CONVERTING WASTE INTO VALUABLE RESOURCES WITH THE GASPLASMA® PROCESS

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Abstract

This paper reports on a novel process development to convert waste into renewable energy using gasification. Advanced Plasma Power (APP) has developed an advanced thermal conversion technology, (Gasplasma®), capable of treating a wide range of organic and inorganic wastes. In the two-stage thermal process, the fluidised bed gasifier (FBG) converts the waste to a crude syngas containing significant levels of char, ash, tars and other liquid organic contaminants. This gas stream, together with the char and ash product from the gasifier, is then treated in a high temperature plasma converter unit to produce a reformed and consistent quality synthetic gas (syngas) which (after tertiary cleaning of the acid gases and particulates) is suitable for high efficiency generation of power in a gas engine or gas turbine. The inorganic ash fraction is vitrified in the plasma converter unit to produce a dense, environmentally stable vitrified product (Plasmarok®), which has a wide variety of end uses and leads to a very low level of waste requiring disposal. An important aspect of the design concept was to employ commercially tried and proven techniques. The breakthrough innovation stems from how these technologies have been effectively integrated to enable the highly efficient production of a clean syngas and secondary aggregate.The electrical conversion efficiency that can be achieved using a gas engine is c.40% compared to 25% for a steam turbine system (at an equivalent thermal input). In the past, it has been the problem of tar and char contamination of the syngas, associated with conventional gasifiers, that has prevented the widespread adoption of waste gasification to power gas engines and turbines.The operation of the Swindon (UK) facility, since 2007 has continually demonstrated the successful integration of the main process elements, producing a syngas that can be utilised directly in a gas engine/turbine.

This very high efficiency and flexible advanced thermal process uses proven technology in a unique combination and can be used to provide power from RDF and other wastes. The plant is compliant with all EU emissions limits and has a high level of availability. Apart from producing power through gas engines or turbines the clean syngas has other potential uses within the liquid biofuel sector as well as the hydrogen economy. The standard size of the plant has been set at 150,000 tonnes of MSW or 90,000 tonnes of RDF per annum but it is scalable for larger cities.

Introduction

Finding effective, sustainable solutions to combat the effects of anthropogenic global warming will be the greatest challenge that the global community face in the 21st century. A major part of this endeavour will be in developing means of securing dependable sources of renewable energy and also in greatly reducing the amount of materials obtained from virgin reserves.

Within Europe, the EC has set ambitious targets to increase the proportion of energy from renewable sources from around 8.5% today to 20% by 2020[1]. The Commission has also sought to encourage best practice in the management of wastes which includes reducing the proportion of biodegradable material sent to landfill and increasing the recovery of recyclates and (renewable) energy from the waste[2].

The total volume of Municipal Solid Waste (MSW) waste produced annually is very considerable and is anticipated to grow in the future. Within the EU 27 countries the amount of MSW waste generated in 2007 was around 262.4 million tonnes[3] and this is forecast to increase to around 338 million tonnes by 2020[4]. It is feasible that a significant proportion of renewable energy could be derived from MSW/ Trade waste streams which, typically, have a biogenic content in the range 60-65%[4,5]. In a 2007 report commissioned by the Institute of Civil Engineers (ICE)[6] it was estimated that around 17% of the UK's total electrical power could be generated from current arisings of MSW and trade wastes.

Additionally, some trade waste streams traditionally landfilled could be seen as a valuable source of materials. However, markets and prices of recovered components are controlled by the ability for these materials to meet relevant materials specifications[7]. This usually makes the potential value of recovered materials from many waste streams relatively low, especially when there exists a potential for residual contamination of recyclates with hazardous materials.

