Waste-to-Energy through thermochemical processes: matching waste with process

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Abstract

The novel concepts of Enhanced Waste Management (EWM) and Enhanced Landfill Mining (ELFM) intend to place landfilling of waste in a sustainable context.[1,2] In the ELFM vision, a landfill is no longer considered a final solution but rather a temporary storage place awaiting further valorisation. ELFM offers the opportunity to select the most suitable moment to valorise – either as materials (Waste-to-Product, WtP) or as energy (Waste-to-Energy, WtE) – certain waste streams, depending for instance on the state of the technology. The ELFM concept envisages a major shift in both waste management vision and waste management technology. Therefore, its success not only depends on technological improvements and breakthroughs, but also on surmounting a multitude of socio-economic barriers (*i.e.* regulations, social acceptance, economic uncertainty and feasibility). The ELFM approach includes the combined valorisation of landfill waste as both materials (WtP) and energy (WtE), and incorporates the goal to prevent CO_2 and pollutants emissions during these valorisation processes. The present paper reviews thermochemical technologies for energetic valorisation of calorific waste streams (WtE), with focus on municipal solid waste (MSW), possibly processed into refuse derived fuel (RDF). This review summarises the technological approaches that have been developed, presents some of the basic principles, provides details of some specific processes (more emphasis is put on new advanced technologies, such as plasma technology), and concludes with a comparison between the different technologies, stressing factors affecting their applicability and operational suitability.

Introduction

Integrated solid waste management is typically governed by the 'Ladder of Lansink', which specifies a generally accepted hierarchy of preferred methods for dealing with waste. Although reuse and recycling are preferred, energy recuperation (the process of converting energy to heat and/or electricity starting from waste is also known as the Waste-to-Energy (WtE) concept) and landfilling are still key aspects with respect to waste management.[3] Presently, in the transition to Sustainable Materials Management (SMM) two innovative concepts – Enhanced Waste Management (EWM) and Enhanced Landfill Mining (ELFM) – are defined as the pillars. In EWM, prevention and reuse/recycling become even more important, while the idea of landfilling as 'a final solution' is disregarded. Landfills are still part of EWM, provided they are considered as 'temporary storage places awaiting further treatment'. ELFM, the second pillar of SMM, targets both new and old landfills. The latter contain waste streams that can be valorised (at the most suitable moment, depending on *e.g.* the state of the technology) as both materials and/or energy, meanwhile, within the ELFM concept, preventing the emissions of CO_2 and pollutants.[2] Therefore, sustainable WtP and WtE technologies are highly needed. The present paper reviews WtE

technologies, with focus on thermochemical conversion technologies, using (pre-processed) municipal solid waste (MSW) as input.

Despite increasing attention for waste prevention and sustainability, total MSW generation in the EU25 has increased from about 150 million tonnes in 1980 to more than 250 million tonnes in 2005 and is forecasted to reach 300 million tonnes by 2015.[4] MSW is a heterogeneous feedstock containing materials with widely varying sizes, shapes and composition. If the MSW is used in an as received condition as input to WtE processes, this can lead to variable (and even unstable) operating conditions, resulting in a fluctuating product quality. Refuse derived fuel (RDF), which is a processed form of MSW, is often used as input to WtE processes. This pretreatment usually consists of size reduction, screening, sorting, and, in some cases, drying and/or pelletisation to improve the handling characteristics and homogeneity of the material. Therefore, a trade-off between the increased costs of producing RDF from MSW and potential cost reductions in system design and operation, needs to be found. The main benefits of converting MSW to RDF are a higher heating value, more homogeneous physical and chemical compositions, lower pollutant emissions, reduced excess air requirement during combustion and finally, easier storage, handling and transportation.

In the present paper the available technologies for thermochemical treatment of (calorific) waste are reviewed, the scope being limited to technologies that have been commercially proven in a full-scale plant, or that have at least demonstrated their viability through pilot plant testing. This review summarises the approaches that have been developed, presents some of the basic principles, provides details of some specific processes (more emphasis is put on new advanced technologies, such as plasma technology), and concludes with a comparison between the different technologies, stressing factors affecting their applicability and operational suitability. As such, this review constitutes the basis for selecting best available technique(s) for energetic valorisation of specific calorific waste streams. Apart from providing quantitative data, qualitative information is presented to deliver a more complete picture to correctly interpret the results and their associated uncertainties. This review focuses on MSW, possibly processed into RDF. Current practice shows mainly large scale centralised waste processing plants.

Thermochemical conversion technologies: overview

Figure 1 summarises the available waste-to-energy conversion technologies. The conventional approach for energetic valorisation of waste is direct combustion or incineration. Besides incineration more advanced thermochemical approaches, such as pyrolysis, gasification and plasma-based technologies, have been developed since the 1970s.[5] In general these alternative technologies have been applied to selected waste streams and on a smaller scale than incineration, and attempt to control process temperatures and pressures in specially designed reactors (see Table 1). Each conversion technology gives a different range of products, sets different requirements for the input, and employs different equipment configurations, operating in different modes.

Both pyrolysis and gasification differ from incineration in that they may be used for recovering the chemical value from the waste, rather than its energetic value. The chemical products derived may in some cases then be used as feedstock for other

processes or as a secondary fuel. However, when applied to wastes, pyrolysis, gasification and combustion based processes are often combined, usually on the same site as part of an integrated process. When this is the case the installation is, in total, generally recovering the energy value rather than the chemical value of the waste, as would a conventional incinerator do.

In a first step the waste is converted into a secondary energy carrier (a combustible liquid, gas or solid product), while in a second step this secondary energy carrier is burned (in a steam turbine, gas turbine or gas engine) in order to produce heat and/or electricity. The conversion of solid wastes to secondary energy carriers allows for a cleaner and more efficient process. Smaller flue gas volumes allow reduced gas cleaning equipment sizes. Furthermore, it enables a greater market penetration since these secondary energy carriers are compatible with gas turbines and gas motors, characterised by a high electrical efficiency.

The following sections discuss the main available thermochemical conversion technologies for calorific waste (RDF) treatment:

1. Incineration: full oxidative combustion;
2. Gasification: partial oxidation;
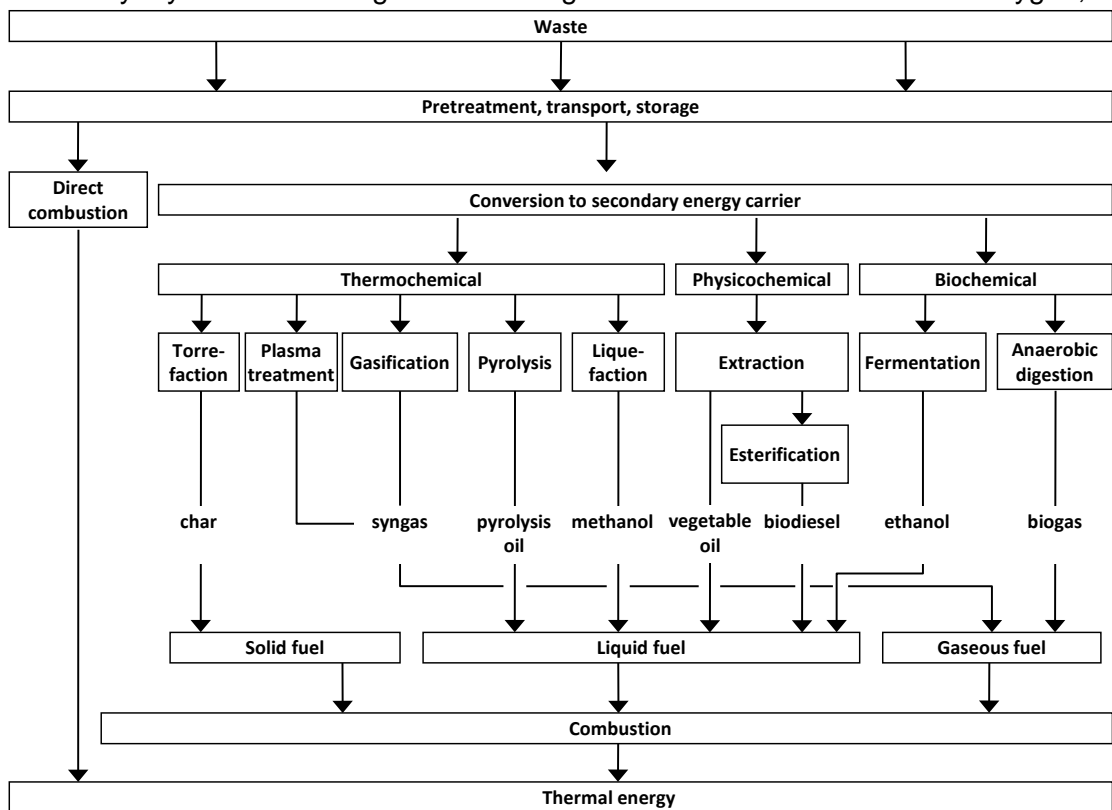3. Pyrolysis: thermal degradation of organic material in the absence of oxygen;

Figure 1: Waste-to-energy conversion technologies (based on Kaltschmitt and Reinhardt[6]).

4. Plasma-based technologies: combination of (plasma-assisted) pyrolysis/gasification of the organic fraction and plasma vitrification of the inorganic fraction of waste feed.

Incineration is by far the most widely applied, the degree of demonstration (as measured by overall throughput and operational hours) of pyrolysis and gasification on the main European waste streams is low compared to incineration. The reaction conditions for these thermal treatments vary, but may be roughly differentiated as indicated in Table 1.

Incineration

The objective of waste incineration, in common with most waste treatments, is to treat waste to reduce its volume and hazardous characteristics, hereby capturing (and thus concentrating) or destroying potentially harmful substances. Incineration processes can also provide a means to enable recovery of the energy, mineral and/or chemical content of waste (the former being more common than the latter). The incineration sector has undergone rapid technological development over the last 10 to 15 years.

Table 1: Typical reaction conditions and products from pyrolysis, gasification, incineration and plasma-based processes (based on Kolb and Seifert[5]).

	Pyrolysis	Gasification	Combustion	Plasma treatment
Temperature [°C]	250 – 900	500 – 1800	800 – 1450	1200 – 2000
Pressure [bar]	1	1 – 45	1	1
Atmosphere	Inert/nitrogen	Gasification agent: O_2, H_2O	Air	Gasification agent: O_2, H_2O Plasma gas: O_2, N_2, Ar
Stoichiometric ratio	0	< 1	> 1	< 1
Products from the process:				
Gas phase	H_2, CO, H_2O, N_2, hydrocarbons	H_2, CO, CO_2, CH_4, H_2O, N_2	CO_2, H_2O, O_2, N_2	H_2, CO, CO_2, CH_4, H_2O, N_2
Solid phase	Ash, coke	Slag, ash	Ash, slag	Slag, ash
Liquid phase	Pyrolysis oil and water			

Much of this change has been driven by legislation specific to the industry and this has, in particular, reduced emissions to air from individual installations. Continuous process development is ongoing, with the sector developing techniques which limit operating costs and at the same time maintaining or improving environmental performance.

Incineration is used as a treatment for a very wide range of wastes. Basically, incineration is the oxidation of the combustible materials contained in the waste. Waste is generally a highly heterogeneous material, consisting essentially of organic substances, minerals, metals and water. During incineration, flue gases are generated that contain the majority of the available fuel energy as heat. The organic

waste substances burn when they have reached the ignition temperature and come into contact with oxygen. The actual combustion process takes place in the gas phase in fractions of seconds and simultaneously releases energy. Where the heating value of the waste and oxygen supply are sufficient, this can lead to a thermal chain reaction and self-supporting combustion, *i.e.* there is no need for the addition of other fuels.[7] The main stages of the incineration process are: drying and degassing, pyrolysis and gasification, oxidation. These individual stages generally overlap, meaning that spatial and temporal separation of these stages during waste incineration may only be possible to a limited extent. Nevertheless it is possible to influence these processes so as to reduce pollutant emissions, for example by using measures such as furnace design, air distribution and control engineering.

In fully oxidative incineration the main constituents of the flue gas are water vapour, nitrogen, carbon dioxide and oxygen. Depending on the composition of the material incinerated and on the operating conditions, smaller amounts of CO, HCl, HF, HBr, HI, NO_X, SO_2, VOCs, PCDD/F, PCBs and heavy metal compounds (among others) are formed or remain.[7] Incineration can thus cause severe environmental pollution, but can also be an environmentally friendly method if it is combined with energy recovery, control of emissions and an appropriate disposal method for the ultimate waste. Depending on the combustion temperatures during the main stages of incineration, volatile heavy metals and inorganic compounds (*e.g.* salts) are totally or partly evaporated. These substances are transferred from the input waste to both the flue gas and the fly ash. A mineral residue fly ash (dust) and heavier solid ash (bottom ash) are created. The proportions of solid residue vary greatly according to the waste type and detailed process design. In MSW incinerators, the bottom ash constitutes approximately 25 to 30% by weight of the solid waste input. Additional treatment can improve bottom ash characteristics and would allow its use in concrete aggregates. Fly ash quantities are much lower, generally 1 to 5% by weight of the input.[8] Fly ash immobilisation is required in order to make it environmentally safe for landfill disposal.

