

# Energy Recovery from Municipal Solid Wastes by Gasification

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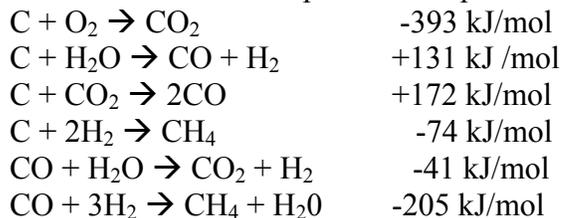
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## Abstract

Recovery of energy from MSW by combustion in Waste-to-Energy (WTE) plants reduces landfilling and air/water emissions, and also lessens dependence on fossil fuels for power generation. The objective of this study was to assess the potential of gasification processes as an alternative to the combustion of MSW. Gasification uses a relatively small amount of oxygen or water vapor to convert the organic compounds into a combustible gas. Its advantages are a much lower volume of process gas per unit of MSW and thus smaller volume of gas control equipment; also, gasification generates a fuel gas that can be integrated with combined cycle turbines or reciprocating engines, thus converting fuel energy to electricity more efficiently than the steam boilers used in combustion of MSW. The disadvantages are the need to pre-process the MSW to a Refuse Derived Fuel (RDF) and the formation of heavy organic compounds (tars), that may foul the downstream gas cleaning and energy conversion systems. This paper presents two prominent gasification processes and compares their energy characteristics with a mass burn WTE and a suspension firing WTE that uses shredded WTE. The results showed potential energy and capital cost advantages for gasification. However, the operational difficulties experienced at several pilot and demonstration plants indicate that long-term operating results from a large industrial plant are needed before gasification can be considered a reliable alternative to combustion.

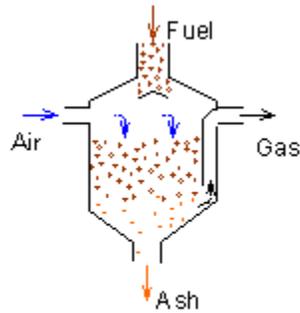
## The Gasification Process

Gasification is a thermochemical process that consists of two stages: In the first, pyrolysis releases the volatile components of the organic compounds at temperatures below 600°C (1112°F) and results in a char consisting of fixed carbon and the inorganic compounds in the feed. In the second stage, the carbon in the char is reacted with steam, air, or pure oxygen. Gasification with steam (“reforming”) results in a hydrogen and carbon dioxide rich “synthetic” gas (syngas). Gasification with air produces a high-N<sub>2</sub>, low Btu fuel gas and with oxygen a high Btu mixture of carbon monoxide and hydrogen. The exothermic reaction between carbon and oxygen provides the thermal energy required to drive the pyrolysis and char gasification reactions. The basic gasification reactions are either endothermic or exothermic and their rates depend on temperature, pressure and oxygen concentration:



Wood-fired *downdraft gasifiers* (Figure 1) have been used for a long time to power the engines of buses and other vehicles. The fuel and air supply are introduced at the top and the gases flow through the combustion bed. a gas suitable for an internal combustion engine.

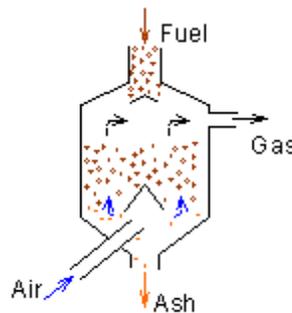
Downdraft gasifiers are not suitable for waste treatment because they require a low ash fuel to prevent clogging.



Downdraft gasifier

**Figure 1.**

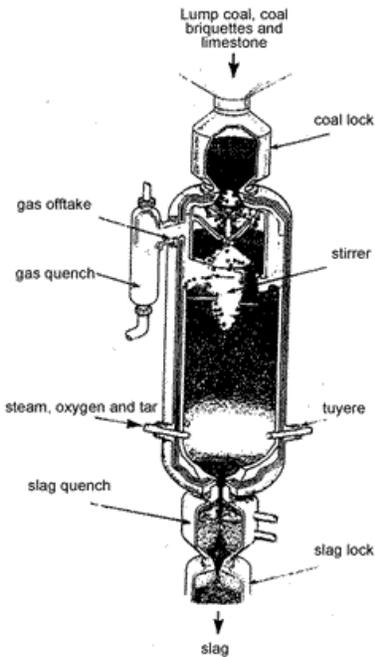
In *updraft gasifiers* (Figure 2), the gas flows upwards and leaves the gasifier at relatively low temperatures (typically less than 500°C) and the process has a high thermal efficiency; therefore, feed containing 50% moisture can be gasified without any pre-drying. However, the product gas contains tars and requires extensive reforming for use in power applications.



