ATTACHMENT B

TECHNICAL APPENDIX: GASIFICATION TECHNOLOGIES REVIEW

CITY OF SYDNEY ADVANCED WASTE TREATMENT MASTER PLAN

Gasification Technologies Review

TECHNOLOGY | RESOURCES | IMPLEMENTATION SCENARIOS

PREPARED FOR THE COUNCIL OF THE CITY OF SYDNEY

FINAL REPORT – AUGUST 2013

twe

efficiency | renewables | innovation

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Authorship and acknowledgments

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Front cover: Lahti Energia's Kymijärvi II gasification facility, Lahti, Finland.
Credits: Metso Power, 2012.

Executive Summary

The study, developed within the scope of the City's forthcoming *Advanced Waste Treatment Master Plan*, explores its integration with the *Trigeneration* and *Renewable Energy* components of the City's Decentralized Energy Master Plan.

The main objective of this study is to enable the City devise a robust project development pathway for the development of an integrated Syngas from Waste (SfW) facility, integrating thermal conversion of residual waste resources to obtain a synthetic gas mixture (the synthetic gas) and upgrading of the syngas into a substitute natural gas product (SNG) that could be delivered to the City's proposed trigeneration network.

While all the key technology components – conversion, gas upgrading and delivery – are commercially mature and readily available, the network-level integration of such a platform is a development unique to the City's *Green Infrastructure Strategy*, complementing the generation of renewable electricity from intermittent resources such as wind and solar energy, with a large, reliable supply of storable and transportable renewable gases.

The study includes a comprehensive technology review, detailed assessment and characterization of the residual waste resource available within the City of Sydney Local Government Area (LGA) and neighboring Councils in the Southern Sydney Regional Organization of Councils (SSROC) area, and a detailed evaluation of alternative conversion technology and implementation schemed for a Syngas from Waste facility.

Key study highlights

The modelling framework presented in *Section 4. Advanced Waste Treatment Scenarios*, has evaluated the potential contribution of a Syngas from Waste facility across 9 alternative conversion technology and 4 implementation scenarios.

Technologies included in the assessment have been organized in three conversion strategy groups: low-temperature conversion (LTC, including slow-pyrolysis and fixed-bed gasification), high-temperature conversion (HTC, including pyro-gasification and fluid-bed gasification) and high-temperature conversion + melting (HTCM, including pyro-gasification + melting, fluid-bed gasification + melting, and plasma gasification).

The implementation scenarios have considered the domestic (MSW) and commercial and industrial (C&I) waste streams, and two resource catchments: the City of Sydney LGA and the SSROC region.

The assessment has focused on the key dimensions of resource and energy recovery

Resource recovery

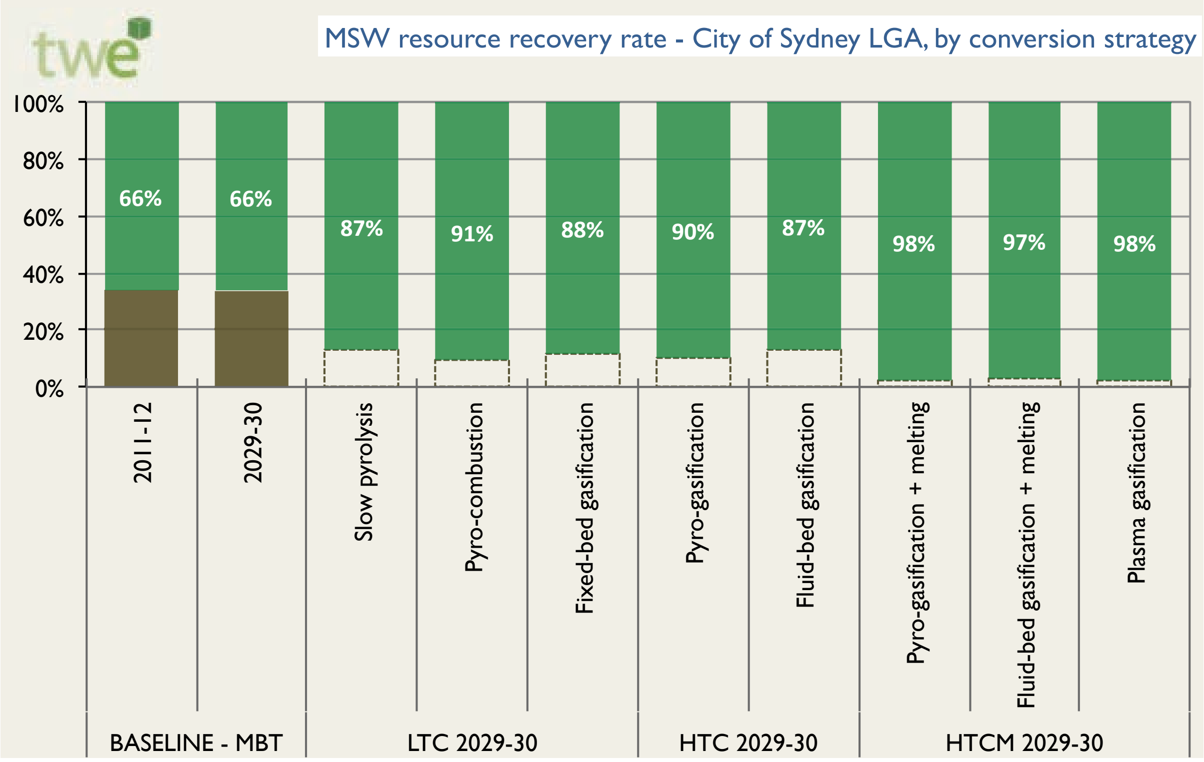
Resource recovery within the City LGA has been historically limited to source-separated materials (kerbside recycling and garden organics), accounting for a resource recovery rate of 24.95% in 2008-09.

From 2011-12 onwards, domestic waste residuals have been diverted to another AWT facility operated by SITA Environmental Solutions. This transitional arrangement allows for about 98% of mixed waste collected to be diverted to the SITA AWT facility. With about 40,000 t to be diverted in 2011-12, the resource recovery rate increased to 66%, meeting the state-wide target set by the NSW Government two years ahead of the target year of 2014.

The SITA facility has a waste processing efficiency of 60% (Hyder Consulting 2012), with the remainder of the diverted material to be returned to landfill as AWT residual.

Adopting an Alternative Waste Treatment strategy based on thermal conversion technologies brings significant benefits against the baseline scenario with mechanical-biological treatment, bringing resource recovery rate from 66% in the baseline scenario, up to between 87% (slow pyrolysis) and 98% (pyro-gasification + melting and plasma gasification. The results are summarised in the diagram below.

Figure 1. AWT residuals to landfill - MSW, City of Sydney LGA

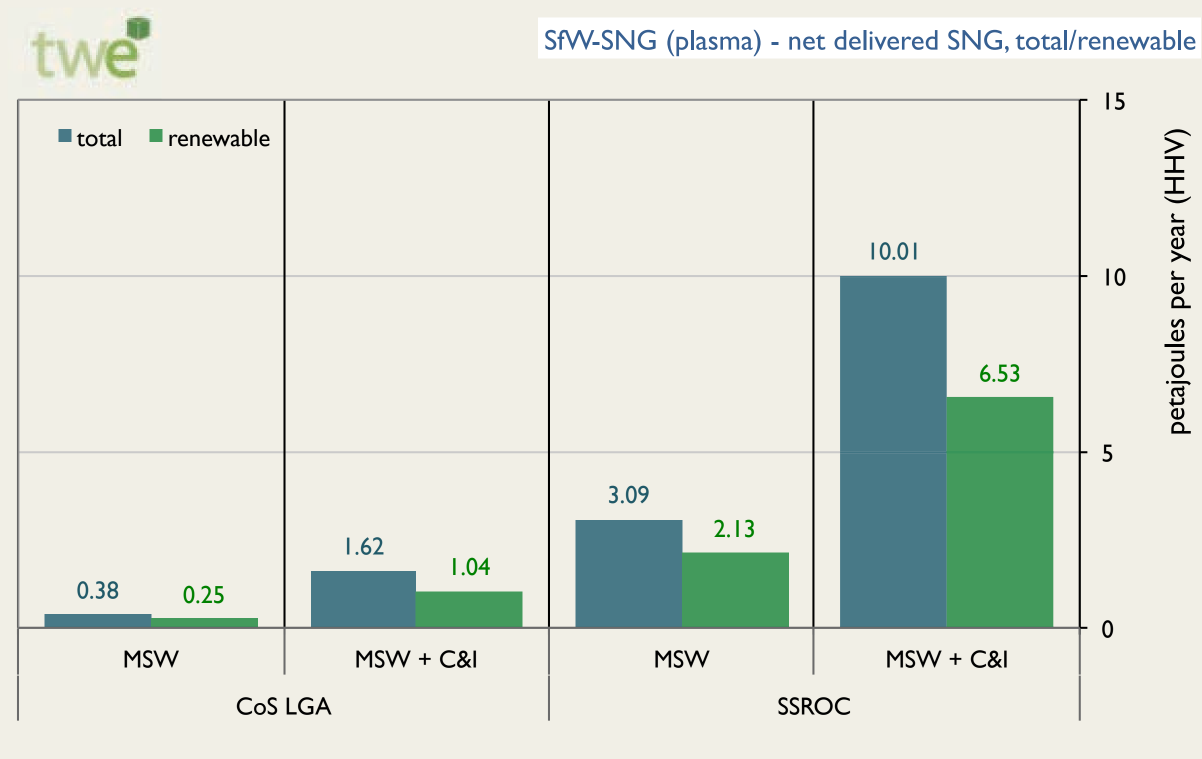


Energy recovery

The modelling presented has shown how High-Temperature Conversion + Melting (HTCM) technologies deliver the highest energy recovery and waste management benefits, enabling the City to divert the highest amount of materials to a Syngas from Waste AWT facility and to achieve resource recovery rates in excess of 97%.

Energy recovery is also maximised with these three families of technologies, with the highest net, delivered SNG yields obtained via plasma gasification, with up to 10.01 PJ/y (6.53 PJ/y renewable), recoverable from the SSROC region, as summarized in the diagram below.

Figure 2. SfW-SNG (plasma) – net, delivered SNG, total/renewable.



Abbreviations

ar	*as received*
db	*dry basis*
APC	*air pollution control*
CCHP	*combined cooling, heat and power*
CHP	*combined heat and power*
est.	*estimated*
EfW	*energy from waste*
GCU	*gas clean-up*
LfG	*landfill gas*
LGA	*Local Government Area*
MRF	*material recovery facility*
PPA	*power purchase agreement*
RDF	*refuse-derived fuel*
SNG	*substitute natural gas*
T&D	*transmission and distribution*
WTE	*waste to energy*
LfG	*landfill gas*
SfW	*syngas from waste*
SsB	*small-scale biogas*
SMA	*Sydney Metropolitan Area*
SSROC	*Southern Sydney Regional Organization of Councils*

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Introduction

Thermal conversion of residual waste through pyrolysis or gasification, that yield an intermediate gaseous fuel (synthesis gas) that can be cleaned and upgraded ahead of combustion, offers the opportunity to integrate energy recovery from waste with advanced generation technologies, such as gas engines, gas turbines and fuel cells.

The variety of syngas upgrading and delivery options available also enable the establishment of a integrated energy supply schemes where synthesis gases developed by a portfolio of thermal conversion facilities can be upgraded, integrated and delivered to a distributed network of energy conversion facilities, including power, combined heat and power (CHP) and combined cooling, heating and power (CCHP or *trigeneration*) as well as used as fuels for transportation applications.

The network-level integration of waste and biomass conversion facilities with a network distributed tri-generation facilities is a development unique to the City of Sydney's *Green Infrastructure Strategy* presented in the *Trigeneration* and *Renewable Energy* Master Plans.

The City's *Trigeneration Master Plan4*[1] - adopted by Council in June 2013 - seeks to improve the supply of energy services to businesses and residents in the City of Sydney through the deployment of a network of 15 precinct-scale trigeneration facilities – for a total installed capacity of 372 MWe by 2030 – connected to form a reticulated heating and cooling network, servicing buildings within four *low-carbon infrastructure zones*.

The City's *Renewable Energy Master Plan*[2], released for public consultation earlier this year, has identified the potential for renewable gases, from conversion of residual waste and biomass resources available within 250 km from the City of Sydney LGA, to supply 48.96 petajoules per year (PJ/y, HHV basis[3]) of pipeline-quality substitute natural gas (SNG)

The *Renewable Gas Supply Infrastructure Study*[4], developed by Talent with Energy within the scope of the Renewable Energy Master Plan, has evaluated the least-cost portfolio of renewable SNG supply resources that can meet the projected demand by the proposed trigeneration network – 27.06 PJ/y by 2029-30, augmented to 33.08 PJ/y by accounting for a 20% supply reserve margin – as follows:

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[1] *City of Sydney Decentralised Energy Master Plan - Trigeneration* FINAL, ADOPTED, City of Sydney, March 2013.

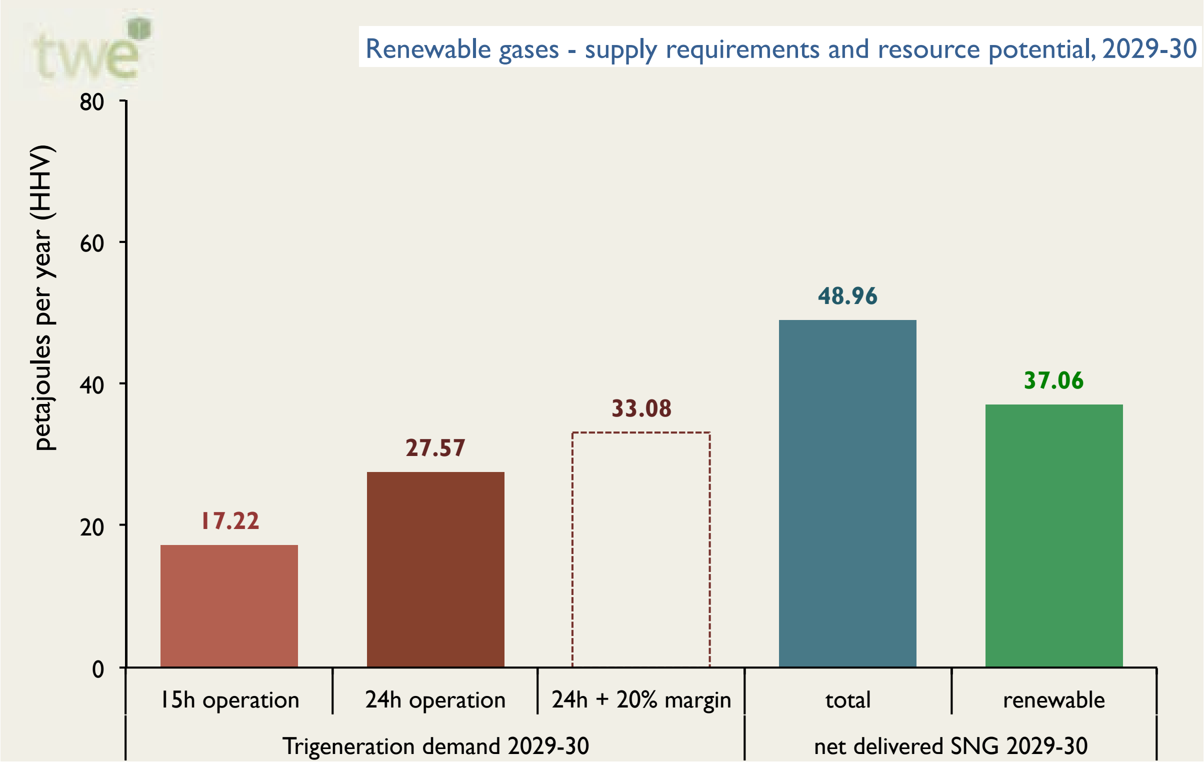
[2] *City of Sydney Decentralised Energy Master Plan - Renewable Energy* DRAFT, City of Sydney, June 2013.

[3] throughout this study, energy quantities are reported on a higher heating value (HHV) basis.

[4] *Renewable Gas Supply Infrastructure Study*. FINAL DRAFT, prepared by Talent with Energy Pty Ltd for the City of Sydney's Decentralised Energy Master Plan, March 2013.

- **Syngas from Waste SNG (SfW-SNG), 28.09 PJ/y –** synthesis gas from thermo-chemical conversion of waste residues, upgraded to SNG and delivered to the City;
- **Small-scale Biogas (SsB-SNG), 2.98 PJ/y –** biogas from biological conversion (eg anaerobic digestion) of sewage sludge biosolids, upgraded to SNG and delivered to the City; and
- **Landfill Gas SNG (LfG-SNG), 2.01 PJ/y –** landfill gas captured, upgraded to SNG and delivered to the City.

Figure 3. Renewable gases - total/renewable net delivered SNG and supply requirements[5]



With 84.9% of the least-cost supply resource, Syngas from Waste SNG is thus the key enabling pathway for the provision of renewable gases to the City's proposed trigeneration network.

As a key contribution to the City's forthcoming *Advanced Waste Treatment Master Plan*, this study aims to provide the City with a robust and comprehensive knowledge base on technologies for thermal conversion of waste, and syngas upgrading and delivery.

It also evaluates the potential for the development of an integrated, *Syngas from Waste* (SfW) facility for conversion of waste resources generated within the City's LGA and the surrounding regions, and outlines a recommended project development pathway.

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[5] reproduced from (TWE 2013)

In the remainder of this chapter we introduce the main thrust and rationale behind these activities and outline the structure of the main report and technical appendices developed for this study.

Rationale for thermal treatment of waste

Thermal treatment of residual wastes, after material recovery has been undertaken, offers the opportunity to further increase the recovery rate, and to generate energy from waste, as well as to achieve a range of key waste management benefits, such as:

- volume reduction and stabilization in landfills,
- detoxification, dilution and sanitation,
- regulatory compliance and,
- environmental impact mitigation.

Technologies such as pyrolysis and gasification, are rapidly emerging as the platform of choice for energy-from-waste (EfW) schemes, as they present the following key advantages when compared with traditional combustion-based schemes, such as mass-burn incineration or refuse-derived fuel (RDF) combustion:

1. energy output flexibility (energy recovered as gaseous or even liquid fuels),
2. compact and flexible gas clean-up and emission control systems,
3. high degree of integration with advanced resource recovery operations, and
4. improved public acceptance profile.

Energy output flexibility

In traditional waste incineration or biomass combustion schemes, where a single reactor assembly integrates thermal treatment (combustion) and energy recovery, the latter is limited to generation of steam from recovery of heat in the hot flue gases and power generation in steam turbines.

Thermo-chemical conversion technologies de-couple thermal treatment from energy recovery and generate instead an intermediate fuel gas (the raw synthesis gas) offering a variety of energy recovery options including:

- *direct use* as a fuel in industrial kilns and steam generators (industrial or power plant boilers),
- *cleaning and use* as a fuel in advanced energy conversion equipment, such as gas engines, gas turbines and fuel cells,

- *upgrade* to several energy products, including substitute natural gas (SNG), hydrogen or methanol.

The ability to clean-up the synthesis gas to required fuel specifications, and the inherent compactness of conversion technologies, offer the flexibility to co-locate EfW facilities with combined heat and power (CHP) or combined, cooling heat and power (CCHP) units.

Clean syngas can also be upgraded to substitute natural gas (SNG) integrated (and stored) with other renewable gases such as landfill gas (LfG) or biogas from anaerobic digestion.

SNG, as well as other upgraded syngas products (hydrogen, methanol) can also be exported, delivered off-site for a variety of energy conversion and/or transport applications.

Gas Clean-Up and Air Pollution Control

One key advantage of thermal conversion technologies is the inherent simplicity and compactness of the *pre-combustion* Gas Clean-Up (GCU) and *post-combustion* Air Pollution Control (APC) process trains when compared with the Air Pollution Control (APC) trains for schemes based on conventional incineration or combustion processes.

In thermo-chemical conversion schemes, the combined scale of the CGU and APC assemblies is much smaller because on one side, the gas clean-up effort deals only with the relatively small gas stream (raw syngas) leaving the conversion reactor, whereas the air pollution control effort deals with a much cleaner flue gas stream from combustion of a clean, homogeneous gaseous fuel.

This contrasts with the scale of APC systems required for treatment of conventional incinerator flue gases, as these contain much higher concentration of hazardous substances to remove as well as have been greatly expanded in volume by the addition of the large quantities of combustion air required for complete combustion of the solid, heterogeneous waste feedstock. As a consequence, equipment and operating costs for thermo-chemical conversion schemes can be substantially lower.

Significantly, stack size can also be significantly reduced, mitigating the negative visual impact of the facilities (Niessen 2010).

Integration with resource recovery

Incineration plants and the associated air pollution control (APC) equipment suffer adverse economies of scale, which tends to drive design decisions toward high throughput plants.

The limited capability of these technologies to operate at less than full load compounds this problem. Furnace designs and energy recovery schemes based on steam generators need to operate at near constant thermal load due to the issues associated with thermal stability during start-up and shutdown processes. While maintaining constant thermal load (and power output) presents a good match with the waste management task it presents a significant drawback in terms of the plant's ability to meet its revenue requirements through energy sales. The near constant power output limits the plant to marketing only base-load power, often through low-price, high-liability contractual mechanisms such as power purchase agreements (PPAs).

The economic feasibility of incineration-based schemes relies thus heavily on gate fees based around high throughputs (to recover revenue requirements) and a security of waste supply (to secure continuous operation and thus avoid energy contract penalties). These two factors combined tend to create a situation whereby the implementation of a waste-to-energy (WTE) scheme would disproportionately lay claim to the waste available in a specific 'catchment', at the expense of upstream material recycling and resource recovery options.

On the other hand, thermal conversion technologies, such as pyrolysis and gasification, lend themselves to a better integration with resource recovery. The majority of these technologies require a higher degree of pre-processing of waste (drying, size reduction and homogenization) that benefits greatly from the integration with upstream material recovery facilities (MRF), while some technology concepts are based on integrated energy and material recovery operations, offering significant opportunities to increase the economic efficiency and overall performance of integrated waste management systems through efficient streamlining and integration of collection, recycling, material and recovery operations.

The economic feasibility of conversion technologies relies more heavily on revenue from energy sales through products such as gas or fuels, which are not locked to base-load power sales. The ability to operate in these higher value energy markets and the inherent compactness and modularity of conversion technologies, make thermal conversion-based schemes feasible at lower level of throughputs. This allows for the integration of such energy-from-waste (EfW) schemes as another resource recovery option across the waste management chain, without generating competition for waste supply.

Public acceptance

Communities worldwide are increasingly aware and actively promote and require the adoption of an integrated waste management hierarchy that places reduction, re-use and recycling waste management options ahead of material/energy recovery, destruction and landfilling.

Concerns around competition for waste resource generated by large, incineration-based WTE schemes have traditionally been a main driver of community opposition to such facilities, alongside with an established, yet unfounded (based on the performances of modern pollution control technologies) perception of high levels of uncontrolled noxious emissions (particularly dioxins and furans) being associated with such facilities.

As discussed earlier, EfW schemes, based on pyrolysis or gasification are inherently different in that they naturally integrate with resource recovery options, and that they cater for the adoption of an air pollution control strategy centred on extensive gas clean-up ahead of combustion, thus resulting in simpler, more compact and effective post-combustion APC systems.

This, and the increased benefits associated with increased efficiency of energy recovery, and thus higher yield of renewable energy when compared to *mass-burn* WTE schemes, make EfW schemes the ideal candidate in an integrated waste management system, to bring diversion from landfill beyond the levels achievable through recycling and recovery, and closer to the objective of 100% diversion.

The perception of such benefits and the ability to differentiate in the public eye conversion-based EfW schemes, from incineration-based WTE schemes will be key to gain public support for such developments. Successful implementation of energy from waste (EfW) facilities will rely heavily on early and comprehensive engagement with key stakeholders, and extensive community awareness and consultation.

Structure of this report

The main body of this report is organized as follows:

- **Section 1. Synthesis Gas Generation from Residual Waste Resources** presents a review of thermo-chemical conversion of waste, with an introduction to operating principles, available processes and technologies and a review of waste management, environmental, energy and material recovery performances;
- **Section 2. Synthesis Gas Utilization and Upgrading** covers processes for conversion of syngas into heat and power, and associate syngas cleaning requirements as well as options for upgrading of syngas and delivery of upgraded syngas products such as substitute natural gas (SNG) and hydrogen;
- **Section 3. Feedstock Resources** presents a detailed assessment of residual waste resources available from the City of Sydney LGA and within the region surrounding Sydney that could be used as feedstocks in thermal conversionfacilities;

- **Section 4. Syngas from Waste Scenarios** explores options for development of a thermal conversion facility for generation of synthesis gas from municipal solid waste and commercial and industrial waste collected within the City of Sydney LGA, and surrounding Councils in the Southern Sydney Regional Organization of Councils;
- **Section 5. Advanced Waste Treatment and the City of Sydney Green Infrastructure Strategy** highlights the role of Syngas from Waste SNG in the context of the City's Renewable Energy Master Plan.
- **Section 6. Enabling Actions** concludes this report outlining a set of further analysis, planning and project development activities enabling AWT and REMP developments.

A set of three appendices completes this report:

- **Appendix A. Waste Resources Assessment and Characterization;**
- **Appendix B. Performances, Costs and Emissions survey; and**
- **Appendix C. Case Studies.**

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SECTION 1. SYNTHESIS GAS GENERATION FROM RESIDUAL WASTE RESOURCES

Pictured: Plasma gasifier arrives at Tees Valley Renewable Energy Facility, UK.
Credits: AlterNRG, 2012.

Overview

Advanced Waste Treatment is a key element of an integrated waste management strategy. Thermal processing of residues from material recovery facilities, or *post-MRF residuals*, enables recovery of energy and further recovery of materials from the incoming waste stream, while bringing significant reductions in both the volume and toxicity of the residues requiring landfill disposal.

In traditional waste to energy (WTE) schemes – based on combustion of the incoming waste stream *as is* (*mass burn* incineration) or pre-processed to obtain a refuse derived fuel (RDF combustion) – the large amount of flue gases and the extensive pollution control requirements, limit energy recovery options to the generation of steam for power generation or industrial heating purposes, with low overall energy efficiencies.

Energy from Waste (EfW) schemes, based on thermo-chemical conversion processes – such as pyrolysis and gasification – operate instead a thermal degradation of waste resources to yield a synthetic gaseous fuel mixture (*syngas*) and a range of by-products and residues.

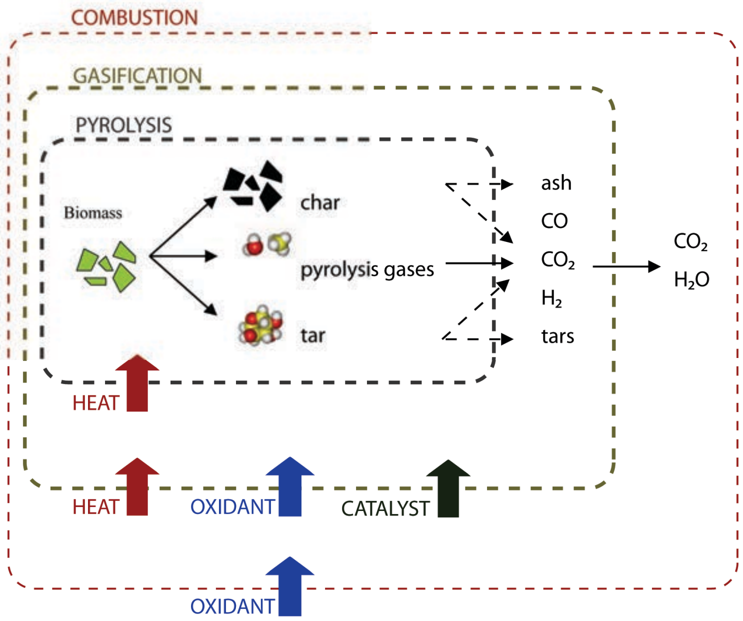
By converting the waste feedstock into an intermediate gaseous fuel, the raw syngas, thermo-chemical conversion technologies enable the adoption of advanced energy and material recovery schemes, where the gases can be cleaned and/or upgraded to meet the quality requirements for several applications, including power and heat generation, transport and as a feedstock to industrial chemical processes.

In this section we introduce the principles of thermo-chemical conversion of waste resources, discuss the range of process alternatives and review typical energy and material recovery performances associated with integrated Energy from Waste (EfW) schemes.

Principles of thermo-chemical conversion

Thermo-chemical conversion (or more simply conversion), of waste and biomass ma involves a staged approach to the degradation of organic materials, where the intermediate steps of pyrolysis and gasification, and the final step of combustion are carried out and contained in separate reactors.

Figure 4. Thermal conversion processes: pyrolysis, gasification and combustion[6]



Pyrolysis

Pyrolysis is always the first step in combustion and gasification processes, where it is followed by the oxidation – partial, for gasification or total, for combustion – of its primary products as described in the schematic presented in Figure 4. In pyrolysis processes, the feedstock is heated inside a conversion reactor in the absence of air or oxygen (the oxidant).

Following the release of moisture (above 100°C) and other volatile fractions, the pyrolysis process begins at temperatures between 300 and 400 °C, with the release of light hydrocarbons (mostly methane, CH_4), followed by the release of oxygen, hydrogen and carbon from weaker, terminal bonds and, at higher temperatures, by the release and evaporation of larger hydrocarbon chains.

Overall, the process of thermal decomposition of the waste feedstock in the absence of oxidant (oxygen or air) yields three main product streams:

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[6] Partially adapted and modified from (BTG 2008), Figure 2, p.4.

- a **raw syngas,** a gaseous mixture containing carbon monoxide (CO), carbon dioxide (CO_2), hydrogen (H_2), methane (CH_4) and other light hydrocarbons;
- a **synthetic oil,** obtained from cooling of a stream of condensable vapours, including water, methanol, acetic acid, acetone and heavy hydrocarbon chains; and
- a **char residue**, containing the residual solid carbonaceous and inert materials from conversion of the incoming feedstock stream.

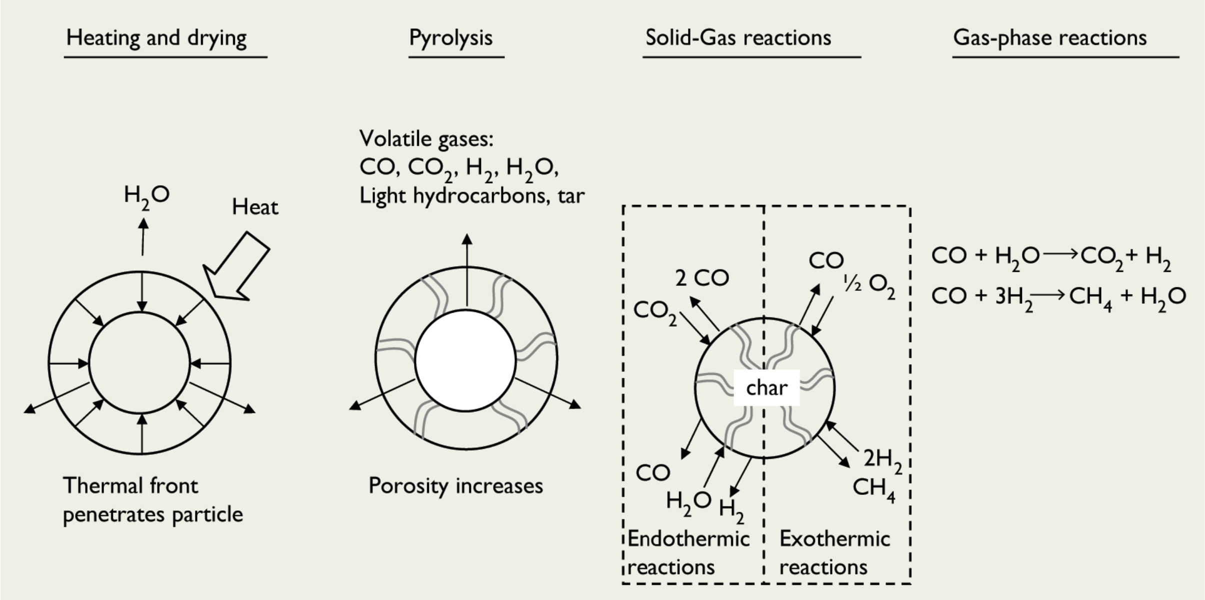
The relative distribution of these products depends on chemical composition of the fuel and process conditions such as the heating rate and the temperature achieved in the reactor.

Low pyrolysis temperatures and long residence times (slow pyrolysis) increase the yield of solid pyrolysis product (char), moderate temperatures and short residence times (low-temperature fast pyrolysis) are optimum for maximising yields of liquid products and high temperature and short to long residence times increase gas yields.

Gasification

In gasification processes, the conversion of solid carbonaceous fuels is carried out at high temperatures – in excess of 750-850 °C – and in a controlled atmosphere with sub-stoichiometric levels of oxidant (air, oxygen or steam). The overall process, often referred to as partial oxidation, is endothermic and requires either the simultaneous burning of part of the fuel (directly-heated gasification) or the delivery of an external source of heat (indirectly-heated gasification). Figure 5 below illustrates the key steps of thermal gasification.

Figure 5. Key steps in thermal gasification[7]



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[7] Partially modified and adapted from (Kayhanian et al. 2007). Figure 25.17 p.25-43.

Heating and drying

In this first step the residual moisture content is removed as the thermal front advances into the interior of the fuel particles. The heating and drying step is not normally accompanied by chemical reactions: until complete removal of residual moisture the temperature of the fuel particles remains too low to initiate the subsequent step of pyrolysis.

Pyrolysis

The pyrolysis step involves a complex series of chemical reactions resulting in the thermal decomposition of the organic compounds in the fuel yielding a large variety of volatile organic and inorganic compounds, the types and the rates depending on the fuel composition and processing conditions. These volatile compounds include gases such as carbon monoxide (CO), carbon dioxide (CO_2), methane (CH_4), and high molecular weight compounds that condense to a tarry liquid if cooled before they are able to burn.

The large flux of volatile fractions released from the particle surface limits the availability of oxygen and thus the extent of oxidation occurring in the pyrolysis zone. The solid residue resulting from the thermal decomposition of fuel particles in the pyrolysis zone, or char, is a porous carbonaceous material with small amount of mineral matter interspersed.

Solid-gas reactions

The third step of gasification is solid–gas reactions, converting solid carbon into gaseous CO, H_2, and CH_4 as described in the set of equations in (1):

$$\begin{array}{lll} Carbon - Oxygen\ reaction: & C + 0.5 \cdot O_2 \leftrightarrow CO & \Delta H_r = -110.5\ kJ/mol \\ Bouduard\ reaction: & C + CO_2 \leftrightarrow 2CO & \Delta H_r = 172.4\ kJ/mol \\ Carbon - Water\ reaction: & C + H_2O \leftrightarrow H_2 + CO & \Delta H_r = 131.3\ kJ/mol \\ Hydrogenation\ reaction: & C + 2H_2 \leftrightarrow CH_4 + CO & \Delta H_r = -74.8\ kJ/mol \end{array} \tag{1}$$

The first of these, known as the carbon–oxygen reaction, is strongly exothermic and is important in supplying the energy requirements for drying, pyrolysis, and endothermic solid–gas reactions. The hydrogenation reaction also contributes to the energy requirements of the gasifier, although significantly more char reacts with oxygen than hydrogen in the typical air-blown gasifier.

Gas-phase reactions

The fourth step of gasification is gas-phase reactions, which determine the final mix of gaseous products, these are described in (2):

$$Water - Gas\ shift\ reaction: \quad CO + H_2O \leftrightarrow H_2 + CO_2 \quad \Delta H_r = -41.1\ kJ/mol$$

$$Methanation\ reaction: \quad O + 3H_2 \leftrightarrow CH_4 + H_2O \quad \Delta H_r = 172.4\ kJ/mol \tag{2}$$

The final gas composition is strongly dependent on the amount of oxygen, air or steam admitted to the reactor as well as the time and temperature of reaction. For sufficiently long reaction times, chemical equilibrium is attained and the products are essentially limited to the light gases CO, CO_2, H_2, and CH_4 (and nitrogen if air was used as a source of oxygen). CH_4 formation is generally favored at low temperatures and high pressures, whereas high temperatures and low pressures favor the formation of H_2 and CO.

Often gasifier temperatures and reaction times are not sufficient to attain chemical equilibrium and the producer gas contains various amounts of light hydrocarbons such as C_2H_2 and C_2H_4 as well as up to 10 wt% heavy hydrocarbons that condense to a black, viscous liquid known as “tar.” This latter product is undesirable as it can block valves and filters and interferes with downstream conversion processes.

Steam injection and addition of catalysts to the reactor are sometimes used to shift products toward lower-molecular weight compounds.

Combustion

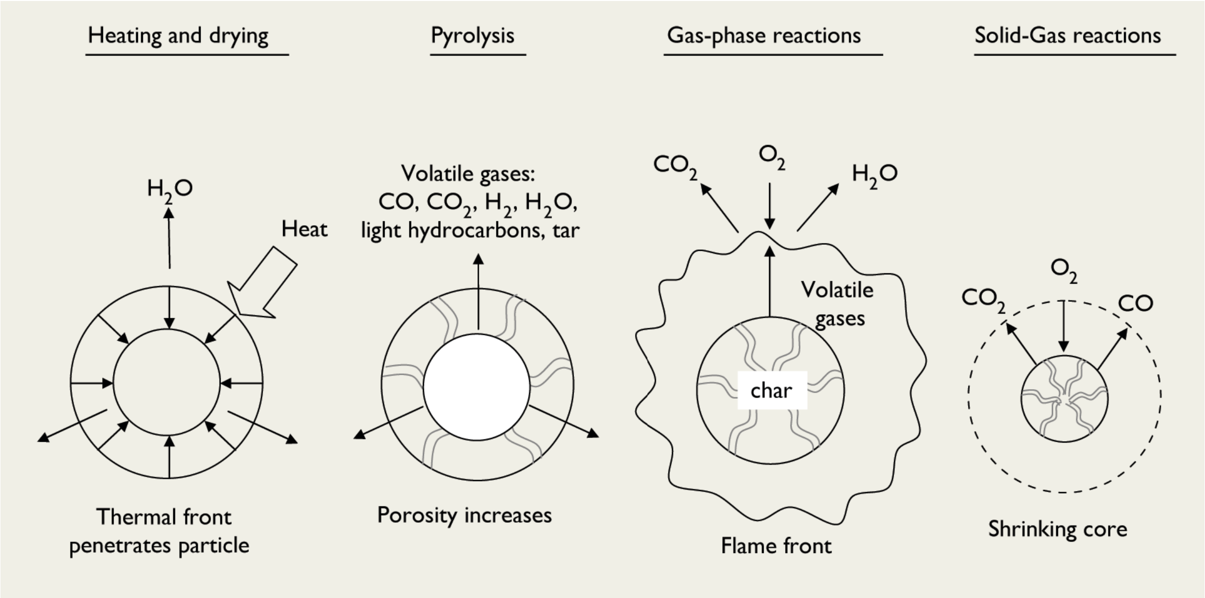
Combustion is the rapid and complete oxidation of fuel to obtain energy in the form of heat. Since waste and biomass feedstocks fuels are primarily composed of carbon, hydrogen, and oxygen, the main products of complete combustion are carbon dioxide and water although fuel-bound nitrogen can be a source of significant nitrogen oxide emissions.

The key steps involved in the combustion of solid fuels are illustrated in Figure 6 below.

Heating and drying, pyrolysis

The first two steps, heating and drying, and pyrolysis, are similar to the corresponding processes for gasification described earlier.

Figure 6. Processes of solid fuel combustion[8]



Gas phase reactions: flaming combustion

Flaming combustion results from oxidation of the volatile gases above the solid fuel results in flaming combustion. The ultimate products of volatile combustion are CO_2 and H_2O although a variety of intermediate chemical compounds can exist in the flame, including CO, condensable organic compounds, and long chains of carbon (soot).

Combustion intermediates will be consumed in the flame if sufficient temperature, turbulence, and time are allowed. In the absence of good combustion conditions, a variety of noxious organic compounds can survive the combustion process including CO, soot, polycyclic aromatic hydrocarbons (PAH), and families of toxic chlorinated hydrocarbons known as furans and dioxins.

Solid-gas reactions: glowing combustion

The next step in combustion of solid fuels is solid–gas reactions of char, also known as glowing combustion. Char oxidation is controlled by mass transfer of oxygen to the char surface rather than by chemical kinetics, which is very fast at the elevated temperatures of combustion. Both CO and CO2 can form at or near the surface of burning char. These gases escape the immediate vicinity of the char particle where CO is oxidized to CO_2 if sufficient oxygen and temperature are available; otherwise, it appears in the flue gas as a pollutant.

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[8] Partially modified and adapted from (Kayhanian et al. 2007),Figure 25.15, p.25-38.

Thermo-chemical conversion processes

in this chapter we introduce the range of conversion processes and reactor designs available, including:

- Gasification processes;
- Pyrolysis processes; and
- Hybrid processes.

Gasification processes

Gasification processes are typically classified on the basis of the gasification agent, or the configuration of the reactor assembly.

Gasification agent

On the basis of the gasification agent we identify the following three modes of thermal gasification (Bridgwater 2003).

- **air-blown gasifiers,** the main products are CO, CO_2, H_2, CH_4, N_2 and tars. This gives a low heating value gas of ~5 MJ/Nm^3. Utilisation problems can arise in combustion, particularly in gas turbines;
- **oxygen-blown gasifiers,** the main products are CO, CO_2, H_2, CH_4, tar (no N_2). This gives a medium heating value gas of ~10–12 MJ/m^3. The cost of providing and using oxygen is compensated by a better quality fuel gas;
- **steam gasification,** The main products are CO, CO_2, H_2, CH_4, tar. This gives a medium heating value gas of ~15–20 MJ/m^3. The process has two stages with a primary reactor producing gas and char, and a second reactor for char combustion to reheat sand which is recirculated. The gas heating value is maximised due to a higher methane and higher hydrocarbon gas content, but at the expense of lower overall efficiency due to loss of carbon in the second reactor

Reactor types

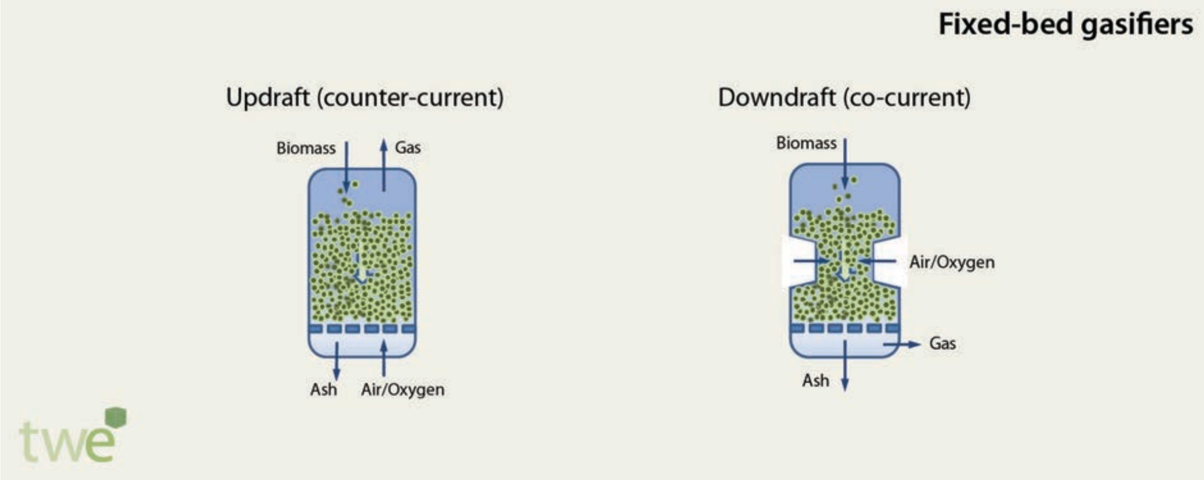
Gasification reactors are generally classified according to the method of heat transfer to the fuel:

- **fixed bed gasifiers** (updraft or downdraft);
- **fluidised beds** (bubbling and circulating, single or dual-bed);
- **entrained flow gasifiers**; and
- **plasma gasifiers**.

Fixed bed gasifiers

The two types of fixed-bed gasifiers, updraft and downdraft fixed bed, are shown in the Figure below.

Figure 7. Fixed bed gasification reactors[9]



Updraft gasifiers are the simplest type of gasifiers, they are little more than grate furnaces, with chipped or shredded biomass fuel admitted from the upper sections of the reactor, and sub-stoichiometric amounts of the oxidising agent (air, oxygen or steam) entering from below. These are often referred to as counter-current fixed bed gasifiers, as the biomass and the oxidising agent (and thus the gas produced) move in opposite directions through the reactor.

Above the grate, where air first contacts the fuel, combustion occurs and very high temperatures are produced. Although the gas flow is depleted of oxygen higher in the fuel bed, hot H_2O and CO_2 from combustion near the grate reduce char to H_2 and CO. These reactions cool the gas, but temperatures are still high enough to heat, dry, and pyrolyze the fuel moving down toward the grate. Since pyrolysis releases both condensable and non-condensable gases, and the producer gas leaving an updraft gasifier contains large quantities of tars on the order of 50 g/m^3. As a result, updraft gasifiers are generally not strong candidates for biomass or waste to energy applications.

In **downdraft** gasifiers, fuel and gas move in the same direction. This design assures that condensable gases released during pyrolysis are forced to flow through the hot char bed, where tars are cracked. The producer gas is relatively free of tar (<1 g/m^3), making it a satisfactory fuel for engines. A disadvantage is the need for tightly controlled fuel properties (particles sized to between 1 and 30 cm, low ash content, and moisture less than 30%).

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[9] Adapted from (Taylor et al. 2009), Table 1, pp.4-5.

Another disadvantage is a tendency for slagging or sintering of ash in the concentrated oxidation zone. Rotating ash grates or similar mechanisms can solve this problem.

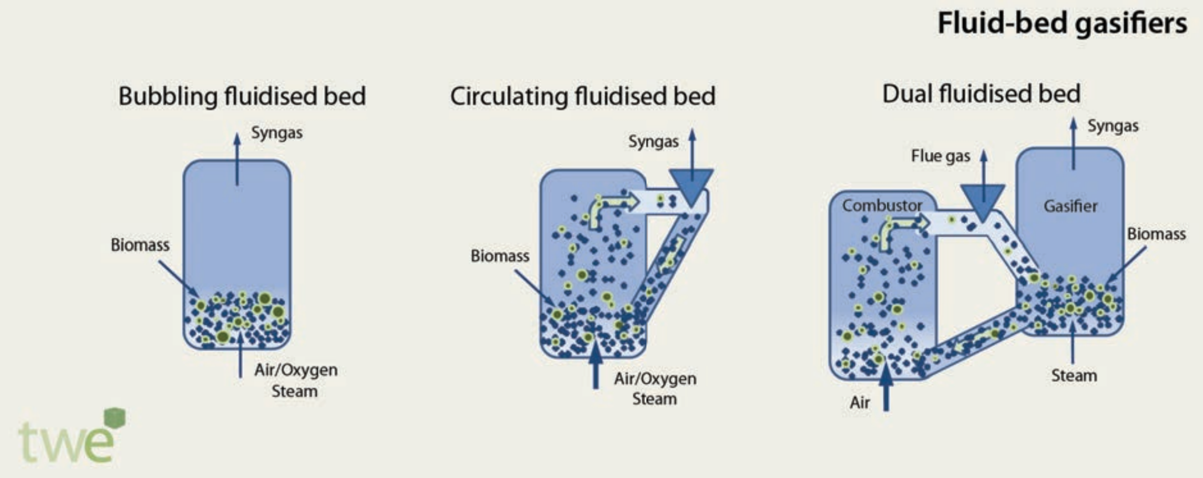
Fluidized bed gasifiers

In fluidized bed gasifiers a gas stream passes vertically upward through a bed of inert particulate material to form a turbulent mixture of gas and solid. Fuel is added at such a rate that it is only a few percent by weight of the bed inventory.

Unlike the updraft and downdraft gasifiers, no segregated regions of combustion, pyrolysis, and tar cracking exist. The violent stirring action makes the bed uniform in temperature and composition with the result that gasification occurs simultaneously at all locations in the bed.

The three types of fluid-bed gasifiers, bubbling (BFB), circulating (CFB) and dual-bed (DFB), are shown in the Figure below.

Figure 8. Fluidised bed gasifiers[10]



- **bubbling fluidized bed (BFB) gasifiers**, where the oxidizing agent is blown upward through the bed just fast enough (1-3 m/s) to agitate the material;
- **circulating fluidized bed gasifiers (CFB)**, where the speed of the oxidizing agent is fast enough (5-10 m/s) to suspend the bed material throughout the gasifier, and generate a circulation through a secondary channel; and
- **dual fluidized bed (Dual FB) gasifiers** where the heat for the reaction in the primary CFB gasification reactor provided indirectly by means of the hot gas stream leaving a secondary chamber

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[10] Adapted from (Taylor et al. 2009), Table 1, pp.4-5.

Typically, fluidized-bed gasifiers operate at temperatures below 900 °C to avoid ash melting and sticking that could prevent or interrupt the fluidization process. By injecting fuel in the base of the bed, much of the tar can be cracked within the fluidized bed. However, a large insulated space above the bed, known as the freeboard, is usually included to promote additional tar cracking as well as more complete conversion of char. Nevertheless, tar production is intermediate between updraft and downdraft gasifiers (about 10 g/Nm^3).

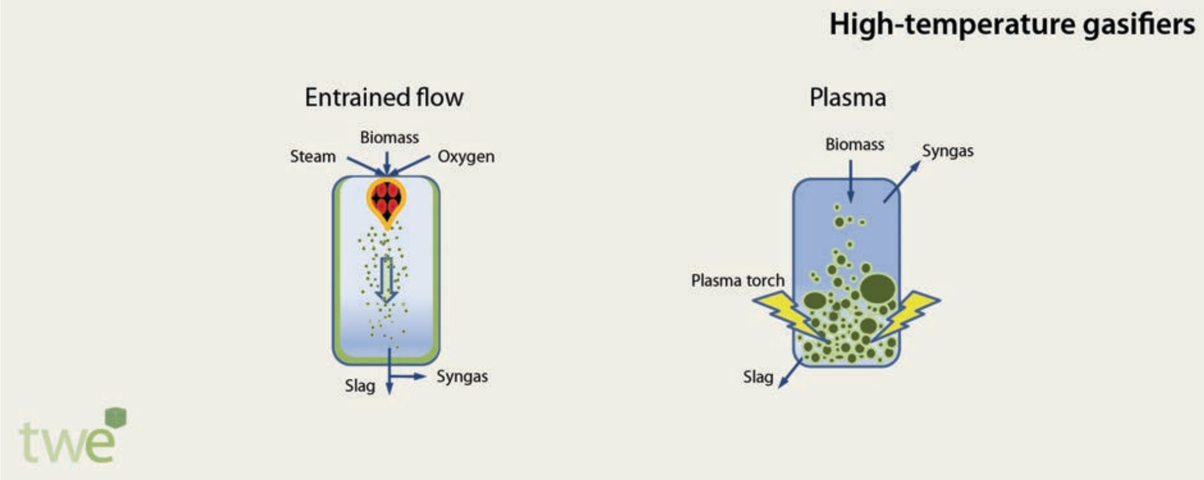
Fluidized beds are attractive for biomass and waste gasification. They are able to process a wide variety of fuels including those with high moisture content and small particle size. They are easily scaled to large sizes suitable for electric power production.

Disadvantages include relatively high power consumption to move gas through the fluidized bed; high exit gas temperatures, which complicates efficient energy recovery; and relatively high particulate burdens in the gas due to the abrasive forces acting within the fluidized bed.

High-temperature gasifiers

Two types of gasifier reactors are designed to achieve temperatures above the melting point of waste and glass materials: entrained flow and plasma gasification reactors.

Figure 9. High-temperature gasifiers[11]



Entrained flow reactors, employing finely pulverized fuel, were historically developed for steam-oxygen gasification of coal at temperatures of 1200-1500 °C.

These high temperatures ensure excellent char conversion (approaching 100%) and low tar production and convert the ash to molten slag, which drains from the bottom of the reactor. Issues associated with pre-treatment of feedstock and the lower maximum temperatures

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[11] Adapted from (Taylor et al. 2009), Table 1, pp.4-5.

that can be reached with biomass and waste feedstocks when compared to coal have limited the application of this technology with biomass, with the exception of gasification of pretreated biomass (such as char and pyrolysis liquids).

In plasma gasification, untreated biomass and waste materials fed to the reactor enter in contact with an electrically generated plasma (through non-transferred arc plasma torches), usually at atmospheric pressure and temperatures of 1500-5000 °C.

Organic materials in the feedstock are converted into very high-quality syngas, whereas inorganic matter (minerals and metals) is molten and recovered at the bottom of the reactor as vitrified slag and metal shots, or granules.

Pyrolysis

Pyrolysis is thermal decomposition of organic material with no or limited oxygen. It can be applied in principal to any forms of biomass. The main products of pyrolysis are gas, oil/tar liquids and char, with flexibility in their respective outputs. Slow pyrolysis increases char yields and fast (or ‘flash’) pyrolysis increases the liquid fraction.

Slow pyrolysis

Slow pyrolysis is characterised by taking several minutes for the biomass to transit the system. Moderate heating rates in the range of about 20 to 100 °C/min and maximum temperatures of 600°C give an approximately equal distribution of oils, char and gases because the residence time of vapours is long enough that most of the biomass is cracked.

Fast pyrolysis

In fast pyrolysis higher yields of liquid are obtained through rapid decomposition of biomass and subsequent cooling and collection of the vapour phase exiting the reactor. The main product, bio-oil, is obtained in yields of up to 75% by weight on a dry-feed basis. The by-products, char and gases, are typically used within the process to provide the process heat requirements. Fast pyrolysis is not a technology of interest in the context of syngas generation.

Hybrid schemes

Pyro-gasification

Recent research in biomass gasification has focused on improving the heating value of the synthesis gas. Conventional gasification admits sufficient air or oxygen to the reactor to oxidise part of the fuel, thus releasing heat to support pyrolysis of the rest of the fuel. Gas produced in air-blown biomass gasifiers typically has heating value that is only 10%–20%

than that of natural gas. This low heating value is largely the result of nitrogen from the air intake diluting the fuel gas. Oxygen can be used as the gasification medium, but high capital costs limit its application to large energy from waste schemes.

Indirectly heated gasification also referred to as pyro-gasification or two-step gasification can improve the heating value of the synthesis gas by physically separating the oxidation (combustion) and pyrolysis zones. As a result, the products of combustion do not appear in the synthesis gas. Higher heating values of 14.2 MJ/m^3 or higher are expected.

Pyro-combustion

In pyro-combustion processes, syngas and char from the primary reactor are transferred to a closely coupled, secondary thermal oxidizer, or combustion reactor.

Melting furnaces

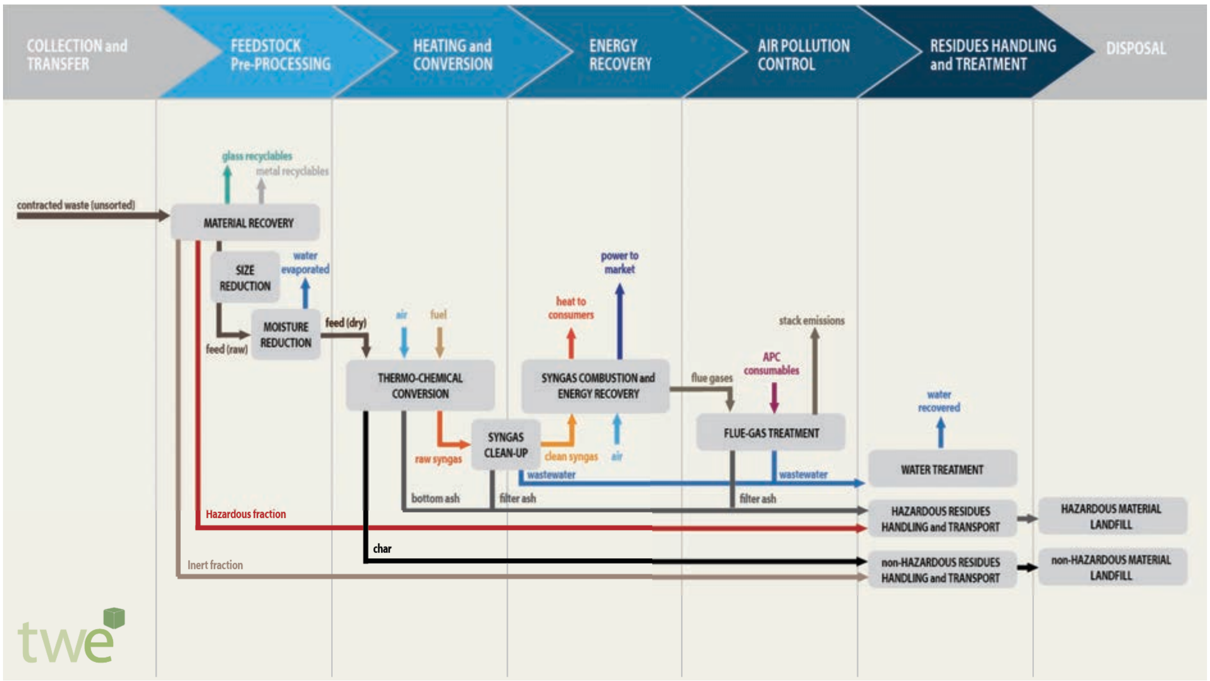
In addition to entrained flow and plasma gasification reactors, where temperatures in excess of 1200 °C can be achieved within the primary reactor chamber, a number of lower temperature processes integrate a secondary, high-temperature ‘melting’ furnace, where the high temperatures required for melting are achieved by burning auxiliary fuel, or part of the raw synthesis gas leaving the primary reactor through the addition of controlled quantities of air, or oxygen.

Energy from Waste conversion

The diagram below illustrates a typical Energy from Waste conversion scheme, integrating the key processing steps of:

- **Feedstock Pre-processing**;
- **Heating and Conversion**;
- **Energy Recovery**;
- **Air Pollution Control**; and
- **Residues Handling and Treatment**.

Figure 10. Energy from waste (EfW) and energy from biomass (EfB) thermo-chemical conversion schemes



Feedstock Pre-processing

Pre-processing of waste and biomass feedstocks is primarily targeted at reducing particle size and moisture content to the levels required by the specific conversion technology.

For waste feedstocks, a material recovery facility (MRF) might also be integrated as part of the conversion scheme to separate recyclable (glass and metals) and non-processable (inert and hazardous) fractions in the incoming waste stream.

Size reduction

The cross-section of waste and biomass components has a direct effect on the efficiency of heat transfer inside a conversion reactor and thus on the residence time needed to achieve pyrolysis temperatures. Conversion technologies often require subdivision of waste and biomass at cross sections below 50 mm.

The table below summarizes typical feed pre-processing requirements for different gasification technologies.

Table 1. Summary of feedstock pre-processing requirements[12]

Gasifier	Size	Moisture	Composition	Other
EF	 <1mm	15%	Should not change over time. Limited proportion of high-ash agricultural residues	Pre-treatment steps being used
BFB (and Dual with BFB gasifier)	 <50-150mm	10-55%	Can change over time Care needed with some agricultural residues	
CFB (and Dual with CFB gasifier)	 <20mm	5-60%	Can change over time Care needed with some agricultural residues	
Plasma	 Not important	Not important	Not important, can change over time. Higher energy content feedstocks preferred	Used for a variety of different wastes, gate fees common

Size reduction is typically achieved through shredding; a classification stage usually follows where valuable recyclable fractions such as aluminium, ferrous iron, and other metals are recovered and undesirable fractions such as glass, "dirt," rocks, and ceramic are removed.

Moisture reduction

Moisture reduction, or drying of post-MRF waste residues and biomass feedstocks ahead of their introduction in the conversion reactor is required to reduce the thermal load associated with the evaporation of free moisture and ultimately improving the thermal efficiency of the gasification process. Typically, drying is achieved through a combination of:

- Natural drying, where moisture content of the biomass and waste feedstock is partly obtained through stock-piling at the plant site or at intermediate transfer and storage facilities, and
- Artificial, or forced, drying, where residual moisture content is brought down to plant specifications by means of direct heat exchange against a flow of warmed air, in trommel-like or similar devices; the air itself is usually heated by heat exchange

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[12] Adapted from (Taylor et al. 2009).Table 10, p.29

against the flue gases or steam from downstream conversion and energy recovery operations.

Refuse-derived fuel processing

A more advanced pre-processing strategy is that of integrating a series of material recovery and processing steps, including removal of materials, size reduction, size separation and drying, with the endgame of generating a homogeneous feedstock, or refuse-derived fuel (RDF). RDF processing is often considered when there is a requirement for:

- a “portable” feedstock, with better handling (bulk density and weight) and combustion (particle cross-section and moisture content) than the ‘as received’ waste or biomass feedstock, and/or
- the conversion process is based on an advanced (combustion or conversion) reactor design highly sensitive to variations in feedstock size and composition.

There is a trade-off between the increased efficiency of RDF-based, advanced conversion designs, and the increase in cost associated with installation and operation of pre-processing equipment and intermediate storage and transfer facilities for the RDF material.

Heating and Conversion

The core processing unit in a thermo-chemical conversion scheme is represented by the conversion reactor (or reactors for multi-stage and hybrid processes).

Heat is applied in a conversion reactor to achieve a series of fundamental physical and chemical changes in the waste and biomass components in the feedstock, including:

- Temperatures at or above 100 °C: evaporation of residual moisture in the feedstock;
- Temperatures at or above 3-400 °C: decomposition of organic compounds in mixtures of low-molecular-weight gases (methane and ethane), intermediate hydrocarbons and partially oxygenated species (alcohols, ketones, aldehydes, organic acids, etc.), and high molecular-weight tars such as (often carcinogenic) polynuclear compounds. Carbonaceous char remains as a solid residue along with the other inorganic “ash”. Residual aluminium materials (waste feedstocks) melt in this range.
- Temperatures above 850 °C: softening and liquefaction of glass (waste feedstocks); and
- Temperatures above 1500 °C: softening and melting of ceramics and most common metals (waste feedstocks).

As temperatures increase, so does the reactivity of the chemical species present, fostering a range of oxidation, rearrangement, and reforming reactions.

A range of different heating methods are applied, alone or in combination, in conversion reactors to achieve heating of the biomass and waste components in the feedstock to the desired pyrolysis and gasification temperatures, these include:

- **Indirect heating methods,** such as hot surface, heated gases and non-transferred arc plasma torch heating;
- **Direct heating methods,** such as induction and transferred arc plasma torch heating; and
- **Partial combustion** of the feedstock, and heating of fresh incoming feedstock against the flow of combustion flue gases.

Hot surface heating

Heat transfer to the feedstock achieved in a rotating, kiln-like unit heated externally, or internally through an augering screw.

Rotating the kiln or auger abrades the waste mass against a hot surface with exchange of heat by a kind of rubbing convection. The tumbling action of the waste assures uniform contact of the waste with the hot surface and, by stoking the mass, helps to break up the charge. The inclination of the kiln or the pitch of the screw acts to move the waste from the feed point to discharge.

Most often, the reactor is heated by burning a fraction of the synthesis gases exiting the conversion reactor, although some technologies favor the use of purchased natural gas or liquefied petroleum gases (LPG).

Heated gases

In this method, the feedstock temperature is increased to pyrolysis conditions by contact with a stream of hot gases generated by combustion of natural gas or a portion of the product syngas, or exiting a secondary heat exchanger.

The resulting thermal interaction between gas and waste solids is rapid and effective. In some cases, means are required to augment the sensible heat of the incoming gas (such as by adding hot sand to the mix) due to the low heat capacity of gases compared to the sensible and latent heating load of the incoming waste solids and associated free moisture.

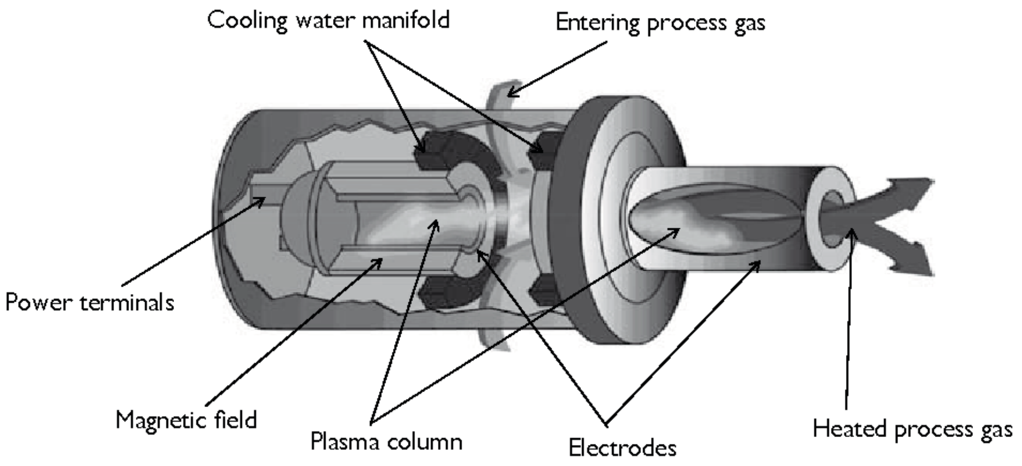
For some technologies, the contactor design is configured to allow multiple waste–gas contact. An example of the latter type of contactor is a circulating fluidized bed (CFB).

Nontransferred Arc Plasma Torch

Nontransferred Arc (NTA) plasma torch is a method for producing a ionized, superheated gas stream (plasma) with which to transfer heat to a feedstock material. Plasma is formed when heat from an electrical arc strips away electrons from gas molecules and generates an ionized gas stream that has an almost liquid-like viscosity. Since this superheated gas stream (plasma) is conductive, it can be heated to even higher temperatures by an electric current. Passing an electrical discharge through the gas is sufficient to increase the temperature to levels exceeding 5000 °C.

A schematic view of a (NTA) plasma torch is presented in Figure 11 below.

