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The crucial role of Waste-to-Energy technologies in enhanced landfill mining: a technology review

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ABSTRACT

The novel concepts Enhanced Waste Management (EWM) and Enhanced Landfill Mining (ELFM) intend to place landfilling of waste in a sustainable context. The state of the technology is an important factor in determining the most suitable moment to valorize – either as materials (Waste-to-Product, WtP) or as energy (Waste-to-Energy, WtE) – certain landfill waste streams. The present paper reviews thermochemical technologies (incineration, gasification, pyrolysis, plasma technologies, combinations) for energetic valorization of calorific waste streams, with focus on municipal solid waste (MSW), possibly processed into refuse derived fuel (RDF). The potential and suitability of these thermochemical technologies for ELFM applications are discussed. From this review it is clear that process and waste have to be closely matched, and that some thermochemical processes succeed in recovering both materials and energy from waste. Plasma gasification/vitrification is a viable candidate for combined energy and material valorization, its technical feasibility for MSW/RDF applications (including excavated waste) has been proven on installations ranging from pilot to full scale. The continued advances that are being made in process control and process efficiency are expected to improve the commercial viability of these advanced thermochemical conversion technologies in the near future.

1. Introduction

Waste management has – in accordance with the waste hierarchy as defined in the Waste Framework Directive (2008/98/EC, 2008) – evolved to a stronger focus on waste prevention, material recuperation and recycling (e.g. glass, paper, metals). Despite increasing attention to prevention and sustainability, total municipal solid waste (MSW) generation in the EU25 has raised from about 150 million tons in 1980 to more than 250 million tons in 2005 and is forecasted to reach 300 million tons by 2015 (ETC/RWM, 2007). Increased MSW generation combined with the growing problem of natural resources depletion, makes the transition to Sustainable Materials Management (SMM) crucial.

Sustainable Materials Management comprises the reframing of materials cycles and waste management concepts, targeting closed loop systems (Jones et al., in this issue). Traditional landfilling (i.e. discarding materials on dumps or landfills) cannot be part of SMM as it opposes the idea of a fully closed material cycle. The novel concepts Enhanced Waste Management (EWM) and Enhanced Landfill Mining (ELFM) intend to integrate landfilling of waste in a sustainable context. In EWM, prevention and reuse/recycling become even more important, while landfilling is no longer considered *a final solution*. Instead, landfills are considered *temporary storage places awaiting further treatment* or also *future mines for materials*. Enhanced Landfill Mining represents an iterative valorization approach, targeting both new and old landfills. Waste valorization is its use as material or the conversion into energy or fuels, with particular focus on environmental indicators and sustainability goals. It is covered by the greater objective of loop-closing. Enhanced Landfill Mining offers the opportunity to select the most suitable moment to valorize – as materials (Waste-to-Product, WtP) and/or as energy (Waste-to-Energy, WtE) – certain waste streams, depending for instance on the state of the technology. The non-recyclable fraction needs to be stored again in

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such a way that future mining is possible. Additionally, the 'Enhanced' in ELFM incorporates the goal to prevent the emissions of CO_2 and pollutants arising during the energy/material valorization processes (Jones et al., in this issue). Therefore, sustainable WtP and WtE technologies are greatly needed. The present paper reviews WtE technologies using (pre-processed) MSW as input.

Waste-to-Energy is the process of recovering energy, in the form of electricity and/or heat, from waste. In the past, waste incineration was a technology to reduce the volume and destroy harmful substances in order to prevent threats to human health. Nowadays, waste incineration is almost always combined with energy recovery. The importance of the energy recovery part has increased over time. Denmark and Sweden have been leaders in using the energy generated from incineration for more than a century. In 2005, waste incineration produced 4.8% of the electricity consumption and 13.7% of the total domestic heat consumption in Denmark (Kleis and Dalagar, 2007).

Table 1 gives an overview of the most relevant types of waste and waste derived fuels. Hogland et al. (2010) and van Vossen (2005) estimated that the amount of landfill sites across Europe is between 150,000–500,000 containing a significant amount of MSW. Municipal solid waste is a heterogeneous feedstock containing materials with widely varying sizes, shapes and composition. If the MSW is used 'as received' as input to WtE processes, this can lead to variable (and even unstable) operating conditions, resulting in quality fluctuations in the end product(s). In addition, the more advanced thermochemical treatment technologies require an input feed with a sufficiently high calorific value in order to obtain high process efficiencies. For these reasons, refuse derived fuel (RDF) – a processed form of MSW – is often used as input to WtE systems (Klein, 2002). In general, the process of converting MSW into RDF consists of shredding, screening, sorting, drying and/or pelletization in order to improve the handling characteristics and homogeneity of the material. In case the MSW is excavated from landfill sites, the preprocessing step should be carefully matched to the excavated waste properties in order to obtain a high quality RDF. The main benefits of converting MSW to RDF are a higher calorific value, more homogeneous physical and chemical compositions, lower pollutant emissions, lower ash content, reduced excess air requirement during combustion and finally, easier storage, handling and transportation (NETL, 2012). 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.

Table 1
Different types of waste and waste derived fuels (EIONET, 2012; Lupa et al., 2011; Wagland et al., 2011; Zevenhoven and Saeed, 2003).

Fuel type	Definition
Fuel	Energy carrier intended for energy conversion
Municipal Solid Waste (MSW)	Waste generated by households (may also include similar wastes generated by small businesses and public institutions), e.g. paper, cardboard, metals, textiles, organics (food and garden waste), and wood
Commercial & Industrial Waste (C&IW)	Waste derived from commerce and industry, e.g. packaging, paper, metals, tyres, textiles, and biomass
Refuse Derived Fuel (RDF)	Fuel produced from MSW and/or C&IW that has undergone processing (i.e. separation of recyclables and noncombustible materials, shredding, size reduction, and/or pelletizing), has an input-driven specification
Solid Recovered Fuel (SRF)	Comparable to RDF but considered more homogeneous and less contaminated, is market-driven due to tighter quality specifications
Automotive Shredder Residue (ASR)	Complex mixture of plastics (rigid and foam), rubber, glass, wood, paper, leather, textile, sand plus other dirt, and a significant fraction of metals

The focus in this paper is on available technologies for thermochemical treatment of (calorific) waste streams. The scope is 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 summarizes 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. The evaluation criteria are based on environmental impact, energy efficiency, material recuperation and system operation (e.g. flexibility in dealing with input variation). Hence, this review constitutes the base for selecting best available technique(s) for energetic valorization of specific calorific waste streams. Focus is on MSW, possibly processed into RDF as the majority of advanced thermochemical technologies require a homogeneous process input. Furthermore, a closer look is taken at technologies offering the added benefit of recovering materials – in addition to energy – from the waste feed. In the Waste-to-Product (WtP) concept, waste treatment by-products are used to manufacture valuable (i.e. saleable) coproducts.

2. Waste valorization: boundary conditions

2.1. Bottlenecks

Nowadays, sustainability and its conciliation with the waste management system are hot topics. However, despite the various technologies available for waste valorization, a large number of issues remain unaddressed (Stehlík, 2009).