For effective oxidative combustion, a sufficient oxygen supply is essential. The air ratio number of the supplied incineration air to the chemically required (or stoichiometric) incineration air, usually ranges from 1,2 to 2,5, depending on whether the fuel is gas, liquid or solid, and the furnace system. Waste incinerators receive a waste feed with a certain heating value. In a large majority of cases, the energetic content of the waste exceeds the process requirements which may result in the net generation of heat. MSW incinerators in particular, offer a large potential source of energy, especially in the case where combined heat and power (CHP) is applied.

The size of incineration installations varies significantly across Europe. Variations in size can be seen within and between technology and waste types. The average capacity of MSW plants in Europe equals 193 kton/a.[7] The basic linear structure of a waste incineration plant is presented in Figure 2 and may include the following operations: incoming waste reception, storage of waste and raw materials, pretreatment of waste (where required, on-site or off-site), loading of waste into the process, thermal treatment of the waste, energy recovery (*e.g.* boiler) and conversion, flue gas cleaning/residue management/discharge, emissions monitoring and control, waste water control and treatment (*e.g.* from site drainage, flue gas treatment, storage), (bottom) ash management and treatment (arising from the combustion stage), solid residue discharge/disposal.[9] The detailed design of a waste

incineration plant will change according to the type of waste (chemical composition, physical and thermal characteristics) that is being treated. Moreover, the types and quantities of generated residues vary greatly according to installation design, its operation and waste input.

Processes designed for a narrow range of specific inputs can usually be optimised to a larger extent than those that receive wastes with greater variability. This in turn enables improvements to be made in process stability and environmental performance, and may allow a simplifying of downstream operations such as flue gas cleaning. As flue gas cleaning is often a significant contributor to overall incineration costs (*i.e.* approximately 15 to 35% of the total capital investment) this can lead to a significant cost reduction. The external costs of pretreatment, or the selective collection of certain wastes, can however add significantly to the overall costs of waste management and to emissions from the entire waste management system.

The three main incinerator types are described below: grate incinerators, rotary kilns and fluidised beds.
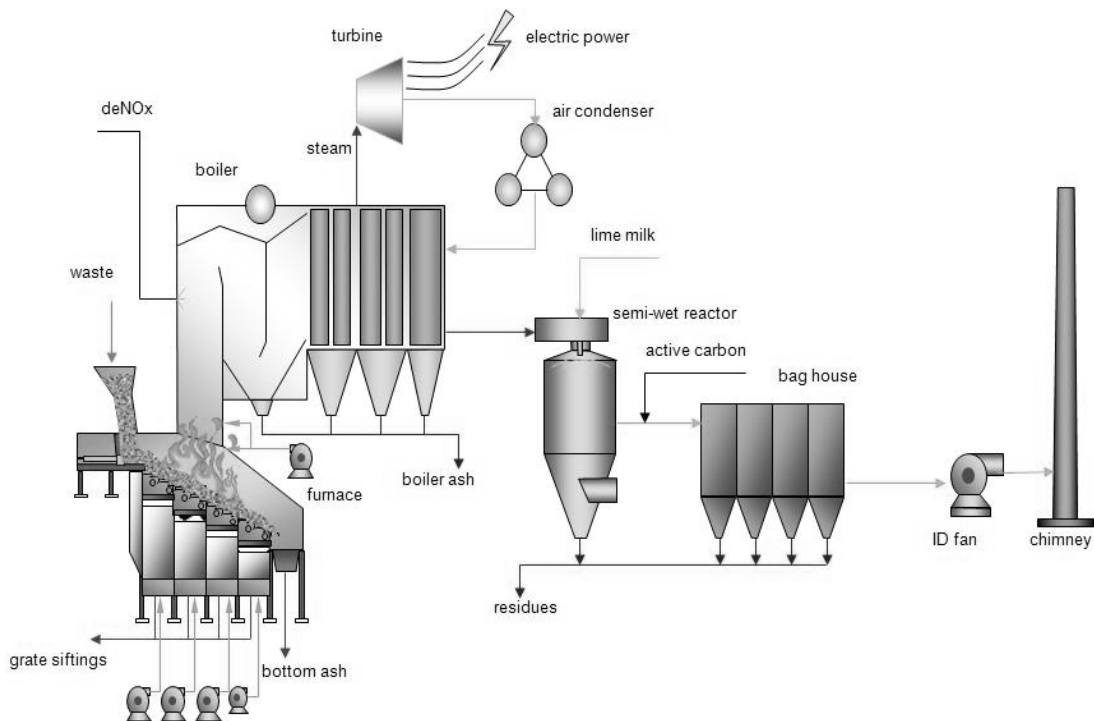

Figure 2: Example layout of a MSW incineration plant.[54]

Grate incinerators

Grate incinerators are widely applied for the incineration of mixed MSW. In Europe, approximately 90% of the incinerators treating MSW use grates. Other wastes commonly treated in grate incinerators, often mixed with MSW, include commercial and industrial non hazardous wastes, sewage sludge and certain clinical wastes. The principal reason for the wide adoption of the grate combustion technology is its relative simplicity. Additionally, it can handle a wide range of object sizes.

Grate incinerators usually have the following components: waste feeder, incineration grate, bottom ash discharger, incineration air duct system, incineration chamber, auxiliary burners.[9]

Rotary kilns

Rotary kilns are very robust and allow almost any waste, regardless of type and composition, to be incinerated. Rotary kilns are widely applied for the incineration of hazardous wastes and are also commonly used for clinical wastes, but less for MSW. Operating temperatures of rotary kilns range from around 500°C (as a gasifier) to 1450°C (as a high temperature ash melting kiln). When used for conventional oxidative combustion, the temperature is generally above 850°C. Temperatures in the range 900°C – 1200°C are typical when incinerating hazardous wastes.

The rotary kiln consists of a cylindrical vessel slightly inclined on its horizontal axis. The vessel is usually located on rollers, allowing the kiln to rotate or oscillate around its axis (reciprocating motion). The waste is conveyed through the kiln by gravity as it rotates. Solid waste, liquid waste, gaseous waste, as well as sludge can be incinerated in rotary kilns. Direct injection is used particularly for liquid, gaseous or pumpable wastes, especially when safety risks are present. The residence time of the solid material in the kiln is determined by the horizontal angle of the vessel and the rotation speed. A residence time of between 30 to 90 minutes is normally sufficient to achieve good waste burnout. In order to increase the destruction of toxic compounds, a post-combustion chamber is usually added. Additional firing using liquid waste or additional fuel may be carried out to maintain the temperatures required to ensure the destruction of the waste being incinerated.[7]

Fluidised beds

Fluidised bed incinerators are widely applied to the incineration of finely divided wastes (*e.g.* RDF and sewage sludge). It has been used for decades, mainly for the combustion of homogeneous fuels. Among these are coal, raw lignite, sewage sludge, and biomass (*e.g.* wood).

The fluidised bed incinerator is a lined combustion chamber in the form of a vertical cylinder. In the lower section, a bed of inert material, (*e.g.* sand or ash) on a grate or distribution plate is fluidised with air. The waste for incineration is continuously fed into the fluidised sand bed from the top or side.[10] Preheated air is introduced into the combustion chamber through holes in the bed-plate, forming a fluidised bed with the sand contained in the combustion chamber.

In the fluidised bed, drying, volatilisation, ignition, and combustion take place. The temperature in the free space above the bed (the freeboard) is generally between 850°C and 950°C. Above the fluidised bed material, the freeboard is designed to allow retention of the gases in the combustion zone. In the bed itself the temperature is lower, and may be around 650°C. Because of the well-mixed nature of the reactor, fluidised bed incineration systems generally have a uniform distribution of temperatures and oxygen, which results in stable operation.

For heterogeneous wastes, fluidised bed combustion requires a preparatory process step for the waste so that it complies with particle size specifications (usually a maximum diameter of 50 mm holds). For some waste streams this may be achieved by a combination of selective collection of wastes and/or pretreatment such as

shredding. Some types of fluidised beds can receive larger particle size wastes than others, it is reported that average acceptable diameters for rotating fluidised beds are 200 – 300 mm.[11] The relatively high cost of pretreatment processes required for some wastes has restricted the economic use of these systems to larger scale projects.

During incineration the fluidised bed contains the unburned waste and the ash produced. The ash surplus is usually removed at the bottom of the furnace.[7,9] The heat generated by combustion can be recovered by devices either integrated inside the fluidised bed or at the exit of the combustion gases or a mixture of both layouts. The following fluidised bed furnace technologies can be differentiated according to the gas speeds and design of the nozzle plate: stationary (or bubbling) fluidised bed (atmospheric and pressurised), rotating fluidised bed and circulating fluidised bed.

Gasification

Gasification is a partial oxidation of organic substances at elevated temperature (500°C - 1800°C) to produce a synthesis gas (often called syngas) that can be used as a feedstock (through some reforming processes), or as a fuel.[9] The synthesis gas contains CO, CO_2, H_2, H_2O, CH_4, trace amounts of higher hydrocarbons such as ethane and ethane, inert gases originating from the gasification agent and various contaminants such as small particles.[12] The partial oxidation can be carried out using air, oxygen, steam, carbon dioxide or a mixture of these. Air gasification produces a low heating value (LHV) gas (4-7 MJ/Nm^3 higher heating value), while oxygen gasification produces a medium heating value (MHV) gas (10-18 MJ/Nm^3 higher heating value).[13] This synthesis gas can be used for efficient production of electricity and/or heat, or second generation liquid biofuels. Several different gasification processes are available or being developed which are in principle suited for the treatment of MSW, certain hazardous wastes and dried sewage sludge. Good operation of the gasification reactor and minimisation of tar formation requires that the nature (size, consistency) of the waste input remains within certain predefined limits. This often requires special pretreatment of MSW, thereby increasing the cost.

Special features of gasification processes are:

- smaller gas volume compared to incineration (up to a factor of 10 by using pure O_2),
- smaller waste water flows from synthesis gas cleaning,
- predominant formation of CO rather than CO_2,
- capturing of inorganic residues, *e.g.* within slag in high temperature slagging gasifiers,
- high operating pressures (in some processes), leading to small and compact aggregates,
- material and energetic utilisation of the synthesis gas.

The following gasification reactors are used in practice: entrained flow gasifier, fluidised bed gasifier, cyclone gasifier, packed bed gasifier. For utilisation in entrained flow, fluidised bed or cyclone gasifiers, the feeding (waste) material must be finely granulated. Therefore pretreatment is necessary, especially for MSW. Hazardous wastes may be gasified directly if they are liquid or finely granulated.

Examples of gasification processes

Presently, an *entrained flow gasifier* is in use for the gasification of fluid hazardous wastes at SVZ Schwarze Pumpe GmbH (Germany). The fluid waste enters into the reactor through the burner system and is transformed into synthesis gas at temperatures of 1600 – 1800°C. Since 1995, approximately 31,000 ton of waste oil has been treated in this plant.[9]

Moreover, SVZ Schwarze Pumpe GmbH runs six *packed bed gasifiers* for treatment of coal-waste mixtures. The feed rate proportion for waste amounts up to 85%. In the reactors, each with a capacity of 8 – 14 ton per hour, mainly compacted waste plastics, dehydrated sewage sludge and contaminated soils are treated. The waste enters into
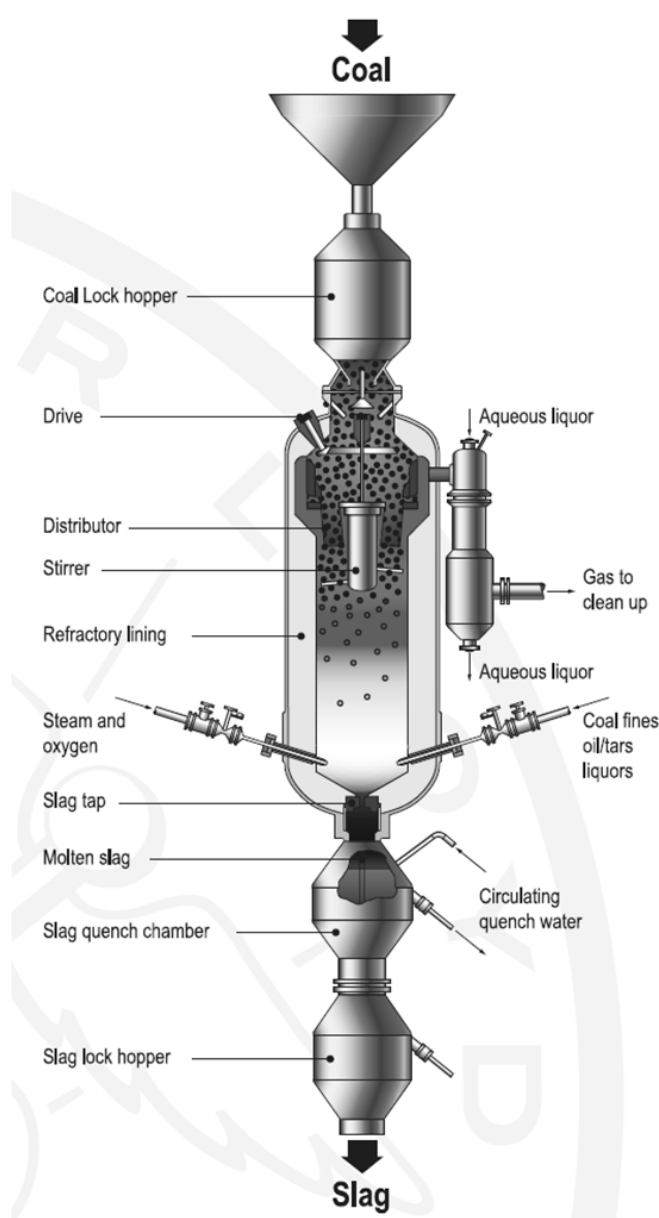

Figure 3: Slag bath gasifier.[55]

the reactor through the entry lock and is transformed into synthesis gas at approximately 800 – 1300°C and 25 bar by using steam and oxygen (the gasification agent).[9]

The *slag bath gasifier* is a further development of these packed bed gasifiers. Figure 3 shows a slag bath gasifier, currently operating on a trial basis, receiving up to 70% waste, at a throughput rate of 30 ton per hour.[9] The gasifier operates at a temperature of up to 1600°C and the slag is discharged as a liquid.

