Intended for
North London Waste Authority

Document type
Report

Date
November 2014

NORTH LONDON HEAT AND POWER PROJECT - A REVIEW OF THERMAL TREATMENT OPTIONS

RAMBOLL

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1 EXECUTIVE SUMMARY

Introduction

When developing an energy recovery facility (ERF) for municipal waste treatment (MSW) one of the fundamental technical decisions is the selection of the most suitable technology. Today there appears to be a choice between well proven advanced moving grate systems and the less proven alternative technologies.

Alternative technology suppliers have made significant marketing efforts and lobbied government to provide assistance with the launch of their schemes on claims of higher efficiencies, smaller footprints and other less technical points.

To make the right technology choice it is important to look at the key criteria as the facility will be operated for many years, needing to provide a reliable and robust service.

Background

The ERF will provide a vital part of the waste management infrastructure for the North London Waste Authority (NLWA). The existing Edmonton facility has provided a much needed service since the early 1970s, exhibiting very good reliability. This has resulted in not only a cost effective and efficient solution, but also the diversion of millions of tonnes of waste from landfill disposal. As a local service it has meant that waste can be collected and treated in a short cycle avoiding waste build up and the consequent hygiene and other risks associated with storage of untreated putrescible waste.

In the current climate a number of other criteria must be addressed. These include:

- Energy efficiency and recovery;
- Environment – emissions, health and safety;
- Flexibility to handle variations in waste composition;
- Fit within the local infrastructure and plans for the future; and
- Ability to operate at the "capital city" scale.

Technical Options

The technical options that are considered include:

- Advanced moving grate technology;
- Pyrolysis;
- Gasification; and
- Two stage combustion.

Advanced moving grate technology has evolved over many years. Research and even further development of this technology continues today. Its performance has made significant steps over the last 10 years to achieve very high levels of reliability and high efficiency, especially when combined with a district heating scheme. The technology can meet and exceed strict regulatory limits on emissions and yet it offers the flexibility to accept waste of varying composition and calorific value. To this end it is considered as a bankable solution. Examples of this technology can be found across the globe and many new advanced moving grate plants are under construction and at the design stage today. Technology suppliers continue to expend a considerable research and development (R & D) budget to keep this technology at the cutting edge of efficiency, performance and reliability.

The gasification and pyrolysis technologies are commonly referred to as 'advanced' thermal treatment technologies. The reason being that thermal gasification processes produce syngas, which can potentially be used to produce electricity with higher efficiency or for producing liquid fuels or chemicals. Syngas has about half the energy density of natural gas. Syngas is used in a boiler or other device for power production. Therefore, the main question is whether the additional technical complexity and increased energy consumption of the gasification processes can be justified by the potential increase in efficiency and/or attractiveness of the by-products when compared to conventional combustion.

Thermal gasification of municipal solid waste (MSW) has experienced around 25 years of often challenging development. These alternative technologies generally require MSW to undergo extensive pre-processing. In addition, operational experience is sparse, availability has been shown to be significantly lower than that of modern advanced moving grate plants, and operational costs are higher. Furthermore, the operational data from reference facilities shows that the overall energy efficiency of thermal gasification processes are less efficient than direct combustion plants.

Two stage combustion technologies have a number of reference plants. Some facilities have been in operation for circa 10 years. Most of the facilities are designed with relatively low steam parameters, thus achieving lower energy efficiency. Furthermore, pre-treatment of waste is required and plants may experience lower availability when compared to modern advanced moving grate fired plants.

Whilst a number of alternative technologies are actively promoted by development companies, there is little evidence to suggest they have achieved sufficient track records and performance levels required to meet the aims of NLWA for (i) safe and secure residual waste treatment (ii) combined with ability to deliver high service availability and (iii) high levels of consistent energy production into a local energy network. The commercial and stakeholder relationship consequences of service failure or short comings at a municipal scale are significant for any waste management authority. On this basis, Ramboll recommends the use of well proven advanced moving grate combustion.

Table 1 provides a general comparison of the different thermal treatment technologies.

Table 1 – Comparison of technologies

Parameter	Adavanced Moving Grate	Thermal Gasification / Pyrolysis	Two Stage Combustion
Waste requirements • Pre sorting • Size reduction	Not required Only items > 1000 mm	Removal of metals Shredding required	Removal of metals Shredding required
Energy* • Gross electricty • Net electricity • CHP mode ** of lower calorific value*	25 – 33% 22 - 30% Up to 100%	Limited data 0 – 10% Up to 100%	Limited data * Limited data ** Up to 97% *in theory close to avanced grate technology , if material and design are adjusted/changed to handle higher steam parameters. ** loss of additional 2-3% points compared to advanced moving grate due to pretreatment.
Environment • Bottom ash (depends on ash in waste)	≈ 16-20% by weight	≈ 16-20%* by weight	≈ 16-20% by weight
• Health and safety	Minimal contact with waste	Contact with waste during cleaning of pre-treatment plant	Contact with waste during cleaning of pre-treatment plant
Compliance with EU regulation	Yes	Yes * Pyrolysis results in the production of a char. A Defra report classifies municipal solid waste pyrolysis char as *"Hazardous waste, but could be used as coal replacement in certain combustion applications or as a gasifier feedstock."*	Yes
Operation experience Information level	Well documented	Limited data available	Limited data available
Handling changes in waste composition	Higher flexibility	Lower flexibility	Medium flexibility
Annual availability	≥8,000 hrs	<5,500 hrs	<7,000 hrs
Net electricity production at 10 MJ/kg	0.6 - 0.65 MWh/t	0 – 0.25 MWh/t	0.4 - 0.45 MWh/t

Parameter	Adavanced Moving Grate	Thermal Gasification / Pyrolysis	Two Stage Combustion
Technical risks			
Overall assessment	Low	High	Medium
Proven treating MSW or MSW derived waste	Well proven	Well proven in Japan. (with very limited net electricity production)	Further demonstration of track record still required from independently owned plants.
Number of plants	>1,500	Unclear, around 50 to 80 facilties	Less than 10 facilities (with lower steam parameters and mainly 'heat only' plants.)
Advantages	- Well proven - High availability - High efficiency	- Facilities could apply for renewables benefits (previously double ROCs) - Better public perception in the UK	- Facilities could apply for renewables benefits (previously double ROCs - Potentially better public perception in the UK
Disadvantages	- Limited access to renewables benefits from government - Less positive public perception in the UK	- Low net efficiency - Availability uncertain - Unproven technology to produce syngas for use in gas turbine or upgrade to fuel	No reference plants achieve steam parameters or/and availability similar to facilities based on advanced moving grate technology.
Number of modules for a large scale thermal waste treatment facility e.g. 700,000 tpa	2 lines of 44 t/h	Circa 90+ modules of 1 t/h, could base design on around 8 to 10 larger capacity units.	Circa 18 to 20 lines of 5 t/h

2 INTRODUCTION

Over the last decade there has been a considerable push towards improved ERF efficiency. Advanced moving grate has made considerable progress in terms of efficiency and reliability. Efficiency figures for electricity only plants have improved from 20% to 25% or more. The inclusion of district heating supplies can increase the efficiency much further and Scandinavian plants using advanced grate technology combined with district heating are now achieving above 80% efficiency.

