WASTE TECHNOLOGIES: WASTE TO ENERGY FACILITIES

A Report for the Strategic Waste Infrastructure Planning (SWIP) Working Group

Complied by WSP Environmental Ltd for the Government of Western Australia, Department of Environment and Conservation

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List of Abbreviations

APCr	Air Pollution Control residues
ATT	Advanced Thermal Treatment
BAT	Best Available Techniques
BREF	Best Available Techniques reference document (EU)
C&I	Commercial & Industrial
C&D	Construction & Demolition
CFB	Circulating Fluidised Bed
CO2	Carbon Dioxide
CO2e	Carbon Dioxide equivalent
CO	Carbon Monoxide
CV	Calorific Value
EC	European Commission
ELV	Emission Limit Values
EPA	Environmental Protection Authority
EU	European Union
FP	Fine Particles
HPA	Health Protection Agency (UK)
IED	Industrial Emissions Directive (EU)
GHG	Greenhouse Gas
IBA	Incinerator Bottom Ash
LHV	Lower Heat Value
MBI	Mass Burn Incineration
MBT	Mechanical Biological Treatment
MHT	Mechanical Heat Treatment
MSW	Municipal Solid Waste
MW	Megawatts
NO2	Nitrogen Dioxide
PM	Particulate Matter
RDF	Refuse Derived Fuel
rMSW	Residual MSW
SO2	Sulphur Dioxide
SRF	Solid Recovered Fuel
TEQ	Toxic Equivalent
VOC	Volatile Organic Carbon
WFD	Waste Framework Directive (EU)
WID	Waste Incineration Directive (EU)

1 Introduction

1.1 Objectives

The Western Australian Waste Strategy (the Strategy) sets out waste recovery targets for municipal solid waste (MSW), commercial and industrial (C&I) and construction and demolition (C&D) waste streams and the measures that will assist the achievement of these targets. Allied to the Strategy, the Department of Environment and Conservation (DEC) and the Waste Authority established a Strategic Waste and Recycling Infrastructure Plan (SWIP) for the Perth Metropolitan and Peel regions, with a SWIP Working Group convened to support and guide its development.

This review has been prepared to provide the working group with supporting information on thermal Waste to Energy (WtE) technologies that should be considered during the development of the SWIP. This incorporates a description of the various thermal WtE technology types and differences covering key development and operating parameters at facility level based on information provided by established plants or available generic literature/data. Where appropriate, process specific information is also provided in tabulated format.

1.2 Scope

The focus of this study is on thermal treatment technologies.

- Direct Combustion (incineration).
    - Grate
    - Fluidised Bed
- Gasification
    - Grate
    - Fluidised Bed
    - Slagging
    - Plasma
- Pyrolysis

1.3 Structure of this Report

- Section 2 – General overview of thermal treatment WtE
- Section 3 – Review of key characteristics for variant technologies
- Section 4 – Summary and conclusions for the SWIP

2 Overview of Waste to Energy Technologies

2.1 Introduction

Waste to Energy (WtE) is a very broad term that covers any process that converts waste into energy, or an energy-carrying product, such as a gas or oil. Despite the existence of many different technologies, the aims of all WtE processes are essentially the same:

- Reduce the volume of waste and hence reduce the volume requiring disposal in landfill;
- Reduce the biodegradable fraction of waste to zero, and
- Produce a useful commodity (typically electricity and/or heat) from non-recyclable waste.

WtE can be split into two main categories:

- **Thermal** - includes combustion, gasification and pyrolysis, related processes all of which subject waste to high temperatures but with varying oxygen concentrations.
- **Biological** – anaerobic digestion (AD). AD is can be used to recover energy from wet, biodegradable waste streams (such as food waste and farm slurry). AD uses micro-organisms in carefully controlled conditions to convert biomass into biogas consisting primarily of methane and carbon dioxide, and a stabilised residue known as digestate.

For the purpose of this study we only consider thermal technologies as AD is not suitable for the treatment of solid mixed municipal and commercial waste. Landfill gas collection will also be excluded from this report as this should be covered in the parallel document on landfill technologies.

The general market status of the three main thermal WtE technology groups are summarised below and in **Figure 1**. The processes and technologies are described in the following sections.

Direct Combustion (Incineration)

Combustion (incineration) of waste is very well established. Moving grate combustion is a mature technology with hundreds of examples worldwide. Fluidised bed plants are also well established, but require preparation of fuel and there are fewer examples. The vast majority of plants recover heat from the flue gases via a steam boiler. Very low emissions and high overall thermal efficiencies can be achieved in modern waste combustion plant.

Gasification

Gasification of waste is an emerging technology, but is mature in some regions, particularly Japan where there are many examples. Gasification takes place in a restricted oxygen atmosphere, where waste is converted to a synthesis gas (syngas). Most plants then simply combust this gas (known as ‘close-coupled gasification’); however it is possible to use syngas in a gas engine or turbine, resulting in higher efficiencies and other potential advantages (‘advanced gasification’), but this is technically challenging and yet to be fully proven commercially.

Gasification appears to be at the point of being able to compete with more established combustion processes, including at larger scales, so we expect to see a substantial increase in the number of waste gasification plants in the coming years.

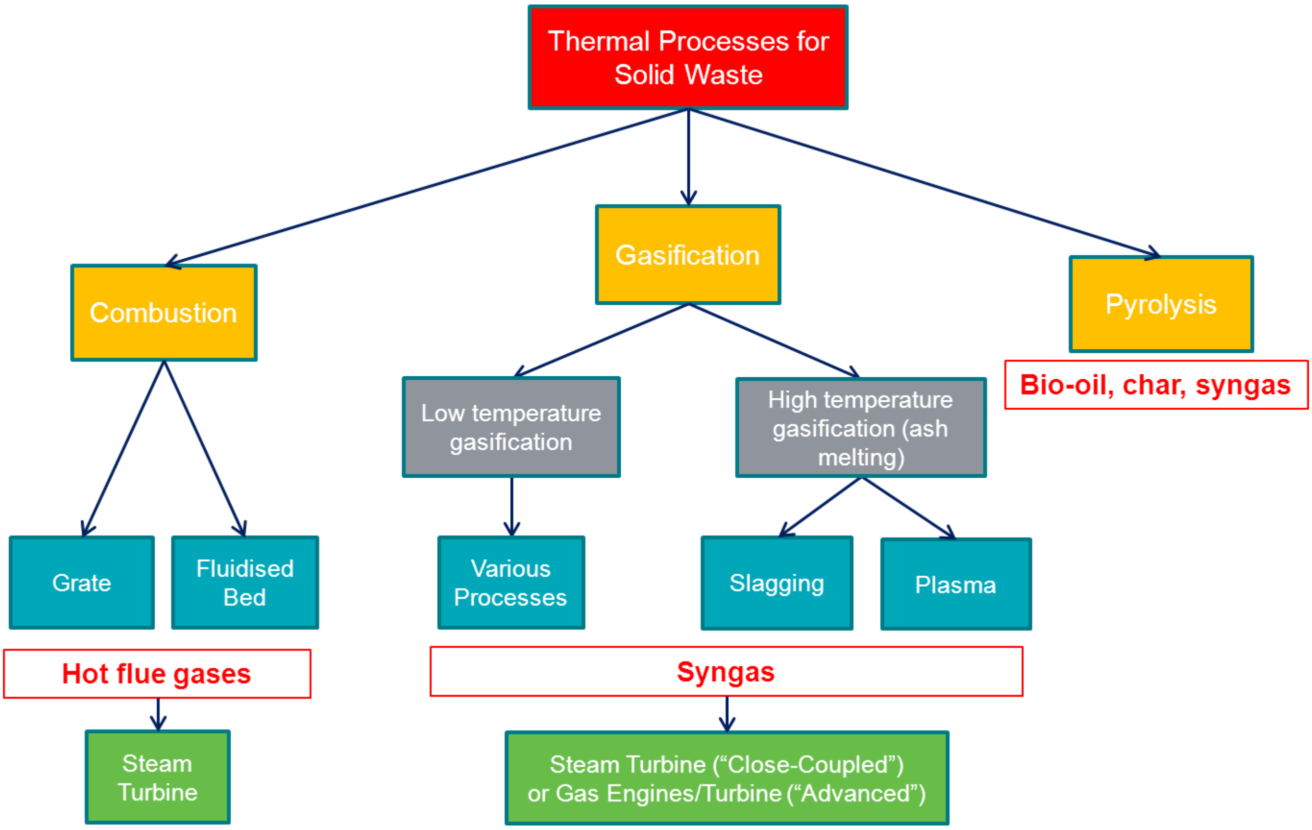
Plasma gasification is an emerging technology with few commercial plants but a number planned, including at least one large scale example.

Pyrolysis

There are no known examples of commercial-scale mixed waste pyrolysis plants. Various technologies exist that include a pyrolysis stage that have reached commercial deployment (e.g. Thermoselect), but no true pyrolysis processes where bio-oil is the primary product have been successfully deployed.

We consider it unlikely that pyrolysis of mixed waste will be commercially viable in the near future.

Figure 1: Thermal treatment options for solid waste



2.2 Direct Combustion (Incineration)

Combustion (incineration) of waste is achieved by heating waste in an excess of oxygen. 'Mass burn' refers to a process that accepts raw or post recycling municipal solid waste (MSW) without any additional pre-treatment (e.g. no shredding or refuse derived fuel (RDF) production). The process can best be explained by examination of the combustion of waste in grate furnaces, where the fuel forms a bed on top of the grate and the combustion air is injected through the grate. The different local temperatures and oxygen concentrations cause a succession of reactions from drying through pyrolysis and gasification to final combustion.

Combustion is actually a sequence of close-coupled physical and chemical reactions; initially the waste dries, then pyrolysis and gasification reactions occur as volatile compounds are heated and de-volatilise from the solid phase into the gaseous phase and are then combusted. As this process occurs an ash comprised mainly of inorganic components is left behind. Combustion usually takes place with an excess of air (which is provided from below the grate as underfire air and via secondary and tertiary injection as overfire air), in order to ensure the proportion of fuel reacting with the oxygen is maximised. Combustion of MSW is a very well established technology with many hundreds of operational plants worldwide. Energy recovery is invariably in the form of a steam boiler which recovers heat from the hot flue gases to generate superheated steam. A steam turbine is used to generate electricity, except in cases where the steam can be used directly in a co-located industrial process for district heating or desalination.

The net electrical efficiency of a WtE combustion plant generally varies from 15 – 25% depending on the size of the plant and steam conditions. Efficiencies are relatively low compared to fossil fuel plant because of the lower calorific value of the fuel and limitations on steam temperatures to avoid excessive corrosion caused by acid gases and other compounds produced by the combustion of MSW. However efficiencies of up to 30% (electricity only) are achievable using more advanced energy recovery techniques, and there are also a couple of examples of WtE combustion plants which are integrated with Combined Cycle Gas Turbine plants to boost the electrical efficiency considerably. However, technical challenges and economics often limit the efficiency in practice, and such advanced techniques are normally only possible where financial support is available (such as a premium on the electricity price from WtE or other government subsidies).

In order to exceed an overall efficiency of 30% without the input of an external heat source, plants generally need to export heat as well as, or instead of, electricity. Thermal efficiencies above 30% are possible in combined heat & power configurations, where a proportion of the heat which is rejected to atmosphere in plants that produce only electricity is recovered for process use. The highest levels of energy recovery are achieved in heat-only configurations where thermal efficiencies can exceed 80%.

Mass burn combustion only converts the organic content of the MSW to energy and leaves behind the inert content which is called ash comprised of inorganic material mixed with post combustion residues of ferrous/non-ferrous metals. The amount of ash varies with the demographics of the communities being served by the facility and the extent of recycling that is undertaken. However, typical thermal processing facilities produce ash in the range of 20% to 30% by weight of the total waste feed. However, since ash is relatively dense, on a volume basis, the waste is reduced in volume by about 90%. Depending on the regulatory framework and treatment process, ash from the combustion grate (bottom ash) can be treated and reused as construction material after further treatment, such as weathering (carbonation) or melting via plasma or slagging processes. Ash collected from the flue gases (including ash particulates arising from the boiler and air pollution control residues from bag filters) will contain hazardous compounds and generally requires pre-treatment, stabilisation and careful disposal in fully engineered landfills.

2.2.1 Grate Systems

A grate furnace is capable of burning untreated waste. In a grate furnace, the waste is fed in via a feeding chute and then pushed into the combustion chamber by a hydraulic ram or a travelling grate. There are a number of different grate designs in operation but their prime function is the controlled transport of the waste through the combustion chamber. The design has to guarantee efficient mixing of the fuel bed and permanent coverage of the metal parts to protect them against over-heating. In all grates the primary air is injected from below, through the grate. As the waste is dried and combusted the remaining volatiles are further combusted above the grate assisted by proper mixing of the gases with the overfire air. The combustion grate is designed to have sufficient length to allow the remaining waste to fully combust prior to the ash being discharged out of the furnace.

There are four main types of grate:

- forward reciprocating;
- reverse reciprocating;
- roller; and
- horizontal

The hot flue gases produced in the combustion furnace pass into a water tube boiler where the energy is recovered via heat transfer to form superheated steam inside the tubes. The gases then pass through the air pollution control (APC) system to be cleaned where pollutants such as acid gases, oxides of nitrogen (NOx), heavy metals and dioxins/furans are removed before the cooled flue gas is emitted to atmosphere via a chimney.

The superheated steam is used within a steam turbine to generate electrical power.

Two types of solid residues are generated by the combustion process; incinerator bottom ash (IBA) and air pollution control (APC) residues incorporating fly ash from the abatement equipment.

- IBA is usually classified as non-hazardous waste. It is initially processed to remove metals for recycling and can then be further treated to produce an approved aggregate material with applications for road building and construction, and
- Ash from the particulate filtration system is generated as fly ash and APC residues and usually classified as hazardous waste due to the residual alkalinity and ecotoxicity (attributed to chemicals removed from the flue gases). These residues are usually treated, neutralised and then sent for storage in underground mines or disposal in an appropriately permitted landfill.

2.2.2 Fluidised Bed Systems

Fluidisation is the term applied to the process whereby a fixed bed of fine solids is transformed into a liquid-like state through contact with an upward flowing gas, usually air. The technology for fluidised bed (FB) combustion has been known for the greater part of the last century, though there were extremely rapid developments in FB technology during the 1970's throughout the world. Today, it is a well-established and proven process for energy conversion. The technology was originally developed for power generation from the combustion of coal but it has been applied to a much wider range of fuels in recent years, such as sewage sludge, biomass and solid wastes.

FB furnaces consist of a rectangular or cylindrical combustion chamber where wastes with a relatively small particle size are burned in a fluidised sand bed, sometimes with the addition of dolomite for the capture of acid gases. Today they are deployed mainly in Japan for the processing of MSW, although there are several plants operating on MSW in Europe. Currently, they are becoming more popular for the combustion of solid recovered fuel (SRF) and biomass.

All FB furnaces have the advantage of establishing a uniform distribution of the waste in the fluidised fuel bed, which enables homogeneous and stable combustion. Another advantage is the wide range of calorific value fuels that can be burnt in this type of furnace. The energy density in the fuel bed can be varied by controlling the share of fuel in the bed. FB technology is sometimes chosen due to the need to minimise plant floor area e.g. in some inner city locations. A vertical furnace design can result in a higher incineration capacity per unit area than typical grate-fired units; there is however the potential for an increased height profile with FB technology to raise concerns over their visual impact in certain locations.

In order to establish fluidisation, the particle size has to be limited; therefore pre-treatment (i.e. shredding, chipping etc.) of the fuel is required. Another limitation is the fuel bed temperature, which is typically kept < 850°C to avoid melting and agglomeration of ash components and the collapse of the fluidised bed.

There are three types of FB reactor:

- bubbling (BFB);
- circulating (CFB), and
- revolving (internally recirculating FB).

As for moving grate systems, the hot flue gases formed in the FB combustors pass through a waste heat recovery boiler to produce steam for use in a steam turbine to generate electricity. The flue gases are then cleaned in the APC process before being discharged to atmosphere.

