

ATTACHMENT E

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 REVISED REPORT – AUGUST 2014



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 neighbouring Councils in the Southern Sydney Regional Organization of Councils (SSROC) area, and a detailed evaluation of alternative conversion technology and implementation schemes 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

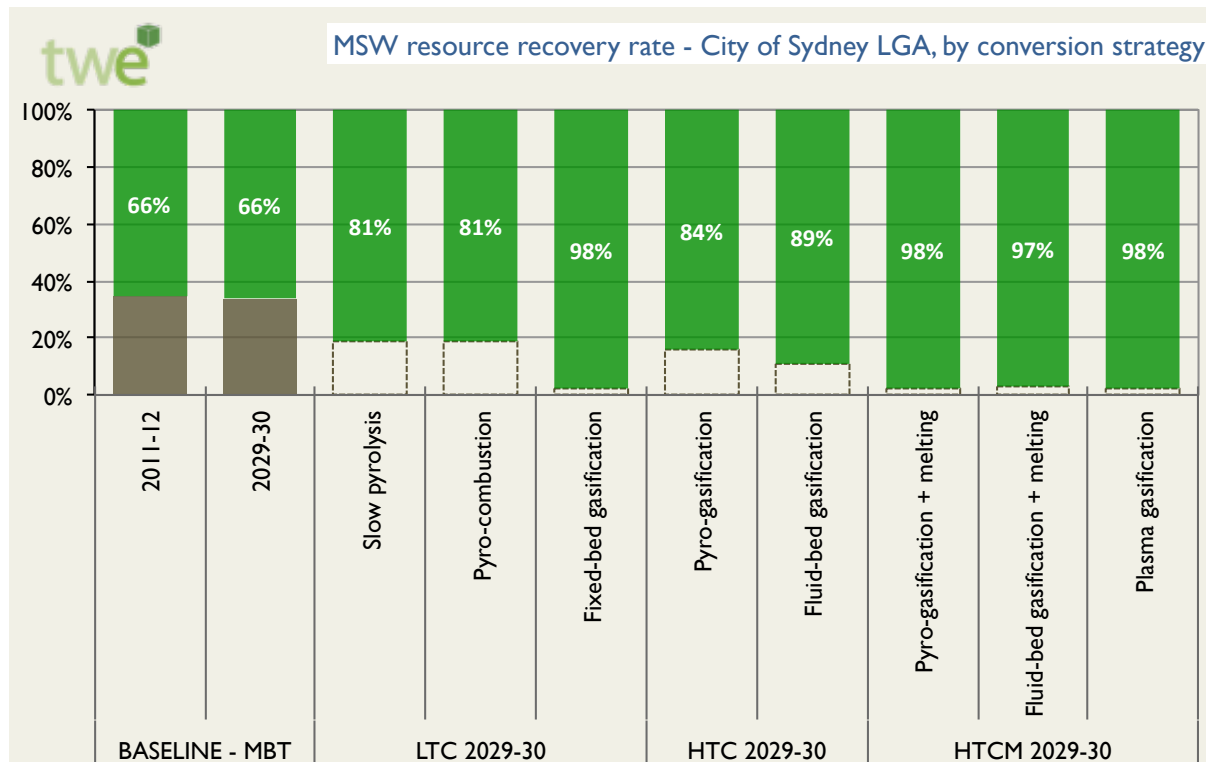
Resource recovery within the City LGA has been historically limited to source-separated materials (kerbside recycling and garden organics), accounting for a resource recovery rate of 24.95% in 2008-09.

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% (fixed-bed gasification, 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