The environmental aspect including the emissions of pollutants and greenhouse gases, is of particular interest. Waste streams often consist of diverse types of materials, originating from a number of different sources. These raw materials may contain elements such as chlorine, sulfur and heavy metals that could affect the quality of the products formed in the waste treatment process (e.g. syngas, bottom ash, fly ash, digestate, vitrified slag). Consequently, special abatement technologies need to be used to reduce the content of pollutants in the products generated and/or in the emissions to air, water and soil. Evidently, these stringent measures come at a price.

Another bottleneck is the economic feasibility of ELFM which depends strongly on the development of innovative technologies with high WtE efficiencies (Van Passel et al., in this issue). These new technologies need to prove their economic viability prior to full-scale implementation. Energy efficiency is an important system indicator used for comparison with conventional, well-established technologies. A lack of data (both experimental and theoretical) often hampers such a comparative study.

An urgent need exists to gain modeling expertise in the field of waste valorization processes. A validated system model facilitates system design and optimization, in addition to reducing the need for experimental work. Numerical experiments can be used to predict operating conditions when scaling up or down and as such to define optimal operating windows. Furthermore, the suitability of various feedstock can be assessed.

A basic prerequisite for waste treatment processes is the adequate characterization of materials contained in the available waste streams. Characterization data give an indication of the suitability of a specific waste stream for the different valorization options. Furthermore, these data are of crucial importance in determining the technical and economic feasibility of available valorization processes. Unfortunately only limited data are currently available describing the characteristics of wastes from landfills.

The existing environmental legislation mainly focuses on disposal of waste on landfills and on conventional waste treatment techniques, hereby acting as a barrier to the introduction of innovative waste valorization technologies. The ongoing shift towards more sustainability through valorization of waste as both energy and materials should contribute to improve and adapt the existing policy.

2.2. *Waste feed*

As mentioned before, the majority of WtE processes requires pretreated MSW (often processed into RDF) as input. The characteristics of solid waste feedstock are influenced by various factors ranging from storage method (influence on humidity), maturity (large range for excavated landfill waste), sorting policy (differs from country to country) and many more (Quaghebeur et al., in this issue). The successful implementation of WtE technologies in the concept of ELFM depends on the WtE process efficiencies which are in their turn dependent on the feed quality. Previously landfilled materials constitute an important waste stream in the loop-closing concept. Therefore it is crucial to ensure that the composition and characteristics of MSW excavated from landfills (possibly processed into RDF) fall within the range of the WtE process input requirements. Table 2 shows the composition of MSW and RDF as found in the Phyllis database (Phyllis, 2011), both mean value and range are given. It is clear from the provided data that the ash content can vary widely, the same is true for the calorific value. An experimental study on excavated MSW from a landfill has been conducted in Belgium (CMK, 2010). By applying conventional pretreatment techniques (shredding, screening, sorting, drying and/or pelletization), the waste has also been processed into RDF. The results (see Table 2) demonstrate that the waste composition of RDF falls within the ranges of values found in the Phyllis database.

3. Thermochemical conversion technologies: overview

Fig. 1 summarizes the available technologies for energetic valorization of waste. Direct combustion or incineration is the most conventional Waste-to-Energy approach, directly generating heat.

Table 2
Composition of MSW and RDF: mean values and [min.–max.].

		MSW (Phyllis, 2011)	RDF (Phyllis, 2011)	RDF processed from landfill waste
Water content	wt% wet	34.2 [31.0–38.5]	10.8 [2.9–38.7]	14.4 [12–35.4]
Volatiles	wt% daf[a]	87.1 [87.1]	88.5 [74.6–99.4]	80.4
Ash	wt% dry	33.4 [16.6–44.2]	15.8 [7.8–34.5]	27.1
NCV[b]	MJ/kg daf	18.7 [12.1–22.5]	22.6 [16.1–29.3]	22.0
C	wt% daf	49.5 [33.9–56.8]	54.6 [42.5–68.7]	54.9
H	wt% daf	5.60 [1.72–8.46]	8.37 [5.84-15.16]	7.38
O	wt% daf	32.4 [22.4–38.5]	34.4 [15.8–43.7]	NA[c]
N	wt% daf	1.33 [0.70–1.95]	0.91 [0.22–2.37]	2.03
S	wt% daf	0.51 [0.22–1.40]	0.41 [0.01–1.27]	0.36

[a] Dry ash free.
[b] Net calorific value.
[c] Not available.

Besides incineration more advanced thermochemical approaches, such as pyrolysis, gasification and plasma-based technologies, have been developed since the 1970s (Kolb and Seifert, 2002). In general these alternative technologies have been applied to selected waste streams and on a smaller scale than incineration. Process conditions are strictly controlled in specially designed reactors (see Table 3). 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 the sense that they may be used for recovering the chemical value of 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. In general, these types of integrated processes recover, in total, 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 into 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 engines, characterized by a high electrical efficiency. In order to compare the economic performance of different technologies, the net electrical efficiency $\eta_{P,e}$ is often used. This number is defined as the ratio of the exported electricity (i.e. produced electricity *minus* consumed electricity) over the input energy (i.e. waste feed rate *times* net calorific value):

$$\eta_{P,e} = \frac{\dot{E}_{\mathrm{el,exp}}}{\dot{m}_{\mathrm{waste}} \cdot \mathrm{NCV}_{\mathrm{waste}}}$$

with $\dot{E}_{\mathrm{el,exp}}$ the amount of electricity exported (kW), $\dot{m}$ the mass flow rate (kg s^{-1}), and NCV the net calorific value (kJ kg^{-1}).

The following sections discuss and compare the main available thermochemical conversion technologies for calorific waste treatment:

1. incineration – full oxidative combustion;
2. gasification – partial oxidation;
3. pyrolysis – thermal degradation of organic material in the absence of oxygen;
4. plasma-based technologies – combination of (plasma-assisted) pyrolysis/gasification of the organic fraction and plasma vitrification of the inorganic fraction of waste feed.

The reactor conditions of these thermal treatments vary, Table 3 provides a rough indication.

3.1. *Incineration*

Basically, incineration is the oxidation of the combustible materials contained in the waste. Incineration is used as a treatment for a very wide range of wastes. Waste is generally a highly heterogeneous material, consisting essentially of organic substances, minerals, metals and water. 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