Updraft gasifier

**Figure 2**

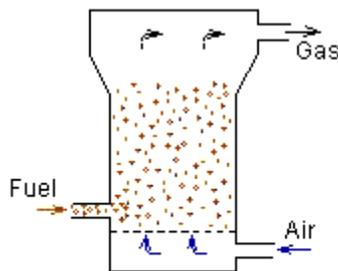
*The updraft slagging gasifier* (Figure 3) was originally developed for the gasification of coal briquettes and operates at temperatures up to 1600°C and pressures up to 30 atmospheres. The high temperatures crack all organic compounds into light combustible gases and the non-combustible components form a molten slag that flows out of the bottom of the combustion chamber, as is done in iron blast furnaces. Dynecology, Inc. has developed a version of the Lurgi/British Gas slagging gasifier for use with a briquetted fuel consisting of 50% MSW and 50% coal (Schultz, 2000). The potential problems for such systems are furnace maintenance and slag removal from the furnace.



**Figure 3. Lurgi Slagging Fixed Bed Gasifier for Mixed MSW & Coal**

Source: Schultz 2000

In *bubbling fluid bed gasifiers* (Figure 4), an inert material (e.g. coarse sand) and solid fuel are fluidized by means of air, or other reagent gas, injected below the grate supporting the bed. The fluidized bed behaves like a boiling liquid. Waste is introduced through a feed chute or an auger. Fluidized-beds have the advantage of very good mixing and high heat transfer rates. They are suitable for large capacity generators (>10 MW) because they can use different fuels, require a relatively compact combustion chamber and provide good operating control (Morris, 1998). The two main types of fluidized beds for power generation are bubbling and circulating fluidized beds. In both systems, the bed temperature is controlled so as to attain complete combustion and at the same time avoid fusion of the ash that would lead to defluidization. The ash is eventually carried over in the gas flow and is separated in the gas control system. Typical desired operating temperatures range from 900° to 1000 °C.

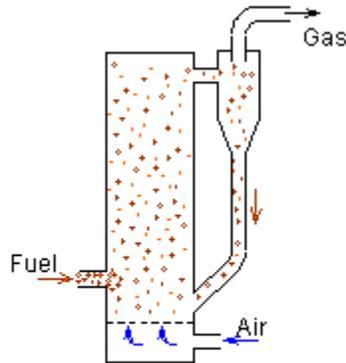


Bubbling fluidised bed gasifier

**Figure 4**

In *circulating fluid bed gasifiers* (Figure 5), there is no distinct interface between the gas phase and the fluidized bed. Fluid bed densities are of the order of 560 kg/m<sup>3</sup>, as compared to the bubbling bed density of about 720 kg/m<sup>3</sup> (Babcock and Wilcox 1992); the

corresponding air rates are 9.1 m/s (30 ft/s) vs 1.5-3.7 m/s (5 - 12 ft/s) for bubbling beds (Hollenbacher 1992).



Circulating fluidised bed gasifier

**Figure-5**

The principal advantage of circulating fluid bed boilers is their capacity to process different feedstocks with varying compositions and moisture contents. Table 1 shows the thermal capacity ranges for the gasifier designs discussed above.

**Table 1. Thermal capacity of different gasifier designs (Morris 1998)**

Gasifier Design	Thermal Capacity
Downdraft	1kW – 1MW
Updraft	1.1MW – 12MW
Bubbling FB	1MW-50MW
Circulating FB	10MW-200MW

**MSW as a fuel**

The heat content of Refuse Derived Fuel (RDF) depends on the concentration of combustible organic materials in the waste and its moisture content. Mixed plastics and rubber contribute the highest heating values to municipal solid waste and food and yard wastes the lowest. Figure 6 shows the heating values of various fuels including raw MSW. Pre-processing MSW to RDF is an important aspect in the gasification process. If too much metal and glass are allowed to pass through into the gasifier, the heating value of the RDF decreases and there are constant operating problems. Therefore, waste gasification will be most successful in communities where there is good recycling practice. This is one example that material recovery, by recycling, and energy recovery from waste are complementary in an integrated plan for waste management. Table 2 shows the typical specifications for the RDF feed to a gasification system (Niessen et al 1996).