For example, when an automobile reaches the end-of its useful life, it may contain amongst others 57.5% ferrous metals, 10% non-ferrous metals (including aluminium, zinc, copper, lead and magnesium species), 7.5% plastics, 7.3% textiles, 2.9% rubber, and 5.2% glass,[8]. In Europe, the European Commission enacted the End-of-Life Vehicle (ELV) Directive to encourage 95% recycling and recovery materials by 2015[9] of the c. 14 million end-of-life vehicles (ELVs) arising annually in Europe[10]. To achieve such targets, vehicle processes first remove potentially polluting materials such as automotive fluids and batteries, and then economically valuable components are recovered, with the remaining bulk being sent for shredding. At this stage, ferrous and non-ferrous metals are separated from lighter fractions. These lighter fractions, which may represent 25% of the ELVs mass, are interchangeably termed automotive shredder residues (ASRs), auto fluff or auto shredder fluff. These residues may be divided into heavy, light, middling, and dust fractions which contain varying quantities of glass, fibre, rubber, automobile liquids, plastics, dirt, and mix of ferrous and non-ferrous (mainly alloys of copper and aluminium) metal components. ASR still contains potentially recoverable materials, but the difficulty of achieving sufficient separation and purity usually makes the potential value of recovery of materials from ASR relatively low. The Gasplasma® process allows recovery of a high proportion of these valuable components, including valuable metallic components, whilst also generating an energy-rich synthetic gas (syngas).

The EU waste management strategy promotes minimization, recycling and reuse of waste with landfill being considered as the least desirable, "pariah" option. However, landfill still remains the main method of waste treatment, currently accounting for around 41% within the EU 27, and although this figure is anticipated to fall to around 35% by 20204, the increasing levels of MSW and other wastes generated means that the total amount of waste reporting to landfill is unlikely to reduce markedly over this period.

The main method for diverting waste from landfill has focused on the use of waste materials as sources of renewable energy. Many approaches have been considered, but Advanced thermal conversions (ATC) technologies, which encompass gasification and pyrolysis, are increasingly being considered as the preferred choice for thermal processing of wastes. The main reasons are that these renewable processes reduce dependency on fossil fuels and lower green house gas emissions, move away from the more polluting practice of disposal to landfill and are considered to manage wastes in a more sustainable way making them publically more acceptable[11,12].

In addition to applying to the waste currently destined for landfill, the same approach may be applied to enormous quantities of wastes, held in landfill sites, that contain significant levels of recoverable energy and materials, the potential for "mining" these sites is self evident. However, to date, there have been relatively few references where this has been practiced commercially and, even in these cases, the extent of the mining activity tends to be limited either to recovery of energy or a specific recyclate stream from the waste.

Gasplasma® technology developed by Advanced Plasma Power, is an advanced thermal conversion (ATC) technology consists of a bubbling fluidised bed gasifier (BFBG) followed by a single carbon electrode plasma converter. This ATC technology allows processing of a broad range of wastes, including amongst others: MSW-sourced Refuse Derived Fuel (RDF), ASR and biomass.. The process provides high conversion efficiencies using waste feed, and is designed specifically to cope with ash components and problem species (e.g. PVC found in ASR), while allowing enhanced materials recovery (e.g. metals, glass, etc.) from process feeds. The plasma converter vitrifies the ash which otherwise poses disposal problems for most other gasification or combustion process and yields a environmentally stable and non-leachable product with a variety of uses.

Waste gasification principles

The physico-chemical processes taking place between the gasification agents and the waste, yielding synthetic gas (syngas), are complex, influenced by varying feed, process design and operating conditions. However, gasification chemistry may be considered as a two distinct conversion mechanisms. Firstly, as the waste is injected into the reactor, it is devolatised rapidly[13], being exposed to low ignition temperatures of 250-350°C. This is usually referred to as pyrolysis, resulting in the water vapour, organic liquids and non-condensable gases, such as CO, H2, CO2, being separated from the solid carbon (i.e. char) and ash content of the fuel. The vapour/liquid product comprises mostly of polyaromatic hydrocarbons (PAHs) and tar (i.e. dark, oily, viscous material, consisting mainly of heavy organic and mixed oxygenates).