There has been considerable interest in new technologies to see if even greater efficiencies and performance levels can be achieved. Of particular interest are the gasification and pyrolysis options as an alternative to advanced moving grate based systems. The technical and financial factors are set out below:

The three main technical motivations for gasification/pyrolysis are:

- Syngas can potentially be used to produce high-value energy carriers or materials. This includes possible syngas use as a feedstock for gas-engines, which have high energy efficiency, as a liquid fuel in the transport sector in the form of hydrogen, or converted to ethanol or methanol which can be used in the chemical industry;

- Reduced production of mono-nitrogen oxides (nitric oxide and nitrogen dioxide) (NOx), hydrogen chloride (HCl) and sulfur dioxide (SO_2). However, the cleaned emissions from conventional facilities are likely to be similar due the strict emission requirements in the Industrial Emission Directive, (IED); and

- Gasification technologies most often melt ash residues to form a vitrified bottom ash, which effectively immobilizes heavy metals. This has been a key driver in Japan, where it is a regulatory requirement to vitrify bottom ash.

The main financial motivation for gasification/pyrolysis has been:

- Ability to apply for double ROCs (Renewables Obligation Certificate) in the UK. This subsidy will not be available after March 2017 when it is to be replaced by new arrangements.

ROCs have now been replaced by an alternative electricity sale mechanism called Contract for Difference (CfD) and the level of support or subsidy is no longer certain.

3 TECHNOLOGY DESCRIPTION

This section provides a general description of the main types of thermal treatment processes and provides general performance data.

There are three basic processes for thermal treatment of MSW:

- **Combustion (more commonly referred to as incineration when waste is the feedstock)** is complete oxidation with surplus oxygen. The combustion process does not require an external energy source because it releases heat and is self-supporting. The temperature in the combustion chamber is typically >1,000 °C. The flue gas (primarily comprising water vapour, carbon dioxide (CO_2), hydrogen chloride (H_2O), mono-nitrogen oxides (nitric oxide and nitrogen dioxide) (NO_x) and oxygen (O_2)) has no calorific value because all the energy is converted into heat.

- **Pyrolysis** is the thermal breakdown of waste in the absence of oxygen. Waste is heated to high temperatures (>300°C) by an external energy source, without adding steam or oxygen. The products are char, pyrolysis oil and syngas (pyrolysis gas). The pyrolysis gas has a high calorific value. Due to a high level of tar syngas needs extensive cleaning before use.

- **Gasification** is the thermal breakdown/partial oxidation of waste under a controlled oxygen atmosphere where the oxygen content is lower than necessary for combustion. Waste reacts chemically with steam or air at a high temperature (>750 °C). The process requires, as for pyrolysis, an external energy source to heat the process. Syngas from gasification, primarily comprising carbon monoxide (CO) and hydrogen (H_2), has a lower calorific value than pyrolysis gas and is dependent upon the gasification process. The tar levels in the syngas are lower than for pyrolysis gas and the amount depends on the actual gasification technology.

The above processes are illustrated in **Figure 1**.

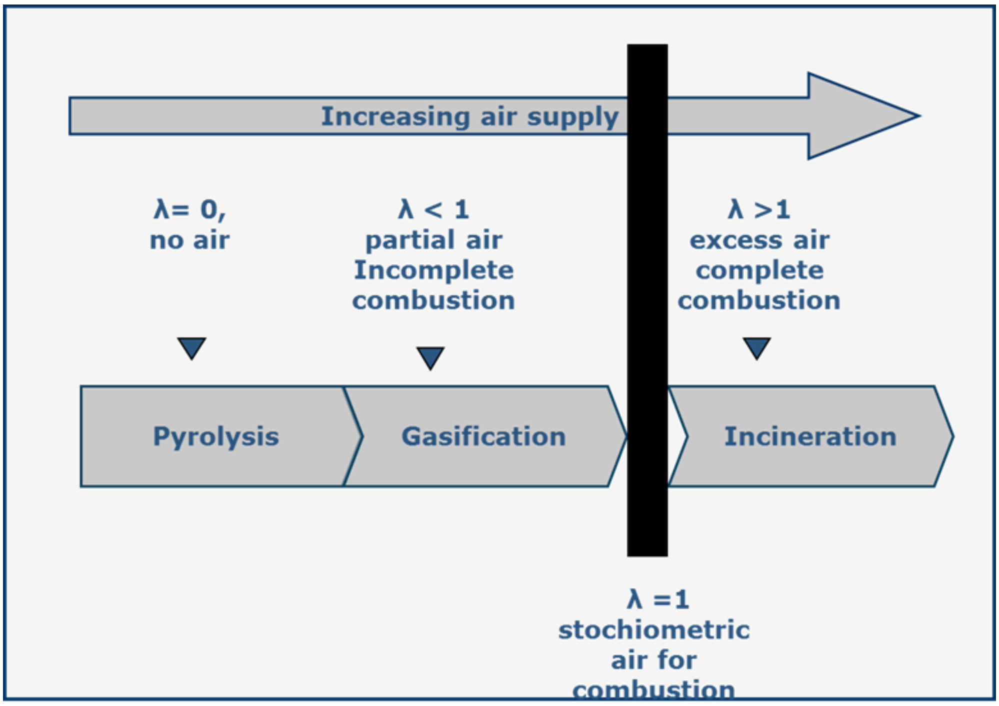


Figure 1: Air supply for thermal treatment technologies

Complete combustion of waste in an ERF facility consists of a sequence of pyrolysis, gasification and combustion steps. With a conventional ERF combustion system these three steps are integrated. Alternative conversion systems generate an intermediate product and the combustion process is carried out later. **Figure 2** presents an overview of the process. If limited heat and air is added then gasification occurs. If excess air is supplied then complete combustion takes place. The left side of the figure illustrates the three steps in the combustion process whereas the right side shows different forms of energy use.