A waste gasification process consisting of *the combination of a fluidised bed and an entrained flow reactor* (see Figure 4) is used in Japan to generate synthesis gas from plastic packaging waste or other high calorific waste material. The main components of the process are the fluidised bed gasifier and the second stage high temperature gasifier. The fluidised bed enables rapid gasification of rather heterogeneous materials, which are pelletised for smooth feeding. Several per cent of non-combustible components, even metal pieces, are acceptable, as the ash is continuously discharged from the fluidised bed.

The high temperature gasifier is designed as a cyclone, to collect the fine ash particles on the wall. After vitrification the slag is discharged through a water seal. Both reactors are operated under elevated pressure, typically 8 bar. A first plant of this technology was under commercial operation in 2001 to treat plastic packaging waste. The capacity of this demonstration plant is 30 ton per day. An additional plant of 65 ton per day started operation in 2002. The synthesis gas produced is fed to an adjacent ammonia production plant. Other similar plants are under construction.[14]

Other variations on gasification processes have been tried and are being developed, for a variety of waste stream. Examples can be found in.[15]
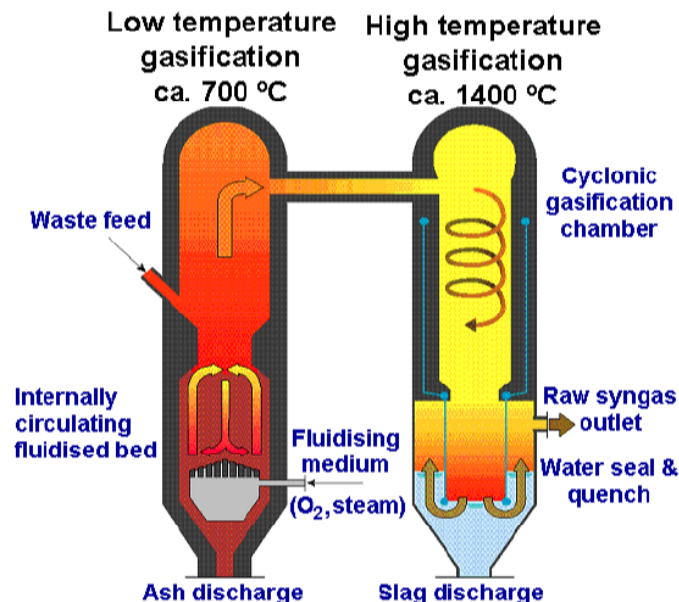

Figure 4: Fluidised bed gasifier with high temperature slagging furnace.[14]

Pyrolysis

The recent consciousness of the need for abatement of air pollution leads to worldwide interest in and investigation of pyrolysis as a major process for waste treatment. Pyrolysis is thermal degradation either in the complete absence of an oxidising agent, or with such a limited supply that gasification does not occur to an appreciable extent; the latter may be described as partial gasification and is used to provide the thermal energy required for pyrolysis at the expense of product yields. Relatively low temperatures (400-900°C, but usually lower than 700°C) are employed compared to gasification. Three products are obtained: pyrolysis gas, pyrolysis liquid and solid coke, the relative proportions of which depend very much on the pyrolysis method and reactor process parameters. The characteristics of the main modes of pyrolysis are summarised in Table 2.[16,17] The heating value of pyrolysis gas typically lies between 5 and 15 MJ/m³ based on MSW and between 15 and 30 MJ/m³ based on RDF.[9]

Table 2: Pyrolysis technology variants (RT and HR stand for residence time and heating rate, respectively).

pyrolysis technology	RT	HR	T_{max} (°C)	product
carbonisation	hours-days	very low	400	charcoal
slow	5-30 min	low	600	charcoal
				pyrolysis oil
				gas
fast	0.5-5 s	fairly high	650	pyrolysis oil
flash				
liquid	< 1 s	high	< 650	pyrolysis oil
gas	< 1 s	high	> 650	chemicals
				fuel gas
ultra	< 0.5 s	very high	1000	chemicals
				fuel gas
vacuum	2-30 s	medium	400	pyrolysis oil
hydropyrolysis	< 10 s	high	< 500	pyrolysis oil
				chemicals
methanopyrolysis	< 10 s	high	> 700	chemicals

Pyrolysis plants for waste treatment usually include the following basic process stages:

1. Preparation and grinding: the grinder improves and standardises the quality of the waste presented for processing, and as such promotes heat transfer.
2. Drying (depends on process): a separate drying step improves the LHV of the raw process gases and increases efficiency of gas-solid reactions within the reactor.
3. Pyrolysis of wastes: besides the pyrolysis gas, a solid carbon-containing residue is generated which contains mineral and metallic compounds.

4. Secondary treatment of pyrolysis gas and pyrolysis coke: condensation of the gases for the extraction of energetically usable oil mixtures and/or incineration of gas and coke for the destruction of the organic compounds and simultaneous utilisation of energy.

Conventional pyrolysis reactors have one of the following configurations: fixed bed, fluidised bed, entrained flow, moving bed, rotary kiln, ablative reactor, *etc.*, and often require waste pretreatment. The interaction between a large number of thermochemical phenomena results in a large diversity of substances obtained and increases the complexity of the process. Several hundred different compounds are produced during waste pyrolysis, and many of these have not yet been identified. A thorough understanding of the characteristics and concentration of effluents to be processed is essential, especially when hazardous substances are concerned.[13] The usefulness of pyrolysis for secondary fuel production or substance recovery from waste depends on the presence of potential pollutants, which could make the pyrolysis products useless, or at least difficult to use, *e.g.* the presence of arsenic in pyrolysis oil resulting from chromated copper arsenate (CCA) treated wood waste makes the oil very difficult to use as a fuel.[18]

In addition to the thermal treatment of some MSW and sewage sludge, pyrolysis processes are also used for: decontamination of soil, treatment of synthetic waste and used tyres, treatment of cable tails as well as metal and plastic materials for substance recovery. Often waste pretreatment is required. The potential advantages of pyrolysis processes may include:

- possibility of recovering (part) of the organic fraction as material/fuel (*e.g.* as methanol);
- possibility of recovering the char for external use, after some treatment (*e.g.* washing of chlorine);
- possibility of more efficient electricity generation using gas engines or gas turbines (instead of steam boilers);
- reduced flue gas volumes after combustion, which may reduce the flue gas treatment capital costs to some degree.

Example of waste pyrolysis in combination with a power plant

The ConTherm plant is designed to be added to an existing power plant. It consists of two lines of indirectly heated drum-type kilns with a scheduled annual MSW throughput of 50 kton each. The kilns operate at 450-550°C in the absence of oxygen, producing coke, pyrolysis gas, metals (appearing in metallic form which allows collection at high purity) and inert materials within a residence time of 1 hour. The solid residue is separated into a coarse fraction (metals, inerts) and a fine fraction, containing 99% of the carbon as coke. After sieving, the coarse fraction is supplied to a wet ash remover, cooled and directed to a reprocessing plant separating the coarse fraction into ferrous and non-ferrous metals. The resulting pyrolysis gas consists of vapourised H_2O, CO, H_2, CH_4 and higher carbohydrates. A cyclone de-dusts the pyrolysis gas, after which the deposited dusts and carbon particles are added to the pyrolysis coke.

The existing boiler unit is supplied with pyrolysed substitute fuels up to 10% of the furnace thermal output at full load, which is 790 MW. In addition to the regular fuels: coal, coke and petroleum coke, pyrolysis coke and pyrolysis gas can also be used.

The coke is first fed into the coal bunkers, ground together with the coal and then blown into the boiler with dust burners. The incineration of the pyrolysis product runs at temperatures of approximately 1600°C. Due to the high ratio of sulphur to chlorine in the crude flue gas, and because of the cooling to approximately 120°C, any new formation of dioxins is prevented. All toxic agents that have not been vapourised, are bound into the melting chamber granulate together with the recycled airborne dust and the ground inert material.

The energy and mass balance of the ConTherm plant are illustrated in Figure 5. Depending on the heating value of RDF (15 – 30 MJ/m³) it is possible to reduce primary fuel such as coal in the range of 0,5 to 1,0 ton of hard coal per ton of RDF. Emission data are not available.

Combination processes

Besides the individual processes (incineration, gasification or pyrolysis), combinations of these processes, possibly combined with other processes (*e.g.* melting, distillation, *etc.*) are also applied. In the following subsections some of these combinations are presented.

Combination pyrolysis – gasification

Both *subsequent processes* and directly connected processes are applied. In the former type, the waste needs to be dried and shredded before being introduced in the
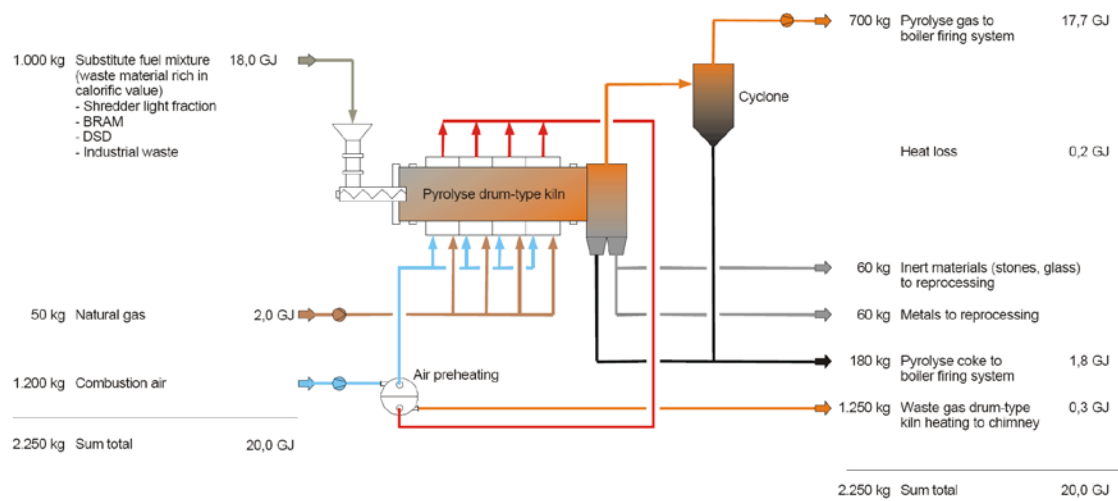

Figure 5: Mass and energy balance of the ConTherm plant (BRAM stands for Brennstoff aus Müll – 70-85 wt% paper and pulp, 10-13 wt% polymers and other components, DSD stands for synthetic granules from the Dual System Germany).[9]

first thermal stage. Metals and, if required, inert material may be removed after the pyrolysis step. As pyrolysis gas and pyrolysis coke require reheating during the gasification process, the technical and energetic requirements are higher compared to directly connected processes. The pyrolysis gas is cooled to condense exhaust vapour and pyrolysis oil. At this stage, metals and inert materials can be removed

from the pyrolysis coke. The pyrolysis gas is then supplied, together with the pyrolysis oil and the fine solid fraction, to the second thermal stage, which is an entrained flow gasifier. The oil and the fine fraction are gasified in the entrained flow at high pressure and at a temperature of 1300°C. The resulting synthesis gas is cleaned and then combusted for energy recovery. Solid residues are withdrawn as melted granulates through a water bath. A conversion plant for the treatment of 100 kton per year of MSW and 16 kton per year of dehydrated sewage sludge was approved at Northeim (Germany).[9]

Directly connected processes are characterised by improved electricity generation rates, however the metals and inert material go into a melt for which no use has been found to date. The un-shredded waste is dried in a push furnace and partially pyrolysed, whereafter it is transferred directly and without interruption into a packed-bed gasifier. In the lower part oxygen is added resulting in gasification at temperatures up to 2000°C. Pure oxygen is also added in the upper part of the gasification reactor to destroy the remaining organic components in the generated synthesis gas, through oxidation, gasification and cracking reactions. Although reported to be capable of treating a wider range of wastes, this process is mainly used for MSW and non-hazardous industrial wastes. The only requirements are: LHV of 6 – 18 MJ/kg and moisture content below 60%. Automotive shredder residues (ASR) with a chlorine content of up to 3.5% have been treated with approximately equal amounts of MSW.[7] The synthesis gas is subjected to a gas cleaning process and then combusted to utilise the energy value. The solid residues leave the reactor molten. During test operations, approximately 220 kg of bottom ash was treated with approximately 30 kg metals accumulated per ton of waste input. A plant of this type with a MSW throughput of 108 kton per year is currently under construction at Ansbach (Germany). Another plant with a throughput of 225 kton per year has been built at Karlsruhe (Germany), but has not yet achieved the design throughput. Seven plants of this type are running in Japan.[19]

Combination gasification – combustion

Figure 6 shows the combination of a fluidised bed gasifier and high temperature combustor, resulting in ash melting. Shredding residues, waste plastics or shredded MSW are gasified in an internally circulating bubbling fluidised bed, which operates at about 580°C. Larger inert particles and metals are discharged at the bottom and separated from the bed material. The bed material is returned to the gasifier.