Residues (bed ash and fly ash) are removed from the plant for recycling or disposal, Section 3.2.6 discusses this in more detail.

2.3 Gasification

Gasification is a partial oxidation process, in which the majority of the carbon and hydrogen in the waste is converted into the gaseous form (syngas), comprising mainly carbon monoxide (CO) and hydrogen (H2), and leaving a solid residue consisting of inert ash and a char consisting of the inorganic compounds that entered with the waste and fixed carbon rejected by the gasification process. Gasification converts about 80% of the chemical energy in the waste fuel into chemical energy in the gas phase. The gas can be combusted immediately, cleaned and used directly in gas engines or upgraded to higher fuels or chemicals.

There are a number of different gasification processes and process configurations that have been marketed as alternatives to incineration for treating MSW and RDF. These include different designs of the core gasification reactor such as fluidised bed, rotary kiln, updraft and downdraft reactors, each of which is tailored to give certain benefits when gasifying various types of wastes. The main configurations are summarised in **Table 1**. This technology evaluation will only focus on those designs that are close to reaching commercial application using MSW or similar feedstock.

Table 1: Gasification reactor variants

Reactor Type	Mode of Contact
Fixed Bed	
Downdraft	Solids move ↓, Gas moves ↓, ie: co-current
Updraft	Solids move ↓, Gas moves ↑, ie: counter-current
Cross-draft	Solids move ↓, Gas moves at right angles ie: ← or →
Variants	Stirred Bed; Two stage gasifier
Fluidised Bed	
Bubbling	Relatively low gas velocity, inert solid stays in reactor
Circulating	Much higher gas velocities, inert solid is elutriated, separated and re-circulated
Entrained bed	Usually there is no inert solid, has highest gas velocity of lean phase systems
Twin reactor	1st stage - steam gasification and/or pyrolysis; 2nd stage – char combustion
Moving Bed	Mechanical transport of solid, usually horizontal. Typically used for lower temperature processes, ie: pyrolysis
Variants	Multiple hearth, Horizontal moving bed, sloping hearth, screw/augur kiln
Other	
Rotary kiln	Good gas-solid contact
Cyclonic reactor	High particle velocities and turbulence to effect high reaction rates

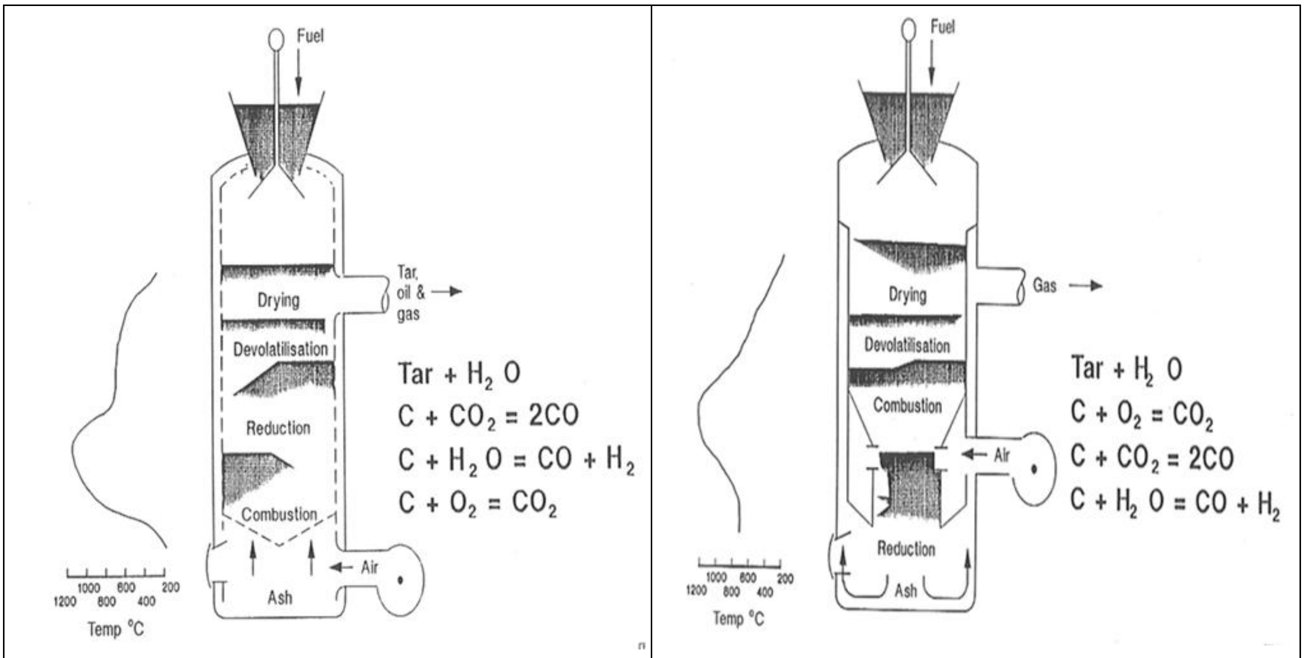
Source: WSP analysis

Typical gasification temperatures are 900-1,100°C with air and 1,000-1,400°C with oxygen. Air gasification is the most widely used technology. It is cheaper than oxygen gasification but results in relatively low energy syngas, containing up to 60% nitrogen, with a heating value of 4-6 MJ/Nm3. Oxygen gasification gives a higher heating value syngas of 10-18 MJ/Nm3 but requires an oxygen supply with an associated cost and energy requirement. High temperature gasification also has the benefit of melting the ash (inorganic content of the input waste) to produce a slag, which is inert. The high temperatures necessary to melt the ash (typically over 1,600°C) are produced by adding supplementary fossil fuel such as coke, injecting oxygen or by the use of plasma to provide the necessary heat input (see Slagging Gasification and Plasma Gasification below). In this report we refer to processes that do not melt the ash as 'low temperature' gasification and processes that do as 'high temperature' gasification.

Syngas contains CO, H2 and smaller quantities of methane (CH4) depending on the reactor type, as well as some of the unconverted reactants such as carbon dust, mineral ash, carbon dioxide (CO2) and nitrogen (N2) when air gasification is used. In addition, traces of other organic and inorganic compounds are produced or released in the gasification process and need to be cleaned from the syngas prior to utilisation.

Updraft and downdraft gasifiers, as presented in **Figure 2** have been used for many years in the chemical industries for numerous applications very successfully. The updraft gasifier can be scaled-up to very large size but it produces a dirtier syngas because the flow of the produced syngas passes through lower temperature zones within the reactor and the tars and liquid droplets produced are not cracked to lower molecular weight hydrocarbons. Conversely, downdraft gasifiers produce very clean syngas as a result of it being forced downwards through high temperature zones within the reactor before passing upwards and out via the annular design. However, the downdraft design is limited in its scale-up potential because of the internal geometry of the design and requires careful control over particle size.

Figure 2: Schematic representation of Updraft and Downdraft gasification reactors



Updraft gasifier | Downdraft gasifier

Fluidised bed plants require feedstock to be shredded to reduce the particle size to a suitable level for the gasifier to accept.

Gasification offers a number of potential advantages over direct combustion of the MSW, depending on how the process is configured:

- The resulting syngas can be utilised in a range of applications, including gas engines for conversion to heat and electricity with potentially increased efficiency over conventional steam cycle;
- There is potential for improved combustion control and reduced emissions at source associated with combustion of a gaseous fuel rather than a heterogeneous solid fuel; and,
- There is potential for the flue gas clean up system to be substantially scaled down when gas engines are used, due to much lower volumes of flue gas and reduced formation of certain pollutants.

2.3.1 Gasification with Steam Cycle ('Close-Coupled' Gasification)

Most commercially available waste gasification processes use a steam turbine to generate electricity in the same way as conventional combustion plants. The syngas produced by the gasifier is immediately combusted (in the same vessel or in a separate reactor). The heat produced by combustion is carried by flue gases and passes through a heat recovery boiler in order to raise steam to power a steam turbine. This is referred to as 'close-coupled' gasification.

Gasification in combination with combustion has a number of advantages over 'advanced' gasification (where syngas is used in gas engines or a gas turbine, or in high pressure boilers):

- Syngas does not require any treatment (cleaning syngas is an 'Achilles heel' of more advanced gasification processes);
- The energy from the tars and volatile organics are recovered;
- More conventional and proven steam boiler/steam turbine systems can be used for energy recovery;
- Tried and tested flue gas cleaning methods can be used to abate potentially harmful pollutants, and
- As a result of the above, it is seen as a lower risk, more bankable technology and financing can be more straightforward.

There are also however a number of significant disadvantages with this approach:

- The efficiency of a steam turbine generator is inherently lower than a gas engine or gas turbine. At small scale a close-coupled gasification process may generate electricity with an efficiency of around 20%, whereas gas engine or gas turbine systems could theoretically achieve efficiencies of 30 - 40%;
- The process is likely to have a larger plant profile than those configurations that produce a syngas because of the high flue gas volumes that require a gas clean-up system and stack similar to that required by a moving grate combustion plant, and
- The plant will require a much larger stack than an 'advanced' gasification plant.

2.3.2 Gasification with Syngas to Gas Engines or Turbine ('Advanced' Gasification)

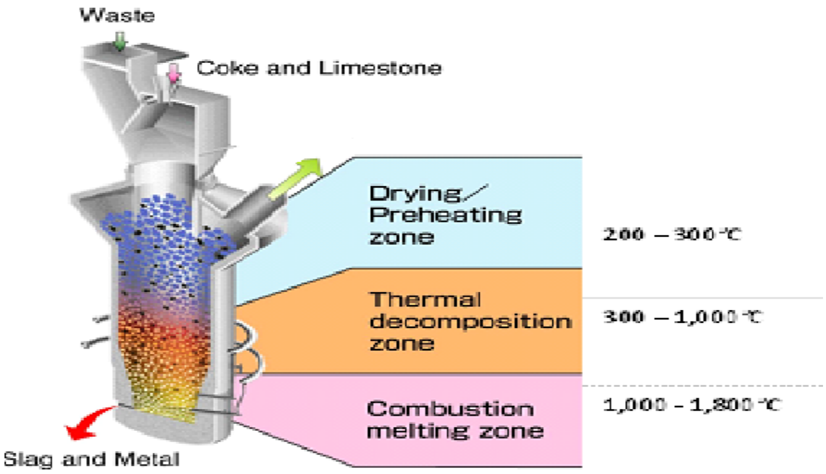
Higher electrical efficiencies can be achieved when the syngas is used in gas engines. However, there are few plants operating in this manner due to the requirement to clean the gas to a standard appropriate for use in gas engines. Few systems have been proven technically at commercial scale, with JFE's Thermoselect process being a notable exception that is currently operating at seven plants in Japan with five of them cleaning the syngas and using gas engines. However, we understand JFE are no longer offering this technology due to the costs of the process.

2.4 Slagging Gasification

Slagging gasification processes are designed to combine gasification of the waste with melting of the inorganic material (ash and metals) present in the waste. This practice is particularly prevalent in Japan where the main objective of waste management is volume minimisation and maximised recycling. The resulting melted ash, a type of vitrified slag, is physically stable, environmentally inert and is predominantly recycled as a construction material in Japan. Total residues requiring disposal to landfill from a slagging gasification plant can be very low when outlets can be found for the slag. Metals can also be separated.

To melt the inorganic ash, high temperatures are required and in some processes the required temperatures are facilitated by the use of oxygen rather than air for gasification and/or the use of plasma processes to provide the necessary input of heat energy. High-energy supplementary fuels such as coke are often also added to the waste stream to boost the temperature in the melting zone of the reactor to temperatures in the range of 1,600°C required for melting to occur. The production of oxygen is costly and usually energy intensive although Pressure Swing Adsorption (PSA) oxygen generation systems are being used in Japan, which produces oxygen enriched air flow, which is much more cost effective than cryogenic air separation systems. **Figure 3** shows an example of an updraft slagging gasifier.

Figure 3: Slagging gasification process example



Source: Nippon Steel (temperature ranges added by WSP)

The vast majority of operational slagging gasifiers recover energy from the flue gas using a steam cycle, but the use of syngas in gas engines or turbines is also possible.

Slagging gasification produces less electricity and heat for export than equivalent systems that do not melt the ash, and requires a fossil fuel input to produce the high temperatures. However it maximises recycling potential and minimises ultimate disposal to landfill by producing a high quality, non-leachable product from the ash. Sections 3.2.5 and 3.2.6 discuss solid process residues in more detail.

2.5 Plasma Gasification

Plasma gasification uses extremely high temperatures in an oxygen starved environment to decompose organic waste materials into basic molecules. The extreme heat and lack of oxygen results in pyrolysis and gasification reactions taking place, which convert the organic matter in the waste into syngas. The heat source is plasma gas, which is generated by the input of electrical energy to a gas (usually air). The plasma gas briefly attains temperatures between 3,000 and 8,000°C in the plasma plume, though in most plasma processes waste is not exposed directly to the plasma arc, and the temperature in the reactor may be between 1,000 and 2,000°C.

Some processes use plasma torches just to melt the ash from the gasification or combustion process in a separate reactor and this produces a stabilised slag similar to that from a slagging gasification process. It is also possible to utilise Plasma melting technology in a combination with a mass burn combustion plant to vitrify the ash resulting from the process. The combination of processes has been implemented by a number of technology providers in Japan.

There are three main variants of plasma gasifiers available:

- Direct exposure to plasma torch (only some high-level hazardous waste);
- Plasma assisted gasification; and,
- Plasma for syngas polishing (cleaning by cracking of hydrocarbons).

2.6 Pyrolysis

There is very limited commercial scale operational experience with waste pyrolysis plants, so there is uncertainty around technical performance and ability to meet emissions limits, etc. It is also unproven at any commercial scale, which means obtaining project finance is likely to be extremely challenging. The following overview of pyrolysis is included to ensure this document provides a broad scope review of WtE technologies.

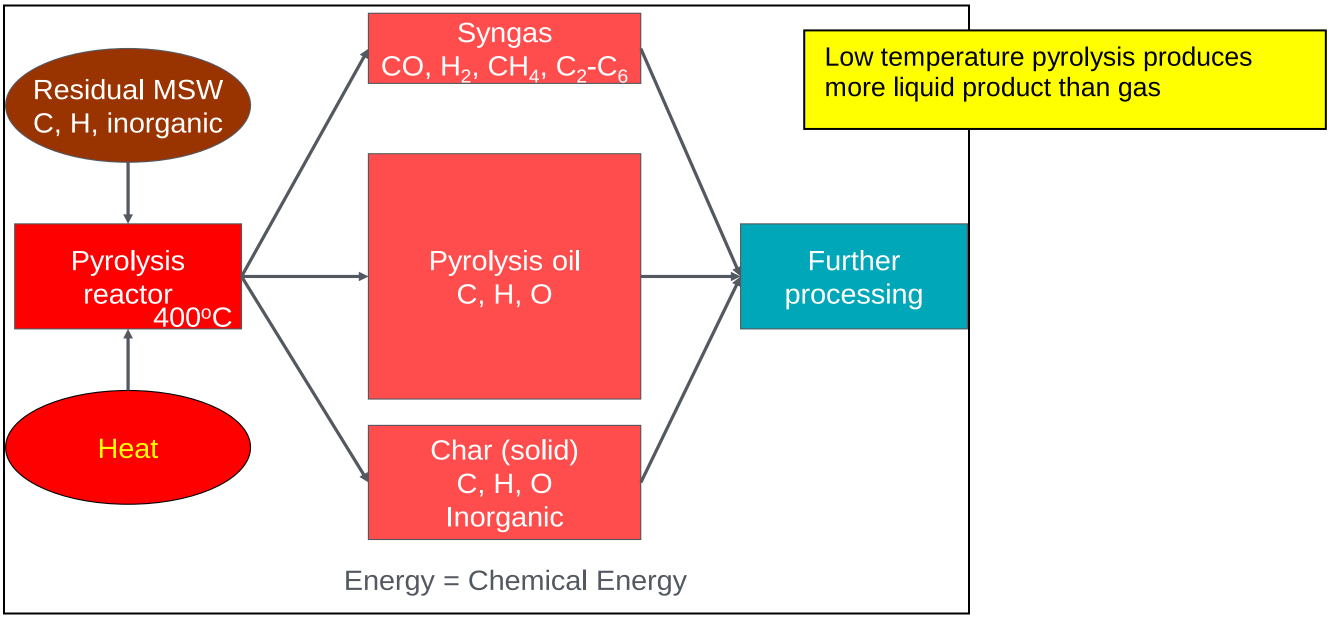
Pyrolysis is a thermal conversion process where waste is heated in the absence of oxygen. The reactor is heated externally to produce the elevated temperature environment that causes the organic solids (waste input) to breakdown via physical and chemical processes into three products; solid char, pyrolysis oil and pyrolysis gas with the proportions of each being governed by the operating temperature within the pyrolysis reactor. Typically, pyrolysis is operated at relatively low temperature to produce a primary liquid product (pyrolysis oil) and lesser quantities of char and pyrolysis gas.