Figure 11. Non transferred arc plasma torch[13]



Conversion technology applications of NTA Plasma refer to processes that heat waste and biomass components in the feedstock to high temperatures (up to 5000 °C) using a sustained electrical arc. Heating is conducted in an oxygen-free or oxygen-starved environment, causing the waste to pyrolyze into a primary product of relatively large molecules that, in subsequent passage through the system, are ultimately discharged as simpler molecules.

The specific energy requirement (SER) for each waste stream, that is the amount of energy required within the plasma system to completely gasify and vitrify a ton of the specific waste stream, is the fundamental energy input term characterizing this approach to waste processing. The products of the process are the following:

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[13] Adapted from (Niessen 2010).Figure 12.1, p.484.

- a combustible gas derived from the organic matter; and
- a molten slag from the inorganic matter, that vitrify when cooled.

In principle, the plasma environment can be used to process almost any waste to produce a glassy, non leachable vitrified residue, and, compared with full oxidation in an incinerator, a minimal volume of gaseous products requiring clean up.

Induction heating

When an alternating electrical current is applied to the primary coil of a transformer, an alternating magnetic field is created. If the secondary coil of the transformer is located within the magnetic field, an electric current will be induced. In a basic induction heating application, a solid state, radio frequency power supply sends an AC current through a water-cooled copper coil, and the material to be heated is placed inside the coil. The coil serves as the transformer primary and the part to be heated becomes a short-circuited secondary. When a conducting metal is placed within the induction coil and enters the magnetic field, circulating eddy currents are induced within the metal, generating precise and localized heat without any direct contact between the metal and the coil.

It is easier to heat magnetic materials because, in addition to the heat induced by eddy currents, magnetic materials also produce heat through what is called the hysteresis effect.

During the induction heating process, conductive magnetic materials offer resistance to the rapidly alternating electrical fields, and this causes enough friction to provide a secondary source of heat. This effect ceases to occur at temperatures above the temperature at which a magnetic material loses its magnetic properties (its Curie point). The relative resistance of magnetic materials is rated on a “permeability” scale of 100–500; while nonmagnetic materials have a permeability of 1, magnetic materials can have a permeability as high as 500.

Transferred arc plasma torch

In contrast to the case of the NTA, the transferred arc is struck between the torch electrode and the melt or between two graphite electrodes. This approach is similar to that used in metal arc furnaces. In this instance, a substantial fraction of the electric energy passes directly into the melt. This mode has the advantage that large masses of material can be heated to the fusion point with less pre-treatment.

In waste processing, the arc is struck between the torch and a pool of metal (derived from the waste) on a refractory hearth.

Partial combustion

For many of the heating concepts discussed previously, the energy source is purchased or self-generated electricity or fuel. These energy inputs detract from the energy yield of the process or represent a significant operating expense. An alternative strategy involves the addition of a quantity of oxygen to the waste mass that is less than stoichiometric but which generates a quantity of hot flue gas sufficient to effect the drying and pyrolysis process. Clearly, some of the waste's energy content is consumed, but the form value of the energy is at the lowest level of any other energy source. If pure or highly enriched oxygen is used to release the heat, there is minimal dilution of the product gases, whereas if air is used, the atmospheric nitrogen in the air adds to the volume of flue gas produced, thus increasing the size and both capital and operating cost for subsequent APC, fans, ducts, and so on, and decreases the product gas heat content and its utility as a chemical feedstock.

Gas clean-up

After heating has gasified the waste, some processes include a step where tars (high molecular-weight compounds) are broken down into simpler molecules (a "cracker"). Many processes then remove a portion of the sensible heat (using a waste heat boiler or by simple water sprays) followed by one or more stages of gas clean-up (GCU) ahead of combustion, which may include:

- Particulate removal;
- Acid gas removal;
- Hydrogen sulfide (H_2S) removal;
- Amine/ammonia removal; and
- Other control requirements (tars, COS, etc. that impact downstream components).

GCU assemblies for conversion technologies are fairly compact, as the clean-up effort need only deal with the relatively small gas stream from the gasification reactor. This contrasts with the scale of clean-up for conventional incinerator flue gases that have been greatly expanded in volume by the addition of almost twice the theoretical quantity of combustion air and the dilution associated with nitrogen and excess oxygen.

As a consequence, the equipment and operating cost for environmental emissions control for gasification facilities can be substantially lower than for incineration (See Section 2).

Product streams from thermo-chemical conversion

Fuel-gas intermediates

Raw synthesis gases produced in a conversion technology, composed mainly of CO, H_2, and light hydrocarbons, are usable as a fuel gas for conventional burners and boiler equipment and, subject to more extensive cleaning and upgrading, in gas engines, gas turbines and fuel cells.

An important characteristic of the process gas stream is its small volume when compared to the volume of the fully air-oxidized flue gas stream produced by incineration technologies. Because of its compressed volume, clean-up of the gas ahead of any ultimate combustor or chemical process involves smaller (less costly) equipment acting on more concentrated (easier to treat) gas streams.

Syn-gas intermediates

The syngas mixtures of CO and H_2, after suitable cleanup, can be used as the starting point for a range of conventional and development-stage processes to produce hydrogen, methanol, ethanol, and other simple petrochemical-type industrial chemicals, for use as chemical commodities or as energy carriers.

In many cases, this synthesis technology is reliable and well-developed and can be accessed through several industrial chemical design firms, whereas the selection of development-stage processes can introduce significant additional capital and operating costs and add a layer of technology and operational risk and uncertainty into the process selection decision.

The availability, maturity and performances of different syngas upgrading and reforming options is discussed in detail under Section 2.

The economics of manufacture, transportation, and sale of these chemicals and energy carriers need to be evaluated at the scale of most municipal waste management systems. Section 2 presents a treatment of alternative delivery options and comparison of the associated costs and performances.

Energy recovery

Raw synthesis gases generated from thermo-chemical conversion of waste and biomass resources can be utilized in various ways:

- **direct use of raw syngas** as a fuel in industrial kilns and steam generators (industrial or power plant boilers);

- **clean-up and use of clean syngas** as a fuel in advanced energy conversion equipment, such as gas engines, gas turbines and fuel cells;
- **clean-up and upgrade to syngas products**, including substitute natural gas (SNG), hydrogen or methanol.

Air Pollution Control

Thermal conversion of waste and biomass materials can yield a wide array of air pollutants, including:

- *Particulate matter* (PM), from fly ash,
- *Acid gases*, like hydrogen chloride (HCl), hydrogen fluoride (HF) and Sulphur Dioxide (SO_2),
- *Heavy metals*, like mercury (Hg), lead (Pb), Zinc (Zn), etc. and their compounds,
- *Nitrogen oxides* (NO_x), and
- *Volatile organic compounds* (VOCs) including polychlorinated dibenzo-dioxins (PCDD, more commonly referred to as *dioxins*) and polychlorinated dibenzo-furans (PCDF, more commonly referred to as *furans*).

Air pollution control strategies

Air pollution control (APC), and the associated monitoring and diagnostic equipment is one of the most important and most expensive process stages in thermal conversion facility.

Failure to comply with the relevant regulations and operating permit of the plant can result in the enforcing authorities directing the temporary or even continued shutdown of a facility, with obvious consequences on the plant’s ability to process the contracted waste quantities and its overall profitability.

In addition to this, some regulations, such as in the European Union, prescribe the implementation of redundant APC capacity, further adding to the cost of this plant subsystem.

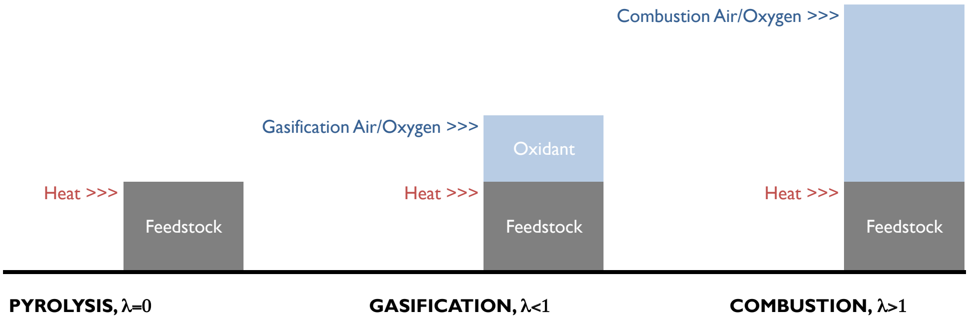
In *combustion* plants, where untreated waste or refuse-derived fuels are burned directly in sufficient excess air, APC strategies are limited to *post-combustion* or *flue-gas treatment* whereby a combination of technologies is required to maintain the concentration of pollutant species within the limits set in the relevant regulations and the plant’s specific operating permits.

By contrast, in *conversion* facilities, based on pyrolysis or gasification processes, the gaseous products or *syngas intermediates* can be instead cleaned or upgraded prior to combustion, with the aim to obtain a higher-energy content, cleaner fuel that can be used in downstream energy conversion or further processing.

As noted earlier, the option of operating an intermediate syngas clean-up step represents one of the key advantages of conversion technologies over combustion or incineration. Since conversion processes use no (pyrolysis processes) or sub-stoichiometric air or oxygen as the gasification medium (gasification processes), the volume flowrate (in Nm^3/h) of gases to be treated – the key sizing parameter for the design gas clean-up equipment – is significantly lower than in the case of incineration (where most technologies use the stoichiometric amount of combustion air).

The diagram below provides a graphical representation of the volume flowrates associated with air pollution control/gas clean-up equipment for combustion and conversion technologies operating on municipal solid waste (MSW).

Figure 12. Comparative representation of exhaust gas from primary reactors in conversion technologies



Despite this key advantage, many of the available conversion technologies operate a closely-coupled energy conversion step, where the syngas intermediate leaving the conversion reactor is burned in boilers or gas engine generator sets for generation of steam and/or electricity, without prior clean-up, leaving an air pollution control task not unlike that of incinerator technologies.

In the remainder of this section we describe the major families of *post-combustion* or *flue-gas treatment* strategies, whereas clean-up and upgrading of syngas intermediates are described in the Section 2 – *Synthesis and Renewable Gas Utilization*.

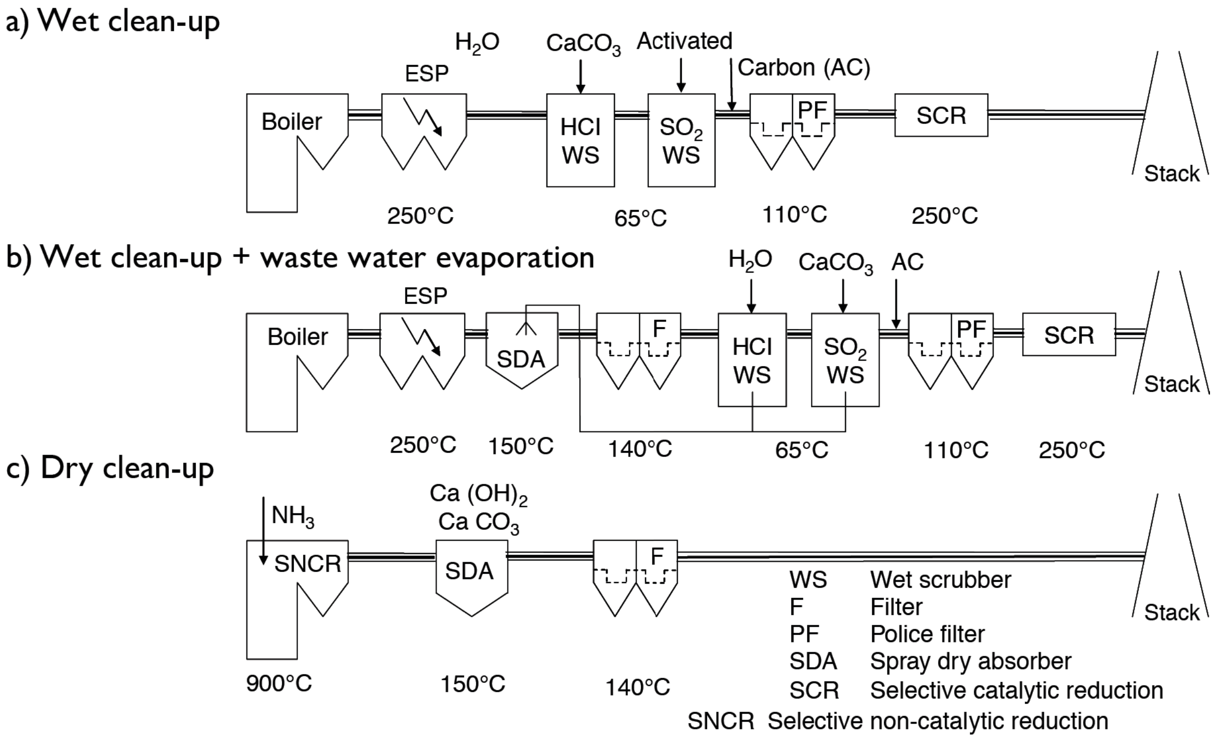
Air pollution control systems

In order to guarantee reliability of plant operation and compliance with emission limits set in the operating permits, waste conversion facilities, where thermal conversion is closely coupled with combustion and energy recovery, employ a number of air pollution control technologies. We describe here typical clean-up system configurations and the key the clean-up steps.

APC configurations

The diagram below presents a process schematic for each of the three configurations for post-combustion APC trains.

Figure 13. Possible configurations for post-combustion air pollution control train[14].



Wet clean-up processes present the highest complexity, with electrostatic precipitators for particulate matter removal, followed by wet scrubber trains for removal of acid gases (HCl, SO_2), activated carbon beds for separation of dioxins and selective catalytic reduction (SCR) for removal of NO_x.

A variant of the wet system is commonly adopted in Germany, where exists also a requirement for concentration of the scrubber blowdown solutions through evaporation of the wastewater from the APC train, this is usually achieved by means of an external evaporator or by installing a spray dryer and a fabric filter into the hot flue gas stream.

Dry clean-up systems are in contrast less complex. Acid gases, mercury and dioxins are first separated in a spray drier with addition of activated carbon and removed in a fabric

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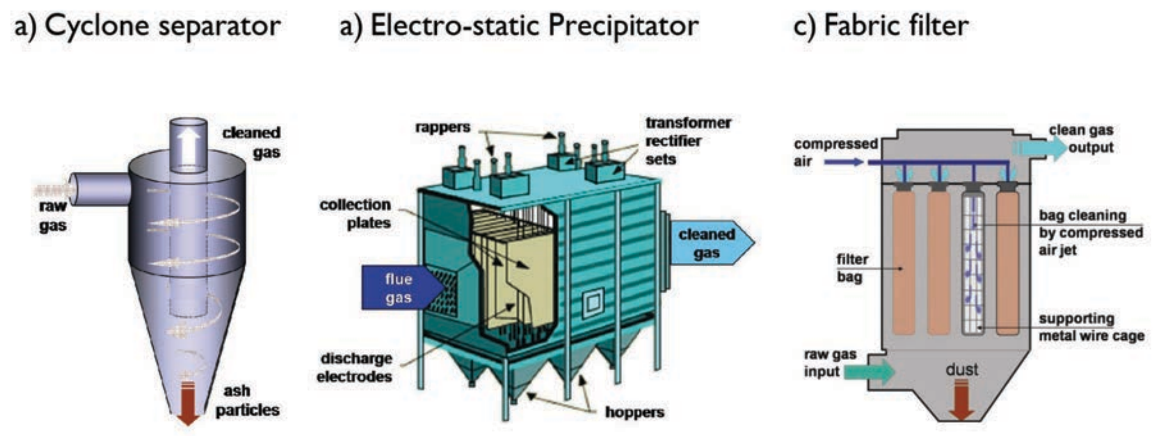
[14] Adapted from (Spliethoff 2010) Fig. 6.45, p. 438.

filter along with fly ash. NO_x are separated in a selective non-catalytic reduction (SNCR) reactor. In some plants, the fly ash is removed separately beforehand.

Separation and removal of particulate matter

Particulate matter (also referred to as fly ash or dust) can be separated from the flue gas stream by means of cyclone separators, electrostatic precipitators (ESPs) or fabric filters (also called baghouse filters). The three process alternatives are presented in the Figure below.

Figure 14. Particulate removal processes



Cyclone separators (a) use inertial impaction for fly ash separation. The gas enters a cylindrical chamber tangentially at high velocity and is forced into a cylindrical path. The centripetal force acting on the particles causes them to collide with the walls where they impinge and settle down into the discharge hopper. The gas is extracted through a central tube. Due to their limited removal efficiency for fine particles, cyclone separators are not often found in modern plants or they serve for pre-deposition of the coarse fly ash.

In an ESP (b), the flue gas passes an electric field with spray anodes charging the dust particles and cathodic collection plates where they are deposited. ESPs have the advantage of being cheaper and of causing a lower pressure loss than bag filters, but have the disadvantage of a lower removal efficiency, which limits their application to APC trains featuring downstream wet scrubbers and additional removal of pollutants such as acid gases (HCl, SO_2). ESPs operate at temperatures of up to 280 °C.

In a fabric filter (c) the raw gas passes through fabric bags supported by metal cages from the outside to the interior. The fly ash stays on the outer surface of the filter bags and is periodically removed by an air pulse blown into the bag from the interior. This cleaning releases the particles which fall into the discharge hopper. Fabric filters are typically the technology of choice for spray drier processes, as the mist on the filter linings enhances sorption of pollutant species (particularly dioxins and furans). The operating temperatures of fabric filters are usually between 140 and 200 °C.

Separation of acid gases

Separation of acid gas components, such as HCl, HF, SO_2 and SO_3, can be achieved with comparable removal efficiencies through either wet or dry removal processes.

In wet processes the gas is passed through scrubbing columns where a solution or slurry is adopted to strip the gas of the acid compounds. The process runs typically in two steps: in the first step, HF, HCl and Hg compounds are scrubbed with water and in the second step, SO_2 and SO_3 are separated by the addition of a lime slurry or sodium hydroxide.

Wet scrubbing methods have the advantage of good mass transfer and near-stoichiometric conditions, keeping the consumption of absorbent additives low. On the other side, the wastewater from wet scrubbing requires further treatment, or concentration by evaporation.

Dry or spray drying processes, in contrast, do not produce wastewater. In dry absorption or in an entrained-flow absorber, solid absorbents like calcium hydrate or sodium carbonate are fed to the reactor to separate the acid components, whereas in spray drying, anaqueous lime slurry is finely atomised and completely evaporated.

The good mass transfer between the gas and the liquid in spray draying is again advantageous. The salt particles formed as a consequence of evaporation of the water and chemisorption are removed from the gas flow in a filtering separator. In this case, fabric filters offer the advantage of further removal via the solid layer of matter on the filter. Spray drying processes typically run at temperatures of 150–170◦C. Addition of activated carbon or charcoal as an adsorbent achieves further reduction of organic pollutants (dioxins and furans) or heavy metals.

Removal of dioxins and furans

Dioxin emission from EfW plants principally results from dioxins that may exist in the waste or that are newly formed (*de novo*) when cooling down the flue gas.

Dioxins fed with the waste into the EfW plant can be effectively destroyed at high temperatures and sufficient residence time. Accordingly, a residence time of 2 s at 850 °C is required in the flue gas path of an EfW plant.

The de novo formation of dioxins is a heterogeneous gas-solid reaction, in which the fly ash or solid carbon provides the surface for the reaction. The de novo reaction takes place in a temperature window of 180-450 °C, with a maximum formation at about 300 °C, and is dependent on the residence time of the gas and in particular the fly ash in that temperature range.

Effective primary measures to reduce the de novo formation of dioxins are as follows:

- A complete burnout, which reduces the potential of dioxide formation by destroying the aromatic compounds and soot. The residence of 2 s at 850 °C, which serves to destroy existing dioxins also promotes a complete burnout;
- A low residence time of the flue gas and fly ash in the temperature range of 180–450 °C. This can be achieved by rapid cooling or quenching of the flue gases.

Particle filters should be installed at lower temperatures, preferably below 180 °C.

High dioxin emissions from EfW plants in the past were mainly caused by de novo formation in particle filters installed at excessively high temperatures in combination with an incomplete burnout. Additionally, dioxins can be reduced by secondary flue gas cleaning adopting the same technologies and systems used for heavy metal compounds discussed below.

Removal of toxic heavy metals

Toxic heavy metals (e.g. Hg, Cd, Pb, Zn) and organic compounds (dioxins and furans) are typically removed in entrained-flow and fixed bed adsorbers, where they are adsorbed by carbonaceous surfactants such as activated carbon or lignite coke.

Entrained-flow processes are designed for the separation of heavy metals by adsorption onto reactants which are injected to the flue gas stream. In a fixed bed adsorber, the separation process occurs as the flue gas flows through a packed bed of carbonaceous adsorbents.

Single-chamber systems with fillings of activated carbon/lignite coke and multi-chamber systems with various adsorbents are used.

Both entrained-flow and fixed bed adsorbers can be used as safety or “police” filters at the end of the flue gas cleaning train. Remaining heavy metals or dioxins are removed by adsorption onto carbonaceous material and remaining acid components can be absorbed by the addition of calcium hydroxide.

Abatement of nitrogen oxides

Nitrogen oxides can be reduced through the following strategies:

- *primary measures* such as controlling NO_x formation through control of combustion temperature and rapid cooling through addition of dilution air downstream of combustion,
- *selective non-catalytic removal* (SNCR), by injection of ammonia or another nitrogen containing compound into the hot flue gas (at about 950 °C) in the first flue of the boiler; or
- *selective catalytic reduction* (SCR) at a temperature level of 250 to 300°C, in most cases at the end of the gas cleaning system after reheating of the flue gas.

SCR offers the highest reduction rates but also involves the highest cost, because of catalyst addition and regeneration. In the low-dust SCR configurations which are most common in Europe and Japan, the catalyst is arranged after the scrubber to prevent deactivation. This configuration has the disadvantage of the need to reheat the flue gases to the operating temperature of the catalyst (above 240 °C). In the USA it is common to use SNCR (and not SCR) in EfW plants.

Residues handling

Conversion technologies offer the opportunity to recover a number of sidestreams and residues, including:

- inert fraction and RDF unprocessables,
- recyclable metals,
- vitrified ash,
- ash,
- char solids, and
- scrubber blowdown and other wastewater streams.

Sidestream and residue management processing technologies are proven, and some conversion technology developers claim revenue streams from marketing these materials, or in some cases, particularly for development-stage technologies, claim for the sales of these materials to be able to cover a large fraction of the conversion plant revenue requirements.

However, these add-on processing steps add to both capital and operating cost and they present additional risks and both operating and commercialization challenges which should be taken carefully into account.

Recyclable Metals

Waste resources from residential, commercial and industrial collection activities include numerous components that cannot be gasified. These elements and compounds thus leave any processing system in solid form. A fraction may correspond to “items of commerce” such as ferrous iron, aluminum, and various other metals and alloys such as copper, brass, stainless steels, and so forth. To the degree that these metals can be economically concentrated and separated in relatively pure states, they are marketable. Generally, as the purity decreases, so does the selling price until, at some point, hauling costs may be greater than the ultimate value.

Vitrified Ash

Some of the conversion technologies, such as the ones based on plasma torch heating, include zones where temperatures are high enough to melt residual solids to glassy, non-leaching materials. With minimal grinding and grading, these residues can be used as clean fill or as aggregate for building blocks, asphalt, or road base.

Ash and other solids

Some conversion technologies (and conventional incineration) produce residue streams that are a mix of inorganic solids, glass, metals, and some unburned char.

After the removal of ferrous metal, some or all of these residues have been used as landfill cover, asphalt aggregate (“Glassphalt”), or road base. Often, however, these materials are simply landfilled.

Char materials

In some cases, particularly for biomass feedstocks with high carbon content and low levels of contaminants such as chlorinated and fluorinated plastics, and heavy metals, the solid organic residues of thermal conversion (chars) can be used in a range of applications, including:

- coal substitute for metal reduction applications (such as steel making),
- activated carbon for filters and environmental applications,
- agronomic additive (biochar).

Wastewater Streams

The final class of sidestreams includes the process-specific aqueous streams, some of which require treatment before sewer discharge. For example, scrubber blowdown may require specialized wastewater treatment (more like industrial wastewater treatment than plants for domestic wastewater): one or more stages of precipitation; pH adjustment; and concentration or other chemical, thermal, or biological steps that, ultimately, may result in a benign residue suitable for the sewer or appropriately permitted landfill.

Significant heavy metal content in the sludge generated in these treatment processes may limit or place special requirements on sludge disposal options.

Inert and Hazardous Fractions

Some conversion process concepts require the incoming MSW to be shredded and, often, classified or otherwise pre-processed to concentrate one or other streams because they are either desirable (e.g., they have a high energy content) or undesirable in the downstream steps (e.g., they are wet, generate a problematic slag, contribute an important air pollutant, or can jam the materials handling systems).

The unprocessable shredder by-product (which can be as much as 25–35% of the raw MSW stream) usually goes to landfill. This major sidestream detracts significantly from the assertion that the conversion technology involved is a “zero waste” (no landfilling) alternative even though the core, conversion technology stage itself may, indeed, have no net residuals to be shipped to a landfill.

The destruction and removal efficiency (DRE) of RDF-based conversion technologies should be evaluated taking into account the RDF manufacturing steps, often carried out at separate facilities.

Technology review

Conversion strategies

Throughout this study we adopt a classification of conversion technologies focused on the range of conversion temperatures, grouping the range of technologies of interest into one the following categories:

- **Low Temperature Conversion (LTC)** for technologies operating with maximum conversion temperatures below 750 °C, including slow pyrolysis and fixed-bed gasification technologies;
- **High Temperature Conversion (HTC)** for technologies operating with maximum conversion temperatures at or above 750 °C, including pyro-combustion, pyro-gasification and fluidized bed gasification technologies; and
- **High Temperature Conversion + Melting (HTCM)** for technologies integrating a ultra-high temperature *melting* zone (above 1500 °C) where minerals (ashes) and metals present in the waste stream are brought above their fusion temperature and recovered respectively as vitrified slag and molten granulates. These include plasma gasification, pyro-gasification + melting and fluidized bed gasification + melting technologies.

This classification, is particularly useful in the context of alternative waste treatment (AWT) applications, as it groups available conversion technologies on the basis of the types of feedstocks that they are able to process, thus enabling an explicit assessment of the role the conversion facility can play within the context of an integrated waste management strategy.

In the remainder of this section we provide a detailed review of conversion technologies under each of the three technology groups, covering reaction designs, performance, cost and other key characteristics of commercially available and near commercial technologies.

Low temperature conversion technologies

Reactor designs

The following reactor designs are available for low-temperature conversion:

- **slow pyrolysis reactors**, for single-stage thermal degradation of waste and biomass feedstocks in the absence of oxygen;

- **fixed-bed gasification reactors**, for single stage thermal degradation of waste and biomass resources at low temperatures in sub-stoichiometric air, oxygen or steam environments; and
- **pyro-combustion reactors**, two-stage thermal degradation and energy recovery with a secondary thermal oxidation (or combustion) chamber closely-coupled to the primary slow pyrolysis reactor.

Applications

One key advantage of most low-temperature conversion technologies is feedstock flexibility, with minimal pre-processing requirements (for drying and size reduction):

- **advanced waste treatment**: for source-separated materials with low contamination of glass and metal; and
- **biomass energy recovery:** for a variety of organic feedstocks, including greenwaste, woody biomass residues, agricultural crop residues and biosolids from wastewater treatment plants.

Commercial technologies

Commercial low temperature conversion technologies include:

- the **WtGas** fixed-bed (starved air) gasification technology developed in Australia by **Entech Renewable Energy Systems (Entech-RES)** with several commercial facilities operating through South-East Asia, and a new commercial facility being built in the Pilbara region of Western Australia by New Energy Corporation.
- the **Eddith** slow pyrolysis technology developed in France by **Thide Environnemental**.
- the **APS** pyro-combustion technology developed in California by **International Environmental Solutions**.

High temperature conversion technologies

Reactor designs

The following reactor designs are available for high-temperature conversion:

- **fluidized-bed gasification reactors**, for single stage thermal degradation of waste and biomass resources at high temperatures in substochiometric air, oxygen or steam environments; and
- **pyro-gasification reactors**, two-stage thermal degradation with a secondary gasification chamber closely-coupled to the primary slow pyrolysis reactor.

Applications

High-temperature conversion technologies achieve higher energy and conversion yields, but typically require higher feedstock homogeneity and more advanced pre-processing requirements (for drying and size reduction):

- **advanced waste treatment**: source-separated materials with low contamination of glass and metals; and
- **biomass energy recovery:** for high-energy content, homogeneous feedstocks including forestry and grain crop residues.

Commercial technologies

Commercial high temperature conversion technologies include:

- the **Advanced Pyrolytic System (APS)** pyro-combustion technology developed in California by **International Environmental Solutions (IES)**;
- the **SK 1000** pyro-gasification technology developed by **OE Gasification**;
- the **Termiska AB** fluid-bed gasification technology developed by **TPS** and demonstrated at a commercial-scale facility in Italy;
- the **Pyropleq** pyro-gasification technology developed in the UK by **WasteGen;**
- the **Metso** fluid-bed gasification process, developed by **Metso Power** and demonstrated at a full commercial-scale facility in Finland.

High temperature conversion + melting technologies

Reactor designs

The following reactor designs are available for high-temperature conversion + melting:

- **fluidized-bed gasification + melting reactors**, integrating a high-temperature 'melting' zone where the syngas immediately downstream of the reactor is combusted in oxygen-rich environments to enable melting of glass and metal residues and destruction of dioxins;
- **pyro-gasification + melting reactors**, integrating a high-temperature 'melting' zone where the syngas immediately downstream of the secondary gasification reactor is combusted in oxygen-rich environments to enable melting of glass and metal residues and destruction of dioxins; and
- **plasma gasification reactors**, where the high temperature achieved in the plasma zone enable melting of inorganic (glass and metal) fractions and an effective conversion and control of formation of poly-chlorinated compounds.

Applications

Advanced waste treatment: for waste residuals with minimal source-separation and high degree of inert and hazardous contaminants.

Commercial technologies

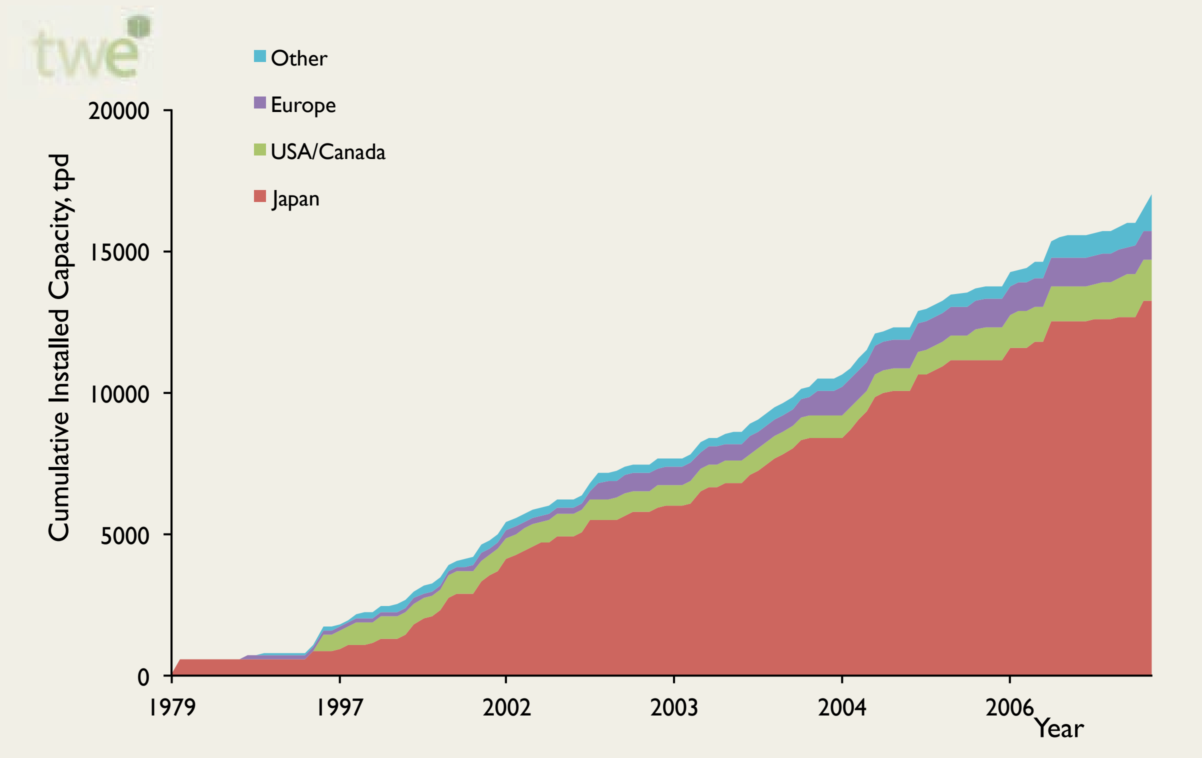
Commercial high temperature conversion + melting technologies include:

- the **PGVR** plasma gasification technology developed by **AlterNRG**;
- the **TFiG** fluid-bed gasification + melting technology developed by **Ebara/TwinRec** and operated at several commercial facilities in Japan;
- the **PEM** plasma gasification technology developed by **InEnTec**;
- the **R21** pyro-combustion+melting technology developed by **Mitsui**;
- the **DMS** gasification and melting technology developed by **Nippon Steel**;
- the **PGP** plasma gasification technology developed in Canada by **Plasco**;
- the **HTR** pyro-gasification + melting technology developed by **Thermoselect** and operated at commercial facilities in Europe and Japan;
- the **PKA** pyro-gasification + melting technology developed in Japan by **Toshiba**.

Commercial maturity

Worldwide installed capacity

Figure 15. Worldwide installed capacity, thermal conversion of waste



Waste management and environmental performances

Diversion from landfill

Diversion from landfill is the key objective of waste minimisation activities, it measures the percentage reduction in waste quantities delivered to landfill.

Waste quantities, and ultimately volumes, delivered to landfill reduce the residual lifetime of existing landfills, and increase pressure on territorial authorities to expand current facilities or develop new landfills, or both.

Diversion from landfill is thus a *system-level* performance parameter, providing a measure of the overall effectiveness of an integrated waste management system and can be tracked over time to measure the improvement of new waste management measures being adopted across the waste lifecycle, such as:

- reduction at source, through promotion of measures to reduce waste generated through improvement in resource use, re-use of materials and reduction in packaging waste;
- recycling of materials such as glass, metals and plastic separated from the waste stream at collection (kerbside recycling) or post collection at material recovery facilities (MRF);
- reduction of residual waste volumes sent to landfill through alternative waste treatment (AWT) technologies, such as mechanical-thermal treatment (autoclaves), mechanical-biological treatment (composting), biological treatment (anaerobic digestion) or thermal treatment (combustion) or thermo-chemical conversion.

Achievable volume diversion from landfill for alternative waste treatment technologies is thus a combination of two factors:

- the types (or fractions) of waste materials accepted by the specific AWT process;
- the impact those fractions or technology pre-processing demands on the levels of shredder residues; and
- the percentage reduction in waste quantities (or volumes) that are achieved through the process.

Often AWT technology manufacturers quote the second figure (a measure of volume reduction at the *process-level*) only as a proxy for the overall, *system-level*, percentage reduction in volumes sent to landfill.

Conversion performance

From the perspective of thermal (combustion) and thermo-chemical conversion (pyrolysis and gasification), two metrics are more commonly adopted to evaluate the performance of the conversion process:

- destruction and removal efficiency (DRE); and
- carbon conversion efficiency (CCE).

Destruction and removal efficiency

The destruction and removal efficiency (DRE) is a measure of performance commonly applied to hazardous waste incineration, to measure the combined effects of the combustion process (destruction) and of the air-pollution control systems (removal) in reducing the amount of hazardous materials (usually organic compounds) that are emitted to air as part of the system exhaust stream.

DRE focuses on destruction and removal of certain specified substances in the incoming waste stream, and can not be thus interpreted as a proxy of diversion from landfill.

In the US, the EPA prescribes that hazardous waste incineration systems operate at a DRE of 99.99% or higher for a number of hazardous compounds, referred to as principal hazardous organic constituents (PHOC).

Carbon conversion efficiency

In thermo-chemical conversion processes, such as pyrolysis and gasification, another parameter, the *carbon conversion efficiency* (CCE) is more commonly adopted as a measure of performance of the conversion process.

The CCE measures the amount of carbon converted by the process as the percent of carbon found in the raw synthesis gas, relative to the amount of volatile (eg, non-fixed) carbon in the incoming feed. CCE is defined as:

$$CCE = \left(1 - \frac{C_{residue}}{C_{feed}}\right) \cdot 100$$

Where:

- $C_{residue}$ is the amount of residual, unconverted carbon remaining in the process by-product streams (bottom and filter ash residues); and
- C_{feed} is the amount of carbon in the waste or biomass resource feedstock to the conversion process.

CCE increases rapidly with temperature, to reach values close to 100% for temperatures exceeding 800 °C. Several empirical formulas are available to correlate the carbon conversion efficiency to parameters such as the maximum conversion temperature in the process, the residence time at the maximum temperature, and the equivalence ratio (the amount of gasification air relative to the stoichiometric amount of air required for combustion).

CCE is a convenient measure to help estimate the gas production rate, or yield, as the amount of carbon converted in the gaseous constituents of the synthesis gas (CO, CO_2, CH_4 etc.) can be correlated to the amount of carbon and mass throughput of the feedstock stream.

Air pollutant emissions

Thermal conversion of waste and biomass materials might yield a wide array of air pollutants, including:

- *Particulate matter* (PM), from fly ash,
- *Acid gases*, like hydrogen chloride (HCl), hydrogen fluoride (HF) and Sulphur Dioxide (SO_2),
- *Heavy metals*, like mercury (Hg), lead (Pb), Zinc (Zn), etc. and their compounds,
- *Nitrogen oxides* (NO_x), and
- *Volatile organic compounds* (VOCs) including polychlorinated dibenzo-dioxins (PCDD, more commonly referred to as *dioxins*) and polychlorinated dibenzo-furans (PCDF, more commonly referred to as *furans*).

Air emission limits

Control of air emission from waste incineration (with and without energy recovery) and thermal treatment plants has been a major concern of regulators from the late 1970s particularly in regard to dioxins and furans, especially since the 1976 accident at an industrial facility in Seveso, Italy.

In Europe, air emission limits are set out in the *Waste Incineration* Directive (2000/76/EC) are the most stringent of all emission regulations applicable to industrial combustion processes, with regulations of similar stringency being in force in the US and Japan.

In order to consistently eliminate the effects of dilution on pollutant emissions, the different standards prescribe pollutant concentrations in flue gases to be reported on a dry-basis and on the basis of a standard oxygen concentration.

Different concentration limits apply for sampling at different time intervals, with standards and operating permits prescribing typically daily and half-hourly average values. The daily average concentration limits currently in force in Europe, the US and Japan are reported in the Table in the table below.

Table 2. Emission limits in Europe, Japan and the US

Specie	Unit	Europe 2000/76/EC	Japan Japan	US US-EPA
Oxygen (O_2), reporting basis	%vol	11	12	7
Particulate matter (PM)	mg/Nm^3	10	10-50	24
Hydrogen Chloride (HCl)	mg/Nm^3	10	15-50	25
Hydrogen Fluoride (HF)	mg/Nm^3	1		
Sulphur Dioxide (SO_2)	mg/Nm^3	50	10-30	30
Nitrogen Oxides (NO_x)	mg/Nm^3	200	30-125	150
Carbon Monoxide (CO)	mg/Nm^3	50	50	100
Mercury (Hg)	mg/Nm^3	0.05	0.03-0.05	0.03-0.05
Cadmium (Cd) + Thallium (Tl)	mg/Nm^3	0.05		0.02
Other[a]	mg/Nm^3	0.5		
TOC	mg/Nm^3	10		
Dioxins/Furans (PCDD/PCDF)	$ng_{I\text{-}TEQ}/Nm^3$	0.1	0.5	0.14-0.21

[a] Sb, As, Pb, Cr, Co, Cu, Mn, Ni, V

Concentration values for the dioxin and furan families (also referred to as PCDD/PCDF) are expressed on the basis of the *International Toxicity Equivalence factor* (I-TEQ), reporting the toxicity of the different species in terms of its equivalence to the most toxic of these compounds, tetrachlorodibenzo-dioxin (TCDD or 2,3,7,8 dioxin).

Emission performances of conversion technologies

As discussed earlier, conversion technologies have the key advantage of offering the opportunity to perform an intermediate gas clean-up step for the removal of air pollutants and toxic compounds prior to combustion.

This strategy, not always adopted by conversion technology developers, has clear implications in terms of the compactness and reduced cost of APC systems, but also allows EfW plants based on conversion technology to operate safely and reliably well within the emission limits set in the current set of regulations.

While regulation in the US, Japan and more notably in the EU, with the recent evolution of the *large-scale combustion* and *waste* directives, provide now an integrated regulatory framework for allowed emission limits from both traditional power plants, industrial combustion facilities and incineration-based waste-to-energy technologies, conversion technologies operate still in a sort of *regulatory vacuum*.

In the absence of emission regulations specifically designed for conversion technologies, these are subject to the stringent emission limits and practices associated with incineration-based, waste-to-energy technologies, while in reality having the inherent potential to yield even lower emission levels when intermediate syngas cleanup and upgrading is adopted, comparable (if not superior) to the emission performances of natural gas based traditional power plants.

Moreover, the regulatory frameworks still do not detail practices specific to the integration of conversion schemes for the purpose of upgraded fuel production, to be delivered and used off-site, rather than the traditional, on-site energy recovery.

A survey of emission performances from operating commercial conversion facilities (presented in Appendix C – *Cost, Performance and Emissions Survey*) has revealed a comfortable operation of these plants within the relevant emission limits.

The results, normalized to the reference oxygen concentration of 11 vol% (as per EU regulations) are reported in the Table below.

Table 3. Emission performance survey

	PM	HCl	NO_x	SO_x	Hg	PCDD/PCDF
	mg/Nm^3 @ 11% O_2					$ng_{I\text{-}TEQ}$/Nm^3
European Standard	10	10	200	50	0.05	0.1
Japanese Standard	10.1-50.6	15.2-50.6	30.3-126.4	10.1-30.3	0.03-0.051	0.51
US Standard	24.3	25.3	151.7	30.3	0.03-0.051	0.14-0.21
Plant						
Ebara TwinRec - Kawaguchi, JAPAN	1.34	2.68	39.24	3.83	6.70E-03	6.89E-05
Entech - Kuznica, POLAND	0.94	7.56	243.08	49.67	7.66E-03	2.68E-02
InEnTec - Richland, WA, USA	3.16	2.58	155.03	-	6.41E-04	6.41E-03
INEOS Bio - Fayetteville, AK, USA	1.91	-	9.57	-	9.57E-05	2.87E-03
IES - Romoland, CA, USA	5.5	-	123.45	0.42	-	5.56E-04
JFE/Thermoselect - Nagasaki JAPA	4.5	11.1	-	-	-	2.39E-02
Mitsui R21 - Toyohashi, JAPAN	0.96	53.4	79.24	24.79	-	4.31E-03
Nippon Steel DMS - Kazusa, JAPAN	13.49	11.96	29.86	20.96	-	4.31E-02
Plasco - Ottowa, CANADA	12.25	2.97	143.55	24.88	1.91E-04	1.55E-02
OE Gasification - Heanam, KOREA	8.23	26.22	100.48	35.89	6.70E-04	5.37E-02
OE Gasification - Bosung, KOREA	7.18	24.21	56.46	17.9	6.70E-04	9.41E-02
OE Gasification - Pyungshan, KORI	10.81	20.19	73.88	39.33	6.70E-04	2.69E-02
OE Gasification - Hapchon, KORE	8.09	22.2	80.58	28.61	6.70E-04	5.38E-02

SOURCE: (CERT 2009), values adapted to 11% O_2

In Australia, where emission regulations are defined at the State level, the recent policy statement on energy from waste has indicated the intention for New South Wales to adopt EU Waste Incineration Directive standards (NSW EPA 2013). Similar provisions have been recommended for Western Australia (WA EPA 2013).

Energy and material recovery performances

High-level mass and energy balances

High–level mass and energy balances for three reference technologies have been provided here to highlight the following sets of energy and material recovery performances associated with thermo-chemical conversion technologies reviewed as part of this study, including:

- the **mass reduction rate**, a measure of material recovery performance measuring the amount of feedstock material converted to energy and/or recoverable by-products; and
- the technology **cold gas efficiency (CGE)**, a measure of energy recovery efficiency measuring the ratio of the energy in the syngas exiting the reactor, to the energy inputs (feedstock and auxiliary fuels).

The results presented here have been derived from available literature data to reflect the performances of the core conversion reactor (e.g. ahead of energy recovery) for three reference technologies:

- **Low-Temperature Conversion:** the **APS** pyro-combustion technology developed in California by **International Environmental Solutions**;
- **High-Temperature Conversion:** the **Termiska AB** fluid-bed gasification technology developed by **TPS**; and
- **High-Temperature Conversion + Melting:** the **PGVR** plasma gasification technology developed by **AlterNRG.**

Low-Temperature Conversion

Table 4. Low-Temperature Conversion, representative mass balance for pyro-combustion

INPUTS	Consumption		OUTPUTS	Yield	
Stream/component	kg/h	kg/t$_{feed}$	Stream/component	kg/h	kg/t$_{feed}$
TOTAL INPUTS	4725.20	1000.00	TOTAL OUTPUTS	4725.20	1000.00
Feedstocks @ 20% moisture			Products		
post MRF MSW	4725.20	1000.00	Pyro-gas	2988.96	632.56
			Recoverable by-products		
			Water	945.04	200.00
			Residues		
			Char	567.00	119.99
			Cyclone Ash	175.80	37.20
			Baghouse Ash	48.40	10.24
			CONVERSION and RECOVERY PERFORMANCES		
			Total By-products	945.04	200.00
			Total Residues	791.20	167.44
			MASS REDUCTION (solids)		83.26%

SOURCE: (Wood 2007)

Table 5. Low-Temperature Conversion, representative energy balance for pyro-combustion

INPUTS			OUTPUTS		
Stream	GJ/t$_{feed}$	MW	Stream	GJ/t$_{feed}$	MW
TOTAL INPUTS	13.74	18.03	TOTAL OUTPUTS	13.74	18.03
Feedstocks			Syngas	7.83	10.3
MSW	12.30	16.1			
			Residues		
Fuels			Char solids	5.10	6.7
Natural gas	1.44	1.9			
			Losses		
			Heat losses	0.81	1.06
			ENERGY RECOVERY PERFORMANCES		
			Syngas energy, @ ambient temperature		10.27
			THERMAL EFFICIENCY, HHV basis		94.13%
			COLD GAS EFFICIENCY, HHV basis		56.97%

SOURCE: (Wood 2007)

High-Temperature Conversion

Table 6. High-Temperature Conversion, representative mass balance for fluidized-bed gasification

INPUTS	Consumption		OUTPUTS	Yield	
Stream/component	kg/h	kg/t_{feed}	Stream/component	kg/h	kg/t_{feed}
TOTAL INPUTS	4366.40	1047.94	TOTAL OUTPUTS	3681.25	883.50
Feedstocks			Products		
RDF	4166.67	1000.00	Syngas	3681.25	883.50
Oxidant			Residues		
Air	199.73	47.94	Char	951.25	228.3
Oxygen	--	--	Ash	63.25	15.18
Steam	--	--			
			CONVERSION and RECOVERY PERFORMANCES		
			Total By-products	0.00	0.00
			Total Residues	1014.50	243.48
			MASS REDUCTION (solids)		75.65%

SOURCE: (Granatstein 2003)

Table 7. High-Temperature Conversion, representative energy balance for fluidized-bed gasification

INPUTS			OUTPUTS		
Stream/component	GJ/t_{feed}	MW	Stream	GJ/t_{feed}	MW
TOTAL INPUTS	19.36	22.41	TOTAL OUTPUTS	19.36	22.41
Feedstock - RDF			Syngas	11.67	13.51
RDF	17.20	19.91			
			Heat losses	7.69	8.90
Fuels					
Natural gas	2.16	2.50			
Electricity					
BoP, kWh/t_{feed}	195.79	0.82			
			ENERGY RECOVERY PERFORMANCES		
			Syngas energy, @ ambient temperature		10.27
			THERMAL EFFICIENCY, HHV basis		94.13%
			COLD GAS EFFICIENCY, HHV basis		60.30%

SOURCE: (Granatstein 2003)

High-Temperature Conversion + Melting

Table 8. High-Temperature Conversion + Melting, representative mass balance for plasma gasification

INPUTS	Consumption		OUTPUTS	Yield	
Stream/component	kg/h	kg/t_{feed}	Stream/component	kg/h	kg/t_{feed}
TOTAL INPUTS	48223.00	1543.14	TOTAL OUTPUTS	48223.00	1543.14
Feedstocks			Products		
MSW	29583.00	946.66	Syngas	37629.00	1204.13
Tyres	1667.00	53.34			
			Recoverable by-products		
Additives			Aggregate (slag and metal)	9550.00	305.60
Coke	1250.00	40.00			
Limestone	3209.00	102.69	Residues		
			Char solids	142.60	4.56
Oxidant			Other residues	901.40	28.84
Air	2345.00	75.04			
Oxygen	10169.00	325.41			
Steam	--	--			
			CONVERSION and RECOVERY PERFORMANCES		
			Total By-products	9550.00	305.60
			Total Residues	1044.00	33.41
			MASS REDUCTION (solids)	96.66%	0.03

SOURCE: (Willis *et al*. 2010)

Table 9. High-Temperature Conversion + melting, representative energy balance for plasma gasification

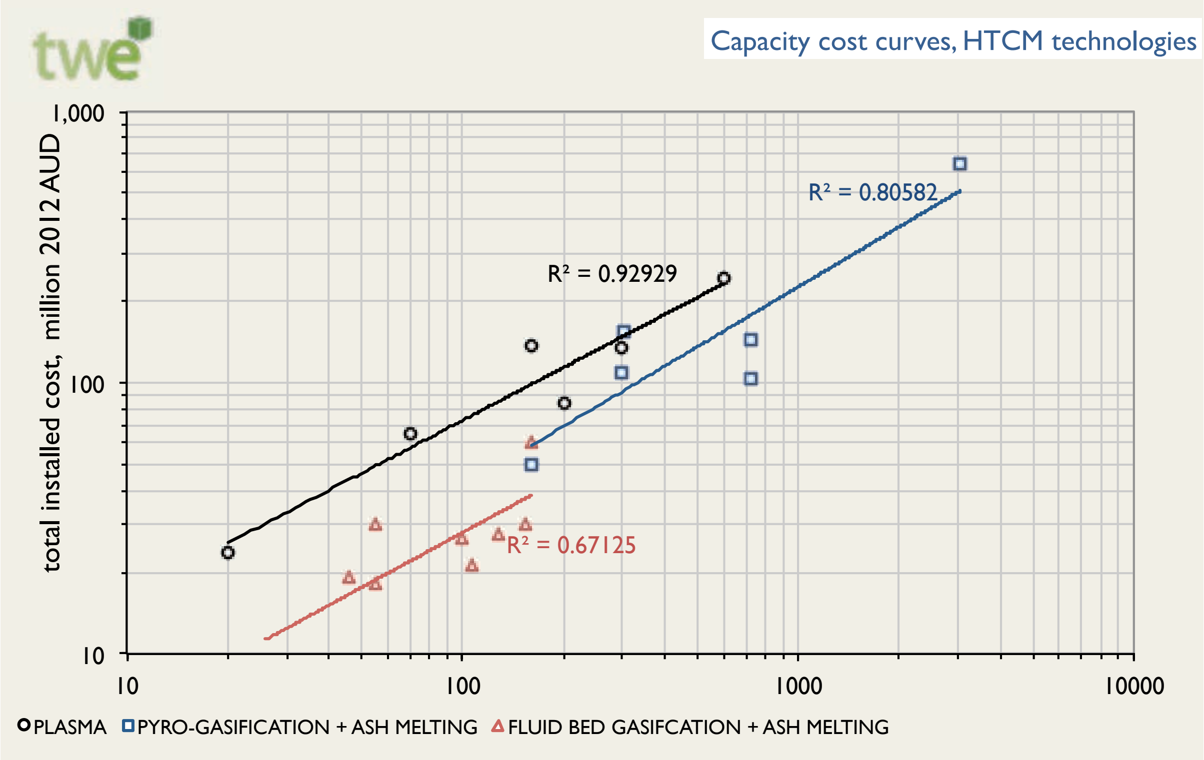
INPUTS			OUTPUTS		
Stream/component	GJ/t_{feed}	MW	Stream	GJ/t_{feed}	MW
TOTAL INPUTS	15.15	119.24	TOTAL OUTPUTS	15.15	119.24
Feedstocks			Syngas		
MSW	12.31	101.13	Energy content	9.83	80.30
Tyres	1.67	0.77	Sensible heat	1.79	15.54
			Latent heat	0.49	4.22
Additives					
Coke	1.18	10.20	By-products		
Limestone	--	--	Slag	0.60	5.17
Electricity			Residues		
Plasma torch, kWh/t_{feed}	102.94	3.22	Char solids	0.15	1.30
Oxygen facility, kWh/t_{feed}	125.52	3.92	Other residues		
			Losses		
			Heat losses	1.35	4.50
			Plasma torch losses	0.06	0.48
			Limestone calcination	0.13	1.10
			Other losses	0.76	6.63
			ENERGY RECOVERY PERFORMANCES		
			Syngas energy, @ ambient temperature		80.30
			THERMAL EFFICIENCY, HHV basis		94.90%
			COLD GAS EFFICIENCY,HHV basis		67.34%

SOURCE: (Willis *et al*. 2010)

Costs

The diagram below presents capacity cost curves for HTCM technologies derived from capital cost figures reported in Appendix B. Performances, Costs, and Emissions Survey.

Figure 16. HTCM technologies, capacity cost curves



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SECTION 2. SYNTHESIS GAS UTILIZATION, UPGRADING AND DELIVERY

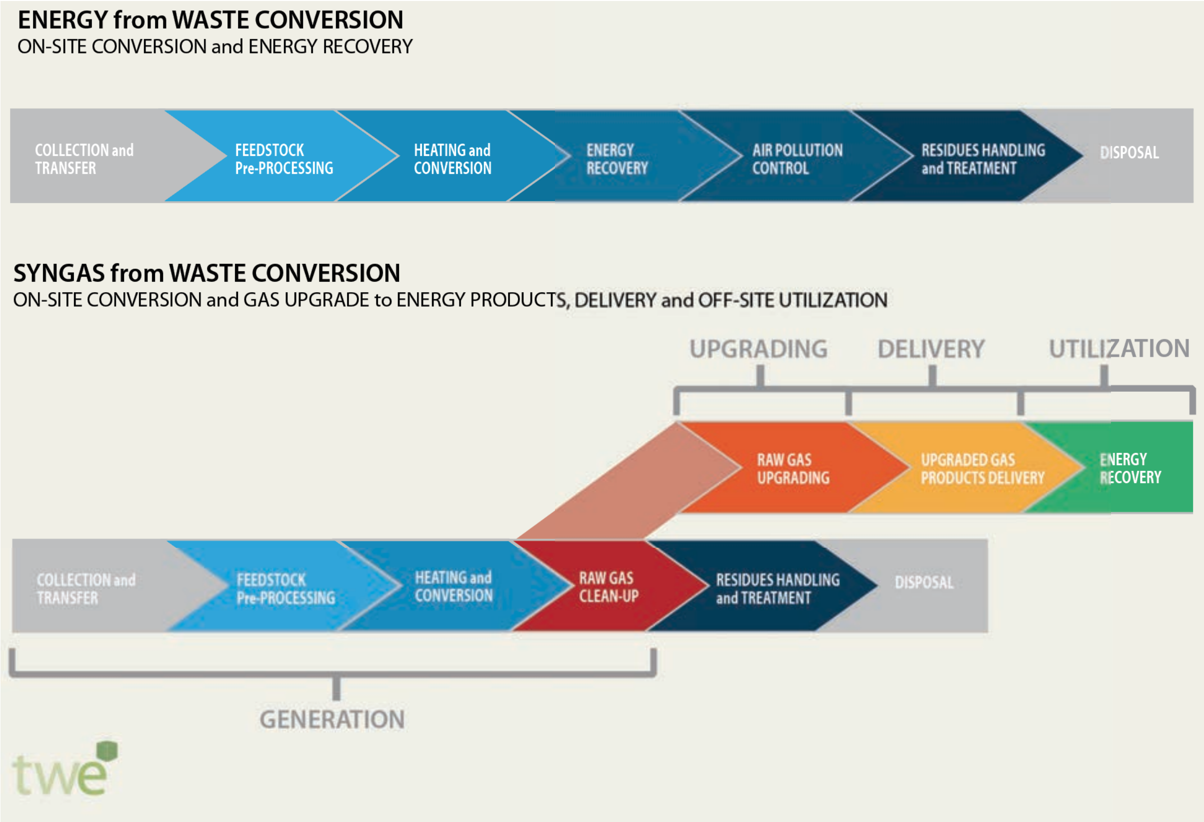
Pictured: Syngas cleaning at Kymijärvi II gasification facility, Lahti, Finland.
Credits: Metso Power, 2012

Overview

The generation of intermediate gaseous fuels from residual waste and biomass resources enables the adoption of advanced energy recovery schemes, where the gases can be cleaned and/or upgraded to meet quality requirements for several applications, including power and heat generation, transport and as a feedstock to industrial chemical processes.

This enables a novel platform of waste to energy recovery schemes, or *pathways*, where the key operations of conversion and end-use energy recovery are effectively de-coupled, we refer to them as *syngas from waste* (SfW) pathways, to differentiate from traditional energy from waste schemes with on-site conversion and energy recovery.

Figure 17. Traditional energy from waste schemes and syngas from waste conversion and energy recovery



Throughout the remainder of this study, we adopt a *pathway-based* perspective, organizing operations along the syngas from waste supply chain into three major pathway steps:

- **generation** including (waste and biomass) resource harvesting, collection and transfer, (thermo-chemical or biological) conversion;
- **upgrading and delivery** including raw syngas clean-up and upgrade, handling, transport and distribution of upgraded syngas products; and
- **utilization** for end-use energy recovery.

Synthesis gas utilization

Raw synthesis gases generated from thermo-chemical conversion and renewable gases from waste and biomass resources can be utilized in various ways:

- **direct use of raw gas** as a fuel in industrial kilns and steam generators (industrial or power plant boilers),
- **clean-up and use** as a fuel in advanced energy conversion equipment, such as gas engines, gas turbines and fuel cells,
- **clean-up and upgrade**, including substitute natural gas (SNG), hydrogen or methanol.

Direct use of raw syngas

Raw syngas from thermo-chemical conversion processes can be used directly as a fuel to generate process heat in industrial kilns (eg. cement kilns), steam and/or power in industrial or power plant boilers. This utilization pathway presents minimal gas clean-up requirements, mainly:

- primary cleaning, such as by cyclone separators, for removal of particulates, and
- tar conversion and scrubbing, in order to avoid fouling and corrosion of the burners.

This last step however can be avoided if the gas stream is kept at temperatures above 500 °C before injection in the burners.

The majority of the commercially operated gasifiers supply gas for such thermal purposes. Among these, the plant at Rudersdorf, Germany, with a thermal output of 100MW, is the largest at present. The combustion of a gas instead of solid biomass simplifies the combustion process in the steam generator or the lime kiln (Rdersdorf) and reduces ash-related restrictions. However there is no gain in efficiency over direct firing of biomass.

Clean-up and use of clean syngas

Gas engines

Engines with capacities between 50kWe and 10MWe are suitable for use in connection with atmospheric fixed bed or fluidised bed gasifiers.

With syngas use in engines, the power rating of gas engine generators is usually lower than for natural gas use due to the lower volumetric energy density of synthesis gas fuels. The generation efficiency varies between 35% and 40%, although by including waste heat utilisation, for cogeneration or trigeneration the overall efficiency can be higher. Smaller plants yield lower efficiencies of up to about 25-30%. These efficiencies are somewhat above those that can be achieved by steam turbines in this capacity range. Turbo-charged engines require an even higher gas quality for operation.

Gas turbines

From a capacity of about 5MW$_e$, gas turbines are the better technology. The gasifiers suitable for use in connection with such turbines are atmospheric or pressurized fluidised bed reactors. With gas turbines, it is possible to increase the efficiency up to 45-48%% by installing a tailing waste-heat boiler with a further steam turbine (capacities > 25MW$_e$).

Only a few integrated gasification processes using gas turbines have been demonstrated, so experience with such plants is limited. In Vaernamo, Sweden, a pressurized fluidised bed furnace with an electrical output of 6 MW$_e$ was in service from 1993 to 2000. An atmospheric bubbling fluidised bed using the TPS (Termiska Processor AB) system, with an electric output of 8MW$_e$, was put into service in 2000 (ARBRE Project, Great Britain). Both systems are now out of service due to economic reasons.

Fuel cells

Fuel cells are electrochemical devices operating a direct conversion of the chemical energy of a fuel into direct current (DC) power.

The current produced by a cell is a function of the rate of supply of fuel and the efficiency of the energy conversion within the cell. Energy that is not converted into electricity appears in the form of heat. This can be captured from the gaseous exhaust streams from the fuel cell or by a separate cooling fluid.

A fuel cell system comprises several sub-systems, broadly:

(a) A fuel processor which is a series of reactors that are used to convert a readily available fuel (e.g. natural gas, or bio-gas) into a hydrogen-rich gas for the fuel cell stack,

(b) A fuel cell stack that produces DC power and heat, and

(c) A power-conditioner/inverter for converting the raw DC from the stack into useful AC electricity.

Invariably the sub-systems are closely integrated and the challenge for developers over the years has been to ensure that this integration is carried out in such a way that energy loss from the system is minimized (i.e. that the conversion of energy from the fuel into power is achieved with a high efficiency), and that the total cost is kept low enough to ensure that the system is commercially viable. Much engineering expertise is therefore focused not just on the design of the fuel cell stack but the other "balance of plant" components in the system.

Industrial uses of synthesis gases

Synthesis gases are used extensively in a range of industrial applications: As raw feedstocks for the production or synthesis of various products in the chemical industry and as reducing or treatment agents in metal manufacturing processes. The major industrial uses of synthesis gases include (Häring, *Ed.* 2008):

- Synthesis of methanol;
- Synthesis of ammonia (by synthesis of N_2 and H_2).
- Production of synthetic hydrocarbons and fuels (Fischer–Tropsch synthesis)
- Formation of aldehydes and alcohols from olefins (oxosynthesis)
- Reduction gas for the production of metals from oxides or ores (in special furnaces)
- Heat treatment gas for neutral annealing or carbonisation of iron and steel (e.g. on site production in gas generators starting from hydrocarbons or by cracking of CH_3OH).

Syngas clean-up and upgrading

Syngas cleaning technologies

Syngas cleaning refers to the processing steps adopted to bring the raw synthesis gas mixture from the gasification reactor to the desired composition and purity required by the different applications.

Selection criteria

Water-Gas shift reactors

This processing step is commonly adopted to increase the hydrogen-to-carbon-monoxide (H_2/CO) ratio in the synthesis gas, according to the *water-gas shift* reaction:

Based on the temperature range, a distinction is made between high-, medium- and low-temperature shift (HTS/MTS/LTS) reactors. Typically, a combination of medium- to high-temperature (higher reaction rates) and low-temperature shift reactors (lowest residual CO) are employed based on the catalyst reaction rates and the dew point of the synthesis gas.

Removal of Carbon Dioxide and Acid Gases

Usually, carbon dioxide and acid sulphuric components like H_2S and COS are removed using chemical or physical scrubbing processes. More typically in sulphur-containing synthesis gases (such as those from the gasification of coals, waste or heavy oils) chemical scrubbing can be adopted, integrated with sulphur-tolerant catalyst.

Syngas upgrading options

Substitute Natural Gas (SNG)

One emerging application for synthesis gases is the generation of substitute natural gas (SNG), compatible with pipeline and engine/turbine specifications.

SNG as a syngas upgrade pathway presents the key following advantages:

1. Accepts a wide range of synthesis and renewable gases (e.g. biogas),
2. Generates an energy carrier compatible with existing infrastructure and technology.

Substitute Natural Gas is produced through the *methanation* process, where carbon oxides (CO, CO_2) and hydrogen react to form methane according to the following reactions:

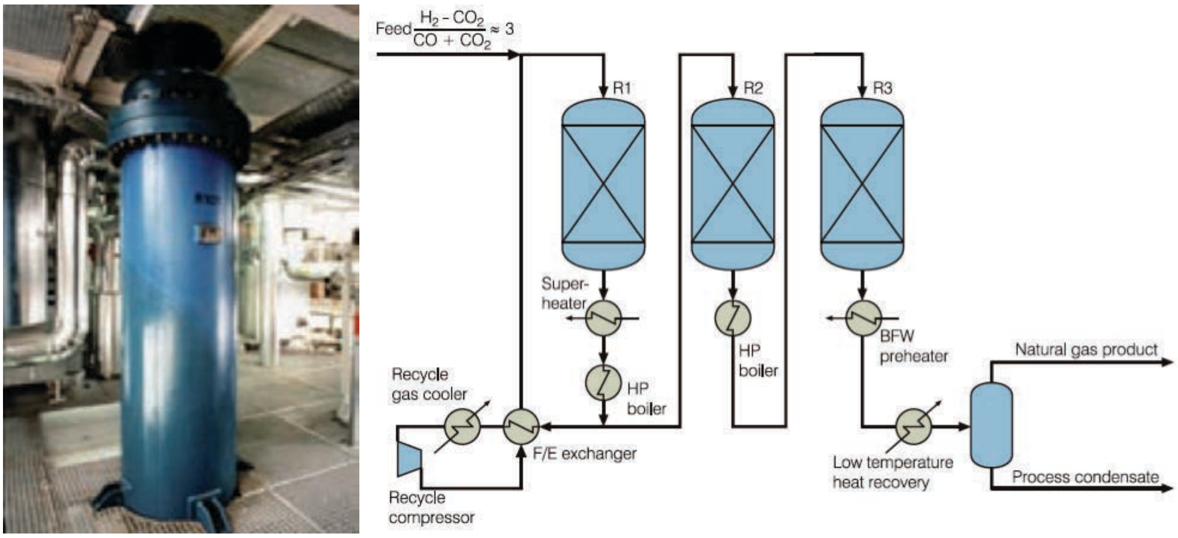
$$CO + 3H_2 \leftrightarrow CH_4 + H_2O$$

$$CO_2 + 4H_2 \leftrightarrow CH_4 + 2H_2O \tag{3}$$

Near stoichiometric amounts of hydrogen, carbon monoxide and carbon dioxide downstream of water-gas shift reactors are combined to yield a natural gas product compatible with pipeline specifications. Both reactions are highly exothermic, and industrial methanation technology recovers about 20-22% of the heating value of the synthesis gas in the form of high-pressure, high-temperature steam.