Fine ash, small char particles and combustible gas are transferred to the cyclonic ash melting chamber, where air is added to achieve the desired temperature for ash melting (normally 1350 ºC - 1450ºC). The ash melting chamber is an integrated part of the steam boiler, used for energy recovery. Products from this process – besides power or steam – are ferrous and non-ferrous recyclable metals, a vitrified slag (low
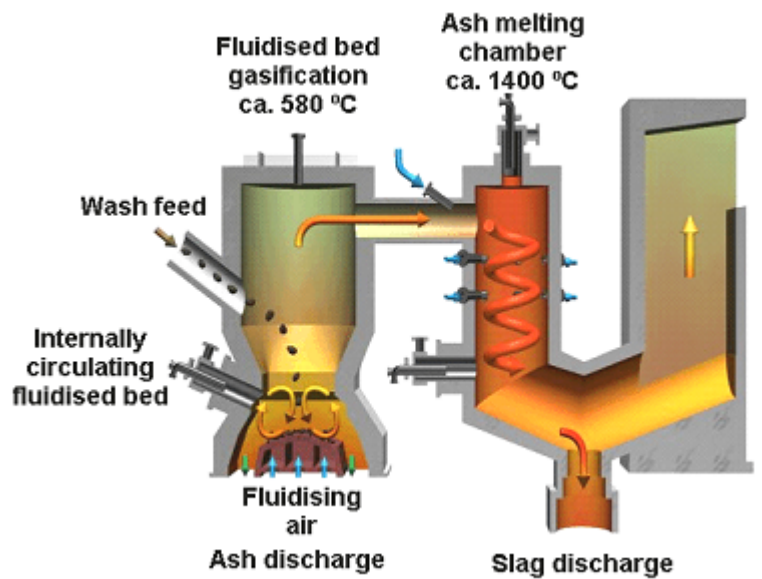
Figure 6: Combined fluidised bed gasification and high temperature combustion process.[14]

leaching risks and stable) and metal concentrates derived from the secondary ash. In contrast to other gasification processes, this process is operated at atmospheric pressure and using air rather than oxygen. Pretreatment of MSW by shredding is necessary to reduce particle size to 300 mm diameter. Wastes already within this specification can be treated without shredding. In the various plants in operation, other wastes like sewage sludge, bone meal, clinical waste and industrial slag and sludge are treated in addition to MSW.[14]

Pyrolytic distillation

Pyrolytic distillation can be seen as the combination of pyrolysis and distillation. Pyrolysis reactions occur in the warm zone at the bottom of a high reactor column. Both temperature and pressure decrease stepwise with the height of the column, similar to what is found in a distillation process. The main difference with conventional pyrolysis is the absence of a liquid product due to the successive cracking, cooling and condensation processes when a vapour is flowing upwards. After condensation on the solid products it moves downwards again, being exposed to higher temperatures and being cracked again. Consequently, pyrolytic distillation results in solid and gaseous products only.

The Chartherm process is a pyrolytic distillation process which aims at maximising the useful recovery of both materials and energy from waste. The process, developed by the company Thermya (France), is a thermochemical process on industrial scale (capacity of 1500 kg per hour wood waste). The Chartherm process is schematically presented in Figure 7. The complete process can be divided into three sections: crushing, 'chartherisation' (thermochemical conversion) and separation (or refining).[21] This process can be considered as a commercially proven technology for treating wood waste and other organic waste, in particular wood that has been impregnated with heavy metals (*e.g.* CCA wood waste). Conventional gasification and pyrolysis of wood produce a sticky tar fraction which can cause maintenance problems (*e.g.* fouling of heat exchanger). However, the temperature gradient in the chartherisation reactor breaks down the heavy tar components in favour of lighter volatile components, hence avoiding the tar problem.

The volatile combustible gases, free of metals, leave at the top of the reactor where they are washed by a water scrubber and subsequently burned in a gas burner that supplies energy to the system. The charcoal product is cooled, compressed to powder and fed to the subsequent separation stage. In order to obtain a clean carbon product on the one hand, and a powder containing the metals, minerals and some carbon on the other hand, an appropriate centrifugal separation technique needs to be applied.
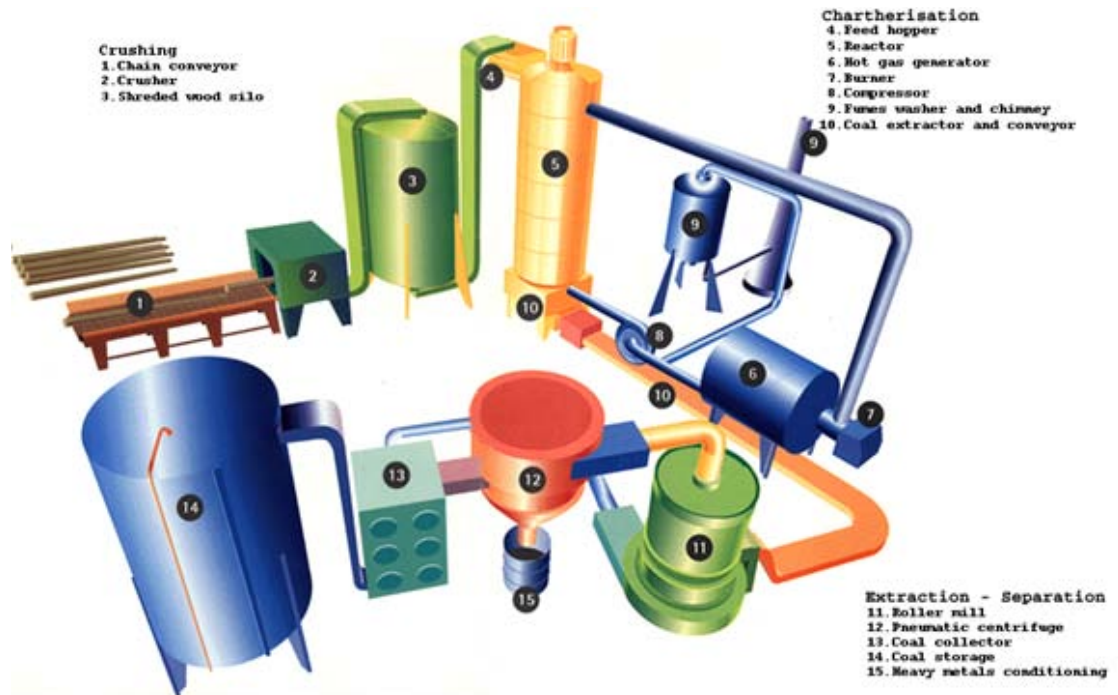

Crushing
1. Chain conveyor
2. Crusher
3. Shreded wood silo

Chartherisation
4. Feed hopper
5. Reactor
6. Hot gas generator
7. Burner
8. Compressor
9. Fumes washer and chimney
10. Coal extractor and conveyor

Extraction - Separation
11. Roller mill
12. Pneumatic centrifuge
13. Coal collector
14. Coal storage
15. Heavy metals conditioning

Figure 7: Schematic presentation of the Chartherm process.[20]

More detailed information about the Chartherm process for CCA wood waste treatment can be found elsewhere.[21] Other types of solid organic waste have also been fed to the installation but more detailed information has not been supplied.

The pyrolytic distillation process offers the following advantages:

- The operating temperatures (300°C – 400°C) are relatively low compared to conventional pyrolysis and gasification processes (500°C – 1500°C). Consequently, energy requirements are also expected to be lower.
- Tar and dioxin emissions are avoided, resulting in reduced gas cleaning equipment.
- It is possible to recover both materials and energy from the waste feed. Separation of the charcoal product results in the recovery of a high calorific carbon product on the one hand, and valuable metals and minerals on the other hand. Furthermore, the pyrolysis gases are burned to supply thermal energy to the reactor.

For the treatment of heterogeneous waste streams with a variable composition (*e.g.* RDF), the Chartherm process might not be the most appropriate technique. The process requires close monitoring of the process conditions in order to ensure

optimal working conditions within the chartherisation reactor. It is relatively straightforward to set the optimal process conditions for a homogeneous waste input with fixed composition (*e.g.* wood chips). However, a heterogeneous input with variable composition would require constantly changing process conditions in order to ensure a high process efficiency and elimination of harmful emissions, which is very complex. Moreover, the fluctuations in composition of the input waste are likely to be reflected in the quality of the carbon product which strongly reduces its market value.

Plasma-based technologies

Plasma is known as the fourth state of matter. The presence of charged gaseous species makes the plasma highly reactive and causes it to behave significantly different from other gases, solids or liquids. Plasma is generated when gaseous molecules are forced into high energy collisions with charged electrons, resulting in the generation of charged particles. The energy required to create plasma can be thermal, or carried by either an electric current or electromagnetic radiations.

Depending on the energy source used and the conditions under which the plasma is generated, two main groups of plasmas can be distinguished: the high temperature or *fusion plasmas*, in which all species are in a thermodynamic equilibrium state and the low temperature plasmas or *gas discharges*.[22] The low temperature plasmas can further be divided into *thermal plasmas* in which a quasi-equilibrium state occurs (high electron density and 2.000°C < T_{plasma} < 30.000°C), and the *cold plasmas* characterised by a non-equilibrium state.[23] Most thermal plasmas are generated by either an electric arc, created by a plasma torch, or by a radio-frequency induction (RFI) discharge. Two types of plasma arc torches exist, the transferred torch and the non-transferred torch.[24] The transferred torch creates an electric arc between the tip of the torch and a metal bath or the conductive lining of the reactor wall. In the non-transferred torch configuration, the arc is produced within the torch itself. The plasma gas is fed into the torch, heated, and then exits through the tip of the torch.

The application of plasma-based systems for waste management is a relatively new concept. The principal advantages that plasma offers to waste treatment processes have been summarised by Heberlein[25]:

1. High energy densities and high temperatures, characteristics which allow:

   - rapid heating and reactor start-up,
   - high heat and reactant transfer rates,
   - smaller installation size for a given waste throughput,
   - melting of high temperature materials.

2. Use of electricity as the energy source, resulting in:

   - decoupling of the heat generation from the oxygen potential and the mass flow rate of the oxidant or air, increasing process controllability and flexibility,
   - lower off-gas flow rates and consequently lower gas cleaning costs,

- the possibility of producing valuable (saleable) co-products.

For the majority of wastes, economic considerations dictate the use of several treatment technologies. Plasma technologies use electricity, an expensive energy vector, turning economic considerations into the strongest barrier for using plasmas for waste treatment. The use of plasmas is attractive whenever the valuable (co-)products compensate for the actual costs. Generation of synthesis gas, hydrogen or electricity are prime examples of such (co-) products.

Plasma technologies for waste treatment can be divided into different categories: plasma pyrolysis, plasma gasification, plasma compaction and vitrification of solid wastes, and combinations of the three already mentioned (in particular for solid wastes with high organic contents).[24] In selecting the optimal waste treatment process, the waste composition is an important parameter. For waste streams that contain high concentrations of organic materials with high heating value, plasma processes can offer an attractive alternative to complete combustion and steam generation as the plasma treatment recovers the energetic content of the waste in the form of a synthesis gas. Waste streams with a high concentration of halogens, including most of the plastic materials, require a very high temperature treatment and quenching in order to prevent or reduce toxic emissions, and to control the product composition. The economics are usually unfavourable since it is more difficult to obtain a valuable (co-)product. Waste streams containing inorganic solid materials can be treated for recuperation of valuable components or can be reduced in volume through melting (increasingly being used for hazardous wastes) or can be oxidised and immobilised in a vitrified non-leaching slag.

Plasma pyrolysis

Among the different plasma waste treatment processes, the most extensive scientific studies have been performed on plasma pyrolysis.[24] These studies include computational fluid dynamics (CFD) calculations of the plasma flow in the reaction chamber combined with chemical reaction calculations; more information can be found in the literature.[26,27,28] Different kinds of organic wastes, varying from plastic and used tires to agricultural residue and medical waste, have been subjected to plasma pyrolysis tests in laboratory and pilot-scale projects.[22] Plasma pyrolysis of organic waste usually results in two product streams: a combustible gas and a carbonaceous residue (char). Plasma pyrolysis is an attractive technique for material recovery. Laboratory experiments have shown that plasma pyrolysis offers potential for carbon black recovery from used tires.[29] Hereby, the inorganic components and the carbon black filler are discharged as solid residue relatively unaltered and therefore can theoretically be recycled in carbon black related applications. Although important research progress in this area has been made in recent years, there are still considerable technical challenges to be faced in developing and modifying plasma pyrolysis processes for treating *solid* waste streams, for industrial applications.