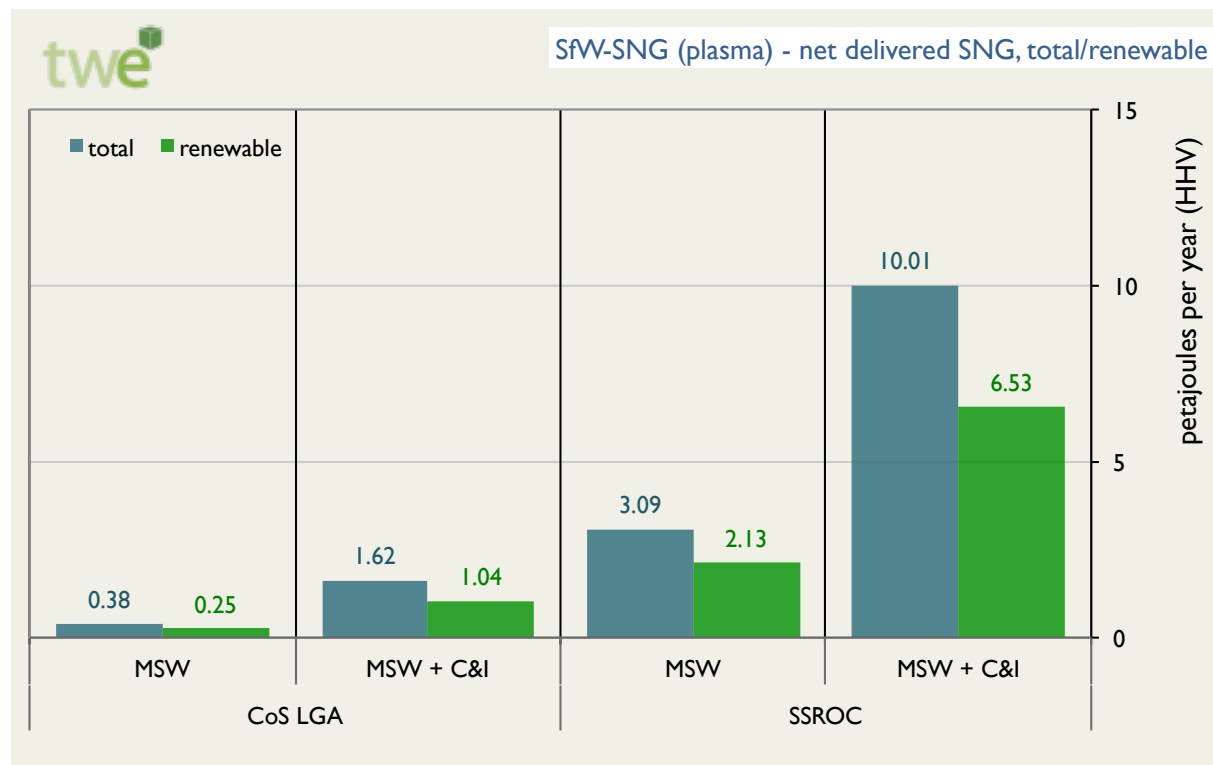


Energy recovery

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

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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 an integrated energy supply scheme 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 Plan*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 basis³) 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:

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

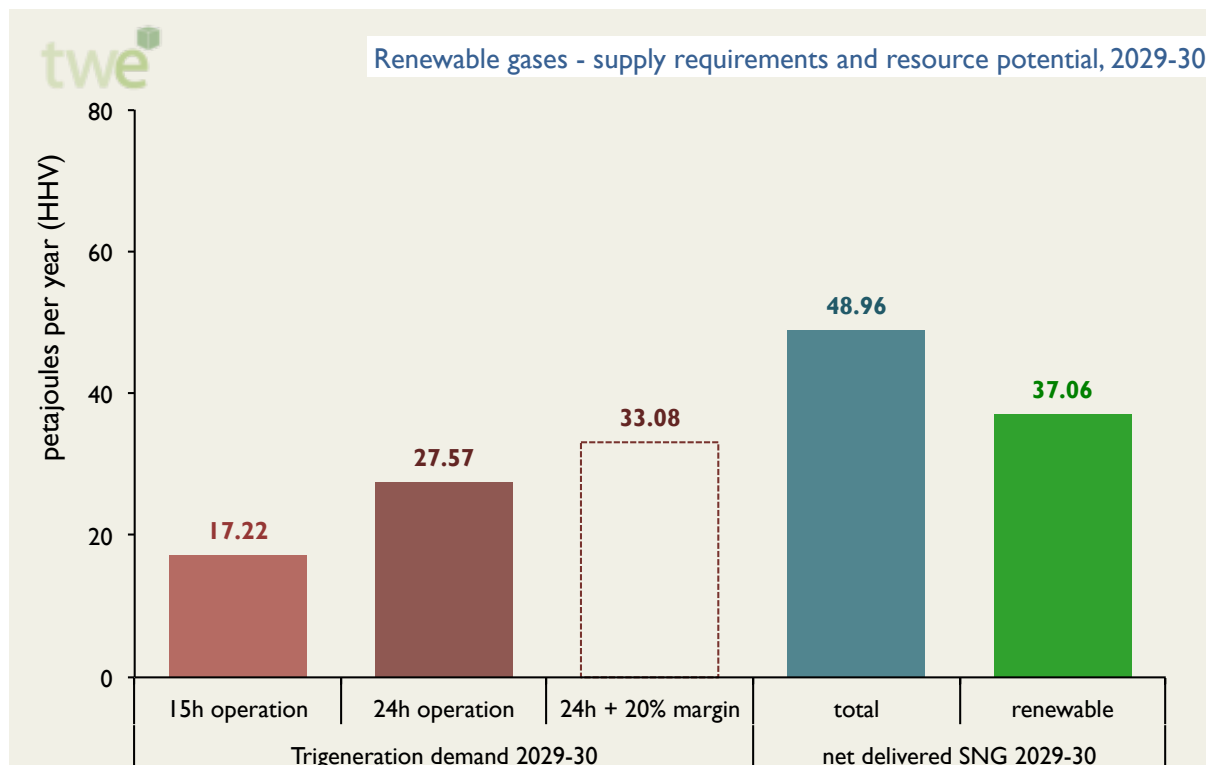
² *City of Sydney Decentralised Energy Master Plan - Renewable Energy* DRAFT, City of Sydney, June 2013.

