>
</tr>
<tr>
<td>HHV MAF</td>
<td>10,640</td>
<td>8,720</td>
<td>9,860</td>
<td>10,290</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Waste Material</th>
<th>Blended Fuel Composition in RDF</th>
<th>HHV of Waste (BTU/lb)</th>
<th>HHV of RDF (BTU/lb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wood</td>
<td>0.3258</td>
<td>5,000.0</td>
<td>1,629.2</td>
</tr>
<tr>
<td>Paper and Cardboard</td>
<td>0.0170</td>
<td>7,712.0</td>
<td>130.8</td>
</tr>
<tr>
<td>Plastics</td>
<td>0.3469</td>
<td>15,161.0</td>
<td>5,259.3</td>
</tr>
<tr>
<td>Sewage Sludge</td>
<td>0.0286</td>
<td>5,000.0</td>
<td>142.9</td>
</tr>
<tr>
<td>Waste Tires</td>
<td>0.0569</td>
<td>17,178.0</td>
<td>977.1</td>
</tr>
<tr>
<td>Ash</td>
<td>0.0215</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Water</td>
<td>0.2034</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Total for RDF</td>
<td>1.0000</td>
<td></td>
<td>8,139</td>
</tr>
<tr>
<td>MAF HHV (Estimate)</td>
<td></td>
<td></td>
<td>10,500</td>
</tr>
</tbody>
</table>
High BTU fuels such as tire shreds, as shown below in Figure 14 can be used 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](image)

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

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 gasification 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\(^{26}\). 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.](image-url)
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.

![Figure 16](image.png)

**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 CO₂ 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 SO₂ 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 SO₂ 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.

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\cite{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\cite{28}, and one in Canada\cite{19}, neither of which is commercial scale.

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

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

* 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\cite{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\cite{19} and given the requirement for torch electrode replacement in many 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

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

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

<table>
<thead>
<tr>
<th>Performance Parameter</th>
<th>Incineration</th>
<th>Pyrolysis</th>
<th>Plasma Arc Gasification</th>
<th>Air Fed Gasification (PRM)</th>
<th>Anaerobic Digestion / Co-Gen</th>
<th>Aerobic Digestion / Gasification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Environmental</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SOx Emission mg/m3</td>
<td>1-40</td>
<td>35</td>
<td>26</td>
<td>1.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NOx Emission mg/m3</td>
<td>40-100</td>
<td>77-139</td>
<td>150</td>
<td>26</td>
<td></td>
<td></td>
</tr>
<tr>
<td>VOC Emissions</td>
<td>1-20</td>
<td></td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Particulate</td>
<td>1-20</td>
<td>5.75</td>
<td>12.8</td>
<td>0.018</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HCL</td>
<td>1-8</td>
<td></td>
<td>3.1</td>
<td>0.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ash (% of fuel mass)</td>
<td>5/-10 in Char</td>
<td>2-4</td>
<td>4.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RDF/Mass</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lifecycle CO2/kWh</td>
<td>14-35</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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 comparing the two. In general, landfill gas recovery and use for firing reciprocating or turbine engines, even in combined 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].

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

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.
14. References


29. Circeo, LJ  Plasma Arc Gasification of Municipal Solid Waste  