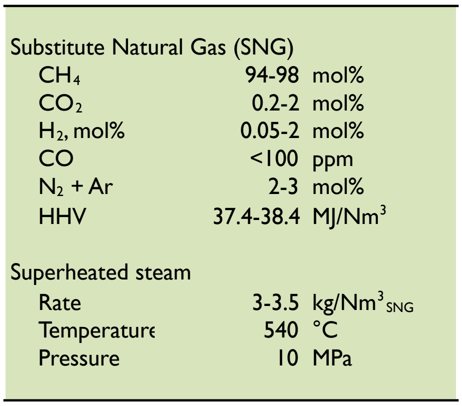
One example of industrial methanation technology is the Haldor-Topsøe TREMP™ process. A 200 Nm^3/h unit, and a schematic of the process are shown in the figure below.

Figure 18. Haldor-Topsoe TREMP™ SNG process.



In the TREMP™ process, close to 85% of the heat released by the methanation reactions is recovered in the form of superheated steam. Typical SNG and steam specifications are reported below.

Table 10. Typical product specification for TREMP™ SNG process



Substitute Natural Gas (SNG)		
CH_4	94-98	mol%
CO_2	0.2-2	mol%
H_2, mol%	0.05-2	mol%
CO	<100	ppm
N_2 + Ar	2-3	mol%
HHV	37.4-38.4	MJ/Nm^3
Superheated steam		
Rate	3-3.5	$kg/Nm^3{}_{SNG}$
Temperature	540	°C
Pressure	10	MPa

SOURCE: (Haldor Topsøe 2009)

This steam could be used upstream to support the gasification process, or for electricity generation in a steam turbine generator (STG) assembly.

Hydrogen

Hydrogen generation from raw synthesis gases is common industrial practice, and represents the biggest source of industrial hydrogen in Australia, sourced from the Bulwer Island Refinery in Queensland and Kwinana Refinery in Western Australia, where the hydrogen is recovered from reforming of naphtha, visbreaker and other heavy fraction of the main distillation process, and the raw synthesis gas (mostly H_2 and CO) is first treated in a series of *water-gas conversion shift* (WGS)reactors (for conversion of CO, into CO_2 and further H_2) and then brought to the desired level of purity through a pressure swing adsorption (PSA) reactor assembly.

With biomass- or waste- derived syngas, the reforming reactor is replaced by the gasification reactor, where as the downstream steps of upgrading and purification are based on the same technology platform (WGS for upgrading and PSA for purification).

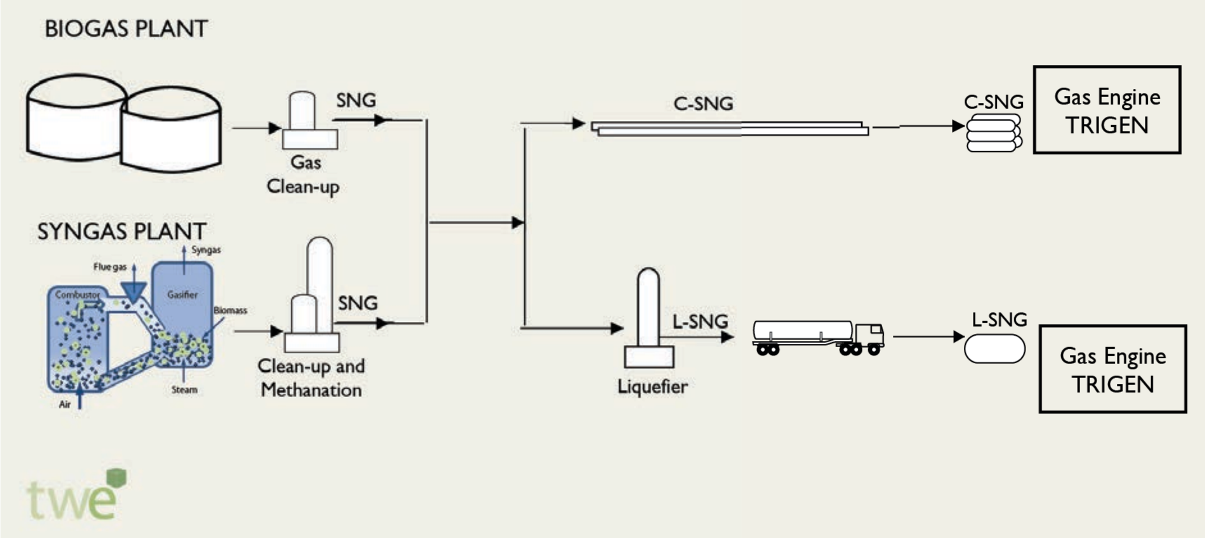
Renewable gas delivery

SNG delivery pathways

Two families of delivery pathways are considered in this overview:

- **gaseous SNG delivery**, with cleaning and upgrading of raw syngas to substitute natural gas and delivery via existing pipelines, and
- **liquid SNG (LSNG) delivery**, with cleaning and upgrading of raw syngas to substitute natural gas, liquefaction and delivery via tanker trucks.

Figure 19. Substitute Natural Gas delivery pathways



Small-scale LNG infrastructures

The development of small-scale liquefied natural gas (LNG) technologies in recent years has brought forward a number of gas delivery applications of particular interest to the scope of work being undertaken by City of Sydney under the Renewable Energy and Trigeneration Master Plans.

The technologies, originally developed with a focus on dedicated fleet refueling for heavy duty transport applications are also well-suited to ‘virtual pipeline’ appications, where road or rail hauling of LNG tanks can overcome the absence of pipeline infrastructure to deliver natural gas to sparse, remote users, or provide a convenient and effective means of delivery for substitute natural gas (SNG) from biogas and synthesis gases in situations where local regulations do not allow injection in the existing pipeline networks.

We review here two small-scale LNG projects, recently completed in Australia by BOC and Energy Developments Limited (EDL).

BOC micro-LNG plant – Westbury, Tasmania

The 50 tpd liquefied natural gas (LNG) plant developed by BOC, the local subsidiary of the Linde Group, in Westbury, Tasmania the first micro-LNG system to operate in Australia.

Figure 20. The BOC micro-LNG plant in Westbury, Tasmania.

The plant, approved by the local, Meander Valley Council, and the Tasmania Environmental Protection Agency (EPA) in July 2009 has been commissioned in February 2011.

The 150 mAUD project was developed with 5 mAUD financial support from the State and Federal Governments represents the Tasmanian component of a proposed LNG haulage highway planned for the Eastern seaboard (RET 2011). The cost of the project is inclusive of six LNG fuelling stations in Tasmania, featuring a state-of-the-art filling system based on BOC/Linde's *Cryostar* technology.

The LNG is supplied by BOC to LNG Refuellers, a consortium of seven transport and haulage companies, operating 125 natural gas powered heavy-duty trucks in Tasmania.

The micro-LNG plant will process 19,720 tpy of natural gas, and is expected to require 13,000 MWh/y of electricity, or ~650 kWh_e per tonne of natural gas processed.

EDL virtual pipeline – Karratha, Western Australia

The Australian firm Energy Development Limited (EDL, also cited in regard to the SWERF technology) has worked with specialized LNG engineering firm Salof/Kryopak to design, build, and commission an LNG facility in Karratha, Western Australia, as part of the West Kimberley Power Project (WKPP).

Figure 21. EDL virtual pipeline facility: LNG storage tanks (left) and cold box unit (right).

The plant uses a process similar to the one described for the BOC plant, with the exception that the refrigerant used in the cold-box exchangers is the proprietary ammonia-based Kryopak Pre-Cooled Mixed Refrigerant Cycle (PCMR).

The 300,000 Nm^3 liquefaction facility has an LNG production capacity of 200 tpd and covers an area of 3.65 Ha. Natural Gas is sourced from the Dampier to Bunbury pipeline, power requirements for the liquefaction plant and auxiliaries are met by means of an on-site gas turbine generation plant with three units.

The LNG is stored on-site in six 150,000 m^3 storage tanks and delivered via road-train at distances up to 2000 km to the towns of Broome, Derby, Halls Creek, Fitzroy Crossing and Looma in the booming Kimberley region of Western Australia.

Other delivery pathways

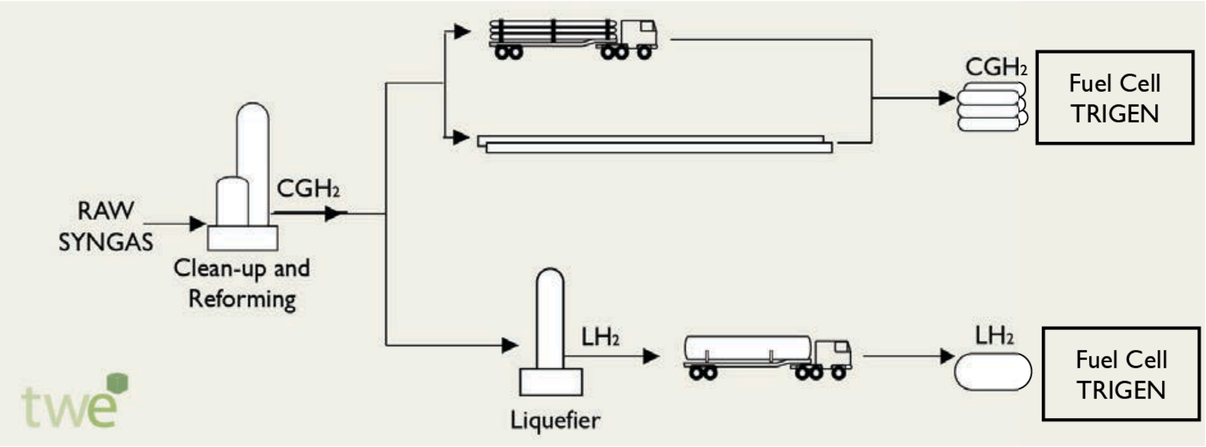
Hydrogen-based pathways

Fuel-cells are considered in the Trigeneration Master Plan as a future technology option, to replace the engines as the thermal source for the combined cooling, heating and power (CCHP) scheme.

Two families of delivery pathways are considered in this overview:

- **gaseous hydrogen (CGH2) delivery**, with cleaning and upgrading of raw syngas to pure hydrogen, its compression and delivery via tube-trailer trucks (CGH2-T) or pipelines (CGH2-P), and
- **liquid hydrogen (LH2) delivery**, with cleaning and upgrading of raw syngas to pure hydrogen, its liquefaction and delivery via tanker trucks (LH2-T).

Figure 22. Hydrogen delivery pathways

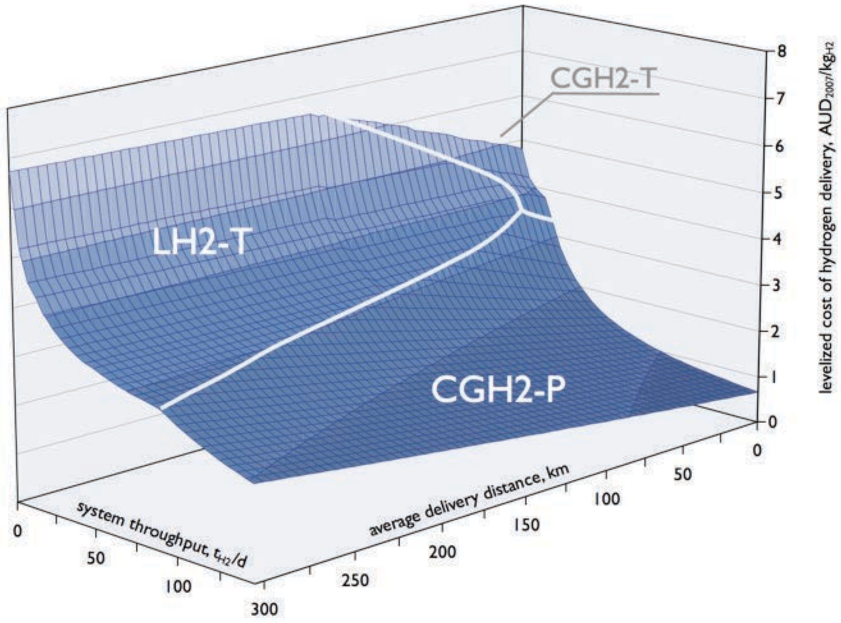


The liquid and gas paths transport pure hydrogen in its molecular form (H_2) via truck, pipeline, rail, or ship/barge. Liquid or gaseous truck and gas pipelines are the primary methods by which industrial hydrogen is delivered today.

An analysis of the least-cost landscape for point-to-point transmission of hydrogen in centralized delivery pathways, was developed recently in (Pigneri and Nolan 2009).

This analysis covered the complex of systems and operations for processing and handling and transport delivery steps. The results of this analysis are summarized by the graph below.

Figure 23. Hydrogen transmission: least-cost delivery as a function of system throughput and distance[15]



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[15] Reproduced from (Pigneri and Nolan 2009), Figure 38., p.146.

SECTION 3. FEEDSTOCK RESOURCES

Pictured: Waste containers in Sydney before New Year's Eve.
Credits: Maroual, 2009.

City of Sydney LGA

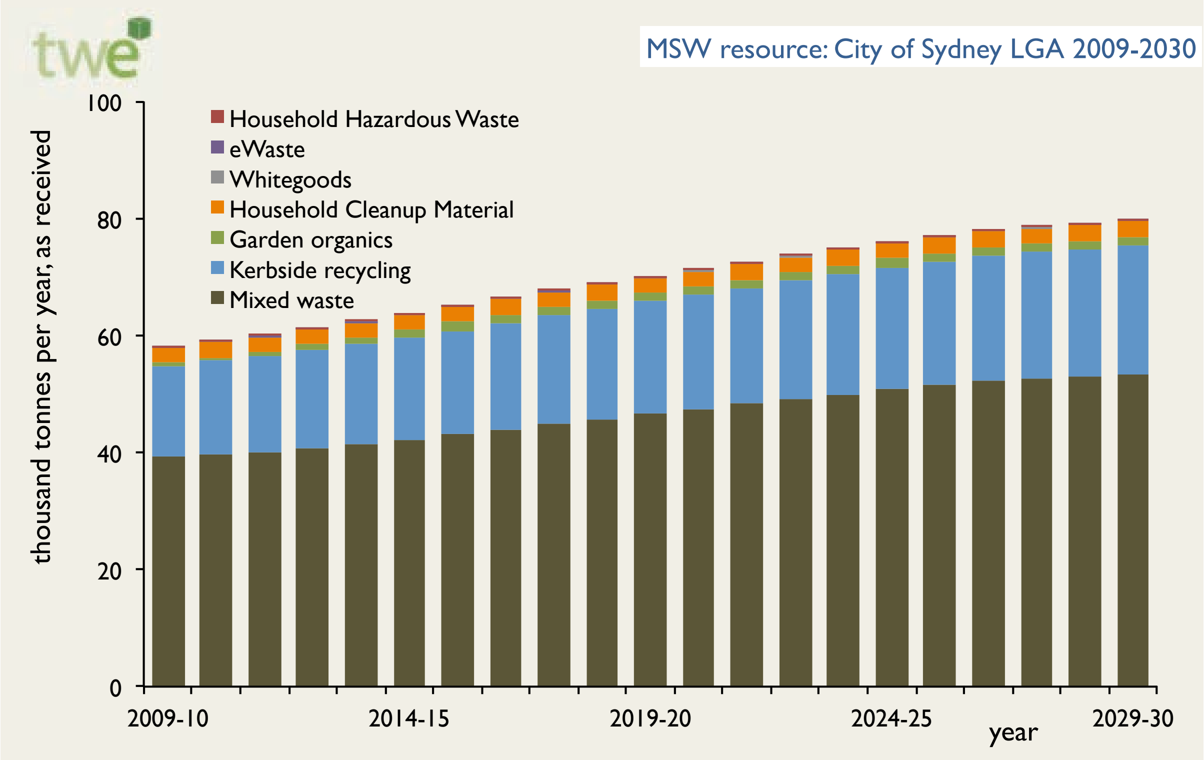
Domestic waste

Waste collection

The diagram below illustrates current and projected quantities of domestic waste generated within the City of Sydney LGA, broken down by collection method.

In 2010-11, the total amount of waste collected from domestic customers was 59,121.2 t, a quantity projected by City of Sydney to increase to just below 80,000 t in 2029-30. At 67% of total waste collected in 2010-11, mixed waste represents the largest fraction of the domestic waste stream, followed by kerbside recycling, accounting for 27% of the total collected in the same year.

Figure 24. Domestic waste quantities collected, City of Sydney LGA, 2009-30.

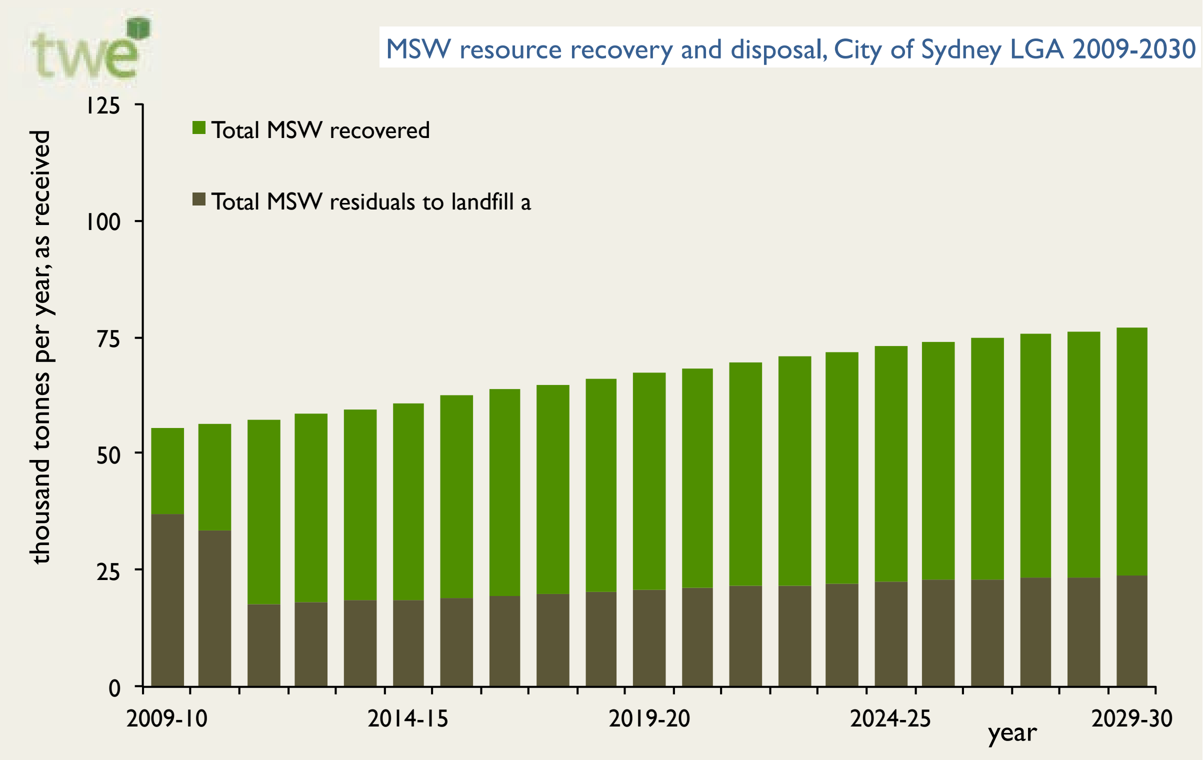


Recovery, treatment and disposal

Resource recovery within the City LGA has been historically limited to source-separated materials (kerbside recycling and garden organics), accounting for a resource recovery rate of 24.95% in 2008-09. This figure increased to 49.05% in 2010-11 through diversion of 20,437 t of domestic waste to the ArrowBio Alternative Waste Treatment (AWT) facility operated by WSN Environmental Solutions at Jacks Gully, near Camden.

From 2011-12 onwards, domestic waste residuals have been diverted to another AWT facility operated by SITA Environmental Solutions, as a transitional measure prior to final decisions on the City's own SfW processing solution.

Figure 25. Domestic waste – resource recovery and disposal, City of Sydney LGA, 2009-30.



This transitional arrangement allows for about 98% of mixed waste collected to be diverted to the SITA AWT facility. With about 40,000 t to be diverted in 2011-12, the resource recovery rate increased to 66%, meeting the state-wide target set by the NSW Government two years ahead of the target year of 2014.

The SITA facility has a waste processing efficiency of over 50%, with the remainder of the diverted material to be returned to landfill as AWT residual.

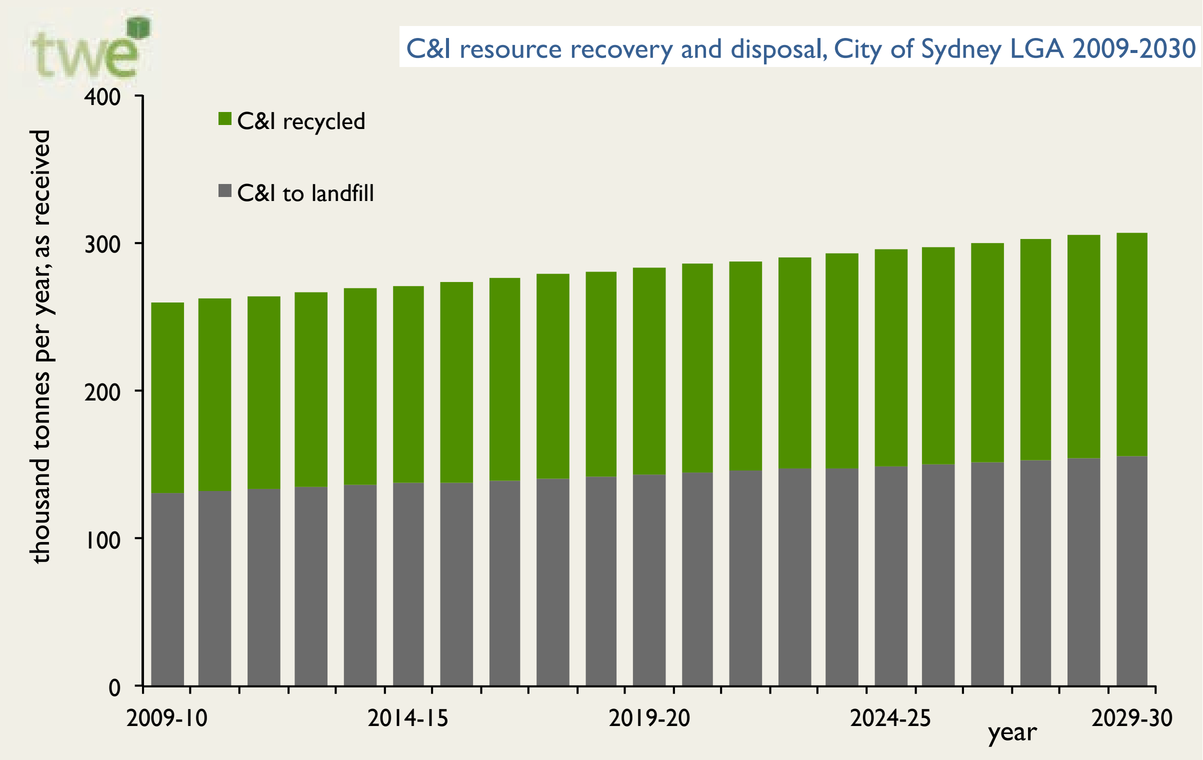
Commercial and Industrial Waste

Management services for Commercial and Industrial (C&I) wastes generated across the Sydney region are provided through private contractors.

In a disposal-based survey conducted in 2008, the NSW Department of Environment, Climate Change and Water (DECCW) estimated the fraction of C&I waste collected within the City of Sydney LGA at 7% of total collected across the Sydney metropolitan area (DECCW 2010). Resource recovery rates were estimated by the same source at 42% in that year.

Based on these figures and projections developed by Hyder Consulting for the City of Sydney (Hyder Consulting 2011), total C&I waste collected across the City of Sydney LGA is estimated at 261,749.4 t in 2010-11, a quantity projected to grow up to 307,153.7 t in 2029-30, as summarized in the diagram below.

Figure 26. Commercial and Industrial waste – resource recovery and disposal, City of Sydney LGA, 2009-30.



The assessment of residual waste resources available within the region surrounding Sydney is based on a detailed resource assessment presented under Appendix A.

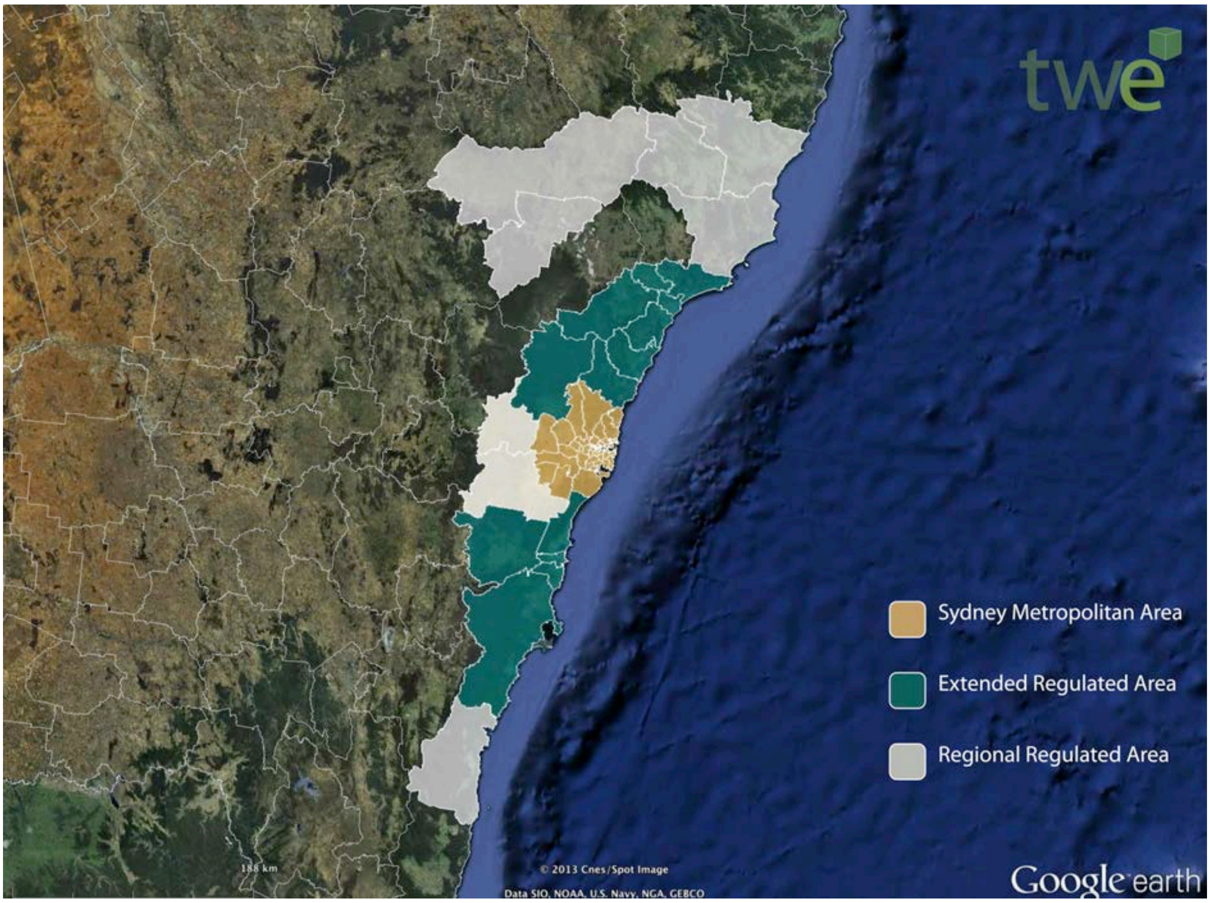
Beyond the City

Regulated areas

The NSW EPA defines four regulated waste and resource recovery (WARR) regulated areas:

- the **Sydney Metropolitan Area (SMA)**, including local government areas (LGAs) in the greater Sydney region;
- the **Extended Regulated Area (ERA)**, including LGAs in the Newcastle, Central Coast and Illawarra Regions;
- the **Regional Regulated Area (RRA)**, including the Hunter Region, and the Blue Mountains, Wollondilly and Eurobodalla LGAs; and
- the **Non Regulated Area (NRA)**, including the rest of New South Wales.

Figure 27. Regulated waste management areas, New South Wales



Domestic waste resources

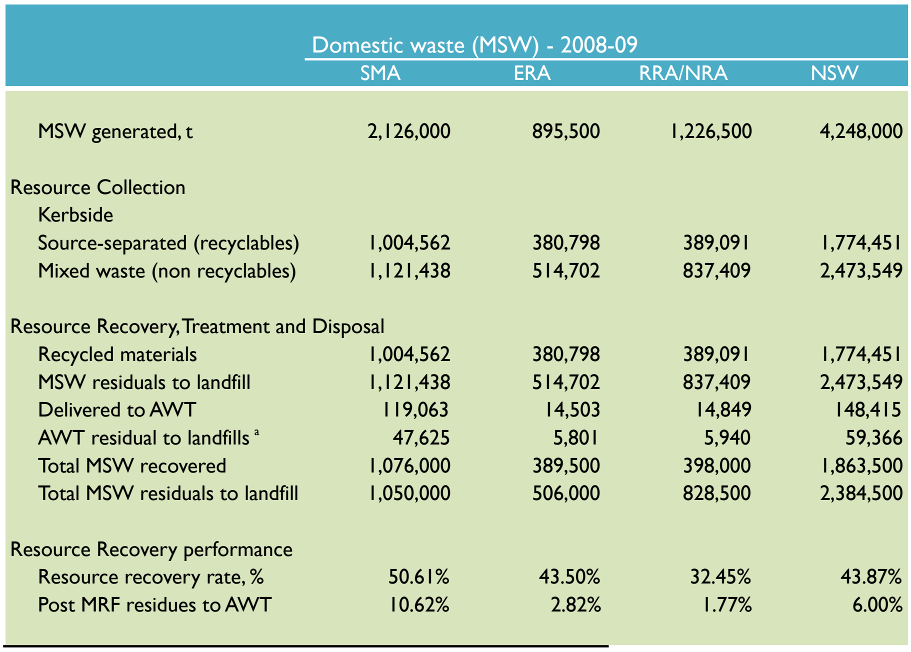
Generation, recovery, treatment and disposal

The table below reports the latest available data on domestic waste (MSW) generation, recycling and disposal from the regulated areas of NSW, as published by the NSW Department of the Environment, Climate Change and Water (DECCW 2011b).

The two regions focus of this assessment, SMA and ERA, accounted in 2008-09 for 50.05% and 21.08% of the total MSW generated in New South Wales, respectively. In the same year, resource recovery rates across the two areas were 50.61% for the SMA and 43.50% for the ERA.

Use of alternative waste treatment (AWT), through mechanical-biological conversion (MBT or composting), is more advanced in the SMA, with 10.62% of the post-MRF residuals diverted to these facilities, compared to 2.82% in the ERA.

Table 11. domestic waste generation, recycling and disposal – NSW 2008-09, by regulated area



	Domestic waste (MSW) - 2008-09			
	SMA	ERA	RRA/NRA	NSW
MSW generated, t	2,126,000	895,500	1,226,500	4,248,000
Resource Collection				
Kerbside				
Source-separated (recyclables)	1,004,562	380,798	389,091	1,774,451
Mixed waste (non recyclables)	1,121,438	514,702	837,409	2,473,549
Resource Recovery, Treatment and Disposal				
Recycled materials	1,004,562	380,798	389,091	1,774,451
MSW residuals to landfill	1,121,438	514,702	837,409	2,473,549
Delivered to AWT	119,063	14,503	14,849	148,415
AWT residual to landfills [a]	47,625	5,801	5,940	59,366
Total MSW recovered	1,076,000	389,500	398,000	1,863,500
Total MSW residuals to landfill	1,050,000	506,000	828,500	2,384,500
Resource Recovery performance				
Resource recovery rate, %	50.61%	43.50%	32.45%	43.87%
Post MRF residues to AWT	10.62%	2.82%	1.77%	6.00%

SOURCE: adapted from (DECCW 2011b), Table B2, p.5

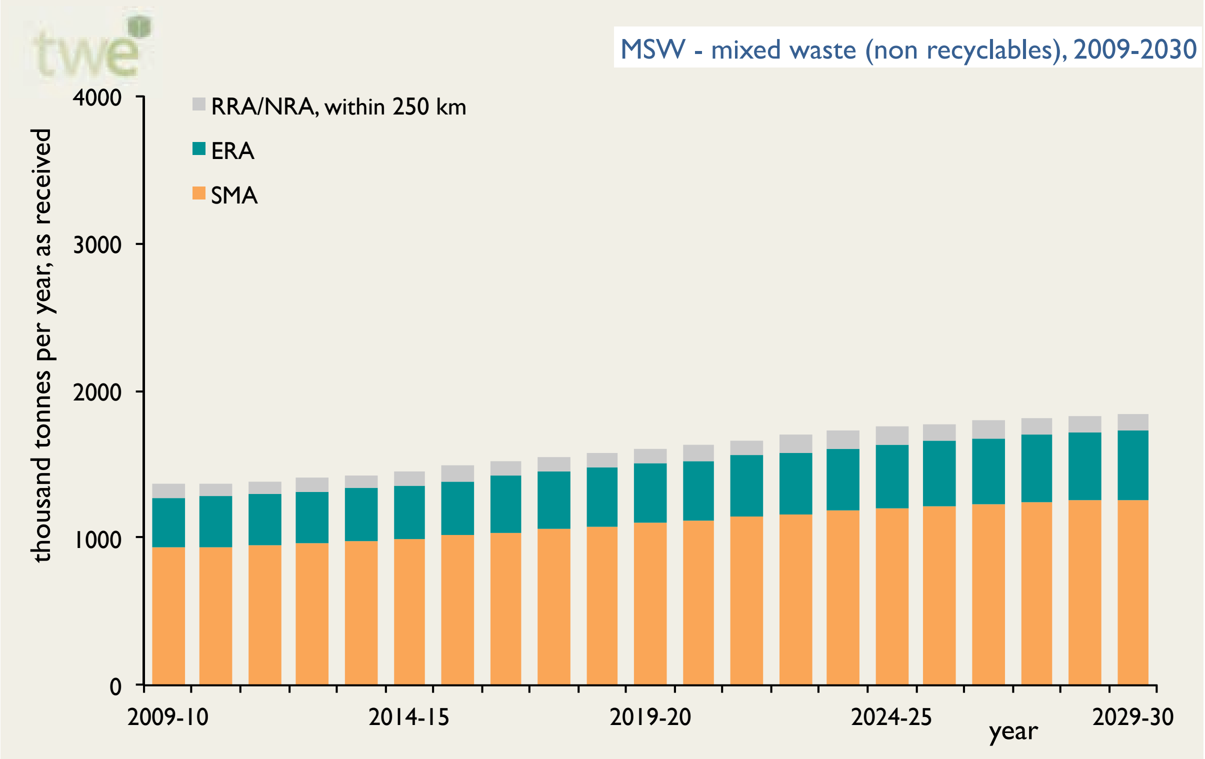
[a] AWT resource recovery efficiency 60% (Hyder Consulting 2012)

Within the scope of this Study, Talent with Energy has developed a set of projections for this resource, providing an estimate of total waste generated, resource recovery and residual MSW delivered to landfills through to 2029-30.

Target resource

Thermal conversion is a treatment option more advanced than mechanical-biological treatment under both a waste management and energy recovery perspective. For this reason we assume that Syngas from Waste facilities, once in operation, will replace MBT as the preferred Alternative Waste Treatment (AWT) option for Councils in the catchment region. Accordingly, the target feedstock resource considered within this study is the fraction of waste generated that is not source-separated for downstream resource recovery, eg. the *mixed waste* stream from kerbside collection activities. The chart below illustrates the projected evolution of this resource through the 2009-2030 timeframe.

Figure 28. MSW – mixed waste (non recyclables), 2009-2030

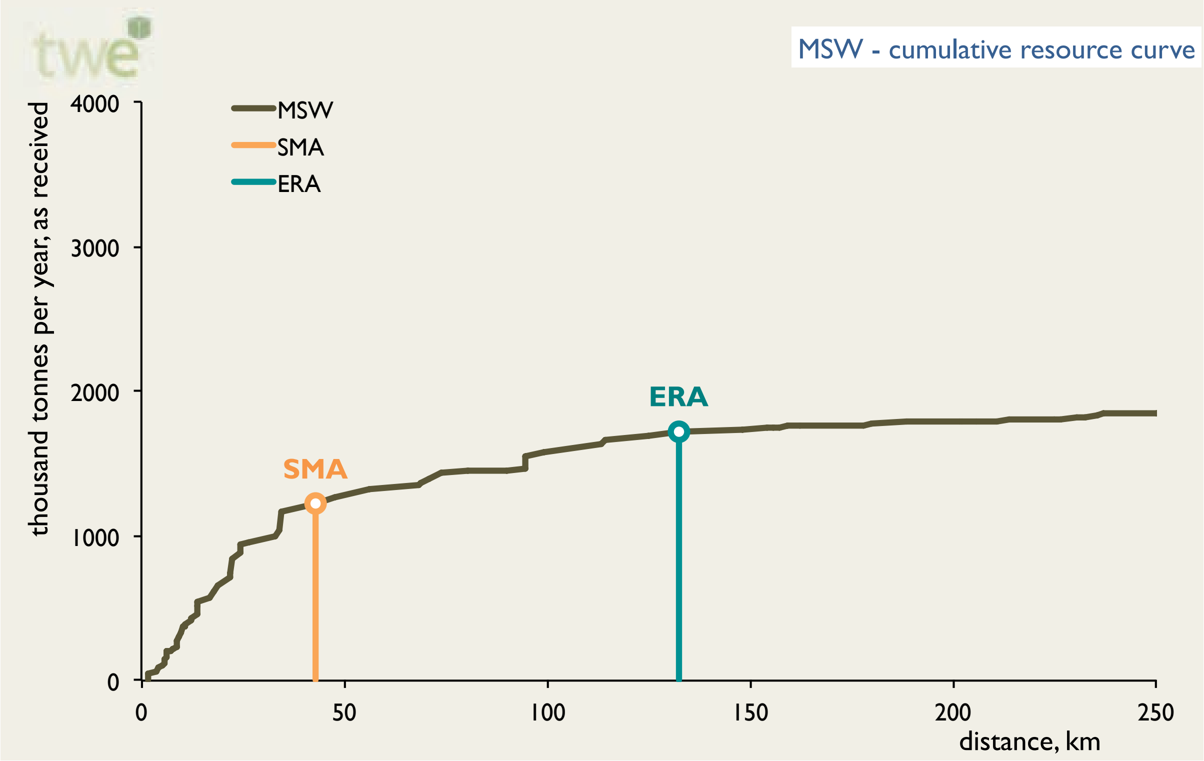


The total residual MSW resource available within a 250-km radius from the City of Sydney LGA is projected to grow 35.52% over this timeframe, from 1.381 million tonnes per year in 2009-10 to 1.871 million tonnes per year in 2029-30.

Resource distribution

The 2029-30 *cumulative resource curve*, below illustrates the distribution of the available resource with regard to its distance from the City.

Figure 29. MSW non recyclables – cumulative resource curve, 2029-30



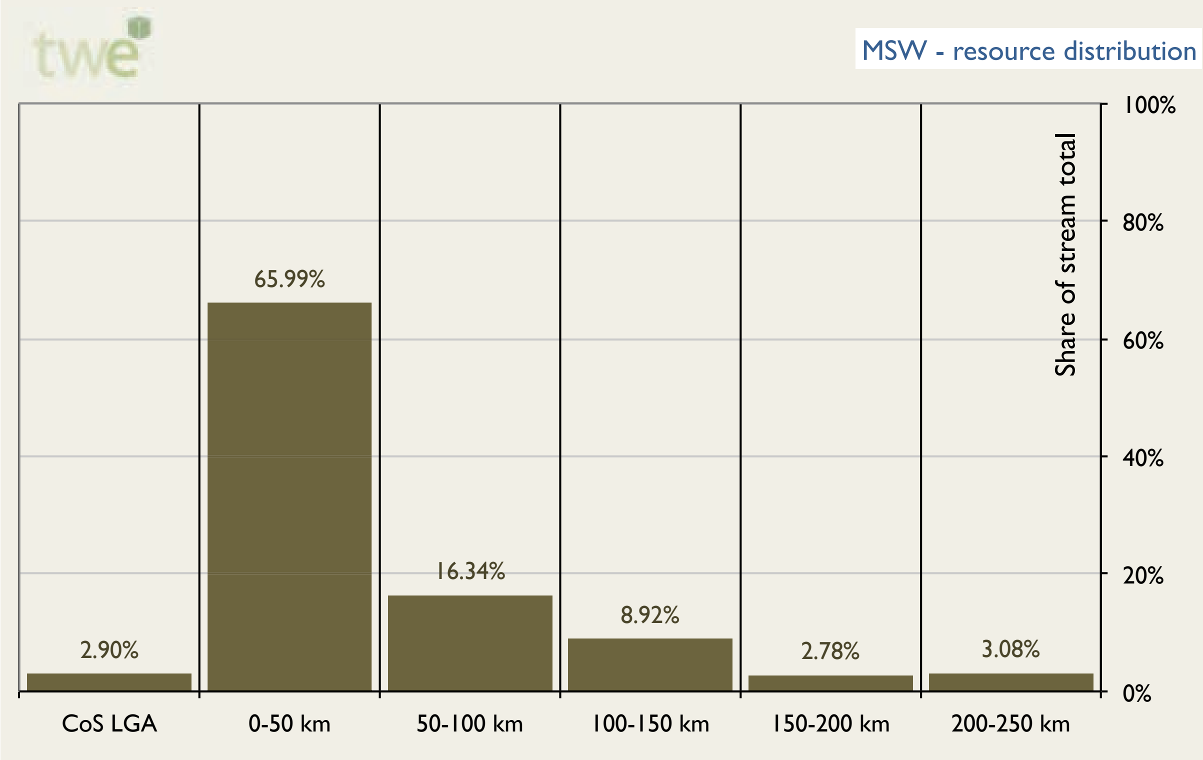
The two vertical lines indicate the boundaries of the SMA and ERA regions, set at 34.66 km (Camden SLA) and 106.97 km (Port Stephens SLA) from the City of Sydney LGA, respectively.

Collectively, the SMA and ERA regions accounts for 1.723 million tonnes per year or 92.1% of the total, 1.871 million tonnes per year, available in 2029-30 within a 250-km radius from the City of Sydney LGA.

This is illustrated further in the diagram below, where the available resource within a 250-km radius from the City is broken down in 50-km resource bands.

The densely populated areas in the region surrounding Sydney contribute the majority of this resource, with 70.7% of the total resource available within a 50-km radius from the City. Other significant contributions derive from the Wollongong, Newcastle and Central Coast areas, with a further 19.77% available between 50 and 100 km from the City.

Figure 30. MSW non recyclables – resource distribution, 2029-30



Commercial and Industrial waste resources

Generation, recovery, and disposal

New South Wales

The table below reports the latest available data on commercial and industrial (C&I) waste generation, recycling and disposal from the regulated areas of NSW, as published by the Department of the Environment, Climate Change and Water (DECCW 2011b).

Table 2. Commercial and Industrial waste generation, recycling and disposal – NSW 2008-09, by regulated area

	Commercial and Industrial waste (C&I) - 2008-09			
	SMA	ERA	RRA/NRA	NSW
Waste generated, t	3,671,000	904,500	849,500	5,425,000
Waste recycled, t	1,816,500	546,500	473,500	2,836,500
Residues to landfill, t	1,854,500	358,000	376,000	2,588,500
Resource recovery rate, %	49.48%	60.42%	55.74%	52.29%

SOURCE: adapted from (DECCW 2011b), Table B2, p.5

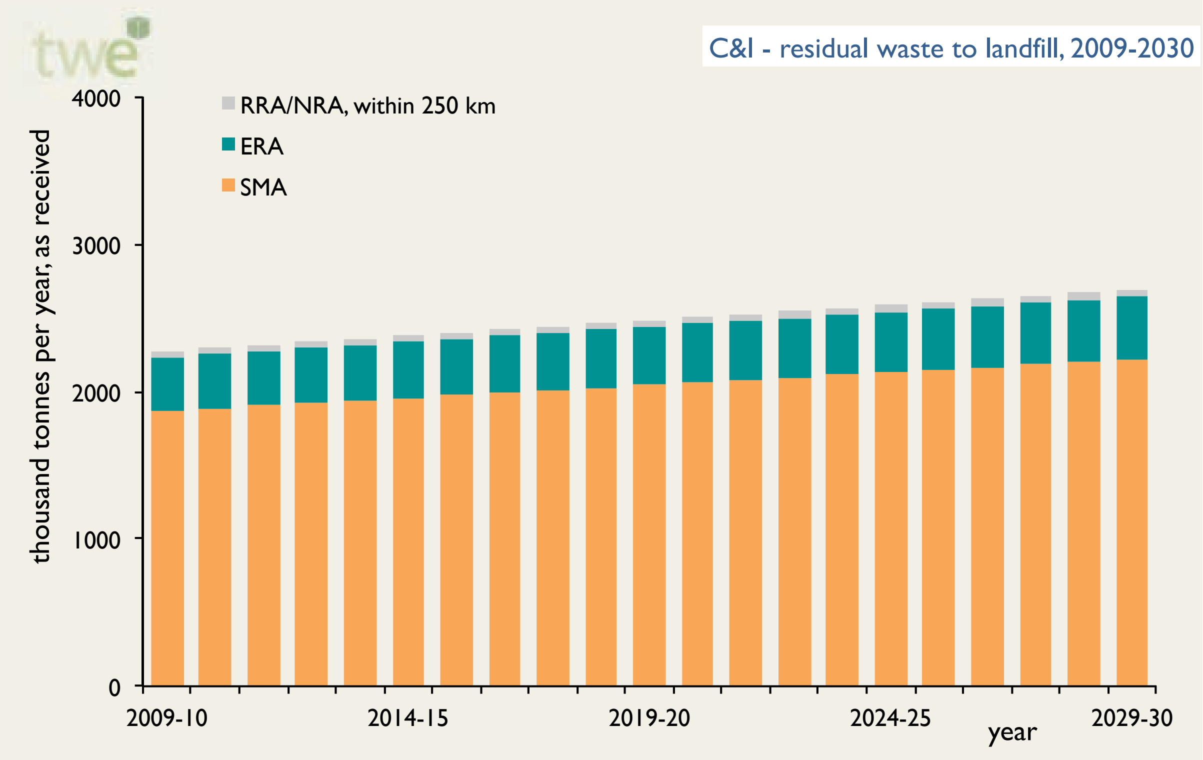
As for MSW, Talent with Energy has developed a set of projections for this resource, providing an estimate of total waste generated, resource recovery and residual C&I to landfills through to 2029-30.

Target resource

The target resource considered for this stream is the residual C&I waste delivered to landfill downstream of resource recovery activities. The chart below illustrates the projected evolution of this resource through the 2009-2030 timeframe.

The total residual C&I resource available within a 250-km radius from the City of Sydney LGA is projected to grow 21.79% over this timeframe, from 2.286 million tonnes per year in 2009-10 to 2.707 million tonnes per year in 2029-30.

Figure 31. C&I – residual waste to landfill, 2009-2030

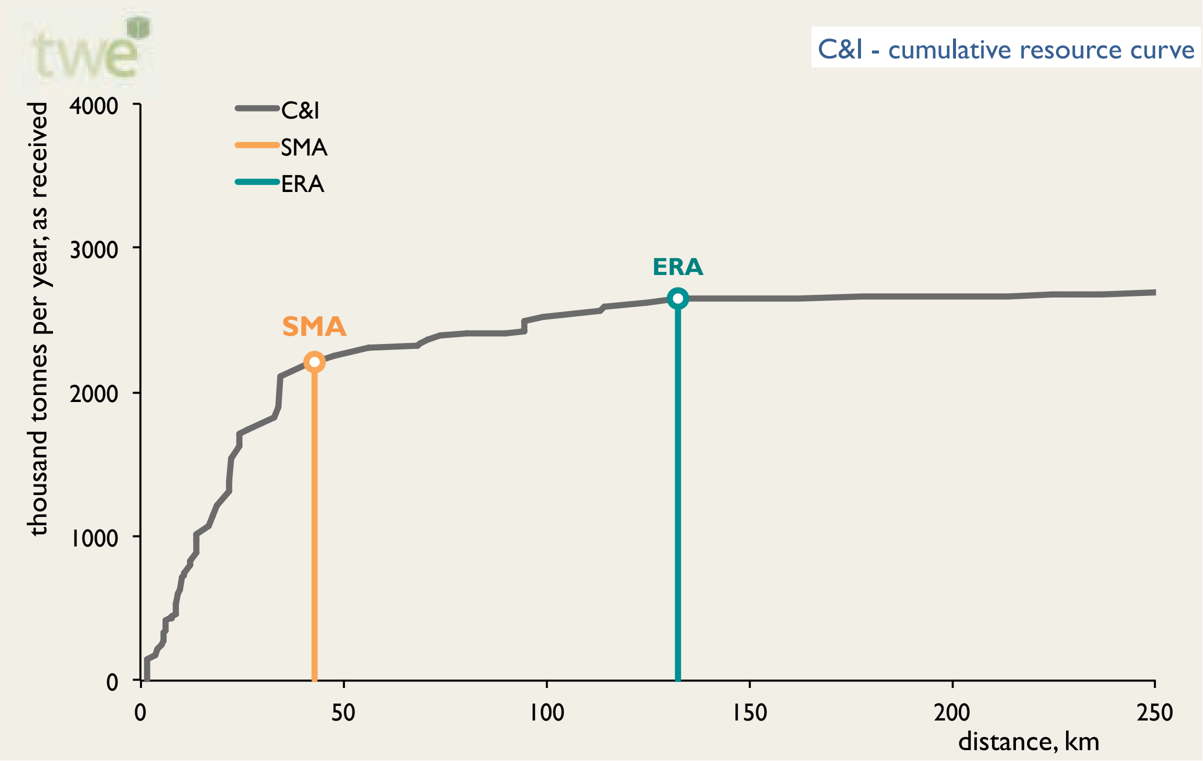


Resource distribution

For this resource stream, the contribution from the SMA and ERA region to the total resource available within 250 km - 2.707 million tonnes per year available in 2029-30 – is 2.645 million tonnes per year, or 97.7% of the total. This higher prpoportion than that observed for MSW reflects the higher degree of concentration of commercial and industrial activities in these metropolitan areas, when compared to the rest of the catchment region.

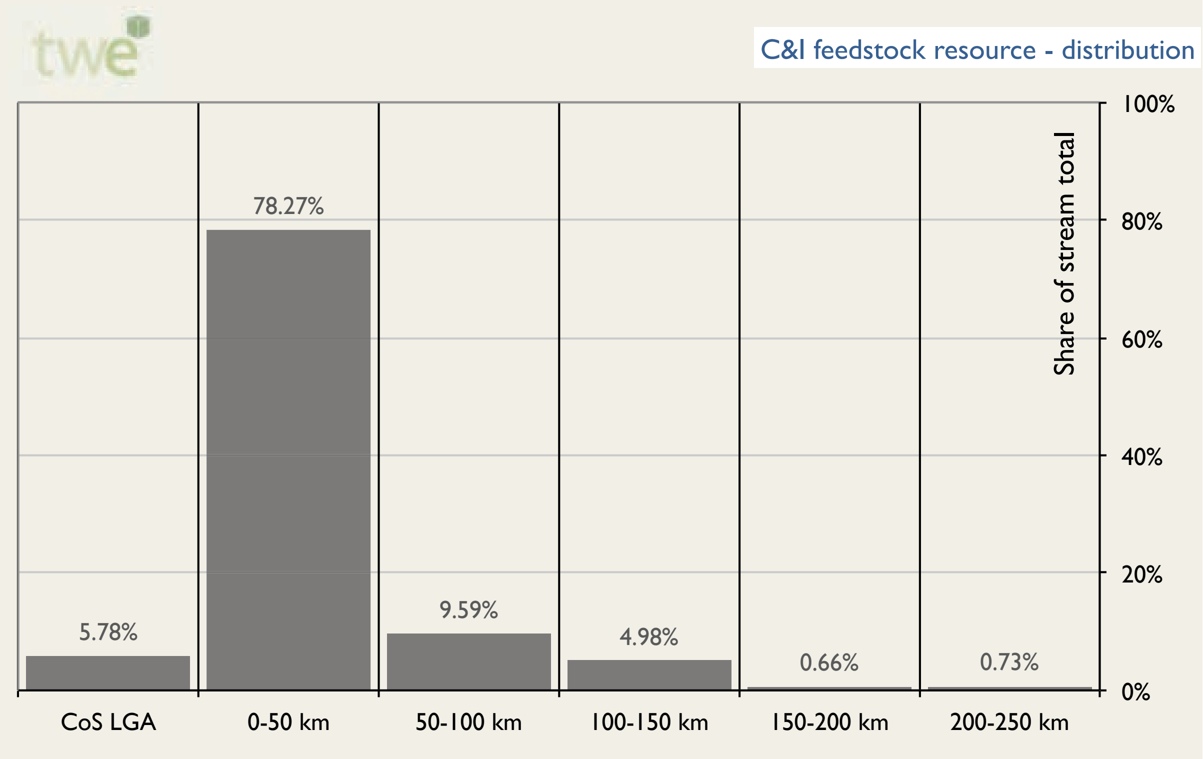
The 2029-30 *cumulative resource curve* for residual C&I is illustrated below.

Figure 32. C&I residues to landfill – cumulative resource curve, 2029-30



This is illustrated further in the diagram below, where the available resource within a 250-km radius from the City is broken down in 50-km resource bands.

Figure 33. C&I residues to landfill - resource distribution, 2029-30



The densely populated areas in the region surrounding Sydney contribute the majority of this resource, with 85.1% of the total resource available within a 50-km radius from the City. Other significant contributions derive from the Wollongong, Newcastle and Central Coast areas, with a further 11.69% available between 50 and 100 km from the City.

Resource characterization

Within the scope of this study, Talent with Energy has established a detailed feedstock resource characterization framework for residual waste to landfill from the MSW and C&I resource streams. The framework is described in detail in *Appendix A. Waste resource assessment and characterization*, we present here the key data of relevance to the modelling activities described further in this report, these include:

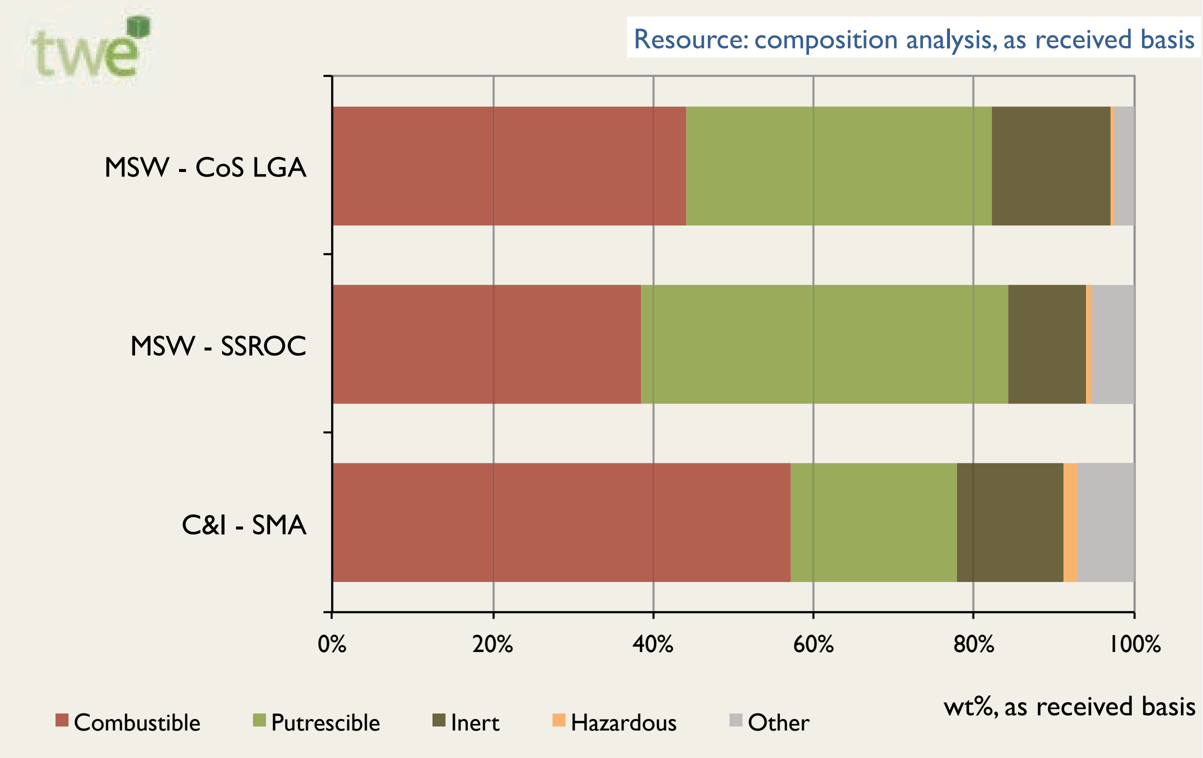
- waste stream composition
- feedstock elemental analysis and energy content;
- feedstock renewable fraction analysis.

Waste stream composition

The diagram below summarizes the resource composition data for this analysis, these are based on results from the following audit activities:

- **Domestic wastes**, collected within the City of Sydney LGA, and the SSROC region, sourced from (APC 2011a), and (APC 2011b), respectively; and
- **Commercial and Industrial wastes**, collected within the Sydney Metropolitan Area (SMA), sourced from (DECCW 2010).

Figure 34. Waste resource – composition analysis



Feedstock elemental analysis and energy content

Based on the matrix of processable fractions, the resource characterization framework presented in Appendix A enables to establish the following feedstock characteristics;

- the **elemental analysis**, or its chemical composition expressed in terms of its content, by weight, of carbon (C), hydrogen (H), oxygen (O), nitrogen (N), sulphur (S), inorganic compounds (Ash) and water content (Moisture); and
- the **energy content**, calculated from the feedstock elemental analysis data on the basis of an empirical correlation published in (Channiwala & Parikh 2002).

The four charts below present the resulting elemental analysis and energy content data for the two categories of LTC/HTC and HTCM feedstocks.

LTC/HTC feedstocks

Figure 35. LTC/HTC waste feedstocks – elemental analysis, as received basis

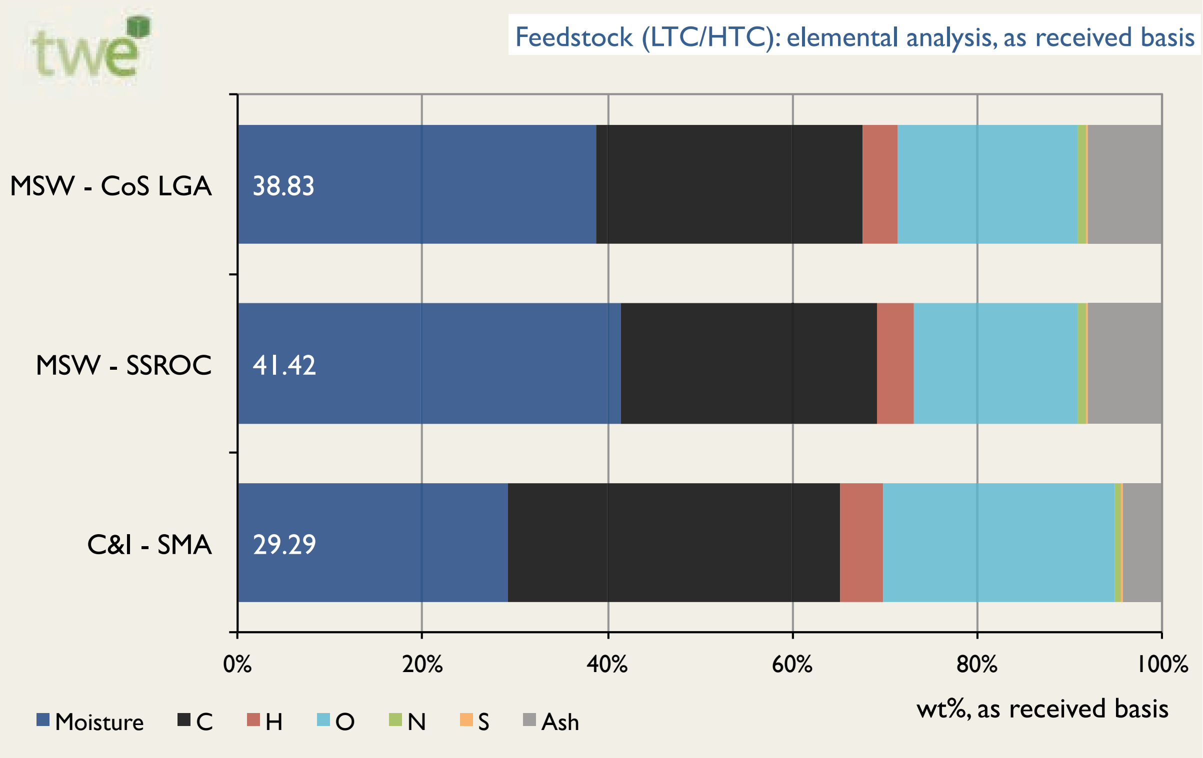
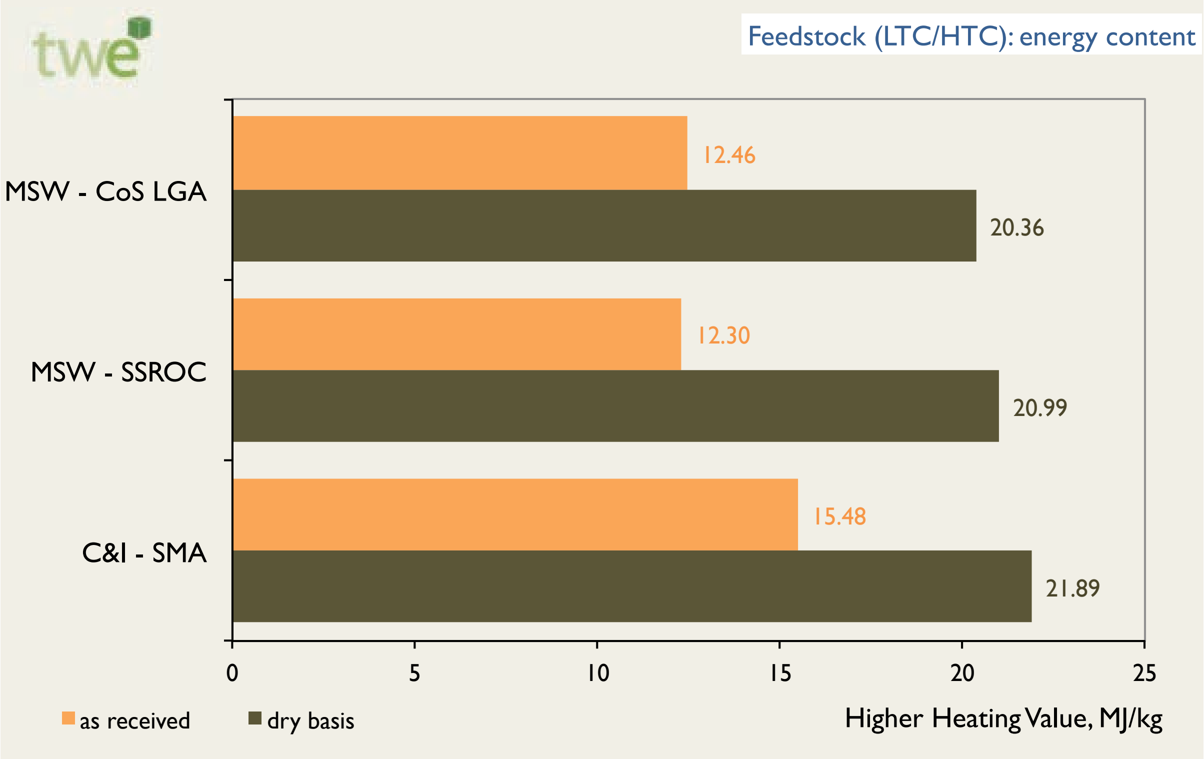


Figure 36.LTC/HTC waste feedstocks – energy content, HHV basis



HTCM feedstocks

Figure 37.HTCM waste feedstocks – elemental analysis, as received basis

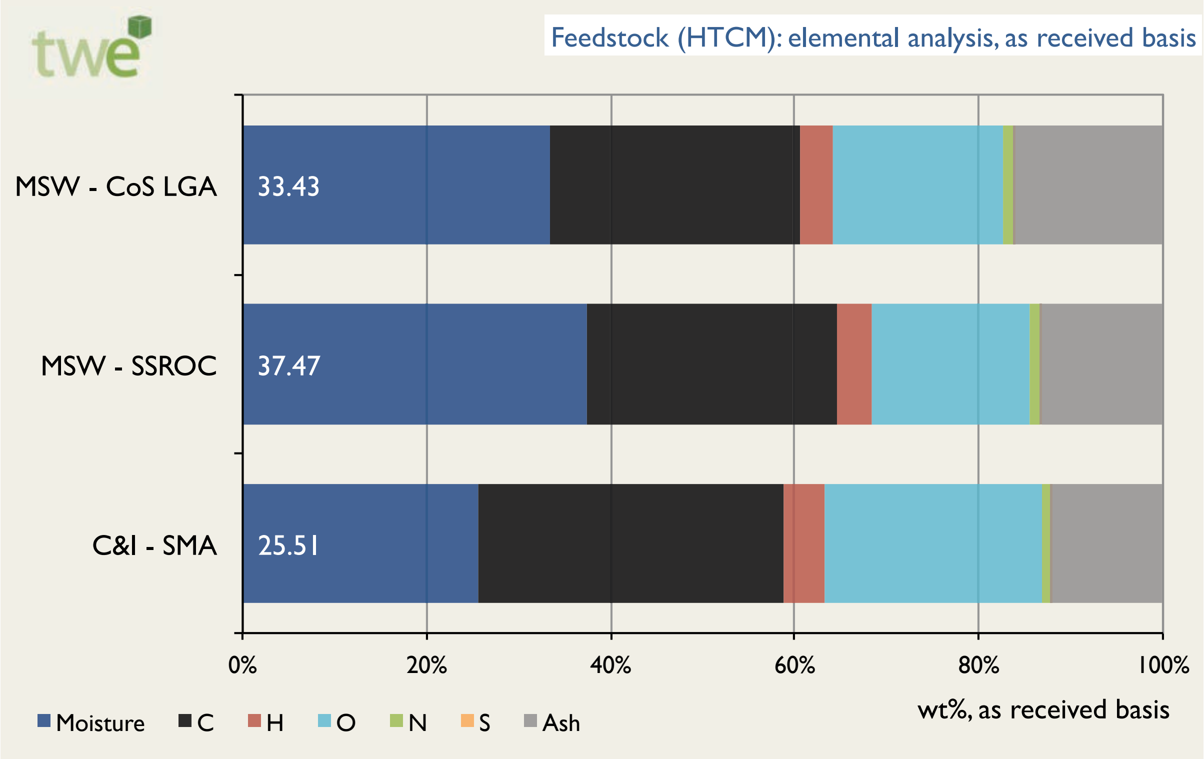
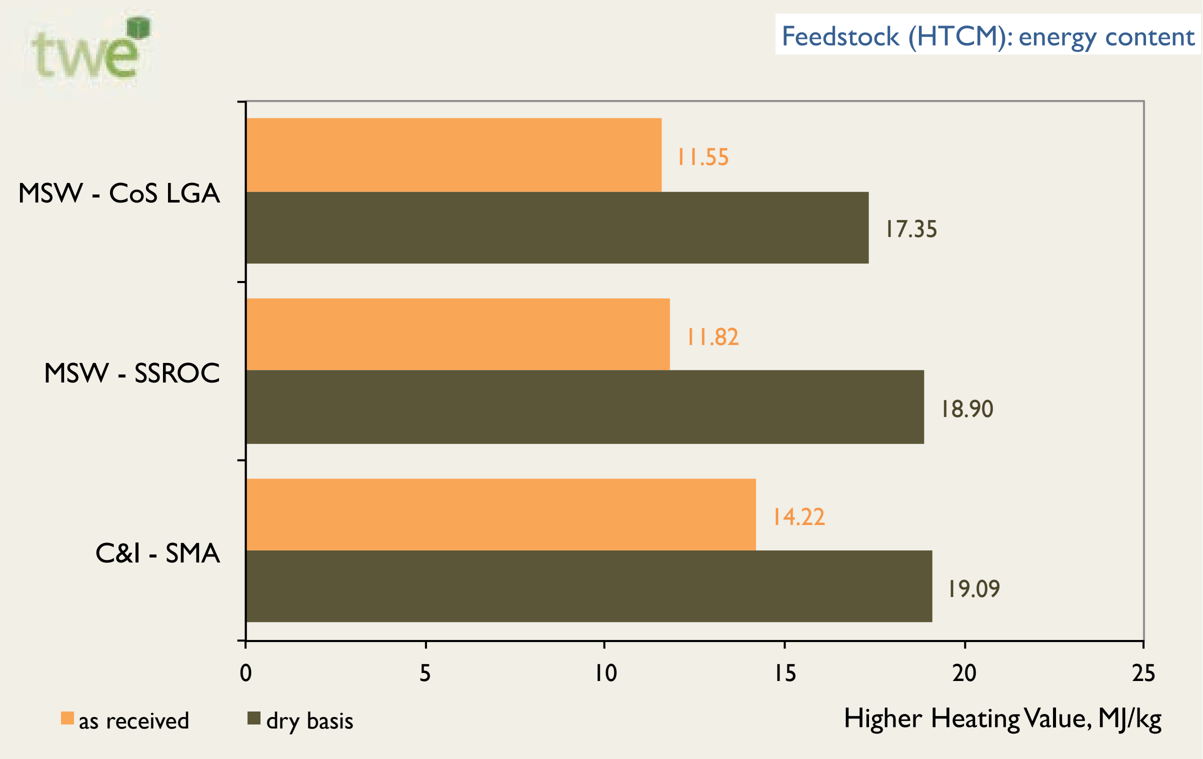


Figure 38. HTCM waste feedstocks – energy content, HHV basis



Feedstock renewable fraction analysis

For the purpose of this study we consider the renewable fraction of residual waste resources on the basis of its organic, or biomass fractions, in accordance with methods prescribed in the National Greenhouse and Energy Reporting (NGER) guidelines (DCCEE 2012) and the consolidated general methodology ACM0022 *Alternative Waste Treatment Porcesses* published under by the UNFCCC Clean Development Mechanism (CDM EB 2012) these are[16]:

- **Biomass fractions:** Food, paper, green waste, wood, textile, leather and rubber;
- **Non-biomass fractions:** oils, plastic, construction and demolition waste, glass and metal, hazardous fractions and other (e-waste, whitegoods, shredder residues, etc.)