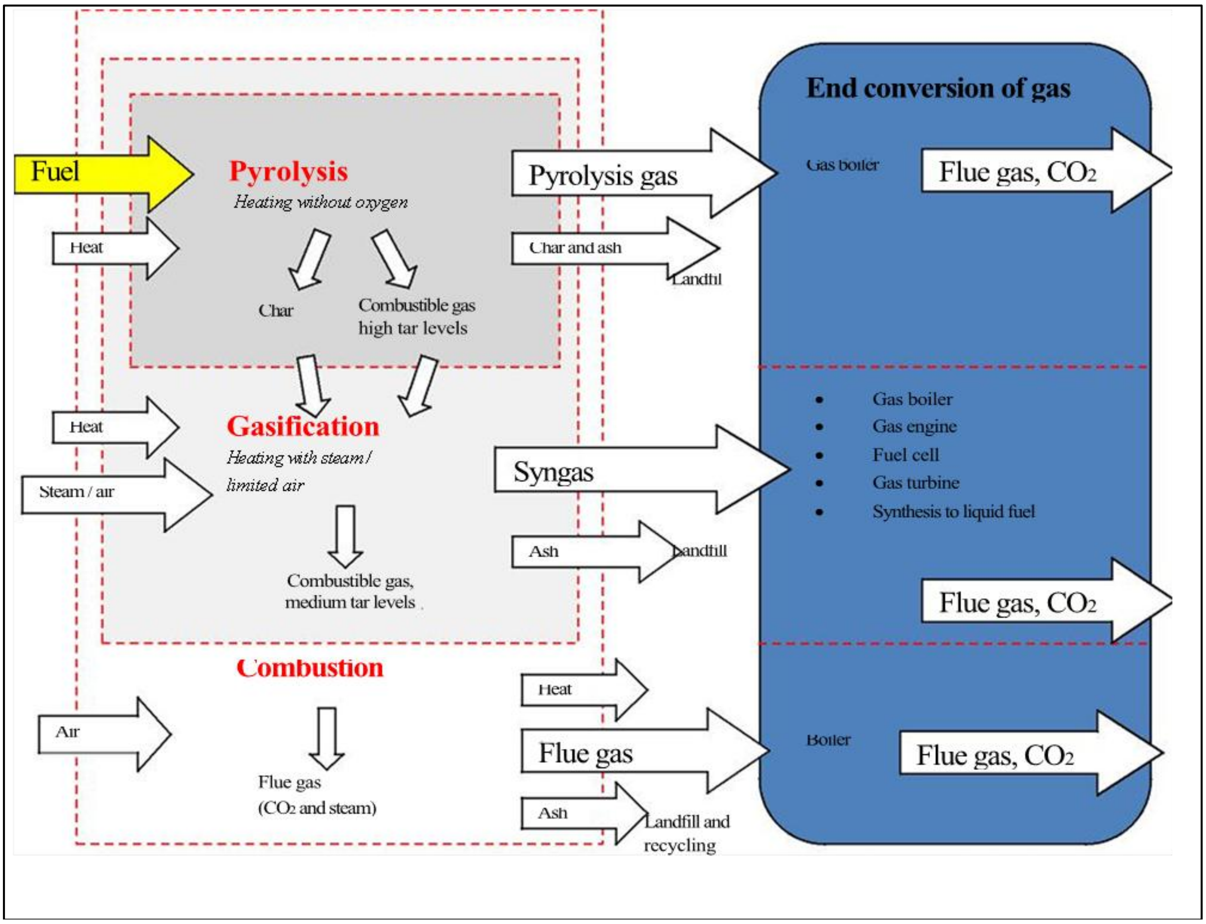


Figure 2: Overview of thermal processes

Some technology providers offer a two-stage combustion process. The first stage of the combustion is operated with limited amount of oxygen, resulting in gasification. However, these processes do not generate a syngas output, as the gas is immediately burnt in a combustion chamber with excess air injection. The gasification chamber and the combustion chamber are fully integrated. Energy recovery takes place in a conventional boiler followed by flue gas cleaning using systems that are no different from those at a modern ERF. The technology is more correctly characterized as a two-stage combustion technology. However, in the UK these technologies have been classed as gasification processes for the purposes of the ROC scheme.

Combustion type processes can be split into the following two types:

- Advanced moving grate technology
- Fluidised bed technology

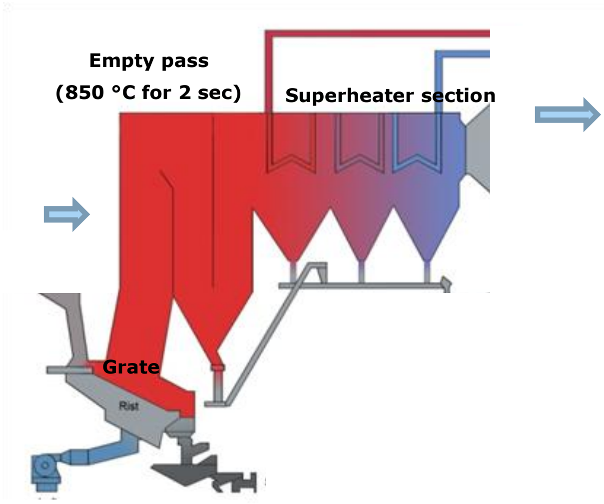
Advanced moving grate technology is the most popular and successful thermal treatment technology worldwide. There are examples of fluidised bed facilities installed to treat residual waste, both in Europe and the UK.

3.1 Advanced Moving Grate Technology

Key information about advanced moving grate technology is summarised in **Table 2** below.

Table 2 – Assessment of Advanced Moving Grate Technology

Technology Assessment – Advanced Moving Grate Technology	
Historical Background:	Moving grate technology was first employed in the 1930's.
Technology Development:	Many hundreds of grate fired lines have been installed in Europe and other parts of the world. The technology has undergone continuous development to achieve very high levels of efficiency, reliability and performance. It is the preferred technology worldwide to recover energy from residual waste. Technical developments include: - Modern advanced moving grate plants incorporating combined heat and power can achieve efficiencies of more than 80%. - Increase in steam parameters from the well proven 400 °C/40 bara to around 425 °C/60 bara. Some facilities have increased steam parameters further but it is always a trade-off between corrosion issues and the additional income from electricity sale. - The use of high quality metal alloys (e.g. Inconel) to reduce corrosion issues. - Lower boiler outlet temperature to increase amount of heat used for steam generation. - High temperature steam may be drawn from the turbine and used for district heating system improving overall energy efficiency. - Condensation step to recover energy from the clean flue gas prior to entering the stack (chimney). The additional heat can be transferred to district heating networks and further increase plant efficiencies. New plants in Scandinavia incorporating flue gas condensation units coupled with district heating schemes achieve near 100% energy efficiency. Flue gas condensation for heat recovery requires a low temperature district heating scheme. - Automatic combustion control to ensure a very efficient burn-out rate, typically around 99%. - Automatic deNOx control system to ensure efficient mono-nitrogen oxides (nitric oxide and nitrogen dioxide) (NOx) removal and low consumption of ammonia water. - Automatic flue gas control system that use raw gas measurement to adjust dosing of chemicals and secure low emission values.
Technical Description:	Waste is taken from a storage bunker by a crane and dropped into a chute. At the bottom of the chute waste is fed onto the combustion grate. The waste on the grate is combusted at a temperature of 850 °C or more with combustion air injected from below the grate. Waste is moved forward on the grate and the residue (bottom ash) drops into a water bath at the end of the grate. Complete gas phase combustion is reached by injection of secondary air above the grate. The system ensures that a temperature of at least 850 °C for a minimum of 2 seconds is reached (EU requirement). Auxiliary fuel is only used for start-up and shutdown to achieve regulatory temperature conditions for waste feed. Energy released from waste combustion is transferred to the boiler system. This typically has as an energy efficiency of around 85% for steam production. A conservative design for steam parameters is typically 40 bara and 400°C for electricity production. Many new advanced moving grate combustion facilities use higher steam parameters (i.e. 60 bara and 425 °C). The selection of steam parameters is a trade-off between efficiency of the turbine and acceptable boiler corrosion rates that affect plant availability and maintenance costs. Flue gas from combustion is often treated in a dry/semi-dry gas clean-up system, where hydrated lime or in a few cases sodium bicarbonate is injected upstream of a large filter to neutralise the acidic gases (hydrogen chloride (HCl), sulfur dioxide (SO_2) and hydrogen fluoride (HF)). Activated carbon is added to