There is a certain amount of misunderstanding concerning the differences between gasification and pyrolysis. True pyrolysis is a low temperature thermal conversion technology that operates in an air-free environment and produces a primary liquid product as well as lesser quantities of gas and solid phase products. If pyrolysis is operated at high temperature (>800°C) then the primary product becomes syngas but the process will also produce liquid and solid phase products in lesser amounts. The quantity of char produced at low and high temperatures does not vary greatly.

For biomass and waste processing the lower temperature pyrolysis processes have been used with the objective of maximising the production of pyrolysis oil, referred to as bio-oil, which is a potential precursor to the production of many other chemicals in a bio-refinery context.

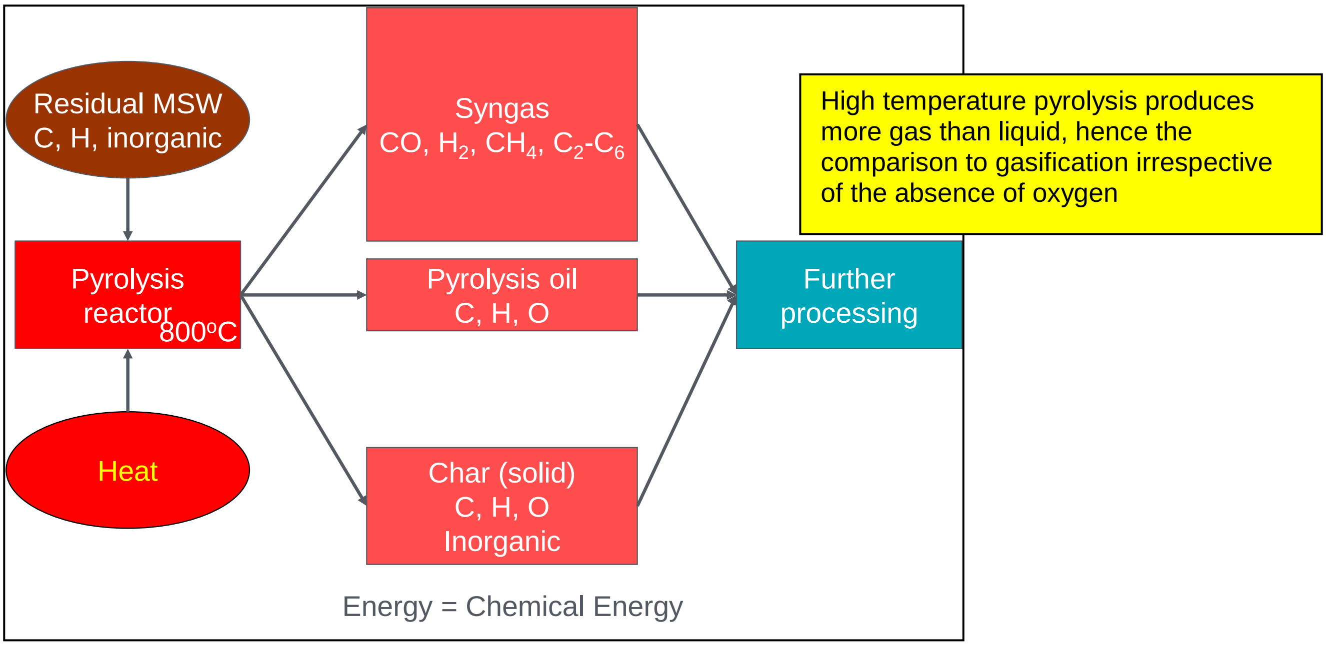
In a waste processing context the higher temperature pyrolysis processes have been developed in order to maximise the production of syngas, which is more easily converted to electricity. Despite the lack of oxygen, these processes can be considered similar to gasification i.e. the sole objective is to produce syngas like gasification. The composition of the syngas will differ however, having a higher calorific value (CV) but higher levels of tars and impurities. **Figure 4** and **Figure 5** provide a breakdown of pyrolysis products based upon lower and higher temperature operations with associated impacts on outputs.

Figure 4: Schematic representation of a low temperature pyrolysis process



By increasing the operating temperature the thermodynamics governing the reactions taking places cause a greater production of pyrolysis gas (syngas) at the expense of pyrolysis oil. The quantity of char produced at low and high temperatures does not vary greatly.

Figure 5: Schematic representation of a high temperature pyrolysis process



For biomass processing the lower temperature pyrolysis processes have been used with the objective of maximising the production of pyrolysis oil, referred to as bio-oil, which was seen as a pre-cursor to the production of many other chemicals in a bio-refinery context.

In a waste processing context the higher temperature pyrolysis processes have been developed in order to maximise the production of syngas, which is more easily converted to electricity. Processes designed to maximise production of syngas we consider to be gasification; those producing bio-oil are considered to be pyrolysis. There are numerous hybrid processes that employ both pyrolysis and gasification stages (such as the Thermoselect process), but as the final product is a gas we consider this to be a gasification technology.

Pyrolysis gas and oil has high energy content but is dirty and challenging to clean, more so than syngas from gasification, the clean-up of which in itself is the cause of problems in many systems. Pyrolysis gas and oil produced from municipal waste is unproven with combustion engines. When the gas is combusted in a boiler to raise steam pyrolysis offers no clear advantage over gasification/combustion systems.

3 Key Characteristics Review

3.1 Introduction

This section provides an overview the key characteristics for each type of thermal waste treatment technology incorporating examples of specific operational plants representing each variant where relevant. Where appropriate process specific information is also provided in tabulated format for easy reference.

3.2 Key Parameters

3.2.1. Feedstock

All of the WtE technology variants reviewed for this report have the capability to process MSW and C&I wastes. Some however require the waste to be pre-treated prior to the energy recovery stage, predominantly those based on a fluidised bed reactor which we consider further here.

Fluidised bed reactors require feedstock to be reduced in size to allow effective combustion or gasification. It is often also desirable to remove metals to avoid issues with bed material fusing, which can impair performance. Therefore upfront equipment to shred and remove metals from waste is usually installed before a fluidised bed plant. Often plants of this design will use a Refuse Derived Fuel (RDF) or Solid Recovered Fuel (SRF), which may be prepared at a separate site and delivered to the WtE plant. Grate-based plants can also use RDF or SRF, but this is not a requirement.

Pre-treatment systems suitable for producing prepared feedstock for use in a fluidised bed plant include Material Recovery Facilities (MRF) or Mechanical Biological Treatment (MBT). These plants are designed to maximise extraction of recyclable material from the input stream .MBT technology is considered in a separate, parallel report. Here we briefly describe the role of MRFs.

MRF Overview

A material recovery facility (MRF) is an automated, semi-automated or manual sorting process designed to separate a mixed MSW or C&I materials streams into various fractions for recycling, disposal or energy recovery.

There are two broad types of MRF:

- 'Clean' MRF – sorts co-mingled recyclables from kerbside collection[1] and/or waste recycling centres.
- 'Dirty' MRF – processes and sorts mixed waste streams including residual waste, which usually produces lower grade materials and processing losses are higher than a clean MRF due to the contamination with wet fractions such as food and other biodegradable wastes.

The exact layout of an MRF will depend upon a number of factors including the available space, the number materials to be sorted, the level of manual sorting that is economic to carry-out, etc.

'Clean' MRF

Clean MRFs sort co-mingled recyclables, typically from a kerbside recycling collection or source segregated recyclable wastes from industrial or commercial premises. Clean MRFs are usually designed to maximise recycling and not to produce RDF or SRF. Whilst a clean MRF is designed to only accept recyclable materials (albeit with a small proportion of non-recyclable contaminants), alternative treatment for the residual component will be required; typically this would be a thermal process.

[1] Where recycled materials are separated by the householder or business prior to disposing of their waste. Specific containers are provided for the separate storage of recyclables (either co-mingled of source segregated) from residual waste materials.

Typical outputs from a clean MRF include:

- 80 – 95% - dry recyclables
- 5 – 20% residue to landfill or preferably WtE

'Dirty' MRF

Dirty MRFs recover recyclable materials from the mixed MSW stream with little or no prior segregation of materials at source. Typically the MSW is de-bagged and shredded and then metals, plastics, paper and inert materials are separated using a range of techniques.

The quality of the separated materials produced from a dirty MRF will be lower than from a clean MRF because cross-contamination will occur during the collection, compaction, transport and processing steps. As a result, the level of recycling and income from selling the recyclable material will be significantly lower. This type of process will often be configured to recover relatively high value, easy to recover recyclables (which may primarily be recovered by manual sorting); often the primary product from the organic waste stream being RDF.

The absence of a drying or biological treatment stage to stabilise the non-recyclable and organic fraction means it can be difficult to produce a homogeneous fuel or control the output to a particular specification. Producing a high quality SRF (e.g. to specified quality standards) generally requires a biological or heat treatment process. MBT plants, discussed in more detail in a related report to this, integrate the biological treatment of the organic fraction at the same facility.

3.2.2. Scale

Waste to energy technologies are available at a wide variety of scales, though some technologies have no demonstrable examples or are not economically viable at certain capacities.

Capacity

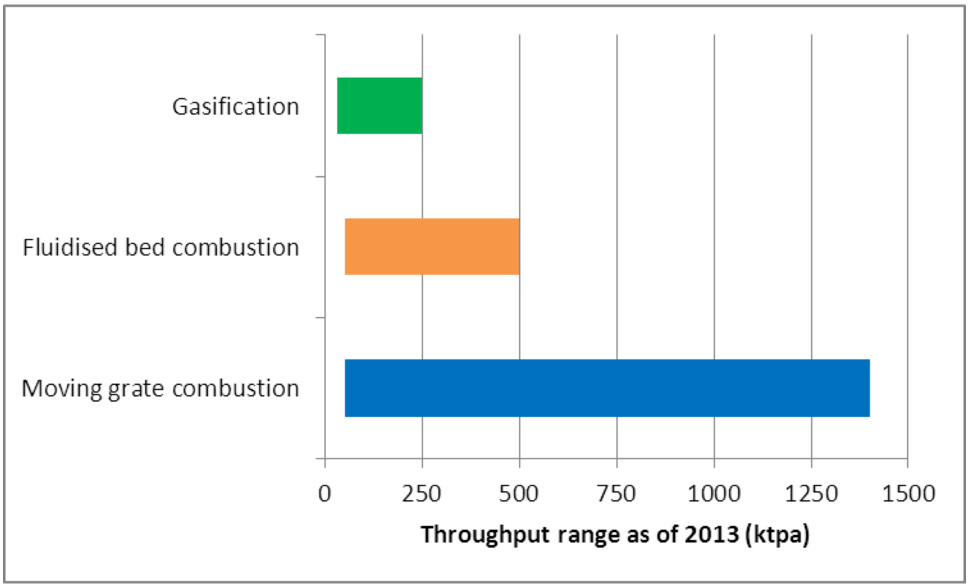
WtE combustion plants are proven at a wide range of scales. There is no practical limit at the upper end as individual combustion lines (grate or fluidised bed) can be large and any number of combustion lines can theoretically be added providing space is not constrained. The largest plant in the world is the AEB Amsterdam plant which is capable of processing 1,400,000 tonnes per year of MSW in 6 lines (2 newest lines added well after construction of original plant). Large plants can have advantages over small plants in a number of areas; for example the larger the plant the more efficiently it can generate and export electricity, and the lower the specific capital cost. However, larger plants often require waste to be transported over greater distances and clearly require higher overall investment which can make obtaining project finance more challenging. The requirements for high tonnages of waste can increase the risk of failing to secure sufficient feedstock; additionally care is required to make sure thermal treatment plants do not discourage waste minimisation, reuse and recycling efforts over the lifetime of the plant which could be a risk if the plant is designed to be too large.

Smaller plants may be well suited to smaller towns and rural communities where it could be economically and environmentally detrimental, as well as challenging logistically, to develop a larger plant with a large waste catchment area. However, unlike at the larger end of the scale, there is a practical limit at the smaller end which must be considered. Combustion plants are rarely smaller than around 50,000 tonnes per year. Below this combustion of waste is still possible, but the efficiency of energy recovery falls rapidly and the specific capital cost increases considerably such that it is not generally economic to develop smaller plants; there are many examples of operational plants between 50,000 and 100,000 tonnes per year, but very few less than 50,000 tonnes per year.

Gasification plants can have an advantage at the smaller end of the scale. The scale of combustion plants is largely limited by the rapidly falling efficiency of the steam cycle at low steam production rates (and hence waste throughput). Small modular gasification units are available, and where syngas is sent to gas engines high efficiencies can be achieved at much smaller scales. However though offering promise, such processes are yet to be fully proven commercially and the vast majority of commercial waste gasification plants at present use a steam cycle to recover energy and hence have the same problems associated with viability at small scales.

Figure 6 provides an indicative throughput range for three technologies based on current operational plants. It is important to note that it is does not indicate the range these technologies are restricted to; however it does indicate the typical applications at present.

Figure 6: Range of scales by technology (based on existing plants)



Operational costs will also fall somewhat with increasing capacity, though the impact is largely restricted to fixed overheads such as staff costs, land costs, environmental compliance etc.; These elements do not tend to increase proportionally with throughput. There will also be some economies of scale associated with major lifecycle maintenance, a good example is the overhaul of a turbine; the costs for maintaining two turbines one twice the output of the other will not differ by a factor of two. However routine maintenance costs tend to be reasonably proportional to throughput. Similarly the costs of consumables and disposal of by-products associated with each tonne of waste treated (including flue gas treatment reagents, ash disposal, support fuel etc.) does not tend to change significantly with increasing capacity.

Gate fees will vary depending on a multitude of factors, and plant capacity will usually have some impact. In general the lower specific capital cost per tonne of waste throughput and the higher specific electricity output effectively results in a lower overall cost per tonne of waste processed for larger plants, theoretically meaning a lower gate fee could be charged for a larger facility compared to an otherwise identical smaller facility (a considerable component of the gate fee is typically required cover repayment of the facility). However, there are many other factors involved in calculating an appropriate gate fee and individual facilities of the same capacity may charge greatly differing gate fees depending on the national and local waste market, incentives and policy instruments, plant financing mechanism, waste composition, efficiency of energy recovery etc, so it should not be inferred that larger facilities will necessary see a lower gate fee. See Section 3.2.9 for more information on gate fees.