However, plasma pyrolysis of hazardous *liquids and gases* is becoming increasingly important and is already a commercially proven technology. The PLASCON process (developed by CSIRO and SRL Plasma Ltd. in Australia, and now owned by DoloMatrix International Ltd.) uses plasma pyrolysis to treat fluid wastes containing halogenated hydrocarbons, CFCs, HFCs, PCBs and other harmful components. The process uses a direct current (DC) plasma torch with tungsten cathode and argon as

plasma gas. Presently, ten plants are operating in Australia, Japan, USA and Mexico.[24]

In this review, the focus is on treatment of solid wastes, MSW and RDF in particular. For this type of waste streams, plasma pyrolysis is often combined with gasification in order to generate a synthesis gas with higher heating value while reducing the energy consumed by the plasma torches to gasify the waste.[30] This is explained by the exothermic nature of the gasification reactions taking place. The introduction of a controlled amount of air, O_2 and/or O_2-enriched air into the reaction zone promotes the following reactions:

(1) $C_xH_y + (x/2)O_2 = xCO + (y/2)H_2$

(2) $2C + O_2 = 2CO$

(3) $C + H_2O = CO + H_2$
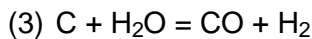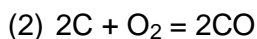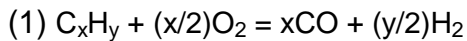
The oxidative reactions (1) and (2) are exothermic, reaction (3) is endothermic in nature. The controlled input of O_2-enriched air supplies enough oxygen to initiate the oxidative reactions (1) and (2), but not enough to promote the complete oxidative combustion reaction (4). As a result, the energetic efficiency increases.

(4) $C_xH_y + (x + y/4)O_2 = xCO_2 + (y/2)H_2O$
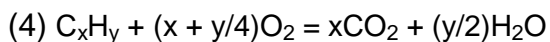
There exist relatively small scale plasma pyrolysis installations for treating polymers[31], medical waste[32] and low-level radioactive waste[33]. However, no information was found on industrial plasma pyrolysis installations processing MSW or RDF. Plasma gasification and vitrification, a technology being discussed in the next subsection, seems to be preferred over plasma pyrolysis for this type of waste streams. For this reason, plasma pyrolysis is not discussed in more detail here.

Plasma gasification and vitrification

Although gasifiers such as fluidised bed systems exist for many years, the energy contained in a plasma allows the use of low-energy fuels, such as household and industrial wastes that often cannot sustain their own gasification without additional fuel. For this reason, there is an increasing interest in plasma gasification, an innovative technology for converting waste streams into a valuable synthesis gas and a vitrified slag by means of a thermal plasma.

The high temperature conditions that are reached in plasma gasification result in the decomposition of organic compounds into their elemental constituents, forming a high-energy synthesis gas, consisting mainly of hydrogen and carbon monoxide. On the one hand, tar, char and dioxins are broken down, resulting in a synthesis gas that is cleaner compared to conventional gasification processes. The inorganic fraction (glass, metals, silicates, heavy metals) on the other hand, is melted and converted into a dense, inert, non-leaching vitrified slag. The synthesis gas can be used for efficient production of electricity and/or heat, or second generation liquid (bio)fuels (*e.g.* Fischer Tropsch diesel).[34] The vitrified slag should be inert for leaching processes and consequently applicable as, for example, a building material additive.[35]

The synthesis gas produced in the plasma gasification process contains the plasma gas components. *Air* is used most frequently, for economic reasons and for providing oxygen for reactions with organic components. In some applications it can be advantageous to use *oxygen* as plasma gas as this reduces the total gas flow in the reactor as well as the nitrogen amount.[24] Plasma torches operating with *nitrogen* and *carbon dioxide* provide higher arc voltages, increasing the jet power. A similar effect can be obtained with *steam* plasmas. R&D activities at the Czech Academy of Sciences[36] and at the Tokyo Institute of Technology[37], have shown that plasma torches operating with steam offer definite advantages for waste processing applications. However, it should be noted that the mixture of hydrogen, oxygen and hydroxide radicals leads to strong electrode erosion. *Argon* can also be used as plasma gas. It offers long electrode life, but the low specific heat of argon results in relatively low torch power levels and enthalpy fluxes of the gases leaving the torch. Moreover, reactive species such as oxygen atoms are generated only indirectly through energy transfer from argon to oxygen which leads to low energy transfer rates due to the relatively low thermal conductivity of argon.[24]

The fact that Gasplasma[TM] technologies for waste treatment use electricity as energy source instead of the energy content of the treated substances, makes the system very flexible and controllable. The plasma torch is an independent heat source, which allows controlling the process temperature independently from fluctuations in feed quality and supply of air/oxygen/steam required to gasify the feed.[38] Therefore, variable waste inputs do not pose problems. Among the different plasma processes, thermal arc plasmas dominate in waste treatment because they are relatively insensitive to changes in process conditions. Furthermore, solid waste treatment often requires decontamination in combination with volume reduction and immobilisation of inorganic contaminants. Therefore, most plasma-based waste treatment systems make use of transferred arc reactors offering high heat fluxes, advantageous for solids melting.[24]

Westinghouse (Madison, USA) and Europlasma (Morcenx, France) pursue a different approach; their design includes a non-transferred plasma torch to provide part of the heat required for waste processing, while the remainder of the process energy is provided by the heating value of the waste or by the addition of coke. The *Westinghouse* plasma reactor is a plasma fired furnace containing the waste and coke (about 4 wt% of the total charge). Plasma heating of a fraction of the air reduces the amount of coke and air needed to generate the high temperatures in the furnace. The waste composition determines how much of the incoming air needs to be plasma heated. *Europlasma* uses plasma reactors with non-transferred arc torches for incinerator residue compaction, the waste is heated directly with plasma jets. The plasma direct melting reactor installed in Cenon (France) processes up to 10 ton/day of fly ash, a larger installation in Shimonoseki (Japan) can process 42 ton/day of fly ash and bottom ash. Europlasma plans to build, in 2011, a 12 MW gasification plant for solid waste treatment in Morcenx (France).[39] The design includes two plasma torches, a first one to refine the raw synthesis gas produced during gasification, and a second one to vitrify metals and minerals. It is not clear, however, to which extent the plasma treatment (patented under the name TurboPlasma) replaces the different synthesis gas cleaning stages.

A fundamentally different type of plasma arc waste conversion uses plasma to refine gases produced during waste conversion (two-stage process) rather than to destroy

waste by brute force as occurs in the above-mentioned plasma systems (single-stage). *Plasco Energy Group* completed a plasma-arc waste demonstration plant in Ottawa (Canada) to process 85 ton/day of MSW. Plasco uses plasma only to refine the gases released from the gasification of the waste in an oxygen-starved conversion chamber. With the torches interacting only with the gas, there is limited electricity demand. In the process, waste is converted into a synthesis gas that is used to run internal combustion gas engines.[40]
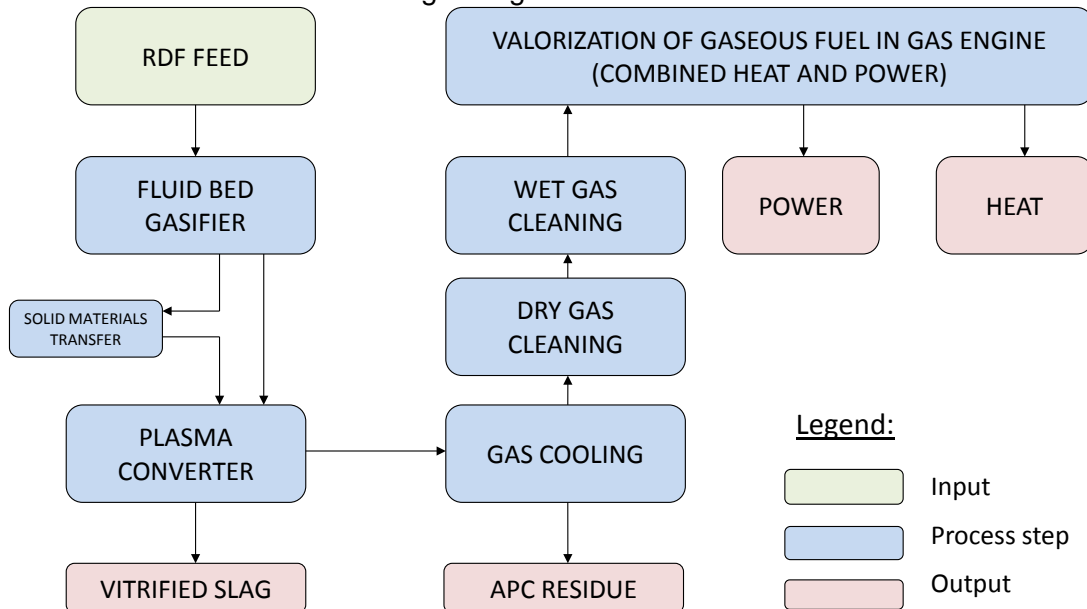

Figure 8: Flow sheet of the Gasplasma™ process (based on online information provided by Advanced Plasma Power).[41]

Tetronics developed a similar process (the Gasplasma™ process) which combines fluidised bed gasification with plasma cleaning of the resulting hydrogen rich synthesis gas.[24] Figure 8 shows the Gasplasma™ system flow sheet. The synthesis gas production process comprises two steps; first, in a fluidised bed gasifier volatile organic compounds (VOCs) and carbon are converted into a crude synthesis gas using a fraction of the thermal energy in the waste and next, a plasma converter provides the high temperature environment for converting residual tars and chars, allowing vitrification of the ash into a non-leaching slag. This technology has been commercialised by Advanced Plasma Power (Swindon, United Kingdom).

The purpose of developing a two-stage gasification process (with plasma gas cleaning) was to overcome some drawbacks related to the process combining gasification and plasma conversion in one reactor. The latter has a relatively low throughput, poor control of VOCs/tars and a low conversion efficiency to a valuable synthesis gas (*i.e.* a clean and high calorific synthesis gas). These parameters relate to the interaction of the waste feed (RDF) with the plasma system. The reduced throughput is caused by to the fact that plasma decomposition of RDF is much slower than the decomposition of tars and chars in the synthesis gas. Single-stage plasma gasification processes consume approximately 800 kWh electricity per ton of MSW, corresponding to approximately 2.000 kWh of primary energy (assuming an average efficiency of 40% for electricity generation) which is close to the total energy contained in one ton of MSW (*i.e.* 2.500 kWh). Such high energy consumptions can only be justified in case of wastes that cannot be processed in another way (*e.g.*

asbestos-containing). Therefore, the single-stage gasification process seems to be the better choice when dealing with small difficult-to-treat process streams (*e.g.* hazardous or medical waste), while the two-stage gasification process performs better for larger waste streams.[42]

Table 3 lists specific electricity requirements for a number of plasma gasification waste treatment processes.[24] It is clear that published results cover a wide range of electricity requirements. This is caused by differences in plant dimensions (pilot versus full scale), waste input, operating conditions, *etc.* Modern incinerators consume less electricity per ton waste processed (typically around 130 kWh/ton[43,44]) than plasma based systems. Electricity consumption is however not the only economic consideration in waste treatment. Plasma systems show potential for higher net electrical efficiencies than waste incinerators since gas engines generate electricity more efficiently than steam turbines. Other parameters in favour of plasma technologies include the avoidance of landfill cost, the added value of reusable vitrified slag and, in the long-term perspective, the development of a more sustainable waste management practice.

Table 3: Electric power requirements for plasma gasification processes.[24]

Plasma gasification technology	Feedstock	Electric power requirement [kWh/ton]
Westinghouse Plasma Corp. (Japan)	MSW + ASR	100 – 250
Europlasma (France, Japan)	Fly ash	800 – 1.300
Tetronics (United Kingdom)	Bottom ash	550
Integrated Environmental Technologies (USA)	Medical waste MSW	1.100 845
Pyrogenesis Corporation (Canada)		

It was mentioned earlier that process efficiencies can be increased by using plasma heat as an auxiliary source of energy, *e.g.* in the Plasco process and the Gasplasma™ process. The economic feasibility study of plasma arc gasification conducted on behalf of the City of Marion, Iowa, USA states that the net electricity production for plasma processes equals, on average, 450-550 kWh/ton.[45] Furthermore, it is mentioned that independent third party sources have determined that net power outputs for plasma processes can be significantly lower, depending on the plasma technology and plant configuration. The same study indicates a net electrical efficiency of 24% for the Plasco process. This corresponds to a net electricity production of 600 kWh/ton. On the other hand, an expertise assessment of the Plasco gasification process for MSW treatment reports an electrical efficiency of only 19% due to operational and design issues resulting in low plant availability.[40]

Literature reviews on plasma technologies for waste conversion are limited. Literature data is often restricted to lab-scale or pilot-scale installations, and only rarely covers full-scale facilities since they are not yet widely spread. In Japan, however, several commercially-proven plasma gasification facilities for waste treatment can be found,

e.g. in Utashinai and in Mihama-Mikata, processing respectively 180 and 22 ton/day. These two plants make use of the Westinghouse plasma gasification process which has been critically reviewed by Juniper Consultancy Services Ltd.[46] In the following subsections the Westinghouse plasma gasification process and the Gasplasma[TM] process are described in more detail.