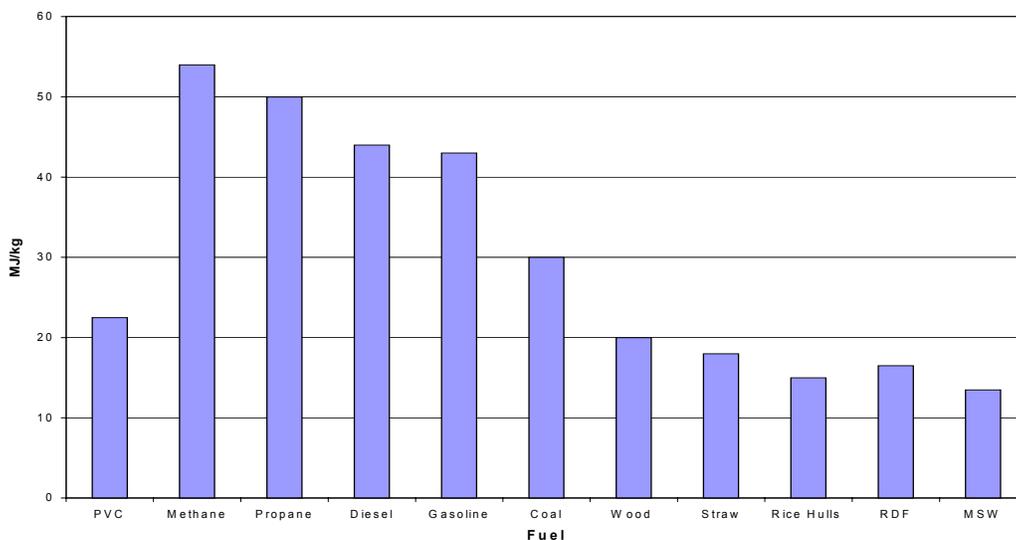


Figure 6. Heating values of various fuels

**Table 2. RDF feed specifications for gasification (Niessen et al)**

Diameter	10 to 15 mm (.4 to .6 in)
Length	50 to 150 mm (2 to 6 in)
Bulk density	500 to 700 kg/m <sup>3</sup> (31 to 42 lb/ft <sup>3</sup> )
Net calorific value	16-18 MJ/kg (6980 to 7850 Btu/lb.)
Moisture	6-10 %
Volatile matter	71.1 %
Fixed carbon	11.4 %
Sulfur	.5 %
Chlorine	.4 to .6%
Total non-combustibles	11 %

### Product Gas

The gas product of gasification contains tars, particulates, halogens, heavy metals and alkaline compounds that must be removed before the gas is used in power generating equipment. Tars range from 0.1 to 10% of the product gas and their condensation temperature ranges from 200° to 600°C (Milne & Evans, 1998). Uncontrolled tar formation can deactivate reforming catalysts and damage compressors, heat exchangers, ceramic filters, and gas turbines or engines. Elliot (1998) classified tars into three categories, depending on their temperature of formation (Table 3).

**Table 3. Categories of tars (Milne and Evans, 1998)**

Category	Formation Temperature	Constituents
Primary	400-600°C	Mixed oxygenates, phenolic ethers
Secondary	600-800°C	Alkyl phenolics, heterocyclic ethers
Tertiary	800-1000°C	Polynucleic aromatic hydrocarbons

Both lignin and cellulose in the fuel result in the formation of tertiary tar compounds. Tars in the product gas can be reduced either by physical or chemical processes. The main disadvantages of wet scrubbers is that water containing tars is classified as hazardous waste and its treatment can add significantly to the overall cost of the gasification plant.

Chemical tar treatment processes include thermal, steam, partially oxidative, and catalytic processes. Thermal destruction above 1,000°C breaks down aromatics but such high temperatures can have adverse effects on heat exchangers and refractory surfaces. The presence of oxygen during gasification accelerates the destruction of primary tar products and the conversion of phenolic to aromatic compounds (Evans and Milne 1997).