This initial stage is followed by a second stage where the volatiles and char undergo a second gasification step where their composition is modified due to the occurrence of several reactions (see Table 1) to become syngas. Most of these reactions are endothermic and require a consistent amount of energy to proceed.

Table 1: Typical gasification reactions[14]

Reaction pathway	**Reaction**	**Energy (MJ/kmol)**
Exothermic pathways:		
$C + O_2 \rightarrow CO_2$	Combustion	-398.3
$C + ½ O_2 \rightarrow CO$	Partial oxidation	-123.1
$CO + H_2O \rightarrow H_2 + CO_2$	Water-gas shift	-40.9
$CO + 3H_2 \rightarrow CH_4 + H_2O$ $2CO + 2H_2 \rightarrow CH_4 + CO_2$	CO methanation	-217.0 -257.0
Enothermic pathways:		
Biomass → Char + volatiles+ $CH_4 + CO + H_2 + N_2$	Pyrolysis	+200 to +400
$CH_4 + H_2O \leftrightarrow CO + 3H_2$	Steam reforming	206.0
$C + H_2O \rightarrow CO_2 + H_2$	Water gas/steam carbon	118.4
$C + CO_2 \rightarrow 2CO$	Boudouard	159.9

These primary and secondary conversion mechanisms occurs over distinctly different time periods, with the initial devolatilization taking place over a milliseconds scale, whilst the reminder of gasification processes occur over time periods one or two orders of magnitude longer[15].

Gasplasma Process

The Gasplasma® process, which comprises a bubbling fluidised bed gasifier (BFBG) and a plasma converter, is designed specifically for steam/oxygen gasification. The process has been designed to treat household and trade wastes and can also be successfully applied to various other solid wastes like automotive shredder residues. The Gasplasma® system is shown schematically in Figure 1.

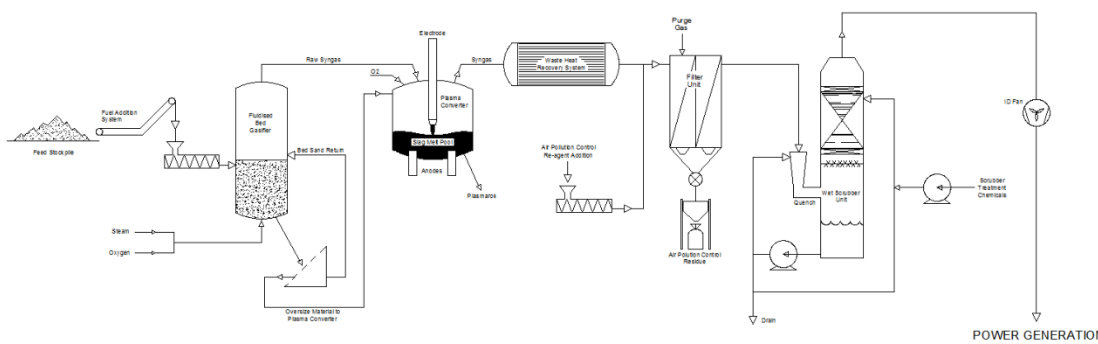

Figure 1: Schematic of the Gasplasma® process

The gasifier contains a bed of nominally 1 mm mullite particles, and is fed with a supply of steam and oxygen as the gasification medium. The fluidised bed is maintained at a temperature of between 700 and 850 °C, with the optimum operating condition depending on fuel characteristics and desired reaction profiles (see Figure 2). The flows of steam and oxygen are finely controlled to maintain the bed temperature, good fluidization (25% higher than minimum fluidization velocity) of the gasifier bed and also to obtain the required syngas quality. Figure 3 shows the effects of oxygen availability within the gasification reactions on the syngas calorific value, with a maximum achieved at a stoichiometric ratio (the ratio between the oxygen available and that required for complete combustion) of around 0.4, a value that depends on the composition of the RDF/waste being utilised as a feedstock.