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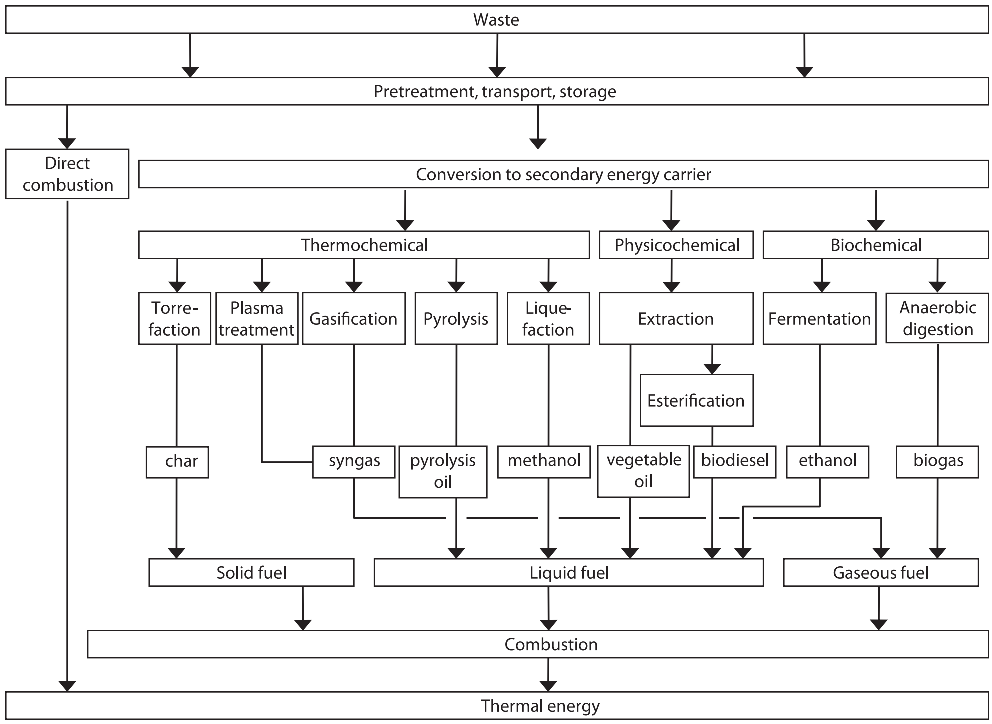

Fig. 1. Waste-to-Energy technologies, based on (Kaltschmitt and Reinhardt, 1997).

during waste incineration may only be possible to a limited extent. It is however possible to influence these processes in order to reduce pollutant emissions, for example by using measures such as furnace design, air distribution and control engineering.

During incineration, flue gases (CO_2, H_2O, O_2, N_2) are generated that contain the majority of the available fuel energy as heat. 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 are formed or remain (BREF, 2006). Nevertheless, waste incineration can 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. Waste incinerators produce a higher gas volume for the same feed rate in comparison with gasification, pyrolysis and plasma-based systems working under substoichiometric conditions. The gas cleaning equipment scales accordingly. The proportions of solid residue (fly and bottom ash, slag, filter dust, other residues from the flue gas cleaning – e.g. calcium or sodium chlorides – and sludge from waste water treatment) vary greatly according to the waste type and detailed process design. In MSW incinerators, the bottom ash constitutes approximately 25–30 % by weight of the solid waste input. Additional treatment can improve bottom ash characteristics and would allow its use in concrete aggregates and other construction materials. In particular, vitrification receives a lot of attention as a promising technology for the transformation of MSW bottom ash into inert materials. However, since vitrification is an energy-intensive process involving high costs, its use can only be justified if a high-quality product can be fabricated. Research in this field is ongoing (Schabbach et al., 2012). Fly ash quantities are much

Table 3
Characteristics of the main thermochemical conversion technologies (based on Kolb and Seifert (2002)).

	Pyrolysis	Gasification	Combustion	Plasma treatment
Aim	Maximize thermal decomposition of solid waste into coke, gases and condensed phases	Maximize waste conversion into high calorific fuel gases	Maximize waste conversion into high temperature flue gases	Maximize waste conversion into high calorific fuel gases and an inert solid slag phase
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, water			

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lower, generally 1–5 % by weight of the input (EMIS, 2010). Fly ash immobilization is required in order to make it environmentally safe for landfill disposal.

The incineration sector has undergone rapid technological development over the last 10–15 years. Much of this change has been driven by legislation specific to the industry. The application and enforcement of modern emission standards stands as an example. The use of modern pollution control technologies has reduced emissions to air to levels at which pollution risks from waste incinerators are now considered to be very low (BREF, 2006). Continuous process development is ongoing, with the sector developing techniques which limit operating costs and at the same time maintaining or improving environmental performance. The 4th generation WtE plant that has been built by Amsterdam's Afval Energie Bedrijf (AEB) in the Netherlands offers a leading example of how incinerators can attain both a high energy and material recovery. The net electrical efficiency is expected to reach>30%, as opposed to the 22–26% net electrical efficiency of current state-of-the-art incineration plants. Process data obtained for one year of operation (09/2009–09/2010) show a net electrical efficiency between 20% and 31% (Van Berlo, 2010) which confirms it is possible to meet the high expectations but not continuously. Furthermore, it was not reported whether the plant was continuously operating under full load. Bottom ash is treated in a slag reprocessing pilot plant facility where valuable metals (Al, Cu, Fe) are recovered and the bottom ash residue is processed into granulate for the construction industry. Fly ash is separated in the electro-filter and can be used in asphalt concrete. In one of the flue gas treatment steps, acids react with limestone ($CaCO_3$). This stream is further processed into a purified calcium chloride salt solution (used for road de-icing). Gypsum is another byproduct of the flue gas treatment, it can be used in the production of building materials, plaster blocks, and plasterboard walls. The available data did not allow to judge the effectiveness and maturity of the abovementioned techniques. The authors expect to obtain more detailed information in future published results of the AEB's waste treatment facility in Amsterdam.

The three main incinerator types are grate incinerators, rotary kilns and fluidized beds. Table 4 summarizes the key features of these three incinerator types. More detailed process descriptions can be found elsewhere (BREF, 2006; BREF, 2010; Limerick, 2005; UBA, 2001). The detailed design of a waste incineration plant will change according to the type of waste that is being treated. Key drivers are the chemical composition, physical and thermal characteristics of the waste together with the variability of these parameters. Processes designed for a narrow range of specific inputs can usually be optimized 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 simplification of downstream operations such as flue gas cleaning. As flue gas cleaning is often an important contributor to overall incineration costs (i.e. 15–35% 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 substantially to the overall costs of waste management and to emissions from the entire waste management system. Within the context of ELFM, screening and characterization of landfilled material is of crucial importance. This step allows to sort out the recyclable fraction but it also provides information about the waste composition and its heterogeneity, which are both very important in determining the appropriate treatment technique and process conditions. Elsewhere in this journal issue, this topic is discussed in more detail (Quaghebeur et al., in this issue).

3.2. Gasification

Gasification is a partial oxidation of organic substances at elevated temperature (500–1800 °C) to produce a synthesis gas. This synthesis gas or syngas can be used as a feedstock for the chemical industry (through some reforming processes), or as a fuel for efficient production of electricity and/or heat (UBA, 2001). The synthesis gas contains CO, CO_2, H_2, H_2O, CH_4, trace amounts of higher hydrocarbons such as ethane and propane, inert gases originating from the gasification agent and various contaminants such as small char particles (Bridgwater, 1994). A gasifier can use air, oxygen, steam, carbon dioxide or a mixture of these as gasification agents. Air gasification produces a low-energy gas (4–7 MJ Nm^{-3} NCV), while oxygen gasification produces a medium-energy gas (10–18 MJ Nm^{-3} NCV) (Helsen, 2000).

Table 4
Process characteristics of the three main incinerator types (based on BREF (2006)).