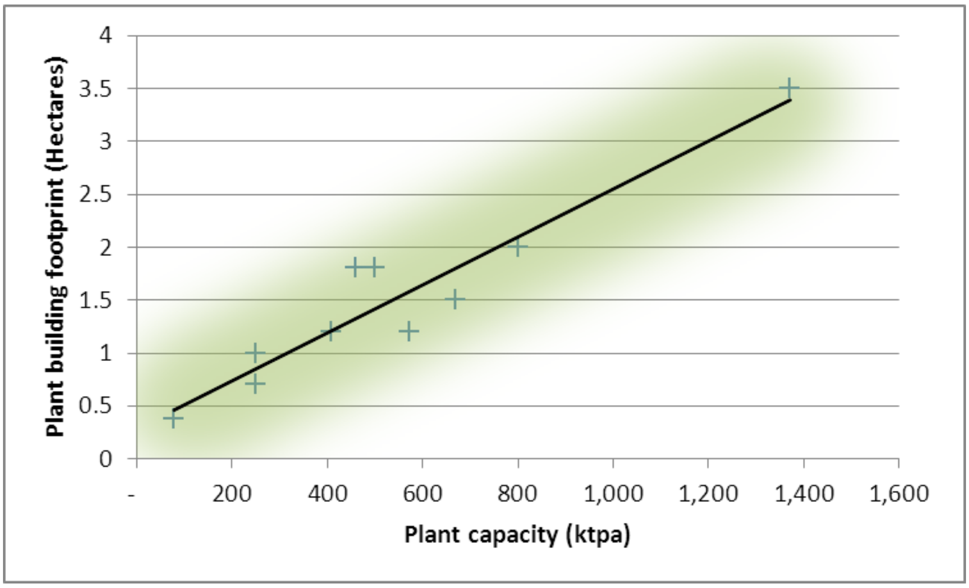
Land Take and Building Size

WtE plants require less land to process a given throughput of residual solid waste than most alternative treatment and disposal technologies such as mechanical and biological processes and landfill. Furthermore, the waste is reduced considerably in volume and there is good potential to recycle some of the ash produced as a by-product as discussed in Section 3.2.6. Despite the relatively compact nature of such plants, the land requirements and siting issues are still important factors to consider when locating a WtE facility.

Although a wide range of thermal treatment technologies are available, the building footprint for plants with a conventional steam boiler and turbine tends to be similar for a given throughput capacity. This is because many elements of the plant are common to the vast majority of processes, such as waste reception, flue gas clean-up, heat recovery steam generator, energy recovery plant and condenser. The building footprint of a sample of 10 WtE plants of different scales is plotted against plant capacity in **Figure 7**. It can be seen there is a reasonably good correlation and the trendline on the chart can be used to roughly predict the footprint of a conventional WtE plant, with the green shaded area representing the approximate range based on the facilities considered in this review.

The overall site area is subject to much greater variation depending on the location of the plant. An unconstrained, greenfield WtE plant will typically take up a much greater land area than a constrained urban plant. Typically the overall site area needs to be at least 3 times the building footprint to allow for vehicle movements, construction and maintenance access and laydown and auxiliary equipment.

Figure 7: WtE building footprint by capacity



Land Take and Building Size - Technology Comparison

Footprint

As stated above, the differences in footprint of current commercially available WtE technologies tends to be fairly small since many components are similar. However there are some differences.

The footprint required for close-coupled gasification plants appears similar to combustion plants and within the range indicated in Figure 7. For gasification plants that incorporate syngas treatment systems it is of note that the equipment required to polish the gas can take up significant space. For example the ceramic polishers on the Metso plant are very bulky units; based on an indicative layout provided to WSP these appear to take up around one third of the footprint of the plant. However, the overall footprint is comparable to an equivalent capacity combustion plant.

Gasification plants with gas engines can in theory be designed to be significantly smaller than equivalent capacity gasification or combustion plants using a traditional steam cycle. This is because they forego the requirement for a boiler/heat recovery steam generator (HRSG), turbine and condenser, as well as much of the bulky flue gas clean up equipment. However this is dependent on the particular technology, and in some cases such syngas to gas engine technologies may offer no land take advantages. For example one of the few commercially operating technologies using waste to produce syngas to gas engines is the Thermoselect process. These plants have relatively large footprints; for example the 300tpd (approximately 100,000tpa equivalent) Chiba plant in Japan has a building footprint of 0.6 ha, giving it a larger area per tonne of treatment capacity than any of the conventional plants in Figure 7. This would appear to be a feature of this specific technology, which includes a large horizontal pyrolysis reactor as well as a vertical gasifier and syngas clean up equipment.

Height

WtE plants are normally tall structures, with the height to building roof typically being 30 – 50m above ground level. This is due to the furnace and boiler which must have a reasonable height to allow the waste to be fully and cleanly combusted, and for heat to be recovered from the flue gases (this is equally applicable to both grate and fluidised bed designs). The height can be reduced somewhat by using a horizontal boiler rather than a vertical boiler, though this has a modest impact and tends to increase the footprint. Should building height be a particular concern, equipment can be located below ground level though this can incur substantial costs. There are numerous examples where this has been done; the Issy Les Moulineaux plant in France is a good example of a plant designed with a low profile, the plant is sunk 30m such that the height to the building roof extends only 27m above ground level.

Fluidised bed plants are also tall, particularly circulating fluidised bed (CFB) designs. Some less common furnace designs can be lower, including those using oscillating kilns, but this design is unsuitable at larger scales.

Plants with steam boilers require a stack to disperse the cleaned flue gases, which is usually 40 – 100m+ high. The height of the stack is dictated by local emissions legislation and planning and permitting requirements; usually dispersion modelling is required to determine the required height which can vary considerably. Where height is a major constraint it is possible to design a WtE plant with a low stack; for example as well as a low building height the Issy Les Moulineaux plant has an exceptionally low stack protruding only around 5m above the roof despite being located in an urban environment (the plant has very effective gas clean up equipment to reduce the level of pollutants in the flue gas to very low levels meaning significant dispersion is not necessary to meet local and national legislative requirements).

Gasification plants using gas engines or turbines do not require a high stack, and the building can be designed to be lower since there is no requirement for a large furnace and boiler. This means such plants are better able to fit into non-industrial surroundings more discretely than traditional plants with steam boilers.

Architectural enhancements can be used to help disguise the scale of WtE plants. The Issy Les Moulineaux plant is an unusual example of a conventional grate combustion plant which manages to blend into non-industrial surroundings (it looks similar to a modern office building); however this was a very expensive plant with major expenditure on civil works to sink the plant 30m below the ground next to the River Seine as well as the considerable architectural enhancement.

Scale and Environmental Impact

A 2009 study[2] suggests the environmental impact of installations dedicated to the treatment of MSW is not strictly proportional to treatment capacity. A more significant role is played by the qualitative aspects of the MSW.

3.2.3. Energy Production and Efficiency

All thermal WtE technologies allow energy to be recovered from waste, but the means by which energy is recovered differs. For virtually all combustion plants and most existing gasification plants the burning of waste or syngas produces high temperature flue gases, which are used to raise steam to drive a turbine and generator to generate electricity. A proportion of the electricity generated is used to meet the internal requirements of the plant (the "parasitic load") with the remainder exported to the grid. Heat can also be exported in the form of steam or hot water. It is possible to use syngas produced by gasification or pyrolysis to directly drive a gas engine or turbine, or syngas can be "upgraded" to higher fuels for vehicles, though these are emerging technologies with very limited commercial experience using waste feedstock.

In summary a WtE plant will be configured in one of the following ways:

- Electricity only;
- Electricity and heat, known as Combined Heat and Power (CHP);
- Heat only;
- Producing syngas which is then upgraded to produce a vehicle fuel or higher chemicals – advanced gasification and pyrolysis processes only.

Most plants generate electricity only, despite the maximum attainable efficiency being considerably lower than for plants that supply heat or both heat and electricity. This is for several key reasons:

[2] Rada, EC et al (2009) Trends in the management of residual municipal solid waste. Environmental Technology 30 (7) 651-661

- Electricity is more valuable than heat (which often more than negates the lower efficiency with which it can be produced and exported);
- Unlike heat, electricity does not require the generator to be located in close proximity to the end user, or have a consistent demand, as electricity can simply be exported to the local grid, and
- WtE plants are often financed partly on electricity sales to the grid, which can be necessary to give investor confidence; heat users can disappear overnight but there is a high level of certainty that electricity can be exported to the grid over the lifetime of the plant.

The export of heat requires a co-located demand, typically an industrial process or residential and commercial development where heat can be piped to consumers to meet domestic heating needs. Where a suitable demand is available, overall efficiency and total revenues can be considerably higher (over 70%) than for equivalent electricity-only plant. CHP and heat only plants can be more challenging to develop and often require greater investment in infrastructure, but there are many successful examples particularly in Northern Europe. Plants exporting heat via a district heating network are more attractive in colder climates, and may be inherently unsuitable for much of Western Australia where annual demand for space heating is low. However, there may still be good opportunities for supplying industrial demand, and heat can be used to provide cooling to buildings and processes by using adsorption chilling.

Electricity Only

The vast majority of WtE plants recover energy from the hot flue gases using a steam boiler coupled with a turbine generator. Electrical efficiency can be expressed in a number of different ways; here we focus on the net efficiency:

- Gross efficiency – electrical power produced by the generator as a proportion of the total energy input to the plant;
- Net efficiency – electrical power exported by the plant (excluding power consumed by the plant itself) as a proportion of the total energy input to the plant.

Large fossil fuel steam turbine power plants can achieve net efficiencies in excess of 40%, but the maximum efficiency for WtE plants is limited by the lower calorific value (energy content) of the feedstock and the corrosive environment which places a practical limit on steam temperatures; this results in efficiencies being limited to around 25% - 30%. However the actual efficiency is often lower. At small scale the efficiency falls because there are greater losses in the steam circuit and the parasitic load per tonne of waste treated is higher.

Based on data available to WSP, the average net efficiency of WtE (moving grate combustion) plants in the UK in 2011 was 20%, ranging from around 15% to 25%.

The use of advanced techniques can boost efficiencies to over 30%. The AEB plant in Amsterdam is the most efficient in the world and uses a reheat cycle and advanced corrosion protection to allow higher steam temperatures and pressures than normally achievable.

Advanced gasification and pyrolysis technologies have potential to give higher electrical efficiencies than traditional combustion plants, particularly at small scale. The use of gas engines and turbines for syngas can definitely give considerable benefits where gasification and pyrolysis can have a big advantage over conventional WtE. The issue is getting the syngas sufficiently clean which has long been a major barrier. Gas must be cooled to remove tars and cleaned to remove impurities. Though the technology is moving closer to more widespread commercial deployment, steam turbines continue to dominate.

The Thermoselect process has achieved an electrical efficiency of 37%[3] , which shows the benefit of using gas engines over a steam turbine, although oxygen is used in the process which has a negative impact on the overall energy balance, meaning the efficiency figure is overstated somewhat.

Gasification plants that simply combust the syngas without cleaning and raise steam demonstrate efficiencies that are no better than for similar combustion plant. When syngas is cleaned there is potential to use a higher pressure boiler, giving higher efficiencies; WSP are aware of a process claiming a net efficiency of around 27% (but using a high CV feedstock).

[3] Thermoselect Waste Gasification and Reforming Process, JFE TECHNICAL REPORT No. 3 (July 2004)

Table 2 shows the range of efficiencies from existing plants based on data available to WSP. The low efficiency for gasification is a result of the inclusion of a technology not optimised for electricity generation; efficiencies should be at least as high as combustion for most optimised plant.

Table 2: Typical and Best Practice Efficiency for Various WtE Technologies

Technology	**Net efficiency (exported)**	
	Typical	**Best Practice**
Combustion	15% – 25%	30% with currently available advanced energy recovery techniques
Gasification (steam turbine)	10% - 27%	Uncertain, likely >30% (potentially slightly higher than combustion)
Advanced Gasification (gas engine/gas turbine)	30 – 40%[4]	Uncertain, 40 - 50% potentially achievable with gas turbines

As a rough rule-of-thumb a typical 100,000 tpa WtE plant will export around 7MW of electricity, which is sufficient to power approximately 10,000 homes[5].

CHP and Heat Only

All WtE technologies can be configured to export heat, instead of or as well as electricity. Overall efficiencies of around 70% are theoretically achievable for CHP plants and over 80% for heat only plants.

In general however the demand for heat is not constant, so the actual efficiency on an annual basis is usually lower though still in excess of that achieved by most electricity-only plants.

Production of Higher Fuels

The potential to use gasification and pyrolysis to produce higher fuels (particularly for transport) from waste is of much interest, and it is theoretically possible to produce higher fuels by upgrading the syngas via a variety of chemical processes such as the Fischer–Tropsch process[6] to produce higher hydrocarbons, including synthetic diesel fuels, from the main components of syngas (hydrogen and carbon monoxide).

Though proven on fossil fuels and to some extent on biomass and other homogenous wastes (plastics for example), WSP are not aware of any plants using mixed municipal and commercial solid waste as a feedstock on a commercial scale at present. However this is an area of much research and development work and in future may be an attractive option for treatment of residual solid waste.

Given the immaturity of this technology, proposals from organisations claiming to be able to do so at present should be rigorously examined.

3.2.4. Recovery Status and the Waste Hierarchy

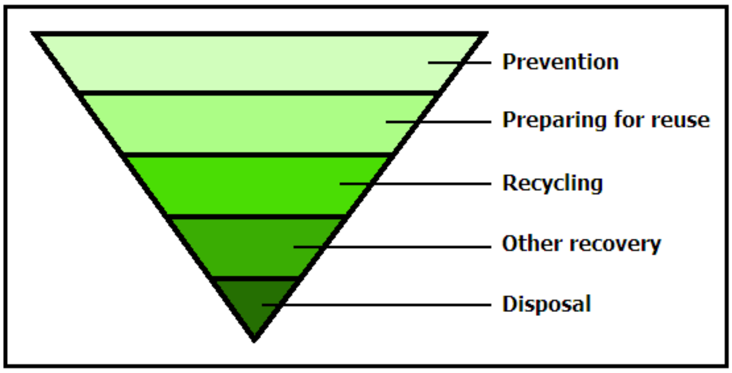
The waste hierarchy as defined by the EU **(Figure 8**) provides a priority order in waste and resource management and is enshrined in legislation in some jurisdictions. This requires waste producers to prioritise the prevention, re-use and recycling of waste over (energy) recovery and disposal (to landfill). All organisations that produce, keep or manage waste must demonstrate that the hierarchy has been applied when transferring waste to another party.

[4] Very few successful examples where verified data is available, Range is an estimate based on data on the Thermoselect process which is one of the few technologies to be commercially demonstrated using gas engines.

[5] Based on an average electricity consumption of 6,000 kWh per household per year

[6] P4ocess where a synthesis gas (syngas) consisting of a mixture of carbon monoxide and hydrogen, is converted into liquid hydrocarbons over a catalyst

Figure 8: The Waste Hierarchy



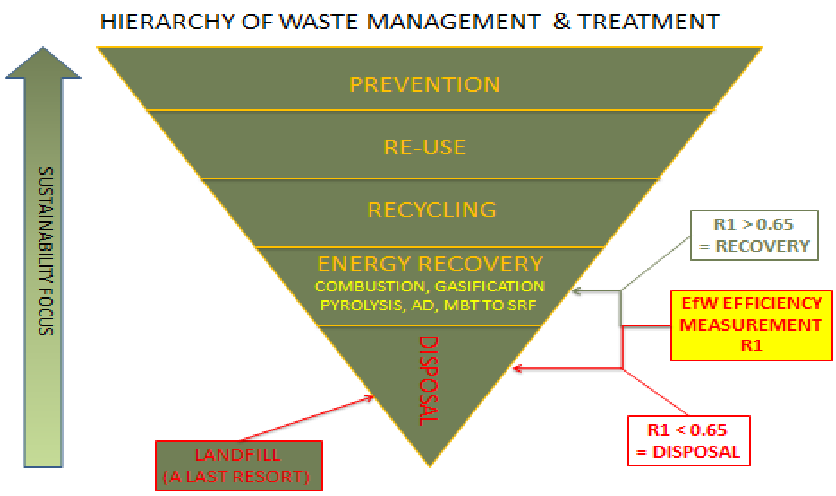
With specific relevance to thermal WtE technologies, the revision of the Waste Framework Directive in the EU provided a reference point for WtE plants to be considered as a recovery operation i.e. if it meets minimum energy efficiency requirements defined by the 'R1 efficiency'.. This outcome ensured that any new or proposed WtE plant that demonstrates an R1 value above a certain level (0.65) would be consider a 'resource recovery' plant and therefore sit higher up the waste hierarchy than less efficient plants.