Feedstock biomass content

The biomass content (BC) is the ratio of the combined weight of the biomass fractions, to the weight of the incoming waste feedstock, both calculated on an as received basis.

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[16] the guidelines for evaluation of eligibility of energy recovery from waste (including combustion, gasification and pyrolysis) under the Large-scale Generation Certificates under the Renewable Energy Ac, as set out in (Nolan-ITU 2001) exclude leather and textiles from eligibility, in situations where the synthetic (non renewable) contamination in these materials can not be determined. Within the context of this study we have considered the entire amount of wastes from the leather, rubber and textiles categories as eligible for consistency with the methods prescribed under (CDM EB 2012), and (DCCEE 2012).

Figure 39. LTC/HTC waste feedstocks – biomass content, as received basis

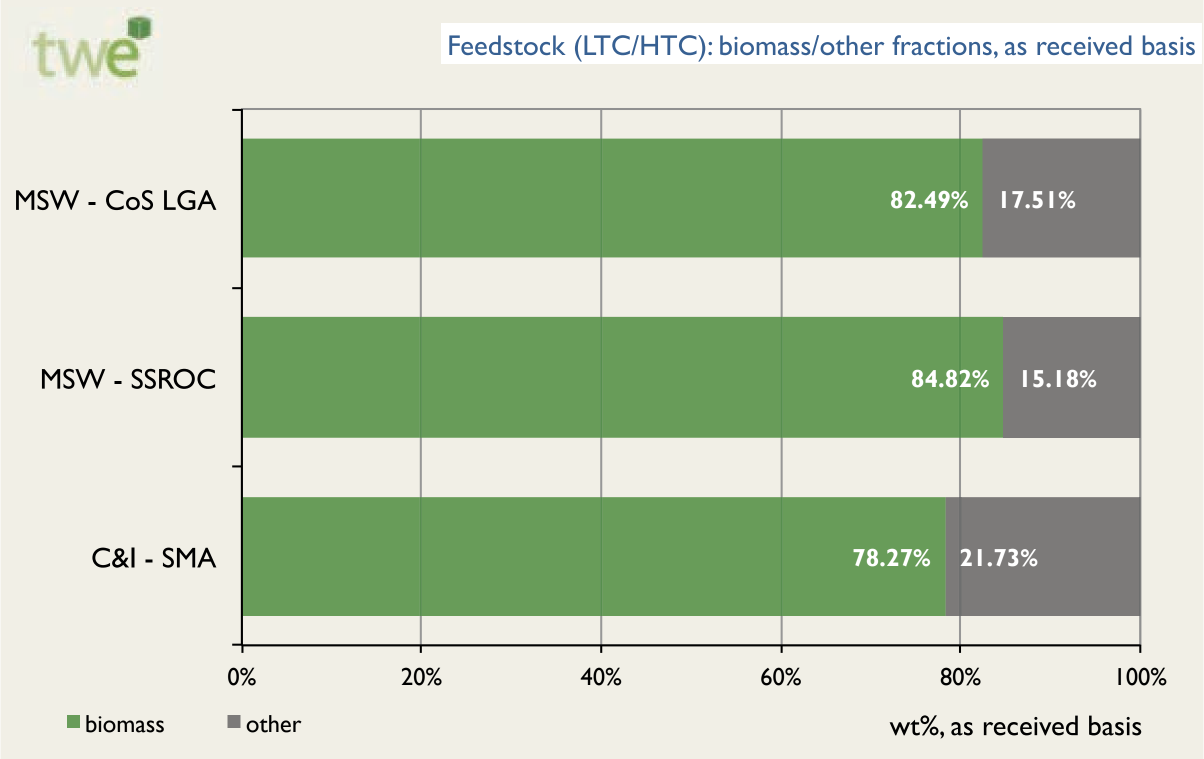
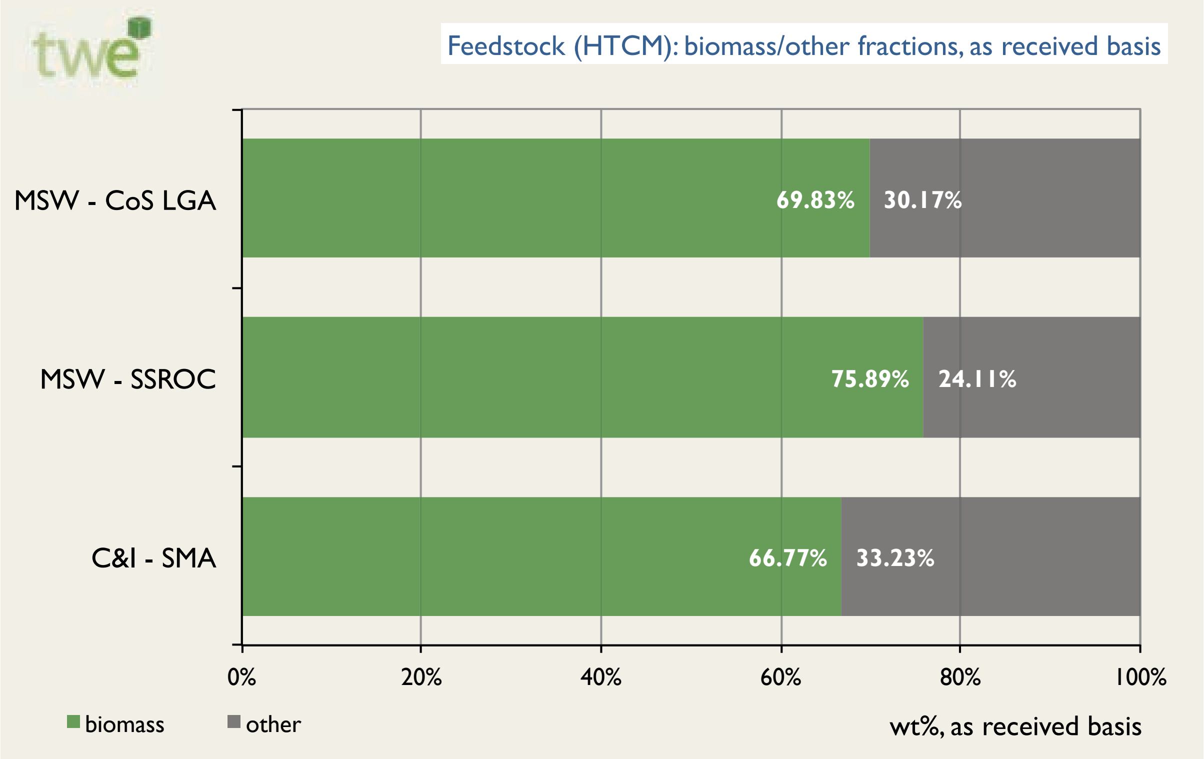


Figure 40. HTCM waste feedstocks – biomass content, as received basis



The addition of the inert fraction to the feedstock mix contributes to lower overall biomass contents for HTCM feedstocks across the three different feedstock resources considered.

Renewable energy content

The renewable energy content (REC) of the feedstock, is the ratio of the combined energy content of the biomass fractions, to the energy content of the incoming waste feedstock, both calculated on an as received, higher heating value (HHV) basis.

The variability observed in the renewable energy content between LTC/HTC and HTCM feedstocks is lower than that observed for the biomass content, as the low energy contents associated with the inert fraction (ranging between 0.70 and 2.72 MJ/kg, HHV as received) have a smaller impact on the total feedstock resource energy content.

The renewable energy content (REC) of the feedstock, adjusted for the introduction of any non-renewable auxiliary thermal input (e.g. from fuel combustion) in the conversion reactor, is used to determine the renewable energy content of the syngas generated, a key performance parameter in the analysis presented in the following section.

Figure 41. LTC/HTC waste feedstocks – renewable energy content, HHV as received basis

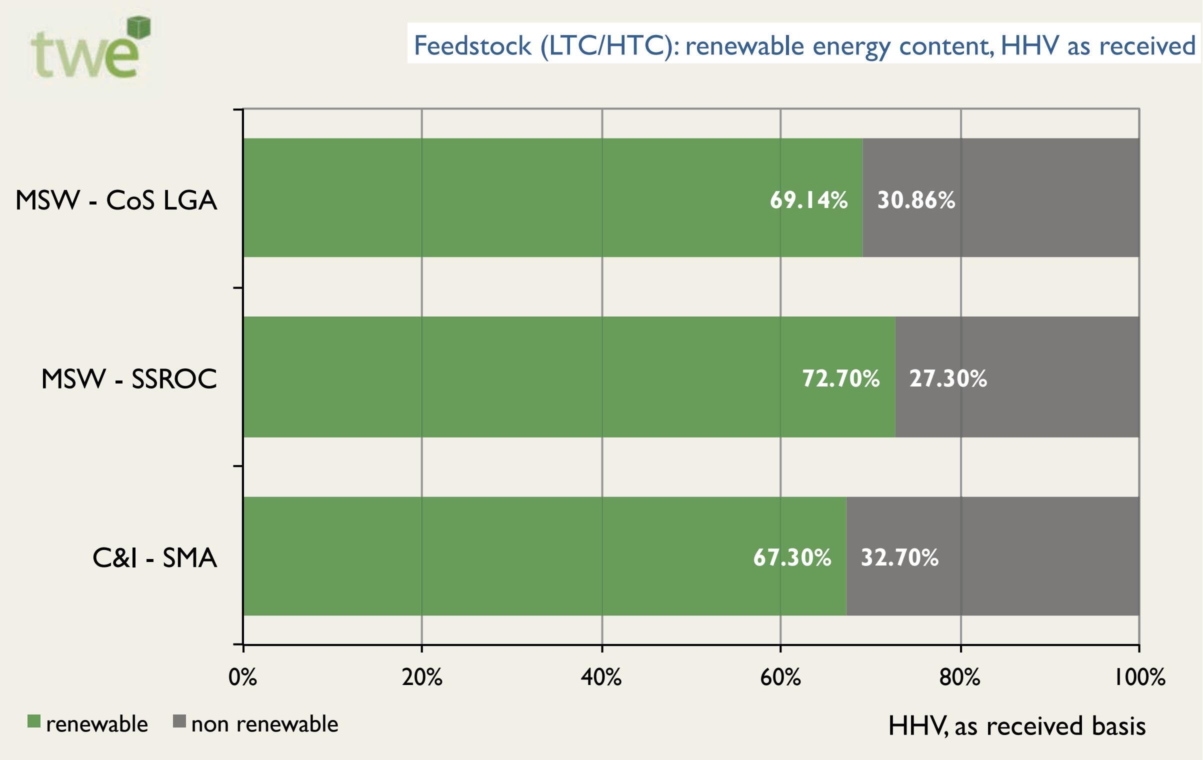
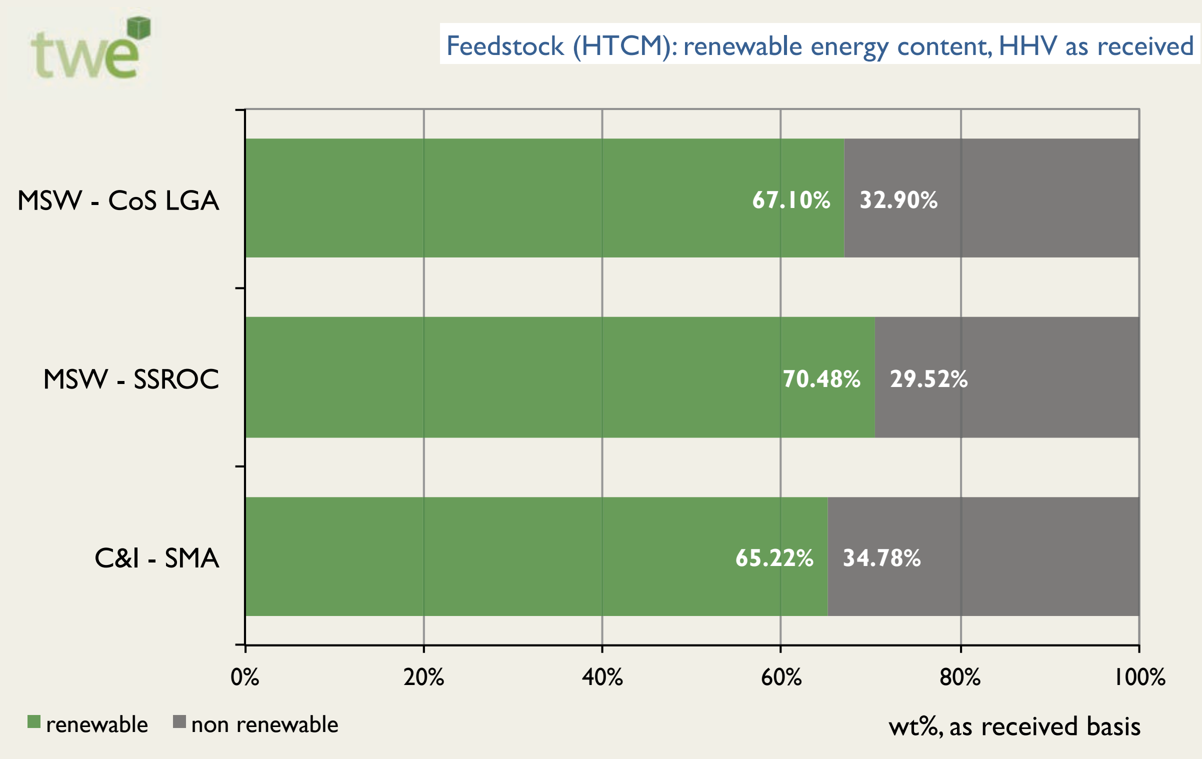
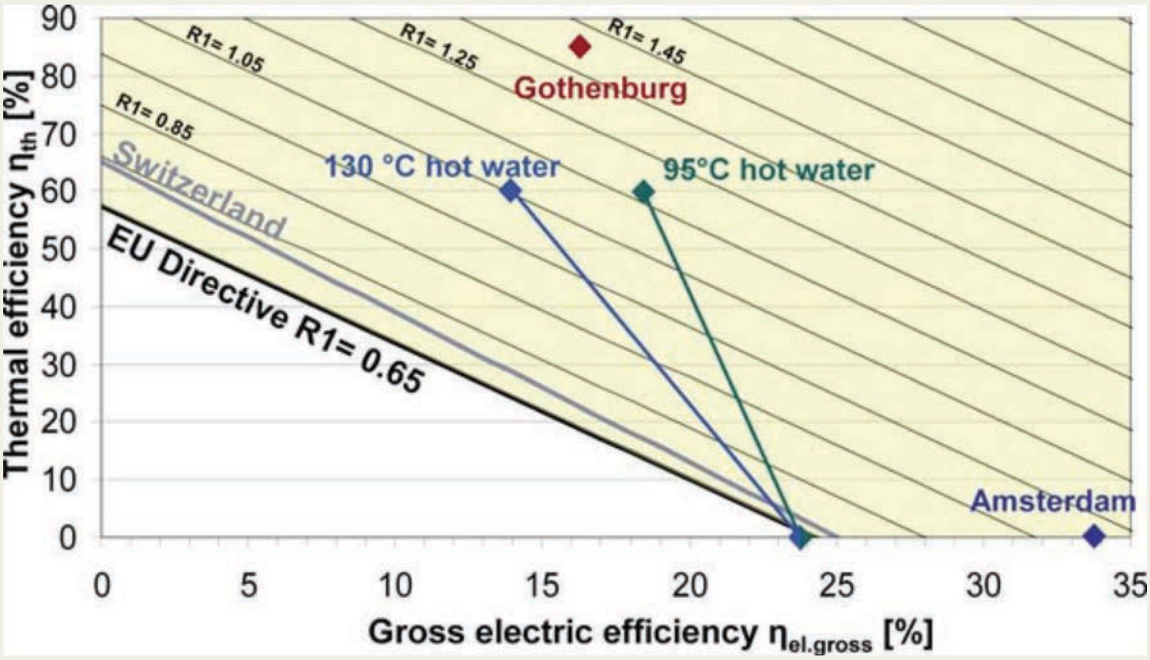


Figure 42. HTCM waste feedstocks – renewable energy content, HHV as received basis



Box 1. The EU WID Energy Efficiency Criterion

European legislation, originally developed in Italy (for the CIP6 green certificates) and Germany (for the country's feed-in tariff programs), and later integrated in the EU Commission Waste Directive, assumes instead energy recovered from waste resources to be *assimilable to renewables* for all energy from waste recovery plants, provided that the combined heat and electricity recovery from energy from waste (EfW) conversion schemes, is above the 'best practice' combined heat and power performances of fossil-fuel generation, through a test also known as the R1 criterion, conducted by means of the gross electric-efficiency/heat recovery rate diagram, shown below for a number of facilities.



The line labeled "EU Directive R1 = 0.65" marks the minimum requirement a plant must fulfil to get the recovery status, and thus access the set of incentives (green certificates or feed-in tariffs) available in the single Member States.

The energy efficiency criterion shifts the focus from the feedstock resource being renewable, to the waste to energy scheme achieving an improvement to the existing fleet of power and heat generation facilities. It also extends the notion of non-renewable resource to the landfills, thus emphasizing the waste management, and associated environmental benefits associated with energy from waste schemes.

It should be noted how, the coupling of advanced gasification with advanced tri-generation systems, far exceeding the average efficiency of electricity, heating and cooling generation, has the potential to outperform, under the energy efficiency criterion, even the most advanced EfW schemes operating.

Biogenic carbon content

The biogenic carbon content (BCC) for waste feedstocks is a key metric used to determine Scope 1 emission factors for the Syngas from Waste SNG.

This is calculated for each resource stream, conversion strategy and catchment region, as the ratio between the carbon content for the biomass fractions and the total feedstock resource stream (both on an as received basis) on the basis of elemental analysis data for each individual waste fraction.

Feedstocks for Low- and High-Temperature Conversion technologies have the highest biogenic carbon contents, ranging from 80.9% (wt%, as received) for MSW feedstocks sourced from the SMA (excluding the Inner Sydney catchment) and ERA regions, to 74.4% (wt%, as received) for C&I feedstocks.

For HTCM feedstocks biogenic carbon contents are lower, ranging from 79.5% (HHV, as received) for MSW to 71.8% (wt%, as received) for C&I feedstocks.

As for renewable energy content, the variability observed between LTC/HTC and HTCM feedstocks for the biogenic carbon content is lower than that observed for the biomass content, as the low carbon contents associated with the inert fractions (ranging between 5.9% and 10.3%, wt% dry basis) have a smaller impact on the total feedstock resource carbon content.

Figure 43. LTC/HTC waste feedstocks – biogenic carbon content, as received basis

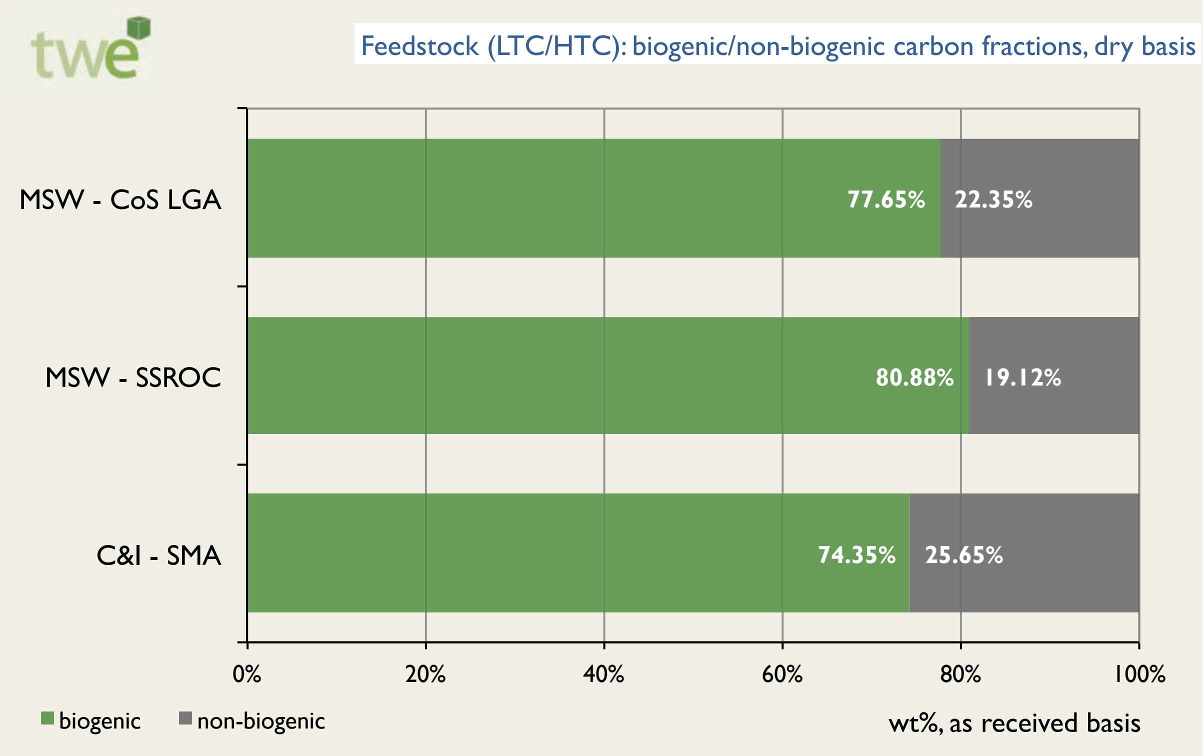
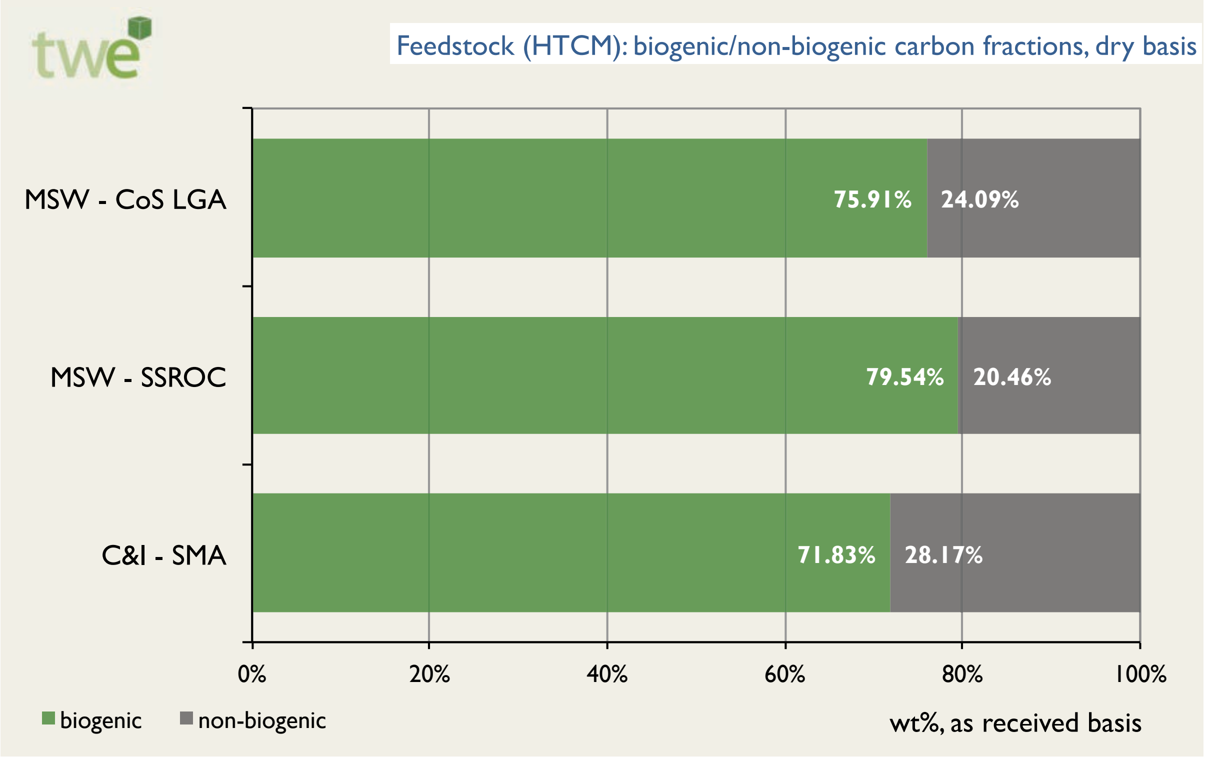


Figure 44. HTCM waste feedstocks – biogenic carbon content, as received basis



SECTION 4. ADVANCED WASTE TREATMENT SCENARIOS

Pictured: Conveyor at Malagrotta 2 gasification facility Rome,
Credits: Co.La.Ri., 2012

Overview

In this section we assess the potential for the establishment of a Syngas from Waste (SfW) facility to supply pipeline-quality substitute natural gas (SNG) to the City's proposed decentralised energy network.

The feedstock considered for the facility is the residual fraction from the mixed domestic (MSW) and commercial and industrial (C&I) waste streams collected within the City of Sydney Local Government Area (LGA) and the LGA from the Southern Sydney Regional Organization of Councils (SSROC).

The assessment presented here, based on typical conversion and energy recovery performances for a set of mature conversion technologies, representative of the 9 technology groupings introduced in *Section 1. Synthesis Gas Generation from Residual Waste Resources*, is focused on the scheme performances in two key areas:

- **waste conversion,** or the ability to contribute further to the City's resource recovery efforts and further reduce the amount of residual waste (including AWT residuals) that is sent to landfill; and
- **energy recovery,** or the ability to cover projected gas demand from the City's proposed network of trigeneration facilities.

The scenarios presented here identify the preferred conversion strategy to be adopted by the City of Sydney and inform the development of an initial shortlist of key commercially mature technologies of interest in regard to future procurement activities outlined in *Section 6. Enabling Actions*.

Syngas from Waste scenarios

A set of scenarios have been developed within the scope of this study to provide the City of Sydney with an initial estimate of the potential energy recovery, waste management and environmental performances associated with the implementation of a syngas-from-waste (SfW) facility within the City of Sydney LGA or in its close proximity.

Scenario framework

A nested scenario framework, summarized in the table below, has been developed to conduct this assessment, designed to highlight the key planning dimensions of:

1. **conversion strategy**, describing three alternative applications for the proposed SfW facility and its role in determining the future of waste collection, recovery, treatment and disposal operations across the City LGA;
2. **conversion technologies**, describing the range of available thermo-chemical technologies to match each of the three SfW-based waste management strategies;
3. **feedstock resource** describing the quantities, mix and characteristics of waste feedstock resource available as potential feedstocks for the proposed SfW facility from the MSW and C&I waste streams; and
4. **implementation approach**, describing alternative strategies for development of the proposed SfW facility based on single-, or two-stage implementation.

Table 12. Syngas from Waste scenarios - analysis framework

Level 1. STRATEGY	Level 2. TECHNOLOGIES	Level 3. RESOURCES	Level 4. IMPLEMENTATION
Low-Temperature Conversion (LTC)			
	Fixed-Bed Gasification Slow Pyrolysis	MSW C&I	LGA (MSW) LGA (MSW+C&I) SSROC (MSW) SSROC (MSW+C&I)
High-Temperature Conversion (HTC)			
	Fluid Bed Gasification Pyro-Gasification	MSW C&I	LGA (MSW) LGA (MSW+C&I) SSROC (MSW) SSROC (MSW+C&I)
High-Temperature Conversion + Melting (HTCM)			
	Pyro-Gasification + Melting Fluid Bed Gasification + Melting Plasma Gasification	MSW C&I	LGA (MSW) LGA (MSW+C&I) SSROC (MSW) SSROC (MSW+C&I)

Baseline scenario

As the baseline scenario, the framework adopts the current waste management model operating within the City of Sydney – with the interim delivery of the mixed waste stream of MSW to a mechanical-biological treatment (MBT) facility, summarized by the diagram in the following page.

City of Sydney LGA

The two tables below present recent data for waste and resource recovery activities in the LGA, for the domestic (MSW) and commercial and industrial (C&I) resource streams.

Table 13. City of Sydney LGA – MSW collection, recovery, treatment and disposal, 2006-12

	Year					
	2006-07	2007-08	2008-09	2009-10	2010-11	2011-12 [b]
MSW - City of Sydney LGA						
Residential population	165,596.0	170,173.0	173,444.0	177,920.0	180,679.0	183,567.0
Resource Collection						
Mixed waste	36,864.7	37,815.7	39,378.2	39,453.2	40,209.0	40,081.2
Kerbside recycling	14,261.0	14,815.3	15,080.8	15,294.9	15,962.0	16,346.7
Garden organics	231.7	339.0	452.9	549.0	744.3	780.2
Household Cleanup Material	2,353.0	2,413.8	2,513.5	2,518.3	2,478.7	2,543.5
Whitegoods	280.0	287.6	222.0	268.5	126.5	110.3
eWaste	n/a	n/a	28.0	36.0	53.0	78.7
Household Hazardous Waste	n/a	n/a	n/a	16.2	15.0	16.2
TOTAL Collected	53,990.4	55,671.3	57,675.4	58,136.0	59,588.5	59,956.9
Resource Recovery, Treatment and Disposal						
Source-separated materials [a]	13,351.8	13,969.0	14,327.2	14,620.3	15,429.3	15,819.2
Delivered to AWT	0.0	0.0	0.0	7,386.5	20,437.0	39,652.8
AWT residual to landfills	0.0	0.0	0.0	3,693.2	8,603.3	15,861.1
Total MSW recovered	13,351.8	13,969.0	14,327.2	18,313.5	27,263.0	39,610.9
Total MSW residuals to landfill [a]	38,005.6	39,000.9	40,584.7	36,983.5	29,652.3	17,597.2
Resource recovery rate, %						
Actual	25%	25%	25%	32%	46%	66%

SOURCE: City of Sydney

[a] assuming 8% contamination of recycling into landfill

[b] projected levels from this date based on historic data, anticipated waste processing and population increases

Table 14. City of Sydney LGA – C&I waste collection, recovery, treatment and disposal, 2006-12

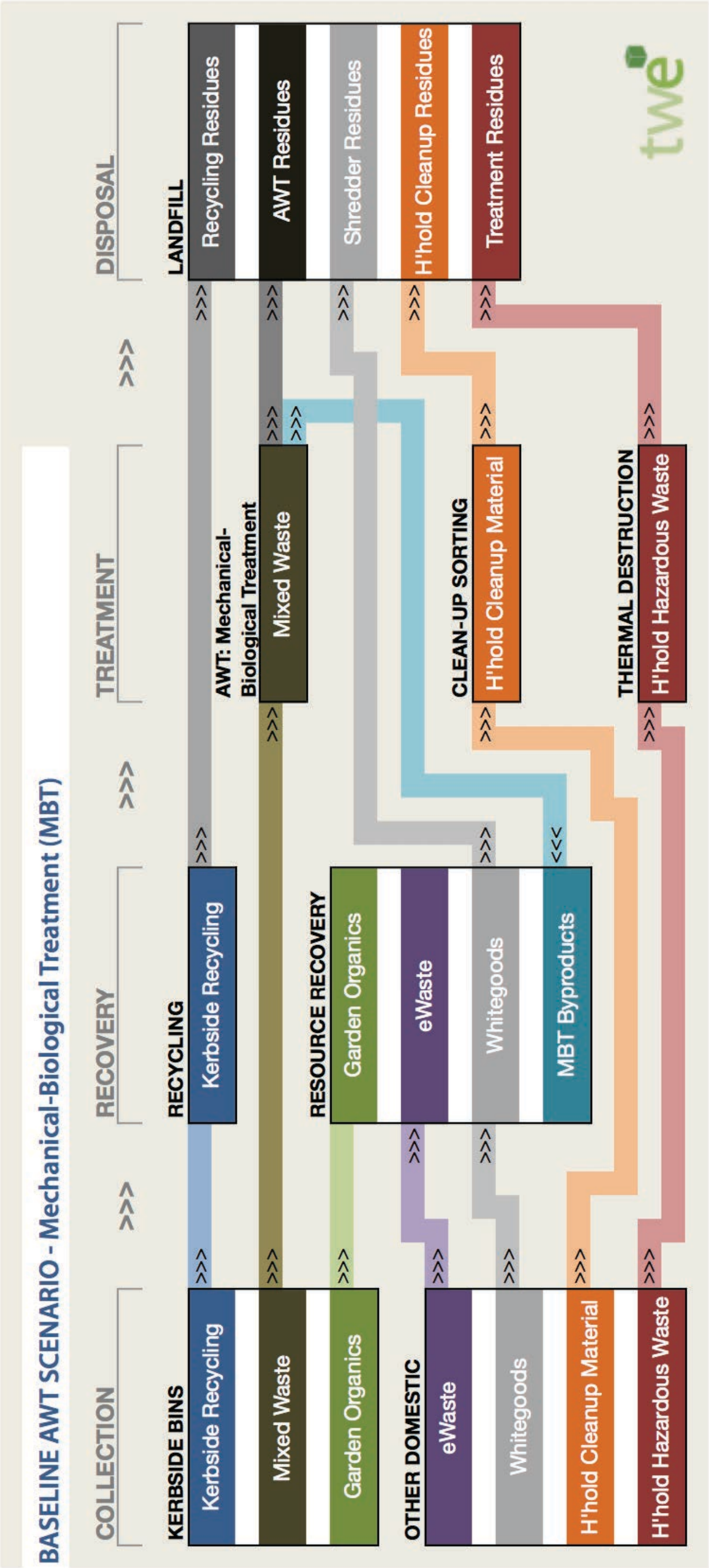
	Year					
	2006-07	2007-08	2008-09	2009-10	2010-11	2011-12
C&I - City of Sydney LGA						
Residential population	165596.0	170173.0	173444.0	177920.0	180679.0	183567.0
Waste Collection	252,190.6	254,580.3	256,970.0	259,359.7	261,749.4	264,139.1
Waste treatment/disposal						
C&I recycled	105,920.1	106,923.7	127,148.8	128,331.2	129,513.6	130,696.0
C&I to landfill	146,270.5	147,656.6	129,821.2	131,028.5	132,235.8	133,443.1
Resource recovery rate (b)	42.00%	42.00%	49.48%	49.48%	49.48%	49.48%

SOURCE: (Hyder Consulting 2011), (DECCW 2010).

(a) adapted from Council projections of employment within the City of Sydney LGA

(a) as reported in (DECCW 2010) for year 2007-08, and (DECCW 2011b) for year 2008-09

Figure 45. Baseline AWT scenario



Conversion strategies

The development of an syngas-from-waste (SfW) facility focused on one of the conversion technologies described earlier offers an opportunity to develop further energy and material recovery activities from waste generated within the City of Sydney's LGA and to increase resource recovery and landfill diversion rates.

Thermal conversion AWT scenarios

A set of three overarching *conversion strategy scenarios* have been developed to identify the key changes in the waste management model for the City of Sydney that would result from the implementation of an SfW facility based on one of the following strategies:

- **Low Temperature Conversion (LTC)**,
- **High Temperature Conversion (HTC)**, and
- **High Temperature Conversion + Melting (HTCM)**.

Low Temperature Conversion

Under this scenario, the interim delivery of mixed wastes to the MBT facility, will cease with the commissioning of an SfW facility based on low temperature conversion technologies such as slow pyrolysis or fixed-bed gasification.

High Temperature Conversion

Under this second scenario, the new EfW facility will be based on high temperature conversion technologies (fluid-bed gasification, pyro-combustion or pyro-gasification).

High Temperature Conversion + Melting

The third conversion strategy considers the implementation of an EfW facility based on high temperature technologies with ash melting capability, such as plasma gasification, fluidized bed gasification + melting, and pyro-gasification + melting.

The choice of these technologies offers the highest processing, and therefore resource recovery/landfill diversion potential, accepting mixed wastes and other streams with minimal or nil pre-processing requirements. In addition to the mixed waste stream, In addition, post-sorting bulky waste items arising from household clean-up and illegal dumping activities, will also be delivered to the new facility.

The hazardous and shredder residues fractions can be also processed by HTCM technologies, but have been excluded from this assessment as, based on experience with the City of Sydney domestic waste streams, they are delivered to specialized alternative waste treatment facilities.

Figure 46. LTC/HTC AWT scenario

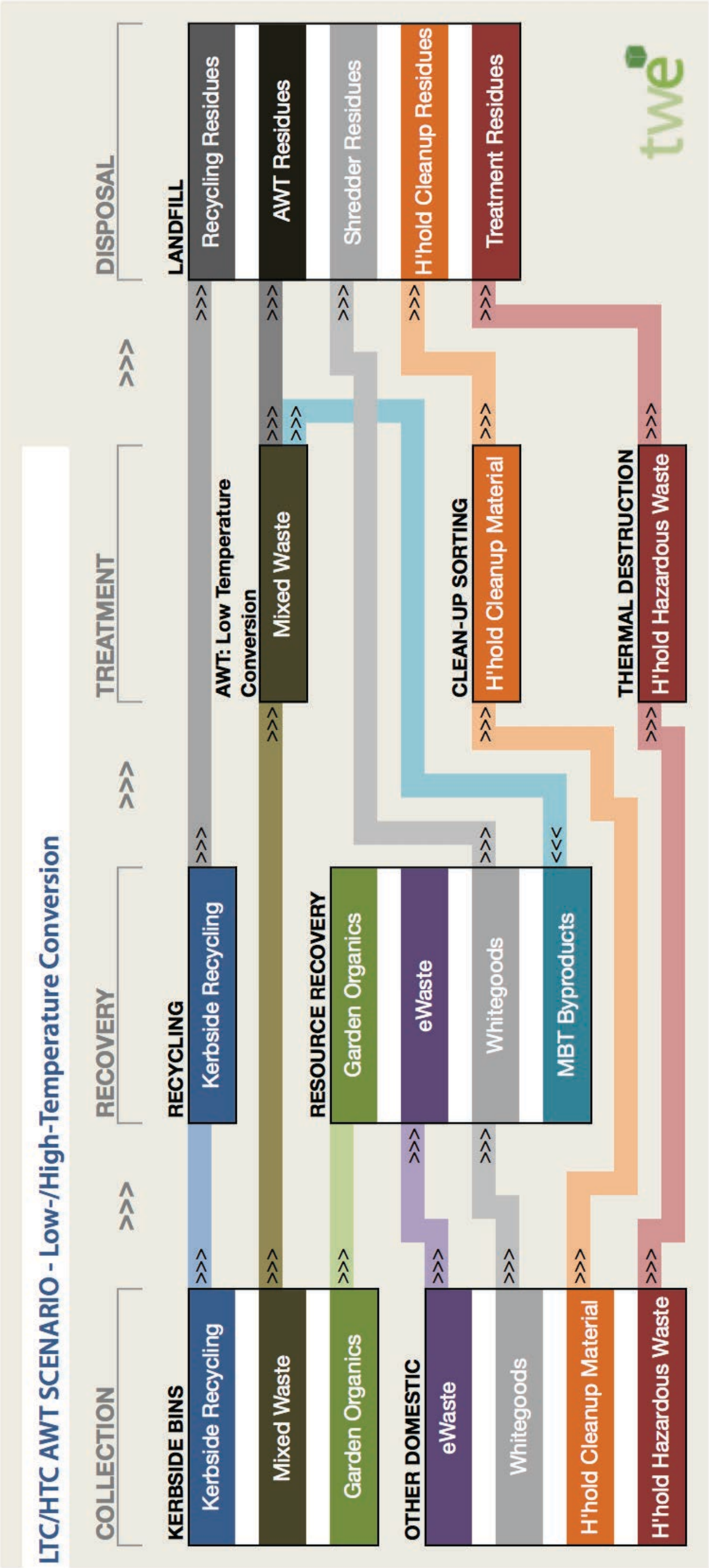
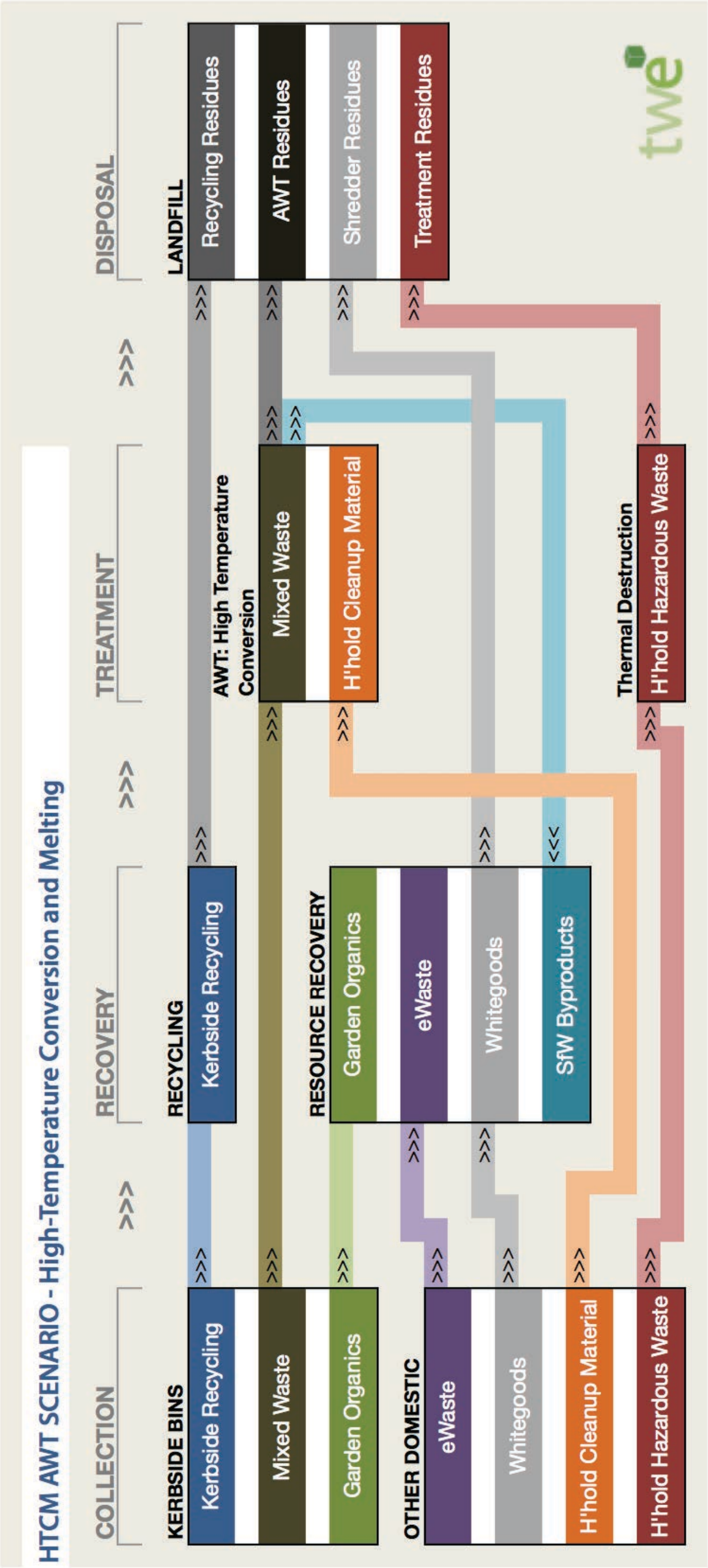


Figure 47. HTCM AWT scenario



Conversion technologies

In this section we present a set of representative conversion technologies that have been selected from our proprietary database as a proxy for each of the technology groups, on the basis of the following set of criteria:

- commercial maturity;
- plant throughput;
- feedstock processing capability;
- process type; and
- energy recovery and syngas processing capability; and
- emissions performance

Selection criteria

Commercial maturity

Technology and operational risk are key considerations in the successful commissioning and operation of energy from waste facilities. For the purpose of the developments of interest to the City of Sydney, we have selected only technologies that can be considered mature with at least one commercial-scale facility operating, and classified as either:

- **demonstrated** with at least one reference facility operating successfully at a commercial-scale;
- **proven** with at least one reference facility in continued, full-commercial operation; or
- **commercial or fully proven** with several reference facilities in continued, full commercial operation.

Plant throughput

In addition to commercial maturity, plant throughput is a key criterion for the selection of suitable conversion technologies.

Our review of technologies and the set of case studies presented in Appendix F have highlighted the risks associated with the scale-up of technologies from demonstration plants to first and subsequent generations of commercial concepts. Selection of suitable technologies should be based on the plant being demonstrated, proven or fully commercial at the scale of interest.

Reactor capacity, or throughput, is expressed in (metric) tonnes per day (tpd). Consistent with established industry practice – see for example (Juniper 2009)Juniper 2009, we adopt the following classification:

- **small-scale facilities** with plant throughput smaller than 25 tpd;
- **medium-scale facilities** with plant throughputs between 25 and 250 tpd; and
- **large-scale facilities** with plant throughputs in excess of 250 tpd.

In the analysis presented below under the *EfW Scenarios* chapter we have identified the potential for development of a medium- to large-scale EfW facility with daily plant throughputs ranging from 144.2 tpd – or 43,802.0 tonnes per year at 85% capacity factor – (MSW feedstock, low-temperature conversion technology) to 487.6 tpd – or 150,248.7 tonnes per year at 85% capacity factor – (mixed MSW and C&I feedstock, high-temperature conversion and melting).

Based on these considerations we have included in the short list technologies with reactor or processing size available in the medium and large-scale ranges, with the required throughputs achievable through development of multiple processing line facilities.

Feedstock processing capability

The key feedstocks of interest for the proposed EfW facility are mixed waste streams from domestic and commercial and industrial sources, with other waste streams (such as shredder residues, sewage sludge and industrial wastes) being considered for co-processing.

The selection has focused on technologies with proven processing capability for these waste stream, either un-processed, or post separation in material recovery facilities (post-MRF) or as a processed refuse derived fuel (RDF).

Conversion technology

Consistent with the set of *Conversion Strategy* scenarios presented below under *EfW Scenarios*, available conversion technologies have been grouped in the following categories:

- **Low Temperature Conversion (LTC)** for technologies operating conversion at temperatures below 750 °C, including slow pyrolysis and fixed-bed gasification technologies;
- **High Temperature Conversion (HTC)** for technologies operating conversion at temperatures at or above 750 °C, including pyro-combustion, pyro-gasification and fluidized bed gasification technologies; and
- **High Temperature Conversion + Melting (HTCM)** for technologies integrating a ultra-high temperature *melting* zone (above 1500 °C) where minerals (ashes) and metals present in the waste stream are brought above their fusion temperature and

recovered respectively as vitrified slag and molten granulates. These include plasma gasification, pyro-gasification + melting and fluidized bed gasification + melting technologies.

Energy recovery and syngas processing capability

The ability to generate a high quality synthesis gas that could be upgraded and delivered off-site to a network of trigeneration installations is a key requirement for the activities the City of Sydney is aiming to develop under its Green Infrastructure Strategy.

Although some technology providers do integrate syngas upgrading concepts in their current designs it should be noted how the configuration of the energy recovery section for EfW plants are typically defined to maximize returns from energy recovery based on the underlying market conditions for heat and power in the region where a plant operates.

Following established practice for waste to energy (WTE) facilities based on mass-burn or fluidized bed combustion, the majority of EfW facilities based on pyrolysis or gasification have historically integrated energy recovery sections designed for direct combustion of the raw synthesis gas (eg without upgrading) and recovery of heat and power in steam generators and steam turbine assemblies.

Increasingly, EfW facilities are designed to integrate intermediate syngas cleaning and upgrading sections, to generate a high-quality clean synthesis gas that can be used in high efficiency conversion technologies (such as gas engines, gas turbines and fuel cells), resulting in flexible operations, and overall improved energy recovery and environmental performance.

The concepts brought forward by the City of Sydney, of developing a market for renewable gases through establishment of a network of trigeneration facilities, is innovative and can be considered in all respects a game-changer in the market for EfW technologies.

While the delivery of clean synthesis gas off-site to industrial facilities (see for example the case study on the Thermoselect Chiba facility, with delivery of syngas to a nearby metalworks furnace via pipeline) or the upgrading and distribution of SNG from upgraded biogas to refuelling stations (see for example emerging C-SNG, or bio-methane refuelling networks in Sweden and Denmark as an example) have had some applications, the platform emerging from the integration of the Renewable Energy and Trigeneration components of the City's Decentralized Energy Master Plans, with the development of an integrated gas supply chain for generation of synthesis gas, upgrade to SNG and delivery to a network of distributed trigeneration facilities represents a further innovation in the use and integration of renewable and synthesis gases.

The review of technologies and the set of case studies presented under the AWT and REMP sections (Appendixes F and G), have identified syngas upgrading and conversion technologies as fully commercial concepts that can be flexibly integrated with thermal conversion technologies as a variation to currently proposed configurations for syngas conditioning/upgrading, energy recovery and air pollution control sections.

In order to provide a representative comparison of syngas yields across the different set of technologies considered, irrespective of the energy recovery configurations, this study has considered the *cold-gas efficiency* (or the ratio of energy in the raw syngas, to energy in the feedstock waste and other auxiliary energy inputs) as the key performance parameter.

At this stage the City of Sydney should consider all technologies matching the set of criteria described above and put forward its requirements for syngas cleaning and upgrading as a key element of its market approach strategy (see below under *Enabling Actions*).

Emissions performance

The ability of thermal conversion and energy recovery technologies to operate within regulated air pollutant emission limits is a key consideration for successful commissioning and operation of EfW facilities. Failure to comply with such limits could result in significant commissioning delays, require costly retrofits to any Air Pollution Control (APC) systems and cause environmental authorities to force continued shutdowns of the facility, all ultimately affecting economic viability.

This review of conversion technologies has confirmed the ability of operating EfW facilities with suitably designed APC systems to operate well within the air pollutant emission standards in force in Europe, the USA and Japan, and the inherent advantages of conversion technologies with intermediate gas clean-up technologies in terms of more compact and less costly APC trains when compared to similar capacity facilities based on incineration. All commercially mature technologies reviewed comply with the relevant emission regulations.

Selected technologies

The table below presents the resulting selection of representative mature conversion technologies that have been adopted for the modelling efforts presented in this section.

Table 15. Representative AWT technologies

Supplier	Technology				
	Name	Type	Scale	Maturity	Application
Low-Temperature Conversion (LTC)					
Thide Environmental	EddiTh	Slow pyrolysis	small-medium	proven	MSW, industrial
IES	APS	Pyro-combustion	medium	demonstrated	MSW, industrial
Entech-RES	WtGas	Fixed-bed gasification	small-medium	commercial	MSW, sludge
High-Temperature Conversion (HTC)					
WasteGen	Pyropleq	Pyro-gasification	small-medium	proven	MSW, sludge
TPS	Termiska AB	Fluid-bed gasification	small-medium	proven	MSW, RDF
High-Temperature Conversion + Melting (HTCM)					
AlterNRG	PGVR	Plasma gasification	medium-large	proven	MSW, SR, RDF
Ebara TwinRec	TFiG	Fluid-bed gasification + melting	medium-large	commercial	MSW, SR
Thermoselect	HTR	Pyro-gasification + melting	medium-large	commercial	MSW

The tables below presents typical conversion and energy recovery performances for the representative technologies in each of the three conversion strategies, sourced from a proprietary TWE database of performances, costs and emissions for thermal conversion technologies.

Table 16. Low Temperature Conversion technologies – performance data

	Low Temperature Conversion		
	Pyrolysis	Pyro-combustion	Fixed bed gasification
Reference technology	Thide - EddiTh	IES - APS	Entech-RES - WtGas
Utility requirements			
Electricity, kWh/tfeed	188.40	48.95	33.14
Natural gas, GJ/tfeed	1.23	1.436	
Fuel oil, GJ/tfeed			0.73
Recoverable by-product yields			
Aggregates, kg/tfeed	--	--	--
Metals, kg/tfeed	27.00	--	--
Minerals, kg/tfeed	--	--	30.00
Water, kg/tfeed	--	38.4	--
Residue yields			
Char	--	119.99	156.70
Ash	343.10	223.45	146.58
Other	--	--	
Performances			
MASS REDUCTION (SOLIDS)	65.69%	65.66%	69.67%
COLD GAS EFFICIENCY, HHV	51.30%	56.97%	54.90%

Table 17. High Temperature Conversion technologies – performance data

	High Temperature Conversion	
	Pyro-gasification	Fluid Bed gasification
Reference technology	WasteGen PyroPleq	TPS Termiska AB
Utility requirements		
Electricity, kWh/tfeed	238.11	195.79
Natural gas, GJ/tfeed	0.92	2.16
Fuel oil, GJ/tfeed	0.26	
Recoverable by-product yields		
Aggregates, kg/tfeed	--	--
Metals, kg/tfeed	22.00	14.79
Minerals, kg/tfeed	--	--
Water, kg/tfeed	--	--
Residue yields		
Char	13.7	28.3
Ash	275.31	175.18
Other	--	--
Performances		
MASS REDUCTION (SOLIDS)	71.10%	79.65%
COLD GAS EFFICIENCY, HHV	57.60%	60.30%

Table 18. High Temperature Conversion + Melting technologies – performance data

	High Temperature Conversion + Melting		
	Pyro-gasification + melting	Fluid-bed gasification + melting	Plasma Gasification
Reference technology	Thermoselect HTR	Ebara TwinRec	AlterNRG PGVR
Utility requirements			
Electricity, kWh/tfeed	229.86	215.68	291.40
Natural gas, GJ/tfeed	1.28	0.44	
Fuel oil, GJ/tfeed		1.21	
Recoverable by-product yields			
Aggregates, kg/tfeed	244.5	--	305.6
Metals, kg/tfeed	32	4.44	--
Minerals, kg/tfeed	25	--	--
Water, kg/tfeed	376	--	--
Residue yields			
Char, kg/tfeed	--	--	4.6
Ash, kg/tfeed	--	50.00	--
Other, kg/tfeed	30.35	--	28.8
Performances			
MASS REDUCTION (SOLIDS)	96.97%	95.00%	96.66%
COLD GAS EFFICIENCY, HHV	52.86%	59%	67.34%

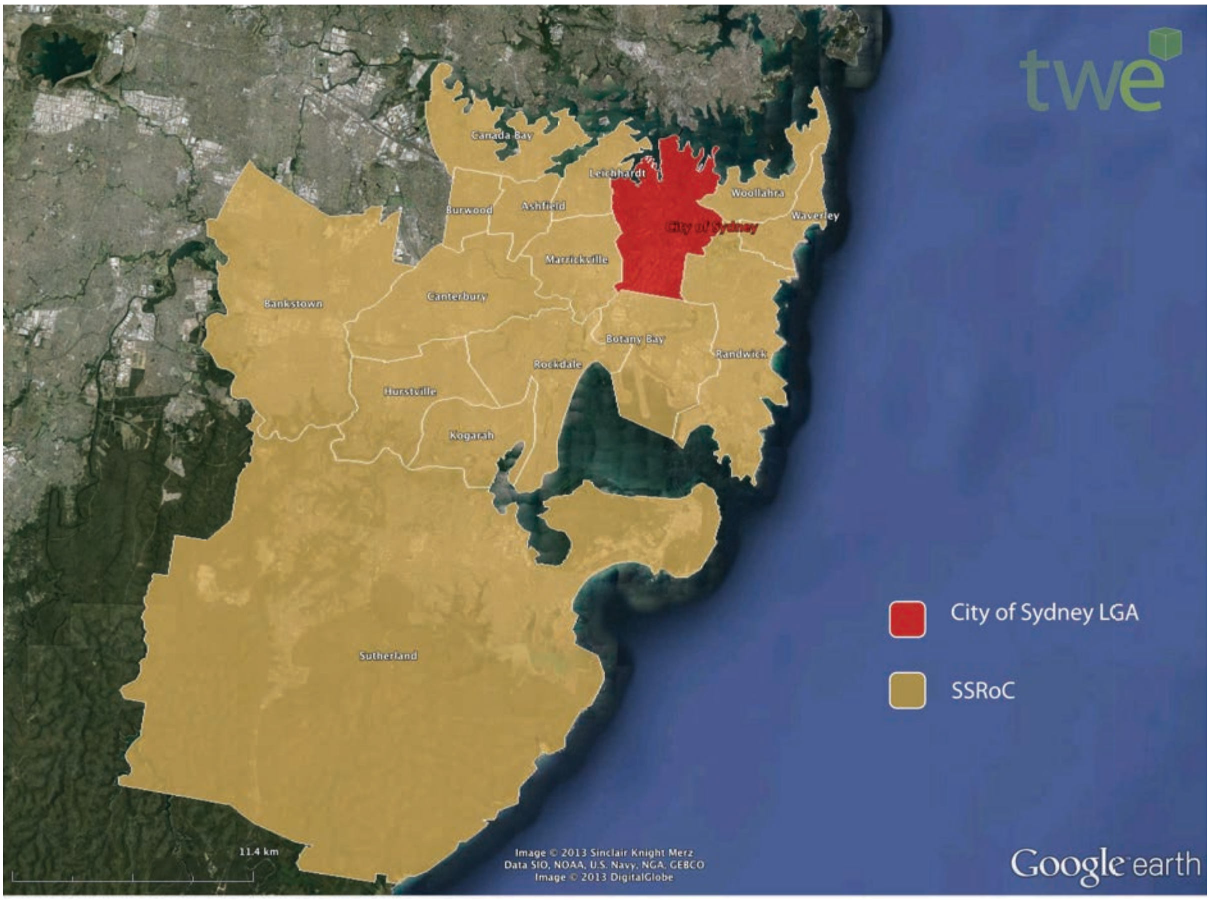
Resource scenarios

Resource catchments

The analysis presented here considers two resource catchments:

- **City of Sydney LGA**; and
- **SSROC region,** covering the LGAs within the Southern Sydney Regional Organization of Councils (SSROC)[17], including the City of Sydney.

Figure 48. Syngas from Waste scenarios - resource catchments



Target resource

Thermal conversion is a treatment option more advanced than mechanical-biological treatment under both a waste management and energy recovery perspective.

For this reason we assume that Syngas from Waste facilities, once in operation, will replace MBT as the preferred Alternative Waste Treatment (AWT) option for Councils in the catchment regions. Accordingly, the target feedstock resource considered within this study is the fraction of waste generated that is not source-separated for downstream resource

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[17] including Ashfield, Bankstown, Botany Bay, Burwood, Canada Bay, Hurtsville, Kogarah, Marrickville, Randwick, Rockdale, Sutherland, Sydney, Waverley and Wollahra

recovery, eg. the *mixed waste* from the domestic and commercial and industrial waste streams. The charts below present projections of these resources for the two catchments.