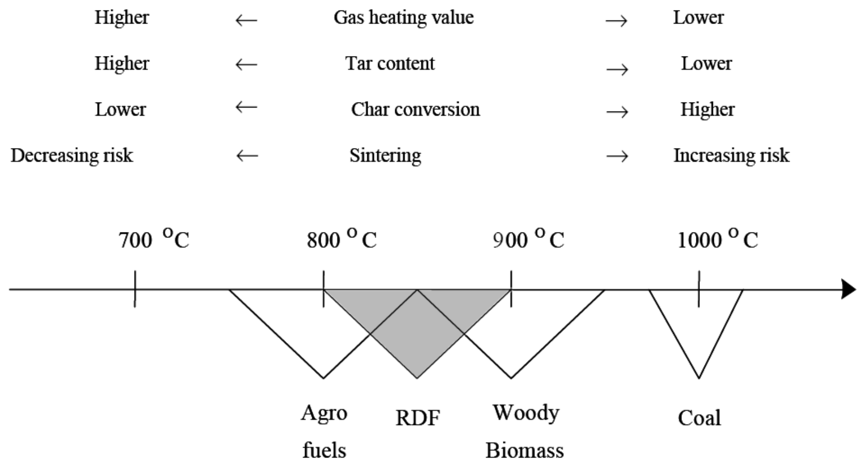

Figure 2: Typical gasification temperature for various feedstock and influence of temperature change on some critical factors[16]

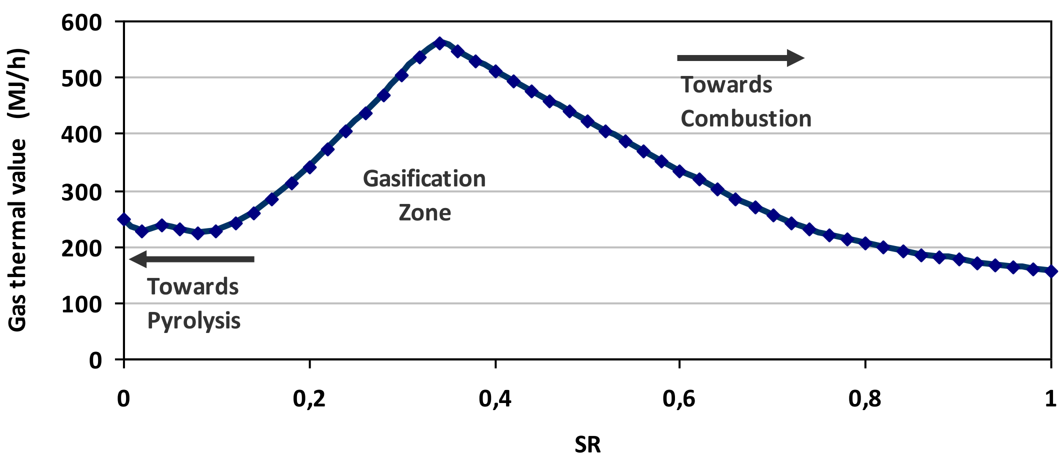

Figure 3: Influence of SR on gas thermal value from gasification of RDF (30 kg/h of dry MSW)

The fluidised bed gasifier permits the process to accept a broader range of feedstock types and physical properties (both in terms of particle size and density). Fluid bed systems allow a more efficient gasification due to a homogeneous temperature, good flow mixing inside the reactor, rapid heating of the feedstock, leading to a more consistent syngas generation and high conversion efficiencies.

The waste is thermally decomposed within the gasifier to produce a crude syngas, containing residual tars, unconverted char and entrained ash particles. This crude syngas enters the side of the converter chamber above the slag level and circulates around the periphery of the chamber allowing the gas to increase in temperature while receiving maximum exposure to the intense ultra violet light within the converter, aiding cracking of tar substances, conversion of the residual char, and promoting the separation of particulates from the syngas. The converter is also designed to capture the particulate materials entrained in the gas flow from the gasifier and convert these into slag. The base of the converter chamber contains a layer of molten slag. The plasma power is controlled to provide a uniform syngas temperature and destruction of the residual tars and chars contained within the crude syngas (see Figure 4).