Alter NRG/Westinghouse plasma gasification process. In 2007 Alter NRG acquired the Westinghouse Plasma Corporation and was regarded as a leader in MSW plasma gasification. The process concept combines the Westinghouse updraft gasification reactor that uses plasma torches to provide part of the energy input, with synthesis gas cleaning in order to convert the synthesis gas to electricity (and heat) or other added value products. The process is compatible with a variety of feedstocks such as MSW, MSW + tyres, RDF, ASR, coal + wood, petcoke and hazardous wastes. The ability to accept heterogeneous, unsorted or differently sized feedstocks reduces the cost required for feed handling prior to gasification.

The *Plasma Gasification Reactor* (PGR, see Figure 9) is a refractory-lined vessel, which can withstand high internal temperatures as well as the corrosive operating conditions within the reactor. At start-up, the reactor is loaded with metallurgic coke to form the coke bed. It absorbs and retains the thermal energy from the plasma torches and creates the appropriate environment for melting inorganics (metal and mineral content of the waste). The coke bed is gradually consumed during operation, so make-up coke is required. However, since metallurgic coke is relatively expensive and is derived from fossil carbon, its use within the process has a negative impact on the overall carbon footprint of the process and its economics. The plasma torches are energy input devices; they are used to provide thermal power into the reactor, supplemented by heat released by the coke bed which is slowly consumed. In the Westinghouse design, the temperature of the plasma plume varies between 5000 and 7000°C and the bulk temperature within the base of the reactor (cupola) is about 2000°C.
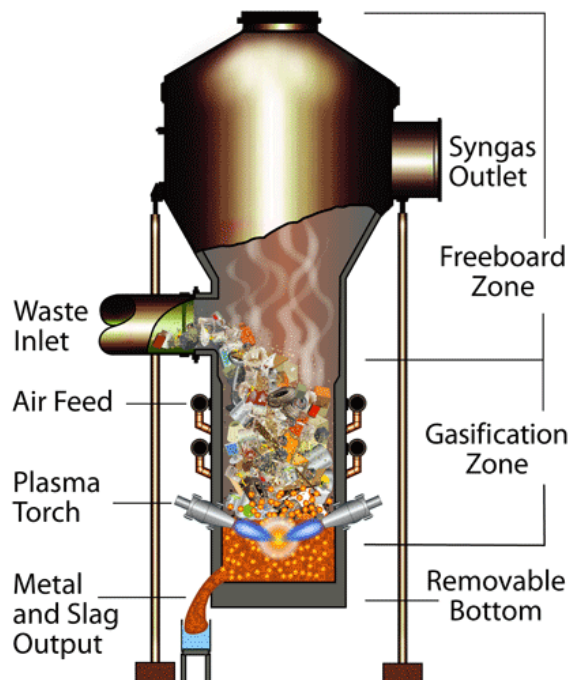
Figure 9: Alter NRG plasma gasification reactor.[47]

The *plasma* assists the gasification reactions to take place. Oxygen and steam are injected into the PGR where they serve as gasifying agents. Compared to air gasification, oxygen/steam gasification improves hydrogen yield and delivers a high calorific synthesis gas.[48] The very high temperatures in the lower part of the PGR significantly increase the kinetic rates of the chemical gasification reactions taking place. These reactions convert the organic components of the waste into a synthesis gas exiting at the top of the reactor, while the inorganic components are converted into a molten slag exiting at the bottom (at about 1650°C). The synthesis gas leaves the PGR at 890-1100°C at near atmospheric pressure, whereafter it is quenched and cleaned for further downstream use. The molten slag is a mixture of non-combustible inorganics and recoverable metals which are sent to the slag handling system for further processing. Long residence times within the reactor ensure there is sufficient time to crack any tars and minimise particulate carryover, a systemic problem for many gasification systems. The electrical energy input to the plasma torches is used as a control parameter to counteract the expected variations in heating value of the waste feed which allows to maintain a relatively constant synthesis gas output quality.

The *synthesis gas* leaving the top of the PGR contains many contaminant species that need to be removed prior to utilisation of the synthesis gas. If the synthesis gas serves as fuel for a gas turbine or gas engine in an Integrated Gasification Combined Cycle process (IGCC), it will require considerable cleaning. For the process variant that uses a secondary combustor in combination with a steam turbine, less synthesis gas cleaning would be required upstream. However, downstream gas cleaning (exhaust gases from the combustor) would still be required in order to meet the regulatory emission limits to air. Raw synthesis gas produced from an MSW feed in an updraft gasification reactor could contain: particulate matter (including carbon dust, alkali metal salts and heavy metal compounds), liquid tar droplets, sub-micron aerosols (including heavy metals such as mercury and cadmium), metal carbonyls, gas phase halogen species (including HCl, HF, HBr and possibly elemental bromine),

sulphur species (including H_2S, COS and SO_2), nitrogen species (including NH_3, HCN).

To comply with the regulatory emission limits, *gas cleaning and conditioning processes* are needed. The hot synthesis gas exiting the PGR is first sent to a water quench (venture scrubber, designed to remove a high percentage of the particulate loading and some of the HCl) and spray tower system. Quenching the synthesis gas results in a rapid temperature decrease, which offers the advantage that dioxins/furans are not able to reform via the de-novo synthesis reactions and therefore the synthesis gas will contain low or negligible levels of dioxins/furans. The cooled synthesis gas, saturated with water droplets, then flows to the spray tower which contains two sections: the lower section separates the liquid from the synthesis gas, while the absorber section removes the remaining HCl by using sodium hydroxide. Secondly, the synthesis gas passes to the Wet Electrostatic Precipitator (WESP) to remove small particulate matter, in particular sub-micron particles (including ZnO) and aerosols. The synthesis gas is saturated with water as it leaves the WESP, it then passes to a cooling stage where water is condensed from the synthesis gas and sent to the water treatment plant. As a third stage, a sulphur impregnated activated carbon filter is used to ensure that trace quantities of mercury and mercuric compounds are removed by forming stable compound mercuric sulphide (HgS) (removal efficiencies of 95% are reached). Carbonyl sulphide (COS) hydrolysis, a catalytic process where steam reacts with synthesis gas over the catalyst bed, converting COS to H_2S and CO_2, constitutes the fourth stage of synthesis gas cleaning. An activated carbon guard bed (which could be the activated carbon filter for mercury removal) is placed ahead of the COS hydrolysis reactor to avoid poisoning of the catalyst by chlorides and metal carbonyls. In a final stage, desulphurisation takes place by the Crystasulf technology (Crystatech Inc.), which is a single stage absorption process that preferentially removes H_2S over CO_2, CO and H_2 and produces a solid elemental sulphur product. Crystasulf technology has not yet been used with synthesis gas produced from waste gasification. Three of the four Japanese gasification plants processing MSW and feeding the synthesis gas to gas engines, use the LO-CAT[®] process which can be considered as moderately well proven in waste applications.

The inorganic metal and mineral content of the waste feed are converted into a *molten slag* by the high temperatures at the base of the PGR. Limestone is added with the waste feed to affect the eutectics of the slag and to control its viscosity. The molten slag leaves the reactor on a continuous base, a refractory lined channel delivers the slag to the slag extraction pipe where it encounters high pressure water sprays, causing the slag to break apart to form small granules. The granulated slag drops into a water bath and is collected by a drag chain conveyor. Then, a magnetic separator sorts out the ferrous metal granules from the mineral granules. The quench water is cooled in an air-cooled heat exchanger and recirculated into the slag quench system. The vitrified slag material could be recycled as an aggregate in construction applications. Presently, the slag produced at the Japanese Mihama-Mikata facility is sold as an aggregate and used locally for construction works. However, the slag produced at the Japanese Utashinai plant is not suitable for these applications due to an increased porosity, thought to be caused by the presence of ASR in the feed blend.

Table 4 presents calculated (not measured) mass and energy balances for the Alter NRG core design (with IGCC) for a typical US MSW (710 ton/day) and tyre (40 ton/day) feed. A 750 ton/day plant would require about 6300 ton/a of metallurgic coke, which imposes a significant operating cost. For this reason, Alter NRG has tested anthracite as a substitute for metallurgic coke and is confident that metallurgic coke usage can be substantially reduced or eliminated.

Table 4: Mass and energy balance for Alter NRG plasma gasification with IGCC (design basis).[46]

MASS BALANCE				ENERGY BALANCE			
inputs	wt%	outputs	wt%	inputs	%	outputs	%
MSW	62.3	Syngas	82.1	Feed	92.7	Syngas (sensible)	15.1
Tyres	3.5	Metal	5.5	Coke	4.2	Syngas (latent)	0.7
Steam	3.4	Slag	12.4	CaCO3	-0.1	Syngas (chemical)	80.3
Coke	2.7			Pre-heated air	1.2	Slag	0.2
CaCO$_3$	4.8			Plasma torch power	2.0	Heat losses	3.7
Air	20.0						
Plasma air	3.3						
total	100%		100%		100%		100%

Further testing is ongoing. The energy balance shows that the energy input (in MW) from the plasma torch to the gasifier is relatively low (2%). The chemical energy contained in the synthesis gas, available for conversion to electric power (after cleaning/conditioning), constitutes approximately 80% of the total energy (in MW) leaving the gasifier. The sensible and latent heat content of the synthesis gas is lost if the synthesis gas is immediately quenched at the exit of the gasifier. However, quenching the synthesis gas is needed to minimise the reformation potential of dioxins/furans.

In Japan two Westinghouse plasma gasification plants have been built for electricity generation from synthesis gas produced from MSW, RDF and ASR: the Utashinai plant and the Mihama-Mikata plant.

The *Utashinai plant* is the first, and at present still the largest, commercial plant in the world for processing MSW using plasma-based technologies. A blended feed (MSW + ASR, 50:50) of approximately 180 ton/day is processed. The lower heating value (LHV) of the MSW was measured to be 12,6 MJ/kg, the LHV of the ASR was found to vary from 8,4 to 20,1 MJ/kg. The MSW and ASR are highly different materials in particle size, composition and moisture content. The two wastes are delivered separately, there is no mixing prior to transferring feed material into the feed hopper. Obviously, this is not an optimal method of feeding the gasification reactor and could be a potential reason for the process instabilities experienced by the plant. The synthesis gas is immediately combusted in a conventional combustion chamber generating electricity in a steam turbine/generator, and sent to a waste heat recovery boiler. The vertical shaft reactor is an updraft gasifier in which the solid waste flows

downwards and the produced synthesis gas flows upwards. Make-up metallurgic coke is added at a rate of 200 – 300 kg/h. Limestone is added as seashells, a cost-effective source of $CaCO_3$ since these shells are locally available to the plant. Fly ash recovered from the boiler, air pre-heater and filter baghouse is treated with chelating agents in order to stabilise the ash and minimise the potential for heavy metal leaching. The slag is porous and not suitable for recycling as an aggregate for construction applications. Both, the ash and the slag are landfilled.

The *Mihama-Mikata gasification plant* is designed to process 22 ton/day of waste, consisting of 17,2 ton of MSW and 4,8 ton of sewage sludge (SS). The MSW is shredded on-site, the SS is partially dried to 50% moisture content by using the hot flue gases from the secondary combustor. A screw feeder transfers the MSW and SS into the gasifier via a side entry. Apart from the feed entry design, the plasma gasification reactor is the same as that used at Utashinai. The synthesis gas is immediately combusted in an afterburner, however no electricity is generated.

Emission data from the two Japanese plants are very limited. The data that were acquired over a period of several years, reflect the plant's operational performance at the time the sampling and analysis took place. Table 5 summarises the emission data for dioxins, particulate matter (fly ash), SO_2, NO_x, CO and HCl for both plants. Table 5 shows that dioxin emissions at Utashinai were above the regulatory limit in 2007, which is explained by a failure of bags in the baghouse. It can be concluded that apart from this one outlier, both facilities have operated in compliance with the performance criteria for dioxin emissions. The dioxin data from these two Japanese plants are the only available dioxin emission data for full-scale plasma gasification processes with MSW feed.

Table 5: Emission data for the Utashinai and Mihama-Mikata plants.[46] All data have been converted to 12% O_2, 101 kPa, 273 K; ng-TEQ/m³ refers to the definition of dioxins on a Toxicity Equivalence basis.