Figure 49. MSW – mixed waste (non recyclables), 2009-2030

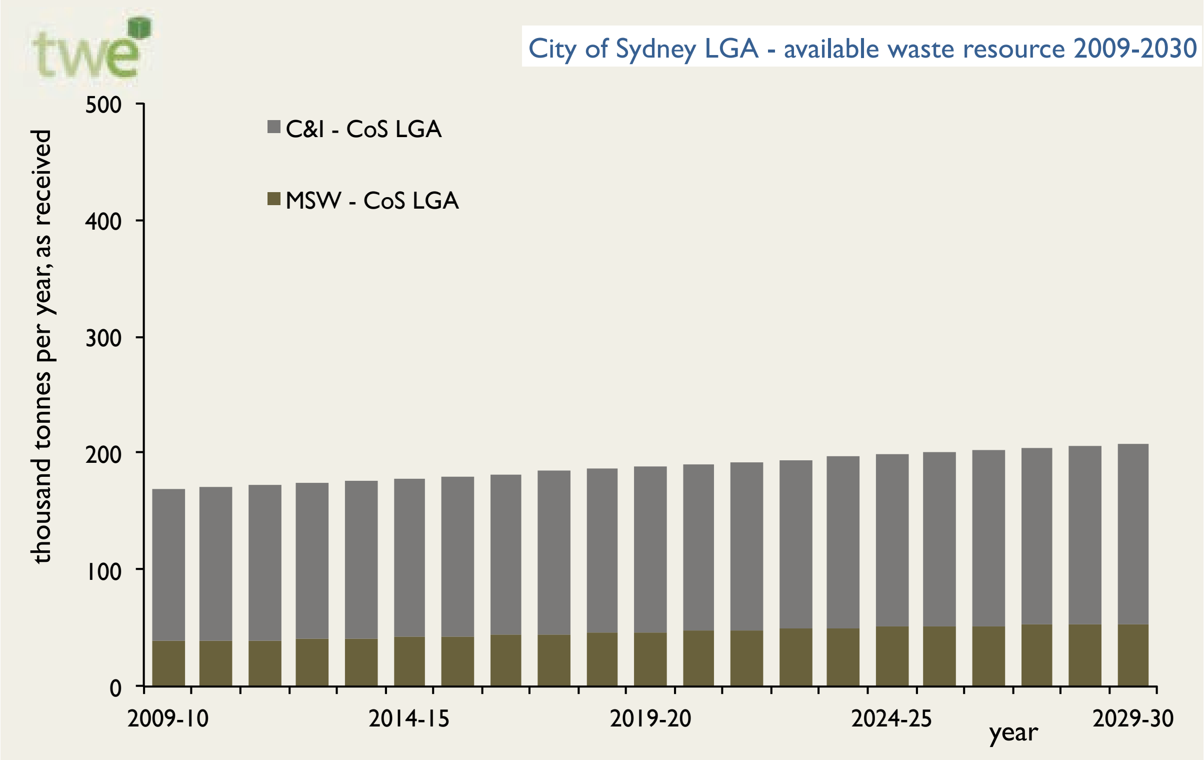
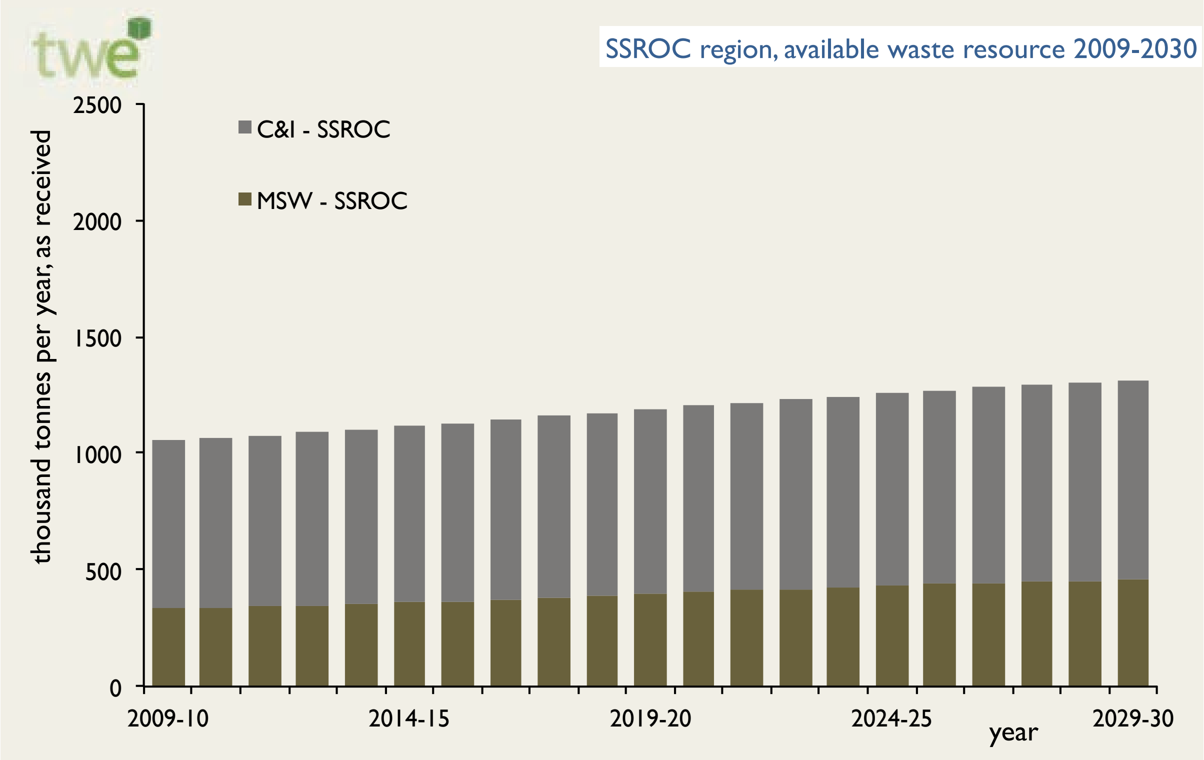


Figure 50. MSW – mixed waste (non recyclables), 2009-2030



Implementation scenarios

The scenario framework initially considers four alternative feedstock mix scenarios:

- **City of Sydney LGA – MSW**, considering the amount of mixed waste from domestic sources collected within the City of Sydney LGA;
- **City of Sydney LGA – MSW + C&I**, considering the amount of mixed waste from the domestic, commercial and industrial sources collected within the City of Sydney LGA;
- **SSROC – MSW**, considering the amount of mixed waste from domestic sources collected within the City of Sydney LGA;
- **SSROC – MSW + C&I**, considering the amount of mixed waste from the domestic, commercial and industrial sources collected within LGAs of the SSROC region.

Feedstock resource throughputs

The table below summarizes the processable fractions for each conversion technology.

Table 19. Syngas from Waste conversion technologies – waste fractions processed, by conversion strategy

STRATEGY/TECHNOLOGY	Mixed Waste Fractions					
	Combustible	Inert	Putrescible	Hazardous	Other	SR [a]
Low-Temperature Conversion (LTC)						
Pyro-Combustion	✓	✕	✓	✕	✕	✕
Slow Pyrolysis	✓	✕	✓	✕	✕	✕
Fixed-Bed Gasification	✓	✕	✓	✕	✕	✕
High-Temperature Conversion (HTC)						
Fluid Bed Gasification	✓	✕	✓	✕	✕	✕
Pyro-Gasification	✓	✕	✓	✕	✕	✕
High-Temperature Conversion + Melting (HTCM)						
Pyro-Gasification + Melting	✓	✓	✓	(✓)	✕	(✓)
Fluid Bed Gasification + Melting	✓	✓	✓	(✓)	✕	(✓)
Plasma Gasification	✓	✓	✓	(✓)	✕	(✓)

[a] Shredder Residues from Whitegoods processing at resource recovery facility

Within the scope of this study, Low-and High-Temperature Conversion technologies are considered to process the combustible and the putrescible fractions of the incoming residual waste stream. High-Temperature Conversion + Melting technologies, by virtue of the high-temperatures reached immediately downstream (for pyro-gasification + melting and fluid-bed gasification + melting) or inside (for plasma gasification) the main reactor, have the ability to process the inert fraction of the residual waste stream[18].

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[18] The hazardous and shredder residues fractions can be also processed by HTCM technologies, but have been excluded from this assessment as, based on experience with the City of Sydney domestic waste streams, they are delivered to specialized alternative waste treatment facilities.

Waste resource data for 2029-30, composition analysis and the matrix of processable fractions, are used to determine feedstock resource throughputs presented below.

Figure 51. MSW – City of Sydney LGA, annual feedstock throughputs, by conversion strategy

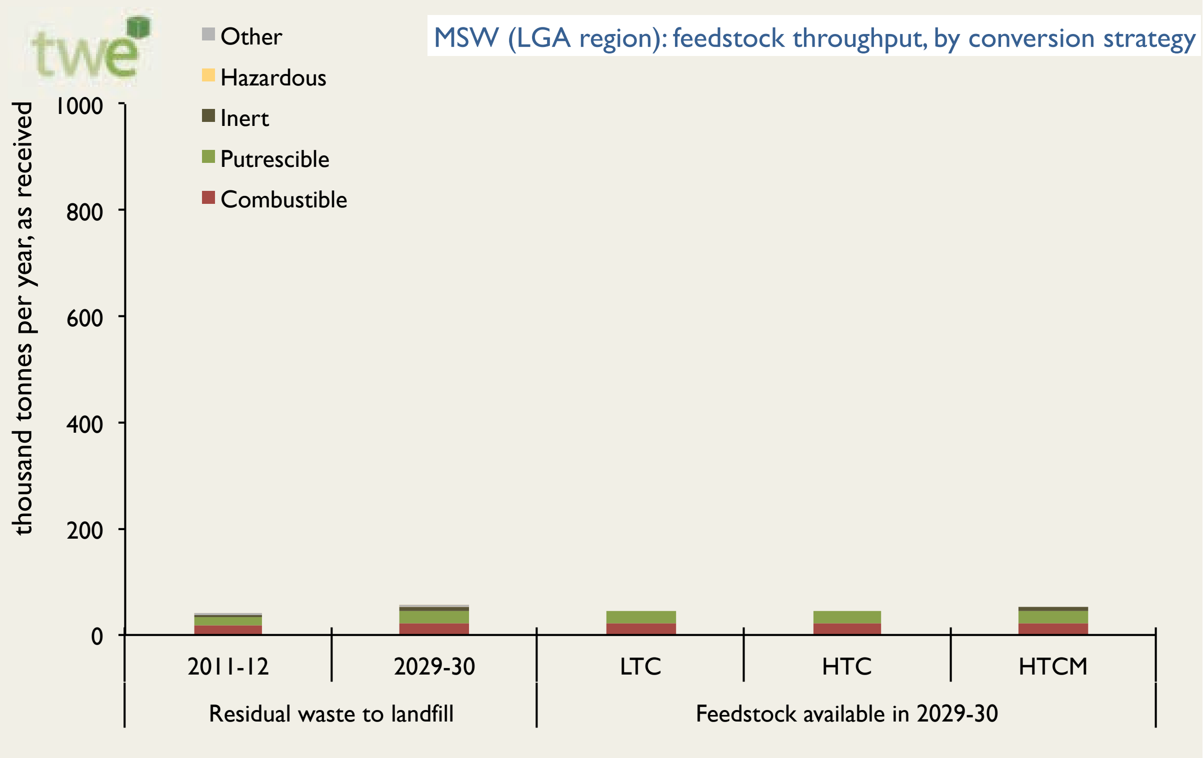


Figure 52. C&I – City of Sydney LGA, 2029-30 annual feedstock throughputs, by conversion strategy

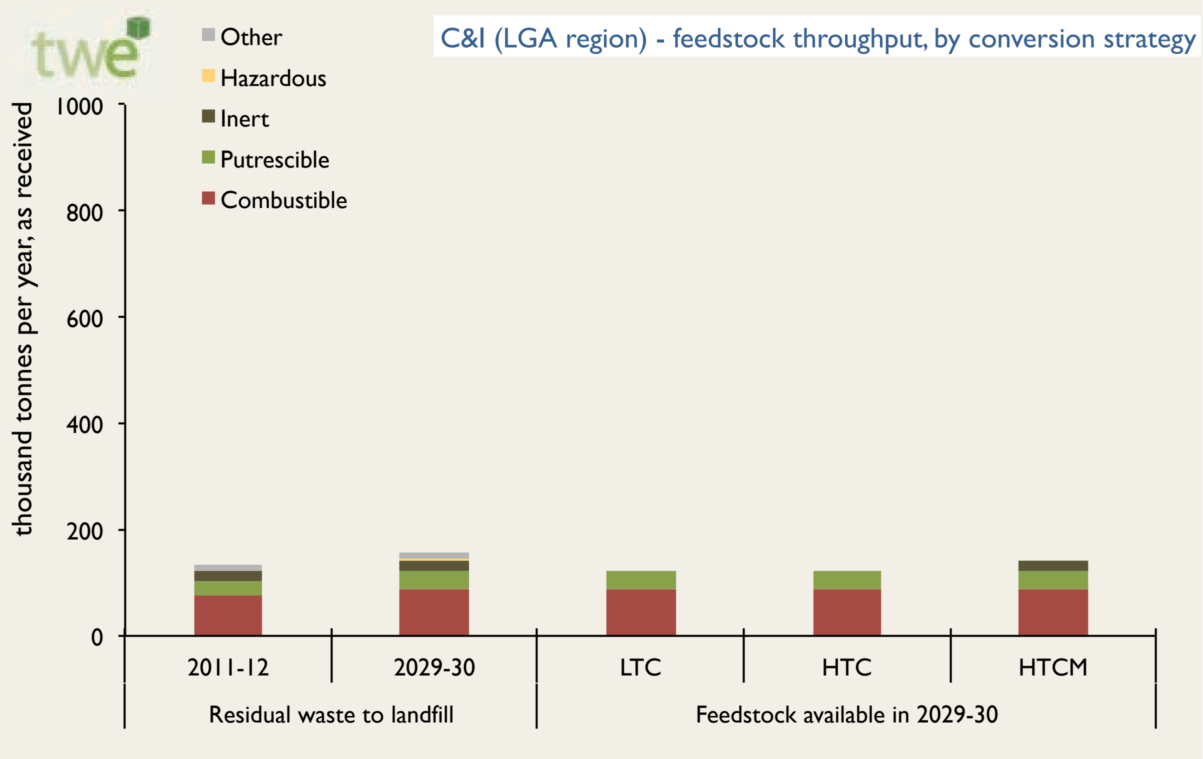


Figure 53. MSW – SSROC region, annual feedstock throughputs, by conversion strategy

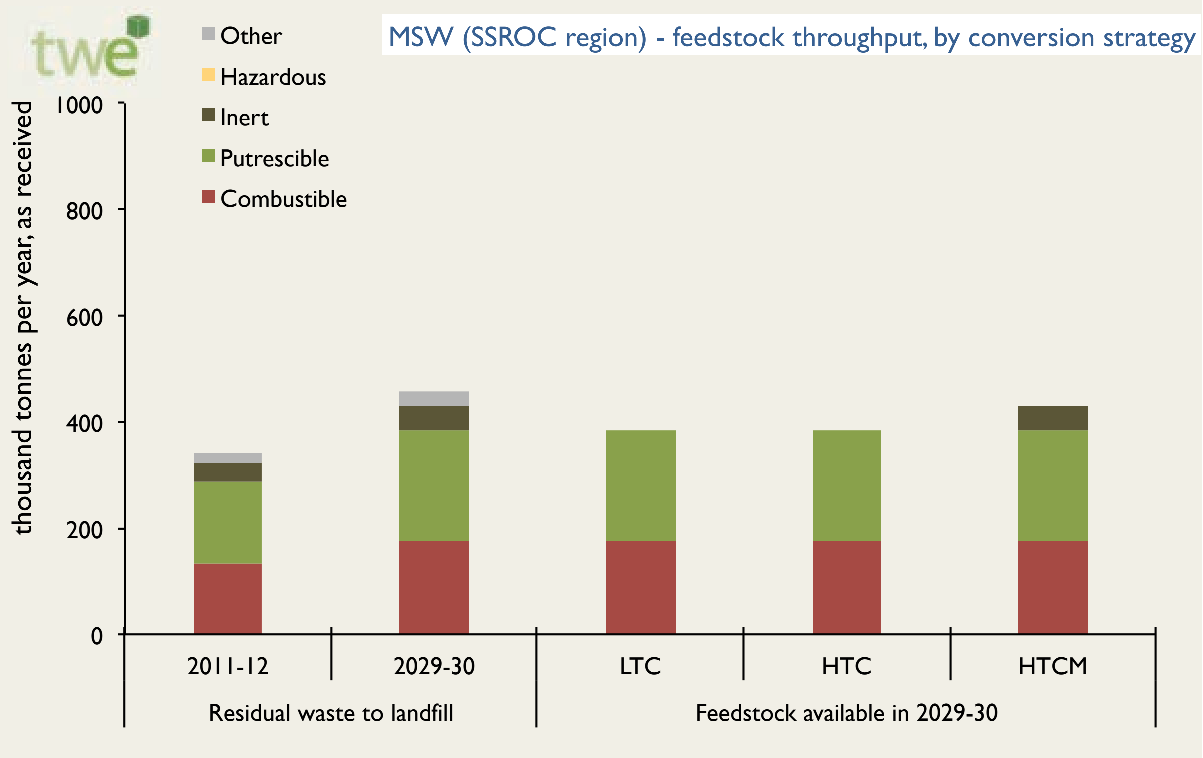
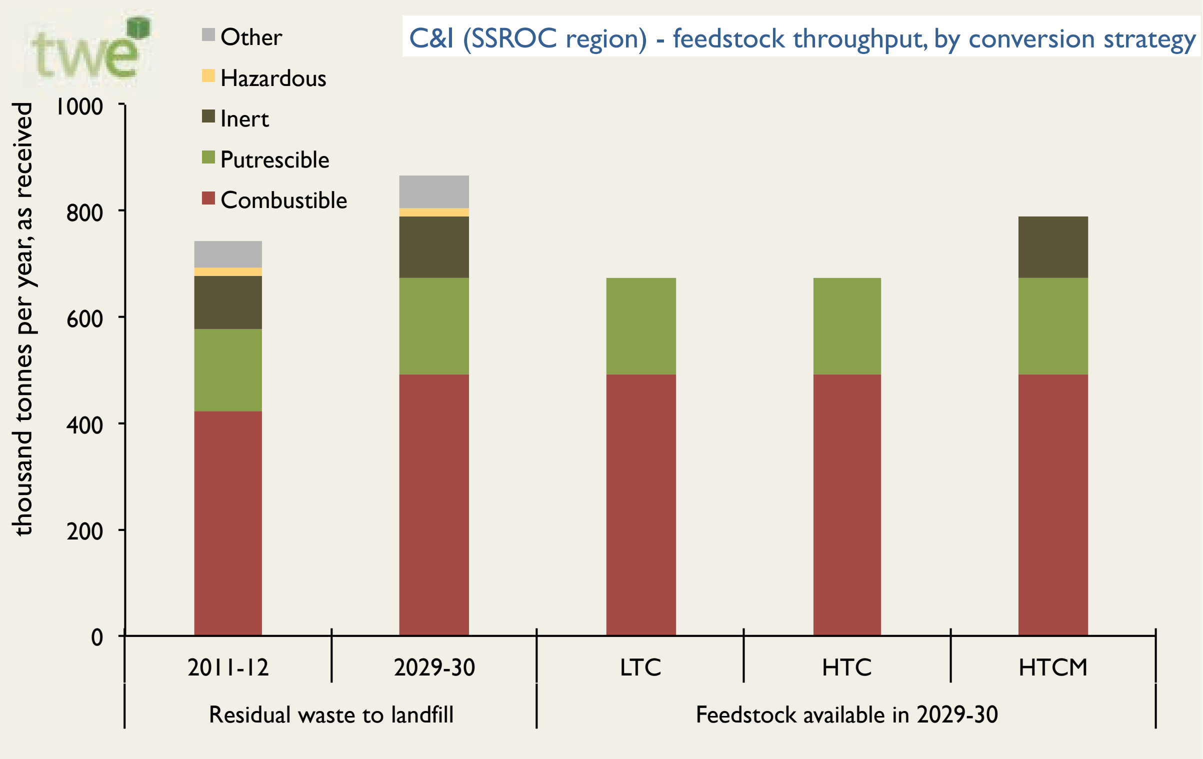


Figure 54. MSW – SSROC region, 2029-30 annual feedstock throughputs, by conversion strategy



Scenario analysis

In this section we present modelling results across the set of Syngas from Waste scenarios in terms of the following key performances:

- **raw syngas yield**, in petajoules per year (PJ/y, HHV basis) estimated, along with an assessment of the renewable energy fractions, for each conversion technology and implementation scenario;
- **net delivered SNG**, where the amount of SNG delivered to the City, net of own use and losses along the upgrading (SNG generation from raw syngas) and delivery chain is estimated;
- **waste diversion from landfill,** or the ability to contribute further to the City's resource recovery efforts and further reduce the amount of residual waste (incl. AWT residuals) that is sent to landfill, in tonnes per year (t/y, as received), by 2029-30.

Raw syngas yield

The raw syngas yield is estimated on the basis of the performance parameters presented earlier, on the basis of the following steps:

1. **design plant throughput**
2. **plant thermal input**
3. **syngas thermal output**
4. **syngas yield**
5. **renewable fraction**

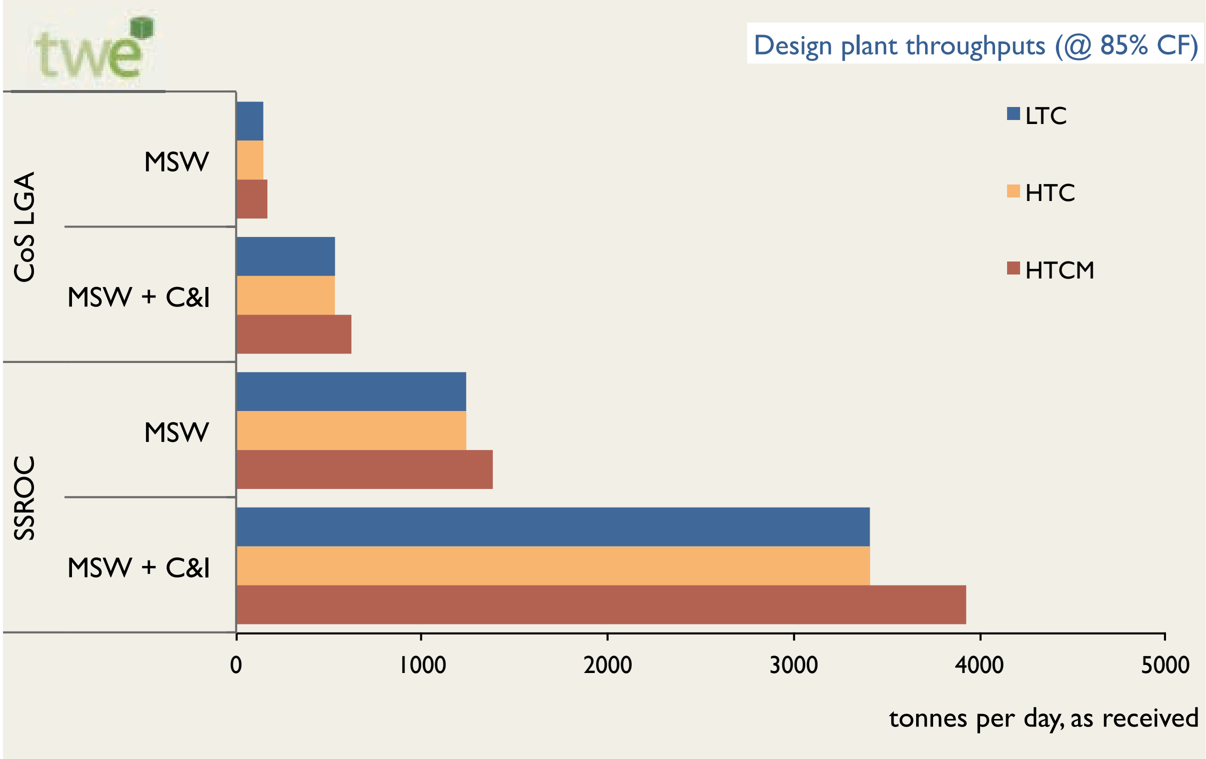
Design plant throughput

The first step is to determine the design plant throughput, in tonnes per day, required under each scenario has been determined based on the waste resource available in 2029-30 (design year) and assuming a capacity factor of 85%.

The resulting figures, also summarized in the diagram below, are:

- **City of Sydney LGA – MSW,** from 141.7 (LTC/HTC) to 167.4 (HTCM) tpd;
- **City of Sydney LGA – MSW + C&I,** from 530.8 (LTC/HTC) to 623.6 (HTCM) tpd;
- **SSROC region – MSW,** from 1,237.0 (LTC/HTC) to 1,382.6 (HTCM) tpd; and
- **SSROC region – MSW + C&I,** from 3,406.5 (LTC/HTC) to 3,925.7 (HTCM) tpd.

Figure 55. Syngas from Waste – design plant throughputs, by conversion strategy and implementation scenario



Plant thermal input

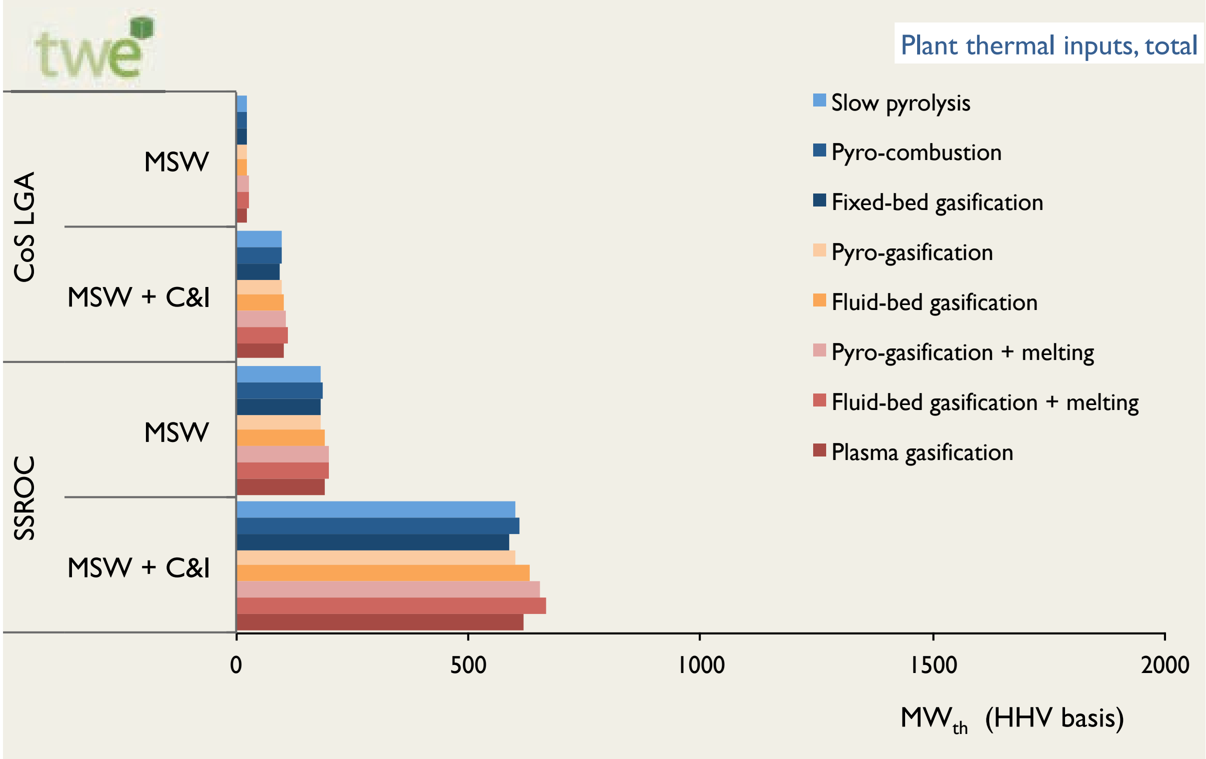
The plant thermal input – expressed in MW_{th} (HHV basis) – is a combination of the following:

- the *thermal energy content of the feedstock*, calculated on the basis of the design plant throughputs presented earlier, and the estimated energy contents (HHV basis) presented under *Section 3. Feedstock* Resources;
- the *auxiliary thermal input*, calculated on the basis of the design plant throughputs presented earlier, and the auxiliary fuel requirements for each of the conversion technologies considered.

The resulting figures, also summarized in the diagram below, are:

- **City of Sydney LGA – MSW,** ranging from 21.4 MW_{th} for LTC – fixed bed gasification, to 26.1 MW_{th} to HTCM – pyro-gasification + melting;
- **City of Sydney LGA – MSW + C&I,** ranging from 94.4 MW_{th} for LTC – fixed bed gasification to 109.9 MW_{th} to HTCM – pyro-gasification + melting;
- **SSROC region – MSW,** ranging from 180.4 MW_{th} for LTC – fixed bed gasification to 199.9 MW_{th} to HTCM – pyro-gasification + melting; and
- **SSROC region – MSW + C&I,** ranging from 587.4 MW_{th} for LTC – fixed bed gasification to 667.0 MW_{th} to HTCM – pyro-gasification + melting.

Figure 56. Syngas from Waste – plant thermal inputs, by conversion technology and implementation scenario



Raw syngas yield

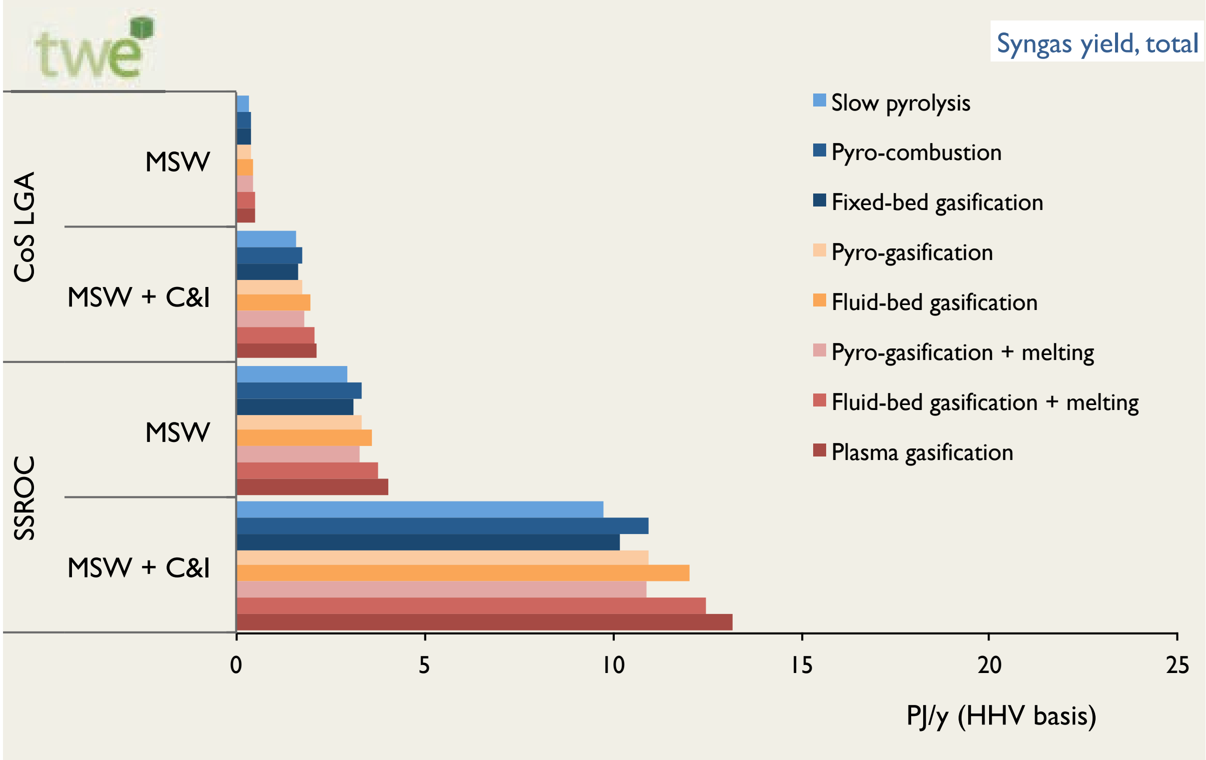
The raw syngas yield – expressed in petajoules per year (PJ/y, HHV basis) – is a calculated from the plant thermal inputs by applying the following:

- *Cold Gas* Efficiency (CGE) figures presented earlier for each of the thermal conversion technologies considered; and
- a *design capacity factor* of 85%.

The resulting figures, also summarized in the diagram below, are:

- **City of Sydney LGA – MSW,** ranging from 0.36 PJ/y for LTC – slow pyrolysis, to 0.50 PJ/y to HTCM – plasma gasification;
- **City of Sydney LGA – MSW + C&I,** ranging from 1.58 PJ/y for LTC – slow pyrolysis, to 2.13 PJ/y to HTCM – plasma gasification;
- **SSROC region – MSW,** ranging from 2.97 PJ/y for LTC – slow pyrolysis, to 4.06 PJ/y to HTCM – plasma gasification; and
- **SSROC region – MSW + C&I,** ranging from 9.75 PJ/y for LTC – slow pyrolysis, to 13.16 PJ/y to HTCM – plasma gasification.

Figure 57. Syngas from Waste – raw syngas yields, by conversion technology and implementation scenario



Renewable syngas yield

The renewable energy content of the syngas – calculated as the renewable energy content of the total energy input into the conversion reactor, by adjusting renewable energy content feedstock figures presented under *Section 3. Feedstock Resources*, to account for the auxiliary energy requirements for each of the conversion technologies – is presented below:

- **slow pyrolysis –** 62.9% (LGA – MSW), 67.4% (SSROC – MSW), 62.3% (C&I – all regions);
- **pyro-combustion –** 61.9% (LGA – MSW), 66.5% (SSROC – MSW), 61.6% (C&I – all regions);
- **fixed-bed gasification –** 65.3% (LGA – MSW), 69.4% (SSROC – MSW), 64.3% (C&I – all regions);
- **pyro-gasification –** 63.1% (LGA – MSW), 67.6% (SSROC – MSW), 62.5% (C&I);
- **fluid-bed gasification –** 58.8% (LGA – MSW), 63.8% (SSROC – MSW), 59.1% (C&I – all regions);
- **pyro-gasification + melting –** 60.5% (LGA – MSW), 64.6% (SSROC – MSW), 59.8% (C&I – all regions);
- **fluid-bed gasification + melting –** 58.9% (LGA – MSW), 63.2% (SSROC – MSW), 58.4% (C&I – all regions); and

- **plasma gasification –** 65.3% (LGA – MSW), 68.9% (SSROC – MSW), 63.7% (C&I – all regions);

Figure 58. Syngas from Waste – syngas renewable energy content, LTC technologies, by resource

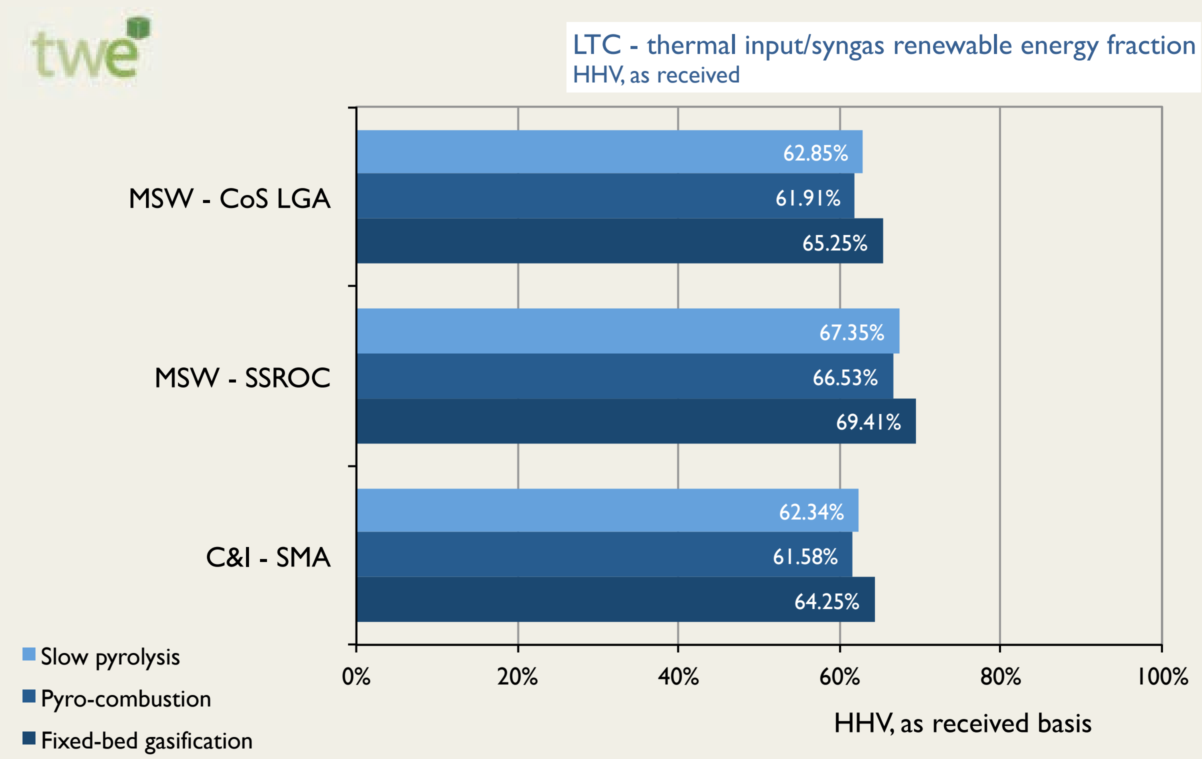


Figure 59. Syngas from Waste – syngas renewable energy content, HTC technologies, by resource

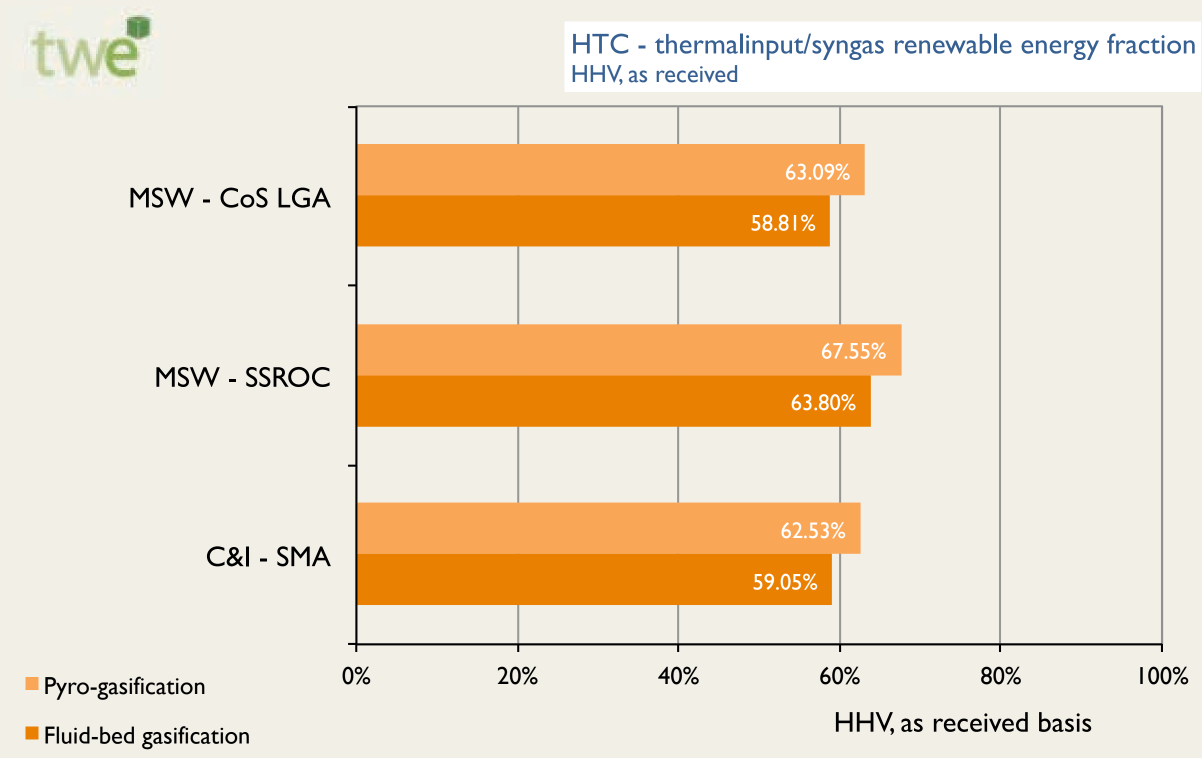
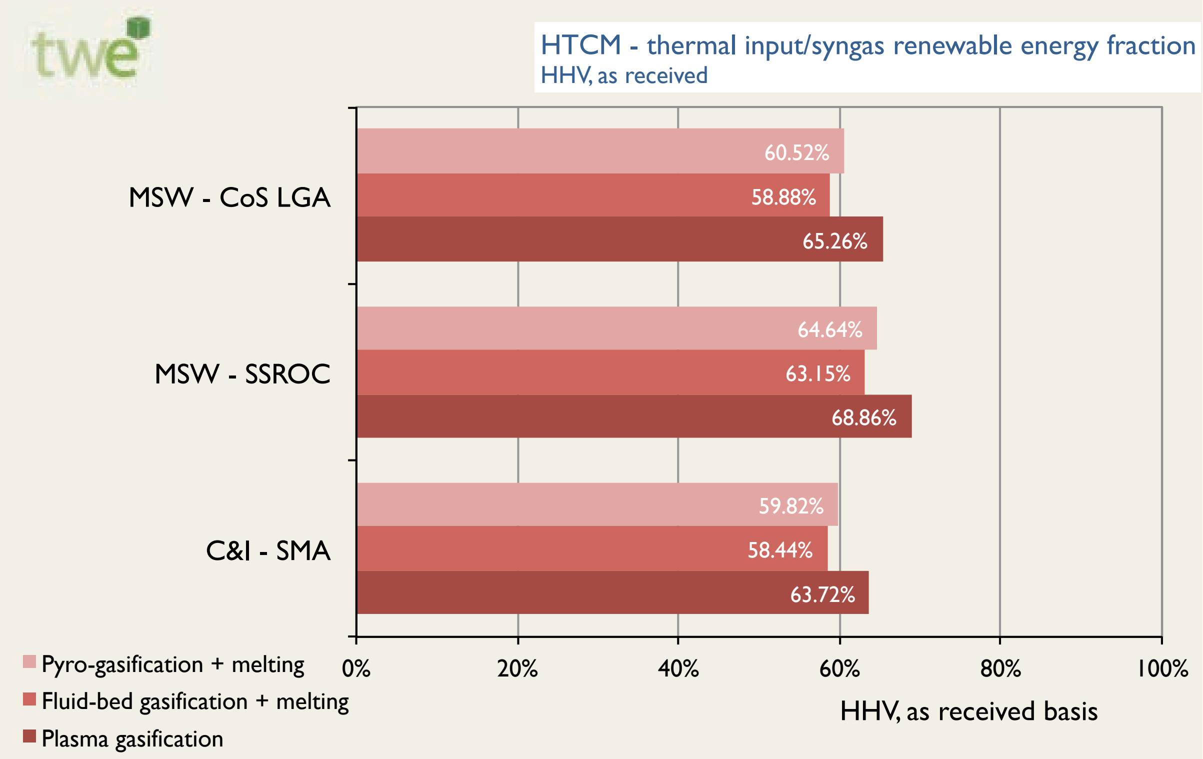
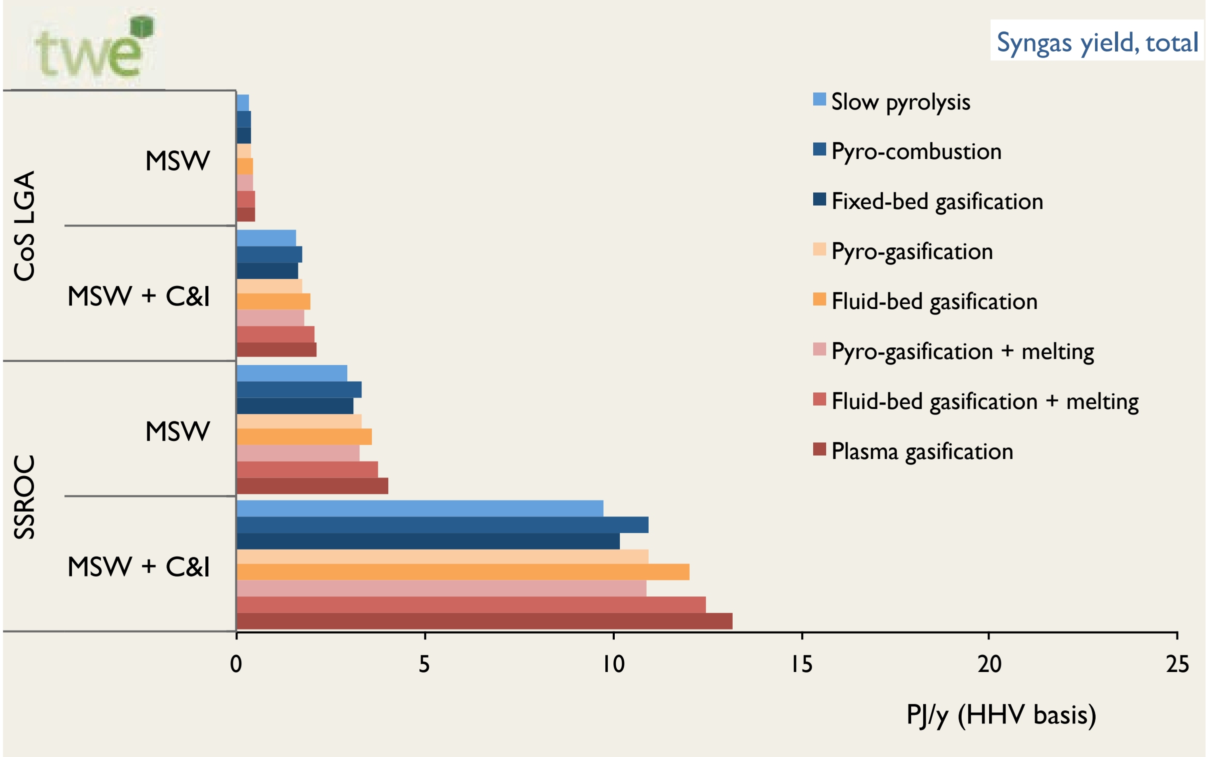


Figure 60. Syngas from Waste – syngas renewable energy content, HTCM technologies, by resource



The resulting renewable syngas yield figures are summarized in the diagram below.

Figure 61. Syngas from Waste – raw syngas yields, by conversion technology and implementation scenario



- **City of Sydney LGA – MSW,** ranging from 0.23 PJ/y for LTC – slow pyrolysis, to 0.33 PJ/y to HTCM – plasma gasification;
- **City of Sydney LGA – MSW + C&I,** ranging from 0.98 PJ/y for LTC – slow pyrolysis, to 1.37 PJ/y to HTCM – plasma gasification;
- **SSROC region – MSW,** ranging from 2.00 PJ/y for LTC – slow pyrolysis, to 2.80 PJ/y to HTCM – plasma gasification; and
- **SSROC region – MSW + C&I,** ranging from 6.23 PJ/y for LTC – slow pyrolysis, to 8.59 PJ/y to HTCM – plasma gasification.

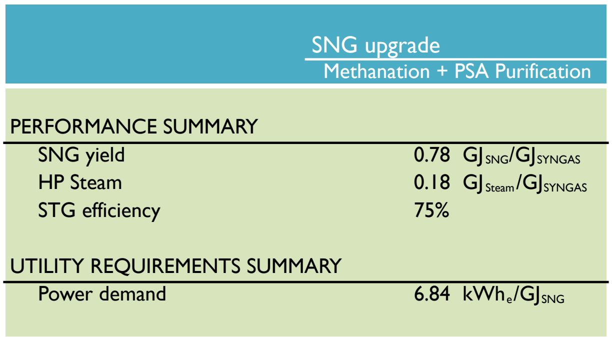
Net delivered SNG

Syngas upgrading

The raw syngas from the Syngas from Waste facility can be upgraded to substitute natural gas (SNG) through a methanation followed by a purification step based on pressure swing adsorption (PSA).

The key performance and operational assumptions for this process, based on the TREMP™ process are summarized in the table below.

Table 20. Upgrading - technology performances and utility requirements



	SNG upgrade Methanation + PSA Purification	
PERFORMANCE SUMMARY		
SNG yield	0.78	GJ_{SNG}/GJ_{SYNGAS}
HP Steam	0.18	GJ_{Steam}/GJ_{SYNGAS}
STG efficiency	75%	
UTILITY REQUIREMENTS SUMMARY		
Power demand	6.84	kWh_e/GJ_{SNG}

As discussed earlier in *Section 2. Syngas Utilization and Upgrading*, syngas upgrading to SNG via methanation yields 78% of the energy content in the incoming raw syngas stream as SNG. The process is highly exothermic, with the balance of the raw syngas energy released as heat. Based on commercial practice, we assume this heat to be recovered in a heat recovery steam generator (HRSG), with typical recovery efficiencies of 80%. This steam could be used upstream to support the gasification process, or for electricity generation in a steam turbine generator (STG) assembly.

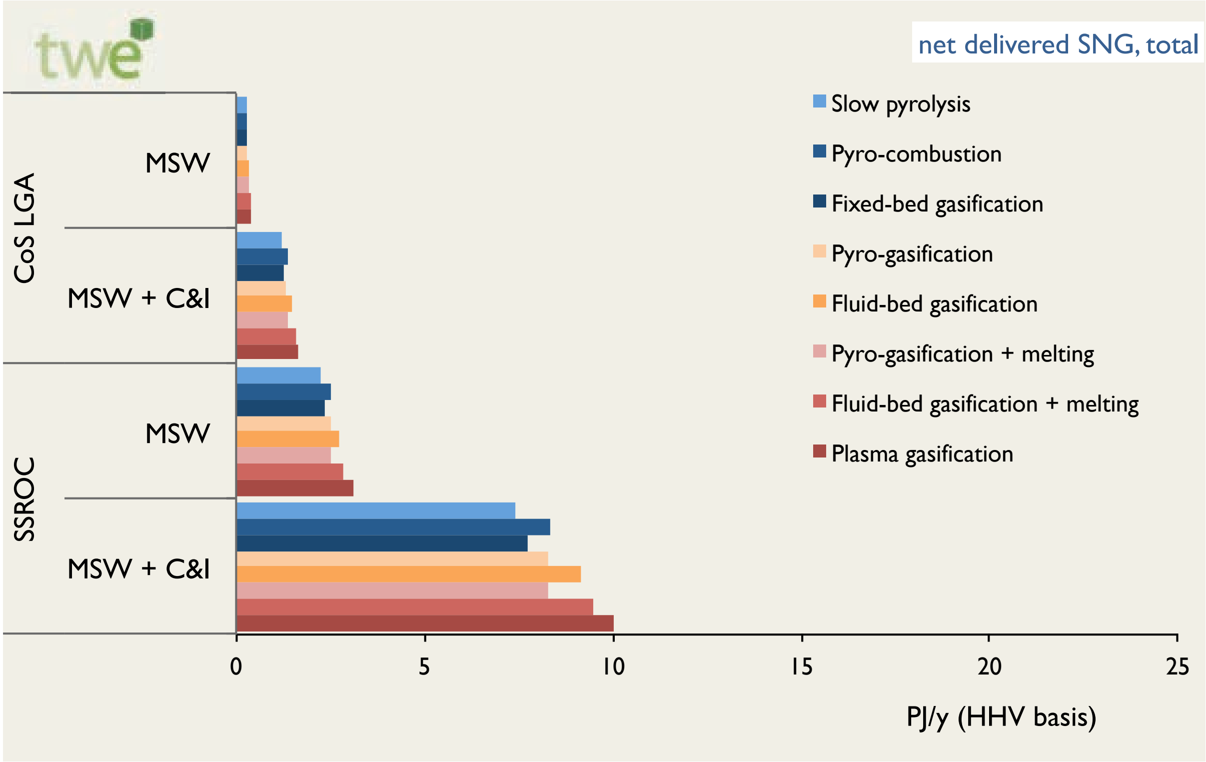
SNG delivery

The net delivered SNG for this pathway is calculated for each supply resource on the basis of the *unaccounted-for gas* (UAG) metric, published annually by the New South Wales Government.

The UAG, defined as the ratio of the annual gas output from the network, to the annual inflow, is a global measure accounting for fugitive losses and own consumption along the pipeline network. The latest reported figure, for 2010-11, was 2.45% (NSW TI 2012).

The resulting figures for net, delivered SNG are presented below.

Figure 62. Syngas from Waste – net, delivered SNG, by conversion technology and implementation scenario



- **City of Sydney LGA – MSW,** ranging from 0.27 PJ/y for LTC – slow pyrolysis, to 0.38 PJ/y to HTCM – plasma gasification;
- **City of Sydney LGA – MSW + C&I,** ranging from 1.20 PJ/y for LTC – slow pyrolysis, to 1.62 PJ/y to HTCM – plasma gasification;
- **SSROC region – MSW,** ranging from 2.25 PJ/y for LTC – slow pyrolysis, to 3.09 PJ/y to HTCM – plasma gasification; and
- **SSROC region – MSW + C&I,** ranging from 7.42 PJ/y for LTC – slow pyrolysis, to 10.01 PJ/y to HTCM – plasma gasification.

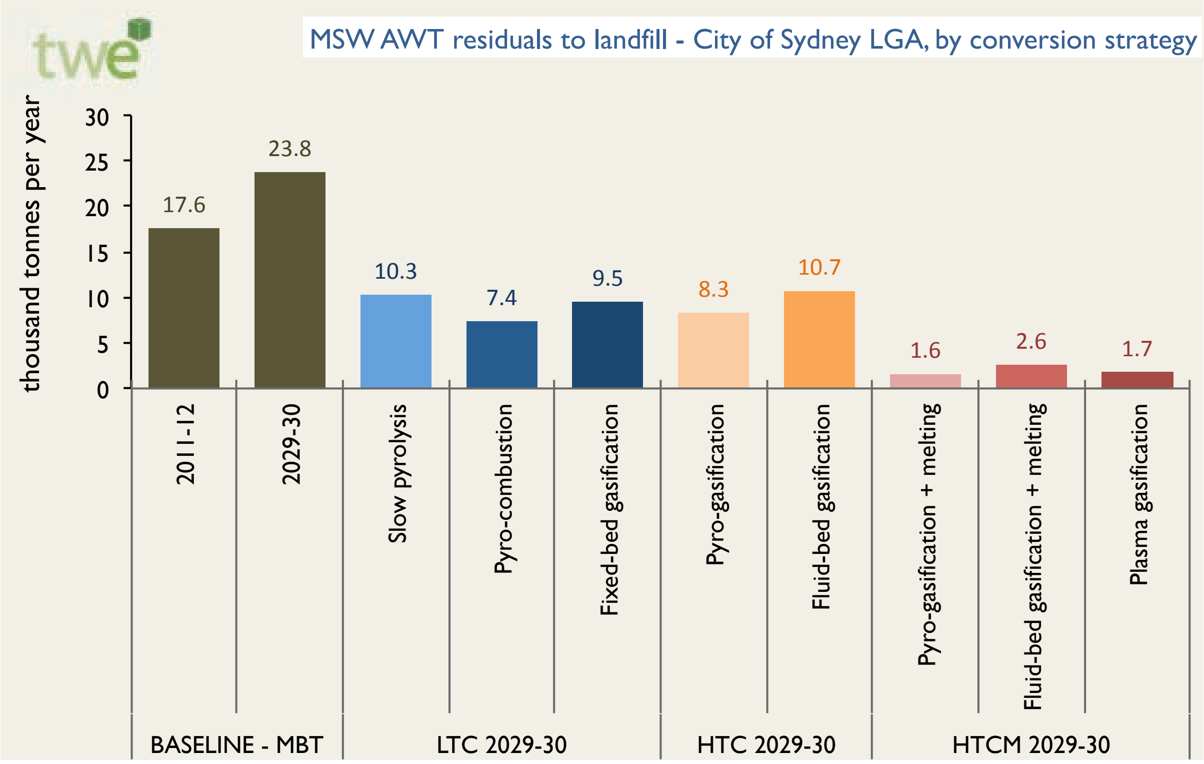
Diversion from landfill

In this section we present results of the total diversion from landfill achieved by 2029-30 for each technology for the domestic waste stream collected within the City of Sydney LGA.

AWT residuals to landfill

The amount of residues delivered to landfill in 2029-30 is reported in the diagram below for each of the conversion technologies, alongside with the amounts of AWT residuals delivered to landfill under the baseline solution (98% of post-MRF residuals delivered to mechanical-biological treatment).

Figure 63. AWT residuals to landfill - MSW, City of Sydney LGA



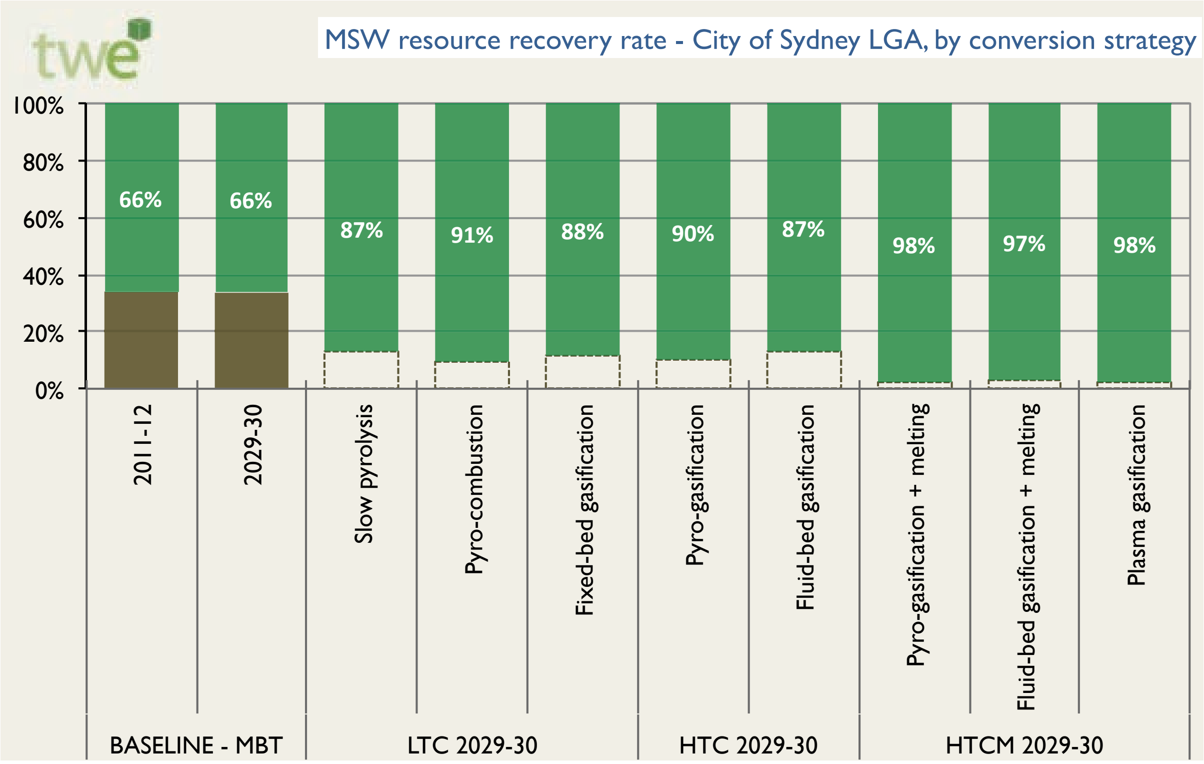
- **mechanical-biological treatment (baseline) –** from 17,281.2 tonnes per year in 2011-12, up to 23,783.6 tonnes per year by 2029-30;
- **slow pyrolysis –** 10,285.6 tonnes per year by 2029-30;
- **pyro-combustion –** 7,359.6 tonnes per year by 2029-30;
- **fixed-bed gasification –** 9,518.4 tonnes per year by 2029-30;
- **pyro-gasification –** 8,305.4 tonnes per year by 2029-30;
- **fluid-bed gasification –** 10,701.7 tonnes per year by 2029-30;
- **pyro-gasification + melting –** 1,575.9 tonnes per year by 2029-30;
- **fluid-bed gasification + melting –** 2,596.2 tonnes per year by 2029-30; and
- **plasma gasification –** 1,734.6 tonnes per year by 2029-30.

Resource recovery

In order to evaluate total diversion from landfill, we combine the AWT residuals to landfill figures with figures from other resource recovery activities, to obtain the resource recovery rate for the MSW component of waste collected within the City of Sydney LGA, across each conversion technology scenario.

All the technologies bring significant benefits against the baseline scenario with mechanical-biological treatment, bringing resource recovery rate from 66% in the baseline scenario, up to between 87% (slow pyrolysis) and 98% (pyro-gasification + melting and plasma gasification. The results are summarised in the diagram below.

Figure 64. AWT residuals to landfill - MSW, City of Sydney LGA



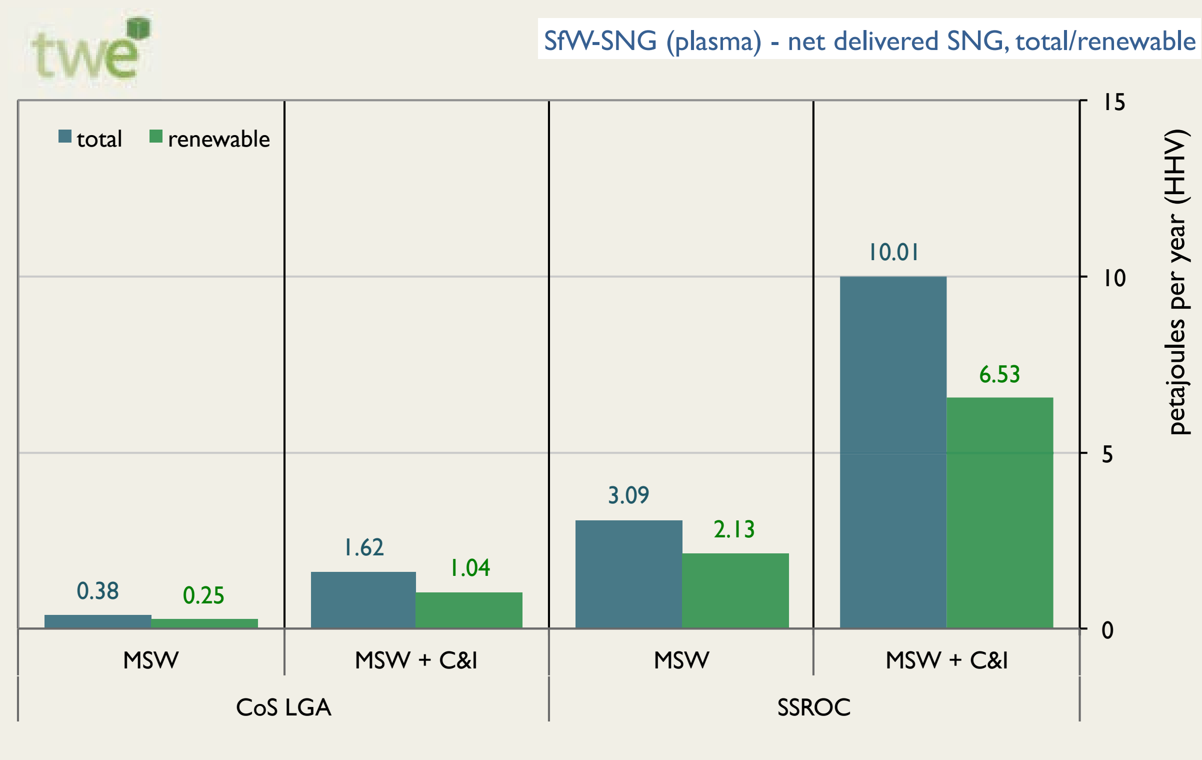
Conclusions

The modelling presented has shown how High-Temperature Conversion + Melting (HTCM) technologies deliver the highest energy recovery and waste management benefits, enabling the City to divert the highest amount of materials to a Syngas from Waste AWT facility and to achieve resource recovery rates in excess of 97%.

Energy recovery is also maximised with these three families of technologies, with the highest net, delivered SNG yields obtained via plasma gasification, with up to 10.01 PJ/y

(6.53 PJ/y renewable), recoverable from the SSROC region, as summarized in the diagram below.

Figure 65. SfW-SNG (plasma) – net, delivered SNG, total/renewable.



It is recommended that the HTCM conversion strategy, with the ability to process inert materials and metallic and inert contaminants in the mixed waste resource stream, form the basis of procurement activities, as described in *Section 6. Enabling Actions*.

An initial technology shortlist for these activities is provided in the table below.

Table 21. HTCM technology shortlist

Supplier	Technology				
Name	Name	Type	Scale [a]	Application	Maturity
AlterNRG	PGVR	Plasma Gasification	medium-large	MSW, SR,RDF	commercial
Ebara	TwinRec	Fluid Bed Gasification + Melting	medium-large	MSW, SR	commercial
Entech-RES	WtGas	Fixed bed Gasification	small-medium	MSW, sludge	proven
Nippon Steel	DMS	Fix Bed Gasification + Melting	medium-large	MSW, sludge	commercial
Plasco	PGP	Plasma Gasification	medium-large	MSW	proven
Advanced Plasma Power	GasPlasma	Plasma Gasification	small-medium	MSW, SR, RD	demonstrated
JFE/Thermoselect	HTR	Pyro-Gasification + Melting	medium-large	MSW	commercial
Toshiba	PKA	Pyro-Gasification + Melting	small-medium	MSW	proven
Metso Power	Metso CFBG	Fluid Bed Gasification	medium-large	MSW, RDF	proven

[a] small-scale <25 tpd; medium scale 25-250 tpd; large-scale >250 tpd

SECTION 5. ADVANCED WASTE TREATMENT IN THE GREEN INFRASTRUCTURE STRATEGY

Pictured: Energy recovery at Kymijärvi II gasification facility, Lahti, Finland.
Credits: Metso Power, 2012

Overview

In previous sections of this study we have provided a comprehensive review of commercially available platforms for the generation of synthesis gas from residual waste resources and upgrading of the resulting raw syngas into a pipeline-quality substitute natural gas (SNG) product; and a detailed assessment of the potential for energy recovery and waste minimization deriving from establishment of an integrated Syngas from Waste SNG (SfW-SNG) facility converting post-recycling residues from domestic, commercial and industrial waste resources collected within the City of Sydney LGA and surrounding Councils in the Southern Sydney Regional Organization of Councils (SSROC).

The *Renewable Gas Supply Infrastructure* study (TWE 2013), developed by Talent with Energy within the scope of the City of Sydney *Renewable Energy Master Plan* (City of Sydney 2013a), has evaluated the potential associated with a range of renewable gas resources – from thermal or biological conversion of waste and biomass residues – available within a 250-km radius from the City of Sydney LGA, to meet gas supply requirements from the network of precinct-scale trigeneration facilities proposed under the City's *Trigeneration Master Plan* ((City of Sydney 2013b).