	adsorb heavy metals (mainly mercury) and dioxins. Other heavy metals are bound to the surface of the fly ash particles and removed in the filter. The residue from the filter requires treatment and disposal as a hazardous waste. More complex wet systems are often installed in Germany, Switzerland and Scandinavia where there are outlets for effluent from the treatment process. Wet systems make it possible to recover additional heat from the flue gas through condensation of the water vapour in the flue gas and thus increase overall efficiency.
Illustration:	
Input Requirements:	Residual waste - No pre-treatment required. Bulky waste - requires shredding. Flexibility to accept changes to inputs e.g. calorific value, composition, moisture content. Can also process refuse derived fuels and solid recovered fuels.
Inputs:	Fuel to auxiliary burners during normal operation - minimal. Ammonia water (25 %) for deNOx: ≈ 4 kg/t (of waste treated) Lime for flue gas treatment: ≈ 14 kg/t Activated carbon: ≈ 0.5 kg/t Internal electricity consumption: ≈ 100 kWh/t (around 3% of the energy content in waste)
Outputs:	Steam from boiler system ≈ 85% of the energy in the waste will be recovered. Electricity for internal use and export Heat for district heating and/or industrial process use Incinerator bottom ash: ≈ 20% by weight FGT residue (incl. fly ash): ≈ 30 kg/t (of waste treated)
Commercial:	Commercial availability: Numerous recognised suppliers.
	Typical capacity range per line: 2.5 - 44 t/h per line Annual processing of up to 350,000 tonnes for each process line.
	Operational data availability: Information on availability, energy recovery efficiencies, level of clean gas emissions and a wealth of other data is available for a large number of plants.

3.2 Fluidised Bed Technology

Key information about fluidised bed combustion is summarised in **Table 3** below.

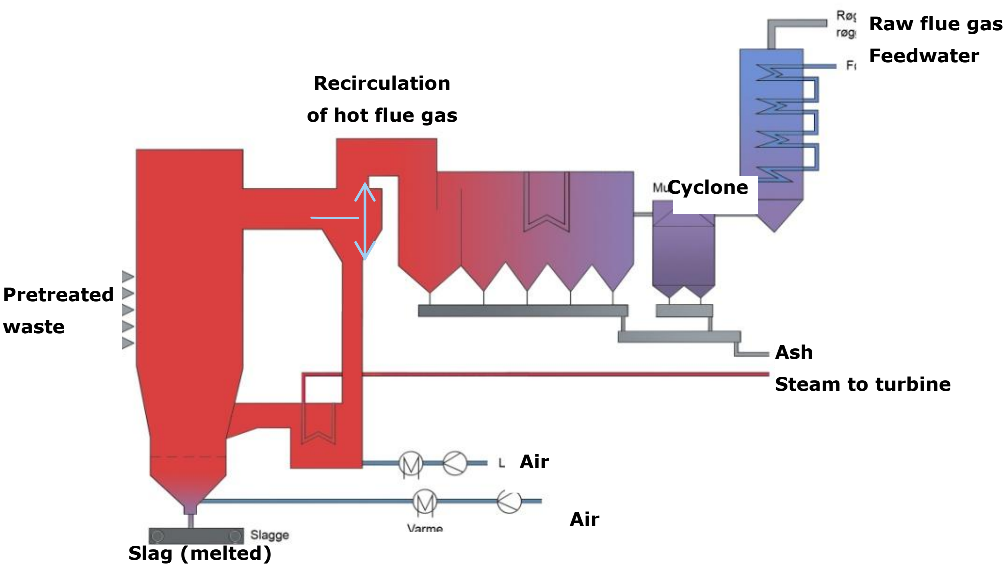
Table 3 – Assessment of Fluidised Bed Technology

<table>
<tr><th colspan="2">Technology assessment - Fluidised Bed Technology</th></tr>
<tr><td>Historical Background:</td><td>The fluidised bed reactor was developed in the 1920’s for coal combustion. It has been successfully developed for the combustion of wood chips and sewerage sludge.</td></tr>
<tr><td>Technology Development:</td><td>Around 40 waste fired plant lines have been established in Europe.

Fluidised bed lines are mostly fuelled by refuse derived fuel (RDF), produced from municipal waste through sorting/recovery of metals and organic matter, and processed wood waste. The technology performs best with a relatively uniform feedstock. Thus very few facilities treat a feedstock comprising residual waste, which is highly variable.

Reference plants have a history of poor and challenging performance. It is believed that very few waste management companies would select fluidised bed technology for waste combustion when given the option of advanced moving grate combustion.</td></tr>
<tr><td>Technical Description:</td><td>Waste undergoes a process of metal removal and shredding for size reduction. It is transferred to the reactor chamber. The reactor chamber contains very hot sand, which is fluidised by an air stream from the wind box below. The combustion process is very fast and the primary typically takes less than 30 seconds. The EU requirement of minimum 2 seconds at 850 °C is achieved in the secondary combustion zone. Energy is recovered as heat in a boiler system similar to a grate fired facility.

Fluidised bed technology inherently produces low mono-nitrogen oxides (nitric oxide and nitrogen dioxide) (NOx) emissions and it is often able to meet EU requirements without the use of a deNOx system. The remaining FGT system is similar to the system required for moving grate technology.

Experience shows that the amount of fly ash will be significantly higher than for a grate fired facility due to the high air velocity which entrains more of the coarse fraction of the bottom ash in the combustion gas. This has a significant adverse financial impact because fly ash is typically classified as hazardous waste, whereas bottom ash is considered non-hazardous waste.</td></tr>
<tr><td>Illustration:</td><td>
</td></tr>
</table>

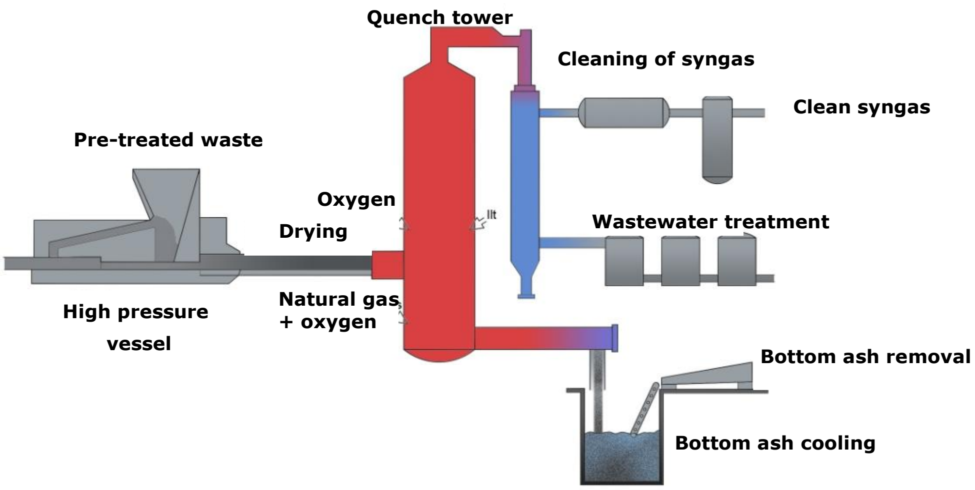
Input Requirements:	Residual waste – Shredding required, typically to a particle size of 5 - 15 cm, and removal of metals. Restrictions on input changes e.g. heating value, ash content and moisture content because the combustion process is sensitive to sudden changes of the waste composition.
Input:	Fuel to auxiliary burners during normal operation - minimal. Ammonia water (25 %) for deNOx: ≈ 0 to 2 kg/t (of waste treated) Lime for flue gas treatment ≈ 10 kg/t Activated carbon ≈ 0.5 kg/t Electricity consumption ≈ 100 kWh/t (around 3% of the energy content in waste) + minimum 50 kWh/t and up to several hundred kWh/t for the pre-treatment step.
Output:	Steam from boiler system ≈ 85% of the energy in the waste will be recovered. Electricity for own use and grid supply Heat for district heating and/or industrial process use Incinerator bottom ash ≈ Depends on inert content. 50% of inert to IBA Boiler ash ≈ 50% inert to fly ash plus carry-over of sand. FGT residue ≈ 30 kg/t (of waste treated) * High velocity of the fluidized air results in a relative high fraction of fly ash compared to IBA.
Commercial:	Commercial availability: Limited recognised suppliers
	Typical range: 5- 20 t/h per line
	Operational data availability: Some plants have published the efficiency of energy recovery and clean gas emissions. Information on electricity requirement for the pre-treatment step is difficult to obtain.