	Grate incinerator	Rotary kiln	Fluidized bed
Process description	The grate moves the waste through the various zones of the combustion chamber (tumbling motion)	Cylindrical vessel located on rollers which allow the kiln to rotate/oscillate around its axis, waste is conveyed by gravity	Lined combustion chamber in the form of a vertical cylinder, the lower section consists of a bed of inert material which is fluidized with air, waste is continuously fed into the fluid sand bed
Commonly applied for	Mixed municipal wastes, possible additions: commercial and industrial non-hazardous wastes, sewage sludge, clinical wastes	Hazardous and clinical waste	Finely divided wastes (e.g. RDF, sewage sludge)
Process temperature	850–1100 °C	850–1300 °C	Freeboard: 850–950 °C Bed: 650 °C (or higher)
Remarks	Most widely applied	- very robust, allows the incineration of solid, liquid, gaseous wastes and sludges - to increase the destruction of toxic compounds, a post-combustion chamber is usually added	3 types: - bubbling: commonly used for sludges (sewage and (petro)chemical) - circulating: especially appropriate for the incineration of dried sewage sludge with high calorific value - rotating: allows for wide range of calorific value of fuels (co-combustion of sludges and pretreated wastes)

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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 (i.e. high conversion efficiencies and minimal tar formation) requires that the nature (size, consistency) of the waste input remains within certain predefined limits. Typically, this requires dedicated pretreatment of MSW, thereby increasing the cost.

The following types of gasification reactors are most frequently encountered in practice: fixed bed gasifier, fluidized bed gasifier, and entrained flow gasifier. Table 5 summarizes the key features of each gasifier type. The feedstock (waste) material must be finely granulated for utilization in gasifiers. Thus pretreatment is necessary, especially for MSW. Hazardous wastes may be gasified directly if they are liquid or finely granulated.

Distinctive features of gasification processes include: 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; and the possibility to recover the material and energy content of the products (synthesis gas and possibly molten slag). The slagging gasifier in particular is very well suited to recover both the energy and material value of the waste feed. EBARA Corp. and UBE Industries Ltd. developed a *two-stage pressurized gasification and slagging* process (EUP) comprising a low temperature and high temperature gasification reactor (Fig. 2), both operating under elevated pressure (7–8 bar). The technology is applied in Japan to generate synthesis gas from pre-processed waste plastics, while also recycling metals and glass granulate. The synthesis gas can serve as a feedstock for the chemical industry (e.g. ammonia synthesis) or as a fuel for combined-cycle power generation. In the first process stage, gasification takes place in an oxy-steam fluidized bed reactor at low temperatures (600–800 °C) to avoid melting of metals like aluminum. This allows a high recovery rate of metals at the bottom of the gasifier in non-oxidized and thus readily marketable form, making the technology particularly attractive for the treatment of waste streams with high metal content (e.g. automotive shredder residue or ASR). On the other hand, low temperatures slow down gasification reactions thus the gas flow leaving the gasification reactor still carries a high load of combustible material. The second stage consists of a cyclonic high temperature gasifier designed to handle flows with a significant content of solids above their melting point (1300–1500 °C). Molten ashes are collected in the quenching bath at the bottom of the cyclonic reactor where they solidify into a totally inert, vitrified granular slag. Presently, a number of plants are operating or under construction in Japan. Unfortunately, most of EBARA's reports on this technology are published in Japanese only, making it difficult to report relevant data from the gasification plants in operation.

Other variations on gasification processes have been tried and are being developed, for a variety of waste streams. Examples can be found elsewhere (BREF, 2006; Bridgwater, 1995; Bridgwater, 2003)

3.3. Pyrolysis

Pyrolysis is thermal degradation either in the complete absence of an oxidizing agent, or with only a limited supply (i.e. partial gasification) in order to provide the thermal energy required for pyrolysis. 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 summarized in Table 6 (Bridgwater, 2003; Helsen, 2000). The calorific values of pyrolysis gas typically lie between 5 and 15 MJ/m^{-3} based on MSW and between 15 and 30 MJ/m^{-3} based on RDF (UBA, 2001).

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

1. Preparation and grinding: the grinder improves and standardizes the quality of the waste presented for processing and so promotes heat transfer.
2. Drying (depends on process): a separated drying step improves the net calorific value of the raw process gases and increases efficiency of gas–solid reactions within the reactor.
3. Pyrolysis of wastes: in addition to the pyrolysis gas, a solid carbon-containing residue accumulates which also contains mineral and metallic portions.
4. Secondary treatment of pyrolysis gas and pyrolysis coke: through 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 ingredients and simultaneous utilization of energy.

Conventional pyrolysis reactors have one of the following configurations: fixed bed, fluidized bed, entrained flow, moving bed, rotary kiln, ablative reactor, etc., and often require waste

Table 5
Process characteristics of the three main gasifier types for waste treatment (based on Bridgwater (1995)).

	Fixed bed	Fluidized bed	Entrained flow
Process description	- downdraft: solid moves down, gas moves down - updraft: solid moves down, gas moves up	- bubbling: low gas velocity, inert material stays in reactor - circulating: inert material is elutriated, separated and recirculated	- type of fluidized bed - usually no inert solid, high gas velocity - can be run as cyclonic reactor
Process temperature	1000 °C	800–850 °C	1200–1500 °C
Remarks	- simple and robust construction - finely granulated feedstock required - downdraft: low moisture fuels required, low tar content in product gas - updraft: low exit gas temperature, high levels of tar in product gas	- greater tolerance to particle size range than fixed beds - moderate tar levels in product gas - bubbling: tolerates variations in fuel quality - circulating: operation more difficult than fixed beds	- finely granulated feedstock required - low tar and methane content in product gas - potential slagging of ash

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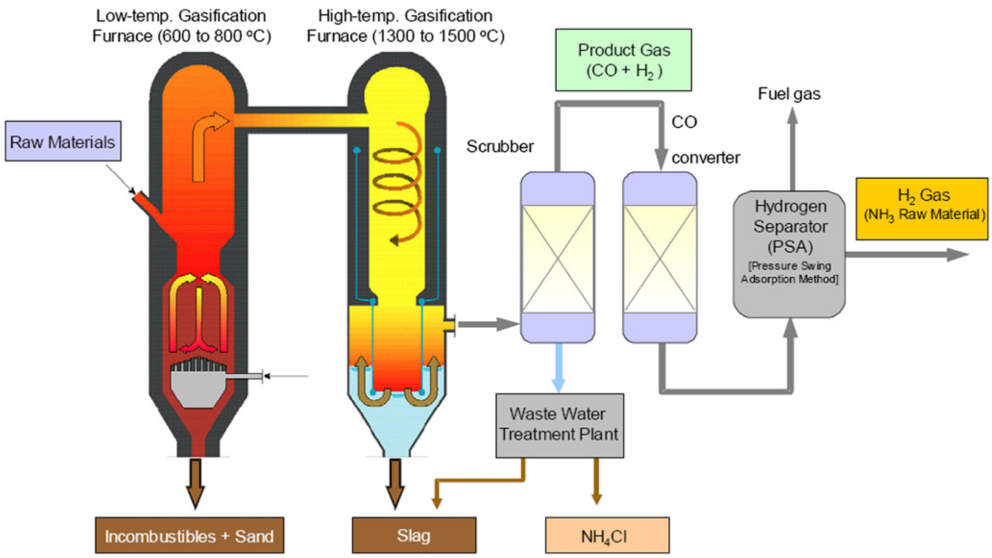

Fig. 2. Two-stage pressurized gasification: combined energy and material recovery (Steiner et al., 2002).