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



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.

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:

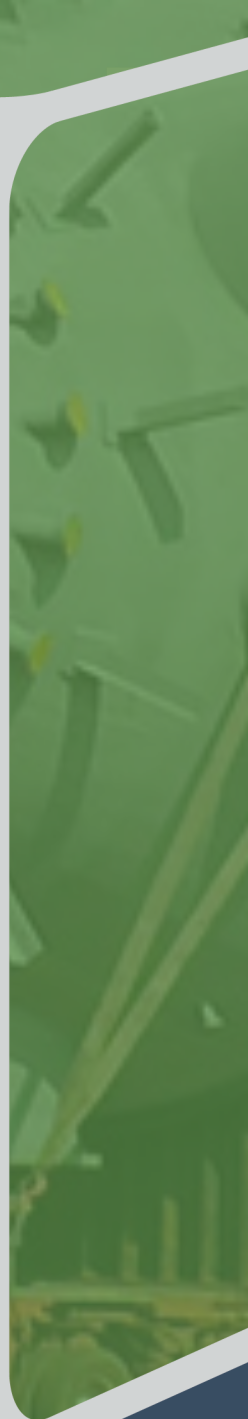
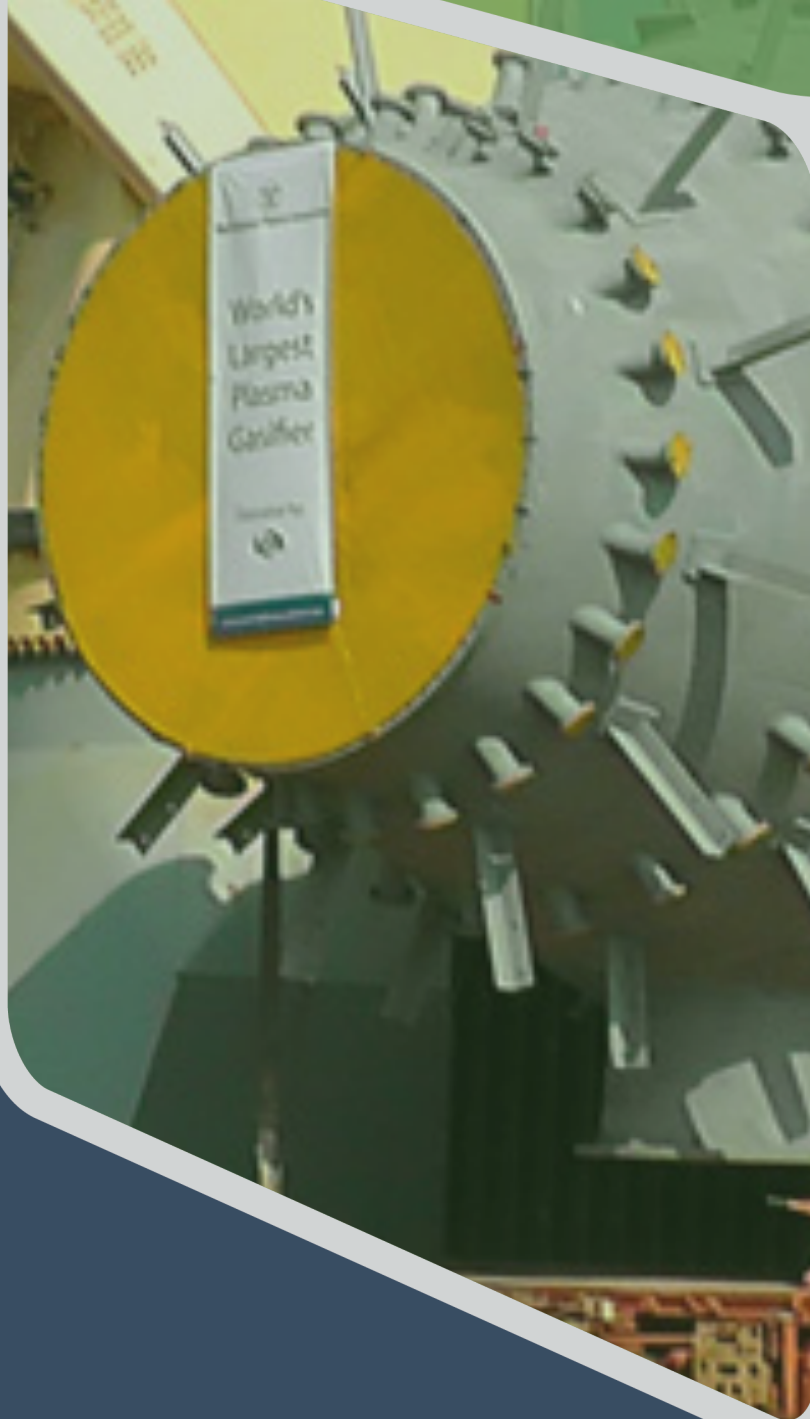
- **Section 1. Synthesis Gas Generation from Residual Waste Resources** presents a review of thermo-chemical conversion of waste, with an introduction to operating principles, available processes and technologies and a review of waste management, environmental, energy and material recovery performances;
- **Section 2. Synthesis Gas Utilization and Upgrading** covers processes for conversion of syngas into heat and power, and associated 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 conversion facilities;