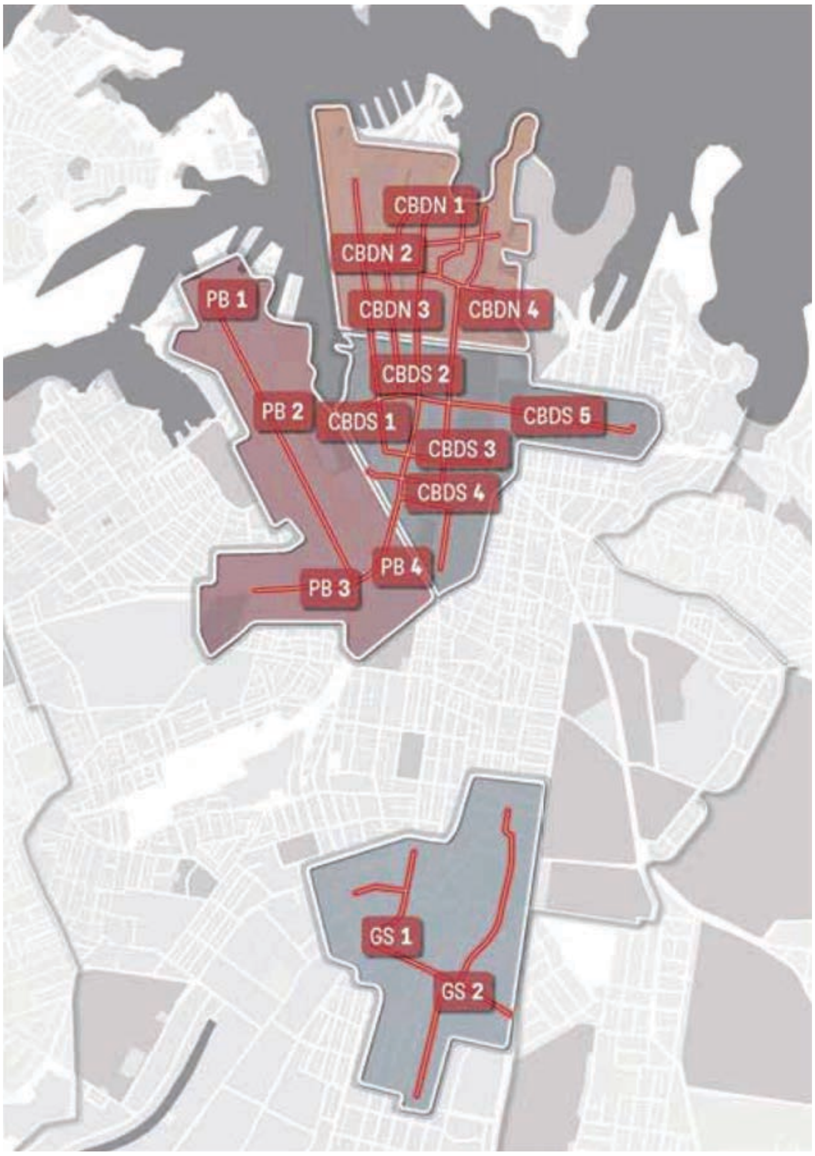
In this section we introduce the key elements of integration between the Trigeneration and Renewable Energy Master Plans, and highlight the key contribution of the SfW-SNG platform in providing a secure and robust renewable substitute natural gas supply for the City's proposed trigeneration network.

Based on the results presented in Section 4, this analysis focuses on the High-Temperature Conversion + Melting (HTCM) family of thermal conversion technologies, and adopts plasma gasification as the reference technology for the purpose of modelling.

Decentralised Energy Network

A central element of the City's Green Infrastructure Strategy, the City's *Decentralised Energy Master Plan – Trigeneration* (hereinafter referred to as the *Trigeneration Master Plan*) seeks to improve the supply of energy services to businesses and residents in the City of Sydney through the deployment of a network of 15 precinct-scale trigeneration facilities – for a total installed capacity of 372 MWe by 2030 – connected to form a reticulated heating and cooling network, servicing buildings within four *low-carbon infrastructure zones*[19]:

Figure 66. Trigeneration Master Plan – Decentralised Energy Network[20]



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[19] *City of Sydney Decentralised Energy Master Plan - Trigeneration*. Prepared by Kinesis for City of Sydney, June 2012. http://www.cityofsydney.nsw.gov.au/.../TrigenerationReport.pdf

[20] adapted from (City of Sydney 2012), Figure 21, p. 25.

Key highlights

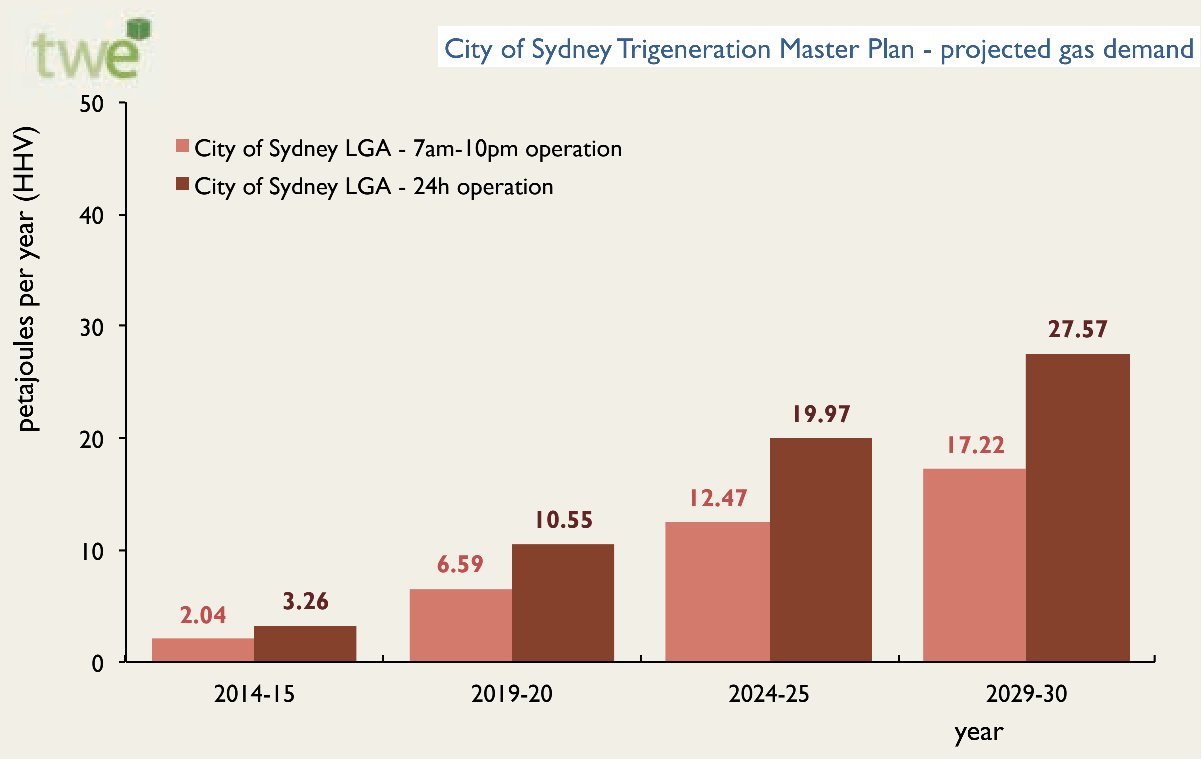
Gas demand

Within the scope of the Trigeneration Master Plan, Kinesis has provided an estimate of the projected gas demand from this network, through to the 2029-30 timeframe, on the basis of two utilization scenarios: 15 h (7am-10pm) operation; and 24h operation.

The chart below illustrates the resulting projected annual demand for natural gas through to 2029-30, expressed in petajoules per year (PJ/y, HHV basis[21]).

This is projected to grow up to 17.22 PJ/y in 2029-30 in the 15hr (7am-10pm) operation scenario, and up to 27.57 PJ/y in the 24h operation scenario (City of Sydney 2012).

Figure 67. Proposed trigeneration network, projected natural gas demand to 2029-30



In addition to this demand, the Master Plan estimates that the network of small-scale trigeneration facilities in the four 'hotspots' areas could reach a total installed capacity of 38 MW_e, adding 2.5 to 3 PJ/y to the annual demand for natural gas in 2029-30.

The proposed network of trigeneration facilities, suitably re-named by the City as *Green Infrastructure*, will deliver power to residents at a higher system-level efficiency, and substantially reduced greenhouse gas intensity than conventional, coal-fired, base-load

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[21] throughout this study, energy quantities are reported on a higher heating value (HHV) basis

power plants (accounting for over 90% of capacity installed in New South Wales) due to the combined effect of:

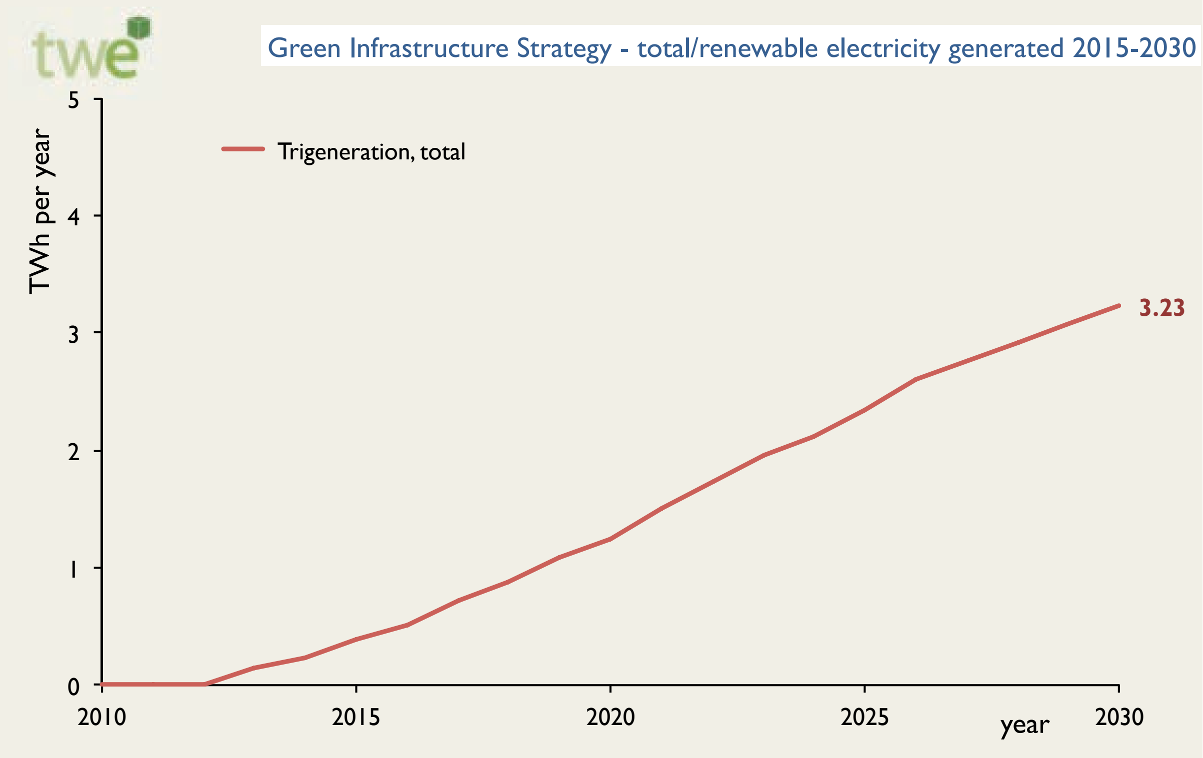
- **increased generation efficiency** versus both established coal-fired steam generation and new, state-of-the art combined cycle gas turbine power plants;
- **lower greenhouse gas emissions** per unit of energy delivered; and
- **reduced transmission and distribution (T&D) losses**.

In addition, waste heat from generation equipment installed at these facilities is used in heat exchangers and absorption chillers to provide heating and cooling as well as water heating services to the cluster of commercial buildings that will be connected to the trigeneration precincts.

Electricity generation

Under the mid-growth, 24h operation scenario total electricity generation from the decentralised energy network is projected by Kinesis to grow to 3.23 TWh per year in 2029-30.

Figure 68. Green Infrastructure Strategy (Trigeneration) – total electricity generated, 2010-30



Greenhouse gas mitigation

Modelling developed by Kinesis for the Trigeneration Master Plan, has estimated the cumulative greenhouse gas (GHG) reduction potential resulting from implementation of the decentralised energy network to be between 8 and 19 million tonnes of CO_2 equivalent (Mt_{CO2-e}) between 2010 and 2030, based on a range of roll-out and operational scenarios.

The analysis presented in our study takes the mid-growth trigeneration roll-out scenario, with 24h operation, as the starting point.

When this scenario is considered, the implementation of the trigeneration master plan brings total 2029-30 emissions down to 1.25 Mt_{CO2-e} per year, a reduction of 1.68 Mt_{CO2-e} per year – or 57.2% – against the 2029-30 baseline of 2.93 Mt_{CO2-e} per year, as illustrated by the emission trajectories presented in the diagram below.

The resulting cumulative emission reductions against the baseline scenario amount to 15.17 Mt_{CO2-e} in the 2010-2030 timeframe.

Figure 69. Green Infrastructure Strategy (Trigeneration) – net annual GHG emissions, 2010-30

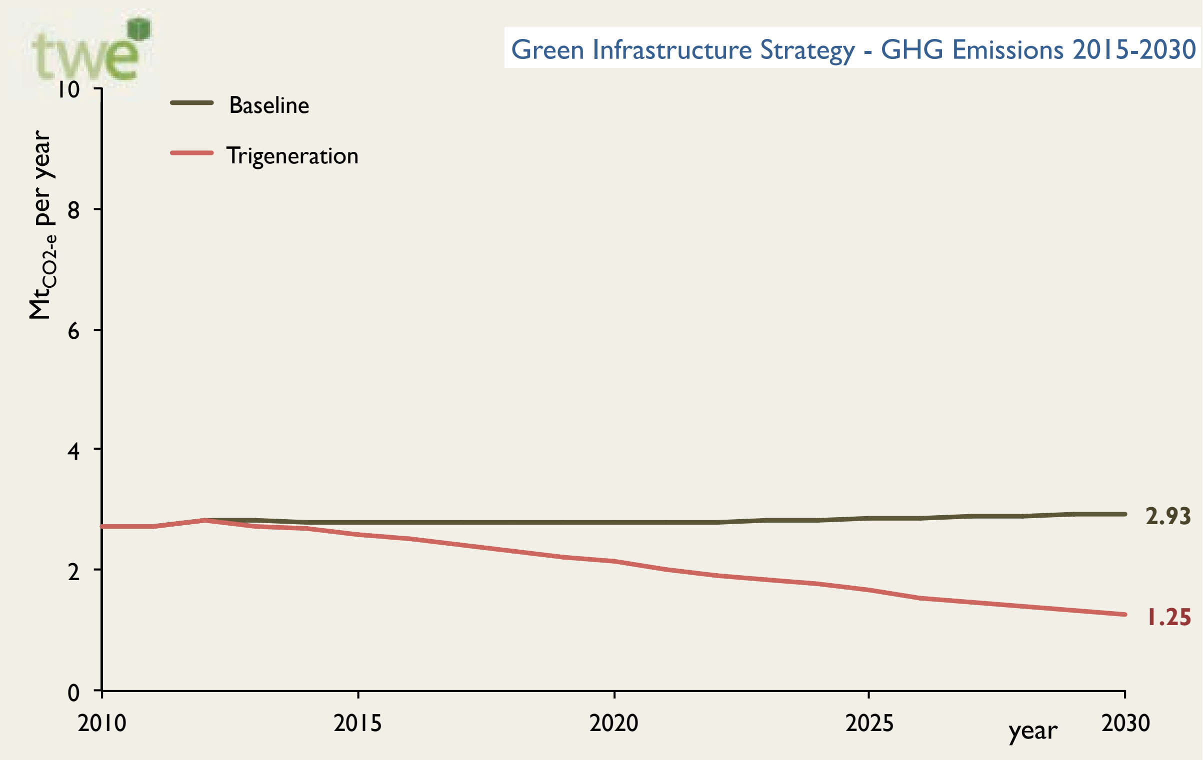
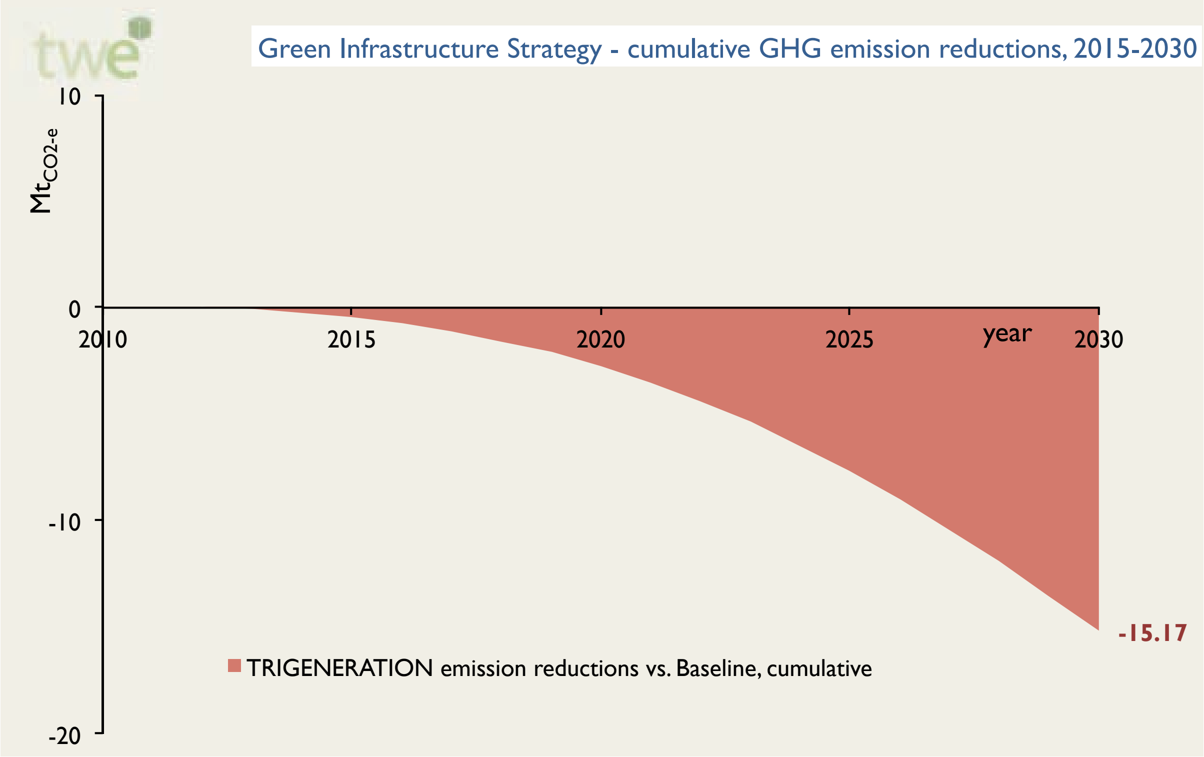


Figure 70. Green Infrastructure Strategy (Trigeneration) - cumulative net GHG emission reductions, 2015-30

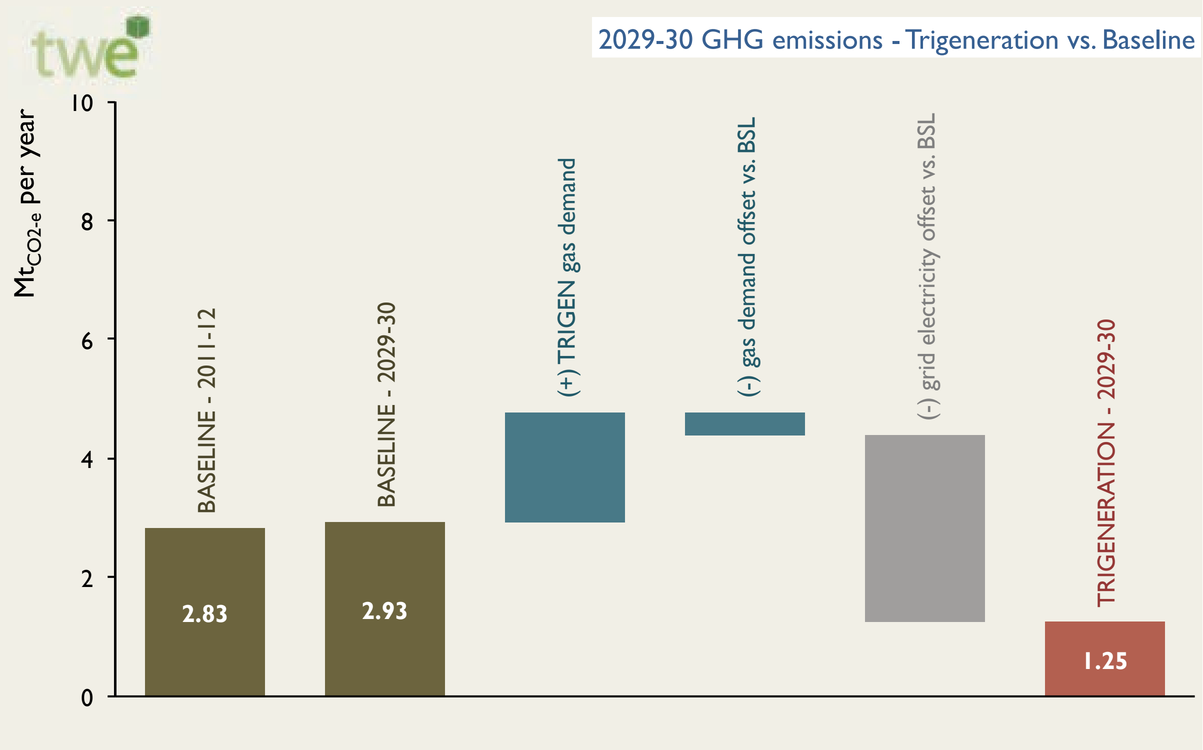


Reductions in GHG emissions, are broken down as follows:

- an increase in GHG emissions of 1.84 Mt_{CO2-e} per year, associated with additional consumption for natural gas from the decentralised energy network;
- a decrease in GHG emissions of 0.38 Mt_{CO2-e} per year, associated with baseline gas consumption displaced by the provision of reticulated heating services through the decentralised energy network; and
- a decrease in GHG emissions of 3.14 Mt_{CO2-e} per year, associated with grid electricity consumption offset through electricity generated and the provision of reticulated heating and cooling services through the decentralised energy network.

The individual contribution of each of these elements and the variation from the baseline are illustrated in the waterfall diagram below.

Figure 71. 2029-30 GHG emissions –Trigeneration vs. Baseline



Advanced Waste Treatment and Renewable Gas Supply

Renewable gases from conversion of residual waste and biomass resources available within the Greater Sydney and the surrounding regions represent the key element of integration between the Trigeneration and Renewable Energy components of the *Decentralised Energy Master Plan*.

To cater for the novel nature of these platforms, the *Renewable Gas Supply Infrastructure Study*, developed by Talent with Energy within the scope of the City of Sydney Renewable Energy Master Plan, has following a unique, *pathway-based* perspective, providing an in-depth assessment of alternative renewable gas supply pathways along the key pathway operations: from resource harvesting to delivery of upgraded renewable gas products to end-users. The study integrates several elements of analysis, including:

- characterization of residual waste and biomass resources;
- residual waste and biomass resource assessment;
- technology performance, cost and emissions survey;
- renewable gas generation and delivery scenarios;
- direct (scope 1) and life-cycle (scope 3) GHG emission profiles;
- levelized cost of gas (LCoG) and least-cost gas supply scenarios;
- marginal cost of abatement and marginal abatement cost curves (MACCs).

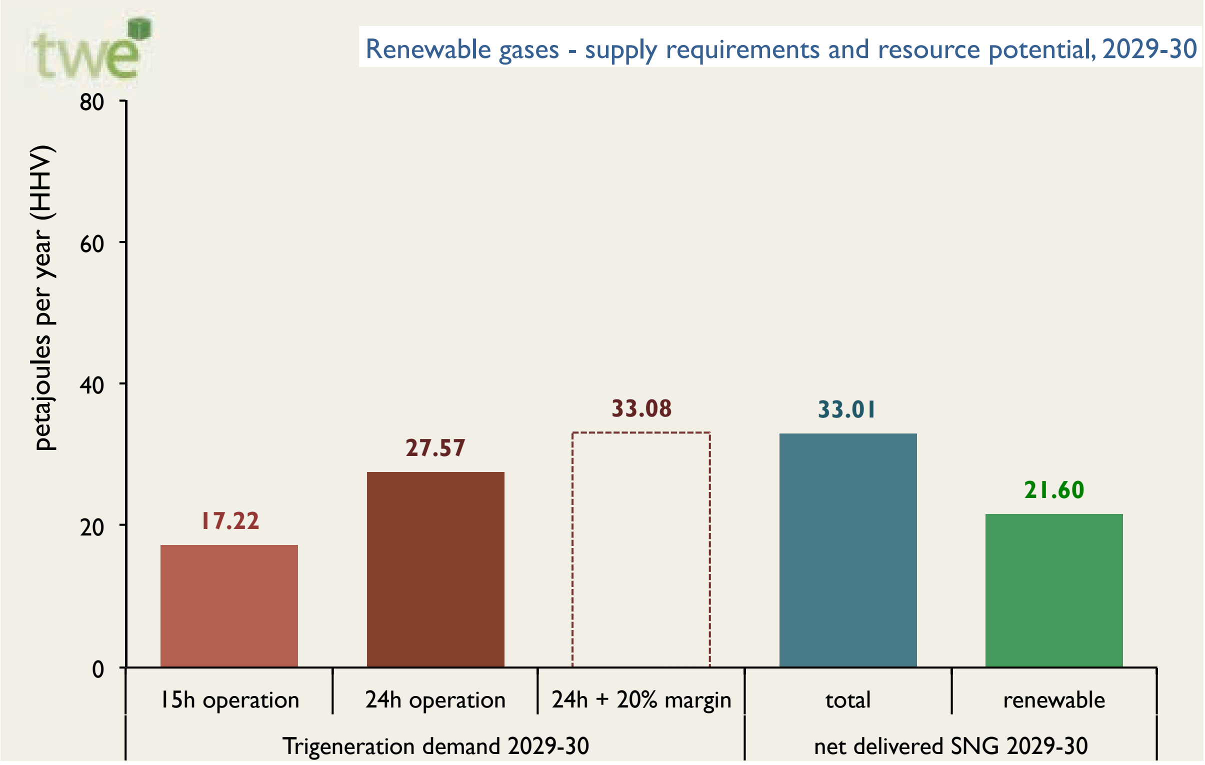
In the remainder of this section we present a summary of the result of this analysis highlighting the key contribution of Syngas from Waste SNG (SfW-SNG) pathways to the establishment of a secure renewable energy supply for the City's proposed trigeneration network.

Security of gas supply

The modelling presented has identified an available resource well in excess of the requirements from the proposed trigeneration network, even in the most demanding 24h operation scenario.

The Syngas from Waste component of SNG supply, 33.01 petajoules per year in 2029-30, compares well with the 2029-30 supply requirement, derived as the projected gas demand plus a 20% reserve margin, of 33.08 petajoules per year. The renewable energy component of the SfW-SNG supply is 21.60 PJ/y by 2029-30.

Figure 72. Syngas from Waste SNG - total/renewable net delivered SNG and supply requirements



Competitiveness of renewable gas supply

The analysis presented in Section 4 has determined, for 79 supply resources across five renewable gas generation pathways, the levelized cost of gas as the minimum selling price that would meet capital and operating costs for the proposed schemes, inclusive of upgrading and delivery operations (connection pipelines and transmission and distribution charges) and a 15% retail margin.

These cost figures, reported in real AUD_{2012} per GJ_{HHV} have been estimated across three timeframes, 2015-20, 2020-25 and 2020-25 for new build renewable gas generation facilities.

The table below compares summarizes the resulting range of LCoG for each pathway with the latest projected cost of gas from the Bureau for Resources and Energy Economics (BREE 2012b).

Table 22. Delivered renewable gas price estimated and natural gas price projections

	SNG delivered, net PJ$_{HHV}$/y		Gas prices (Central), AUD$_{2012}$/GJ$_{HHV}$			
	total	renewable	2014-15	2019-20	2024-25	2029-30
Natural gas (NSW,ACT) [a]			6.99	8.57	10.14	11.71
Substitute Natural Gas [b]	48.96	37.06				
SNG-SfW (plasma)	33.01	21.60	6.2 - 6.4	4.66 - 4.81	3.46 - 3.57	2.55 - 2.63
SNG-SfB [c]	3.52	3.03	10.69 - 13.85	7.44 - 9.63	5.18 - 6.68	3.6 - 4.62
SNG-LsB [c]	7.43	7.43	6.95 - 18.27	5.07 - 13.04	3.68 - 9.28	2.65 - 6.75
SNG-SsB	2.98	2.98	6.18	4.39	3.11	2.19
SNG-LfG	2.01	2.01	6.84	4.76	3.32	2.31

[a] Projected natural gas prices from (BREE 2012), Table 2.3.2

[b] Estimates from Talent with Energy (2012), include delivery operations (10 km injection pipeline for C-SNG delivery), pipeline T&D charges and 15% retail margin

[c] Estimates from Talent with Energy (2012), high estimates for sites with L-SNG delivery

The price escalation trend in natural gas prices, determined by increasing exposure to international gas hub prices with the commissioning of large-scale LNG export terminals in Queensland, is matched by a decreasing price trend for renewable gases, determined by escalation in waste management revenues and decreasing equipment costs deriving from large-scale deployment of renewable gas generation, upgrading and delivery technologies and the associated technology and operational learning mechanisms.

The Syngas from Waste SNG, by far the largest resource, is also one of the most competitive resource, after small-scale biogas and landfill gas, with projected costs, delivered to the City, lower than projected prices for natural gas supply from the 2015-20 timeframe.

Contribution to the City's Green Infrastructure targets

The contribution to the City's renewable electricity generation and GHG mitigation targets has been estimated for the least-cost roll-out determined under Section 4.

The table below summarizes the least gas supply resource mix for the 2015-20, 2020-25 and 2025-30 timeframe and the resulting weighed average renewable energy fraction and greenhouse gas emission factors.

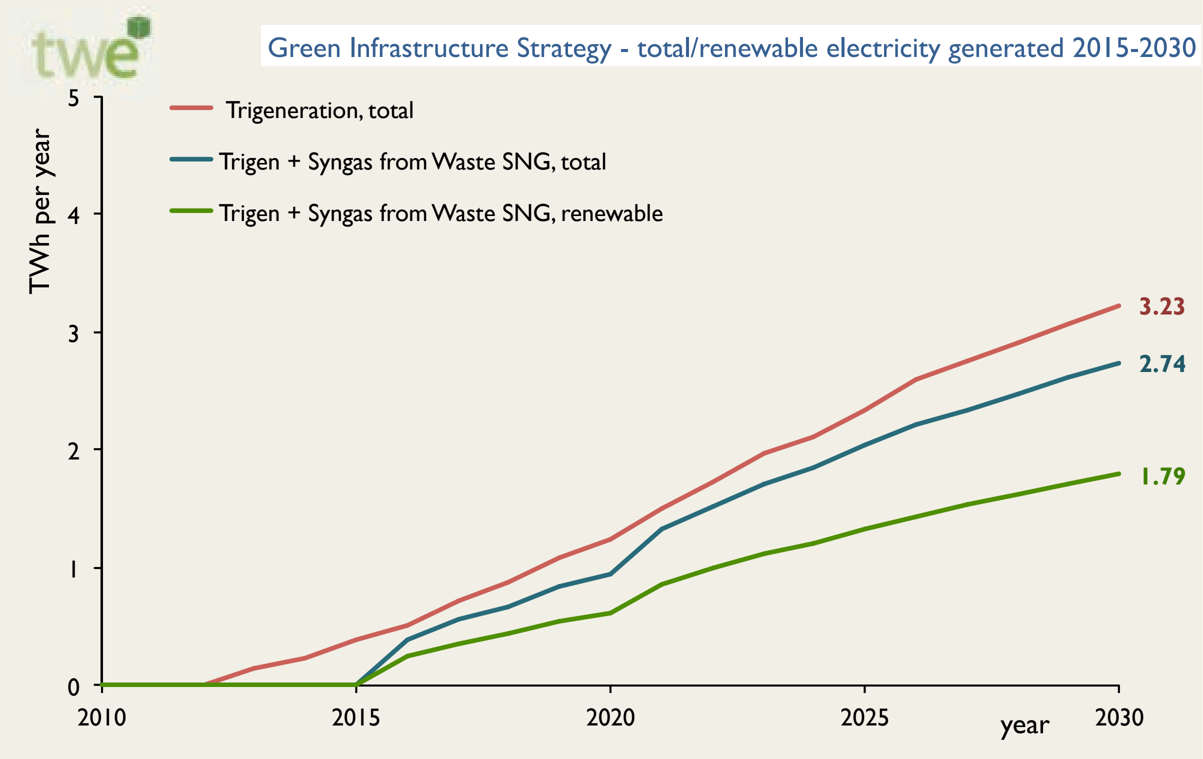
Table 23. Least-cost renewable gas supply – gas resource mix, renewable energy fraction and emission factors

	Conversion strategy					ALL GASES
Pathway/timeframe	SfW-SNG	SfB-SNG	LsB-SNG	SsB-SNG	LfG-SNG	w. average
SHARE of TOTAL SNG generated (HHV basis)						
2015-20	76.44%			23.56%		
2020-25	87.55%			12.45%		
2025-30	84.90%			9.02%	6.08%	
RENEWABLE ENERGY FRACTION (HHV basis)						
2015-20	64.85%			100.00%		73.13%
2020-25	65.15%			100.00%		69.49%
2025-30	65.24%			100.00%	100.00%	70.48%
LIFE-CYCLE EMISSION FACTOR, kg_{CO2-e}/GJ_{HHV}						
2015-20	-26.501			11.499		-17.548
2020-25	-26.660			11.499		-21.909
2025-30	-26.825			11.499	-269.553	-38.124

Renewable electricity generation

The diagram below illustrates the total and renewable electricity generation resulting from the Syngas from Waste SNG component of the least-cost roll-out of renewable gas supply for the trigeneration network (under the 24 h operation scenario.

Figure 73. Syngas from Waste SNG - total and renewable electricity generation

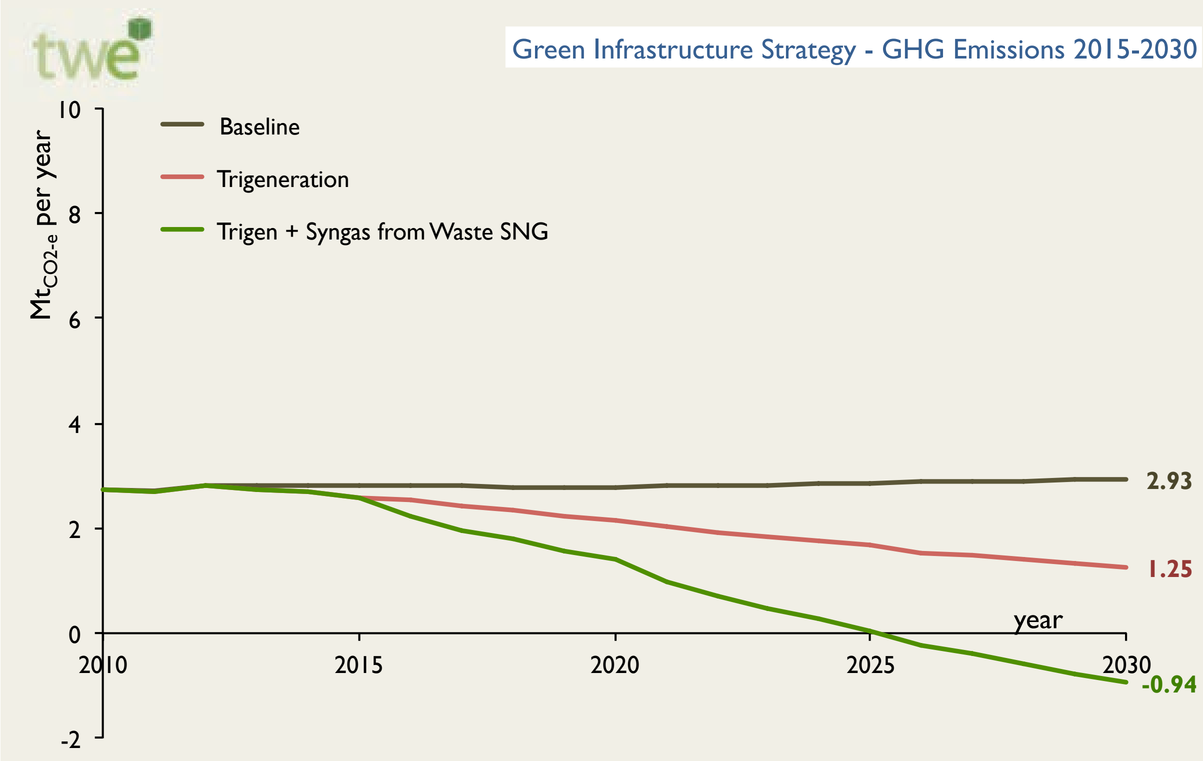


GHG emissions

The chart below illustrates the emission trajectories for the Baseline, Trigeneration (mid-growth, 24h operation) and Trigeneration + Syngas from Waste SNG (least-cost roll-out) scenarios.

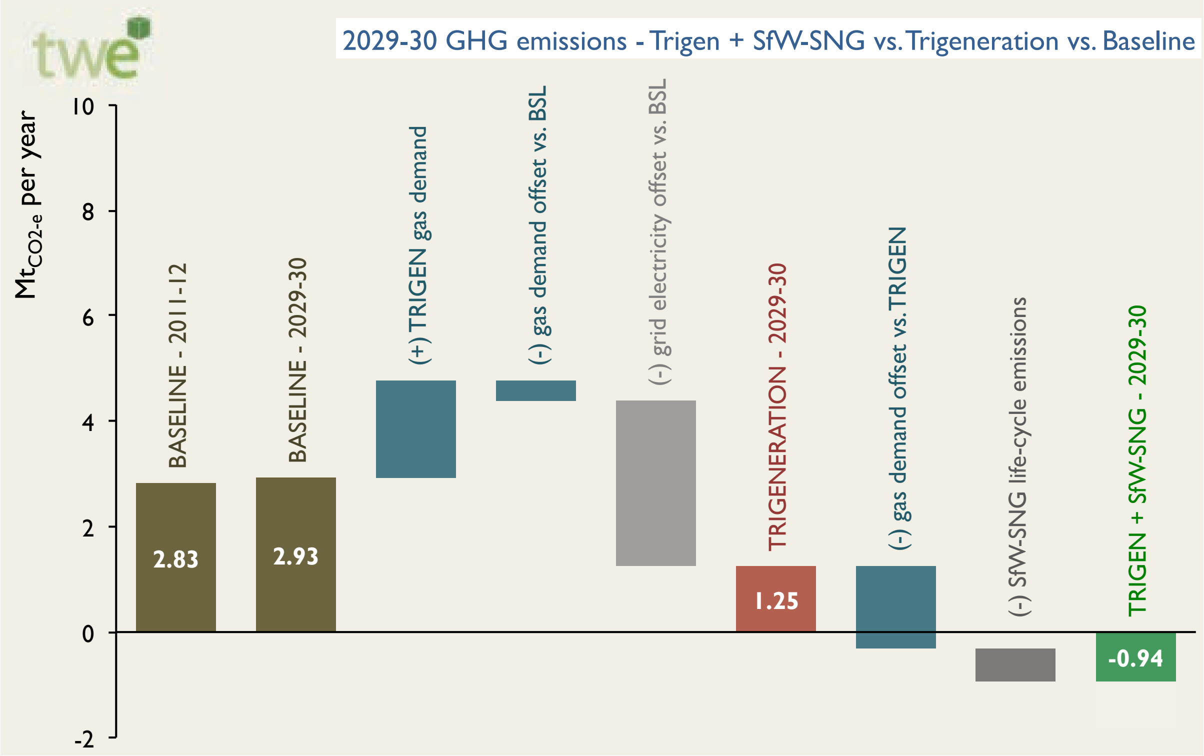
The Trigeneration + Renewable Gases strategy brings about additional GHG emission reductions versus trigeneration of 2.89 Mt_{CO2-e} per year by 2029-30, bringing the emissions from the Low Carbon Infrastructure Zones down to -1.64 Mt_{CO2-e} per year by 2029-30.

Figure 74. Green Infrastructure Strategy (Trigen + Syngas from Waste SNG) – net GHG emissions, 2010-30



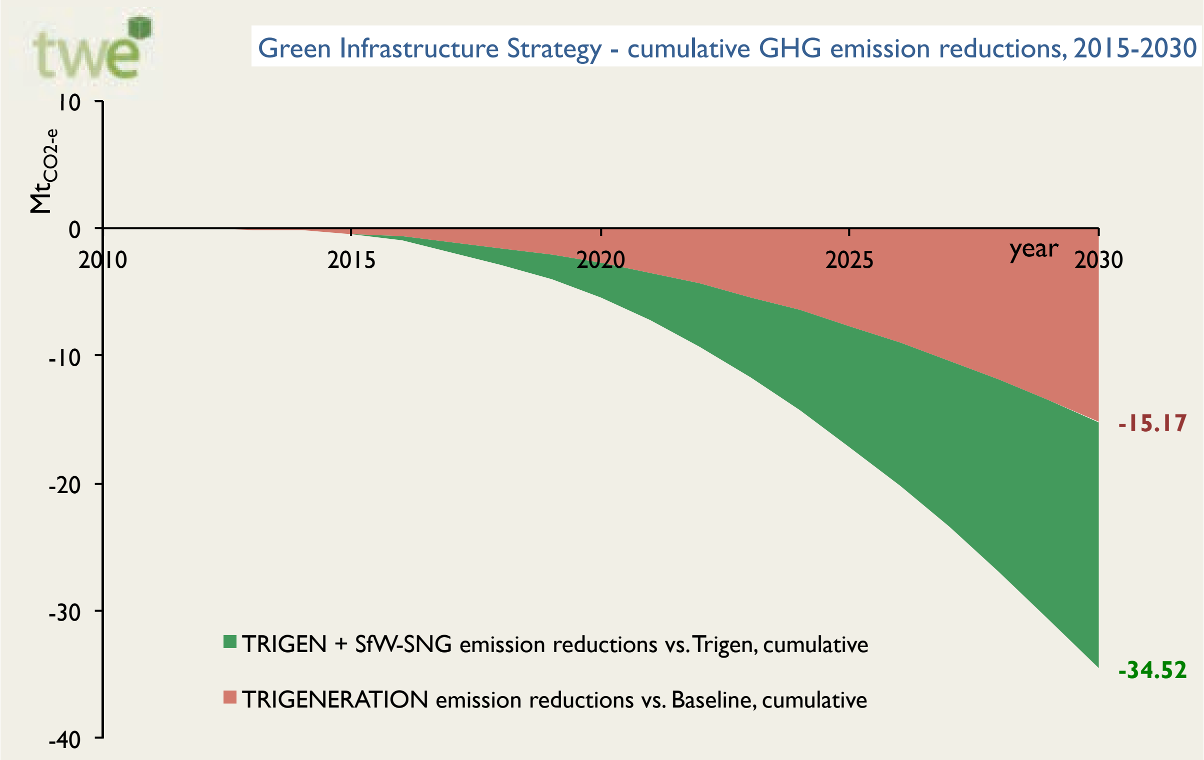
The breakdown of emission reductions, from the baseline 2029-30 emission figure of 2.93 Mt_{CO2-e} per year, to the 1.25 Mt_{CO2-e} per year achieved through implementation of the trigeneration strategy and finally down to -0.94 Mt_{CO2-e} per year achieved through implementation of the trigeneration + syngas from waste SNG strategy is explained in the waterfall diagram below.

Figure 75. 2029-30 GHG emissions – Trigen + Syngas from Waste SNG vs. Trigeneration vs. Baseline



The cumulative emission reductions over the 2015-2030 timeframe, increase from the 15.17 Mt$_{CO2-e}$ brought about by the *trigeneration* strategy to 34.52 Mt$_{CO2-e}$.

Figure 76. Green Infrastructure Strategy (Trigen + SfW-SNG), cumulative net GHG emission reductions



SECTION 6. ENABLING ACTIONS

Pictured: Energy recovery at Kymijärvi II gasification facility, Lahti, Finland.
Credits: Metso Power, 2012

Overview

Successful commissioning of a Syngas from Waste (SfW) plant is heavily dependent on execution of a well planned *project development pathway* – from preliminary planning activities to plant testing and commissioning.

While some aspects of the process are not unlike those required for any energy conversion project, the very nature and variability of the waste resource, the multitude of stakeholders involved, the higher degree of technology and operational risk associated with waste conversion processes and, in some constituencies, issues arising from public perception of waste-to-energy schemes and lack of a clear and comprehensive regulatory framework, do require adoption of a development strategy very specific to this type of facilities.

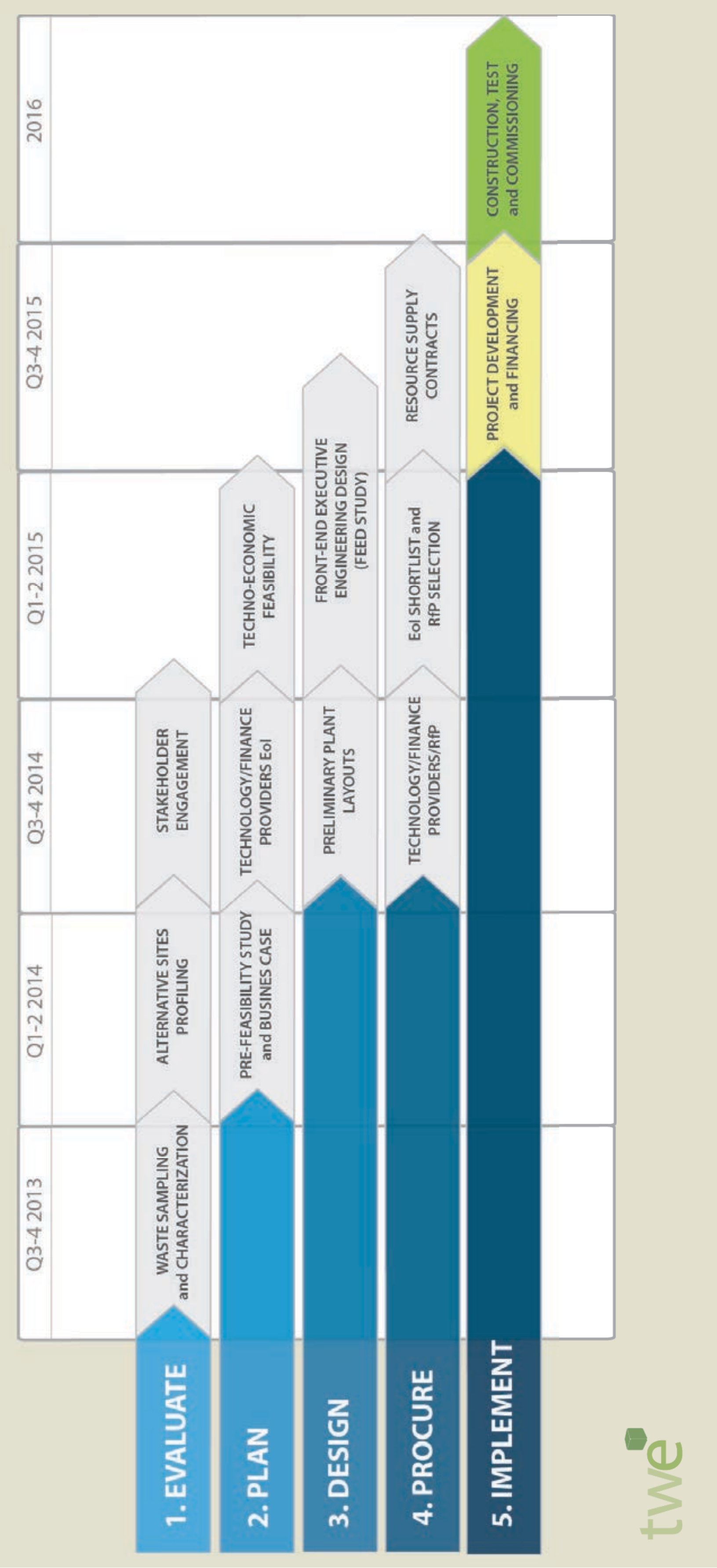
To put this in the context of the proposed EfW facility, presented here is a sketch of such a *project development pathway*, with the aim to highlight the key activities involved, and provide a preliminary timeline for their planning and execution.

These are grouped as follows:

- Preliminary planning: including waste audit, sampling and characterization, Commercial and Industrial (C&I) waste resource assessment, alternative sites profiling, and preliminary feasibility assessment;
- Stakeholder engagement: including stakeholder engagement strategy, institutional stakeholder engagement and broader stakeholder consultation activities;
- Market approach: including an expression of interest for technology and finance providers and subsequent request for proposal,
- Partnership development: negotiations towards the establishment of a project development partnership.
- Project design: including full feasibility study and detailed engineering and construction plans;
- Project development: resource contracts, power purchase and/or gas off take agreements and plant manufacturing and project development contracts;
- Project construction and commissioning.

The project pathway presented below has been built assuming construction and commissioning of the plant (from breaking ground to full commissioning) will take 15 months, from Q3 2014, with ongoing testing and commissioning to carry for at least one year from the plant first firing, with full commercial operation to commence in Q4 2016.

Figure 77. Preliminary SfW project development pathway



The early activities grouped under preliminary planning, stakeholder engagement and market approach are seen as key enabling activities and are described in detail below.

Preliminary planning activities

Waste audit

Knowledge of fractional waste composition is key to determine the likely amounts of waste feedstocks available for the development of the proposed SfW plant under the different conversion strategy scenarios and determine the incremental improvements in resource recovery and landfill diversion rates associated with implementation of such a facility.

The figures presented in the SfW scenario are based on audits conducted in 2011 for the City of Sydney (APC 2011a), and the Southern Sydney Regional Organization of Councils (APC 2011b).

A new audit commissioned by the City for 2011-12, has been conducted at quarterly intervals from Q3 2011 to help characterize the seasonal variability of the waste streams. Results of this audit were not available at the time this report was completed.

It is recommended that the modelling figures here presented be updated to reflect the most recent audit data available, and that new audit campaigns be conducted in conjunction with detailed sampling and characterization campaigns (see below) for at least two years to support planning activities towards establishment of a Syngas from Waste facility.

Domestic waste sampling and characterisation campaign

Waste sampling and characterization campaign

Knowledge of the chemical composition and other physical parameters for the waste resource are key to the development of robust process models supporting preliminary feasibility assessments and detailed project design.

While the estimates presented in this report have provide a preliminary assessment of the likely syngas yield and composition associated with alternative conversion technology strategies, it should be stressed that these are based on internationally benchmarked waste characterization data.

A detailed characterization of the waste streams available within the City of Sydney is thus a key enabling factor for subsequent planning activities including:

- Revision of syngas yield and composition estimates,
- Preliminary feasibility studies,

- Estimation of energy conversion efficiencies for the purpose of renewable energy certification, and
- Enabling detailed process modelling from perspective technology suppliers.

A waste sampling and characterization campaign should be carried out by the City in alignment with the waste audit work currently under way.

The campaign should be carried for at least one year at quarterly intervals, with selection of a statistically significant sample of mixed waste, and other streams of interest, and compositional analysis for the following:

- Moisture content, as received basis (ISO 5068 standard, or equivalent),
- Ash Constituent Analysis (ASTM D1102 standard, or equivalent),
- Ultimate Analysis (ASTM D2439 standard, or equivalent),
- Gross Calorific Value (ISO 1928 standard, or equivalent),
- Proximate Analysis (ISO 562 standard, or equivalent).

Commercial and Industrial waste resource assessment and characterization

The City of Sydney does not hold direct responsibility for the Commercial and Industrial (C&I) waste stream and as such holds no detailed data on the quantities, composition and characteristics of this resource.

The analysis presented in the *EfW Scenarios* sections identifies this resource as a significant additional feedstock to a proposed EfW facility, however C&I waste quantities and composition figures used in this analysis, derived from a low level visual assessment, recently published by the State Government (DECCW 2010), need to be replaced by a more robust resource assessment focused on this stream.

Alternative sites profiling

The selection of a potential site for the proposed EfW facility has not been covered as part of this study, a detailed site profiling and selection analysis is a key enabling activity.

The analysis should consider technical and economic aspects of the site (land availability and cost, access to existing infrastructure, etc.) as well as address the social dimension of the sites considered, allowing factoring in the knowledge developed in the set of downstream stakeholder engagement and project design activities.

Preliminary feasibility study

A pre-feasibility study supporting the AWT Business Case should be completed to enable a preliminary techno-economic assessment of the proposed facility and inform the City of

Sydney on the key economic performance parameters under the different conversion technology and project implementation scenarios considered for this study.

Stakeholder engagement activities

The set of activities the City intends to develop under the AWT Master Plan have a distinct character of novelty in the Australian context, and as such require development of a robust and comprehensive set of stakeholder engagement activities.

Development of a stakeholder engagement strategy, aligned with the broader Green Infrastructure Strategy is a key enabling factor.

A two-pronged strategy, aimed at institutional (State and Federal Government Regulatory Authorities, neighboring Local Government Authorities, Industry Associations, etc.) and public opinion stakeholders should at minimum identify and map key organization on the basis of their perceived position on the City of Sydney's plans and their ability to influence, promote or block the activities the City intends to carry out under the AWT stream of its Green Infrastructure Strategy.

Engagement of institutional stakeholders will be key to assist them develop the regulatory infrastructure required for obtaining adequate operational permits for the proposed facility and will help securing access to funding mechanism developed under the Carbon Tax legislation and other State and Federal Government clean technology funding mechanisms.

Public opinion stakeholders will need to be informed of the key benefits of conversion technologies and engaged in the promotion of the proposed facility.

Funding opportunities

In addition to the wide array of funding opportunities available from State and Federal Agencies, the establishment of the Australian Renewable Energy Agency (ARENA) and the broader program of initiatives established within the framework of the Carbon Tax legislation, open a number of opportunities for supporting renewable energy and energy efficiency research development and demonstration (RD&D) initiatives linked with the proposed scope of initiatives for the City's Advanced Waste Treatment Master Plan, including:

- feasibility studies;
- resource assessment; and
- pilot demonstrations.

Approach to market

A robust and comprehensive market approach will allow the City to refine its understanding of the portfolio of conversion technology solutions and inform the selection of preferred technology, service and finance partners for the proposed facility.

It is important for the City to recognize that the required scope of supply for a Syngas from Waste facility includes elements (syngas upgrading and delivery) that are not usually integrated in the offering of most traditional gasification technology providers, and would require them to team up with industrial gas technology providers, or even have the industrial gas providers stepping in as the leading proponent, much like the case of Air Products in the Tees Valley developments in the UK.

For this reason, we recommend that the market approach be carried out in two stages.

Expression of Interest

The first stage will be an expression of interest (EoI) process designed to engage the shortlist of suppliers presented earlier in this report, and gather additional data on their system based on a matrix of selection criteria capturing the key economic, energy and environmental performance dimensions of interest for the proposed facility.

Following an approach demonstrated by the City and County of Los Angeles (and reviewed in the Appendixes), we recommend that a second parallel EoI should be aimed at perspective finance and waste management services partners, to gauge market interest in engaging with the City of Sydney on the development of a city-wide Waste Management Services Company (WASCo) or similar public-private partnership mechanism for the development and operation of the proposed facility.

Request for Proposals

Following completion of the EoI processes, a detailed request for proposal (RfP) should be issued to the successful participants with full technical specification for the proposed facility, including site selection, detailed waste composition data and waste management fee structure across the City’s LGA and surrounding region.

Submission from the successful RfP respondent will inform the basis for subsequent project design activities, including full feasibility and detailed engineering construction and manufacturing design.

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Appendix A. Waste Resource Assessment and Characterization

efficiency | renewables | innovation

Overview

In order to support energy recovery and GHG emission modelling activities presented in Section 4. Advanced Waste Treatment Scenarios, TWE has developed a framework for detailed waste resource assessment and characterization, including the following:

- **elemental analysis**
- **energy content**
- **biomass content**
- **renewable energy content**
- **biogenic carbon content**

The framework builds on a combination of elemental analysis data for the range of materials typically found in the domestic and commercial and industrial waste streams, sourced from (Niessen 2010), and data from the following activities:

- a regional audit of domestic waste fractions collected within the LGAs of the Southern Sydney Regional Organization of Councils (SSROC), carried out in 2011 by APC Environmental (APC 2011b); and
- a kerbside audit of the domestic waste stream collected within the City of Sydney LGA, carried out in 2011 by APC Environmental Management (APC 2011a);
- a disposal based survey of the Commercial and Industrial waste streams collected in the Sydney Metropolitan Area (SMA), carried out in 2008 by the New South Wales Government's Department of the Environment, Climate Change and Water (DECCW 2010).

In this Appendix we present the framework developed, with details of source data and estimation methods used. Throughout this Appendix and the Study we aggregate data according to a *Waste Breakdown Structure*, organized in four levels:

- **streams,** aggregating waste materials by source (eg. domestic, commercial and industrial, etc.);
- **fractions,** aggregating waste materials into homogeneous fractions for the purpose of processing (eg. recyclable, combustible, putrescible, inert, hazardous, etc.);
- **categories,** aggregating waste materials with similar production methods or characteristics (eg. Oils, Paper, Plastics, Wood, Food wastes, etc.); and
- **materials**, the individual materials typically defined in waste audit activities (eg. for Paper and Paper Newspapers, Magazines, Timber, Leather, Rubber, Glass,etc.);

Reference waste materials

Detailed knowledge of the physico-chemical characteristics of the different materials in the waste stream is key to provide accurate estimates of the resulting moisture content and elemental analysis, and thus energy content of the incoming feedstock for a waste conversion facility. In this regard, the development of a waste sampling and characterization campaign, carried out at quarterly intervals for a minimum period of 12 months horizon is a critical activity in the project development pathway, and has been included in the set of enabling actions recommended to the City in Section 6 of this study.

In the absence of detailed sampling data collected within the Sydney Region, for the purpose of the analysis presented under Section 3 (Feedstock Resource Assessment) and 4 (AWT Implementation Scenarios), we resort here to use in the interim an internationally benchmarked database of physico-chemical characteristics for waste materials and categories, sourced from (Niessen 2010), including the following:

- **moisture content** of homogeneous waste categories;
- **proximate analysis**, to determine fraction composition, by weight as received basis, in terms of moisture content, volatile matter, combustible and inert fractions by weight;
- **ultimate analysis**, to determine elemental composition, by weight dry basis, in terms of key elements (Carbon, Hydrogen, Nitrogen, Oxygen and Sulphur) and inert residuals (Ash).

Physico-chemical characteristics

Moisture content data

Table 24. Typical moisture contents of waste categories (wt%, as received)

Waste category	Moisture content, wt%	
	As-fired	As-discarded
Oils	0	0
Paper	24.3	8
Plastics	13.8	2
Wood	15.4	15
Food wastes	63.6	70
Yard wastes	37.9	55.3
Rubber	13.8	2
Leather	13.8	2
Textiles	23.8	10
Glass	3	2
Metal	6.6	2
Miscellaneous	3	2

Adapted from: (Niessen 2010), Table 4.7, p.111

Proximate analysis data

Table 25. Proximate analysis of waste materials, paper and paper products (wt%, as received)

Category/material	Proximate analysys (as received), wt %			
	Moisture	Volatile matter	Fixed carbon	Non comb.
Paper and Paper Products				
Paper, Mixed	10.24	75.94	8.44	5.38
Newsprint	5.97	81.12	11.48	1.43
Brown Paper	5.83	83.92	9.24	1.01
Trade Magazine	4.11	66.39	7.03	22.47
Corrugated Boxes	5.2	77.47	12.27	5.06
Plastic-Coated Paper	4.71	84.2	8.45	2.64
Waxed Milk Cartons	3.45	90.92	4.46	1.17
Paper Food Cartons	6.11	75.59	11.8	6.5
Junk Mail	4.56	73.32	9.03	13.09

SOURCE: (Niessen 2010), Table 4.32, pp.132-133.

Table 26. Proximate analysis of waste materials, food and food wastes (wt%, as received)

Category/material	Proximate analysys (as received), wt %			
	Moisture	Volatile matter	Fixed carbon	Non comb.
Food and Food Wastes				
Vegetable Food Wastes	78.29	17.1	3.55	1.06
Citrus Rinds and Seeds	78.7	16.55	4.01	0.74
Meat Scraps (cooked)	38.74	56.34	1.81	3.11
Fried Fats	0	97.64	2.36	0

SOURCE: (Niessen 2010), Table 4.32, pp.132-133.

Table 27. Proximate analysis of waste materials, green waste (wt%, as received)

Category/material	Proximate analysys (as received), wt %			
	Moisture	Volatile matter	Fixed carbon	Non comb.
Green Waste				
Green Logs	50	42.25	7.25	0.5
Rotten Timbers	26.8	55.01	16.13	2.06
Demolition Softwood	7.7	77.62	13.93	0.75
Waste Hardwood	12	75.05	12.41	0.54
Furniture Wood	6	80.92	11.74	1.34
Evergreen Shrubs	69	25.18	5.01	0.81
Balsam Spruce	74.35	20.7	4.13	0.82
Flowering Plants	53.94	35.64	8.08	2.34
Lawn Grass	75.24	18.64	4.5	1.62
Ripe Leaves	9.97	66.92	19.29	3.82
Wood and Bark	20	67.89	11.31	0.8
Brush	40	--	--	5
Mixed Greens	62	26.74	6.32	4.94

SOURCE: (Niessen 2010), Table 4.32, pp.132-133.

Table 28. Proximate analysis of waste materials, domestic wastes (wt%, as received)

	Proximate analysys (as received), wt %			
Category/material	Moisture	Volatile matter	Fixed carbon	Non comb.
Domestic Wastes				
Upholstery	6.9	75.96	14.52	2.62
Tires	1.02	64.92	27.51	6.55
Leather	10	68.46	12.49	9.1
Leather Shoe	7.46	57.12	14.26	21.16
Shoe, Heel & Sole	1.15	67.03	2.08	29.74
Rubber	1.2	83.98	4.94	9.88
Mixed Plastics	2	--	--	10
Plastic Film	3-20	--	--	--
Polyethylene	0.2	98.54	0.07	1.19
Polystyrene	0.2	98.67	0.68	0.45
Polyurethane	0.2	87.12	8.3	4.38
Polyvinyl Chloride	0.2	86.89	10.85	2.06
Linoleum	2.1	64.5	6.6	26.8
Rags	10	84.34	3.46	2.2
Textiles	15-31	--	--	--
Oils, Paints	0	--	--	16.3
Vacuum Cleaner Dirt	5.47	55.68	8.51	30.34
Household Dirt	3.2	20.54	6.26	70

SOURCE: (Niessen 2010), Table 4.32, pp.132-133.

Table 29. Proximate analysis of waste materials, municipal wastes (wt%, as received)

	Proximate analysys (as received), wt %			
Category/material	Moisture	Volatile matter	Fixed carbon	Non comb.
Municipal Wastes				
Street Sweepings	20	54	6	20
Mineral	2-6	--	--	--
Metallic	3-11	--	--	--
Ashes	10	2.68	24.12	63.2

SOURCE: (Niessen 2010), Table 4.32, pp.132-133.

Ultimate analysis data

Table 30. Ultimate analysis of waste materials, paper and paper products (wt%, dry basis)

	Ultimate analysis (dry basis), weight %					
Category/material	C	H	O	N	S	Ash
Paper and Paper Products						
Paper, Mixed	43.41	5.82	44.32	0.25	0.2	6
Newsprint	49.14	6.1	43.03	0.05	0.16	1.52
Brown Paper	44.9	6.08	47.34	0	0.11	1.07
Trade Magazine	32.91	4.95	38.55	0.07	0.09	23.43
Corrugated Boxes	43.73	5.7	44.93	0.09	0.21	5.34
Plastic-Coated Paper	45.3	6.17	45.5	0.18	0.08	2.77
Waxed Milk Cartons	59.18	9.25	30.13	0.12	0.1	1.22
Paper Food Cartons	44.74	6.1	41.92	0.15	0.16	6.93
Junk Mail	37.87	5.41	42.74	0.17	0.09	13.72

Adapted from: (Niessen 2010), Table 4.28, p.127

Table 31. Ultimate analysis of waste materials, food and food wastes (wt%, dry basis)

Category/material	Ultimate analysis (dry basis), weight % C	H	O	N	S	Ash
Food and Food Wastes						
Vegetable Food Wastes	49.06	6.62	37.55	1.68	0.2	4.89
Citrus Rinds and Seeds	47.96	5.68	41.67	1.11	0.12	3.46
Meat Scraps (cooked)	59.59	9.47	24.65	1.02	0.19	5.08
Fried Fats	73.14	11.54	14.82	0.43	0.07	0

Adapted from: (Niessen 2010), Table 4.28, p.127

Table 32. Ultimate analysis of waste materials, green waste (wt%, dry basis)

Category/material	Ultimate analysis (dry basis), weight % C	H	O	N	S	Ash
Green Waste						
Green Logs	50.12	6.4	42.26	0.14	0.08	1
Rotten Timbers	52.3	5.5	39	0.2	1.2	2.8
Demolition Softwood	51	6.2	41.8	0.1	<.1	0.8
Waste Hardwood	49.4	6.1	43.7	0.1	<.1	0.6
Furniture Wood	49.7	6.1	42.6	0.1	<.1	1.4
Evergreen Shrubs	48.51	6.54	40.44	1.71	0.19	2.61
Balsam Spruce	53.3	6.66	35.17	1.49	0.2	3.18
Flowering Plants	46.65	6.61	40.18	1.21	0.26	5.09
Lawn Grass	46.18	5.96	36.43	4.46	0.42	6.55
Ripe Leaves	52.15	6.11	30.34	6.99	0.16	4.25
Wood and Bark	50.46	5.97	42.37	0.15	0.05	1
Brush	42.52	5.9	41.2	2	0.05	8.33
Mixed Greens	40.31	5.64	39	2	0.05	13

Adapted from: (Niessen 2010), Table 4.28, p.127

Table 33. Ultimate analysis of waste materials, domestic wastes (wt%, dry basis)

	Ultimate analysis (dry basis), weight %					
Category/material	C	H	O	N	S	Ash
Domestic Wastes						
Upholstery	47.1	6.1	43.6	0.3	0.1	2.8
Tires	79.1	6.8	5.9	0.1	1.5	6.6
Leather	60	8	11.5	10	0.4	10.1
Leather Shoe	42.01	5.32	22.83	5.98	1	22.86
Shoe, Heel & Sole	53.22	7.09	7.76	0.5	1.34	30.09
Rubber	77.65	10.35			2	10
Mixed Plastics	60	7.2	22.6	--	--	10.2
Plastic Film	67.21	9.72	15.82	0.46	0.07	6.72
Polyethylene	84.54	14.18	0	0.06	0.03	1.19
Polystyrene	87.1	8.45	3.96	0.21	0.02	0.45
Polyurethane	63.27	6.26	17.65	5.99	0.02	4.38 (a)
Polyvinyl Chloride	45.14	5.61	1.56	0.08	0.14	2.06 (b)
Linoleum	48.06	5.34	18.7	0.1	0.4	27.4
Rags	55	6.6	31.2	4.12	0.13	2.45
Textiles	46.19	6.41	41.85	2.18	0.2	3.17
Oils, Paints	66.85	9.63	5.2	2		16.3
Vacuum Cleaner Dirt	35.69	4.73	20.08	6.26	1.15	32.09
Household Dirt	20.62	2.57	4	0.5	0.01	72.3

Adapted from: (Niessen 2010), Table 4.28, p.127

Table 34. Ultimate analysis of waste materials, municipal wastes (wt%, dry basis)

	Ultimate analysis (dry basis), weight %					
Category/material	C	H	O	N	S	Ash
Municipal Wastes						
Street Sweepings	34.7	4.76	35.2	0.14	0.2	25
Mineral	0.52	0.07	0.36	0.03	0	99.02
Metallic	4.54	0.63	4.28	0.05	0.01	90.49
Ashes	28	0.5	0.8	--	0.5	70.2

SOURCE: (Niessen 2010), Table 4.32, pp.132-133.