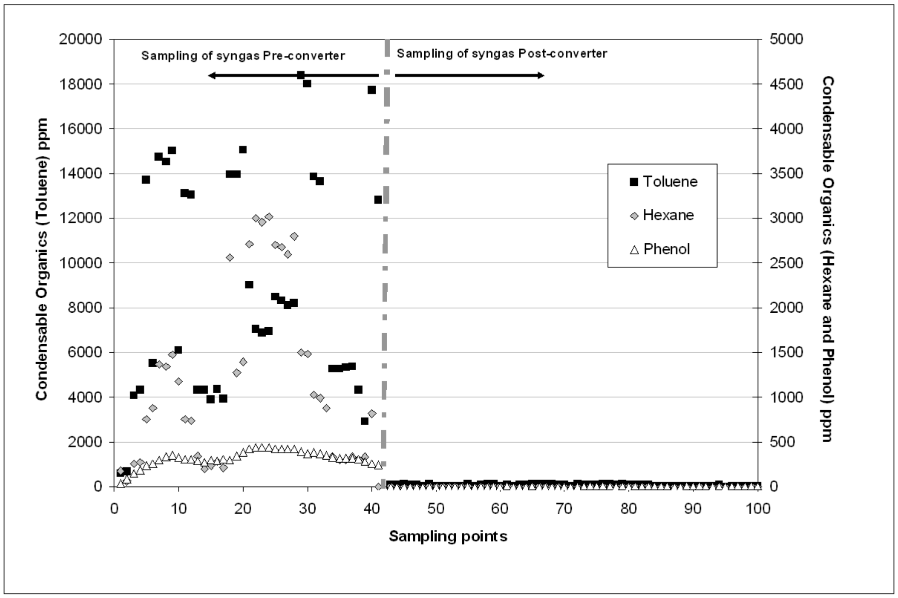

Figure 4: Destruction of tar-like materials within the Plasma Converter

This two-stage approach physically separates the principal unit operations of pyrolysis-preliminary gasification zone from the final conversion zone, providing longer residence time whilst making a more efficient use of the oxygen required to support the endothermic steam reactions. This results in higher yield of synthesis gas than is possible by single stage partial oxidation[17].

In these single-stage gasification processes, residual char is the heterogeneously reacted, via slow and endothermic pathways, with steam and carbon dioxide; processes that are usually enhanced by use of elevated temperatures achieved through use of additional oxygen.

APP has a demonstration Gasplasma® plant in Swindon, UK which is in constant use for research and development purposes and testing of new materials. The demonstration plant has maximum feed capacity of 100 kg/h whereas the generic full scale plant has been designed for 12 t/h feed basis. The core principal of the gasifier and the plasma converter described above is applied for both full scale and demonstration plant. In the demonstration plant, the hot syngas from the plasma converter is cooled through a thermal fluid heat exchanger, reducing the syngas temperatures to around 200 °C whereas in full scale plant, this sensible heat would be recovered to generate steam, which would then be used for power generation via steam turbine. The cooled syngas is further cleaned to remove fine particulate and acid gases in the gas cleaning system which is a combination of dry and wet cleaning process.

In the demonstration plant, measurement is made of the process in order to provide stable temperature and pressure operating profiles during gasification. Syngas composition is constantly monitored to provide guidance on the adjustment of process parameters to achieve consistent high quality syngas which is subsequently used for power generation via a gas engine.