3.3 Thermal Gasification Technology

Key information for thermal gasification is summarised in **Table 4** below. The 'Two-Stage Combustion' technology, also considered as gasification, review is set out below in **Section 3.5**.

Table 4 – Assessment of Thermal Gasification

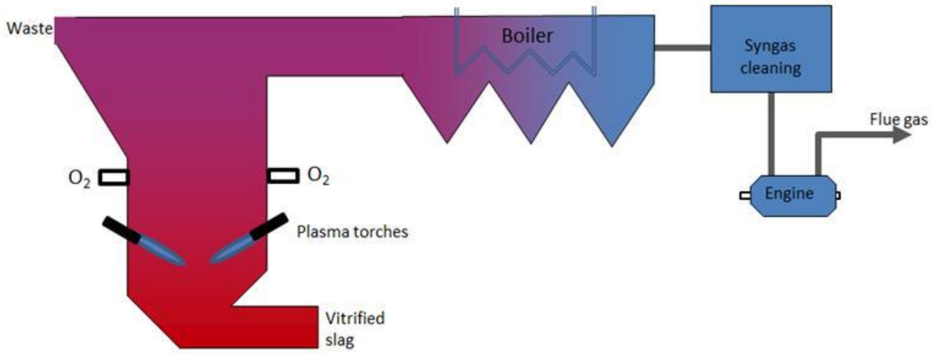
Technical Assessment - Thermal Gasification	
Historical Background:	Thermal gasification was invented in the 1800's to produce city-gas from coal. The technology is now commonly used in areas with large coal deposits to convert coal into a gas and subsequently produce diesel and oil.
Technology Development:	Most gasification plants treating residual waste are located in Japan. The high operational temperature (up to 1,600 -2,000 °C) makes it possible to melt bottom ash and fly ash into a clinker. This was a common requirement in a Japanese environmental permit. There appears to be no clear conclusion regarding the environmental benefits of clinker compared to bottom ash. Relatively fewer gasification facilities are presently built in Japan, as the production of clinker appears to be a less common requirement today. A few large gasification plants were built in the 1990's in Europe for municipal solid waste treatment. These plants experienced operational problems and ceased to operate. According to a 2008 survey by Juniper, up to 80 waste processing gasification lines were in operation with only a handful located outside of Japan. Limited information is available about the types of waste processed and capacities of the plants. Only a few facilities appear to use syngas from gasification in a gas turbine to produce electricity. This would theoretically achieve a higher electrical efficiency than plants using steam turbine technology.
Technical Description:	Waste is indirectly exposed to a high temperature which causes the organic matter to crack and volatilise. Only limited oxygen is added to ensure that limited combustion takes place at this stage. There are a number of suppliers, primarily Japanese companies. The technical concept is dependent on the technology supplier. However, the general concept includes cooling of the hot flue gas prior to gas utilisation. Often the original intent was to use the gas in reciprocating engines with a net electricity efficiency of circa 40% - compared with a steam turbine with an efficiency of circa 30%. However, at most plants the energy is recovered through a boiler system with similar steam parameters as a grate combustion facility. This is due to operational problems with alternative approaches offering higher theoretical efficiencies. Flue gas is treated in a similar system as for advanced moving grate fired facilities.

Illustration:	Concept Example 
Input Requirements:	Residual waste – after shredding to particle size of around 15 cm Restrictions on input changes e.g. heating value, ash content and moisture.
Input:	Fuel to auxiliary burners during normal operation: Unknown, but significant amount Ammonia water (25%) for deNOx: <0-2 kg/t (of waste treated) Lime for flue gas treatment: <10 kg/t Activated carbon <0.5 kg/t Electricity own consumption: Unknown Enriched air (high oxygen) Unknown
Output:	All residues are normally melted into a relatively inert clinker, rock-like material. Net electricity is very limited and may even be negative for some plants – based on information collected during Ramboll's site visits in Japan. Better energy efficiency is achieved by processes that do not melt the inert fraction.
Commercial status:	Commercial availability: A number of suppliers, but none with a proven track record relevant to the scale of the North London Heat and Power Project
	Typical capacity range: 1 - 10 t/h per line
	Operational data availability: Difficult to obtain on public domain.

3.4 Plasma Gasification Technology

Key information for plasma gasification technology is summarised in **Table 5** below. Plasma gasification is a variant of gasification as syngas is produced, but it varies from other gasification processes as a plasma torch (electric arc) is used the destruct waste at extremely high temperatures.

Table 5 – Assessment of Plasma (Thermal Gasification)