The calculation formula for the R1 Efficiency Indicator can be found in the WFD[7] and is based on work undertaken by the EU Best Practice Committee in Seville, Spain[8] and initially proposed in the BREF[9]

Typically, the energy efficiency of a WtE plant, based on the ratio of 'useful energy out' to 'energy in', is in the range 18 - 22% for older plants producing electricity only. Modern plants, particularly at large scale, can meet the criterion on the basis of producing only electricity, due mainly to improved boiler design and enhancements to the high pressure steam cycle, achieving efficiencies in the region of 25 - 27%. These plants readily achieve the R1 criterion of >0.65 and are thereby classified in the EU as recovery operations. There are unique facilities such as the AEB plant in Amsterdam that has taken steam cycle modification to the extreme and achieve a continuous efficiency in the region of 30%.

The use of Combined Heat and Power (CHP) can dramatically increase the thermal efficiency and help to meet the R1 recovery criterion.

Figure 9: R1 and the Waste Hierarchy



7 http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2008:312:0003:0030:EN:PDF

8 BREF entitled Waste Incineration (WI) produced as a result of an information exchange carried out under Article 16(2) of Council Directive 96/61/EC (IPPC Directive)

9 Best Available Technique (BAT) Reference Document

The variant technologies covered in this report can all meet R1 status, particularly if heat recovery is a feature of the process. It should be noted slagging and plasma gasification processes may have difficulty achieving R1 status without heat recovery.

Carbon Dioxide Emissions and Recovery

Municipal and commercial wastes are considered partially renewable fuels, as they are partly made up of biomass (e.g. paper and card, food and green waste). WtE plants also prevent methane emissions associated with the decay of biogenic wastes in landfills.

The true CO2 performance of WtE is the subject of much debate and there is considerable research on the subject. The actual impact on CO2 emissions is dependent on many factors, including the alternative disposal options, level of recycling, plant efficiency and the type of fuels displaced. However it is clear that high-efficiency WtE can give significant CO2 savings, especially when displacing electricity and heat that would otherwise be produced by fossil fuels (especially coal) and when used to treat only non-recyclable wastes.

Ignoring the external factors, the greatest impact on the CO2 emissions performance of a WtE plant is the efficiency of energy recovery. Therefore CHP schemes give greater CO2 savings than electricity only plants. Another important factor is whether the plant requires support fuel or electricity in normal operation (as slagging and plasma gasification processes do), as these plants will perform less well in terms of CO2 emissions than plants that do not. It is not the case that more advanced technologies are inherently ‘greener’ than more traditional processes; for example a basic waste combustion plant exporting all heat to an industrial customer may give substantially greater CO2 savings than an advanced gasification plant using syngas to power a gas engine as the overall efficiency may be much higher in the former case.

Other factors are mostly indirect and not technology dependent, such as vehicle movements (mostly dependent on plant location).

3.2.5. Solid Residues and Landfill Diversion

Whilst all of the variant technologies considered for this review have the capability to meet the R1 criterion, it is important to remember this actually refers to the treatment process applied to the waste received e.g. MSW, RDF etc. The application of the waste hierarchy must then be applied beyond the initial treatment process for residual waste produced as a result of this e.g. bottom ash, fly ash or APC residues. For the purpose of this review, we will consider this in the context of landfill diversion, summarised in **Table 3** The landfill diversion figures assume furnace residues e.g. IBA will be recycled and Fly Ash/APC residues will be landfilled after treatment.

Table 3: Landfill Diversion Potential for Solid Residues arising from Different Thermal Treatment Technologies

Process	Feed Vari-ants	Technology Variant	Bottom/Bed Ash/Slag & Metal	Fly Ash/APCr	Total Solid Residues	Typical Landfill Diversion
			Expressed as % wt waste feedstock			
Direct Combustion	MSW Typi-cally 9-10 MJ/kg	Grate	24.6	2.6	27.2	97.4
		Fluidised Bed	11.0	12.0	23.0	88.0
Gasification	C&I Range 8-18 MJ/kg	Grate	21	7	28.0	93.0
	RDF12-13 MJ/kg	Fluidised Bed	11.7	8.8	20.5	91.2
	Wide Range	Slagging	11	5	16.0	95.0
	Wide Range	Plasma	Vitrified Slag	Information Not Available		

Note: The information we have used for the above is the best available however the overall ash content for different feedstock will vary irrespective of technology i.e. different proportion of ash.

The data provided above for **direct combustion** using **grate furnace** technology is based on eight established plants:

- AEB Amsterdam, Netherlands;
- Lakeside, UK;
- Spittelau, Austria;
- Issy Le Moulineaux, France;
- Zabalgarbi, Spain;
- Riverside, UK;
- Mainz, Germany, and
- Sheffield, UK.

Table 4 shows the range of output variants used to apply the mean values above, based on the plants listed above.

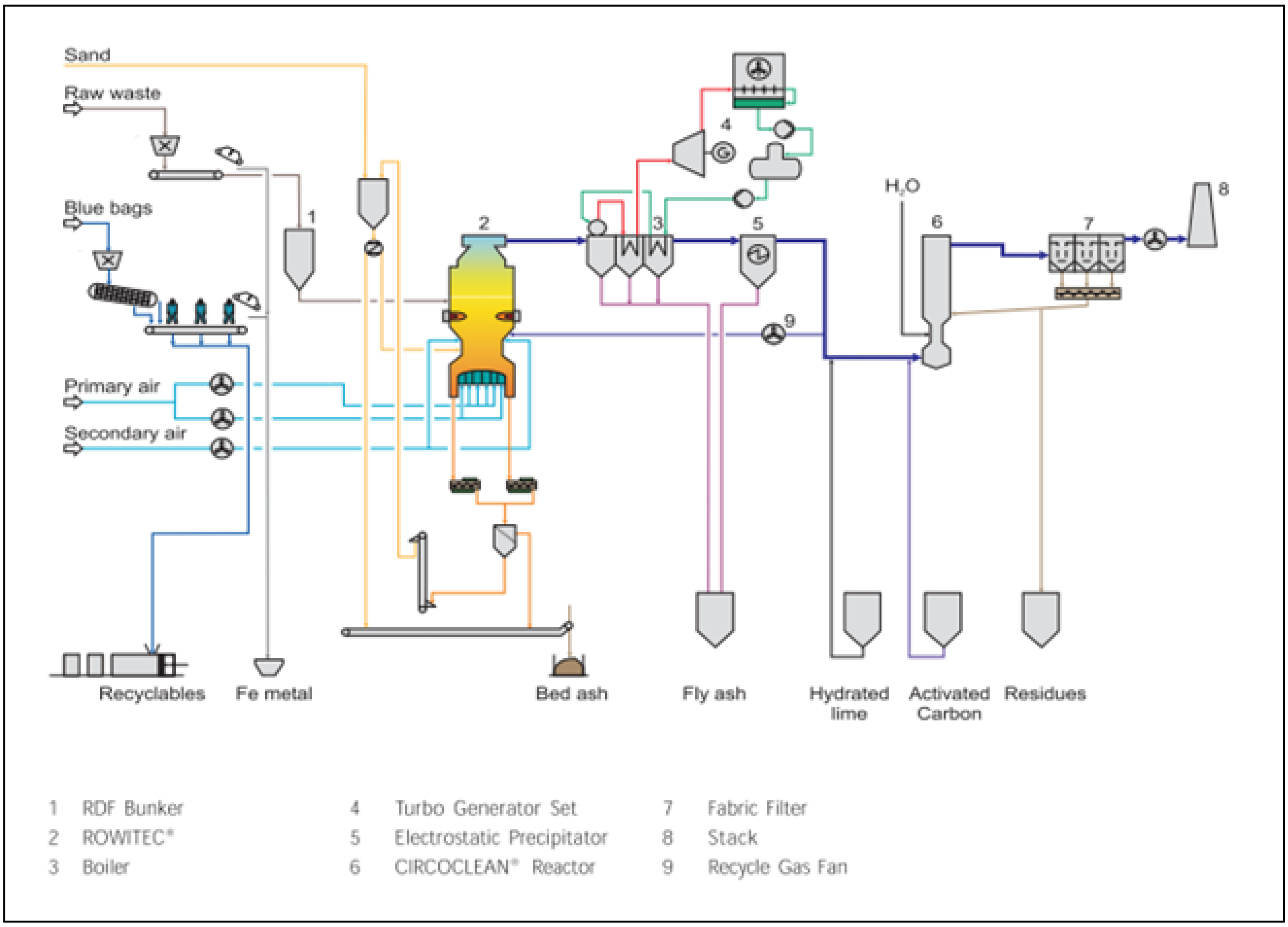
Table 4: Solid residue characteristics for direct combustion grate technologies

	RANGE (% by Wt)	MEAN (% by Wt)
IBA/Metals	22-29	24.6
IBA	19-24	21.3
Ferrous	1.5-5.0	2.8
Non-Ferrous	0.2-0.5	0.4
APC/Fly Ash	1.0-3.7	2.6
Calorific Value MJ/kg	7 to 13	9.6

The **direct combustion fluidised bed** summary in Table 3 used the Allington (UK) plant as a typical example, a large scale facility (greater than 300,000 tonnes per annum) based on Ebara's established Twin-Interchanging Fluidised Bed Incinerator (TIF) technology.

The APC/Fly Ash percentage by weight for fluidised bed combustion is relatively high when compared to other technologies, especially grate processes, which appears to be due to a higher carryover of furnace residues than in the grate models. **Figure 10** shows a combined fly ash stream arising from the boilers and electrostatic precipitators. This combined residual waste produces approximately 55% of the total solid waste residues. As the combined residues contain a higher concentration of dangerous substances and residual alkalinity when compared to typical IBA, they cannot easily be recycled and require treatment prior to landfill classified as hazardous waste. This could explain the lower overall landfill diversion achieved when compared to other technologies and the increased overall quantity of hazardous waste produced.

Figure 10: Process schematic of the Allington waste to energy plant



The example used in **Table 3** for **grate gasifiers** is the Energos Sarpsborg II Plant, producing ash residues from the horizontal oil-cooled grate. Whilst the ash could meet the requirements for use in construction applications such as secondary aggregates, there was until recently no local commercial application available. The APC residue at 7% of the input waste feed by weight is relatively high, primarily as a consequence of the high sulphur content of the waste. The resulting landfill diversion outcome based on this plant is currently 72% based on disposal of the bottom ash/APCr, however this could rise to 93% if a commercially viable option for recycling the bottom ash becomes available.

The **slagging gasification** data provided in **Table 3** is based two technologies, a vertical shaft furnace, updraft gasifier and a fluidised bed gasifier, typical technologies with established large scale operational facilities in Japan. **Table 5** summarises the output and origin of the mean values used in **Table 3** and in both cases, the slags are recycled and APC/Fly Ashes are landfilled.

Table 5: Solid residue output for slagging gasifier technologies

	RANGE (% by Wt)	MEAN (% by Wt)
IBA	10-12	11
APC/Fly Ash	4.0-5.8	4.9

The data provided in table 3 for **fluidised bed gasification** is based upon a preliminary mass balance from a UK plant i.e. not actual operational data (Technology Provider Confidential). The bottom ash figure is actually made up of boiler and cyclone ash. The Metso plant in Lahti, Finland provides another example of a modern

CFB gasifier designed to process SRF, however the plant only recently commenced full scale operations (2012) and there is no quantitative information on solid residues available

There are no large scale plants using **plasma gasification** in operation, hence quantitative data on solid residues is not readily available. However from a qualitative perspective, the residues are vitreous and rock-like with a high resistance to leaching (potentially polluting chemicals are immobilised); thus the range of recycling opportunities are increased and disposal if required is less challenging.

Pyrolysis is excluded from the table as there are no commercial scale plants processing MSW for comparative purposes.

3.2.6. Recycling of Ash

Bottom ash is a heterogeneous mixture of ash, metals, glass and other non-combustible compounds, fly ash is particulate matter carried over to the boiler and collected prior to gas treatment, APC residues result from the gas cleaning process including particulate matter removed from the combustion gases plus unreacted gas cleaning reagents. There are opportunities to reuse the bottom ash to create a valuable substance and reduce the amount of waste sent to the landfill. Fly ash and APC residues are rarely reused due to high contaminant levels and are most commonly landfilled.

Usually there is also a small fraction of unburned carbon (must be <3% to comply with legislation in Europe, and in modern plants is usually much lower).

There are two main options for reusing bottom ash; using basic processing and sorting techniques to produce an aggregate directly from the ash, or exposing to high temperatures to melt the ash to produce a more homogenous, stable material. Both products can be used in construction, but have differing properties and production costs.

The reuse of bottom ash in construction has several benefits:

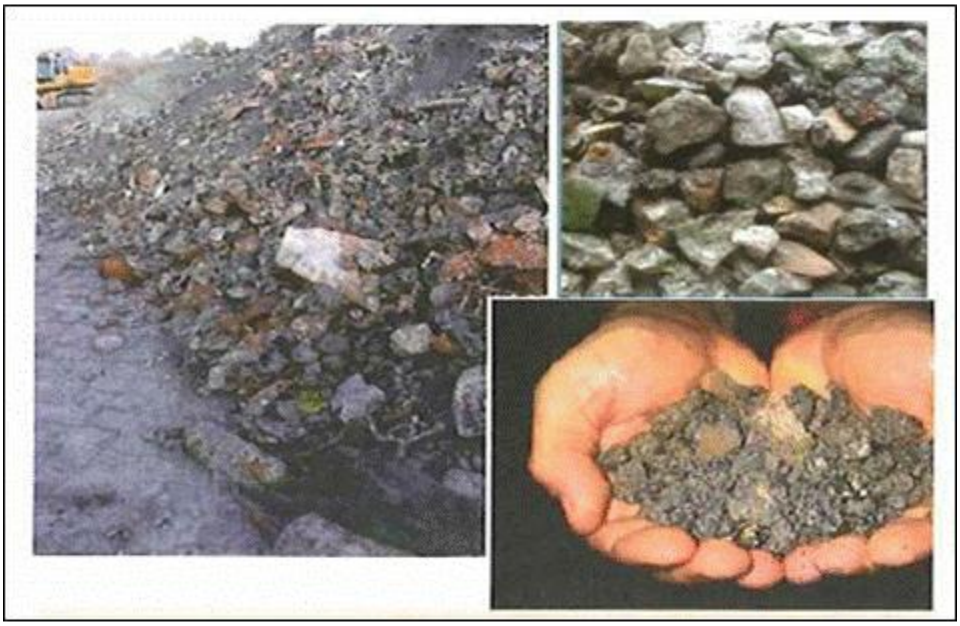
- Reduction in material to landfill
- Reduction of primary aggregate use and associated reduction in CO2 emissions
- Additional revenues from sale of ash (and/or avoidance of landfill costs)

Japan has led the way with ash melting to produce a high-quality material, driven by the severe restrictions in landfill capacity. However, few other countries have operational ash melting plants. The use of incinerator bottom ash (with minimal processing) is commonplace in Europe as a construction aggregate.

Incinerator Bottom Ash Aggregate (IBAA)

IBAA is an aggregate material produced from bottom ash from a mass burn WtE plant. Bottom ash is transferred from the end of the grate (or bottom of the fluidised bed) and is quenched in water to cool. Typically, ferrous metals are then removed using a magnet (if not already recovered in pre-processing), and in some cases non-ferrous metals may also be recovered at this stage using an eddy current separator if economic to do so. The metals are clean and can usually be resold.

Figure 11: Raw bottom ash (left), with metals removed (right)



The ash is stored in piles or windrows and left for a period of time to 'mature'. It is then processed and sorted into differing size fractions which can be put to differing uses. Typically IBAA is used in construction as backfill for roads and other infrastructure projects where it has been proven particularly effective when bound with cement or asphalt. Binding also significantly reduces the potential for leaching of any hazardous compounds. This practice is very common in Europe. However the attitude towards bottom ash use varies markedly from country to country, and in some states it was previously classified as hazardous and disposed of accordingly. The majority of IBA arising in the UK are now used to produce IBAA, and there is strong demand from the construction industry.