Gasplasma Performance and Syngas Uses

The analysis and gross calorific value of a range of wastes derived from a range of RDFs is shown in Table 2. The syngas generated from treating these wastes in the Gasplasma® process was shown to have a net calorific value in the range of 9–11.5 MJ/kg and a CO/CO_2 ratio of 2.2-2.4 and a H_2/CO ratio of 1.6-3.9. This gas is rich in carbon monoxide and hydrogen, and has very low levels of residual chars and tars (see Figure 4).

Table 2: Waste feed analysis and corresponding syngas qualities from Gasplasma® pilot plant trials

Waste feed	Carbon	wt%	46.16	43.50	44.91	54.37
	Hydrogen	wt%	5.98	6.59	6.27	6.93
	O	wt%	15.20	5.48	10.63	17.64
	Moisture	wt%	9.00	9.45	9.21	5.50
	Ash	wt%	22.30	33.50	27.60	13.00
	Gross calorific value	MJ/kg	21.63	21.45	21.55	25.50
Syngas	CO/CO2		2.21	2.39	2.38	2.39
	H2/CO		2.02	1.56	3.86	2.50
	Syngas net calorific value	MJ/kg	11.1	10.7	11.5	9.3
	Energy conversion efficiency	%	93.9	87.0	92.7	92.6

For this assessment the energy conversion efficiency (ECE) as given in Table 2 is defined as:

$$\text{Energy conversion efficiency } (\%) = \frac{\text{Energy content of syngas}}{\text{Energy content of the fuel fed to the system}} \times 100$$

It is seen that for the Gasplasma® process, ECE's of 87.0-93.0% are attained which compares well with published efficiencies for RDF gasification of 73%. Furthermore, when account is made of the parasitic load then, despite the use of a plasma arc to vitrify ash and crack residual tars and condensable organics, the Gasplasma® process reports a net electrical efficiency (NEE) in excess of 25%. These compare well with the published figures of 17.7 to 23% for fluidised bed technologies processing prepared MSW[18,19].

Thus use of the Gasplasma® technology can be effectively and economically employed to both provide a solution to the disposal of wastes and to the generation of clean, renewable power.

The relatively high calorific value of the syngas and the high contents of hydrogen and carbon monoxide all allow consideration of the syngas generated from the Gasplasma® process for use in applications other than power generation. For example, the syngas can be transformed using water/gas shift and methanation reactors to generate a bio-substitute natural gas (Bio-SNG) which meets the specification for injection into the gas network. This Bio-SNG will play a crucial role in the decarbonisation of domestic and industrial heating and will help reach binding carbon reduction targets.

The transformation of waste into a clean, hydrogen-rich syngas allows the use of separation technologies to generate a pure hydrogen gas stream. This gas has long been proposed for use in high efficiency fuel cells for power generation with little environmental impact.

Material Recovery

Plasmarok® is produced from plasma converter from the vitrification of captured fly ash and excess bed materials generated from the fluidised bed gasifier. The high energy density of the plasma arc, which is transferred directly to the molten slag phase in the plasma converter, ensures a high degree of fluidity of the slag so that any solid particle that contacts the melt surface is readily captured and assimilated.

The calcia–alumina–silica rich slag is on cooling, both mechanically strong and highly resistant to leaching[20]. In comparison, the bottom ash residues produced from gasifiers and incinerators are subject to heavy metal leaching and may be prove to be a liability in the future. Indeed, the vitrification of such ashes is already commercially practiced in Japan, to offset this potential liability using dedicated plasma vitrification furnaces[21]. Independent environmental testing of the Plasmarok® product following the two stage BS EN 12457-2 leaching test for granular materials[22] for a wide number of prescribed organic and heavy metal pollutants have demonstrated that the vitrified material was not harmful to the environment or human health, showing that for all the pollutant species analysed, the actual levels recorded were greatly below the compliance limits as set for inert (landfill) material[23]. Indeed, this material has been demonstrated as suitable for a number of aggregates applications and could be specified for use as an unbound aggregate for civil engineering.