Waste stream characterization

In order to develop representative moisture content and ultimate analysis data for the waste streams considered in Section 3, we have reviewed data from recent audit activities conducted within the Sydney region and combined them with the physico-chemical characteristics of the individual waste materials presented earlier, to obtain a dataset of physico-chemical characteristics at the level of the following process fractions (combustible, putrescible, inert and hazardous).

In this chapter we present the raw audit data used, the waste breakdown structure adopted for the aggregation and the resulting dataset of fraction elemental analysis.

Waste audit data

Data presented in this section are sourced from the following audit activities:

- **Domestic wastes**, collected within the City of Sydney LGA, and the SSROC region, sourced from (APC 2011a), and (APC 2011b), respectively; and
- **Commercial and Industrial wastes**, collected within the Sydney Metropolitan Area (SMA), sourced from (DECCW 2010).

Domestic wastes

Table 35. Domestic waste composition, 2011 audit – City of Sydney LGA and SSROC

		CoS LGA - 2011 Audit		SSROC - 2011 Audit	
AWD Code	Material	kg/wk	wt%	kg/hh-wk	wt%
A01	Newspapers	12.7	0.80%	0.112	1.15%
A02	Magazines	54.3	3.43%	0.124	1.28%
A03	Paper Packaging	12.6	0.79%	0.010	0.10%
A04	Corrugated Cardboard	21.8	1.38%	0.066	0.68%
A05	Flat Cardboard	26.9	1.70%	0.159	1.64%
A06	Liquid Paperboard	4.6	0.29%	0.026	0.27%
A07	Disposable Paper Products	6.8	0.43%	0.025	0.26%
A08	Paper Paper	31.7	2.00%	0.103	1.06%
A09	Composite (mainly paper)	11.4	0.72%	0.051	0.52%
A092	Nappies Disposable	85.0	5.37%	0.642	6.60%
A90	Contaminated	115.7	7.31%	0.765	7.87%
B01	Food	485.7	30.69%	3.639	37.43%
B02	Vegetation	51.7	3.27%	0.593	6.10%
B03	Other Putrescible	29.8	1.88%	0.190	1.95%
C01	Wood/Timber	28.6	1.81%	0.121	1.24%
C02	Textile/Carpet	53.0	3.35%	0.330	3.39%
C03	Leather	1.0	0.06%	0.027	0.28%
C04	Rubber	3.5	0.22%	0.035	0.36%
C05	Oils	0.2	0.01%	0.006	0.06%
D0121	Glass Drink Containers	66.1	4.17%	0.143	1.47%
D0122	Other Packaging Glass	25.8	1.63%	0.118	1.21%
D0123	Other Glass	8.0	0.50%	0.045	0.46%
D050	Glass Fines	1.7	0.10%	0.006	0.06%
D02	PET Drink Containers	8.8	0.56%	0.039	0.40%
E01	PET Packaging	7.0	0.44%	0.046	0.47%
E02	PET Other			0.001	0.01%
E03	HDPE Drink Containers	4.6	0.29%	0.014	0.14%
E04	HDPE Packaging	4.7	0.30%	0.028	0.29%
E05	HDPE Other	0.0	0.00%	0.003	0.03%
E06	PVC Drink Containers			0.001	0.01%
E07	PVC Packaging	1.1	0.07%	0.003	0.03%
E071	PVC Other	0.0	0.00%	0.005	0.05%
E072	LDPE Packaging			0.003	0.03%
E073	LDPE Other	0.0	0.00%	0.003	0.03%
E08	PP Packaging	19.0	1.20%	0.060	0.62%
F01	PP Other	1.1	0.07%	0.013	0.13%
F011	EPS Packaging	3.5	0.22%	0.026	0.27%
F012	PS & EPS Other	0.4	0.02%	0.008	0.08%
F03	PS Packaging	2.7	0.17%	0.027	0.28%
F02	Other Plastic	23.5	1.48%	0.122	1.25%
G01	Composite (mostly plastic)	29.3	1.85%	0.124	1.28%
G03	Plastic Bags	32.9	2.08%	0.222	2.28%
G02	Plastic Film	56.4	3.57%	0.371	3.82%
H01	Steel Drink Containers	0.0	0.00%	0.005	0.05%
H02	Steel Packaging	18.9	1.19%	0.102	1.05%
H03	Steel Other	9.0	0.57%	0.052	0.53%
H04	Composite (mostly ferrous)	4.0	0.25%	0.034	0.35%
H05	Aluminium Drink Containers	4.2	0.26%	0.014	0.14%
H06	Aluminium Packaging	1.4	0.09%	0.009	0.09%
H07	Aluminium Other	3.3	0.21%	0.028	0.29%
	Non – Ferrous (specify)	0.5	0.03%	0.003	0.03%
	Composite (mostly non-ferrous)	1.0	0.06%	0.007	0.07%

… continues

SOURCES: City of Sydney LGA data from (APC 2011a), Table 13, p..37-38; SSRoC data from (APC 2011b) Table 18, pp.55-56.

Table 36. Domestic waste stream composition, 2011 audit – City of Sydney LGA and SSROC (continued)

		CoS LGA - 2011 Audit		SSROC - 2011 Audit	
AWD Code	Material	kg/wk	wt%	kg/hh-wk	wt%
continued …					
I01	Paint	2.6	0.16%	0.015	0.15%
I02	Fluorescent Tubes	0.4	0.03%	0.002	0.02%
I03	Single use batteries	0.7	0.04%	0.011	0.11%
Q53	Rechargeable batteries	0.2	0.01%	0.001	0.01%
Y57	Vehicle Batteries			0.005	0.05%
	Household Chemicals	2.5	0.16%	0.012	0.12%
	Asbestos			0.007	0.07%
	Clinical	0.0	0.00%	0.008	0.08%
XX00	Gas Bottles				
	Hazardous Other				
	Building materials	11.7	0.74%	0.181	1.86%
	Ceramics, Dust, Dirt, Rock, Inert, Ash	77.9	4.92%	0.241	2.48%
	Computer Equipment	1.4	0.09%	0.015	0.15%
	TVs				
	Mobile Phones			0.001	0.01%
	Electrical Items and Peripherals	11.0	0.70%	0.095	0.98%
	Toner Cartridges	0.1	0.01%	0.003	0.03%
	Containerised Food & Liquid	72.9	4.60%	0.362	3.72%
	Other	25.9	1.64%	0.054	0.56%
	Total	1,582.8	100.00%	9.722	100.00%

SOURCES: City of Sydney LGA data from (APC 2011a), Table 13, p..37-38; SSRoC data from (APC 2011b) Table 18, pp.55-56.

Commercial and Industrial wastes

Table 37. Commercial and Industrial waste composition, 2008 audit – Sydney Metropolitan Area

	SMA - 2008 Audit	
Material	t/y	wt%
Food/kitchen	282,735.0	16.27%
Food – dense	20,429.0	1.18%
Wood – pallets/ other	142,079.0	8.18%
Wood – mdf/chipboard	77,329.0	4.45%
Wood – furniture	37,512.0	2.16%
Wood – fencing/board/pole (untreated)	14,587.0	0.84%
Wood – fencing/board /pole (treated)	11,911.0	0.69%
Sawdust	4,948.0	0.28%
Plastic – bags & film	136,102.0	7.83%
Plastic – hard	84,727.0	4.88%
Plastic – other	40,766.0	2.35%
Plastic – recyclable containers	22,414.0	1.29%
Polystyrene/foam	9,732.0	0.56%
Paper – all other	128,969.0	7.42%
Paper – office	48,531.0	2.79%
Compacted dry cardboard	77,499.0	4.46%
Loose dry cardboard	25,998.0	1.50%
Compacted wet cardboard	13,224.0	0.76%
Loose wet cardboard	5,320.0	0.31%
Waxed cardboard	2,181.0	0.13%
Compacted dry cardboard production spoils	1,254.0	0.07%
Loose dry cardboard production spoils	270.0	0.02%
Textile – carpet / underlay	39,745.0	2.29%
Textile – cloth	30,512.0	1.76%
Textile – furniture	11,968.0	0.69%
Textile – leather/other	3,305.0	0.19%
Textile – mattress	2,017.0	0.12%
Metal – ferrous	32,314.0	1.86%
Metal – non ferrous	5,317.0	0.31%
Glass – containers/other	15,542.0	0.89%
Glass – plate	9,091.0	0.52%
Vegetation – branches/grass clips	53,003.0	3.05%
Vegetation – tree stumps /logs	3,479.0	0.20%
Rubber – shredded tyres	1,538.0	0.09%
Rubber – other	10,254.0	0.59%
Rubber – tyres/tubes	7,734.0	0.45%
Concrete/cement	28,066.0	1.62%
Clay	19,587.0	1.13%
Plasterboard	17,894.0	1.03%
Rubble > 150mm	33,584.0	1.93%
Rock	11,530.0	0.66%
Tiles	10,580.0	0.61%
Bricks	8,055.0	0.46%
Soil/cleanfill	38,122.0	2.19%
Insulation	1,357.0	0.08%
Fibreglass	652.0	0.04%
Asphalt	513.0	0.03%
Sand	392.0	0.02%
Ceramic	200.0	0.01%
Dirt	71.0	0.00%

… continues

SOURCE : (DECCW 2010), Table A2-3, p.76-77

Table 38. Commercial and Industrial waste composition, 2008 audit – Sydney Metropolitan Area (continued)

	SMA - 2008 Audit	
Material	Amount, t	Percent, %
continued …		
Hazardous/special – chemical/clinical	29,665.0	1.71%
Hazardous/special – light globes	357.0	0.02%
Batteries	346.0	0.02%
Electronics/electrical television etc.	11,003.0	0.63%
Computer/office equipment	716.0	0.04%
Toner cartridges	191.0	0.01%
Whitegoods – washing machine/ fridges	743.0	0.04%
Sludge	6,206.0	0.36%
Foundry sand	5,763.0	0.33%
Storm water	13,522.0	0.78%
Christmas decorations	950.0	0.05%
Animals	376.0	0.02%
Other	82,818.0	4.77%
Total	1,737,595.0	100.00%

SOURCE : (DECCW 2010), Table A2-3, p.76-77

Waste breakdown structure

In this section we present the allocation method used to aggregate the waste composition figures obtained presented above into the following process fractions:

- **Combustible fraction,** including waste materials from the Oils, Paper, Plastics, Rubber, Textile and Wood categories;
- **Putrescible fraction,** including waste materials from the Food and Green waste categories;
- **Inert fraction**, including waste materials from Construction and Demolition (C&D), Glass and Metal categories;
- **Hazardous fraction**, including waste materials from the Hazardous category;
- **Other fractions,** including waste materials from the Whitegoods, e-Waste and Other categories.

Combustible fractions

Table 39. Combustible fractions, Domestic Commercial and Industrial waste

Category	Waste materials	
	Domestic wastes[a]	Commercial and Industrial wastes[b]
Oils		
	C05-Oils	n/a
Paper		
	A01-Newspapers	Paper – all other
	A02-Magazines, Brochures	Paper – office
	A03-Miscellaneous Packaging	Compacted dry cardboard
	A04-Corrugated Cardboard	Loose dry cardboard
	A05-Package Board	Compacted wet cardboard
	A06-Liquid Paperboard Containers	Loose wet cardboard
	A07-Disposable Paper Products	Waxed cardboard
	A08-Print/Writing Office Paper	Compacted dry cardboard production spoils
	A09-Composite (mostly paper)	Loose dry cardboard production spoils
	A092-Contaminated Soiled Paper	
	A90-Nappies	
Plastics		
	E01-PET #1	Plastic – bags & film
	E02-HDPE #2	Plastic – hard
	E03-PVC #3	Plastic – other
	E04-LDPE #4	Plastic – recyclable containers
	E05-Polypropylene #5	Polystyrene/foam
	E06-Polystyrene #6	
	E07-Other Plastic	
	E071-Foams	
	E072-Plastic Bags	
	E073-Film	
	E08-Composite (mostly plastic)	
Rubber		
		Rubber – shredded tyres
		Rubber – other
		Rubber – tyres/tubes
Textile		
	C02-Textile/Rags/Carpet (Organic)	Textile – cloth
	C03-Leather	Textile – furniture
		Textile – leather/other
		Textile – mattress
Wood		
	C01-Wood/Timber	Wood – pallets/ other
		Wood – mdf/chipboard
		Wood – furniture
		Wood – fencing/board/pole (untreated)
		Wood – fencing/board /pole (treated)
		Sawdust

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[a] Domestic waste: adapted from (APC 2011a,b)

[b] C&I waste: adapted from (DECCW 2010)

Putrescible fractions

Table 40. Putrescible fractions, Domestic Commercial and Industrial waste

Category	Waste materials	
	Domestic wastes[a]	Commercial and Industrial wastes[b]
Food		
	B01-Food/Kitchen	Food/kitchen Food – dense
Green waste		
	B02-Garden/Vegetation B03-Other Putrescible	Vegetation – branches/grass clips Vegetation – tree stumps /logs

[a] Domestic waste: adapted from (APC 2011a,b)

[b] C&I waste: adapted from (DECCW 2010)

Inert fractions

Table 41. Inert fractions, Domestic Commercial and Industrial waste

Category	Waste materials	
	Domestic wastes[a]	Commercial and Industrial wastes[b]
Construction and Demolition (C&D)		
	I01-Ceramics I02-Dust/Dirt/Rock/Inert I03-Ash/Earth-based	Concrete/cement Clay Plasterboard Rubble > 150mm Rock Tiles Bricks Soil/cleanfill Insulation Fibreglass Asphalt Sand Ceramic Dirt
Glass		
	D0121-Glass Clear Packaging/Containers D0122-Glass Green Packaging/Containers D0123-Glass Brown/Blue Packaging/Containers D050-Mixed Glass/Fines D02-Miscellaneous/Other Glass	Glass – containers/other Glass – plate
Metal		
	F01-steelCans Food & Pet F011-steel Aerosols F012-steelPaint Cans F03-Composite (mostly ferrous) F02-Other ferrous G01-Aluminium G03-Composite (mostly non-ferrous} G02-Other Non-Ferrous	Metal – ferrous Metal – non ferrous

[a] Domestic waste: adapted from (APC 2011a,b)

[b] C&I waste: adapted from (DECCW 2010)

Hazardous fractions

Table 42. Hazardous fractions, Domestic Commercial and Industrial waste

Category	Waste materials Domestic wastes[a]	Commercial and Industrial wastes[b]
Hazardous		
	H01-Paint H02-Fluorescent tubes H03-Dry cell batteries H04-Car batteries H05-Household chemicals H06-Building Materials H07-Clinical (Medical) -Gas Bottles -Hazardous other	Hazardous/special – chemical/clinical Hazardous/special – light globes Batteries

[a] Domestic waste: adapted from (APC 2011a,b)

[b] C&I waste: adapted from (DECCW 2010)

Other fractions

Table 43. Other fractions, Domestic Commercial and Industrial waste

Category	Waste materials Domestic wastes[a]	Commercial and Industrial wastes[b]
Whitegoods		
	n/a	Whitegoods – washing machine/ fridges
e-Waste		
	Y57-Toner Cartridges -Computer Equipment -Electrical Items -Mobile Phones	Electronics/electrical television etc. Computer/office equipment Toner cartridges
Other		
	XX00 -Other	Sludge Foundry sand Storm water Christmas decorations Animals Other

[a] Domestic waste: adapted from (APC 2011a,b)

[b] C&I waste: adapted from (DECCW 2010)

Composition analysis

The resulting composition analysis of the different process fraction and categories is summarized in the Table below.

Table 44. Composition analysis - domestic, commercial and industrial waste, by waste fraction and category

Fraction/category	MSW - CoS, 2011 Audit		MSW - SSROC, 2011 Audit		C&I - SMA, 2008 Survey	
	kg/wk	wt%	kg/hh-wk	wt%	t/y	wt%
Combustible fractions						
Oils	0.2	0.01%	0.006	0.06%		
Paper	383.4	24.23%	2.083	20.66%	303,246.0	17.45%
Plastics	227.7	14.38%	1.282	12.71%	293,741.0	16.91%
Rubber	3.5	0.22%	0.035	0.35%	19,526.0	1.12%
Leather	1.0	0.06%	0.027	0.27%	3,305.0	0.19%
Textile	53.0	3.35%	0.330	3.27%	84,242.0	4.85%
Wood	28.6	1.81%	0.121	1.20%	288,366.0	16.60%
Total combustible	*697.5*	*44.07%*	*3.884*	*38.52%*	*992,426.0*	*57.11%*
Inert fractions						
C&D	89.6	5.66%	0.422	4.18%	170,603.0	9.82%
Glass	105.2	6.64%	0.330	3.27%	24,633.0	1.42%
Metal	41.2	2.60%	0.247	2.45%	37,631.0	2.17%
Total inert	*235.9*	*14.91%*	*0.999*	*9.91%*	*232,867.0*	*13.40%*
Putrescible fractions						
Food	522.1	32.99%	3.820	37.88%	303,164.0	17.45%
Green waste	81.5	5.15%	0.783	7.76%	56,482.0	3.25%
Total Putrescible	*603.6*	*38.14%*	*4.603*	*45.65%*	*359,646.0*	*20.70%*
Hazardous fractions						
Hazardous	7.3	0.46%	0.068	0.67%	30,368.0	1.75%
Total hazardous	*7.3*	*0.46%*	*0.068*	*0.67%*	*30,368.0*	*1.75%*
Other fractions						
Whitegoods					743.0	0.04%
e-Waste	12.5	0.79%	0.114	1.13%	11,910.0	0.69%
Other	25.9	1.64%	0.416	4.13%	109,635.0	6.31%
Total other	*38.4*	*2.43%*	*0.530*	*5.26%*	*122,288.0*	*7.04%*
Total	1,582.8	100.00%	10.084	100.00%	1,737,595.0	100.00%

MSW - City of Sydney LGA: adapted from (APC 2011a), Table 13, p..37-38.
MSW - SSROC region: adapted from (APC 2011b) Table 18, pp.55-56.
C&I: SMA data adapted from (DECCW 2010), Table A2-3, p.76-77.

Elemental analysis

In this section we present the elemental analysis of process fractions, obtained by combining moisture content and ultimate analysis data from (Niessen 2010) with the composition figures presented earlier for the domestic waste streams collected within the City of Sydney LGA and SSROC region, and commercial and industrial waste streams collected within the Sydney Metropolitan Area.

Domestic waste fractions

City of Sydney LGA

Table 45. City of Sydney LGA, Domestic waste – ultimate analysis (est.), by waste categories and fractions

	Composition	Ultimate analysis (dry basis), weight %					
	wt%	C	H	O	N	S	Ash
Combustible							
Oils	0.01%	66.85	9.63	5.2	2	0.02	16.3
Paper	24.23%	45.4	6.1	42.1	0.3	0.12	5.98
Plastics	14.38%	59.8	8.3	19	1	0.3	11.6
Rubber	0.22%	77.65	10.35	0	0	2	10
Leather	0.06%	60	8	11.5	10	0.4	10.1
Textile	3.35%	46.2	6.4	41.8	2.2	0.2	3.2
Wood	1.81%	48.3	6	42.4	0.3	0.11	2.89
Inert							
C&D	5.66%	13	2	12	3	0	70
Glass	6.64%	0.52	0.07	0.36	0.03	0	99.02
Metal	2.60%	4.5	0.6	4.3	0.05	0.01	90.54
Putrescible							
Food	32.99%	41.7	5.8	27.6	2.8	0.25	21.85
Green waste	5.15%	49.2	6.5	36.1	2.9	0.35	4.95
Hazardous							
Hazardous	0.46%	13	2	12	3	0	70
Other fractions							
Whitegoods	0.00%	13	2	12	3	0	70
e-Waste	0.79%	13	2	12	3	0	70
Other	1.64%	13	2	12	3	0	70
CoS LGA - total	100.00%	39.79	5.46	27.23	1.64	0.19	25.69
Combustible	44.07%	50.47	6.86	34.28	0.69	0.19	7.51
Inert	14.91%	5.95	0.90	5.47	1.16	0.00	86.52
Putrescible	38.14%	42.71	5.89	28.75	2.81	0.26	19.57
Hazardous	0.46%	13.00	2.00	12.00	3.00	0.00	70.00
Other	2.43%	13.00	2.00	12.00	3.00	0.00	70.00
CoS LGA - feedstock resource							
LTC/HTC (comb.+putrescible)		46.87	6.41	31.71	1.67	0.23	13.10
HTCM (comb.+putrescible+inert)		40.59	5.57	27.69	1.59	0.19	24.37

SSROC region

Table 46. SSROC region, Domestic waste – ultimate analysis (est.), by waste categories and fractions

	Composition	Ultimate analysis (dry basis), weight %					
	wt%, dry basis	C	H	O	N	S	Ash
Combustible							
Oils	0.06%	66.85	9.63	5.2	2	0.02	16.3
Paper	20.66%	45.4	6.1	42.1	0.3	0.12	5.98
Plastics	12.71%	59.8	8.3	19	1	0.3	11.6
Rubber	0.35%	77.65	10.35	0	0	2	10
Leather	0.27%	60	8	11.5	10	0.4	10.1
Textile	3.27%	46.2	6.4	41.8	2.2	0.2	3.2
Wood	1.20%	48.3	6	42.4	0.3	0.11	2.89
Inert							
C&D	4.18%	13	2	12	3	0	70
Glass	3.27%	0.52	0.07	0.36	0.03	0	99.02
Metal	2.45%	4.5	0.6	4.3	0.05	0.01	90.54
Putrescible							
Food	37.88%	41.7	5.8	27.6	2.8	0.25	21.85
Green waste	7.76%	59.59	9.47	24.65	1.02	0.19	5.08
Hazardous							
Hazardous	0.67%	13	2	12	3	0	70
Other fractions							
Whitegoods	0.00%	13	2	12	3	0	70
e-Waste	1.13%	13	2	12	3	0	70
Other	4.13%	13	2	12	3	0	70
SSROC - total	100.00%	41.41	5.81	26.72	1.74	0.19	24.13
Combustible	38.52%	50.74	6.91	33.81	0.76	0.20	7.58
Inert	9.91%	6.78	1.02	6.25	1.29	0.00	84.67
Putrescible	45.65%	44.74	6.42	27.10	2.50	0.24	19.00
Hazardous	0.67%	13.00	2.00	12.00	3.00	0.00	70.00
Other	5.26%	13.00	2.00	12.00	3.00	0.00	70.00
SSROC - feedstock resource							
LTC/HTC (comb.+putrescible)		47.49	6.64	30.17	1.70	0.22	13.77
HTCM (comb.+putrescible+inert)		43.20	6.05	27.65	1.66	0.20	21.24

Commercial and Industrial waste fractions

Sydney Metropolitan Area

Table 47. SMA, Commercial and Industrial waste – ultimate analysis (est.), by waste categories and fractions

	Composition	Ultimate analysis (dry basis), weight %					
	wt%	C	H	O	N	S	Ash
Combustible							
Oils	0.00%	66.85	9.63	5.2	2	0.02	16.3
Paper	17.45%	45.4	6.1	42.1	0.3	0.12	5.98
Plastics	16.91%	59.8	8.3	19	1	0.3	11.6
Rubber	1.12%	77.65	10.35	0	0	2	10
Leather	0.19%	60	8	11.5	10	0.4	10.1
Textile	4.85%	46.2	6.4	41.8	2.2	0.2	3.2
Wood	16.60%	48.3	6	42.4	0.3	0.11	2.89
Inert							
C&D	9.82%	13	2	12	3	0	70
Glass	1.42%	0.52	0.07	0.36	0.03	0	99.02
Metal	2.17%	4.5	0.6	4.3	0.05	0.01	90.54
Putrescible							
Food	17.45%	49.06	6.62	37.55	1.68	0.2	4.89
Green waste	3.25%	48.51	6.54	40.44	1.71	0.19	2.61
Hazardous							
Hazardous	1.75%	13	2	12	3	0	70
Other fractions							
Whitegoods	0.04%	13	2	12	3	0	70
e-Waste	0.69%	13	2	12	3	0	70
Other	6.31%	13	2	12	3	0	70
SMA - total	100.00%	41.93	5.66	29.84	1.31	0.16	21.10
Combustible	57.11%	51.26	6.84	34.39	0.69	0.22	6.60
Inert	13.40%	10.31	1.57	9.52	2.21	0.00	76.39
Putrescible	20.70%	48.97	6.61	38.00	1.68	0.20	4.53
Hazardous	1.75%	13.00	2.00	12.00	3.00	0.00	70.00
Other	7.04%	13.00	2.00	12.00	3.00	0.00	70.00
SMA - feedstock resource							
LTC/HTC (comb.+putrescible)		50.65	6.78	35.35	0.96	0.21	6.05
HTCM (comb.+putrescible+inert)		44.72	6.01	31.56	1.14	0.18	16.39

Energy content

The energy content, or *heating value* of a fuel is defined on the basis of either of the following two conventions, as follows (Basu 2010):

- the **higher heating value (HHV),** the amount of heat released by the unit mass or volume of fuel (initially at the standard temperature condition of 25 °C) once it is combusted and the products have returned to the standard temperature, thus including the latent heat of vaporization of water in the combustion product; and

- the **lower heating value (LHV),** is defined as the amount of heat released by fully combusting a specified quantity of fuel, minus the latent heat of vaporization of the water in the combustion product.

Throughout this study we report energy quantities and energy performances on a HHV basis for consistency with other related studies developed for the City of Sydney within the scope of its *Renewable Energy* (City of Sydney 2013a) and *Trigeneration* (City of Sydney 2013b) Master Plans.

The relationship between the LHV and HHV of a fuel is expressed as follows:

$$\boldsymbol{LHV} = \boldsymbol{HHV} - \boldsymbol{h_g}\left(\frac{9\boldsymbol{H}}{100} + \frac{\boldsymbol{M}}{100}\right) \tag{4}$$

where:

- $\boldsymbol{LHV}$ and $\boldsymbol{HHV}$ are the lower and higher heating values of the fuel, respectivelys the latent heat of vaporization for water, 2260 kJ/kg;
- the latent heat of vaporization for water, 2260 kJ/kg;
- $\boldsymbol{h_g}$ is the latent heat of vaporization for water, 2260 kJ/kg;
- $\boldsymbol{H}$ is the hydrogen content, by weight on an as received basis; and
- $\boldsymbol{M}$ is the moisture content, by weight on an as received basis.

The most reliable means of determining the heating value of a fuel is through experimental methods, such as the D5468 standard test method issued by the American Society for Testing of Materials (ASTM D34 2007).

Alternatively, a number of empirical relationships are available to estimate the heating value of fuels on the basis of its ultimate analysis and moisture content data.

Consistent with the approach for the evaluation of pyrolysis and gasification processes presented in (Basu 2010) we compute HHV (dry basis, db) based on the unified correlation published in (Channiwala & Parikh 2002):

$$\boldsymbol{HHV_{db}} = 349.1 \cdot \boldsymbol{C} + 1178.3 \cdot \boldsymbol{H} + 100.5 \cdot \boldsymbol{S} - 103.4 \cdot \boldsymbol{O} - 15.1 \cdot \boldsymbol{N} - 21.1 \cdot \boldsymbol{Ash} \tag{5}$$

where $\boldsymbol{C}$, $\boldsymbol{H}$, $\boldsymbol{S}$, $\boldsymbol{O}$, $\boldsymbol{N}$, and $\boldsymbol{Ash}$ are the percentages, by weight, of carbon, hydrogen, sulphur, oxygen, nitrogen and ash, as determined by ultimate analysis on a dry basis.

The LHV or HHV on an as received basis (ar) can be calculated from the corresponding dry basis figures as follows:

$$HHV_{ar} = HHV_{db} \cdot \frac{M}{100} \tag{6}$$

Domestic waste fractions

City of Sydney LGA

Table 48. City of Sydney LGA, Domestic waste – estimated energy contents, by waste categories and fractions

	Composition	Moisture	Higher Heating Value (MJ/kg)		Lower Heating Value (MJ/kg)	
Category	wt%	wt%	as received	dry basis	as received	dry basis
Combustible						
Oils	0.01%	0	33.77	33.77	31.82	31.82
Paper	24.23%	24.3	14.05	18.57	12.70	16.78
Plastics	14.38%	13.8	24.53	28.46	22.81	26.46
Rubber	0.22%	13.8	33.87	39.29	31.79	36.88
Leather	0.06%	13.8	24.88	28.86	23.21	26.92
Textile	3.35%	23.8	14.68	19.27	13.28	17.43
Wood	1.81%	15.4	16.49	19.49	15.16	17.92
Inert						
C&D	5.66%	3	4.01	4.13	3.55	3.66
Glass	6.64%	3	-1.81	-1.86	-1.89	-1.95
Metal	2.60%	6.6	-0.07	-0.08	-0.33	-0.35
Putrescible						
Food	32.99%	63.6	6.57	18.06	5.62	15.44
Green waste	5.15%	37.9	13.03	20.99	11.68	18.81
Hazardous						
Hazardous	0.46%	3	4.01	4.13	3.55	3.66
Other fractions						
Whitegoods	0.00%	3	4.01	4.13	3.55	3.66
e-Waste	0.79%	3	4.01	4.13	3.55	3.66
Other	1.64%	3	4.01	4.13	3.55	3.66
MSW TOTAL	100.00%	32.55	11.44	16.97	10.20	15.12
Combustible	44.07%	20.39	17.52	22.01	16.04	20.15
Inert	14.91%	3.63	0.70	0.72	0.44	0.46
Putrescible	38.14%	60.13	7.36	18.46	6.34	15.90
Hazardous	0.46%	3.00	4.01	4.13	3.55	3.66
Other	2.43%	3.00	4.01	4.13	3.55	3.66

SSROC region

Table 49. SSROC region, Domestic waste – energy contents (est.), by waste categories and fractions

	Composition	Moisture	Higher Heating Value (MJ/kg)		Lower Heating Value (MJ/kg)	
Category	wt%, dry basis	wt%	as received	dry basis	as received	dry basis
Combustible						
Oils	0.06%	0	33.77	33.77	31.82	31.82
Paper	20.66%	24.3	14.05	18.57	12.70	16.78
Plastics	12.71%	13.8	24.53	28.46	22.81	26.46
Rubber	0.35%	13.8	33.87	39.29	31.79	36.88
Leather	0.27%	13.8	24.88	28.86	23.21	26.92
Textile	3.27%	23.8	14.68	19.27	13.28	17.43
Wood	1.20%	15.4	16.49	19.49	15.16	17.92
Inert						
C&D	4.18%	3	4.01	4.13	3.55	3.66
Glass	3.27%	3	-1.81	-1.86	-1.89	-1.95
Metal	2.45%	6.6	-0.07	-0.08	-0.33	-0.35
Putrescible						
Food	37.88%	63.6	6.57	18.06	5.62	15.44
Green waste	7.76%	37.9	18.20	29.31	16.47	26.53
Hazardous						
Hazardous	0.67%	3	4.01	4.13	3.55	3.66
Other fractions						
Whitegoods	0.00%	3	4.01	4.13	3.55	3.66
e-Waste	1.13%	3	4.01	4.13	3.55	3.66
Other	4.13%	3	4.01	4.13	3.55	3.66
MSW TOTAL	100.00%	35.42	11.64	18.02	9.76	16.04
Combustible	38.52%	20.31	17.69	22.20	16.21	20.34
Inert	9.91%	3.89	1.07	1.11	0.78	0.82
Putrescible	45.65%	59.23	8.14	19.97	7.06	17.33
Hazardous	0.67%	3.00	4.01	4.13	3.55	3.66
Other	5.26%	3.00	4.01	4.13	3.55	3.66

Commercial and Industrial waste fractions

Sydney Metropolitan Area

Table 50. SMA, Commercial and Industrial waste – energy contents (est.), by waste categories and fractions

	Composition	Moisture	Higher Heating Value (MJ/kg)		Lower Heating Value (MJ/kg)	
Category	wt%, dry basis	wt%	as received	dry basis	as received	dry basis
Combustible						
Oils	0.06%	0	33.77	33.77	31.82	31.82
Paper	20.66%	24.3	14.05	18.57	12.70	16.78
Plastics	12.71%	13.8	24.53	28.46	22.81	26.46
Rubber	0.35%	13.8	33.87	39.29	31.79	36.88
Leather	0.27%	13.8	24.88	28.86	23.21	26.92
Textile	3.27%	23.8	14.68	19.27	13.28	17.43
Wood	1.20%	15.4	16.49	19.49	15.16	17.92
Inert						
C&D	4.18%	3	4.01	4.13	3.55	3.66
Glass	3.27%	3	-1.81	-1.86	-1.89	-1.95
Metal	2.45%	6.6	-0.07	-0.08	-0.33	-0.35
Putrescible						
Food	37.88%	63.6	6.57	18.06	5.62	15.44
Green waste	7.76%	37.9	18.20	29.31	16.47	26.53
Hazardous						
Hazardous	0.67%	3	4.01	4.13	3.55	3.66
Other fractions						
Whitegoods	0.00%	3	4.01	4.13	3.55	3.66
e-Waste	1.13%	3	4.01	4.13	3.55	3.66
Other	4.13%	3	4.01	4.13	3.55	3.66
MSW TOTAL	100.00%	35.42	11.64	18.02	9.76	16.04
Combustible	38.52%	20.31	17.69	22.20	16.21	20.34
Inert	9.91%	3.89	1.07	1.11	0.78	0.82
Putrescible	45.65%	59.23	8.14	19.97	7.06	17.33
Hazardous	0.67%	3.00	4.01	4.13	3.55	3.66
Other	5.26%	3.00	4.01	4.13	3.55	3.66

Feedstock resource analysis

Processable fractions

The analysis presented in Section 4. Advanced Waste Treatment Scenarios, considers a range of thermal conversion technologies, grouped into three conversion strategies:

- **Low-Temperature Conversion (LTC) –** including, pyro-combustion, slow pyrolysis and fixed-bed gasification technologies;
- **High-Temperature Conversion (HTC) –** including pyro-gasification and fluid-bed gasification technologies;
- **High-Temperature Conversion + Melting (HTCM) –** including pyro-gasification + melting, fluid-bed gasification + melting, and plasma gasification.

The processable waste fractions for the three families of conversion technologies considered are summarized in the matrix below.

Table 51. Syngas from Waste conversion technologies – waste fractions processed, by conversion strategy

	Mixed Waste Fractions					
STRATEGY/TECHNOLOGY	Combustible	Inert	Putrescible	Hazardous	Other	SR [a]
Low-Temperature Conversion (LTC)						
Pyro-Combustion	✓	×	✓	×	×	×
Slow Pyrolysis	✓	×	✓	×	×	×
Fixed-Bed Gasification	✓	×	✓	×	×	×
High-Temperature Conversion (HTC)						
Fluid Bed Gasification	✓	×	✓	×	×	×
Pyro-Gasification	✓	×	✓	×	×	×
High-Temperature Conversion + Melting (HTCM)						
Pyro-Gasification + Melting	✓	✓	✓	(✓)	×	(✓)
Fluid Bed Gasification + Melting	✓	✓	✓	(✓)	×	(✓)
Plasma Gasification	✓	✓	✓	(✓)	×	(✓)

[a] Shredder Residues from Whitegoods processing at resource recovery facility

Within the scope of this study, Low-and High-Temperature Conversion technologies are considered to process the combustible and the putrescible fractions of the incoming residual waste stream. High-Temperature Conversion + Melting technologies, by virtue of the high-temperatures reached inside the reactor (for plasma gasification) or in a separate high-temperature *melting* zone located immediately downstream (for pyro-gasification + melting and fluid-bed gasification + melting), have furthermore the ability to process the inert fraction of the incoming residual waste stream[22].

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[22] The hazardous and shredder residues fractions can be also processed by HTCM technologies, but have been excluded from this assessment as, based on experience with the City of Sydney domestic waste streams, they are delivered to specialized alternative waste treatment facilities.

Elemental analysis

The matrix of processable fractions has been applied to the elemental analysis presented earlier for each of the waste resource streams considered to determine the ultimate analysis, dry basis, for the resulting feedstock resources for the three families of conversion technologies.

Domestic waste fractions

City of Sydney LGA

Table 52. City of Sydney LGA, Domestic waste – feedstock resource ultimate analysis (est.)

	Composition	Ultimate analysis (dry basis), weight %					
	wt%	C	H	O	N	S	Ash
SMA - total	100.00%	41.93	5.66	29.84	1.31	0.16	21.10
Combustible	57.11%	51.26	6.84	34.39	0.69	0.22	6.60
Inert	13.40%	10.31	1.57	9.52	2.21	0.00	76.39
Putrescible	20.70%	48.97	6.61	38.00	1.68	0.20	4.53
Hazardous	1.75%	13.00	2.00	12.00	3.00	0.00	70.00
Other	7.04%	13.00	2.00	12.00	3.00	0.00	70.00
SMA - feedstock resource							
LTC/HTC (comb.+putrescible)		50.65	6.78	35.35	0.96	0.21	6.05
HTCM (comb.+putrescible+inert)		44.72	6.01	31.56	1.14	0.18	16.39

SSROC region

Table 53. SSROC region, Domestic waste – feedstock resource ultimate analysis (est.)

	Composition	Ultimate analysis (dry basis), weight %					
	wt%, dry basis	C	H	O	N	S	Ash
SSROC - total	100.00%	41.41	5.81	26.72	1.74	0.19	24.13
Combustible	38.52%	50.74	6.91	33.81	0.76	0.20	7.58
Inert	9.91%	6.78	1.02	6.25	1.29	0.00	84.67
Putrescible	45.65%	44.74	6.42	27.10	2.50	0.24	19.00
Hazardous	0.67%	13.00	2.00	12.00	3.00	0.00	70.00
Other	5.26%	13.00	2.00	12.00	3.00	0.00	70.00
SSROC - feedstock resource							
LTC/HTC (comb.+putrescible)		47.49	6.64	30.17	1.70	0.22	13.77
HTCM (comb.+putrescible+inert)		43.20	6.05	27.65	1.66	0.20	21.24

Commercial and Industrial waste fractions

Sydney Metropolitan Area

Table 54. SMA, Commercial and Industrial waste – feedstock resource ultimate analysis (est.)

	Composition	Ultimate analysis (dry basis), weight %					
	wt%	C	H	O	N	S	Ash
SMA - total	100.00%	41.93	5.66	29.84	1.31	0.16	21.10
Combustible	57.11%	51.26	6.84	34.39	0.69	0.22	6.60
Inert	13.40%	10.31	1.57	9.52	2.21	0.00	76.39
Putrescible	20.70%	48.97	6.61	38.00	1.68	0.20	4.53
Hazardous	1.75%	13.00	2.00	12.00	3.00	0.00	70.00
Other	7.04%	13.00	2.00	12.00	3.00	0.00	70.00
SMA - feedstock resource							
LTC/HTC (comb.+putrescible)		50.65	6.78	35.35	0.96	0.21	6.05
HTCM (comb.+putrescible+inert)		44.72	6.01	31.56	1.14	0.18	16.39

Energy content

The empirical correlation in (Channiwala & Parikh 2002) has been used to determine the heating value figures presented in the Table below.

Table 55. Feedstock energy content - domestic, commercial and industrial waste, by conversion strategy

STRATEGY/FEEDSTOCK	Moisture	Higher Heating Value (MJ/kg)		Lower Heating Value (MJ/kg)	
	wt%	as received	dry basis	as received	dry basis
Low-Temperature Conversion (LTC)					
MSW - CoS LGA	38.83	12.46	20.36	11.12	18.18
MSW - SSROC	41.42	12.30	20.99	10.96	18.71
C&I - SMA	29.29	15.48	21.89	14.03	19.85
High-Temperature Conversion (HTC)					
MSW - CoS LGA	38.83	12.46	20.36	11.12	18.18
MSW - SSROC	41.42	12.30	20.99	10.96	18.71
C&I - SMA	29.29	15.48	21.89	14.03	19.85
High-Temperature Conversion + Melting (HTCM)					
MSW - CoS LGA	33.43	11.55	17.35	10.29	15.46
MSW - SSROC	37.47	11.82	18.90	10.52	16.82
C&I - SMA	25.51	14.22	19.09	12.88	17.29

Biomass, renewable energy and biogenic carbon content

Three coefficients – biomass fraction, renewable energy fraction and biogenic carbon content (BCC) – are calculated on an as received basis for each resource stream and conversion strategy on the basis of the feedstock composition analysis data presented earlier. The results for the three coefficients are presented in the Table below.

Table 56. Biomass, renewable energy and biogenic carbon content – all feedstocks, by conversion strategy

Category	Mass, wt% as received		Energy, HHV as received		Carbon, wt% dry basis	
	biomass	other	renewable	non renewable	biogenic	non-biogenic
Low-Temperature Conversion (LTC)						
MSW - CoS LGA	82.49%	17.51%	69.14%	30.86%	77.65%	22.35%
MSW - SSROC	84.82%	15.18%	72.70%	27.30%	80.88%	19.12%
C&I - SMA	78.27%	21.73%	67.30%	32.70%	74.35%	25.65%
High-Temperature Conversion (HTC)						
MSW - CoS LGA	82.49%	17.51%	69.14%	30.86%	77.65%	22.35%
MSW - SSROC	84.82%	15.18%	72.70%	27.30%	80.88%	19.12%
C&I - SMA	78.27%	21.73%	67.30%	32.70%	74.35%	25.65%
High-Temperature Conversion + Melting (HTCM)						
MSW - CoS LGA	69.83%	30.17%	67.10%	32.90%	75.91%	24.09%
MSW - SSROC	75.89%	24.11%	70.48%	29.52%	79.54%	20.46%
C&I - SMA	66.77%	33.23%	65.22%	34.78%	71.83%	28.17%

Biomass content

The fractions considered for the estimation of the total biomass have been selected according to methods prescribed in the National Greenhouse and Energy Reporting (NGER) guidelines[23] and a general methodology document published under by the UNFCCC Clean Development Mechanism (CDM)[24], these are:

- **Biomass fractions:** Food, paper, green waste, wood, textile, leather and rubber;
- **Non-biomass fractions:** oils, plastic, construction and demolition waste, glass and metal, hazardous fractions and other (e-waste, whitegoods, shredder residues, etc.)

Renewable energy content

The renewable energy content is calculated for each resource stream and conversion strategy as the ratio between the energy content (HHV, as received basis) for the biomass fractions and for the total feedstock resource stream.

Biogenic carbon content

The biogenic carbon content (BCC) for waste feedstocks is calculated for each resource stream, conversion strategy and catchment region, as the ratio between the carbon content for the biomass fractions and the total feedstock resource stream (both on an as received basis).

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[23] DCCEE 2012a. National Greenhouse and Energy Reporting System Measurement. Technical Guidelines for the estimation of greenhouse gas emissions by facilities in Australia. Department of Climate Change and Energy Efficiency, Australian Government, July 2012. http://www.climatechange.gov.au/.../national-greenhouse-factors.aspx

[24] CDM 2012. AM0025: Alternative waste treatment processes --- Version 14.0.0. Clean Development Mechanism, United Framework Convention on Climate Change. Valid from 20 July 2012. http://cdm.unfccc.int/methodologies/

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APPENDIX B. PERFORMANCES, COSTS AND EMISSIONS SURVEY

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Performance survey

Energy and Mass Balances

Low-Temperature Conversion

Table 57. Low-Temperature Conversion, representative mass balance for pyro-combustion

INPUTS	Consumption		OUTPUTS	Yield	
Stream/component	kg/h	kg/t_{feed}	Stream/component	kg/h	kg/t_{feed}
TOTAL INPUTS	4725.20	1000.00	TOTAL OUTPUTS	4725.20	1000.00
Feedstocks @ 20% moisture			Products		
post MRF MSW	4725.20	1000.00	Pyro-gas	2988.96	632.56
			Recoverable by-products		
			Water	945.04	200.00
			Residues		
			Char	567.00	119.99
			Cyclone Ash	175.80	37.20
			Baghouse Ash	48.40	10.24
			CONVERSION and RECOVERY PERFORMANCES		
			Total By-products	945.04	200.00
			Total Residues	791.20	167.44
			MASS REDUCTION (solids)		83.26%

SOURCE: (Wood 2007)

Table 58. Low-Temperature Conversion, representative energy balance for pyro-combustion

INPUTS			OUTPUTS		
Stream	GJ/t_{feed}	MW	Stream	GJ/t_{feed}	MW
TOTAL INPUTS	13.74	18.03	TOTAL OUTPUTS	13.74	18.03
Feedstocks			Syngas	7.83	10.3
MSW	12.30	16.1			
			Residues		
Fuels			Char solids	5.10	6.7
Natural gas	1.44	1.9			
			Losses		
			Heat losses	0.81	1.06
			ENERGY RECOVERY PERFORMANCES		
			Syngas energy, @ ambient temperature		10.27
			THERMAL EFFICIENCY, HHV basis		94.13%
			COLD GAS EFFICIENCY, HHV basis		56.97%

SOURCE: (Wood 2007)

High-Temperature Conversion

Table 59. High-Temperature Conversion, representative mass balance for fluidized-bed gasification

INPUTS	Consumption		OUTPUTS	Yield	
Stream/component	kg/h	kg/t_{feed}	Stream/component	kg/h	kg/t_{feed}
TOTAL INPUTS	4366.40	1047.94	TOTAL OUTPUTS	3681.25	883.50
Feedstocks			Products		
RDF	4166.67	1000.00	Syngas	3681.25	883.50
Oxidant			Residues		
Air	199.73	47.94	Char	951.25	228.3
Oxygen	--	--	Ash	63.25	15.18
Steam	--	--			
			CONVERSION and RECOVERY PERFORMANCES		
			Total By-products	0.00	0.00
			Total Residues	1014.50	243.48
			MASS REDUCTION (solids)		75.65%

SOURCE: (Granatstein 2003)

Table 60. High-Temperature Conversion, representative energy balance for fluidized-bed gasification

INPUTS			OUTPUTS		
Stream/component	GJ/t_{feed}	MW	Stream	GJ/t_{feed}	MW
TOTAL INPUTS	19.36	22.41	TOTAL OUTPUTS	19.36	22.41
Feedstock - RDF			Syngas	11.67	13.51
RDF	17.20	19.91			
			Heat losses	7.69	8.90
Fuels					
Natural gas	2.16	2.50			
Electricity					
BoP, kWh/t_{feed}	195.79	0.82			
			ENERGY RECOVERY PERFORMANCES		
			Syngas energy, @ ambient temperature		10.27
			THERMAL EFFICIENCY, HHV basis		94.13%
			COLD GAS EFFICIENCY, HHV basis		60.30%

SOURCE: (Granatstein 2003)

High-Temperature Conversion + Melting

Table 61. High-Temperature Conversion + Melting, representative mass balance for plasma gasification

INPUTS	Consumption		OUTPUTS	Yield	
Stream/component	kg/h	kg/t_{feed}	Stream/component	kg/h	kg/t_{feed}
TOTAL INPUTS	48223.00	1543.14	TOTAL OUTPUTS	48223.00	1543.14
Feedstocks			Products		
MSW	29583.00	946.66	Syngas	37629.00	1204.13
Tyres	1667.00	53.34			
			Recoverable by-products		
Additives			Aggregate (slag and metal)	9550.00	305.60
Coke	1250.00	40.00			
Limestone	3209.00	102.69	Residues		
			Char solids	142.60	4.56
Oxidant			Other residues	901.40	28.84
Air	2345.00	75.04			
Oxygen	10169.00	325.41			
Steam	--	--			
			CONVERSION and RECOVERY PERFORMANCES		
			Total By-products	9550.00	305.60
			Total Residues	1044.00	33.41
			MASS REDUCTION (solids)	96.66%	0.03

SOURCE: (Willis *et al*. 2010)

Table 62. High-Temperature Conversion + melting, representative energy balance for plasma gasification

INPUTS			OUTPUTS		
Stream/component	GJ/t_{feed}	MW	Stream	GJ/t_{feed}	MW
TOTAL INPUTS	15.15	119.24	TOTAL OUTPUTS	15.15	119.24
Feedstocks			Syngas		
MSW	12.31	101.13	Energy content	9.83	80.30
Tyres	1.67	0.77	Sensible heat	1.79	15.54
			Latent heat	0.49	4.22
Additives					
Coke	1.18	10.20	By-products		
Limestone	--	--	Slag	0.60	5.17
Electricity			Residues		
Plasma torch, kWh/t_{feed}	102.94	3.22	Char solids	0.15	1.30
Oxygen facility, kWh/t_{feed}	125.52	3.92	Other residues		
			Losses		
			Heat losses	1.35	4.50
			Plasma torch losses	0.06	0.48
			Limestone calcination	0.13	1.10
			Other losses	0.76	6.63
			ENERGY RECOVERY PERFORMANCES		
			Syngas energy, @ ambient temperature		80.30
			THERMAL EFFICIENCY, HHV basis		94.90%
			COLD GAS EFFICIENCY,HHV basis		67.34%

SOURCE: (Willis *et al*. 2010)

Cost survey

Low-Temperature Conversion

Pyrolysis and Pyro-combustion

Table 63. Pyrolysis/pyro-combustion, capital and O&M cost survey

facility size	capital cost	O&M cost	monetary unit (m.u.)			
tpd	m.u$_{YEAR}$		currency	year	estimate description	source
23	6,500,000	n/a	USD	1993	Conrad Industries proposal	(URS 2005b)
50	8,000,000	n/a	USD	2005	IES test facility, Romoland, CA	(URS 2005b)
161	50,000,000	5,000,000	AUD	2010	50000 tpy pyrolysis plant	(URS 2010a)
163	23,225,500	2,328,650	USD	2005	IES proposal	(URS 2005b)
167	9,936,167	2,526,681	USD	2005	PAR proposal	(URS 2005b)
228	25,000,000	5,000,000	USD	1992	SITA facility, Bochum, Germany	(URS 2005b)
304	60,000,000	3,427,000	USD	2005	WasteGen proposal	(URS 2005b)
335	31,250,000	2,500,000	USD	2001	RWE facility, Hamm-Uentrop, Gerr	(URS 2005b)
1000	60,000,000	n/a	USD	2004	PAR estimate	(ARI 2004)

Fixed bed gasification

Table 64. Fixed bed gasification, capital and O&M cost survey

facility size	capital cost	O&M cost	monetary unit (m.u.)			
tpd	m.u$_{YEAR}$		currency	year	estimate description	source
26	6,500,000	600,000	USD	2005	PRM Philadelphia facility	(URS 2005b)
46	14,000,000	4,800,000	USD	2005	PRM Stanton facility	(URS 2005b)
55	12,000,000	n/a	USD	2010	Middlebury College/Chiptec	(Pytlar 2010)
55	22,000,000	1,500,000	USD	2005	PRM Stuttgart facility	(URS 2005b)
100	19,356,500	1,783,960	USD	2005	Ntech proposal	(URS 2005b)
107	15,500,000	1,557,000	USD	2005	Primenergy proposal	(URS 2005b)
128.5	22,145,328	n/a	EUR	2004	Entech case study, 45 ktpa facility	(Stein and Tobiase
155	20,000,000	n/a	USD	2010	University of South Carolina/Next	(Pytlar 2010)
161	40,000,000	6,650,000	AUD	2010	50000 tpy gasification plant	(URS 2010a)

High- Temperature Conversion

Fluidised bed gasification

Table 65. Fluid bed gasification, capital and O&M cost survey

facility size	capital cost	O&M cost	monetary unit (m.u.)			
tpd	m.u$_{YEAR}$		currency	year	estimate description	source
63	7,000,000	750,000	USD	2005	Omnifuel technologies proposal	(URS 2005b)
93.6	27,900,000	3,590,000	EUR	2003	Greve in Chianti TPS/Ansaldo plan	(Granatstein 200
200	52,000,000	n/a	USD	2010	Burlington facility, FERCO	(Pytlar 2010)
300	14,000,000	n/a	USD	2005	Burlington facility	(URS 2005b)
300	23,100,000	2,000,000	USD	2004	Taylor estimate	(ARI 2004)

Pyro-gasification

Table 66. Pyro-gasification, capital and O&M cost survey

facility size	capital cost	O&M cost	monetary unit (m.u.)			
tpd	m.u$_{\text{YEAR}}$		currency	year	estimate description	source
70.5	47,490,000	3,590,000	USD	2005	GES proposal	(URS 2005b)
161	70,000,000	8,100,000	AUD	2010	50000 tpy pyro-gasification plant	(URS 2010a)

High-Temperature Conversion + Melting

Fluidised bed gasification + Ash Melting

Table 67. Fluid bed gasification, capital and O&M cost survey

facility size	capital cost	O&M cost	monetary unit (m.u.)			
tpd	m.u$_{\text{YEAR}}$		currency	year	estimate description	source
40	14,000,000	n/a	USD	2004	Ebara low end estimate	(ARI 2004)
40	21,000,000	n/a	USD	2004	Ebara high estimate	(ARI 2004)
70.5	47,490,000	3,590,000	USD	2005	Ebara proposal	(URS 2005b)

Plasma gasification

Table 68. Plasma gasification, capital and O&M cost survey

facility size	capital cost	O&M cost	monetary unit (m.u.)			
tpd	m.u$_{\text{YEAR}}$		currency	year	estimate description	source
20	18,000,000	700,000	USD	2002	Mihama-Mikata plant	(URS 2005b)
70.5	47,490,000	3,590,000	USD	2005	GeoPlasma proposal	(URS 2005b)
161	90,000,000	8,500,000	AUD	2010	50000 tpy plasma gasification plant	(URS 2010a)
200	65,000,000	5,500,000	USD	2002	Utashinai plant	(URS 2005b)
300	89,500,000	8,967,345	USD	2010	Proposed plasma arc facility, Mario	(Clark and Rogof
600	161,000,000	n/a	USD	2010	Scaled-up plasma arc facility	(Clark and Rogof
3000	800,000,000	n/a	USD	2005	Rigel estimate	(ARI 2004)
3000	800,000,000	73,050,000	USD	2005	Rigel proposal	(URS 2005b)

Pyro-gasification + ash melting

Table 69. Pyro-gasification + ash melting, capital and O&M cost survey

facility size	capital cost	O&M cost	monetary unit (m.u.)			
tpd	m.u$_{\text{YEAR}}$		currency	year	estimate description	source
161	50,000,000	5,000,000	AUD	2010	50000 tpy pyr-gasification plant	(URS 2010a)
300	80,000,000	13,000,000	USD	2005	Chiba facility	(URS 2005b)
304	75,511,000	10,787,432	USD	2005	IWT proposal	(URS 2005b)
720	120,000,000	19,500,000	USD	1999	Karlsruhe facility	(URS 2005b)
720	110,000,000	8,500,000	USD	2002	Karlsruhe facility	(Hesseling 2002)
3051	457,000,000	n/a	USD	2005	IWT/Thermoselect estimate	(ARI 2004)

Emissions survey

Air pollutant emissions

Table 70. Emission performance survey

	PM	HCl	NO_x	SO_x	Hg	PCDD/PCDF
	mg/Nm^3 @ 11% O_2					$ng_{I\text{-}TEQ}/Nm^3$
European Standard	10	10	200	50	0.05	0.1
Japanese Standard	10.1-50.6	15.2-50.6	30.3-126.4	10.1-30.3	0.03-0.051	0.51
US Standard	24.3	25.3	151.7	30.3	0.03-0.051	0.14-0.21
Plant						
Ebara TwinRec - Kawaguchi, JAPAN	1.34	2.68	39.24	3.83	6.70E-03	6.89E-05
Entech - Kuznica, POLAND	0.94	7.56	243.08	49.67	7.66E-03	2.68E-02
InEnTec - Richland, WA, USA	3.16	2.58	155.03	-	6.41E-04	6.41E-03
INEOS Bio - Fayetteville, AK, USA	1.91	-	9.57	-	9.57E-05	2.87E-03
IES - Romoland, CA, USA	5.5	-	123.45	0.42	-	5.56E-04
JFE/Thermoselect - Nagasaki JAPA	4.5	11.1	-	-	-	2.39E-02
Mitsui R21 - Toyohashi, JAPAN	0.96	53.4	79.24	24.79	-	4.31E-03
Nippon Steel DMS - Kazusa, JAPAN	13.49	11.96	29.86	20.96	-	4.31E-02
Plasco - Ottowa, CANADA	12.25	2.97	143.55	24.88	1.91E-04	1.55E-02
OE Gasification - Heanam, KOREA	8.23	26.22	100.48	35.89	6.70E-04	5.37E-02
OE Gasification - Bosung, KOREA	7.18	24.21	56.46	17.9	6.70E-04	9.41E-02
OE Gasification - Pyungshan, KORE	10.81	20.19	73.88	39.33	6.70E-04	2.69E-02
OE Gasification - Hapchon, KOREA	8.09	22.2	80.58	28.61	6.70E-04	5.38E-02

SOURCE: (CERT 2009), values adapted to 11% O_2

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APPENDIX C. CASE STUDIES

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Alter NRG – PGVR

The Plasma Gasification Vitrification Reactor (PGVR) is a plasma-assisted gasification process commercialized by Alter NRG, a Canadian company, who has recently acquired Westinghouse Plasma Corporation (WPC), the original developer and a leading supplier of non-transferred arc (NTA) plasma torch technology.

The first generation of full-scale commercial PGVR systems has had a mixed success, with one small facility (Mihama-Mikata in Japan, 25 tpd) reporting nearly ten years of successful operation and a second large-scale facility (Utashinai 150-220 tpd) having being plagued by a series of design flaws and commissioning issues, ultimately causing the anticipated shutdown of the plant in 2013.

The second generation PGVR design – integrating all the modifications adopted to address earlier operational issues at the Utashinai facility – has since been installed successfully at one sites in India, with two other projects under development and has been selected for two facilities being installed at the Tees Walley Reneable Energy facility, developed by Air Products in the UK.

Technology development and commercialization

The Westinghouse Electric Corporation conducted early work on non-transferred arc (NTA) plasma torch applications at a 48 tpd pilot plant in Madison, Pennsylvania, still operating to this day as an R&D facility.

In the 1990s, Westinghouse and Hitachi Metals Ltd. joined forces to develop applications of the technology for processing MSW and biosolids, leading to the construction and operation of a demonstration facility in Yoshi, Japan commissioned in 1999.

The Yoshi facility was instrumental to develop operational experience and design information for projection to the first generation full-scale commercial concept of the Plasma Gasification Vitrification Reactor (PGVR). Following the experience at Yoshi, Hitachi Metals developed two commercial facilities in Japan: Mihama-Mikata (25 tpd, started in 2002) and Utashinai (150-220 tpd, started in 2003).

The Mihama-Mikata plant, a commercial success, has now over ten years of operation at full capacity. The Utashinai plant is instead being planned for shutdown in 2013 as a result of significant commissioning issues that have limited its operations and affected its profitability. Lessons learned at Utashinai have determined the improvements made towards the second generation of PGVR being commercialized today by Alter NRG Corp., which purchased Westinghouse Plasma Corporation and their technology in April 2007.

The company is actively pursuing opportunities for a range of potential applications of plasma technology, including waste-to-energy (MSW, biosolids and hazardous waste), co-gasification with coal, waste-to-ethanol to MSW and gasification of petcoke and other refinery residuals.

Two 70 tpd gasification facilities for hazardous waste have been commissioned recently in Pune and Nagpur, India. A substantial pipeline of other commercial prospects is also advertised on the AlterNRG website, with over 30 projects at different stages of development, from site selection to detailed engineering, including three projects in Australia claimed to be all past the site selection, feasibility study and feedstock agreement stages as of Q1 2011:

- a 50 mUSD waste-to-ethanol plant in Melbourne,
- a 30 mUSD waste-to-energy plant in Geelong, and
- a 32 mUSD waste-to-energy plant in Kwinana.

Phoenix Energy[25] commercializes the PGVR technology in Australia on a license from Alter NRG.

Process description

The schematic below represents the PGVR furnace, the core component of AlterNRG plasma gasification systems. The current generation design features a number of design improvements based on the lessons learned at the Utashinai EcoValley facility (see below).

Figure 78. Schematic of the Alter NRG PGVR[26].

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[25] http://www.phoenixenergy.com.au/ (formerly trading as Moltoni Energy).

[26] Adapted from (Willis et al. 2010)

In a typical plant waste-to-energy configuration the PGVR is combined with a waste pre-processing and feed system, a molten residue removal and handling system, a steam power generation island (boiler, turbine, condensers), and air-pollution control (APC) for flue-gas clean-up and handling.

Pre-processing

For solid materials (MSW and other residues), the Alter NRG system requires shredding of the materials to 15 cm top size. A moisture content of ~30% is desirable as the excess water turned into steam in the reactor promotes reforming of carbonaceous components to syngas.

Additional pre-treatment might be required for liquids, sludge to avoid jamming and ensure a continuous feed to the plasma reactors, as well as to avoid leaks and fugitive emissions when delaying with hazardous waste streams.

The high-temperatures in the plasma reactors pose some process control challenges. The implementation of rapid and effective feed shut-off systems is crucial to the safe operation of the plant when operating conditions deviate from the envelope defined by the operating permits.

Heating and conversion

Commercial PGVR units have diameter ranging from 1 to 4.6 m, with the volume above the bed of pyrolyzing waste designed to provide a gas residence time of about 30 s.

The gasifier chambers are operated at slightly sub-atmospheric conditions, with the plasma torches (2 to 4 depending on the unit) distributed radially along the lower sections of the reactor. This design allows for replacement/servicing of the torches without shutting down the unit.

AlterNRG supplies two types of PGVR units:

- the W-15 or Wolverine, rated at 170-250 tpd for waste and 120-300 tpd on biomass; and
- the G-65 or Grizzly, rated at 500-750 tpd for waste and 300-1000 tpd for biomass.

The water-cooled torches use air as the plasma gas and are rated for 1200 h of continuous duty. The torches are powered by a thyristor power supply providing a current controlled DC output. The plasma torches are supplied in three models (MARC 3A, 11H and 11L), with energy inputs and key characteristics listed in the Table below.

Table 71. Key characteristics of AlterNRG/Westinghouse plasma torches.

	Torch model		
	MARC 3A	MARC 11L	MARC 11H
Min rated power, kW	80	350	860
Max rated power, kW	300	800	2400
Max operating current, A	400	1000	2000
Max operating arc voltage	860	950	1200
Air flow, kg/h	42	197	415
Thermal efficiency	70%	85%	85%
Diameter, mm	89	45.7	45.7
Length, mm	18	35	35

SOURCE: (WPC 2013)

The plasma-heated gas stream from the torches is directed to a bed of foundry coke and limestone fed with the waste. The coke mixed with the waste (about 4% of the total mass input) has two key functions: it provides support for the waste bed as it pyrolyzes and vitrifies, and offers a porous surface through which the molten inorganic fraction of the feed can drain to a discharge point.

Further, the superheated combustion products from the coke, rising up through the coke bed, transfer heat to the incoming waste feedstock and bring its temperature to gasification conditions.

In addition to the coke, limestone or sandstone may be added as flux additives (to modify the melting point of the mix of inorganic residues) in quantities up to 10% by volume of the feed, depending on the ash chemistry. These flux additives adjust the base/acid ratio of the ultimate slag to levels that are optimal for slag fluidity at the desired discharge temperature. All additives are added commingled with the waste feed.

Oxygen and/or oxygen-enriched air are injected into the middle of the coke bed through primary inlets. Atmospheric air can also be used as the oxidant but the diluent nitrogen decreases the heat content of the product gas and reduces the flame temperature.

The oxidant gas increases the heat release within the coke bed and also transfers heat to the pyrolyzing mass. Temperatures in the middle of the coke bed zone exceed 3000 °C.

Oxygen and/or air are also added above the coke bed and into the feedstock bulk through secondary and tertiary inlets. The ultimate gas temperature leaving the top of the bed is about 1650 °C.

As the gases rise in the chamber, they pass counter-current to the flow of incoming feed. Heat is exchanged to dry and begin the (endothermic) pyrolysis reactions so that the final product gas temperature is between 900 °C and 1000 °C.

Energy recovery

The synthesis gas exiting the PGVR is burned in a combustor at the entrance of an adjacent boiler, where the hot flue gases generate steam for power generation in a steam turbine. Exhaust flue gases are sent through an Air Pollution Control (APC) system comprised of a caustic scrubber to remove acid gases and activated carbon filters before being sent to the stack.

Process byproduct recovery

Inorganic components of the feed waste, the coke, and the fluidizing agent are fused within the coke bed and percolate down through the bed to a slag pool and slag tap at the bottom of the gasifier chamber.

Depending on the quantity of slag, the pool is tapped either periodically or continuously. The molten slag is subjected to a water spray and falls into a quench tank, where it is withdrawn using a drag chain conveyor. The resulting vitrified residue has very limited solubility and has found use in Japan as an aggregate or other ‘clean fill’ material.