Some questions have been raised around the potential for leaching of hazardous compounds, even when IBA is bound. Bottom ash contains trace quantities of heavy metals as well as chlorides and sulphates that are potential environmental pollutants.

Studies into environmental hazards of IBAA

A recent study[10] (based on a simulation under laboratory conditions) monitored the release of pollutant flux from a road embankment where bottom ash was used in the road construction. The subsequent ecological assessment was based on bioassay tests and the results demonstrated all three species tested were impaired, with toxicity effects increasing with leachate concentration from 1.56% to 8%. The predicted environmental concentration was close to the concentration that caused first effects in microcosms. The leachate toxicity was due mainly to the presence of copper.

A 2007 Danish study[11] investigated selected techniques for bottom ash upgrading. The primary focus was on curing/aging, washing with and without additives, organic matter, sampling techniques, utilisation options, and assessment tools. The research found that no single process ensured compliance with Danish limit values on leaching at the time, however extended curing along with washing could in most cases decreased leaching significantly.

In 2010, a new decree from the Danish Ministry of the Environment on the use of residues such as IBAA for construction works came into force. The Order classifies soil and residues into three categories, depending on the concentration of a number of pollutants, and the potential for leaching of these substances. Typical slag residues are designated category 3 i.e. subject to the residues being used above the highest water table.

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[10] Triffault-Bouchet, G et al (2005) Ecotoxicological assessment of pollutant flux released from bottom ash reused in road construction. Aquatic Ecosystem Health & Management 8 (4) 405-414

[11] Astrup, T (2007) Pre-treatment and utilisation of waste incineration bottom ashes: Danish Experiences Waste Management 27 1452-1457

In the UK, a 2003 study of the environmental and health impacts associated with IBA was carried out by AEA Technology[12]. It concluded that the use of bound IBAA in road construction was not likely to lead to exceedence of any environmental benchmark, with the exception of copper. Copper was found to have potential to leach into watercourses, but only under specific circumstances. The report concludes that the risks are very low. Dioxins were no higher than in surrounding soils and all other environmental pollutants were within acceptable limits.

Despite the above, there remain some concerns around the potential for leachability, and as such there is a variation between different countries to the approach to use of IBAA for construction.

As such sampling of IBA from WtE plants may be carried out to determine whether levels of hazardous compounds are sufficiently low to be used as an aggregate replacement (see UK protocol in the box below).

There is also a proportion of the ash that is too fine to be used as an aggregate material, and this may need to be disposed of to landfill.

Example: Classification of IBA in the UK

IBA can be classified as non-hazardous or hazardous depending on the outcome of an assessment against 15 hazard properties. The hazard assessment methodology applicable to IBA in the UK is detailed in the Environment Agency's Guidance WM2 (periodically updated in line with changes to EU legislation).

In 2010 the Environmental Services Association (ESA) published a 'Sampling and Testing Protocol' to support the assessment of hazard status for IBA. Two samples are randomly taken per month from each facility that produces IBA. These are analysed to determine pollutant concentration (heavy metals, major cations, anions etc). This testing regime is used to determine if the IBA is classed as 'hazardous' or 'non-hazardous', the latter can be used to produce IBAA.

In the data set January-June 2011[13] , all samples analysed were classified as non-hazardous

The land required to process IBA can vary depending upon chosen treatment method and ash composition, but may be substantial given the requirement to mature the material for a number of weeks and the handling and sorting equipment. As an example a £5M ($7.5M) purpose-built IBA processing facility designed to handle up to 170,000 tonnes per year recently opened at Tilbury Docks near London. This utilises approximately 3 hectares.

Figure 12: Aerial image of the Riverside Resource Recovery Ltd's Crane at berth 22 and the Ballast Phoenix IBA processing site, berths 36/38.

[12] Environmental and health risks associated with the use of processed IBA in road construction, EA Technology 2003

[13] http://www.esauk.org/energy_recovery/1_IBA_-_UC9213_05_ESA12_month_IBA_December_Final.pdf

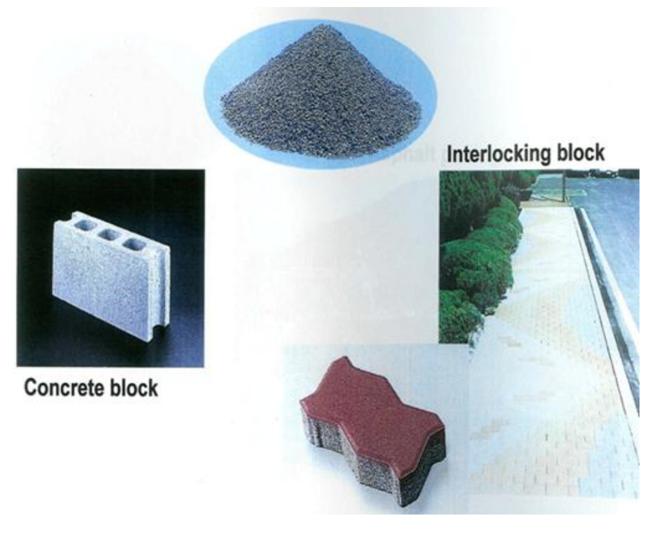
Figure 13: Ballast Phoenix IBA plant, conceptual impression

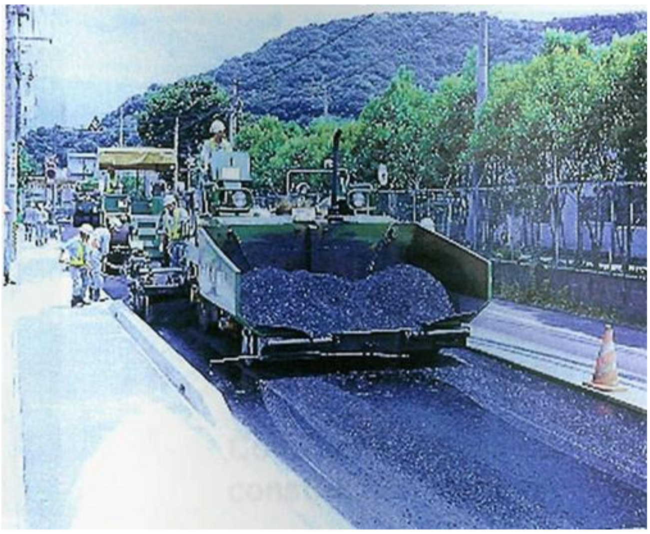
Vitrified Slag

An alternative to producing IBAA is to use high temperatures to melt the ash, either as an integral part of the process (using a slagging or plasma gasifier discussed in Section 2) or via the installation of a melting unit on the back-end of a conventional mass burn combustor or gasifier.

Melting the ash produces a vitrified (glassy) amorphous slag material and a metal fraction. The metal fraction can be recovered and recycled. The slag can be used in construction, and has very low leachability and is a relatively homogenous material.

Figure 14: Vitrified slag uses in Japan





Source: Nippon Steel

Advantages:

- Proven to not leach toxic compounds, so there is greater certainty that the slag will be defined as producing a reduced environmental impact compared to IBAA.
- High quality, homogeneous material with numerous uses in construction applications

- Lower land take

Disadvantages:

- More expensive to process than IBAA in both capital and operational terms (parasitic load and plasma melter/slagging lines)
- High energy consumption; electricity for plasma and fossil fuel and oxygen for slagging gasification. May not be compatible with a high energy efficiency strategy to waste treatment.

3.2.7. Flue Gas Treatment

Modern WtE plants are required to meet among the most stringent emissions requirements of any industrial process, specifically to minimise the emissions of acid gases, particulates, dioxins and heavy metals, In order to reduce pollutant concentrations to the within the regulated levels, extensive cleaning of flue gases is required. A range of APC technologies are used, though some components are common to the vast majority of plants. The most common abatement technologies used in modern WtE facilities are usually categorised as either dry, semi-dry or wet systems, based primarily on the type of acid scrubbing deployed. The exact system used depends on a variety of factors including the emissions limits in the jurisdiction where the plant is located (national and/or local), waste characteristics, specific requirements of the process (such as space or height restrictions) and economic factors.

In the EU, emission limit values are established for specific parameters by the Waste Incineration Directive (WID) and the associated Member State implementing regulations. **Table 6** uses published emissions data from established operational plants (except for plasma gasification where it originates from Alter NRG anticipated emission levels) to provide an overview of typical emission profiles for each furnace technology and how these compare with the required emission limit values (ELVs) set out in the EU WID.

Table 6: Comparative emission data with reference to WID

Process	Feed Variants	Technology Variant	Param-eter		PM10	SO2	CO	NOx	HCl	HF	TOC	Hg	Cd & Tl	Dioxins/ Furans
				WID ELV	10 mg/m^3	50 mg/m^3	100 mg/m^3	200 mg/m^3	10 mg/m^3	2 mg/m^3	10 mg/m^3	0.05 mg/m^3	0.05 mg/m^3	0.1 ng/m^3
Direct Combustion	MSW Typically 9-10 MJ/kg	Grate	Value Range		0.2-3.33	0.1-12.9	1.72-33	28-180	0.3-7.1	0.097-0.13	0.79	0.0009-0.03	0.0005-0.01	0.003-0.021
			Mean % WID ELV		12	9	10	60	35	4	8	16	6	9
		Fluidised Bed	Mean as % WID ELV		68	9	44	76	77	1	31	Not Availa-ble	Not Availa-ble	Not Avail-able
Gasification	C&I Range 8-18 MJ/kg	Grate	Mean as % WID ELV		1.0	59.8	1.7	38.3	40.0	25.0	Not Availa-ble	0.1	0.07	1.5
	Wide Range	Slagging Gasification, Fluidised Bed	Mean as % WID ELV		<10	<5.8	2.5	14.9	<16	Not Availa-ble	Not Availa-ble	Not Availa-ble	Not Availa-ble	7.3
	MSW	Plasma Gasification	Mean as % WID ELV		42	2	19.7	18.5	64.8	Not Availa-ble	Not Availa-ble	Not Availa-ble	Not Availa-ble	Not Avail-able

3.2.8. Availability

Availability is a common measure of the performance and reliability of a WtE plant. A plant's availability is defined as the number of operational hours in a given time period as a proportion of total hours, and is usually expressed as a percentage over the course of a year. There is a strong incentive in most countries for plants to maximise availability to maximise revenues (from energy sales and gate fees).

No WtE plant can operate with 100% availability as scheduled downtime is required for routine maintenance and more major refurbishment and replacement works. Typically most plants have several weeks per year for planned shutdowns. Additionally unplanned shutdowns frequently occur for a variety of reasons.

Most waste combustion plants aim (and technology suppliers will often guarantee) to operate with an availability of between 7,800 and 8,000 hours per year (89% to 91%). The best performing plants can approach 95% availability. As a result of the high number of operational hours it is normal for the actual plant throughput to be close to the design capacity.

Such availability levels are more difficult for emerging technologies to achieve (e.g. advanced gasification, plasma gasification, pyrolysis). There is less operational experience and understanding of the design and operation of these processes, particularly on waste feedstock, and some parts of the process present considerable challenges to maintaining high availability levels (e.g. syngas cleaning system, syngas engines or turbine). As these technologies become more mature and their operation better understood, availability rates should rise but at present suppliers may find it difficult to guarantee availability levels that are competitive with established WtE technology.

One country with a different operational philosophy is Japan, where traditionally the focus has been on waste disposal and landfill diversion rather than maximising energy output. Plants tend to have a higher hourly throughput capacity than an equivalent European plant, and are designed to operate for only around 300 days per year (around 80% availability), with the additional throughput capacity allowing the plant to 'catch-up' during the more extended downtimes. Because of this differing approach, it can be misleading to compare the availability performance of Japanese plants (and particularly slagging gasification processes which are largely restricted to Japan) with WtE plants elsewhere since they will appear to operate less effectively; however this is largely due to the operational philosophy rather than a limitation of the technology.

3.2.9. Economics of WtE

The economics of WtE are complex and plant-specific. Plants are normally bespoke and designed to meet the local requirements for waste treatment and disposal as well as satisfying planning and legislative requirements. This results in capital costs varying greatly from project to project. The overall costs associated with the same technology on two different sites may be very different. As such, care must be exercised when attempting to provide generic cost indicators for WtE.

As there are far fewer examples of gasification and pyrolysis plants, it is even more challenging to gather robust cost information. The immaturity of the technology and variety of systems operated by suppliers' means the reported costs vary considerably. Furthermore, budget costs provided by technology suppliers may bear little relation to the actual installed costs (often a major underestimate).

However, despite the challenges it is possible to provide some indication of the capital and operational costs of WtE in order to allow comparison with alternative waste treatment technologies. We consider the overall costs of actual projects that have been completed in the last few years, or are currently in development, as this gives a much more accurate picture of the true cost than relying on quotes from technology suppliers.

Capital Costs (CAPEX)

In this section we consider the total capital costs associated with a WtE plant. The information in this section is designed only to give an overall indication of WtE capital expenditure (CAPEX).

Overview

The total up-front cost of a WtE plant consists of more than just the process plant required to treat the waste, for example the following must be considered:

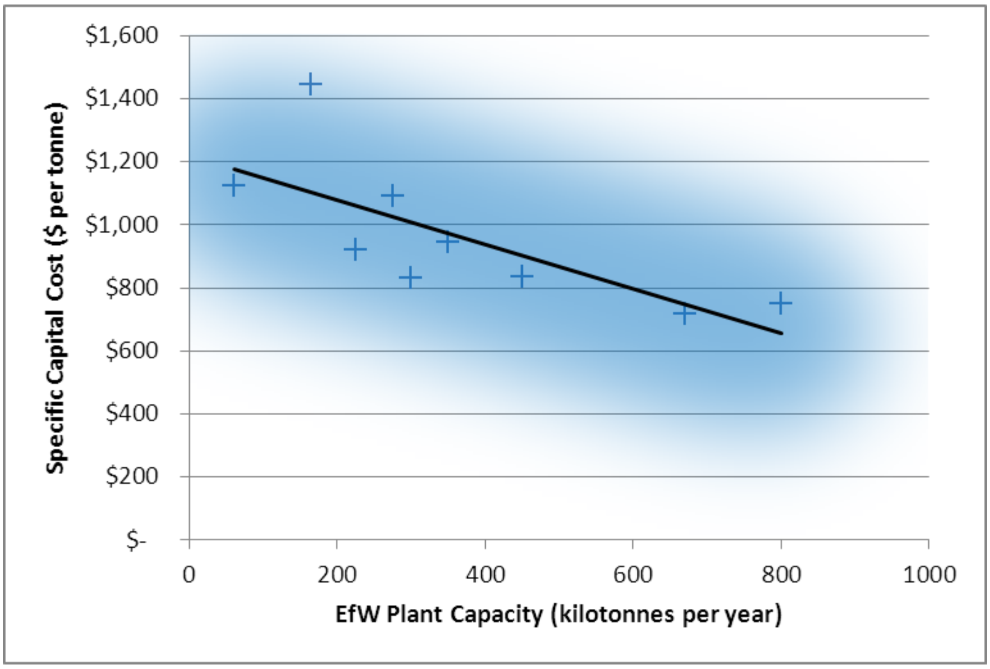
- Process plant (waste reception and handling, furnace and boiler, flue gas treatment, energy recovery system);
- Civil and building works;
- Utilities connections;
- Design, procurement and project management costs;
- Planning and permitting;

WtE Combustion

Published data is available for typical CAPEX for WtE combustion. However as this quickly goes out of date WSP have considered the costs associated with only the most recent constructed plants and those currently being developed to give an accurate picture of the capital cost of WtE plants.

Figure 15 plots the reported CAPEX of 10 WtE plants in the UK that are either in development or have been constructed since 2011. The costs have been adjusted based on the capacity to give a “specific CAPEX” in $ per tonne of waste processed. All of these plants use conventional grate combustion technology.