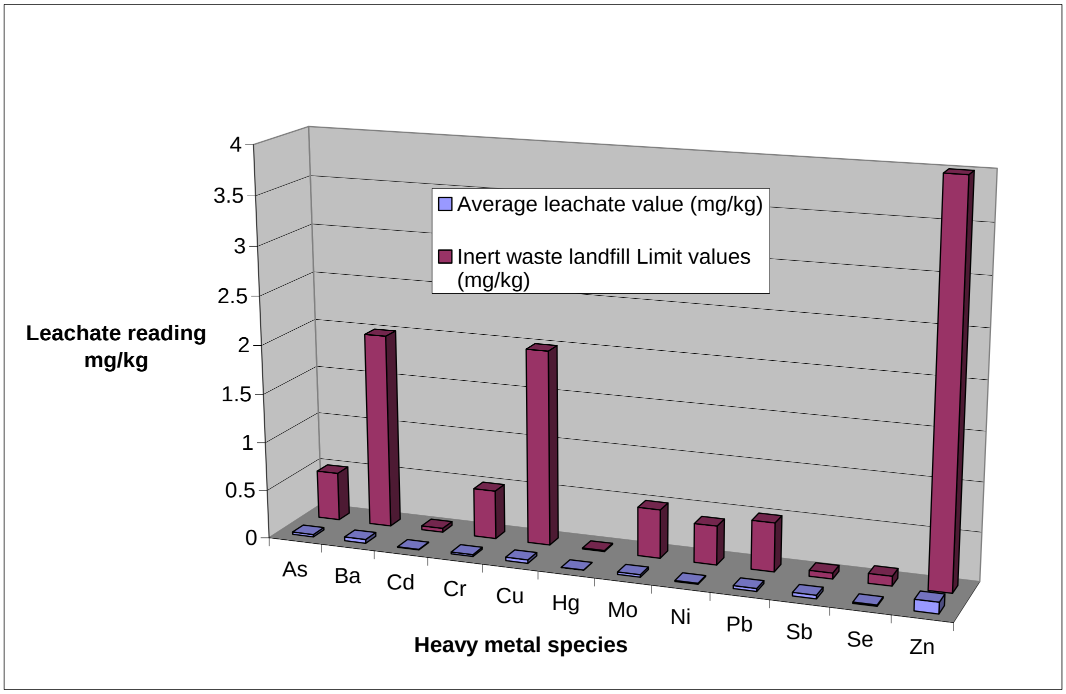

Figure 5: Summary of results for inert WAC limit compliance (BS EN 12457-3 Leaching tests on vitrified sample at particle size <4mm)

While such immobilisation of potentially harmful heavy metals into a vitrified non-leachable material has obvious immediate benefits, it would also allow industries with specific recycling and recovery targets (such as the EU automotive industry) to achieve these goals with the additional benefits of producing a renewable energy source.

Conclusions

Gasification of MSW can play a significant role for the generation of renewable energy, contributing to reducing greenhouse gas emissions and help achieving energy and climate change goals. APP's novel Gasplasma® technology is a promising development, which underpinned with fundamental academic research, can provide an efficient alternative solution for electricity production from the thermal processing of waste compared with incineration, combustion and landfilling. Other than power generation, the process offers also the potential for bio-SNG production from waste gasification. Although fluidized bed gasification systems have limited commercial operation in the UK, they are compatible with high levels of source segregation and therefore, have the potential to contribute towards integrated waste management practices. Furthermore, financial incentives, such as ROCs, supportive policies and active R&D by major industry players and research institutions, are important factors for the full commercialisation of the gasification processes, especially for larger plant scales.

References

[1] European Commission (2008), "20 20 by 2020: Europe's climate change opportunity", Communication From The Commission To The European Parliament, The Council, The European Economic And Social Committee And The Committee Of The Regions, COM(2008) 30 Final, Commission of the European Communities.

[2] Europa (2005). Strategy on the prevention and recycling of waste. Strategy on the Prevention and Recycling of Waste COM(2005) 666.