A widely used catalyst for tar decomposition is dolomite (a mixture of  $MgCO_3$  and  $CaCO_3$ ). The lack of effective and inexpensive tar removal processes has been the primary barrier to widespread commercialization of biomass and MSW as fuels for power generation using the integrated-gasification combined-cycle (IGCC).

### **Halogens and acid gases**

The principal combustion products of halogens are hydrogen halides, (e.g. HCl, HBr) or metal halides (e.g., HgCl). Typical bromine concentrations in MSW are very low (30 - 200 ppm), as compared to chlorine (3,000-6,000 ppm). Chlorine is mainly transformed to HCl and bromine to HBr, both of which are easily removed in all modern scrubbing systems. Since gasification takes place in a reducing atmosphere, sulfur and nitrogen in the waste stream end up as  $H_2S$ , COS,  $N_2$  or ammonia rather than as  $SO_x$  and  $NO_x$ . The reduced sulfur species can then be recovered as elemental sulfur at efficiencies between 95 and 99%, or converted to a sulfuric acid. The typical sulfur removal and recovery processes used to treat the raw syngas are the same as in oil and natural gas refining. A commonly used process to remove sulfur compounds is by scrubbing the gas using an amine-based solvent in an absorber tower. The reduced sulfur species removed in the solvent stripper are converted to elemental sulfur in a sulfur recovery process, such as the Selectox/Claus process (Orr and Maxwell, 2000).

When MSW is gasified, nitrogen in the fuel is converted primarily to ammonia which, in a turbine or other combustion engine, will form nitrogen oxides. Removal of ammonia and other nitrogen compounds in the product gas can be accomplished with wet scrubbers or by catalytic destruction using dolomite or iron based catalysts. This technique is of interest because tars are simultaneously decomposed to lower weight gaseous compounds. Destruction of 99% of the ammonia in the gas stream has been demonstrated by means of these catalysts.

### **Alkalis**

Alkali compounds in the gasifier feed can form sintered or fused deposits and cause operating problems. The primary elements causing alkali slagging are potassium, sodium, chlorine and silica. Eutectic alkali salts mixtures with low melting points are formed on the surfaces of fly ash particles or in the fluidized bed and may cause defluidization. Table 4 shows the concentration of alkali metals in various types of fuels.

**Table 4. Alkali Concentration in Some Fuels**  
(in ppm, dry; Zevenhoven & Kilpinen, 2001; ASME 2002)

	Coal	Scrap Tires	Wood Saw Dust	RDF	Straw
Sodium (Na)	100-500	200-600	40	3,000-5,000	100-5000
Potassium (K)	50-3,000	200-600	500	2,000-3,000	5,000-10,000
Chlorine (Cl)	NA	NA	NA	3000-6000	Na

### Power Generation

The product gas of the gasifier can be used as a fuel in steam boilers, reciprocating engines, and combined cycle turbines. Boilers have the highest tolerance for tars and other impurities but are also the least efficient (about 31%) from the point of view of converting thermal energy to electricity. In contrast, combined cycle turbines and reciprocating engines offer operational efficiencies of over 40%. The *Integrated Gasification Combined Cycle* (IGCC) combines a gasification system with a gas turbine and a steam cycle. The critical operation is the maintenance of the gas turbine. The downtime of the turbine depends on erosion, due to impact of fine particles and high temperature corrosion, due to impurities in the gas. Corrosion of the turbine blades is accelerated by the formation of low melting eutectic salt mixtures, specifically alkali sulfates. Therefore, turbine manufacturers have set specifications for the maximum tolerable metal and particulate concentrations in the gas fuel (Table 5).