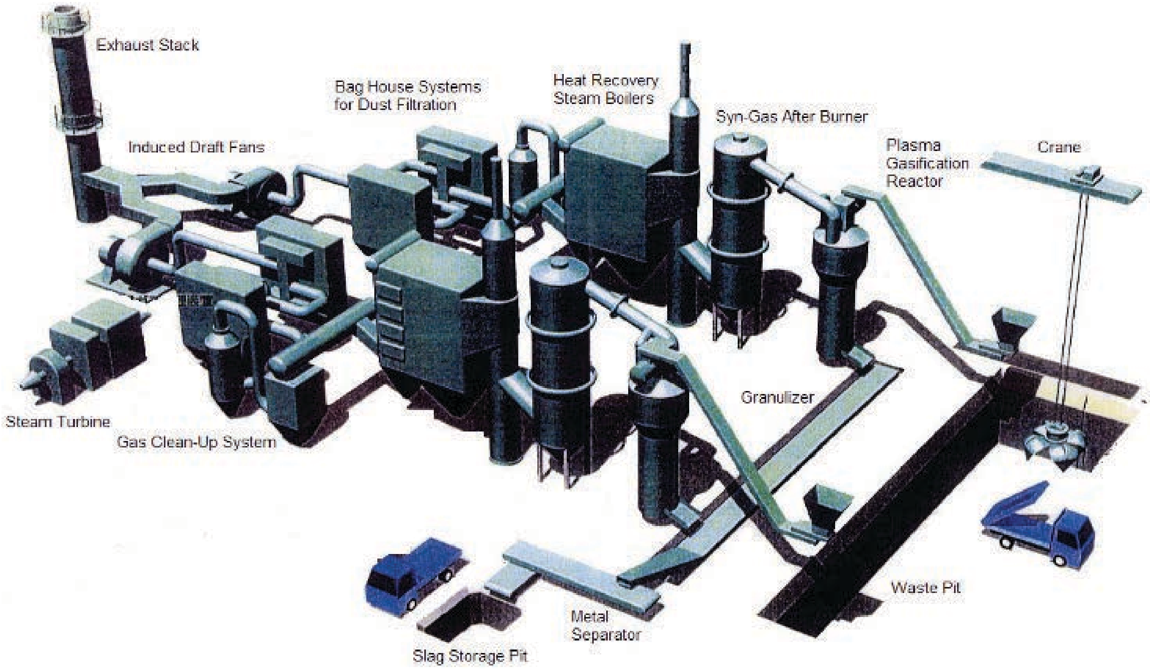
Reference facilities

Utashinai, Japan

The Utashinai EcoValley facility is located in a rural area on the island of Hokkaido. The facility is jointly owned by Hitachi Metals, Hitachi Limited, Hokkaido Prefecture, and the City of Utashinai.

The commercial operation date was April 2003, following a series of operational issues (see below), the EcoValley consortium has decided to cease operation of the facility in 2013. The layout of the Utashinai EcoValley facility is represented in the schematic below.

Figure 79. Layout schematic of the Utashinai EcoValley facility, Japan[27].



The plant was the first plasma gasification facility designed to operate on a flexible feedstock, varying from 100% MSW to 67% MSW and 33% automotive shredder residue (ASR), depending on the deliveries of the two waste streams to the site.

The plant features two lines for a total throughput rating of 220 tpd for 100% MSW operation. When the plant operates with the higher energy content mixed waste feedstock, the thermal capacity of the plant limits the throughput rating to 150 tpd.

Each of the two gasifiers is powered with four MARC-3 plasma torches, with overall power requirements for plasma torches operation varying thus between 320 and 1200 kW.

Energy recovery

The raw synthesis gas from the gasifiers is burned without conditioning in adjacent boilers for steam generation ahead of a 7.9 MW_e steam turbine generator. The net export of electricity from the facility, when operated at capacity on a 50/50 MSW and ASR feedstock, is 1.5 MW_e (Willis et al. 2010).

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[27] Adapted from (Willis et al. 2010)

Cost

The original cost of the Utashinai facility was reported by former Westinghouse Plasma licensee GeoPlasma LLC (pre AlterNRG acquisition) at 65 mUSD for construction and 5.5 mUSD for annual O&M costs (URS 2005).

Design flaws and operational issues

The Utashinai facility has been affected by a series of design flaws and ongoing operational issues, requiring re-engineering of major processing equipment, and causing significant downtime.

On the design front, on commissioning Hitachi Metals discovered a serious internal flaw in the dimensions of the internal diameter of the coke bed portion of the reactor. The diameter, originally determined through a direct scale-up of the Yoshi demonstration plant turned out to be too large, causing excessive penetration of gasification air in the coke bed, and limiting the ability of the four plasma torches to properly heat the coke bed. As a result, a number of *cold spots* formed in the coke bed where slag was observed to solidify, with resulting agglomeration of coke and feedstock particles.

An initial solution implemented was to reduce the internal diameter by increasing the thickness of the refractory lining. This approach was particularly attractive as it did not require re-engineering of the reactor vessel. However, the extra thickness of the refractory layer resulted in excessive insulation of the reaction zone, raising the temperature above the melting point of the refractory material, which caused rapid refractory erosion.

Hitachi Metals had to resort ultimately to re-engineer the reactor vessel, decreasing the diameter of the outer steel shell. This issue was only solved after eighteen months of start-up (Willis et al. 2010).

The refractory erosion issues observed through the re-design of the lower ‘melting zone’ sections of the reactor persisted throughout the early operational life of the plant.

The refractory material initially employed was composed of two layers, an internal high-Alumina (Al_2O_3) layer closest to the coke bed, and an external Silicon Carbide layer. This material was found to have an unacceptably short lifespan, with excessive corrosion observed soon after start-up of the reactor.

After experimenting with a number of refractory layer combinations, Hitachi eventually settled on a solution which is the exact opposite of the original arrangement: high-Alumina on the external ‘cold-face’ layer and Silicon Carbide on the internal ‘hot-face’ layer.

This arrangement takes advantage of the high thermal conductivity of Silicon Carbide, allowing a more effective heat transfer to the outer layer of the refractory. In 2010 Hitachi/AlterNRG reported 4 years of successful operation of the new refractory in the melting zone, projecting its useful lifetime to at least 5 years. The refractory layers in the other portion of the reactor has not been changed since start-up, and Hitachi expects its lifetime to exceed 10 years (Willis et al. 2010).

The third and more serious of the commissioning issues experienced at the Utashinai Eco-Valley facility, was excessive particulate carry-over in the syngas stream which caused significant erosion in the afterburner refractory and frequent shutdowns.

The problem was a combination of multiple factors, including:

- the short distance between the feedport entrance in the gasifier and the syngas exit from the reactor,
- the high percentage of fine dust particles and plastics in the ASR feedstock, and
- the high design temperature (1200 °C) for the syngas exiting the gasifier.

At the original design temperature, the particulate was carried over in a molten state, sticking to the refractory in the afterburner. The ash chemistry of the ASR (particularly the plastics components) compounded the problem, with the molten particulate aggressively attacking the refractory layer.

Some design improvements were implemented, extending the length of the feedport pipe inside the reactor, and thus increasing the distance between the feedstock entrance and the syngas exit. This contributed to reduce the amount of particulate carryover but failed to address the refractory erosion issue. Ultimately Hitachi had to resort to lowering the syngas exit temperature to 750 °C to avoid the slag build-up and associate afterburner refractory issues downstream of the gasifier.

Lowering the syngas exit temperature has come at the expense of the efficiency of the facility. The heat recovery steam generator (HRSG), designed to operate at a temperature of 1200 °C is now operating at 900 °C, with resulting lower steam and electricity outputs.

The design flaws and operational issues described have had a substantial impact on the commercial viability of the EcoValley facility. The diameter design and refractory layer arrangements for the lower sections of the gasifier have caused major downtime in the first two years of operation, whereas the particulate carry-over issue was only solved after 5 years of operation, impacting the availability for all these years.

As a result of the extended shutdowns the EcoValley facility failed to process the contracted ASR quantities causing several the companies that were contracted to deliver the ASR to the plant to find disposal alternatives. The EcoValley consortium finds now itself in a situation where it has solved all of the operational issues but cannot source enough feedstock from the local area. As a result the plant is now running at half capacity and is reporting negative financial results.

Hitachi has announced a decision to cease operations at EcoValley in 2013 (Willis et al. 2010).

Brightstar Environmental – SWERF

The *Solid Waste and Energy Recycling Facility* or SWERF, is an integrated waste minimization and energy recovery process based on two-step gasification, or pyro-gasification technology.

The history of the SWERF process and Brightstar Environmental provides an illustrative example of the importance of process modeling and operational experience in waste management technologies, and energy-from-waste (EfW) schemes in particular. Although proven and extensively demonstrated at pre-commercial scale, the SWERF technology failed to achieve performance and operational reliability targets at a full-commercial scale plant based in Wollongong, leading to the decommissioning and dismantling of the facility and resulting in significant financial losses.

Technology development history

The SWERF process was originally developed in the USA by Brightstar Synfuels from the late 1980s and first demonstrated in 1994 at a large particleboard plant. A demonstration unit with a design throughput of 680 kg/h was constructed in 1996 at a facility located near Baton Rouge, Louisiana. This plant was used to test the process on a variety of biomass and organic waste streams.

From 1998 Brightstar Environmental was established as a joint venture between Brightstar Synfuels and Energy Developments Limited (EDL), to further development and commercialization of the process. An ASX-listed independent power producer focused on landfill gas generation, EDL was the majority partner in the Brightstar Environmental joint venture, holding 88% of stock (Williams et al. 2003).

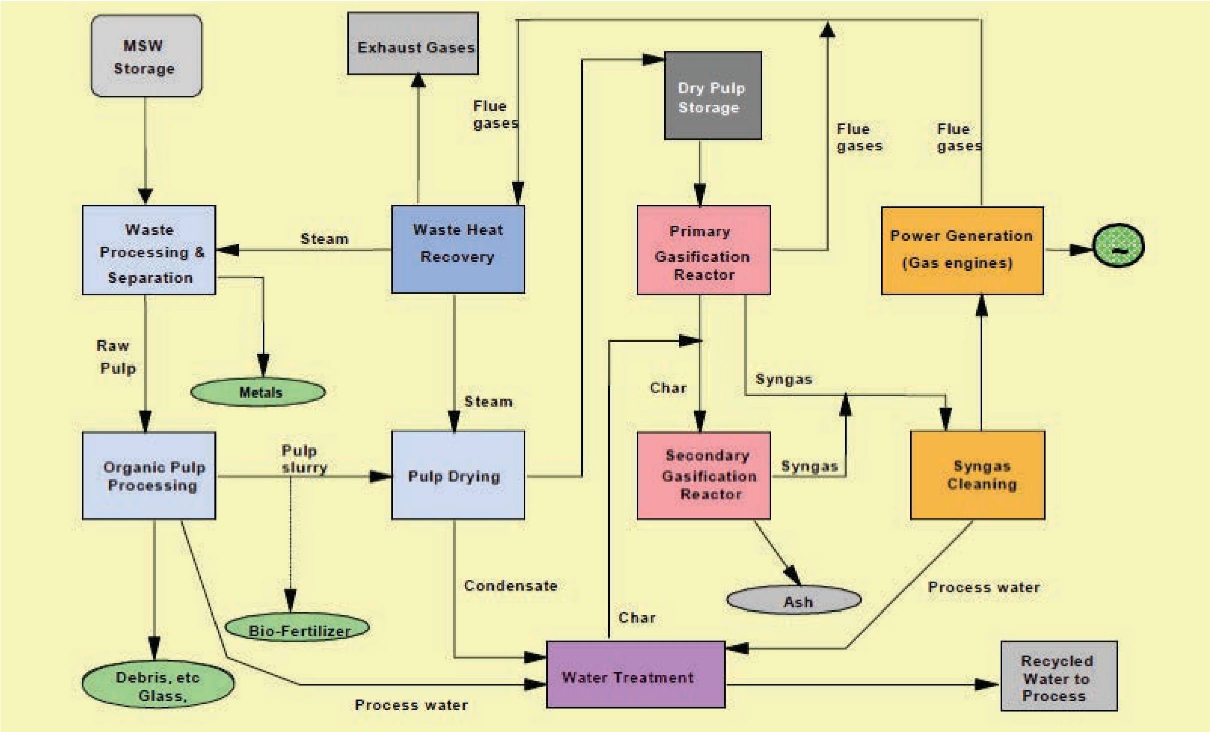
In February 2001, following three years of community consultation and planning activities, a commercial-scale demonstration plant was commissioned at the Kembla Grange site, Wollongong. The plant facility was designed to process 50,000 tonnes per annum (tpa) of unsorted MSW, divert 90% of waste from the White's Gully landfill, and generate up to 5.4 MW_e of electricity.

At the time of the commissioning of the Wollongong facility, BrightStar Environmental marketed aggressively the technology announcing additional projects in Gosnell, Western Australia (27 ktpa initially, then 100 ktpa) and Derby, UK (50,000 tpa) and claiming a pipeline, as of June 2001, of 35 projects and in excess of 9 mtpa of MSW processing capacity (Juniper 2001).

Process description

The core conversion technology for the SWERF process consists of a two-stage gasification unit, with a primary pyrolysis reactor followed by a secondary steam gasification reactor. The diagram below provides a schematic of the SWERF process, the key processing steps are discussed below.

Figure 80. Schematic representation of the SWERF process[28]



Pre-processing

Unsorted MSW is first pre-treated under steam and pressure in an autoclave with the aim of obtaining a homogeneous, sterile pulp. Material separation downstream of the autoclave removes metal and rigid plastics from the waste feedstock and size reduction is applies to achieve cross-size <20 mm. Exhaust heat from the main process is applied to dry the material to moisture content levels below 10%. The SWERF process includes provision for intermediate storage of the organic pulp prior to gasification.

Heating, Conversion and Syngas Cleaning

The core conversion technology consists of a two-stage pyrolysis and steam gasification process. The first stage, pyrolysis, produces a relatively high-methane content syngas and two by-products: pyrolysis oils and chars. Oils and chars are extracted from the high-

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[28] Adapted from (Juniper 2001), Figure E.205, p.E.322.

methane content gas stream and introduced into a second gasification stage producing a high hydrogen content synthesis gas with steam as a gasification agent.

The gaseous product streams from the two reactors are blended to obtain a consistent synthesis gas stream optimized for the generator sets, with typical composition reported in the table below.

Table 72. Syngas composition for the SWERF process

Syngas composition, vol%					
CH_4	H_2	CO	CO_2	N_2	Other
30%	35%	25%	9%	<1%	1%

SOURCE: (Juniper 2001), Figure E.204, p. E.322

Energy recovery

Energy recovery in the SWERF process was through power generation in four generator sets, based on EDL's series 2000 landfill gas generator sets with modified exhaust, fuel management and detonation control systems. The engines were rated at 1.35 MW_e as for the landfill gas-fueled version.

Operational issues

Despite the commercial-scale of the Wollongong facility, the SWERF was in most regards still a developmental-stage technology. Since commissioning, several design issues in the material handling systems had to be solved before the plant could commence continuous operation.

Material handling issues aside, the Wollongong SWERF plant was affected by ongoing issues with the removal of char from the primary pyrolysis reactor and gasification of char in the secondary gasification reactor.

The original design featured hot char removal from the primary reactor, later abandoned as removal of char at temperatures of 4-500 °C proved problematic, particularly due to risk of auto-ignition of the char materials between the removal and secondary gasification reactor feeding systems.

Brightstar reported development and implementation of an alternative char removal solution, based on wet removal (with char quenching) from as early as mid 2001 (Brightstar Environmental 2002).

Seemingly solving char handling issues, the wet removal system caused even more serious problems in the secondary, char gasification reactor, as the char removed through the wet systems was not inert and combined with the pyrolysis oils preventing complete carbon conversion and generating difficulties in operating within the performance parameters (energy and material recovery) and emission limits in the facility's EPA licence.

Development of a new secondary gasification reactor became a critical development path for the technology, with Brightstar Environmental reporting by early 2002 of several unsuccessful attempts with alternative design concepts and prototypes tested.

During the extended shut down of the secondary reactor, chars and pyrolysis oils accumulating from the primary reactor became to represent a serious waste management issue, which compounded operational problems with the facility. Following these issues, EDL ceased to fund further development of the facility from late 2002 and tried unsuccessfully to sell its portion of the Brightstar Environmental stock to a third-party buyer.

The total cost of the project at this stage was already 43 mAUD, with 40 mAUD provided by BrightStar Environmental, and the remainder provided by the then Australian Greenhouse Gas Office (AGO) through its 'Technology Showcase' program (2 mAUD), the NSW Sustainable Energy Development Authority (1 mAUD). Following an announcement of ceased operation in March 2004, Wollongong City Council had spent an additional 1.5 mAUD to convert the site in a material recovery facility (MRF) and waste transfer station.

Reported losses by investors associated with the SWERF facility, including from stranded assets and loss of value in the EDL stock, were reported to be between 120 and 140 mAUD.

EDL continues to operate as a developer and operator of landfill gas generation systems and compressed and liquefied natural gas (CNG/LNG) infrastructure.

Ebara – TwinRec

Ebara is an international engineering company specializing in fluid/machinery systems, precision machinery, and environmental engineering. The firm has successfully developed and implemented over 100 waste processing plants, including both incinerators and gasifiers based on a proprietary fluidized bed design.

The Ebara TwinRec process is a fully commercial process that combines fluidized bed gasification with an ash melting furnace.

Technology development and commercialization

The Ebara TwinRec gasification technology, was first developed in the early 1990s as an evolution of their incinerator design based on an integrated boiler fluidized bed (ICFB), and piloted at two demonstration facilities in Japan: Sodegaura, Japan (1x7 tpd unit) started in 1995 and decommissioned in 1997; and Fujisawa, Japan (1x24 tpd unit) started in 1997 and decommissioned in 2001.

Both facilities were subject to extensive tests to support development of operational experience on a range of feedstocks including municipal solid wastes (MSW), refuse derived fuels (RDF), plastics and automotive shredder residues (ASR). The Fujisawa plant was successfully operated on a single 100-days continuous test run between September and December 1997 (Ebara 2007).

Commercial operation started in 2000 with the commissioning of the Aomori plant, followed by ten more commercial facilities, as listed in the Table below.

Table 73. Ebara TwinRec facilities

Facility	Start-up year	Status	Capacity, tpd	Feedstock	Syngas use
Sodegaura pilot plant, Japan	1995	shut down	95	MSW, RDF, plastic, ASR	ST
Fujisawa pilot plant, Japan	1997	shut down	95	MSW, RDF, plastic, ASR	ST
Aomori, Japan	2000	operational	2 x 225	ASR, sewage sludge	ST
Joetsu, Japan	2000	operational	15.7	Dry sludge, plastics	ST
Kurobe, Japan	2000	operational	63	ASR, plastics, industrial waste	F
Sakata, Japan	2002	operational	2 x 98	MSW	ST
Kawaguchi, Japan	2002	operational	3 x 140	MSW	ST
Ube City, Japan	2002	operational	3 x 66	MSW	ST
Seki, Japan	2003	operational	3 x 56	MSW	ST
Iida, Japan	2003	operational	2 x 46.5	MSW	ST
Nagareyama, Japan	2004	operational	3 x 69	MSW	ST
Tokyo Rinki, Japan	2006	operational	2 x 275	Industrial waste	ST
Hino City, Japan	2007	operational	3 x 60	MSW	ST

SOURCE: (Ebara 2007)

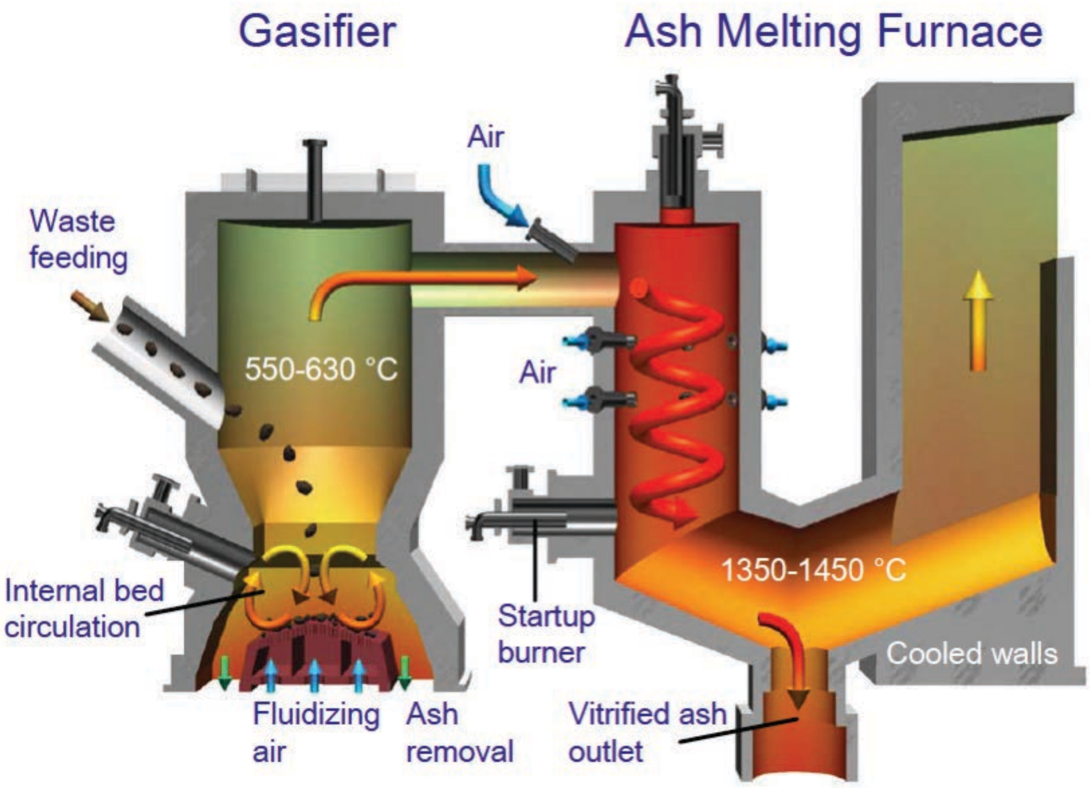
Notes: ASR - automatic shredder residues; CCGT - combined cycle gas turbine; GE - gas engine;
F - direct fuel user; MSW - municipal solid waste; RDF - refuse derived fuel; ST - steam turbine.

The eleven commercial plants currently operated in Japan collectively process 1462 tons of MSW, 1063 tons of industrial waste and 16 tons of sewage sludge per day, for a total installed thermal capacity of 371 MW_{th}.

Process description

The TwinRec process combines a fluidized-bed gasifier, operating at 550-600 °C and atmospheric pressure, with a secondary combustion and ash-melting furnace. The process is summarized in the schematic below.

Figure 81. Schematic representation of the Ebara TwinRec process[29]



Pre-processing

The TwinRec process accepts a wide range of feedstocks, and has been demonstrated using a variety of waste materials to include automobile shredder residues (ASR), waste plastics, electronics waste and other industrial residues, MSW, and sewage sludge. Minimal pre-processing is required, with solid feedstock materials to be shredded to a maximum particle size of ~30 cm.

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[29] Adapted from (Selinger & Steiner 2004).

Heating and conversion

In the TwinRec process, heating of the feed materials to gasification conditions (typically 580 °C) is performed through circulation of hot gases in a fluidized bed reactor.

The reactor is based on the company's proprietary revolving or Twin Interchanging Fluidised Bed (TIF), a design developed by Ebara to improve the operational and heat transfer characteristics of the bubbling fluidized bed (BFB) designs without the operational complexities of circulating fluidized bed (CFB) designs.

In essence, the TwinRec reactor is a hybrid between a fixed-grate and a bubbling fluidized bed design, whereby the combination of the fluidizing air and the movement and design of the grate effect greater movement, and hence turbulence, of the dense phase bed.

The low gasification temperature and high-turbulence of the bed allow for easy process control and limited gasification air requirements, resulting in a compact design for both the primary gasification chamber and for the energy recovery and air pollution control (APC) systems downstream.

Energy recovery

The effluent from the fluidized bed, a hot raw synthesis gas with a substantial residual heating value, is burned at very high-temperature in a secondary cyclonic combustion chambers designed to improve combustion efficiency separate fine particles entrained in the synthesis gas flow.

The hot gaseous effluents from the combustion of the synthesis gases are typically circulated through a water-wall boiler, generating steam for industrial processes or power generation in steam turbine. Due to the overall low excess air ratio, the steam boiler can be compact, maximising recovery of the energy content of the waste. The overall air ratio is about 30% excess air at the entrance of the boiler, except in the smaller plants where operation at 50–60% excess air may be necessary to assure good mixing.

The table below provides an overview of the energy recovery options implemented at some of the operating Ebara TwinRec facilities. All TwinRec plants integrate steam power generation with the exception of the Kurobe plant, the gases are burned directly to provide heat for melting of copper-containing residues in the industrial waste stream (40% shredding residues, 15% plastics and 45% copper slag and sorbents from the nearby copper refining facility).

Table 74. Overview of energy recovery options for operating Ebara TwinRec facilities.

		Feedstock		Energy recovery		Energy use	
Facility	Capacity, tpd	Components	LHV, MJ/kg	Units	Capacity, MW_{th}	Power, MW_e	Steam, t/h
Aomori, Japan	450	ASR, sludge	14.3	2	40	17	
Kurobe, Japan	63	ASR, plastics	10.2	2	7.4	direct use (copper smelting)	
Sakata, Japan	196	MSW	10.9	2	12.3	2	
Kawaguchi, Japan	420	MSW	13	3	21	12	35
Ube City, Japan	198	MSW	12.5	3	9.5	4	
Seki, Japan	168	MSW	11.3	3	7.3	2	
Iida, Japan	93	MSW	8.4	2	4.5	0.78	not specified

SOURCES: (Ebara 2007), plant sheets available on Ebara website.

Process by-product recovery

Recyclable metals

The revolving fluidised bed design has the advantage of allowing for easy and effective separation of metallic residues in the waste stream.

Steel, aluminum, copper and iron are easily recovered thanks to the specific combination of low-gasification temperature, moving bed and large particle sizes in the TwinRec design.

The metal in the waste is not burned, melted, or sintered in the first stage of the process, and can be recovered directly from the bottom off-stream of the primary gasification furnace.

Mineral dust and metal oxide powder are vitrified into the glass granulate and can be separated and recycled afterward.

Vitrified slag

In the cyclonic ash-melting furnace, addition of secondary air to the raw synthesis gases brings the temperature to 1350-1450 °C.

The tars, fine char, and ash residue entrained in the gas stream are melted in the furnace and accumulate on the walls of the furnace, where they are vitrified and drained slowly down to the lower section of the furnace, where they are discharged and quenched in a water bath to form a granulate.

The recovered material is compatible national environmental leaching standards for acceptability for recycling in construction in Germany, Japan, and the Netherlands. In Japan, granulate is used as a filler in asphalt.

Reference facilities

Aomori, Japan

The first of the commercial TwinRec facilities, the Aomori Plant owned by the Aomori Renewable Energy Recycling Corporation a joint venture between Seinan and Ebara, started in February 2000.

Figure 82. TwinRec facility in Aomori, Japan

The plant features two 225 tpd TwinRec units and operates on a mix of automotive and brown/white goods shredder residue and mechanically dewatered sewage sludge in amounts from 0% to 30% (by weight) of the shredder residues amounts.

The ASR materials, delivered from five shredder plants and from two non-ferrous material separation plants, meet the requirements of 30 cm top size, and therefore are fed directly to the gasifier without further treatment. Other waste plastic materials and bone meal (in 1000 ton quantities) are treated as available, and a feeding system for boxed, hospital wastes was added.

The plant has an overall thermal capacity of 2x40 MW_{th} and 17 MW_e of generation capacity.

Materials recovered at the Aomori plant include Ferrous metals (Fe, steel), non-ferrous metals (Al, Cu) from the gasification reactor bottom ash, glass granulates and molten metals in the vitrified flyash (Zn, Pb, Cu).

Kawaguchi City, Japan

The Kawaguchi plant in Japan, is the largest of the Ebara TwinRec installations to operate on 100% MSW, was started in 2002. The facility is operated by Kawaguchi City as the Asahi Environmental Centre.

Figure 83. TwinRec facility in Kawaguchi, Japan

The three processing lines at Kawaguchi process each 140 tpd of mixed MSW including bulky waste with screening and shredding to achieve the maximum particle size of 30 cm. In addition, the plant has the ability to accept up to 27 tpd of bottom ash from the Totsuka Clean Centre, a pre-existing incineration facility in the City.

Energy recovery

The total thermal capacity of the plant is 63 MW_{th}, each of the processing lines generates 25.8 t/h of steam at 3.95 MPa and 400°C. A portion of the steam, at the rate of 35 t/h is delivered as process steam to a recycling facility and a public bath located in proximity of the plant. The remaining steam is used to generate power in a 12 MW_e steam turbine.

Byproduct recovery

The rate of byproduct recovery from the Kawaguchi plant is:

- 10 kg recyclable metals per metric ton MSW processed (ferrous and aluminum);
- 95 kg of vitrified ash (aggregate) per metric ton MSW processed;
- 20 kg inert materials per metric ton MSW processed; and
- 25 kg APC residues per metric ton MSW processed.

The vitrified slag recovered from the three Kawaguchi units was tested for leaching properties according to the stringent Japanese standards in November 2002, the results are reported below.

Table 75. Kawaguchi facility – leachate test results, November 2002

	Units [a]	Facility			
		Kawaguchi #1	Kawaguchi #2	Kawaguchi #3	Op. permit
Slag concentrations					
Cd	mg/kg	<0.5	<0.5	<0.5	9
Pb	mg/kg	213	150	273	600
As	mg/kg	<0.5	0.5	<0.5	50
Total Hg	mg/kg	<0.005	<0.005	<0.005	3
Leachate concentrations					
Cd	mg/l	<0.001	<0.001	<0.001	0.01
Pb	mg/l	0.006	0.002	0.001	0.01
Cr^{6+}	mg/l	8.3	0.7	13	0.05
As	mg/l	<0.001	<0.001	<0.001	0.01
Total Hg	mg/l	<0.0005	<0.0005	<0.0005	0.005
Se	mg/l	<0.001	<0.001	<0.001	0.01

[a] concentrations measured at 12% oxigen

Sources: (Selinger and Steiner 2004), Table 1.

Emissions

The air pollution control system at the Kawaguchi plant includes a bag filter, a wet scrubber, and a catalytic catalyst reactor (fed with ammonia) for NO_x control. The height of the stack is 100 m.

Performance test measurements conducted in November 2002 confirmed the plant's ability to operate within operating permit limits, including dioxin emissions below the limit of 50 $pg_{I\text{-}TEQ}/Nm^3$. The results of the tests are reported below:

Table 76. Kawaguchi facility – air emission test results, November 2002.

	Units [a]	Facility			
		Kawaguchi #1	Kawaguchi #2	Kawaguchi #3	Op. permit
Particulate	g/Nm^3	<0.001	<0.001	<0.001	0.01
HCl	ppm	<1	<1	<1	10
NO_x	ppm	21	32	36	50
SO_x	ppm	<1	<1	<1	10
CO	ppm	2	3	2	10
Dioxins	$pg_{I\text{-}TEQ}/Nm^3$	8.3	0.7	13	50
Total Hg	mg/Nm^3	<0.005	<0.005	<0.005	n/a

Sources: (Selinger and Steiner 2004), Table 1.

Waste diversion from landfill

Implementation of the Asahi Clean Centre has allowed Kawaguchi to achieve high rates of diversion from landfill. The gasification facility and the pre-existing Totsuka Clean Centre incineration facility together process the total of MSW generated within Kawaguchi City and the adjacent Hatogaya City.

Specific features of the Asahi Clean Centre, such as co-vitrification of bottom ash from the Totsuka facility and the recirculation of solidified fly ash in the gasification reactor allow the Kawaguchi plant to achieve a diversion rate of 97% (Selinger & Steiner 2004).

Cost

No cost information specific to the Kawaguchi or Aomori facilities is available in the literature. As a term of comparison, a proposal for a 40 tpd TwinRec facility submitted Ebara in 2005 had a construction cost estimate ranging between 14 and 21 mUSD, or 350-670,000 USD/tpd (URS 2005).

IES – Advanced Pyrolytic System

The Advanced Pyrolytic System is a proven, commercial-scale, energy-from-waste (EfW) technology developed by International Environmental Solutions (IES) in California.

Technology development and commercialization

IES commenced development of the APS in 2000, when it received a permit to operate and construct a 41 tpd pilot plant in Romoland, California (Riverside County). The plant was started in the January 2005.

The plant has provided IES with a platform for extensive testing and further development of the APS process, the 40 tpd facility - one third the capacity of the fully commercial 115 tpd module – has operated successfully for four years on a variety of feedstocks, accumulating process data for over 5000 h of operations.

The facility was successfully tested for emissions against the stringent South Coast Air Quality Management District (SCAQMD) standards in 2005 and 2006.

Experience with the Romoland facility has allowed the development of a number of improvements to the process, including the design of a new char residue conveyor, the integration of an intermediate hot gas cyclone separator for flue gases directed to the heat recovery boilers, and the implementation of a flue gas recirculation system for more effective control of NO_x emissions.

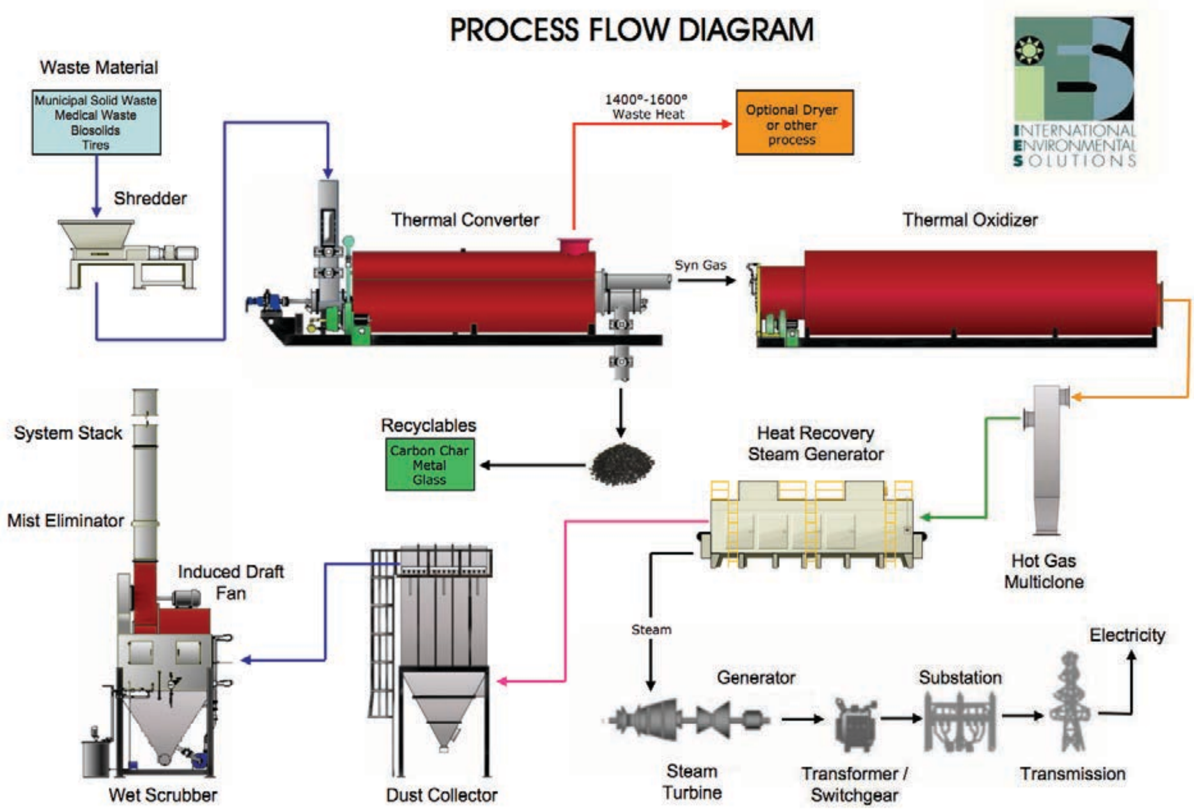
A new demonstration 8tpd unit incorporating all the new designs has been installed at the Technikon Renewable Energy Test Center (RETC) in McLellan California. Start-up for the new demonstration plant was in early 2011, with extensive testing being conducted on a variety of feedstocks.

The Romoland plant has been sold in 2009 and relocated at the Green Gas LLC Mecca facility, in California where it was started-up in December 2010 and will start full commercial operation on tires and MSW from late 2011. The Mecca facility integrates some of the feature of the new designs, namely the carbon discharge conveyor. An expansion of waste processing on the site is planned with the development of a new 125 tpd facility.

Process description

The APS consists of a pyrolysis chamber (the *thermal converter*) followed by a two-stage combustion chamber (the *thermal* oxidizer) and air pollution control (APC) sections, an overview of the APS process is provided in the diagram below.

Figure 84. IES Advanced Pyrolytic System – process schematic



Pre-processing

The APS accepts post-MRF (material recovery facility, for separation of any recyclables) feedstocks requiring minimal pre-processing, i.e. shredding to a maximum top size of 5 cm, then drying to 20 wt% moisture content.

Heating and conversion

Thermal converter

The pre-processed material is fed to the chamber through a screw conveyor. Air locks are utilized at each end of the chamber to maintain a low-oxygen environment and minimize fugitive emissions.

The retort is comprised of a refractory-lined cylindrical shell coaxially surrounding a three-arch, triangular retort, maintained at temperatures in the 760-980 °C range through external heating with a syngas flame (natural gas during start-up).

The two bottom retort arches include specially designed, hydraulically-driven auger screw assemblies that rotate inside the horizontal retort chamber to mix, enhance heat transfer, and translate the waste and residual matter through the retort as pyrolysis occurs. The third, top arch section of the retort serves instead as a conduit through which pyrolysis gases are drawn off for cleaning, use and subsequent exhaust to the atmosphere, or diversion for external heating in the pyrolyzer. Ash and char exit the chamber through a lock hopper into a collection bin.

Thermal oxidiser

The pyrolysis gases leaving the third section of the retort are ducted to the thermal oxidizer, an insulated, horizontal, two-stage, cylindrical chamber equipped with a 0.5 GJ/h gas burner, where they burn at a flame temperature of 1100 °C.

Combustion air in the thermal oxidiser is supplied in two stages, the first stage runs with slightly less than stoichiometric air, while the second stage runs with an excess of air. This staged process minimizes flame impingement in the thermal reactor.

Combustion gases from the first stage of the thermal oxidiser are conveyed through to the radiant heat zone of the pyrolyisis chamber, whereas second stage combustion gases are conveyed to the energy recovery section downstream.

Energy and by-product recovery

The hot, exhaust gases from the thermal oxidizer are first passed through a hot-gas cyclonic separator (for removal of particulates) and further drawn through a heat-recovery steam generator (HRSG), where they raise steam for direct use or for power generation. In a full steam-cycle power generation configurations, the IES system delivers 1.06 MWh_e of electricity (net) per tonne of post-MRF waste processed.

By-products from the APS, when operated on post-MRF waste include:

- Char, 2% (by mass) of waste input,
- Metals, 1.5% (by mass) of waste input, and
- Glass, 10% (by mass) of waste input.

Char and metals can be recovered, achieving a waste diversion rate of 90%.

Air pollution control

The APS does not feature syngas clean-up stages upstream of the thermal oxidizer, as a result, the resulting air pollution control (APC) duty, in terms of the flowrate of exhaust gases to clean-up, is not unlike that of a conventional incinerator.

The air pollution control system consists of selective non-catalytic reduction unit for NOx control, a baghouse for particulate matter (PM) control, and a scrubber unit for control of acid gases and volatile metals.

Thermoselect - HTR

The Thermoselect High-Temperature Reactor (HTR) is a fully commercial process combining slow pyrolysis with high-temperature gasification and ash melting.

Developed with a focus on thermal conversion of MSW and commercial and industrial waste in large-scale facilities, the HTR concept is particularly attractive as an advanced waste treatment (AWT) alternative in direct competition with incineration-based waste-to-energy (WTE) schemes.

The Thermoselect HTR process accepts unsorted waste, with minimal or zero feedstock preparation/preprocessing and integrates an extensive array of material recovery steps, with the ability to operate close to 100% waste diversion from landfill.

Technology development and commercialization

The HTR process has been developed by Thermoselect SA, a privately-held Swiss company, in the late 1980s, and first demonstrated on a commercial basis at the 95 tonnes per day (tpd) Fondotoce facility, Italy, operated between 1992 and 1999.

Following completion of the Fondotoce demonstration, two client-owned facilities were developed in Chiba, Japan[30] (2x150 tpd, start-up in 1999) and Karlsruhe, Germany (3x240 tpd, startup 2000). The operational history of the first two fully commercial Thermoselect plants has been very different. While the Chiba facility was successfully commissioned and still operates to this day, the Karlsruhe facility was plagued by several commissioning problems, and ongoing issues with the air pollution control (APC) system, which led to extended shutdowns of the plant, and ultimately to its decommissioning in 2004. The successful commercial operation of the Chiba plant instead led to 5 further facilities developed in Japan by the JFE. The company website reports development of a large, 5x322 tpd facility, in Caguas, Puerto Rico to commence in 2012.

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[30] developed under license by JFE Engineering Corporation.

Table 77. Thermoselect facilities

Facility	Start-up year	Status	Capacity, tpd	Feedstock	Syngas use
Fondotoce pilot plant, Italy	1992	shut down	1 x 95	MSW, industrial waste, ASR	GE
Chiba, Japan	1999	operational	2 x 150	MSW, industrial waste	GE, F
Karlsruhe, Germany	2000	shut down	3 x 240	MSW, industrial waste, ASR	GE
Matsu (Shimokita Area), Japan	2003	operational	2 x 70	MSW	GE
Izumi, Japan	2005	operational	1 x 95	Industrial waste	ST
Kurashiki City, Japan	2005	operational	3 x 185	MSW, industrial waste	F
Nagasaki, Japan	2005	operational	3 x 100	MSW	GE
Tokushike Yoshino, Japan	2005	operational	2 x 60	MSW	GE
Yorii, Japan	2005	operational	2 x 225	Industrial waste	GE, ST
Caguas, Puerto Rico	2012	proposed	5 x 322	MSW	CCGT

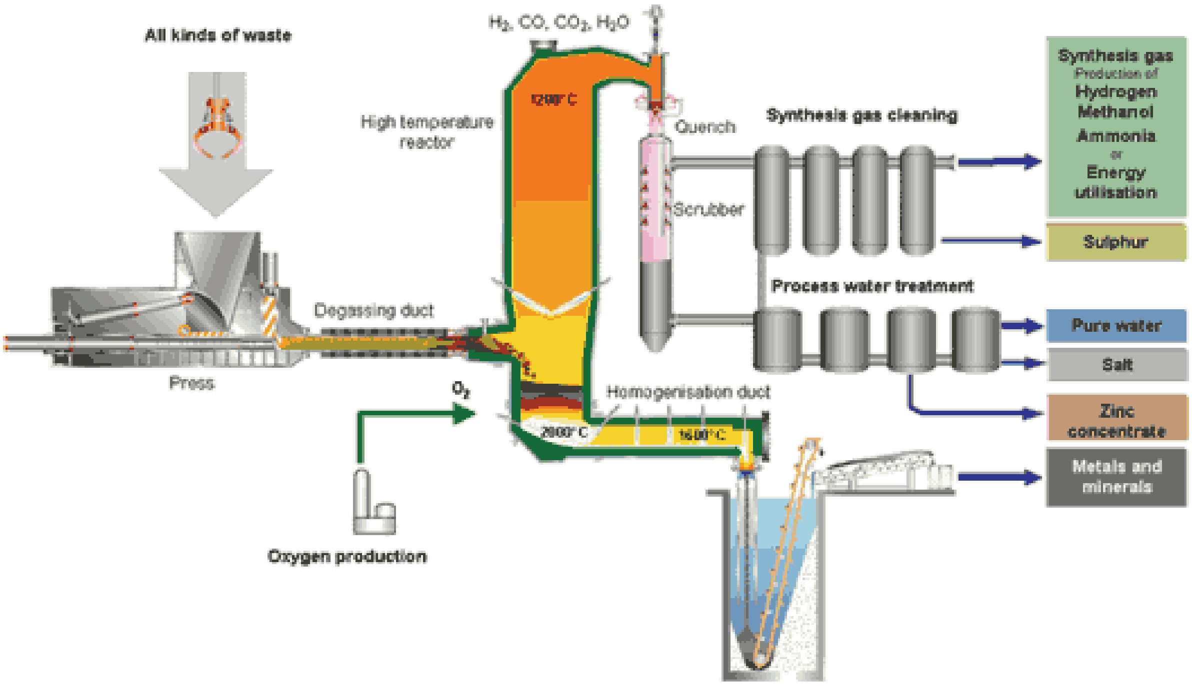
Adapted from: (Niessen 2010), Table 12.23, p.527.

Notes: ASR - automatic shredder residues; CCGT - combined cycle gas turbine; GE - gas engine; F - direct fuel user; MSW - municipal solid waste; ST - steam turbine.

Process description

The Thermoselect HTR process consists of slow-pyrolysis followed by high-temperature gasification in a fixed-bed oxygen-blown reactor and melting of the inorganic component of the feedstock (ashes, metals, etc.) to form a vitrified slag. The process is summarized in the schematic below.

Figure 85. Schematic representation of the Thermoselect HTR process[31]



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[31] Adapted from materials available in the Thermoselect website: http://www.thermoselect.com/

Pre-processing

The Thermoselect technology accepts mixed MSW and industrial waste with no material separation and minimal pre-processing requirements. The raw waste is dropped by grapple from the waste pit into the housing of the compactor, in which the loose material can be pressed against a heavy metal gate. The feedstock is compressed to below 10% of its original volume by means of an industrial scrap metal hydraulic press. The compacted materials are extruded through a gate and fed as a plug of ‘fresh’ materials to the thermal conversion process downstream.

Heating and conversion

Degassing and pyrolysis

Drying, heating and pyrolysis of the feedstock materials is achieved in a primary chamber, the *degassing channel* where the extruded plug of compacted materials is externally heated by the radiant heat flowing back from the secondary, *high-temperature gasification chamber* (HTC).

The temperature at the end of the degassing channel is maintained at 800° C. As the compacted waste materials are heated they pyrolyse releasing volatile components and steam, from the moisture carried in with the solid waste feedstock. The raw, wet synthesis gas is conveyed from the degassing channel to the upper sections of the HTC which is maintained at 1200 °C.

At this point, the waste plug is much smaller because it has lost its volatile components (water and organic matter). The non-volatile organic portion has been carbonized to a high degree. The inorganic portion of the waste has remained virtually unaffected and is part of the carbon matrix. Upon reaching the transition point with the HTC, the carbon matrix breaks apart and falls into the lower section of the secondary chamber. The travel time through the degassing channel is normally < 2 h.

High-temperature gasification

The matrix of carbon and inorganic material from the degassing channel fills the lower section of the HTC, to form a fixed bed where oxygen is introduced, bringing the local temperature to 2000 °C.

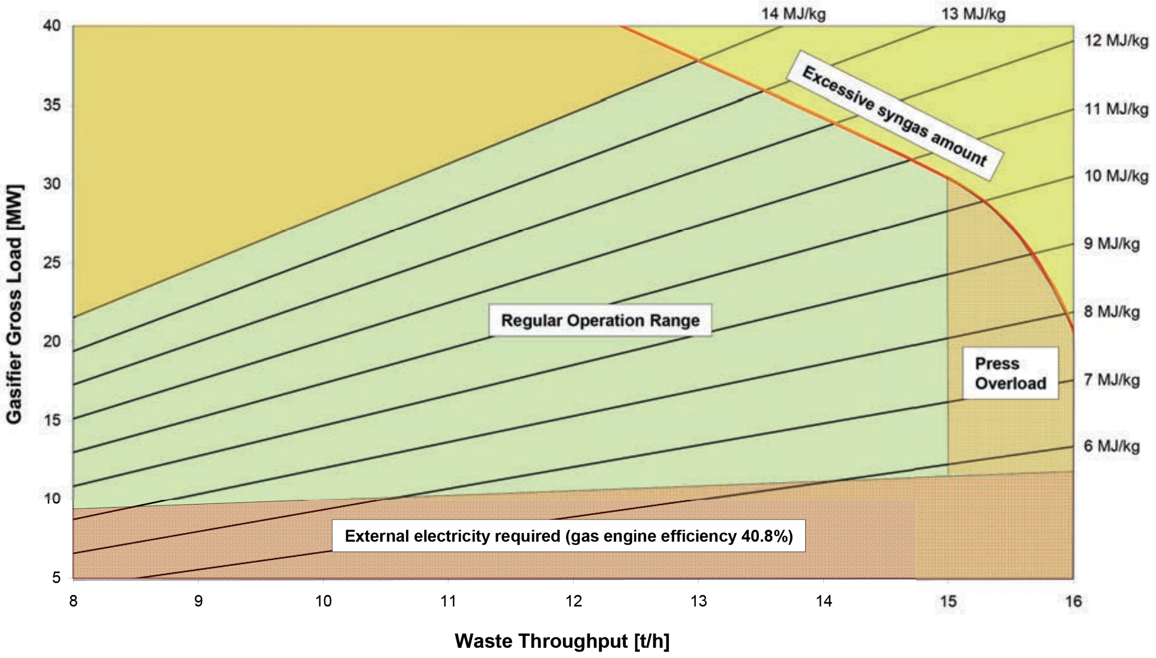
Control of the temperature in this section allows it to effectively perform as a smelter, where the high temperature provides the necessary conditions to melt the inorganic fraction, composed primarily of glass products and various metals that are contained in the carbon matrix.

The inorganic molten mass of mineral and liquid metals flows from the lower section of the HTC into a *homogenization duct*, where it is prepared for removal from the process.

Gases released from the lower sections of the HTC flow upwards to combine with the pyrolysis gases extracted from the degassing channel. The temperature in the upper sections of the HTC is maintained at 1200 °C with the introduction of oxygen, which combined with a residence time approaching 4 s and turbulence is adequate to complete the conversion of the most complex organic compounds and yield a high hydrogen content synthesis gas.

The chart below presents a gasifier firing diagram for a 15 t/h Thermoselect HTC unit. The diagram illustrates the gasifier operating thermal rating (gross) of the gasifier (10-22.5 MW_t) and resulting operating throughput range (8-15 t/h) as a function of the feedstock heat content.

Figure 86. Gasifier firing diagram for a 15 t/h Thermoselect HTC unit



Gas cooling and cleaning

The resultant synthesis gases exiting the HTC at 1200 °C are immediately cooled down to temperatures below 70 °C by means of water quenching in a spray chamber.

The high volume of water in the quenching step quickly lowers the temperature of the gases and captures particulate matter transported with the gaseous stream, including heavy metals, and water-soluble acid gases such as HCl and HF.

A succession of scrubbers operates the separation of reactor gases from the quench water, including an acid wash at ~60 °C, specialized treatment for H_2S removal, and an alkaline wash at 40 °C.

Residual water vapour is removed by further cooling the gaseous stream down to 5 °C to and passing it through a wet electro-static precipitator (ESP). The gas is warmed to ambient temperature before use.

Synthesis gas quality

The table below reports the typical composition of the cleaned synthesis gas from the Thermoselect process, for a waste feed containing 50% organic matter, 25% inorganic matter and 25% water at 11.9 MJ/kg, for an energy content of the syngas of 8.3 MJ/Nm^3.

Table 78. Cleaned reactor gas composition

Syngas composition, vol%					
CH_4	H_2	CO	CO_2	N_2	Other
<0.1%	32-35	34-39%	22-27%	3-4%	1%

SOURCE: (Niessen 2010), Table 12.22, p.527.

Process by-product recovery

One of the key attractiveness of the Thermoselect technology is the extensive array of by-product recovery steps integrated with the process, which combined with minimum pre-processing requirements makes it a particularly well suited solution for EfW applications, with one of the highest waste diversion performances (close to 100%).

Homogenization

The mineral and metal melt flow from the lower sections of the HTC is gravity-fed to an homogenization chamber, where additional oxygen is introduced to react with any remaining carbon particles, bringing the overall oxygen consumption in the Thermoselect plant to ~514 kg per tonne of waste charged, additional heat is also provide to maintain the melt, usually with natural gas or product gas burners at a rate (for natural gas) of 23 kg/ton of waste (Niessen 2010).

A water bath is used to quench the combined molten metal and mineral melt streams. As the temperature drops the vitrified mineral stream forms a mix of granulate, whereas the metal mix freezes, forming metal alloy pellets. The resultant mix of granulates and metal pellets are recovered using a drag chain conveyor.

The glass-like material is suitable for a variety of uses, including aggregates and raw components for construction materials, mineral and insulation fibres and general ‘clean-fill’ material. Thermoselect is also reported to actively investigate potential markets for the use of the metal residues for metallurgical processes (Niessen 2010).

Sulphur recovery

The sulphur-removal system converts hydrogen sulphide (H_2S) to sulphur using a ferric iron complex. In an adjoining stage, the ferrous iron complex is regenerated using oxygen from air and recycled from the main process, with sulphur precipitated as the element.

The removal of elemental sulphur (S), compared with the removal of sulphur as gypsum ($CaSO_4$) common to most control processes based on the use of lime, reduces the mass of sulphur solids end product by a factor of more than four. Thermoselect indicates the sulphur to be of sale quality.

Water recovery

Thermoselect claims the processing-water solutions generated from the gas-cleaning process to comply with sewerage discharge guidelines. Alternatively, the process water can be subjected to chemical treatment and precipitation to remove heavy metal hydroxides and other insoluble portions as a solid concentrate.

A reverse osmosis membrane step removes the remaining salts (primarily sodium chloride), followed by the evaporation of water to concentrate and remove soluble residuals. The clean, distilled water is returned for use in the process-water loops and cooling towers.

Since the process recovers water contained in the original waste input, there is an excess of water recovered as part of the process, which could be recovered for other uses or sprayed on hybrid cooling towers and evaporated.

Reference facilities

Fondotoce, Italy

The Thermoselect technology operated at an industrial-scale demonstration and pilot plant in Fondotoce, Italy, from 1992 to 1998.

Karlsruhe, Germany

The Karlsruhe facility was commissioned in 2000 by owner/operator EnBW GmbH (previously known as electric utility Badenwerke AG). The process consisted of 3x240 tpd HTR modules fed with a mixture of MSW, industrial waste and automatic shredder waste

(ASW). Synthesis gas from the HTR was used in a gas engine system to generate power for export.

Operational and licensing issues

The Karlsruhe plant has been plagued by commissioning problems, causing delays in licensing and complicated by organizational, permit that led ultimately to the plant decommissioning in 2004.

A failure in the Air Pollution Control system (APC) saw EnBW implement a flare chamber, comprised of ignition burners and a chimney, as an interim solution to safely vent the syngas exiting the high-temperature gasification sections.

However the German EPA intervened to notify that operation of the emergency vent was in breach of the conditions for the operating permit for the plant, requiring an APC to operate at all times.

Faced with the prospect of the risks associated with obtaining a new permit from the EPA with adequate provisions for the emergency vent and the obligation to implement a new air pollution control system for the facility, EnBW opted for the latter implemented after over 18 months of idle time and significant additional investment costs.

Following significant reorganizational changes and an unsuccessful attempt to sue Thermoselect for all costs associated with the flare chamber rework, EnBW have mothballed Karlsruhe in an apparent strategy to bolster its legal position in continuing appeal actions.

The lessons learnt at Karlsruhe point to the importance of adequate and comprehensive permitting conditions – particularly for emergency operations – and of the adoption of redundant air pollution control systems (now an obligation under the European Waste and Large-scale combustion sources Directives), rather than flaws in the fundamental environmental and operational performance of the Thermoselect HTR technology, as demonstrated by the successful implementation of new facilities by clients in Japan and elsewhere.

Cost information

The overall cost of the Karlsruhe facility was reported by US-licensee Interstate Waste technologies (IWT) to be 120 mUSD, with 19 mUSD of annual O&M expenditure (URS 2005).

Chiba City, Japan

In 1997, the former Kawasaki Steel, now JFE, with financial support from the New Energy and Industrial Technology Development Organization (NEDO), Ministry for Energy Trade and Industry (METI), began construction of a 300 tpd facility based on the Thermoselect process.

Commissioning tests

During FY 1999, the plant was operated on a demonstration basis, as part of a joint research project between JFE, Chiba City and the Chiba Prefecture, with the aim to test the technology and develop adequate operational expertise prior to its full commercial operation.

The demonstration test, the first of its kind for a full-scale gasification, reforming and ash melting equipment in Japan, saw the plant treat over 15,000 t of municipal solid waste from the Chiba prefecture over a period of 130 days, with the single longest continuous run exceeding 93 days, leading to the full certification of the plant.

Cost information

The overall cost of the Chiba facility was reported by US-licensee Interstate Waste technologies (IWT) to be 80 mUSD, with 13 mUSD of annual O&M expenditure (URS 2005).

TPS – Termiska AB

The Termiska AB is a low-pressure, air-blown circulating fluidized bed (CFB) gasification technology developed specialized process engineering firm TPS, headquartered in Nyköping, Sweden.

The technology is fully proven, with one commercial-scale demonstration facility operating from 1993 in Italy. However, subsequent high-profile commercialization initiatives focused on biomass feedstocks have fallen through at the commissioning stages, with little information available on a pipeline of future projects.

Technology development and commercialization

TPS began development of circulating fluidized bed (CFB) boilers in the late 1970s. In the mid 1980s company embarked in the development of circulating fluidized bed gasifiers, and constructed a constructed a 2 MW_{th} biomass-fuelled atmospheric gasification system pilot plant in 1984.

The pilot plant operated successfully on a range of feedstocks and provided a wealth of process data for scale-up facilities. In 1988 a gas clean-up system was later added to the plant In 1988 the pilot plant was retrofitted with a gas clean-up system comprised of a dolomite tar cracker, cold gas filter and wet scrubber, and a 500 kW_e modified diesel engine for power generation.

In 1988, Termiska Processer AB (TPS) licensed their low-pressure, air-blown, circulating fluidized bed (CFB) gasification process to Ansaldo Aerimpianti SpA, of Italy. In 1992 Ansaldo installed a commercial, two-bed unit in Grève-in-Chianti, Italy. The two units with a combined thermal capacity of 30 MW_{th} are fed on a pelletized RDF fuel from MSW, with seasonal additions of shredded woodwaste and agricultural wastes.

The Greve-in-Chianti remains a successful demonstration of the CFB concept developed by TPS, operated flawlessly throughout the life of the facility, a number of issues with the energy recovery sections however required significant additional investment during the early operational life of the plant (1993-97).

Following successful demonstration at Greve-in-Chianti, the Termiska AB concept was selected for two high-profile biomass gasification projects: the EU-funded 8 MW_e ARBRE biomass integrated gasification combined cycle (BIGCC) project in the UK and the Biomass Integrated Gasification Gas Turbine (BIG-GT) project in Brazil, funded under the World Bank’s Global Environment Facility (GEF) program.

Both projects provided unvaluable operational experience in the development of syngas-fuelled gas turbines, but were stalled at the advanced commissioning stages due to a combination of technical and organizational issues. . No further commercialization of the TPS technology has been reported to date.

Process description

Pre-processing

RDF preparation

The refuse derived fuel (RDF) for the TPS process is prepared through primary shredding of the MSW feedstock in an horizontal shaft hammermill or shear shredder, secondary shredding in an hammermill, followed by magnetic separation for removal of magnetic metals, and disc screening of fines for removal of glass and grit.

Pelletization of the RDF is optional and was implemented at the Greve in Chianti facility, to reduce hauling expenses. It is common to incorporate some kind of intermediate RDF storage as a buffer between RDF preparation and the combustion facility. At the Greve facility, four 80 ton steel silos were used. The RDF feed specifications for the Greve system are the following:

Table 79. TPS/Ansaldo Greve in Chianti facility, RDF specifications

Dimensions	
Diameter, mm	0-15
Length, mm	50-150
Bulk density, kg/m^3	500-700
Proximate analysis	
Lower Heating Value, MJ/kg	17.2
Moisture (typical)	6.5%
Volatile matter	71.1%
Fixed carbon	11.4%
Sulphur	0.5%
Chlorine	0.4-0.6%
Total non-combustibles	11%

SOURCE: (Niessen 2010), p.512.

RDF reclaiming and feeding

In the TPS concept, a twin-screw reclaimer ‘digs’ the RDF from the intermediate storage silos and deposits into a bucket conveyor, from where it is moved through a screw conveyor and discharged in the feed hopper. Another twin-screw reclaimer is used to extract RDF from the hopper, passed through a rotary valve and chuted into the gasifier.

Fluid bed gasifier

The heart of the TPS process is the fluidized bed gasifier: a cylindrical, bubbling bed system, operating at about atmospheric pressure at the top of the bed.

In the lower ‘dense bed’, with temperatures of ~700-800 °C, the RDF feed is maintained for a relatively long residence time, till it volatilizes- As particles are reduced, they are lifted out of the dense bubbling bed zone.

Addition of steam to the dense bed facilitates gasification of carbon in wastes with high fixed carbon content. Secondary air is injected above the dense bed zone.

The combined effects of increased mass flow, and heat release (through further oxidation) resulting from secondary air injection, contribute to increase the upward gas velocity and facilitating carbon oxidation. In this zone, temperatures reach higher zones, referred to by TPS as ‘fast bed’ increases to about 850-950 °C.

In beds firing low-moisture content feedstocks, secondary steam injection to the fluidizing gas flow is necessary to promote gasification of carbon to CO and H_2.

The gases leaving the bed are passes through a duct incorporating U-beam interceptor for the removal of particulate. A large-diameter, refractory-lined cyclone chamber follows where additional particulate recovery occurs.

A vertical accumulation pipe is used to collect the solid streams from the U-beam and cyclone hoppers, where they fom an air seal or plug. The lower mass of solids at the bottom of the pipe is fluidized through nitrogen injection prior to discharge back in the dense phase of the bed.

Gases leaving the bed pass through a duct incorporating U-beam particulate interception. The gas then passes to a large-diameter, refractory-lined cyclone where additional particulate recovery occurs. Solid streams from the U-beam and cyclone hoppers accumulate in a vertical pipe, where they form an air seal or plug. At the very bottom of the accumulation pipe, a small amount of nitrogen is introduced to fluidize the lower mass of solids. Then, by gravity, the fluidized solids flow from the pipe and are reintroduced into the dense-phase, bubbling fluidized bed.

Nitrogen rather than air as the fluidizing medium to avoid the high temperatures that would result if air (with oxygen) was used to move the still-hot, ignitable char solids.

The gas leaving the cyclone is thus a mixture of synthesis gas, hydrocarbons and tars with some residual particulate matter, all diluted with nitrogen from the air used in the process.

Syngas cleaning and utilization

The raw syngas exiting the TPS reactor can be used directly as a medium heat content fuel in industrial combustors (eg. rotary cement or lightweight aggregate kilns or process furnaces), either alone or in combination with fossil fuel to trim operations for load following.

Use of the fuel in an industrial or utility boiler for steam and/or power production requires implementation of a downstream air pollution control (APC) train to remove HCl, HF, SO2, Hg and other heavy metals, particulate, and so on, from the flue gases to the extent required by the chemistry of the RDF and regulatory requirements.

Use of the off-gases from the fluid bed in a gas engine or gas turbine requires clean-up. The TPS concept features a hot-gas cleanup system to avoid effieicny penalties associated with the loss of sensible heat of the fuel gas. The hit-gas cleanup system is comprised of the dolomite tar cracker and associated cyclone appended to the gasifier. The cracker achieves nearly complete conversion of tars into lower molecular-weight compounds and trace quantities of benzene, toluene and naphthalene. Hydrogen cyanide and fuel-bound nitrogen decompose into nitrogen gas (N_2) or ammonia (NH_3).

At the higher temperatures of the cracker bed, carbon containing dust is gasified by residual oxidizing gases (H_20 and CO_2) at the higher temperatures of the cracker bed.

Following the cracker, a heat recovery boiler brings the temperature down to about 200 °C, where a fabric filter system removes particulate matter. The particulate consists mainly of calcined dolomite and fine soot and is of nonabrasive nature. At this point, the gas is suitable for use in many fuel-sensitive combustors.

Air pollution control

In addition to the acid gas control achieved through the dolomitic lime addition, the combustion train is normally equipped with fabric filters for particulate capture. The demonstrated sulfur oxides removal is over 70%. Carbon injection can be provided for mercury control, although the Grève data suggest that acceptable mercury emissions may be achievable without this feature. TPS offers a wet scrubber system when there is a need for enhanced ammonia, tar, acid gas (H2 S and HCl), and condensable vapor removal.

At this point, the fuel gas is of a quality that can be burned in a boiler to generate steam (without further cleanup) or further cleaned to be used as fuel in a gas engine or turbine combustor for the generation of electricity.

Reference facilities

Greve in Chianti

The Greve in Chianti plant is equipped with two TPS CFB gasification units, each rated at 15 MW_t and a capacity of 100 tpd of RDF pellets. The beds also have processed biomass (coarsely shredded wood or agricultural wastes). Fuel gas generated at the plant is either burned in a boiler to generate electricity or used as a fuel in an adjacent lime kiln operation.

These gasifiers are used alternately to feed the single boiler. However, produced gas in excess of that required by the boiler (and gas from the second gasifier, when required) is cooled to 400°C but not cleaned, and transported (by pipeline) a short distance to a nearby cement plant, operated by SACCI. Here, the produced gas is used as fuel for the cement kiln. The SACCI plant also uses the ash and spent lime from the Greve plant, in return providing fresh lime for the scrubber.

The typical gas composition from the Grève facility operated on RDF feed is shown below.

Table 80. Typical off-gas composition for the TPS Greve in Chianti facility

Component	Composition vol%
CO_2	15.65
N_2 + Ar	45.83
CO	8.79
H2	8.61
Methane	6.51
C_xH_y	4.88
H_2S	48.61 (ppm)
H_2O	9.48
Other	0.14
Total	100
LHV, MJ/Nm^3	7.53

SOURCE: (Granatstein 2003).

Cost information

The total investment for the Greve in Chianti facility, inclusive of capital expenditure for redesign of the boiler sections, was 27.8 mEUR (Granatstein 2003).

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