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 (Helsen, 2000). 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.

In addition to the thermal treatment of MSW and sewage sludge, pyrolysis processes are also used for decontamination of soil, treatment of synthetic waste and used tires, treatment of cable tails as well as metal and plastic compound materials for substance recovery. Often waste pretreatment is required.

Pyrolysis processes may offer a number of advantages with respect to material and energy recovery from the feed. It is possible to recover (part of) the organic fraction as material/fuel (e.g. as methanol). Char can be recovered for external use, taking into account any necessary pretreatment (e.g. washing of chlorine). Pyrolysis gas could be used to power gas engines or gas turbines which generate electricity more efficiently than conventional steam boilers. Pyrolysis processes have smaller flue gas volumes (after combustion) than incinerators, this reduces the flue gas treatment capital costs to some degree.

As an illustrative example, the ConTherm pyrolysis plant for waste treatment, developed by RWE Power AG (Hamm, Germany), is briefly discussed here. The pyrolysis plant is designed to be added to an existing power plant (Hauk et al., 2004) with the aim to reduce primary fuel consumption (i.e. coal). The pyrolysis unit consists of two lines of drum-type kilns with a capacity of 50 k tons each. The kilns operate at 450–550 °C in the absence of oxygen, producing coke, pyrolysis gas, metals and inert materials within a residence time of 1 h. The solid residue is separated into a coarse fraction (metals, inerts) and a fine fraction, containing 99% of the carbon as coke. A cyclone de-dusts the pyrolysis gas, after which the deposited dusts and carbon particles are added to the pyrolysis coke. Emission data are not available.

At present, the Contherm plant is no longer in operation. In December 2009, the chimney collapsed due to insulation problems which had led to a very high heat buildup and consequently softening of the steel. Based on the results of a profitability study, it was decided not to rebuild the chimney. Inadequate sorting of the incoming waste material had been indicated as the key issue. Feed composition did no longer match the process as designed, resulting in process temperatures beyond tolerable limits. This case study highlights the importance of matching process and waste input.

Table 6
Pyrolysis technology variants (RT and HR stand for residence time and heating rate, respectively).

Pyrolysis technology	RT	HR	T_{max} [°C]	Product
Carbonization	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

3.4. Combination processes

Besides the individual processes (incineration, gasification or pyrolysis), combinations of these processes, possibly combined with other processes (e.g. melting, distillation) are also applied. A few examples of available technologies are briefly outlined in Table 7.

The cited references provide more detailed information on the combination processes mentioned in Table 7.

Table 7
Examples of combination processes for waste treatment.

Combination	Feedstock	Plants in operation	Reference
Pyrolysis-gasification (Thermoselect)	MSW, non-hazardous IW, ASR	6	(Yamada et al., 2004)
Gasification-combustion (EBARA TwinRec)	Wide range of wastes (max. size: 300 mm)	8	(Steiner et al., 2002)
Pyrolysis-distillation (Chartherm)	Metal impregnated (CCA[a]) wood waste (chips)	1	(Helsen, 2009)

[a] Chromated copper arsenate.

3.5. 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 a 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 (Huang and Tang, 2007): the high temperature or fusion plasmas on the one hand, in which all species are in a thermodynamic equilibrium state and the low temperature plasmas or gas discharges on the other hand. The low temperature plasmas can further be divided into thermal plasmas in which a quasi-equilibrium state occurs (high electron density and $2000\,^{\circ}C < T_{plasma} < 30{,}000\,^{\circ}C$), and the cold plasmas characterized by a non-equilibrium state (Tendero et al., 2006). 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. 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. Plasma offers a number of advantages to waste treatment processes (Heberlein and Murphy, 2008). The high energy densities and temperature that can be achieved in plasma processes allow to achieve high heat and reactant transfer rates, to reduce the size of the installation for a given waste throughput, and to melt high temperature materials which increases the overall waste volume reduction. Since electricity is used as the energy source, heat generation is decoupled from process chemistry which increases process controllability and flexibility. On the other hand, electricity is an expensive energy vector, turning economic considerations into the strongest barrier for using plasmas for waste treatment. Here, the use of plasmas is attractive when the value of the products compensates for the actual costs. Generation of syngas, hydrogen or electricity are prime examples of such valuable products.

Plasma technologies for waste treatment can be divided into different categories (Heberlein and Murphy, 2008): 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). 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 calorific value, plasma processes can offer an attractive alternative to complete combustion and steam generation as the plasma treatment recovers the energy value of 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 unfavorable since it is more difficult to obtain a valuable 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 oxidized and immobilized in a vitrified non-leaching slag.

3.5.1. Plasma pyrolysis

Among the different plasma waste treatment processes, the most extensive scientific studies have been performed on plasma pyrolysis. More information can be found in the literature (Murphy and Kovitya, 1993; Murphy and McAllister, 1998; Murphy and McAllister, 2001). 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 (Huang and Tang, 2007). Plasma pyrolysis of organic waste usually results in two product streams: a combustible gas and a carbonaceous residue (char). Similar to conventional pyrolysis, 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 (Tang and Huang, 2005). 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 in industrial applications.

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.) applies plasma pyrolysis to fluid wastes containing halogenated hydrocarbons, CFCs, HFCs, PCBs and other harmful components. Presently, ten plants are operating in Australia, Japan, USA and Mexico (Heberlein and Murphy, 2008).

There exist relatively small scale plasma pyrolysis installations for treating polymers (Guddeti et al., 2000), medical waste (Nema and Ganeshprasad, 2002) and low-level radioactive waste (HTTC, 2009). However, no information was found on industrial plasma pyrolysis facilities processing MSW or RDF, the type of solid waste this paper focuses on. The preferred plasma-based technology for solid waste treatment seems to be plasma gasification and vitrification. The next subsection describes this technology in more detail.

3.5.2. Plasma gasification and vitrification

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. The energy contained in a plasma allows the use of low-energy fuels, such as household and industrial waste that often cannot sustain their own gasification without additional fuel. 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

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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) (Malkow, 2004). The vitrified slag should be inert for leaching processes and consequently applicable as, for example, a building material additive (Lapa et al., 2002).

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 (Heberlein and Murphy, 2008). 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. Research activities at the Czech Academy of Sciences (Hrabovsky, 2002) have shown that plasma torches operating with steam offer definite advantages for waste processing applications due to the fact that these torches are characterized by a high arc power and a very high plasma enthalpy and temperature. 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 (Heberlein and Murphy, 2008).

The fact that gas plasma 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 (Lemmens et al., 2007). 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. Transferred arc torches offer high heat fluxes which is advantageous for solids melting (Heberlein and Murphy, 2008). An interesting application is the treatment of solid wastes that require decontamination as well as volume reduction and immobilization of inorganic contaminants.