**Table 5. Gas Turbine Specifications for Trace Elements in a Product Gas**  
(Spliethoff 2001)

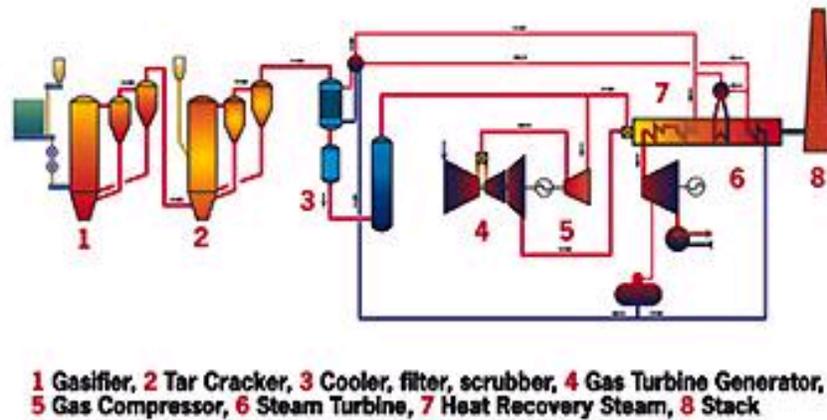
Element	Allowable Concentration	Motivation
Potassium	<1 ppm	Hot Corrosion
Sodium	<1 ppm	Hot Corrosion
Lead	1 ppm	Hot Corrosion
Zinc	1 ppm	Fouling
Tar	<0.5 mg/m <sup>3</sup>	Hot Corrosion
Particulates	< 0.1 ppm	Fouling

### Gasification Technologies Considered: The Termiska and the Battelle Processes

**TPS Termiska** is a Swedish research and development company that focuses on combustion and gasification of solid waste and biomass. In 1992, Ansaldo Aerimpianti started up a commercial, two-unit plant based on the Termiska process at Greve-in-Chianti, Italy. This plant has a total capacity of 200 metric tons of RDF per day (Figure 7) and the two gasifier units have a combined capacity of 30 MWth. The TPS technology uses a combined bubbling and circulating fluidized bed operated at 850°C and atmospheric pressure. Part of the oxidizing air is introduced below the grate and the remainder higher up in the fluidizer. The lower part maintains bubbling fluidization and allows sufficient residence time for the coarse particles to react. The secondary air, introduced above the fluidized bed, increases the

superficial velocity of air through the reactor so that smaller, lighter particles are carried away in the gas flow.

The gas is passed through a dolomite fluidized bed that breaks down the tars formed during gasification and also absorbs acids in the flue gas, including HCl and sulfur oxides. It then passes through two stages of solids separation and then a three-stage dry scrubber. After cooling, the syngas can be compressed and is clean enough to be used with a combined cycle turbine. This gas cleaning technology has been demonstrated successfully at a biomass gasification plant as part of a joint venture with ARBRE Energy LTD in England (Morris, 1998). Termiska has also designed the first commercial power station in the world (Bahia, Brazil) that combines wood gasification and gas turbine technology.



**Figure 7. Flowsheet of the Termiska fluid bed gasifier**

### **The Battelle steam-reforming fluid bed gasifier**

The Battelle gasification process uses a circulating fluidized bed of sand, operated at near atmospheric pressure, to gasify wood, biomass and potentially MSW by reacting it with steam (Figure 8). The hot gas leaving the gasifier carries along the char and some of the sand. The sand and char are separated from the product gas in a cyclone separator and are conveyed to a fluidized bed combustor where the char is combusted and the sand reheated and circulated back to the gasification reactor. Thus the sand circulating between the gasification vessel and the char combustor is the heat transfer medium and there is no need to introduce air into the gasifier. The resulting fuel gas has a heating value of 13-18 MJ/m<sup>3</sup>, using wood as the feedstock.

Battelle has experimented with a RDF feedstock in their Process Research Unit (PRU). This pilot plant has logged over 10,000 operating hours with a variety of feedstocks. The longest continuous operation with RDF was approximately 100 hours at 9.1 metric tons per day. It was concluded from these studies that throughputs of about 20 metric tons per hour per square meter of bed cross section could be attained in an industrial operation. A full material and energy balance for the Battelle gasifier is reported in a study by the National Renewable Energy Laboratory (Niessen, 1996) and is also available in Klein (2002) [www.columbia.edu/cu/wtert](http://www.columbia.edu/cu/wtert) (Klein M.S. thesis 2002).