Date sampled	Total dioxins (ng-TEQ/m³)	Particulate (mg/m³)	SO_2 (ppmv)	HCl (mg/m³)	NO_x (ppmv)	CO (ppmv)
Utashinai (regulatory limit)	0.01	40	120	200	150	--
2003	0.0032 – 0.0098					
2004	0.0020 – 0.0050					
2005	0.0068	< 10	< 2	6 – 31	79 – 130	--[*]
2006	0.0026 – 0.0094					
2007	0.0032 – > 0.01					
Mihama-Mikata (regulatory limit)	0.05	20	60	100	150	30
2006	0.00004 – 0.0017					
2007	0.0024 – 0.0026	< 16 – 17	0.09 – < 5	86 – 93	69 – 84	10 – 13

[*] not measured

It should be noted that the Japanese regulatory authorities define what is included in dioxin emissions differently from other regulatory authorities (Canada, US, Europe). The latter do not include co-planar polychlorinated biphenyls in the definition of dioxins whereas the Japanese do. However, since the measured concentration values from Utashinai and Mihama-Mikata are at least an order of magnitude below the performance criterion, it can be concluded that for dioxin emissions, the required criteria in other countries are likely to be met. The data for other pollutants indicate that both the Utashinai and Mihama-Mikata facilities have generally operated in compliance with the Japanese regulatory criteria. NO_x emissions form a potential problem at Utashinai since these levels were sometimes relatively close to the limit. This could be explained by the ASR feed which contains materials with nitrogen-bound molecules, leading to increased post-combustion NO_x production. In order to meet EU regulatory limits, especially for NO_x and particulate matter, Alter NRG should review and improve its design of gas cleaning equipment.

Gasplasma^{TM} process. In developing the Gasplasma™ process, Tetronics could build on its successful use of plasma treatment for handling hazardous residues.[24] The Gasplasma™ process (see also contribution by Chapman in this volume) converts waste feedstock into a clean hydrogen-rich synthesis gas and a vitrified recyclate called Plasmarok**^{TM}** that can be used as a building material or replacement aggregate. The plasma gasification process generates little emissions and residues; less than 1% of the input volume is claimed to be landfilled.[41] The Gasplasma™ process comprises a two-stage gasification process (gasification, followed by plasma conversion), followed by a number of processes to clean and cool the synthesis gas prior to delivering it to gas engines for conversion to mechanical/electrical energy. According to the Fichtner validation report, the Gasplasma™ process has shown to be capable of producing a synthesis gas which, after passing through further gas treatment, is suitable for use as a fuel in a gas engine.[49] Rigorous pilot plant trials performed on RDF from a different number of sources, justify this statement.

Firstly, the pre-treated waste stream (RDF, pretreated commercial and municipal waste, and refined biomass) is gasified in a *fluidised bed gasifier*. In normal operation, the gasifier sand bed is fluidised by steam and oxygen, injected through nozzles at the base of the bed so as to maintain a starved air atmosphere inside the gasifier. The bed operates in the temperature range of 800-900°C. The volatile organic compounds and the fixed carbon are converted to synthesis gas using a proportion of the energy in the waste. At this stage, the synthesis gas still contains tars and soot. The solid chars and ash from the input material are removed from the base of the gasifier bed and transferred to the plasma converter.

Secondly, the *plasma converter* cracks higher hydrocarbons in the synthesis gas to form a gas comprising primarily hydrogen, carbon monoxide, carbon dioxide and nitrogen. At the same time, the ash and inorganic fraction from the gasifier are vitrified to form Plasmarok**^{TM}**. The plasma converter is a refractory lined chamber with a carbon electrode and electrode control equipment mounted at the centre of the chamber roof. While entering the plasma converter, the synthesis gas is forced to swirl around the chamber, allowing the maximum amount of time for the gas to be exposed to the high temperatures and intense UV light of the electrode arc. Finally, the synthesis gas exits the plasma converter through a refractory lined duct for further processing. The ash and chars are converted to a molten product which is being continuously removed, cooled and processed into a recyclable aggregate. The

plasma converter has a single solid carbon electrode that is held in position by the manipulator which moves the electrode up and down through the roof of the plasma converter as part of the arc control system. The manipulator clamps onto the 'live' electrode allowing power to be transferred to it from the power supply system. As the system operates as a continuous 24 hours, 7 days process, additional electrodes need to be attached without interruption. An electrode jointer is used to screw the new electrode onto the 'live' electrode while the system remains in operation.

The hot *synthesis gas* exits the plasma converter at approximately 1200°C and is cooled in a water tube heat exchanger to reduce the gas temperature to 200°C. During this process, energy is recovered as low-pressure steam of which part is used in the gasification process. Then, the synthesis gas enters the particulate filter where reacting agents are added to enable capture of sulphur-based compounds and volatile metals. The reacted materials are captured as contaminated dust on the filter elements and discharged to a sealed collection system. In a next stage, the synthesis gas enters a quench chamber to reduce its temperature and passes through a vertical counter current packed tower with a strongly alkaline solution. The acidic components react and are neutralised in the solution, leaving a cool clean synthesis gas suitable for use in a gas engine.

The synthesis gas is introduced in the *engines* at a constant pressure, which drive directly coupled generators to produce electricity. The electricity generated is partly used in the conversion process and the surplus is delivered to the distribution grid system. Thermal energy is recovered from the engine exhausts and is converted to steam which is combined with the steam recovered from the synthesis gas cooling system. The steam is used either to provide additional power generation or for export as process steam or hot water, for example to a district heating system.

The pilot plant facility of the Gasplasma™ process in Swindon (UK) is being used for preliminary testing. The influence of chemical and physical properties of the waste feed on the product quality is being investigated, as well as the energetic performance of the global process. The first results are promising and show this technology offers great potential for the energetic valorisation of calorific solid waste streams.

Conclusions

The ELFM approach includes the combined valorisation of landfill waste as both materials (WtP) and energy (WtE), and incorporates the goal to prevent CO_2 and pollutants emissions during these valorisation processes. The current paper reviews thermochemical conversion technologies for the energetic valorisation of waste. Figure 10 gives a simplified schematic overview of the WtE concept, starting from MSW. As shown in Figure 10, some WtE processes (*e.g.* pyrolysis and plasma based technologies) may also lead to material recovery, captured within the WtP concept, resulting in a combined valorisation process.
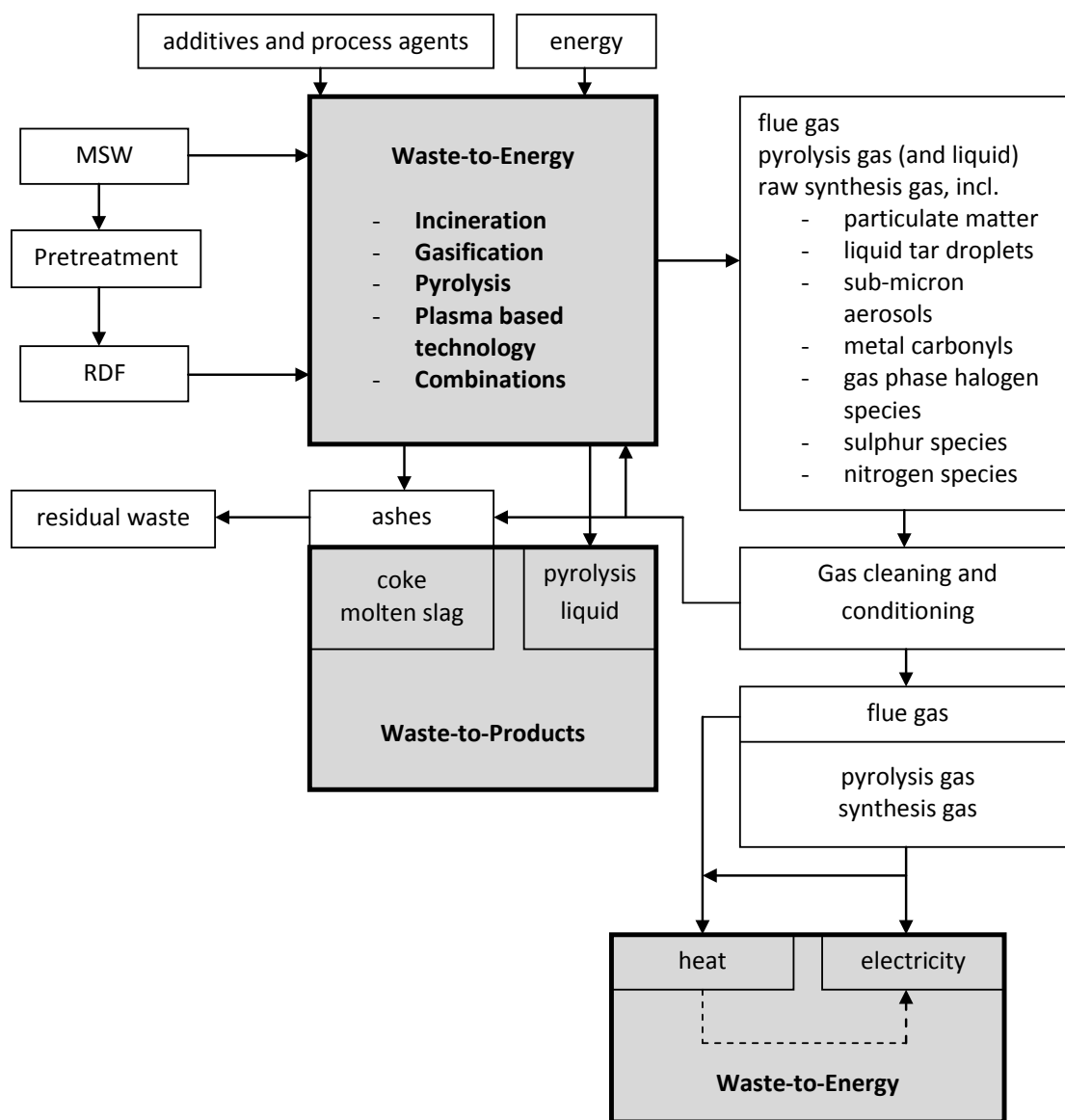
Figure 10: Schematic overview WtE concept

Table 6 provides a comparison of the main applied thermochemical waste treatment technologies and factors affecting their applicability and operational suitability. It is important to note that, although all applied in the waste treatment sector, the degree of demonstration of the technologies listed varies, as does the nature of the waste to which they have been applied successfully. Table 6 clearly shows that waste input and process have to be matched in order to treat the waste in an efficient and sustainable way.

Treatment of waste streams is subjected to increasingly stringent legislation. Furthermore, conventional technologies, such as *incineration,* have their limitations, among them the production of residual waste products, both solid (highly leachable fly ash and bottom ash) and gaseous (NO_x formation and incomplete destruction of halogenated hydrocarbons). By applying flue gas cleaning and conditioning processes some pollutants are shifted from the gaseous to the liquid or solid phase, nevertheless a residual waste stream remains. Although significant waste volume

reduction is obtained, still a substantial volume of residues has to be disposed of – mostly on landfills. Since bottom ash from incineration usually contains dioxins, halogenated hydrocarbons and heavy metals, it might be classified as hazardous in the future. This might call for supplementary vitrification units which require substantial additional energy, resulting in less potential for energy recovery.

A number of pyrolysis projects exist in Europe and elsewhere (notably in Japan) receiving certain specific types or fractions of waste, often after pretreatment. Pretreatment/ aftertreatment is recognised as an essential step in waste pyrolysis. Process conditions need to be optimised with respect to the specific waste input considered. The process viability is highly dependent on the presence of potential pollutants, which could make the pyrolysis products useless, or at least difficult to use, without additional treatment step(s). For this reason, the usefulness of pyrolysis (without any additional pretreatment of the waste input or aftertreatment of the pyrolysis products) for secondary fuel production or substance recovery from waste might be questioned for some types of waste. When used for MSW management, the fact that the ash from the pyrolysis process is usually disposed of in a landfill constitutes one of the major environmental shortcomings of the pyrolysis process.[50]

Gasification has several advantages over traditional combustion of MSW. It requires only a fraction of the stoichiometric amount of oxygen necessary for combustion. As a result, the formation of dioxins, SO_x and NO_x is limited and the volume of process gas is low, requiring smaller and less expensive gas cleaning equipment. Flue gas volumes in waste incineration range between 5.000 and 6.000 Nm³ (dry) per ton of waste processed.[8] Advanced Plasma Power claims their plasma gasification technology (Gasplasma™) produces 1.400 Nm³ crude synthesis gas (dry) per ton of waste processed. The lower gas volume also results in a higher partial pressure of contaminants in the off-gas, which favours more complete adsorption/absorption and particulate capture. Moreover, waste volume reduction is increased compared to incineration. Manufacturers of plasma systems claim a volume reduction of 99% as opposed to an 80-90% volume reduction achieved in combustion. Finally, gasification generates a fuel gas that can be integrated with combined cycle turbines, gas engines and, potentially, with fuel cells for electricity (and heat) generation.