- **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

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.

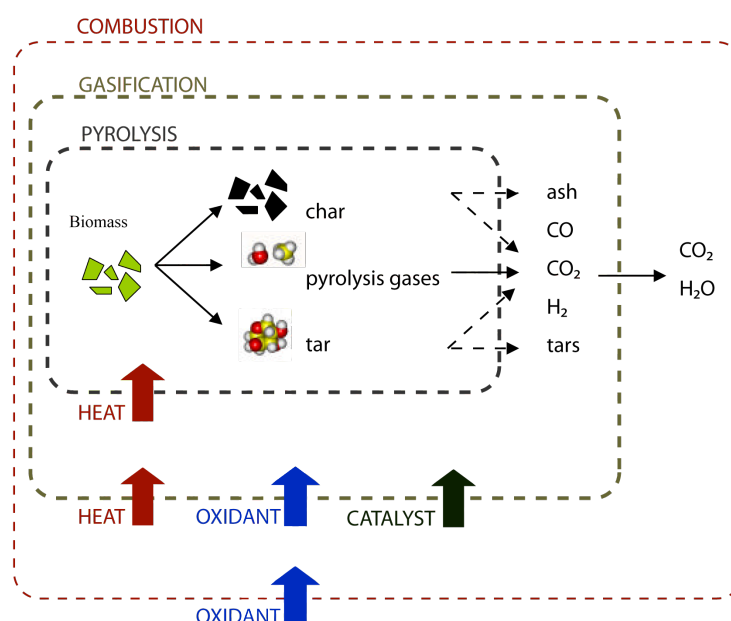
By converting the waste feedstock into an intermediate gaseous fuel, the raw syngas, thermo-chemical conversion technologies enable the adoption of advanced energy and material recovery schemes, where the gases can be cleaned and/or upgraded to meet the quality requirements for several applications,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



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, CH₄), 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:

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

- a **raw syngas**, a gaseous mixture containing carbon monoxide (CO), carbon dioxide (CO₂), hydrogen (H₂), methane (CH₄) 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.