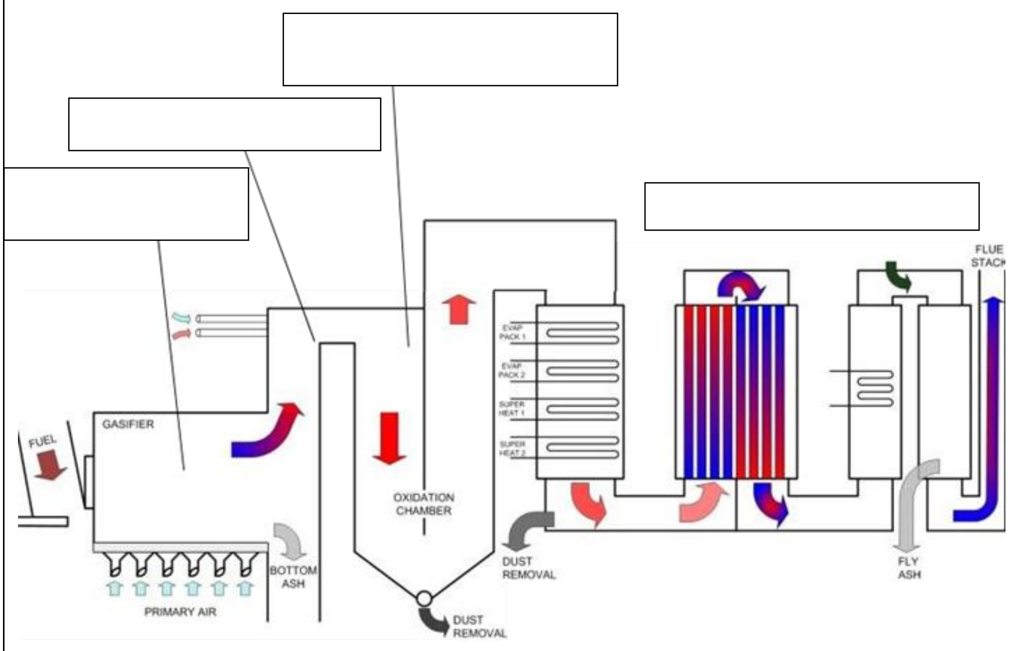
Technical assessment – Plasma (Thermal Gasification)	
Historical Background:	Plasma gasification is a variant of thermal gasification. The energy source for cracking of organic matter is an ionized gas produced by emitting gas through an electrical arc where the gas reaches a temperature up to 3,500 °C. The high temperature vitrifies bottom ash into a glassy clinker.
Technology Development:	Plasma gasification is commercially available and at least three companies are promoting plasma gasification for treatment of residual waste.
Technical Description:	Similar to thermal gasification – except that a plasma torch (electric arc) is used to reach the high temperatures required.
Illustration:	Pre-sorted and shredded waste is introduced at the top of the reactor. Waste is destructed during the downward fall through the extremely hot plasma produced from the electrically powered plasma torches. Inert material melts near the plasma torches. The glass melt is removed from the bottom of the reactor. The syngas exits at top of the reactor, is cooled down in a boiler and requires cleaning prior to further use. 
Input Requirement:	Similar to thermal gasification
Input:	Similar to thermal gasification, but additional high power consumption of the plasma torch.
Output:	Similar to thermal gasification
Commercial status:	Commercial availability: Limited suppliers and none with a proven track record relevant to the scale of the North London Heat and Power Project`
	Typical capacity range: 1 - 10 t/h per line
	Operational data availability: No operational data appears to be publicly available for recognised reference plants.

3.5 Two-Stage Combustion Technology

Key information on 'Two-stage Combustion' is summarised in **Table 6** below.

Table 6 – Assessment of Two Stage Combustion

Technology assessment – 'Two-Stage Combustion'	
Historical Background:	The 'Two-Stage Combustion' process consists of an upstream stage with drying and gasification of waste and a downstream stage for the combustion of the syngas produced. The purpose of the technology was to develop a small scale energy-from-waste plant with minimal emissions to atmosphere and high flexibility in handling different waste types with regard to calorific value, composition and moisture content.
Technology Development:	A number of lines have been established in Europe since 1997 with typical line capacities of 40,000 tpa.
Technical Description:	Residual waste is prepared by removal of metals and shredding for particle size reduction and transferred to a feeder. The primary chamber is operated with limited oxygen to produce a syngas consisting of hydrogen (H_2), methane (CH4) and carbon monoxide (CO). Secondary air is injected into the transfer channel to increase excess oxygen (O_2) content to 7%. This is similar to traditional waste combustion. To our knowledge, there is no experience of syngas extraction for alternative uses i.e. 1) use in gas turbine or 2) upgrade to a liquid fuel. The lower temperature of the waste on the grate is reported to reduce the overall production of hydrogen chloride (HCl) and sulphur dioxide (SO_2). It is reported that raw gas level of mono-nitrogen oxides (nitric oxide and nitrogen dioxide) (NOx) from the process is significantly lower than conventional combustion. Overall, clean gas emissions appear to be comparable with grate combustion. We understand that manual cleaning of the boiler is required up to 4 times per year. Moving grate combustion normally only requires one annual manual boiler clean. Existing plants predominately only produce heat and are operated with lower steam parameters than moving grate combustion plants.

Illustration:	
Input Requirements:	Residual waste: requires shredding and the removal of metals. Bulky waste: requires shredding
Input:	Fuel to auxiliary burners during normal operation - minimal. Lime for flue gas treatment: ≈ 5 to 10 kg/t (of waste treated) Activated carbon: ≈ 0.5 kg/t Electricity consumption: estimated as being about 100 kWh/t (around 3% of the energy content in waste) + around 25 to 50 kWh/t for the pre-treatment.
Output:	Steam from boiler system ≈ 85% of the energy in the waste will be recovered. Electricity for own use and grid supply Heat for district heating and/or industrial process use Incinerator bottom ash: Similar to conventional waste combustion (excluding. any metals removed in fuel pre-treatment) FGT residue: ≈ 25 – 30 kg/t (lower than traditional waste combustion as less lime is required)
Commercial:	Commercial availability: Limited of suppliers and none with a proven track record relevant to the scale of the North London Heat and Power Project`
	Typical range: Typically installed in modules of 5 t/h, corresponding to circa 40,000 tpa.
	Operational data availability: Data regarding energy efficiency and clean gas emissions is available.

4 OPERATIONAL EXPERIENCE

Thermal gasification is, as stated above, not a new technology. Gasification is a commercially-proven manufacturing process that converts feedstock such as coal and biomass into syngas that can be further processed into fuels or used for electricity generation.

During World War II, where oil supplies were limited, thermal gasification reactors were mounted on cars to enable operations on gas engines using syngas from the gasification of biomass. In countries with significant coal resources like South Africa large scale thermal gasification of coal is used to produce syngas. This is subsequently converted to synthetic diesel by catalytic processes.

Gasification of coal and biomass has been used commercially around the world for several decades by the chemical, refining and fertilizer industries and for more than 35 years by the power industry. At least 420 gasifiers, primarily processing coal and, to a limited extent, biomass, were in operation in 2011.

Due to the heterogeneous nature of MSW, thermal gasification of it is more complex. The commercial experience gained from gasification of coal cannot be directly applied to the treatment of MSW. Gasification of MSW has been studied since the 1980s, but there are very few MSW gasification facilities in operation. These are mainly small scale or pilot plants. Numerous large scale MSW gasification facilities have been closed down due to malfunction or high costs.

Most gasification facilities are located in Japan. These plants typically treat industrial process waste e.g. plastic waste and auto shredder fluff. Very few facilities, if any, process MSW.

There are no full-scale commercially operated MSW gasification facilities in operation in Europe or in North America that can provide three years of efficient and well documented operational track record. The UK is the main market for new gasification projects due to financial incentives. A limited number of commercially operated gasification facilities are due to commence operations over the coming years. These facilities will provide a basis for further testing the likely success of using gasification technology to treat MSW.

The number of gasification/pyrolysis installations reported to be in operation varies in different literature studies. The available information carries a high degree of uncertainly with respect to the feedstock types, plant availability, and operational data. The table below presents the figures, which appear to be most valid and are drawn from various independent literature sources.

Table 7 – Operational Experience Summary of Thermal MSW Treatment Technologies

	Pyrolysis	Gasification	Combustion
Years of operation	~30	~10	~125
Numbers of plants	<10	<50	~1,500
Total amount of waste (mill tonnes)	<0.5	<1*)	>100

*) we have tried to omit biomass, coal and other feedstock. However, this figure has a degree of uncertainty and may include separately collected industrial waste or other supporting fuel.