[3] European Environment Agency (2012), Material Resources and Waste – 2012 Update: The European Environment State and Outlook 2010, European Union, Luxembourg

[4] EEA (2008). European Environment Agency (EEA) Briefing Document 2008, 01.

[5] DEFRA (2006), Guidance on the Landfill Allowance Schemes: Municipal Waste, June 2006, London, UK.

[6] P. Lee, D. Fitzsimmons, D. Parker Quantification of Potential Energy from Resuduals, Commissioned by The Institute of Civil Engineers, March 2005.

[7] Henstock ME. The impact of materials substitution on the recyclability of automobiles. Resources Conservation and Recycling, 1988;2:69–85.

[8] GHK (2006). A study to examine the benefits of the End of Life Vehicles Directive and the costs and benefits of a revision of the 2015 targets for recycling, re-use and recovery under the ELV Directive Annex 2; May 2006.

[9] European Commission (2000). Directive 2000/53/EC of the European Parliament and of the Council of 18 September 2000 on end-of-life vehicles. OJ of the EC; 2000.

[10] European Commission (2008), Environmentally friendly recycling of cars, Science for Environment Policy, DG Environment News Alert Service, News Alert Issue 107; 15 May 2008.

[11] Juniper Consultancy Services Ltd. (2001), Pyrolysis & Gasification of Waste – A Worldwide Technology & Business Review, 2nd Edition, Gloucestershire, UK.

[12] London Assembly Environment Committee (2009). Where there's Muck there's Brass – Waste to energy schemes in London, Greater London Authority, London, UK.

[13] Ghani WAWAK, Alias AB, Cliffe KR. (2009), Co-combustion of refuse derived fuel with coal in a fluidised bed combustor. Journal of Engineering Science and Technology, 4(1):122-31.

[14] Basu P, Kaushal P. (2009), Modeling of pyrolysis and gasification of biomass in fluidized beds: A review. Chemical Product and Process Modeling.4(1)

[15] Gomez-Barea A, Nilsson S, Barrero FV, Campoy M. (2010), Devolatilization of wood and wastes in fluidized bed. Fuel Process Technology, 91(11):1624-33.

[16] Hallgren A. Improved technologies for the gasi cation of energy crops. Publishable Final Report (TPS AB), European Commission JOULE III Programme, Project no. JOR3-CT97-0125.

[17] Albal RS, Litka AF, Neoh KG, Westra LF, Woodroffe JA, Stickler DB, (1989). Advanced two-stage gasification system. 1. experimental results. Industrial and Engineering Chemistry Research®. 28(11):1600-7

[18] W. F. Hesseling (2000a), "Case Study: Valene Waste Recovery Facility in Mantes la Jolie, France", IEA Bioenergy Task 23 Report, September 2000.

[19] W. F. Hesseling (2000b), "Case Study: Madrid Waste Recovery Facility", IEA Bioenergy Task 23 Report, April 2000.

[20] Deegan D, Chapman C, Bowen C.T(2004), he production of shaped glass ceramic materials from inorganic waste precursors using controlled atmospheric DC plasma vitrification and crystallisation, High Temperature Material Processes, 7:367-372.

[21] Deegan D, Chapman C, Ismail S, Wise M. (2006), The thermal treatment of hazardous waste materials using plasma arc technology. In: IMechE conference on Delivering waste solutions balancing targets, incentives and infrastructure, 9, IMechE London, UK.

[22] British Standards, BS EN 12457-3: 2002. Characterisation of waste. Leaching. Compliance test for leaching of granular waste materials and sludges; 2002.

[23] Chapman C, Taylor R, Ray R. (2010), The Gasplasma® process: its application in Enhanced Landfill Mining. In: 1st International Symposium on Enhanced Landfill Mining and the Transition to Sustainable Materials Management, Moleheide, Houthalen-Helchteren, Belgium; 2010.