The product gas compositions for the Battelle and TPS Termiska gasification processes are shown in Table 6. The composition of the Battelle gas is based on a simulation in ASPEN

in which a Fortran subroutine controls the simulation of the gasifier. The equations in this subroutine that describe the component mass balance in the gasifier were developed on the basis of the experimental data from the Battelle 10 t/day pilot plant (Craig and Mann, 2000). The values for the Termiska process are based on actual operating data from their plant at Greve, Italy (Morris, 1998). Adjusting the temperature, residence time and pressure within the gasifier can vary these product gas compositions. However, since both systems utilize similar temperatures, pressures and feedstocks, it is assumed that the differences in their gas composition is due to the injection of steam in the Battelle process versus the use of oxidizing air in the Termiska process. In order to examine this assumption, the Termiska molar gas concentrations were recalculated excluding the moisture and nitrogen brought in with the air and are shown in the third column of Table 6. A comparison of this to the dry Battelle product gas indicates that the addition of steam results in higher concentrations of CO and CH<sub>4</sub> formation and in lower concentrations of heavy organic gases and carbon dioxide; clearly, the addition of steam improves gas quality. However, this benefit entails an energy penalty associated with the heat of vaporization of water (44 kJ/mol).

**Table 6. Product gas concentrations from different gasifiers (mol %)**

	<sup>1</sup> Battelle (dry basis)	<sup>2</sup> TPS Thermiska	TPS Thermiska (Dry basis w/o nitrogen)
<b>Gasifier Temp</b>	826	870	870
<b>Pressure (MPa)</b>	0.17	0.14	0.14
<b>H<sub>2</sub></b>	21.2	8.6	19.35
<b>CO</b>	43.17	8.8	19.80
<b>CO<sub>2</sub></b>	13.46	15.65	35.21
<b>H<sub>2</sub>O</b>	N/A	9.5	N/A
<b>N<sub>2</sub></b>	N/A	45.8	N/A
<b>CH<sub>4</sub></b>	15.83	6.5	14.62
<b>C<sub>x</sub>H<sub>y</sub></b>	5.85	4.9	11.02

### **Comparison of energy characteristics of gasification and combustion processes**

Table 7 compares the energy related characteristics of the two gasification processes described above with those of two operating combustion plants: The mass burning WTE of Essex County (NJ, American Ref-fuel) and the suspension firing SEMASS WTE (Rochester, MA; American Ref-fuel) that uses pre-shredded MSW (Themelis et al 2002). Based on the available data, gasification may provide better efficiency in converting the thermal energy of MSW to electricity. The Battelle gasifier generates a product gas with a heating value greater than the Termiska system because its indirect heating system prevents nitrogen from entering the gasification vessel. Also, the volume of gas generated by the Battelle process is significantly lower than all the other plants. The Essex County mass burn WTE requires the least amount of electric energy to operate. This reflects the energy use associated with the shredding of MSW at the SEMASS plant. However, Essex also generates the least amount of electricity per ton of waste demonstrating that a cleaner and more homogenous feedstock results in higher power generation per unit of MSW.

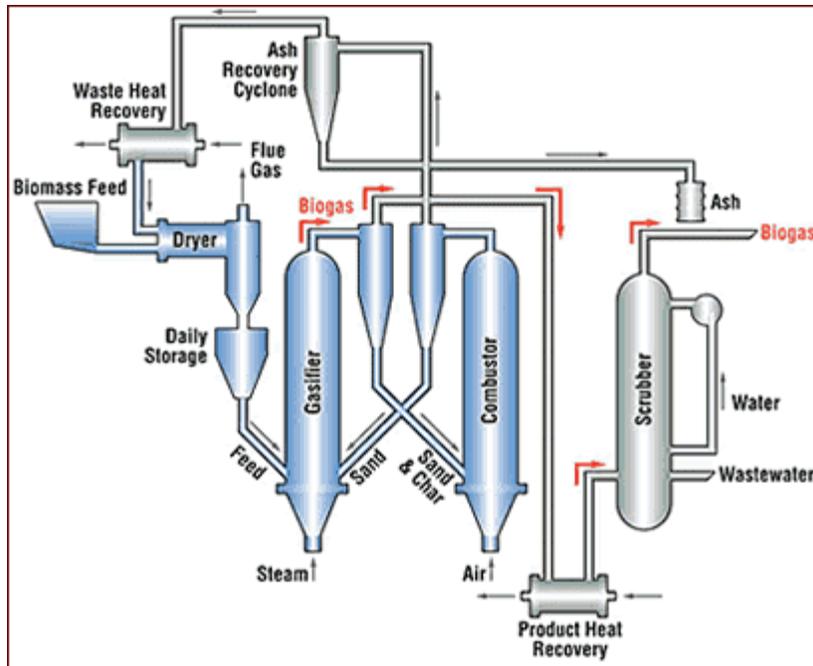


Figure 9. Flowsheet of the Battelle steam-reforming gasifier

Source: [http://www.eren.doe.gov/biopower/projects/ia\\_tech\\_gas4.htm](http://www.eren.doe.gov/biopower/projects/ia_tech_gas4.htm)