5 PRE-TREATMENT AND END PRODUCTS

5.1 Pre-treatment of Waste Feedstocks

Modern advanced moving grate based combustion plants generally accept waste feedstock with average heating values ranging between 7 - 15 MJ/kg and, from a size perspective, up to 1 m in length. In contrast most gasification processes require preparation of the feedstock and have limitations on the type of feedstock that can be processed. Recovery of metals can take place in a front end material recovery facility (MRF) or extracted from bottom ash.

Waste pre-treatment may be required for a number of reasons:

- To increase the calorific value as the acceptable heating value range is typically narrower than for grate combustion. Gasification processes are generally able to accept and prefer a high calorific value feedstock to produce syngas with higher heat content. The performance figures stated by technology developers often assume very high heating values of the incoming waste and intensive front-end sorting to ensure a caloric value between 11 - 15 MJ/kg. MSW typically has a calorific value in the range of 9 to 10 MJ/kg.

- To dry waste because some processes are not designed to process wet/high moisture content waste.

- To remove fractions not suitable for the gasifier. Most gasification technologies have strict requirements to remove inert materials such as glass, concrete, metals and chlorine rich fractions (PVC plastics) from feedstock.

- To reduce the size of particles entering the gasification process. Most gasification technologies are based on fluidized bed or entrained flow reactors. These require homogenous shredded waste. Particle sizes should typically not exceed 5 to 15 cm.

While some of the recovered materials have a market value, e.g. metals, other rejected materials such as glass, porcelain and organic waste with low heating values must be disposed of at a cost.

The equipment necessary for pre-treatment of MSW for gasification requires significant investment and energy input, leading to significant operating costs. It is important to consider the complete process and include all pre-treatment processes when comparing different gasification technologies or comparing combustion with gasification technologies using MSW. A schematic overview is illustrated in **Figure 3**.

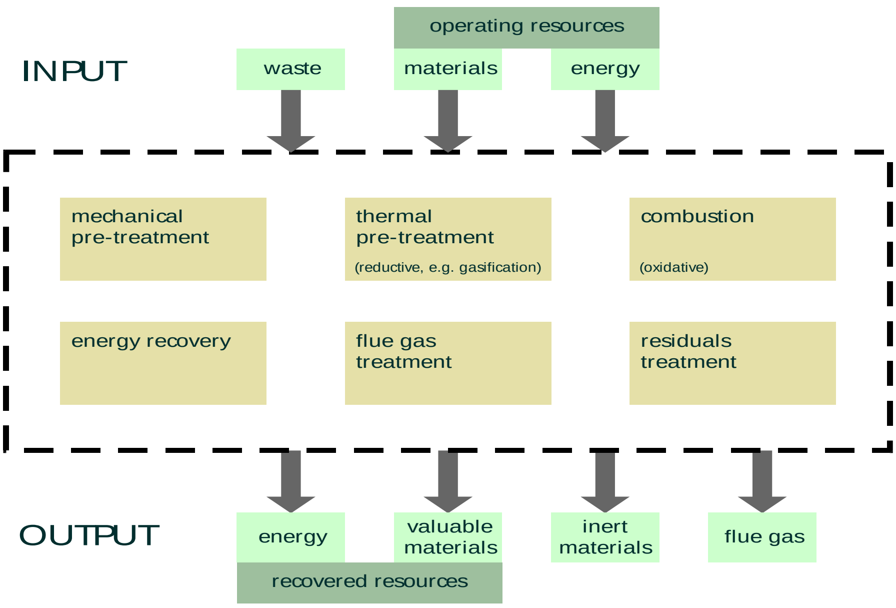


Figure 3: Energy and mass balance concept for thermal treatment processes

5.2 End Products From Thermal Waste Treatment

The environmental impacts and value/costs of different end products from thermal waste treatment technologies are a key discussion point. General guidance on this area is provided below:

Combustion technologies (incl. two-stage combustion):

Three residues are produced:

- Bottom ash: After the recovery of metals, bottom ash may be used as a construction aggregate. Most of the metals from the waste feedstock can be recovered from bottom ash and recycled. Bottom ash typically amounts to about 20 % of the waste processed by weight;

- Boiler ash/fly ash: Heavy metals from the waste are concentrated in fly ash. Fly ash amount is approximately 2 % of the input mass;

- Residues from the flue gas cleaning: Depending on cleaning technology, the residues amount to 1-2 % of the input mass.

Fly ash and residues from flue gas cleaning are typically disposed of at controlled landfill facilities.

Gasification technologies:

Waste products from thermal gasification plants vary with the specific technology used, but normally include:

- Ash, often not separated into fly ash and bottom ash. Therefore, the entire ash amount must be stored in a controlled landfill.

- In some gasification processes ash is vitrified at a high temperature e.g. by use of plasma technology. The leaching of the rock-like material will be lower than for non-melted ash due to the lower surface area. A disadvantage of this is very high electricity consumption to reduce the leaching properties to a very low level.

6 ALTERNATIVE TECHNOLOGIES – RESULTS SO FAR

The main technical and financial drivers for gasification/pyrolysis are to increase the energy/resource recovery from thermal treatment of waste.

The potential applications for syngas are illustrated in **Figure 4**. This technical review shows that, to date, the only long-term application for syngas from MSW has been through direct combustion with heat recovery in a boiler for heat and power production. Other solutions - mainly combustion in a gas turbine or internal combustion engine – appear to have ceased due to technical and financial challenges.

Gasification/pyrolysis plants have generally not been able to provide the benefits promoted by the suppliers.