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 calorific value of the waste and/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 load). 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. More detailed information about the Westinghouse process and its implementation can be found elsewhere (Juniper, 2008; WPC, 2010). *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 tons of fly ash per day, a larger installation in Shimonoseki (Japan) can process daily 42 tons of fly ash and bottom ash. Europlasma is currently building a 12 MW gasification plant for solid waste treatment in Morcenx (France) (Europlasma, 2012). 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 as TurboPlasma®) replaces the different synthesis gas cleaning stages.

A fundamentally different design of plasma arc waste conversion uses plasma to refine gases produced during waste conversion (two-stage or twin-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 tons per day of MSW. Plasco uses plasma only to refine the gases released from waste gasification in an oxygen-starved conversion chamber. The torches interact with the gas only, limiting electricity demand. The process converts waste into a syngas that is used to run internal combustion gas engines (ADEME, 2009).

Tetronics developed a similar process (the Gasplasma™ process) which combines fluidized bed gasification with plasma cleaning of the resulting hydrogen-rich syngas. Fig. 3 shows the Gasplasma™ system flow sheet. The syngas production process comprises two steps; first, in a fluidized bed gasifier VOCs and carbon are converted into a crude syngas 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. Rigorous pilot plant trials are being performed on RDF from a different number of sources (including MSW excavated from a landfill). The first results are promising and show this technology offers great potential for waste valorization. More detailed information on the Gasplasma™ process can be found elsewhere (APP, 2012; Fichtner, 2008).

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 syngas (i.e. a clean and high calorific syngas). These parameters relate to the interaction of the waste feed (RDF) with the plasma system. The reduced throughput relates to the fact that plasma decomposition of RDF is much slower than the decomposition of tars and chars in the syngas. Single-stage plasma gasification processes consume approximately 800 kWh electricity per ton of MSW, corresponding to approximately 2000 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. 2500 kWh). Such high energy consumptions can only

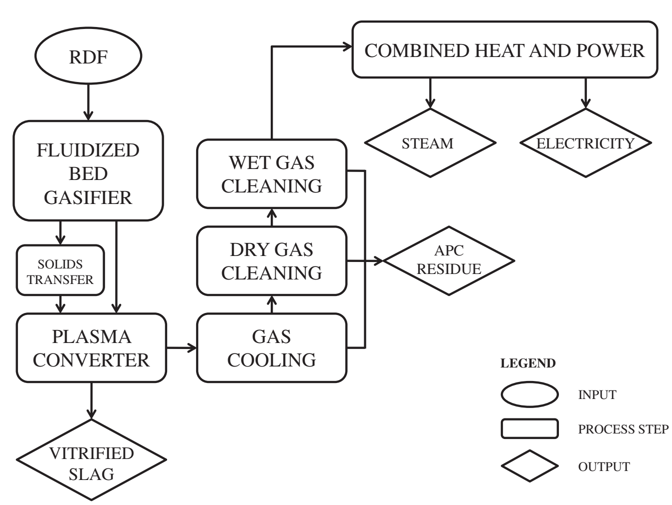

Fig. 3. Flow sheet of the Gasplasma™ process (based on online information provided by advanced plasma power (APP, 2012)).

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 process streams (e.g. hazardous or medical waste), while the two-stage gasification process performs better for larger waste streams (Taylor, 2009). This statement has to be verified by pilot plant tests.

Table 8 lists specific electricity requirements (net electric power consumed per ton waste) for a number of plasma gasification waste treatment processes (Heberlein and Murphy, 2008). 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 per ton (Cleiren and GOM-Antwerpen, 2000)) 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 favor 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.

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 valorization can be found, e.g. in Utashinai and in Mihama-Mikata, processing daily respectively 180 and 22 tons. These two plants are equipped with the Westinghouse plasma gasification process which has been critically reviewed by Juniper Consultancy Services Ltd. (Juniper, 2008).

4. Comparison of the different Waste-to-Energy technologies

Fig. 4 gives an overview of the available WtE technologies for MSW and RDF treatment.

The advantages and disadvantages of the four main types of thermochemical treatment technologies for MSW and/or RDF (i.e. incineration, pyrolysis, gasification and plasma gasification/vitrification) are discussed in more detail below. Focus is put on the possibilities these technologies offer in view of the WtE and WtP valorization routes – an important pillar in ELFM. The key findings are synthesized in Table 9.

Incineration processes can provide a means to enable energy recovery of wastes. Municipal solid waste incinerators in particular offer a large potential source of heat/electricity, especially in the case where combined heat and power (CHP) is applied. As is shown in Fig. 5, the WtE possibilities for MSW incineration consist of recovering heat directly from the process and/or generating electricity using steam turbines. The flue gas quality does not comply with the high-quality standards required for gas turbines and gas engines which produce electricity more efficiently than steam turbines. Nevertheless, state-of-the-art WtE incineration facilities can reach net electrical efficiencies of up to 26%.

Solid waste incinerators can obtain a significant waste volume reduction of about 90% (Cheeseman et al., 2003) but still, a substantial volume of residues has to be disposed of – mostly on landfills. Fly ash requires immobilization to make it environmentally safe for landfill disposal. Incinerator bottom ash is a highly heterogeneous mix of slag, ferrous and non-ferrous metal, ceramics, glass, other non-combustibles and residual organic matter. The composition is directly related to the composition of the waste being incinerated and the sources of various elements in MSW are diverse and influence the characteristics of the bottom ash produced (Cheeseman et al., 2003). The potential risk of leaching of heavy metals has up till now restricted the reuse of bottom ash and it is still mostly disposed of in landfill. The conversion of MSW bottom ash into environmentally benign products calls for advanced thermal treatment options. Vitrification units, for example, require substantial additional energy, resulting in less potential for energy recovery. To conclude, MSW

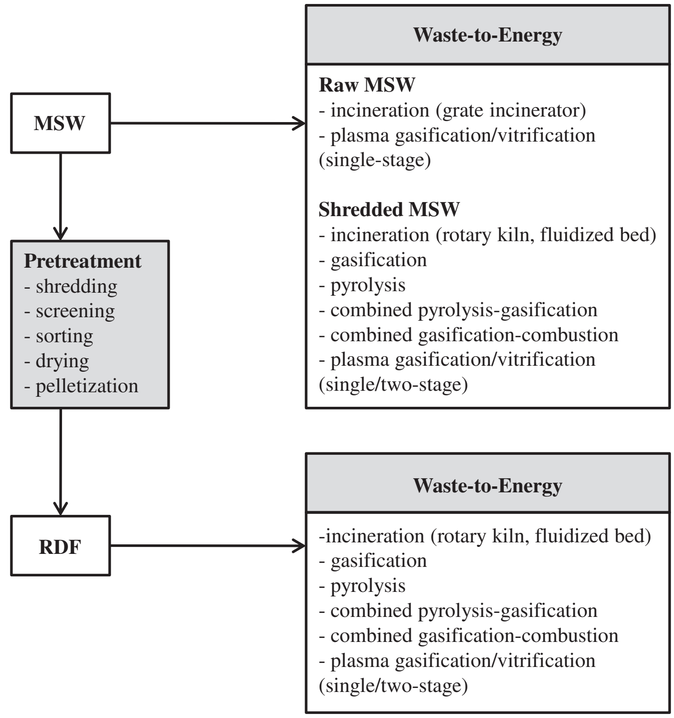

Fig. 4. Thermochemical WtE technologies for MSW and RDF.