Table 7. Comparison of energy characteristics of gasification and combustion processes

Metrics of comparison	Termiska gasification process	Battelle Gasification process	Essex County mass burn WTE	SEMASS suspension-fired WTE
MSW capacity, tons/year	642,400	341,275	831,105	910,000
RDF capacity, tons/year	506,255	239,075	N/A	N/A
HHV of product gas, MJ/cubic meter	7.5	18.6	N/A	N/A
HHV of product gas, GJ per ton MSW	6.8	7.1	N/A	N/A
Volume of product gas cubic meters/ton MSW	906	396.5	6700+	6700
Gross power rating, MW	74.5	47	76	78
Gross power generation, kWh/ton MSW	781	703	501	660
Facility Power Needs (kwh/ton MSW)	130	70	23	110
Energy consumption for RDF, kWh/ton MSW	15	21	N/A	
Net power for sale (kWh/ton MSW)	636	612	476	550

### **Capital costs of gasification**

A comparison by Klein (2002) of the capital costs of the four processes of Table 8 showed that the gasification systems were less costly per kWh of electricity generated than the combustion plants, because of their higher efficiency of converting thermal to electrical energy. On the basis of daily capacity, *i.e.*, the usual measure of total capital costs in the WTE industry (including power generation), the Termiska plant cost was estimated at \$97,000 per short ton of MSW per day, vs. \$86,000 for the Battelle plant, \$114,000 for the Essex County WTE, and \$115,000 for the SEMASS WTE. An interesting fact reported by Klein (2002) was that the capital cost of the RDF preparation units amounted to 37% of the total capital cost of Termiska and 46% of the Battelle plant.

It must be noted that the WTE plant costs are actual numbers while those for the gasification plants are projected from smaller prototypes or demonstration plants. It is not clear whether the projections made for the gasification plants are achievable over long time horizons. The Termiska plant at Greve has experienced problems with slag accumulation on the boiler tubes. This has caused a plant shutdown and long outages for boiler cleaning and rework. This result was in part caused by the boiler design, which was found to be somewhat undersized and not well-configured for burning a high-ash fuel. Termiska believes that these problems can be avoided in a newly designed plant. The longest test with RDF at the Battelle pilot plant was 100 continuous hours at an RDF fuel rate of 10 tons per day. On the basis of these tests, Battelle concluded that more work had to be done on feed preparation and the gas handling system.

As a final note, it is interesting to compare the total capital costs of the two gasification plants (about \$2,200/kW) to the two WTE plants (about \$3,500/kW) and to the “rule of thumb” capital cost of coal-fuelled power plants (about \$1,000/kWh). Evidently, the gasification and WTE plants serve the additional purpose waste disposal. Yet, the capital cost difference from coal-fired plants offers a glimpse of the potential benefit from further development of the WTE technology.

### **Conclusions**

The objective of this study was to assess the potential of the most advanced gasification technologies as an alternative to the combustion of MSW. Gasification uses a relatively small amount of oxygen or water vapor to convert the organic compounds into a combustible gas. It has two inherent advantages over combustion: The volume of process gas per unit of MSW is much lower than that in combustion; also, gasification generates a fuel gas that can be integrated with combined cycle turbines or reciprocating engines and thus convert fuel energy to electricity more efficiently than the steam boilers used in combustion of MSW. The disadvantages are the need for sophisticated pre-processing of the MSW to RDF and the formation of tars and inorganic compounds that must be removed from the product gas prior to using in a turbine or other internal combustion engine. The results of this study showed a capital cost advantage for gasification. However, the operational difficulties experienced at several pilot and demonstration plants indicate that long-term results from a large industrial-scale plant are needed for gasification to be considered a reliable alternative to combustion.

The viability of waste gasification will be increased by applying it not to the entire mixture of MSW but to the natural and man-made organic fraction that is best suited for gasification. Pre-sorting can decrease the capital costs of RDF preparation (currently 40% of the total capital) and also reduce operating problems in the gasification reactor and the gas cleaning

system. The second area of needed development involves the removal of tars and other undesirable compounds from the product gas.

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