For these reasons, *plasma technologies* are becoming more and more attractive.[3] The driving force is to give priority to environmental quality at affordable cost, hereby contributing to sustainable development. Plasma technologies use electricity as heat source rather than thermal energy liberated from combustion, which makes the heat source independent of the treated substances. This provides system flexibility, fast process control and more options in process chemistry, including the possibility of generating valuable (co-) products.[3] Plasma technologies for waste treatment can be divided into different categories; plasma pyrolysis, plasma gasification, and plasma compaction and vitrification. The latter is often combined with plasma pyrolysis or gasification, especially for solid waste containing high fractions of organics. *Plasma pyrolysis* is a proven technology for the treatment of hazardous liquids and gases, in relatively small scale applications. The Plascon process, for example, is designed to treat approximately 2,4 ton/day.[24] No information was found on plasma pyrolysis installations, pilot-scale or full-scale, for processing MSW and/or RDF. *Plasma gasification* has been demonstrated as one of the most effective and environmentally friendly methods for solid waste treatment and energy utilisation.[51] Both single-stage and two-stage plasma gasification systems exist. In the single-stage design the waste

is treated directly with plasma jets, while in the two-stage design, gasification is followed by plasma cleaning of the produced synthesis gas. The purpose of developing a two-stage gasification process was to overcome some drawbacks related to the process combining gasification and plasma conversion in one reactor. The single-stage system has a relatively low throughput, poor control of VOCs/tars and a low conversion efficiency to a valuable synthesis gas.

The high process temperatures reached in plasma gasification allow to vapourise volatile metals in their metallic form, and carry them out of the unit, together with halogens and other acid gases, in the off-gas stream. The gas cleaning unit must be designed to separate, collect and/or chemically treat the materials entrained in the off-gas. Operation failure of this cleaning unit may have dramatic consequences, therefore it should be carefully implemented. A wide range of gas abatement techniques are available for this remedial treatment. Residues from the synthesis gas cleaning processes (fly ash, precipitated metals, *etc.*) can be internally recycled and captured in the slag, which is vitrified and as such shows no leaching risks.

Due to their high cost (electricity is an expensive energy source), plasma systems have primarily been used for the treatment of high-end waste (*e.g.* medical waste, low-level radioactive waste). Nowadays, plasma systems are becoming more accepted and their design is simplified, which means there is potential for widening its foothold in waste management.[52] The cost savings associated with landfill avoidance and the added value of the potentially reusable (co-)products are the main economical advantages of plasma vitrification of wastes. Plasma systems for waste treatment have the potential to offer a viable alternative to landfilling and conventional incineration, with lower air pollution and virtually no co-products requiring final disposal. The synthesis gas produced can be used for efficient electricity and/or heat generation, for conversion to second generation liquid (bio)fuels or for other applications. The vitrified non-leaching slag that is formed can be used as a construction material. It is possible to attain a significant volume reduction with the vitrification process, typically more than 5:1 for ash and more than 50:1 for solid waste.[52] Within a regulatory context, combined plasma gasification and vitrification is regarded as a recovery process, as opposed to a disposal technology.

Only a limited amount of data (concerning emissions, energetic performance, investment and operating costs, technical lifetime, *etc.*) is available from the literature or system developers. Moreover these limited data often refer to different plant specifications (*e.g.* to meet different emission standards, water treatment requirements, *etc.*) or to different waste inputs. Consequently, it is difficult to quantitatively compare plasma technologies with more conventional technologies for waste treatment, such as incineration. However, the data which have been published show that plasma technologies offer great potential for energetic valorisation of calorific solid waste streams.

Table 6: Comparison of thermochemical treatment technologies, and factors affecting their applicability and operational suitability.[7,9,24,46,53]

Technique	Key waste characteristics and suitability	Throughput range (per line)	Operational/Environmental information		Bottom ash quality	Flue gas volume	Cost information
			Advantages	Disadvantages			
Moving grate – air cooled	• Low to medium heating values (LHV 5 – 16.5 GJ/t) • Municipal and other heterogeneous solid wastes • Can accept a proportion of sewage sludge and/or medical waste with MSW • Applied at most modern MSW installations	1 to 50 t/h with most projects 5 to 30 t/h. Most industrial applications not below 2.5 or 3 t./h.	• Very widely proven at large scales • Robust – low maintenance cost • Long operational history can take heterogeneous wastes without special preparation	• Generally not suited to powders, liquids or materials that melt through the grate	Total organic carbon (TOC) 0.5% to 3%	4000 to 7000 Nm³/t waste input. Depends upon the LHV. Typically 5200 Nm³/t.	High capacity reduces specific cost per ton of waste
Moving grate – liquid cooled	Same as air-cooled grates except: • LHV 10 – 20 GJ/t	1 to 50 t/h with most projects 5 to 30 t/h. Most industrial	As air cooled grates but: • Higher heating value waste treatable • Better combustion control possible	As air-cooled grates but: • Risk of grate damaging leaks • Higher complexity	TOC 0.5% to 3%	4000 to 7000 Nm³/t waste input. Depends upon the LHV. Typically 5200 Nm³/t.	Slightly higher capital cost than air-cooled
Grate plus rotary kiln	Same as other grates except: • Can accept very heterogeneous waste and still achieve effective burnout • Not widely used	1 to 10 t/h	• Improved burnout of bottom ash possible	• Throughput lower than grate only • Maintenance of rotary kiln	TOC 0.5% to 3%	4000 to 7000 Nm³/t waste input. Depends upon the LHV. Typically 5200 Nm³/t.	Higher capital and revenue costs
Static grate with ash/waste transport mechanism	• MSW requires selection or some shredding • Less problems with powders etc. than moving grates	Generally low < 1 t/h	• Lower maintenance – no moving parts	• Only for selected/pretreated wastes • Lower throughput • Some static grates require support fuel	< 3% with prepared waste	Slightly lower than other grate systems where staged combustion used (higher if support fuel used)	Competitive with moving grates at small scales (< 100 kt/y)

Rotary kiln	• Can accept liquids and pastes • Solid feeds more limited than grate (owing to refractory damage) • Often applied to hazardous wastes	< 10 t/h	• Very well proven • Broad range of wastes • Good burn out – even of hazardous waste	• Throughputs lower than grates	TOC < 3%	6 – 10000 m³/t waste input	Higher specific cost due to reduced capacity
Rotary kiln (cooled jacket)	As rotary but: • Higher heating value waste possible due to higher temperature tolerance	< 10 t/h	• Very well proven • Can use higher combustion temperatures (if required) • Better refractory life than un-cooled kiln	• Throughput lower than grates	Low leaching vitrified slag	6 – 10000 m³/t waste input	Higher specific cost due to reduced capacity
Fluid bed-bubbling	• Only finely divided consistent wastes. Limited use for raw MSW • Often applied to sludges	1 to 10 t/h	• Good mixing • Fly ashes of good leaching quality	• Careful operation required to avoid clogging bed • Higher fly ash quantities	TOC < 3%	Relatively lower than grates	Flue gas treatment cost may be lower. Costs of waste preparation
Fluid bed – rotating	• Wide range of heating values (7 – 18 MJ/kg) • Coarsely shredded MSW may be treated • Combined incineration of sludge	3 to 22 t/h	• Good mixing/high turbulence • Wide range of LHV • High burnout, dry bottom ash	• Shredding of MSW required • Higher fly ash quantity than grates	• TOC < 3% • Often 0.5 – 1%	4000 to 6000Nm³/t	*Information not supplied*
Fluid bed – circulating	• Only finely divided consistent wastes. Limited use for raw MSW • Often applied to sludges/RDF	1 to 20 t/h most used above 10 t/h	• Good mixing • Greater fuel flexibility than bubbling fluid bed • Fly ashes of good leaching quality	• Cyclone required to conserve bed material • Higher flying ashes quantities	TOC < 3%	Relatively lower than grates	Flue gas treatment cost may be lower. Costs of preparation

Technology	Suitable wastes	Throughput	Advantages	Disadvantages	Residue	Emissions	Cost
Oscillating furnace	• MSW • Heterogeneous wastes	1 – 10 t/h	• Robust – low maintenance • Long history • Low NOx level • Low loss on ignition of bottom ash	• Higher thermal loss than with grate furnace • LHV < 15 G/t	TOC 0.5 – 3%	*Information not supplied*	Similar to other technologies
Pulsed hearth	• Only higher heating value waste (LHV > 20 GJ/t) • Mainly used for clinical wastes	< 7 t/h	• Can deal with liquids and powders	• Bed agitation may be lower	Dependent on waste type	*Information not supplied*	Higher specific cost due to reduced capacity
Stepped and static hearths	• Only higher heating value waste (LHV > 20 GJ/t) • Mainly used for clinical wastes	*Information not supplied*	• Can deal with liquids and powders	• Bed agitation may be lower	Dependent on waste type	*Information not supplied*	Higher specific cost due to reduced capacity
Spreader – stoker combustor	• RDF and other particle feeds • Poultry manure • Wood wastes	*Information not supplied*	• Simple grate construction • Less sensitive to particle size than fluid bed	• Only for well defined mono-streams	Information not supplied	*Information not supplied*	*Information not supplied*
Gasification – fixed bed	• Mixed plastic wastes • Other similar consistent streams • Gasification less widely used/proven than incineration	To 20 t/h	• Low leaching residue • Good burnout if oxygen blown • Syngas available • Reduced oxidation of recyclable metals	• Limited waste feed • Not full combustion • High skill level • Tar in raw gas • Less widely proven	• Low leaching bottom ash • Good burnout with oxygen	Lower than straight combustion	High operation/maintenance costs
Gasification – entrained flow	• Mixed plastic wastes • Other similar consistent streams • Not suited to untreated MSW • Gasification less widely used/proven than incineration	To 10 t/h	• Low leaching slag • Reduced oxidation of recyclable metals	• Limited waste feed • Not full combustion • High skill level • Less widely proven	Low leaching slag	Lower than straight combustion	High operation/maintenance costs Pretreatment costs high
Gasification fluid bed	• Mixed plastic wastes • Shredded MSW • Shredder residues • Sludges • Metal rich wastes	5 – 20 t/h	• Can use low reactor temperatures *e.g.* for Al recovery • Separation of main non-combustibles • Can be efficiently	• Limited waste size (<30 cm) • Tar in raw gas • Higher HHV raw gas • Less widely proven	• If combined with ash melting chamber ash is vitrified • Ash quality without ash chamber – info not supplied	Lower than straight combustion	Lower than other gasifiers

	• Other similar consistent streams • Gasification less widely used/proven than incineration		combined with ash melting • Reduced oxidation of recyclable metals				
Pyrolysis short drum **Pyrolysis medium drum**	• Pretreated MSW • High metal inert streams • Shredder residues/plastics • Pyrolysis is less widely used/proven than incineration	~5 t/h 5 – 10 t/h	• No oxidation of metals • No combustion energy for metals/inert • In reactor acid neutralisation possible • Syngas available	• Limited wastes • Process control and engineering critical • High skill level • Not widely proven • Need market for syngas	• Dependent on process temperature • Residue produced requires further processing sometimes combustion	Very low due to low excess air required for gas combustion	High pretreatment, operation and capital costs
Pyrolytic distillation	• (impregnated) wood wastes • biomass or organic wastes • not (yet) proven for pretreated MSW or RDF	~ 1.5 t/h	• Can use low reactor temperatures • Recovery of metals and valuable carbon product • Very low tar and dioxin release	• Homogeneous waste streams • Limited throughput • Process control and engineering critical • Not widely proven	• Coal-type residue (charcoal) containing metals and minerals, • Possible to separate in mechanical way	Lower than straight combustion	*Information not supplied*

Plasma – pyrolysis	• mainly used for liquid and gaseous wastes • proven technology for treating hazardous liquids and gases • not (yet) proven for pretreated MSW or RDF	~ 0.1 t/h	• Can achieve high destruction efficiencies • Very low dioxin/furan emissions • Material recovery • Combustible gas available	• Limited throughput • Solids need to be converted to liquids/gases before being treated (plascon process) • Mostly no useful by-products • Less widely proven	*Information not supplied*	Low in plasma processes	*Information not supplied*
Plasma – gasification vitrification (single-stage)	• gasification and plasma treatment in 1 reactor • MSW (+ tyres, ASR) • RDF • petcoke • hazardous wastes	~ 10 t/h	• Syngas available • Very low dioxin/furan emissions • Vitrified slag can be used as building aggregate	• Part of process energy provided by energy contained in waste • Process control and engineering critical • Not widely proven	Vitrified, inert, low-leaching slag	Low in plasma processes	*Information not supplied*
Plasma – gasification vitrification (two-stage)	• gasification followed by plasma gas cleaning in separate reactor • MSW (+ tyres, ASR) • RDF • hazardous, medical, low-level radioactive waste	~ 10 t/h	*Compared to single-stage:* • Higher throughput • Higher conversion efficiency to a clean, high calorific syngas • Better control over VOCs/tars	• Process control and engineering critical • Not widely proven	Vitrified, inert, low-leaching slag	Low in plasma processes	*Information not supplied*

Acknowledgements

List of acronyms

ASR	automotive shredder residue
CCA	chromate copper arsenate
CFC	chlorofluorocarbon
DC	direct current
ELFM	enhanced landfill mining
EU25	group of 25 countries belonging to the European Union
EWM	enhanced waste management
HFC	Hydrofluorocarbon
HHV	higher heating value
HR	heating rate
LHV	lower heating value
MHV	medium heating value
MSW	municipal solid waste
PCB	polychlorinated biphenyls
PCDD/F	polychlorinated dibenzodioxin and dibenzofuran
PGR	plasma gasification reactor
RDF	refuse derived fuel
RT	residence time
SS	sewage sludge
SSM	sustainable materials management
TOC	total organic carbon
VOC	volatile organic compound
WESP	wet electrostatic precipitator
WtE	waste-to-energy
WtP	waste-to-products

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