Table 8
Electric power requirements for plasma gasification processes (Genon et al., 2010; Heberlein and Murphy, 2008).

Plasma gasification technology	Feedstock	Electric power requirement [kWh/ton]
Westinghouse Plasma Corp. (Japan)	MSW + ASR	400
Europlasma (France, Japan)	Fly ash	800–1300
Tetronics (United Kingdom)	Bottom ash	550
Integrated Environmental Technologies (USA)	Medical waste	1100
Pyrogenesis Corporation (Canada)	MSW	845

Table 9
Indication of the ELFM potential of the four main thermochemical waste treatment technologies.

	Suitable for MSW/RDF (incl. excavated waste)	WtE and WtP potential	Commercially proven
Incineration	++	–	++
Pyrolysis	––	–	–
Gasification	+	+	+
Plasma gasification /vitrification	++	++	–

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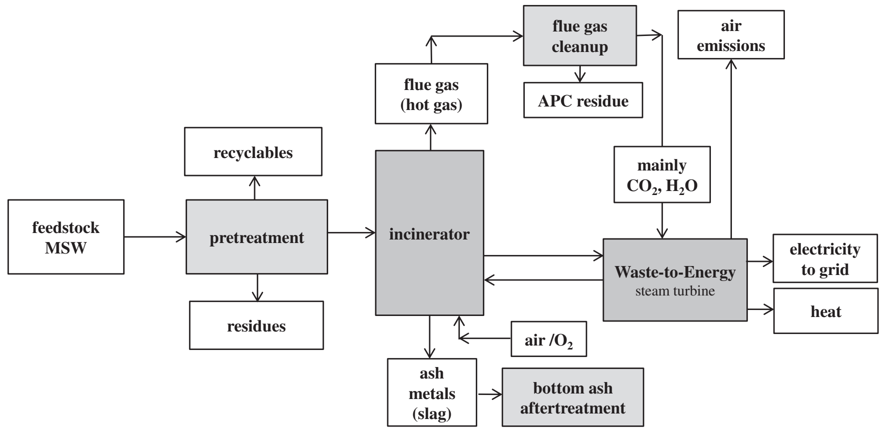

Fig. 5. WtE – from MSW to electricity (and heat) through incineration (APC stands for air pollution control).

incinerators hold a considerable WtE potential but they do not hold a promising WtP potential.

Pyrolysis produces a combustible gas, a solid product and – depending on the type of pyrolysis process – a liquid product. As shown in Fig. 6, the gaseous stream consists primarily of CO and H_2, which makes it suitable for combustion in gas turbines and gas engines, and even for use in fuel cells. Pyrolysis has demonstrated its feasibility for specific feed material (e.g. tires, electronic waste) but it does not offer a complete alternative to MSW incineration. The necessity of waste pretreatment/aftertreatment constitutes the main problem. Also, process conditions need to be optimized 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 example, the solid residue (char) from pyrolysis processes applied to MSW is usually disposed to landfill, a major environmental shortcoming (Young, 2010).

Due to the fact that (excavated) MSW is a highly heterogeneous material, the necessity to process MSW into a stream that complies with the stringent conditions inherent to pyrolysis processes is very likely to endanger the commercial viability of the process.

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_2 and NO_x is limited and the volume of process gas is low, requiring smaller and less expensive gas cleaning equipment. The lower gas volume also results in a higher partial pressure of contaminants in the off-gas, which favors more complete adsorption/absorption and particulate capture. Certain types of gasification reactors are capable of capturing the inorganic waste material in a vitrified non-leaching slag (e.g. the high temperature slagging gasifier (EBARA, 2007) and the plasma gasifier (WPC, 2010)). Moreover, waste volume reduction is increased compared to incineration. Finally, gasification generates a combustible gas that can be integrated with combined cycle turbines, gas engines and, potentially, with fuel cells for electricity (and heat) generation, these components produce electricity more efficiently than steam turbines. Unfortunately, syngas is still commonly burned in steam boilers. In Japan, less than 10% of the gasification plants generate electricity by high efficiency systems after syngas cleaning (Genon et al., 2010). Economical as well as practical considerations play a role here; as tar is burned in the combustor there is no need for extensive gas cleaning equipment which would add significantly to the plant investment costs. The WtE process schematic for MSW gasification is illustrated in Fig. 7. There is a WtP potential if a slagging gasifier is used. The first commercial slagging gasifier developed by British Gas/Lurgi (BGL) was operated at Schwarze Pumpe, from 2000 until 2007, using a broad range of feedstock including waste (Hirschfelder and Olschar, 2010). The process was primarily used for the generation of 'tar-free' syngas with a high calorific value, mainly required in the methanol synthesis

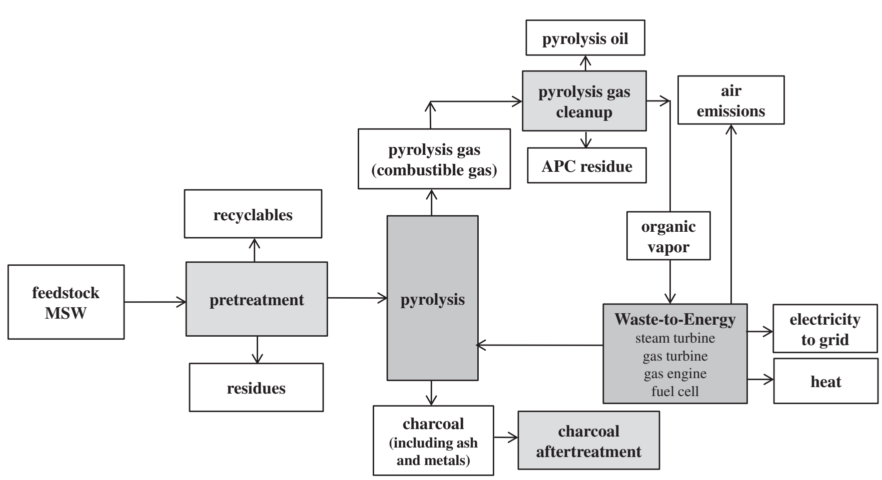

Fig. 6. WtE – from MSW to electricity (and heat) through pyrolysis.