Figure 15: WtE Combustion CAPEX (based on UK plants)



There is a reasonably good correlation, and hence the trend line plotted on the graph should provide a reasonable indicator of the CAPEX of a standard WtE plant on the basis of the UK market. As may be expected, the specific cost per tonne of waste processed falls as capacity increases due to the impact of economies of scale.

However the range of costs for a given capacity is very large, perhaps +/-50% around the mean estimate, roughly approximated by the blue shaded area on the graph. As an example of the variation in costs, **Table 7** presents reported data for two similar size plants constructed in the last five years.

Table 7: Example of differing CAPEX on WtE Projects

	Commissioning Year	Capacity (tonnes per year)	Capital Cost (publically reported, AUD)	Specific Capital Cost (AUD per tonne)
Lakeside (UK)	2010	410,000	$270 million[14]	$660
Issy Les Moulineaux (France)	2008	460,000	$690 million[15]	$1,500
Generic midpoint estimate (predicted by **Figure 15**)		410,000 – 460,000	~$405 million	~$900

Because of the lack of WtE plants processing solid waste in Australia we are unable to provide country-specific cost indicators, although we have no reason to suspect there would be major differences between Metropolitan Australian and UK/European markets.

Fluidised bed processes require up-front processing (usually consisting of shredding and metals extraction), which is an additional CAPEX element not required by grate combustion plants.

Gasification

There is little reliable data available on the costs of gasification plant, but it appears that the costs of close-coupled gasification processes are comparable with combustion plants. This would be expected as the large majority of plant components will be similar.

Cost indicators for advanced gasification plants are very challenging to derive. Actual data is difficult to obtain given the small number of operational plants and the wide variations in technology means the costs are likely to vary significantly. However at present it appears the CAPEX is generally higher than close-coupled processes; as an illustration of this WSP have been advised that JFE are no longer offering the Thermoselect technology due to the high cost. However, in some countries incentives are offered to encourage advanced technologies which may offset the higher CAPEX in some markets.

For plasma gasification and slagging gasification processes higher costs can be expected given the additional complexity. Figures for the largest plasma gasification plant, currently in development at a site in the UK suggest a specific capital cost of just over £900 per tonne ($1,350).

Operational Costs (OPEX)

OPEX can also be highly variable, but certain components tend to be broadly similar for the majority of conventional plants (i.e. combustion and close-coupled gasification). The costs of certain elements will vary from country to country and plant to plant however; staffing costs and consumables can be particularly variable.

WtE plant OPEX can be broken down into the following components:

- Staffing;
- Routine maintenance – minor and frequent repair and replacement work;
- Lifecycle maintenance – major overhaul and replacement work;
- Variable costs - consumables (primarily chemicals for flue gas treatment system and water), support fuel and disposal of residues;
- Other costs – overheads (insurance, environmental compliance etc.)

[14] http://www.grundon.com/how/howWeDoIt.htm

[15] http://www.letsrecycle.com/news/latest-news/waste-management/largest-french-waste-incinerator-unveiled-in-paris

Ash disposal costs depend on whether the material is landfilled or reprocessed for construction use. This can be a cost or an income depending on the destination. Haulage costs are typically a major component, and may cancel out any income from sale to reprocessors if long distances are involved.

APC residues are usually classified as hazardous and require pre-treatment prior to disposal in some jurisdictions e.g. EU, to ensure leachable pollutants are minimised in order to meet landfill waste acceptance criteria; this can be expensive and a key consideration when estimating OPEX.

WTE Combustion

Figure 16 shows overall OPEX for WtE combustion plants of varying scales. This graph is taken from a 2006 report, and OPEX has increased somewhat since this was produced, but it demonstrates the non-linear relationship between capacity and cost.

Figure 16: Extrapolated Operating Costs (GBP) for WtE Facilities vs. Plant Capacity (tpa) [16]

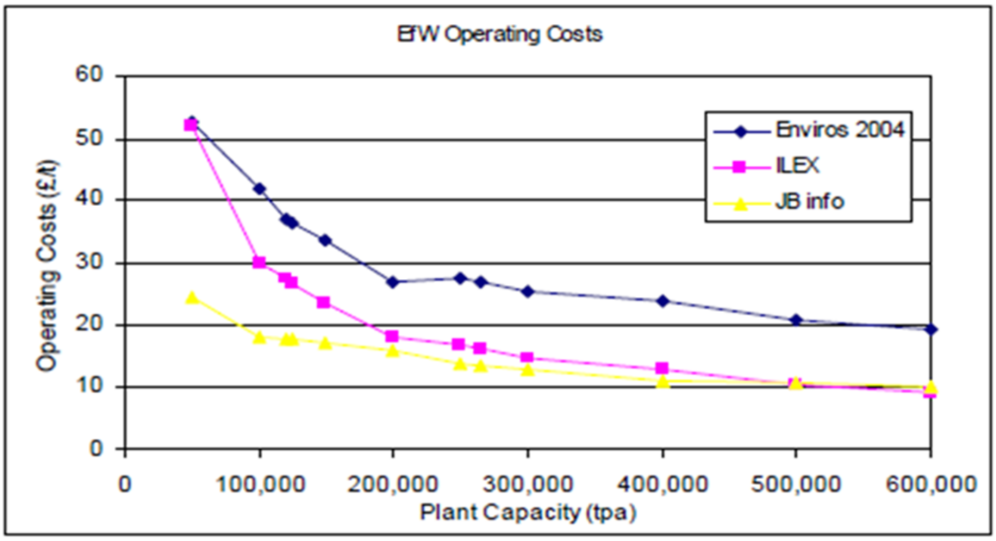


Table 8 presents a typical OPEX breakdown for a conventional grate combustion WtE plant, expressed as a percentage of the overall CAPEX.

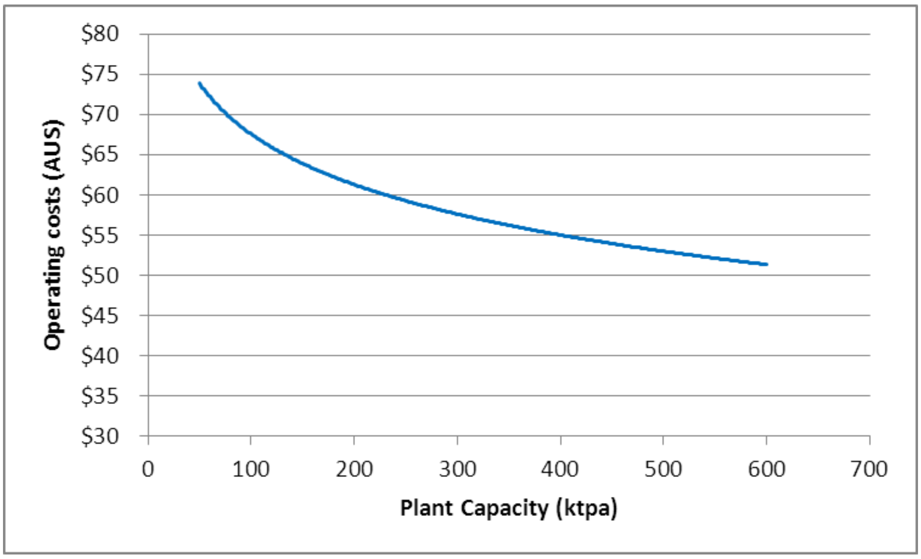
[16] Assessment of the Economies of Scale Associated with the Provision of Waste Treatment Facilities – Jacobs Babtie report for Kent County Council, UK, 2006

Table 8: Typical OPEX for a WtE combustion plant (source: WSP analysis)

OPEX element	Equivalent % of CAPEX
Staffing	1.6%
Routine maintenance (annual average)	1.5%
Lifecycle maintenance (annual average)	1.5%
Variable costs (consumables and support fuel)	1.0%
Variable costs (disposal)	Variable
Other non-maintenance operational costs	0.3%
TOTAL OPEX	**6.0%**

An indication of the total OPEX for a generic WtE combustion plant is shown in **Figure 17**. It should be noted that this is not based on actual plant data, but gives an indication of typical overall OPEX for generic WtE plant.

Figure 17: Indicative OPEX for conventional WtE plants



Gasification

OPEX for close-coupled gasification processes tend to be similar to combustion plants, since staffing, maintenance and consumables requirements are broadly similar.

Advanced gasification processes will have differing consumables requirements since the gas clean-up systems are very different. Support fuel or oxygen may be necessary however. WSP have been unable to source reliable OPEX data for advanced gasification plants.

Slagging and plasma processes produce a high-quality, stable material from the ash, which can command a greater value than untreated bottom or bed ash. However, more energy is required to produce the high temperatures necessary to slag the ash (either support fuel such as coke in slagging furnaces and electricity for plasma melters, and oxygen is also used in the gasifier in some cases). This will increase the OPEX.

Gate Fees

As may be expected given the variation in capital and operational costs, there is considerable variation in gate fees for similar facilities within and between regions/countries. **Table 9** summarises gate fees for WtE plants in the UK for 2012.

Table 9: UK WtE Gate Fees (2012)[17] expressed in AUD

Type	Median	Range
Existing WtE Plants (Pre-2000 facilities)	$96	$48 to $113
Existing WtE Plants (Post-2000 facilities)	$123	$66 to $150
Expected gate fee data (for PFI/PPP projects in planning)		
<200kt	$135	$120 to $195
200kt - 300kt	$114	$84 to $151
350kt - 450kt	$102	$86 to $116

The gate fees above include only the cost of the thermal treatment and do not include the cost of collecting waste or transporting it to the plant.

It is clear that the WtE gate fees in **Table 9** are above typical current landfill gate fees in Western Australia. In Europe the EU Landfill Directive provides a strong driver for member states to reduce dependence on landfill and many EU countries have introduced landfill taxes to help meet the targets. In the UK landfill tax for non-inert waste is currently $108 per tonne (this is in addition to the gate fee which averaged $32 per tonne for non-hazardous landfill in 2012). Hence as **Table 9** demonstrates, WtE can be very competitive against landfill in Europe and other regions that have introduced similar measures to discourage landfill, as well as countries where there is little landfill void space available, resulting in very high gate fees without the need for additional taxes to artificially inflate the cost (e.g. Japan, Singapore).

3.2.10. Social Costs

Social costs can be summarised as impacts on humans, their general welfare or quality of life. Examples include any negative impact on the value of homes, risks from increased localised traffic activity etc. specifically when they are attributed to the presence of a development such as a WtE plant or landfill. These can be considered the counter balance to the social benefits of a development such as the supply of heat and electricity for the local community. The overall balance can be assessed by undertaking a detailed social cost–benefit analysis, however this review summarises some of the key social costs and the potential impacts associated with WtE plants and alternative waste treatment processes where relevant.

Health Impacts

A previous literature search undertaken by WSP for DEC WA provided some commentary on these issues based on recent academic research and government guidance globally. In relation to exposure to airborne emissions, most studies and assessments reviewed comparative impact referring to alternatives waste treatment options or other anthropogenic activity for exposures to risks with which the public are more familiar e.g. traffic emissions.

One of the most common concerns in relation to WtE plants is the health risk associated with exposure to airborne emissions from the stack, highlighted in particular by the Dioxin scare in the eighties when the US EPA published a study attributing more than 80% of known dioxin sources to incineration. This resulted in stricter flue gas treatment requirements globally e.g. Maximum Achievable Control Technology (MACT) regulations in

[17] UK Waste and Resources Action Programme (WRAP), Gate Fees Report 2012

the US. Data on dioxin emissions from WtE plants between 1987 and 2002 i.e. pre and post MACT regulations, demonstrate a 99.9% reduction in air emissions over this period.[18]

The management of ash wastes has also been raised as a public health concern, due mainly to the potential for groundwater pollution arising when the waste is placed in landfill sites or when incinerator bottom ash used in secondary aggregate applications in close proximity to water courses. Some studies have indicated a potential risk to lentic ecosystems from leached pollutants[19] and other studies found the recycling of incinerator bottom ash in bound applications has been shown to greatly reduce their leaching potential[20]. In Japan, slagging gasification processes and the use of plasma melting systems with conventional incineration systems produce a vitrified slag which locks the leachable heavy metals within the slag.

Given the complexity of demonstrating a statistically significant causal link between modern state of the art WtE plants and detrimental health impact, extending this to technology variant presents an even greater challenge. In the UK, the Health Protection Agency (2009) [21] concluded that 'While it is not possible to rule out adverse health effects from modern, well regulated municipal waste incinerators with complete certainty, any potential damage to the health of those living close-by is likely to be very small, if detectable.

Odour

It is of note that perception of risk and impact can also be a considerable concern to the public, potentially having harmful effects on the mental, physical and emotional health of local residents, regardless of whether emissions have any direct effect on health. Anxiety may also therefore be considered as a potential social cost. One assessment of odour and physical symptoms among residents living near waste treatment centres (composting plants in this instance[22]) found residents who were classified as 'annoyed by the odour' reported physical symptoms more than those who did not. The symptoms included unusual shortness of breath, eye irritation, hoarseness/dry throat, toothache, unusual tiredness, fever/shivering, joint pain and muscular pain. The study concludes that reported odour annoyance near waste treatment centres was associated with physical symptoms among residents living in neighbouring areas and that the associations were consistent although not strong.

Odour related to the delivery and storage of untreated waste at WtE plants can be readily mitigated through negative pressure reception halls, irrespective of technology variant.

Traffic

Social costs also include the impact of traffic related to waste operations, essentially vehicles delivering waste for processing and those carrying residues from the plant for off-site treatment. The impact is often assumed to be greater in a rural setting, mainly as the presence of waste vehicles may be considered incongruent with the setting; however more people tend to be affected in urban areas and associated congestion impact may be considered of equal impact by urban dwellers.

The social cost of traffic is less likely to be determined by choice of technology and more likely to be a factor of scale, directly related to vehicle movements unless a multi-modal option is viable.

Visual Impact

Section **3.2.2.** discusses land take and footprint for different WtE technologies, a factor in trying to forecast the visual impact a WtE plant will have on a locality. There is however measures that can be deployed to reduce and minimise the visual impact of a plants, exhibited in some established facilities. The Spittelau plant in Vienna is a relatively old conventional moving grate combustion plant, however it was the first facility that used architectural treatment to gain public acceptance.

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[18] Psomopoulos, CS. et al (2009) Waste to Energy: A review of status and benefits in USA. Waste Management, 29 1718-1724

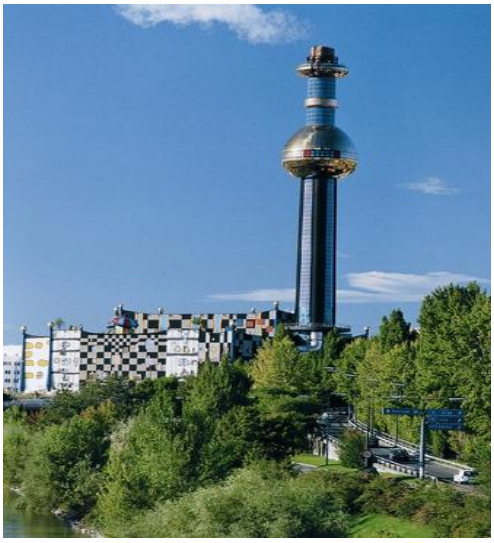
[19] Triffault-Bouchet, G et al (2005) Ecotoxicological assessment of pollutant flux released from bottom ash reused in road construction. Aquatic Ecosystem Health & Management 8 (4) 405-414

[20] Environmental and health risks associated with the use of processed IBA in road construction, EA Technology 2003

[21] UK Health Protection Agency (2009) The Impact on Health of Emissions to Air from Municipal Waste Incinerators

[22] Aatamila, M et al (2011) Odour annoyance and physical symptoms among residents living near waste treatment centres. Environmental Research 111 164-170

Figure 18: Spittelau waste to energy plant



Another example is Issy les Moulineaux, the newest and largest incineration plant in France, built on the side of the River Seine in the centre of Paris. The building has a vertical profile of only 27 metres as 30 metres of the plant is below ground. The roof is flat and covered with grass and shrubs and the exhaust stacks only protrude 5 metres above the building roofline.