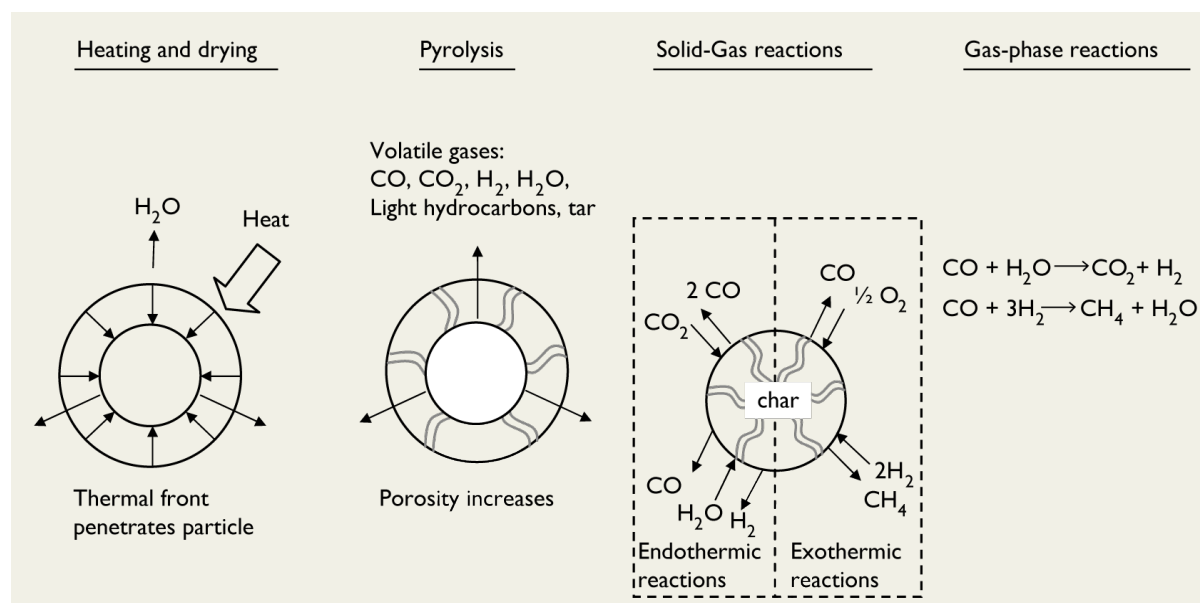
The relative distribution of these products depends on chemical composition of the fuel and process conditions such as the heating rate and the temperature achieved in the reactor.

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 gasification⁷



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.

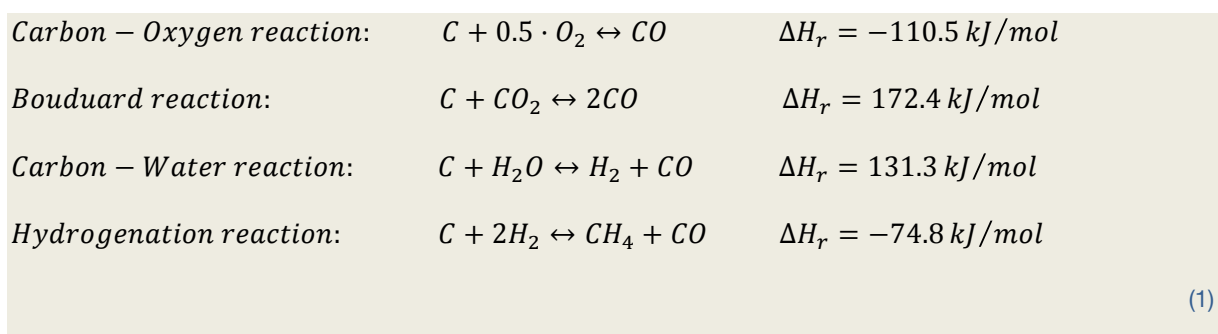
Pyrolysis

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 (CO₂), methane (CH₄), 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