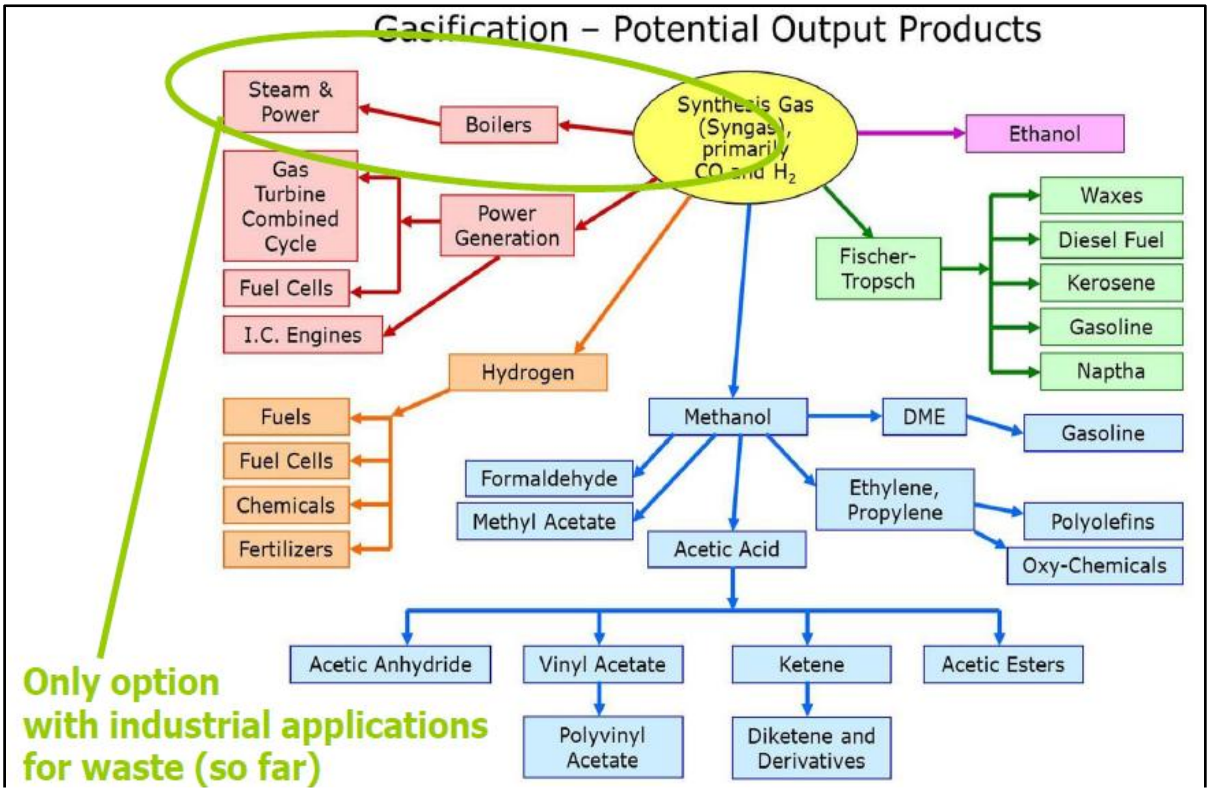


Figure 4: Gasification and the potential products

7 CHALLENGES FOR THERMAL GASIFICATION

This section describes the challenges for gasification technologies processing MSW compared to advanced moving grate-fired combustion.

7.1 Operational Challenges

Limited validated operational data is available for gasification facilities even though the gasification of MSW is much debated and heavily promoted. This is due to the limited number of plants that are in commercial operation as well as technology suppliers withholding information.

One of the challenges of operating a waste fired gasification facility is the production of syngas. Syngas is highly toxic, explosive and contaminated with pollutants and therefore needs significant cleaning before use. The cleaning process has been found to be challenging and costly. In many cases facilities have modified processes to include syngas combustion in a steam boiler followed by a flue gas cleaning module. To reduce the risk of explosion, the process equipment is often placed outdoors.

MSW is a heterogeneous material with inconsistent composition, moisture content, inerts and particle size. This is in sharp contrast to the strict feedstock requirements for gasification technologies.

Gasifiers often run on a partial mix of MSW with industrial and other waste supplies. Therefore, operational data from these facilities is not directly comparable to operating on MSW.

The production of ethanol or methanol from MSW-derived syngas involves the addition of chemical processing equipment to the back-end of an MSW gasification facility. For this reason, all of the consideration presented above for the MSW gasification applies to any MSW gasification-to-ethanol or MSW gasification–to-methanol facility. Once syngas is produced and cleaned sufficiently, the production of ethanol or methanol is a straightforward process that has been proven on a commercial basis. The main challenge is to produce syngas with sufficiently high purity.

Gasification facilities have the appearance of small utility power plants or industrial manufacturing plants. The plants are primarily found to be demonstration facilities or smaller scale facilities with a capacity of 25 - 250 tpd. Attempts to establish full-scale facilities have foundered, and those that tried to date have experienced functional and financial challenges before finally being closed down.

7.2 Energy Production

MSW gasification facilities report theoretical higher electricity generation rates than traditional waste combustion facilities. One of the reasons for this is the higher thermal efficiency of gas-fired power plants when compared to solid-fuel power plants. However, gasification facilities use a significant part of the power generated as process energy for initiating the gasification process and for pre-processing waste (shredding, drying, etc.). Thus, the total net energy production and export has been found to be lower than for advanced moving grate combustion facilities and, in some cases, gasification plants are net importers of electricity.

Very limited information is found in literature about the overall energy performance of existing gasification installations, and it is impossible to find complete dataset for a full mass and energy balance for the complete system because figures are often presented without sufficient detail.

The theoretical energy efficiency should be higher in a gas engine than grate combustion with recovery of energy using a steam boiler and turbine/generator-set. However, some of the more reliable data sources state that the calculated electric efficiencies of a number of thermal gasification technologies with gas engines range between 13 - 24%, even when ignoring the loss of energy during pre-treatment. Pre-treatment can often further reduce this efficiency by half. This ends up significantly lower than the output from modern advanced moving grate combustion plants which achieve an electrical efficiency of 25 - 30%.

In Japan, where most of the operational gasification installations are located, the focus is on minimizing residual products rather than optimizing the energy production. In mainland Europe and elsewhere where energy efficiency is one of the drivers, gasification processes are not prevalent. However, the UK is an exception due to the financial incentives which favour gasification/pyrolysis.

7.3 Costs

Financial information publicly available for gasification technologies is often provided by the technology suppliers and not presented on the basis of any contractual commitments to the parties involved. As a result, it is not clear whether the reported capital costs address all capital and construction cost elements, nor is it clear that reported operating costs address all real costs.

There are no commercial MSW gasification facilities with a long operating track record in North America or in Europe. Japanese facilities represent the best source of actual cost data. Maintenance at Japanese plants is reported by the plant operators to be an on-going and significant process. As a result, scheduled maintenance outages and costs for this technology are significantly higher than for a modern advanced moving grate plant.

The heavy maintenance and the technical challenges reduce the availability of the gasification facilities to 5,000 - 6,000 hours per year or lower. This compares poorly with the availability of advanced moving grate plants that achieve performance figures in the order of 8,000 hours per year. This equates to above 80% annual advanced moving grate plant availability.

Based on information collected through Ramboll' assignments, study tours, and prices published by SWANA (the Solid Waste Association of North American) typical gate fees for gasification are in the area of £180 per tonne, and up to £350 per tonne if all associated waste processes are included. This can be compared to a typical gate fee for advanced moving grate combustion of around £50 to £100 per tonne in Europe.

8 CONCLUSION

This thermal treatment option technology review shows that advanced moving grate is the most well proven, reliable and cost effective means of providing thermal treatment technology for MSW. The robustness, availability and energy efficiency has led to its historic dominance for MSW treatment. Continuous technical development of the advanced moving technology has secured this position today. None of the reviewed alternative technologies (gasification, pyrolysis and plasma technology) are able to match advanced moving grate facilities with regard to energy production efficiency or annual availability.

The appetite for gasification in the UK is mainly driven by energy sales incentives. Elsewhere in Europe there is very little activity with regard to alternative technologies to process MSW due to the lack of financial incentives and due to the last 25 years of problematic thermal gasification projects.

A number of gasification plants and two-stage combustion facilities are now at an advanced project stage in UK. Some gasification plants are entering commercial operation in 2014 or soon after. The next 5 to 10 years will show the performance of gasification in terms of energy production efficiency, emissions, availability and cost of operation.

Ramboll shares the opinion concluded in the report prepared by SWANA (the Solid Waste Association of North American), in December 2011:

- Gasification is unproven on a commercial scale for MSW;
- Gasification of MSW to produce electricity is technologically viable. However, MSW gasification is not a mature technology, and therefore, some risk mitigation strategies would need to be developed to limit risk; and
- Process and equipment scale-up is needed to demonstrate reliable systems and define economics. Commercial applications on MSW will be very challenging and involves high costs.

Future technology advances may or may not change the situation. Until this has been proven by long term operation, it is Ramboll’s view that any project involving thermal gasification of MSW should be considered as a high risk project.