Figure 19: ISSEANE waste to energy plant

Source: Hitachi Zosen Inova

The plant footprint is relatively large however. The horizontal boiler reduces the height but increases the overall length and the addition of the recycling centre further increases the total area. **Table 7** (section 3.2.9) highlights the cost implications of delivering this engineering exemplar.

Comparative social costs

A key consideration in evaluating the social costs of thermal treatment technologies include direct comparison of potential impact with alternative waste treatment options, consideration of relative impact when compared to non-waste related anthropogenic activities and specifically for emission to air, the potential relative impact on air quality conditions.

Landfill and incineration, including thermal WtE technologies, are the most common waste management techniques used to process residual waste. There are many academic studies in the public domain assessing a variety of comparative impacts focussed predominantly on health and the environment associated with these processes. Academic studies of the comparative impacts of variant technologies within the thermal treatment sector however are not available. It is therefore necessary when considering relative impact to use WtE as a generic term, irrespective of the fact that most studies will be based on grate combustion technology.

Public Perception

When a new waste treatment plant is planned the local public will often be focussed on two key words; i.e. waste and incineration. For this reason, proponents of gasification will be focussed on extolling its virtues over incineration/direct combustion techniques e.g. syngas produced by gasification can also be further processed into liquid fuels, slagging gasification can produce a high percentage of solid residuals suitable for recycling (high landfill diversion capability), conversion of energy in gasification can be more efficient than combustion (when gas engines or turbines are used) and finally, gasification produces very low levels of dioxins and other pollutants. It is therefore sometimes seen as politically advantageous to promote gasification as a preferred technology, particularly when a conventional grate incinerator may still be associated with old (pre-MACT) emissions impacts. However, it is important to note that the potential advantages of gasification and other advanced technologies are not always realised in practice, and energy recovery and emissions performance may be no better than traditional combustion.

3.2.11. Development Timeframe

The timeframe associated with the development of a WtE facility can be lengthy, measured typically in the 3-6 year range, potentially influenced by scale and involving a number of interrelated and overlapping stages, including the following:

- Conceptual planning, considering the needs of the local area for future waste management solutions;
- Procurement;
- Financing;
- Development Planning Application;
- Environmental Permit Application;
- Construction, and
- Commissioning

The development timeframe is not necessarily determined by the choice of technology. For example in the UK most WtE plants are based on grate combustion with only one large scale fully operational gasification plant; however recent planning applications for the latter have been processed and approved generally within a 12 month period, whereas there are high profile examples of rejected applications for grate combustion plants. Therefore this review considers typical timeframes for WtE plants in general.

To demonstrate typical process timeframes the following is an example of an actual recent UK WtE plant development, a typical timescale encountered when investing in major waste infrastructure development.

The South West Devon Partnership awarded a £230m ($345m), 25 year agreement for the management of residual waste for the development of 245,000 tonne capacity energy from waste facility located in North Yard, providing electricity and heat to HM Naval Base Devonport.

Reported timescales for procurement of the scheme were:

- PRG approval September 2008;
- OJEU publication October 2008;
- Call for Final Tenders October 2010;
- German energy provider MVV Umwelt announced as preferred bidder in January 2011;
- Financial Close in March 2011 (OJEU to Financial Close: ~29 months);
- Planning application submitted May 2011, approved in December 2011
- Environmental Permit granted March 2012, and

- Work started onsite at the end of March 2012; operations are set to commence 2014.

In summarising typical timeframes for Public Private Partnership (PPP) based WtE developments, the following estimates an expectation of how the overall timeframe breaks down for each element of the process, However some of these periods will overlap and therefore should not be considered to run concurrently e.g. financing.

- Conceptual planning, one to two years depending upon many variables, including waste feedstock availability;
- Procurement, typically in the region of three years for PPP projects;
- Financing, can vary considerably depending upon source of funding, however should not add to overall timeframe as it can run parallel with other stages;
- Development Planning Application, in theory anything from under one year to six/seven years or more if strongly opposed (in exceptional cases this can be 10 years or more, for example the Riverside plant in the UK was 18 years in development mainly due to the arduous planning approval process; this is not the norm though);
- Environmental Permit Application, typically one year assuming proven technology;
- Construction, typically two-three years, and
- Commissioning, typically less than six months.

3.2.12. Barriers and Risks

Table 10 presents some of the main barriers and risks associated with the development and operation of WtE plants. All WtE technologies face similar barriers, but the level of the challenge faced varies by technology variant. For example, advanced gasification projects will face more difficulty obtaining finance, but conversely can in some areas (such as the UK) find gaining planning permission more straightforward.

Table 10: Barriers and mitigation

Barrier/Risk	**Detail**	**Mitigation**
Obtaining long-term feedstock supply	Long term supply contracts are preferable and may be a requirement for financing the plant. A good understanding of the feedstock is necessary to correctly size and specify the plant	Municipal waste often best source as supply can be guaranteed long-term. Commercial waste supply contracts tend to be short-term, risk can be reduced by sourcing waste from multiple sources
Financing	WTE plants are very expensive and require considerable investment. This is a particular issue for new entrants to the market and where WtE is not an established technology such as Western Australia	Use of PPP favoured by many authorities to minimise upfront cost and transfer risk to private sector – but often more costly in long term
Technology immaturity	Unproven technologies may give poor performance or fail to even get off the ground – also difficulties obtaining finance, difficulty winning competitive projects	Use of proven technology main mitigation. Provision of strong performance guarantees for less proven systems vital
Obtaining planning permission	Can lead to projects being cancelled or severely delayed	Plant should be designed to fit into surroundings as far as possible. Careful consideration of vehicle movements essential. Education, consultation and

		communication with all stakeholders essential throughout the process.
Obtaining and maintaining compliance with environmental permits	Essential to allow the plant to operate	Use of proven technology where possible, guarantees from technology suppliers
Obtaining offtake agreements	Necessary to allow electricity export and for the plant to receive water supplies etc.	Choice of appropriate site in reasonable proximity to electricity grid and other utilities

4 Summary and Conclusions for the SWIP

4.1 Summary: Benefits and Disadvantages

In this section we consider the benefits that WtE can offer, and the disadvantages of the technology. The first part looks at WtE in comparison to alternative residual waste treatment and disposal options. The second part considers in more detail the merits and shortfalls of the different WtE technologies.

WtE relative to other waste treatment technologies

Advantages:

Potential to treat a wide range of post-recycling municipal, commercial and industrial wastes

High landfill diversion (>90% possible)

Compact solution for residual waste management

Potential to use majority of outputs

Generally compatible with high recycling rates providing correctly sized to take into account targets

Very low emissions possible, all modern plant treating municipal and commercial wastes should be capable of meeting stringent air and water emissions limits

Generation of electricity and heat, which is partly renewable (usually around 50-70% biomass)

Disadvantages:

High CAPEX

May require fiscal measures or incentives to be financially competitive with landfill

Usually requires a long-term waste supply contract (often 25 years +) which can limit flexibility to both producer of waste and the operator of the plant

Uncertainty around bottom/bed ash classification and hazardous fly ash/FGT residues require careful disposal/treatment

Negative public perception of WTE persists in many areas. NIMBYism can restrict or slow development process

Technology specific benefits and disadvantages

Table 11: Advantages and disadvantages of different WtE technologies

	Advantages	Disadvantages
Combustion	■ Mature, established, many reference plants worldwide ■ No feedstock preparation required; relatively simple, robust technology ■ Numerous reputable experienced technology suppliers & EPC contractors, competitive market ■ Relatively low CAPEX & OPEX compared with some more advanced technologies (especially slagging and plasma gasification)	■ Electrical efficiency is limited ■ Suffers from poor perception, primarily due to legacy of older generation of incinerators but also from advocates of ‘zero waste’ strategies ■ Generally better suited to larger scales (>100,000tpa)

Gasification (Close-coupled)	■ Not seen as incineration (primarily a perceived advantage) ■ Despite few established technology suppliers, recent years have seen several suppliers begin commercial operation, or close to & there is increasing acceptance of such technologies (i.e. easier to finance). Gasification (with steam turbine) appears on the verge of competing with traditional combustion in some markets. ■ Good combustion control possible & less potential for formation of dioxins and NOx than direct combustion due to lower temperatures in gasifier	■ Feedstock preparation necessary for most plants, particularly those using a fluidised bed reactor ■ Existing commercial plants have not demonstrated significant practical advantages over conventional combustion plant in terms of air emissions, efficiency or residues.
Gasification (Advanced)	■ High electrical efficiency possible by use of syngas engines or turbine compared to steam turbines ■ Inherently low emissions for most pollutants and low formation of dioxins given low temperature of combustion, though NOx emissions relatively high ■ Suitable at small scales, potentially feasible at throughput capacities where traditional combustion is not viable ■ Low building profile possible due to the lack of a boiler, and no requirement for high stack ■ Potentially more acceptance of technology due to the above	■ Expensive with high capital and operational costs ■ Cleaning syngas to a purity required for use in gas engines and turbines continues to be a major barrier to commercial deployment ■ Waste feedstock preparation often required to produce a consistent fuel (high quality SRF may be necessary) ■ Many technologies struggling to gain the considerable funding and financing required to overcome technical challenges and move to commercial deployment
Gasification Slagging	■ Maximises landfill diversion potential ■ High quality, stable slag produced by melting ash which has many potential applications ■ Technically and commercially mature technology in Japan with a number of technology suppliers	■ Expensive, high CAPEX/OPEX. Query viability outside Japan, very few plants elsewhere ■ Needs oxygen and/or support fuel e.g. coke to generate high temperatures required to melt ash, negative impact on OPEX & CO_2 performance.
Gasification Plasma	■ Potential to produce a clean syngas for use in engines or turbine ■ Can produce a high quality slag similar to slagging processes ■ Able to 'add-on' plasma units to more established combustion or gasification plants (to polish syngas or melt ash)	■ Expensive with high capital and operational costs ■ High parasitic electrical load ■ Achieving high availability may be challenging

4.2 Conclusions: WtE in WA

Existing and Planned Facilities

WSP are not aware of any WtE plants operating in Western Australia. However, a number of plants are proposed or in the early stages of development. We have briefly described the proposals here:

- Kwinana WtE plant – Phoenix Energy are developing a 300,000tpa WtE plant at Kwinana Industrial Park. The plant will use conventional grate combustion using the proven Martin grate technology (supplied by Mitsubishi Heavy Industries); it also appears the plant will incorporate ash melting technology to produce a vitrified product for construction uses, but the details are unclear. The facility will accept both municipal and commercial waste and will be designed to meet EU emissions limits.
- Port Hedland WtE and Materials Recovery Facility - New Energy Corporation are planning to develop a 255,000tpa WtE gasification plant based on Entech technology at Boodarie Industrial Estate, Port Hedland. The proposals include 5 gasification lines with syngas combusted to raise steam.

Applicability to Local Context

It is usually desirable to locate a waste treatment plant in close proximity to the source of the waste in order to adhere to the proximity principal and minimise waste transport distances. Doing so is often necessary for the plant to be able to export heat, and it often allows easier connections to utility networks. From a purely technical point of view it should be possible to locate most WtE energy plants in metropolitan areas, i.e. reasonably close proximity to residential and commercial development. However it may not necessarily be appropriate to do so if the siting of such a plant could lead to unacceptable negative impacts on residents. This may be in terms of transport movements, aesthetics and how a plant would integrate into the local area, noise etc. Concerns of residents also often focus on perceived health effects and negative impact on house prices. WtE plants can be highly contentious developments, and in many countries the planning system is onerous. However, often these issues can be overcome by ensuring the plant is designed appropriately and the concerns of residents are addressed.

The following points are important to consider for siting of a WtE plant close to population centres:

- Smaller plants designed to treat waste from the locality may be seen as more acceptable
- Advanced' technologies (gasification and pyrolysis) can be seen as more acceptable, as these are not perceived (by some) to be 'an incinerator'.
- Plants using gas engines can have a lower building height with smaller stack, and thus integrate more easily to the surroundings
- Locating a plant in an industrial context, or replacing similar plant is often can help plants to be accepted in a metropolitan area
- Plants can be designed to blend in to the surroundings, or alternatively to stand out as a piece of architecture in their own right (such as the Spittelau plant in Austria which is a significant tourist attraction[23]). This can be very expensive however.
- Stakeholder engagement is very important in order that residents are kept aware of the plans and are able to have their say.

Acceptance of WtE varies from country to country. For example, most plants in Scandinavia are located close to residential and commercial areas as they export heat to large district heating networks. This is much less relevant to Western Australia, but demonstrates however that it is possible to locate plants in population centres.

The advice provided by the Environmental Protection Authority (EPA) to the Minister for Environment (Section 16(e) of the Environmental Protection Act 1986) identified six principles that they and the Waste Authority see as key to the successful operation of waste to energy plants in Western Australia. The following assesses the requirements of these principles in the light of the findings from this report.

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[23] http://www.wienenergie.at/eportal/ep/programView.do/pageTypeId/19118/programId/19742/channelId/-28277

- **Proven technology requirements –** This report highlights the variant technologies available generically and provides examples of proven technologies at established plants;
- **Waste input matched to the technology selected** – The technology variants reviewed within this report are discussed in the light of typical MSW and C&I wastes and where relevant, the pre-treatment requirements to support the technology;
- **Best practice and minimum EU WID emission standards** – This report provides examples of reported gaseous emissions for technology variants, aggregated where relevant and compared directly to the requirements of EU WID;
- **Target waste must be genuine residual waste** – This report provides examples of technology variants based on the processing genuine residual waste e.g. post-kerbside segregated and secondary in-plant processing to further remove recyclable materials;
- **Continuous emissions monitoring** – Available for most parameters subject to emission control;
- **Safe and environmentally conscious management of residual by-products** – This report provides a review of the characteristics for the range of WtE residual by-products, potential reuse options and safe disposal considerations where recycling is not possible. It also quantifies the potential landfill diversion opportunities for these by-products for each generic technology variant, based on real examples of WtE plants globally.

Glossary

Advanced Thermal Treatment (ATT) - Waste management processes involving medium and high temperatures to recover energy from the waste. Primarily pyrolysis and gasification based processes, excludes incineration.

Gasification - The process whereby carbon based wastes are heated in the presence of air or steam to produce a solid, low in carbon and a gas. The technology is based on the reforming process used to produce town gas from coal.

Incineration - The controlled thermal treatment of waste by burning, either to reduce its volume or toxicity. Energy recovery from incineration can be made by utilising the calorific value of the waste to produce heat and/or power.

Materials Recycling Facility/Materials Recovery Facility (MRF) – A dedicated facility for the sorting/separation of recyclable materials.

Mechanical Biological Treatment (MBT) - A generic term for mechanical sorting/separation technologies used in conjunction with biological treatment processes, such as composting.

Municipal Solid Waste (MSW) - Household waste and any other wastes collected by the Waste Collection Authority, or its agents, in some cases including commercial and industrial waste.

Pyrolysis - During Pyrolysis organic waste is heated in the absence of air to produce a mixture of gaseous and/or liquid fuels and a solid, inert residue (mainly carbon)

Refuse Derived Fuel (RDF) - A fuel produced from combustible waste that can be stored and transported, or used directly on site to produce heat and/or power.

Solid Recovered Fuel (SRF) - Refuse Derived Fuel meeting a standard specification developed by a CEN standards committee.

Source-segregated/Source-separated - Usually applies to household waste collection systems where recyclable and/or organic fractions of the waste stream are separated by the householder and are often collected separately.

Syngas - ‘Synthetic gas’ produced by the thermal decomposition of organic based materials through pyrolysis and gasification processes. The gas is rich in methane, hydrogen and carbon monoxide and may be used as a fuel or directly combusted to generate electricity and/or heat, or for transport applications in fuel cells.

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