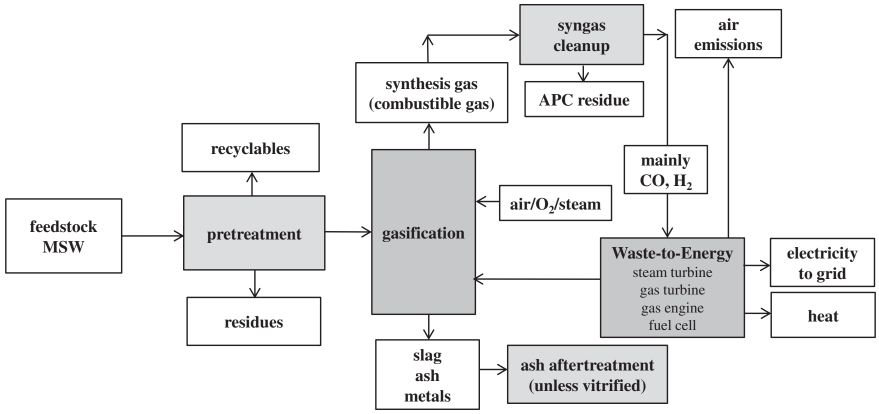

Fig. 7. WtE – from MSW to electricity (and heat) through gasification.

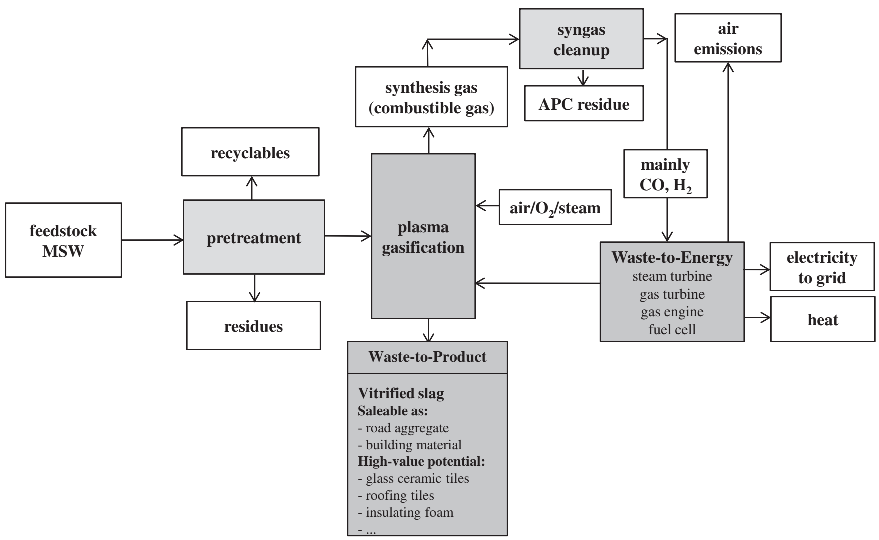

Fig. 8. WtE and WtP – from MSW to electricity, heat, and other valuable products through plasma gasification/vitrification.

(Envirotherm, 2007). The relatively long period of successful operation proves that slagging gasification can be a commercially viable waste treatment technology, offering both a high WtE and WtP potential.

Plasma technologies are becoming more and more attractive. The driving force is to give priority to environmental quality at affordable cost, hereby contributing to sustainable development (Van Oost et al., 2006). 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 products making it an attractive waste treatment option in the ELFM concept. Plasma technologies for waste treatment can be divided into different categories; plasma pyrolysis, plasma gasification, and plasma compaction and vitrification. Plasma gasification is often combined with vitrification for the treatment of solid waste containing high fractions of organics. 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 (i.e. relatively low throughput, poor control of VOCs/tars and a low conversion efficiency to a valuable synthesis gas). Fig. 8 shows the opportunities offered by plasma gasification/vitrification of MSW in the field of WtE and WtP.

Due to their high cost (electricity is an expensive energy source), plasma systems have primarily been used for the treatment of several hazardous wastes (e.g. medical waste, low-level radioactive waste). In this field, plasma vitrification units have already demonstrated their technical feasibility. Nowadays, plasma systems are becoming more accepted and their design is simplified, which means there is potential for widening its foothold in waste management (Gagnon and Carabin, 2006). The cost savings associated with landfill avoidance and the added value of the potentially marketable products are the main economical advantages of plasma gasification and vitrification of wastes. From an environmental point of view, plasma systems have the potential to offer a viable alternative to landfilling and conventional incineration, with lower air pollution and virtually no residual waste streams 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. 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. This vitrified slag can

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be used as a construction material or even as a high-end secondary product (e.g. interlocking blocks, tiles, and bricks). The vitrification process allows to attain a significant volume reduction, typically more than 5:1 for ash and more than 50:1 for solid waste (Gagnon and Carabin, 2006). Within a regulatory context, combined plasma gasification and vitrification is regarded as a recovery process as opposed to a disposal technology, hereby increasing its social acceptance.

5. Conclusions

The ELFM approach includes the combined valorization of landfill waste as both materials (WtP) and energy (WtE), and incorporates the goal to prevent CO_2 and pollutants emissions during these valorization processes. The landfill mining potential (i.e. the potential for recycling and energy/materials valorization) for a specific landfill depends on a number of factors. The characteristics and valorization potential of the stored materials are influenced by the degree of mixing, the age and type of the landfill as well as by the country or region where the landfill is located. Qualitative and quantitative analyses of the stored waste streams are of crucial importance to determine their suitability as feedstock for WtP and WtE processes. Preliminary tests carried out in Belgium show promising results and indicate that it is feasible to process excavated MSW into RDF with a composition similar to RDF processed from 'fresh' MSW.

The current paper reviews thermochemical conversion technologies for the energetic valorization of waste, either 'fresh' waste or previously landfilled waste. Although some WtE processes accept raw (i.e. as received) MSW as input, the majority of WtE processes require a preprocessed form of MSW as the chemistry and fluid dynamics of more advanced technologies are very sensitive to feedstock variations (composition, humidity, ash content, particle size, density, reactivity, etc.). A more homogeneous waste input reduces variable and/or unstable operating conditions as well as fluctuating product qualities. Moreover, the more homogeneous properties allow for tighter process control, thus more stringent product quality specifications can be met.

Some WtE processes (e.g. slagging gasification and plasma based technologies) may also lead to material recovery, captured within the WtP concept, resulting in a combined valorization process. Plasma gasification is a relative newcomer in the field of MSW/RDF treatment. Continued advances are being made in the application of plasma technology for waste treatment, hereby increasing the acceptance of this technology as a viable alternative to more conventional treatment options. 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...) 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 the potential to recover both the energy and material value of the waste feed. The commercial viability of plasma technologies is expected to improve in the future, provided that regulatory, economic and socio-political drivers continue to encourage the implementation of advanced thermochemical conversion technologies.

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Acronyms

APC	air pollution control
ASR	automotive shredder residue
CCA	chromated copper arsenate
CHP	combined heat and power
C&IW	commercial and industrial waste
CFC	chlorofluorocarbon
DAF	dry ash free
ELFM	enhanced landfill mining
EU25	group of 25 countries belonging to the European Union
EWM	enhanced waste management
HFC	hydrofluorocarbon
HR	heating rate
MSW	municipal solid waste
NCV	net calorific value
PCB	polychlorinated biphenyls
PCDD/F	polychlorinated dibenzodioxin and dibenzofuran
RDF	refuse derived fuel
RFI	radio-frequency induction
RT	residence time
SMM	sustainable materials management
SRF	solid recovered fuel
VOC	volatile organic compound
WtE	Waste-to-Energy
WtP	waste-to-product

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