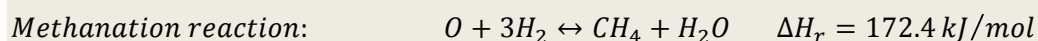
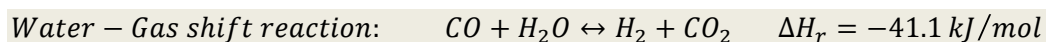
The third step of gasification is solid–gas reactions, converting solid carbon into gaseous CO, H₂, and CH₄ as described in the set of equations in (1):



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):



(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, CO₂, H₂, and CH₄ (and nitrogen if air was used as a source of oxygen). CH₄ formation is generally favored at low temperatures and high pressures, whereas high temperatures and low pressures favor the formation of H₂ 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 C₂H₂ and C₂H₄ 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

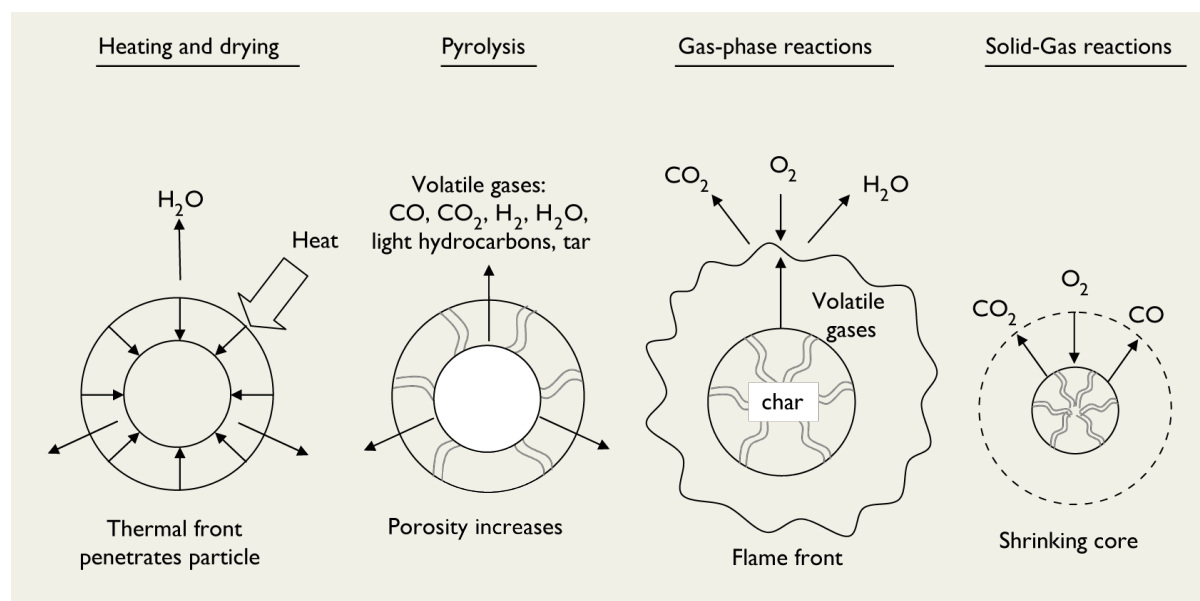
Combustion is the rapid and complete oxidation of fuel to obtain energy in the form of heat. Since waste and biomass feedstocks fuels are primarily composed of carbon, hydrogen, and oxygen, the main products of complete combustion are carbon dioxide and water although fuel-bound nitrogen can be a source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



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 CO₂ and H₂O 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 CO₂ if sufficient oxygen and temperature are available; otherwise, it appears in the flue gas as a pollutant.

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, CO₂, H₂, CH₄, N₂ and tars. This gives a low heating value gas of ~5 MJ/Nm³. Utilisation problems can arise in combustion, particularly in gas turbines;
- **oxygen-blown gasifiers**, the main products are CO, CO₂, H₂, CH₄, tar (no N₂). This gives a medium heating value gas of ~10–12 MJ/m³. The cost of providing and using oxygen is compensated by a better quality fuel gas;
- **steam gasification**, The main products are CO, CO₂, H₂, CH₄, tar. This gives a medium heating value gas of ~15–20 MJ/m³. 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

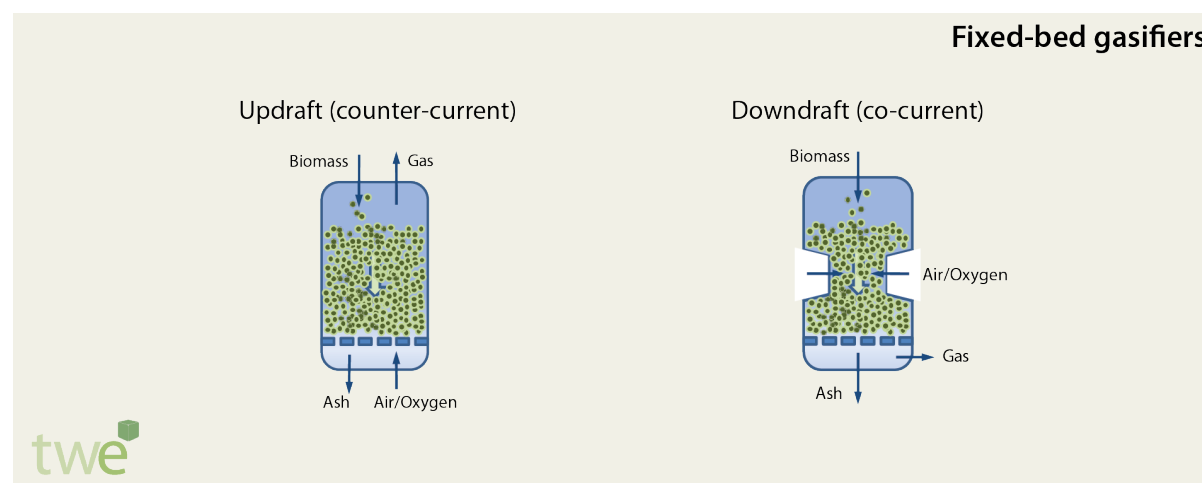
Gasification reactors are generally classified according to the method of heat transfer to the fuel:

- **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



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 ($<1 \text{ g/m}^3$), 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%).

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.

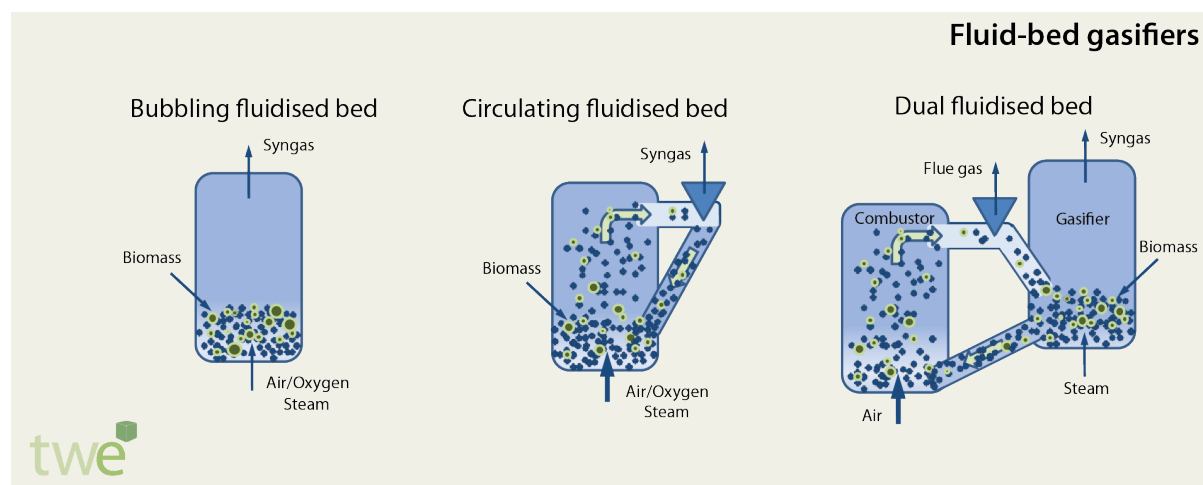
Fluidized bed gasifiers

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



- **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

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/Nm³).

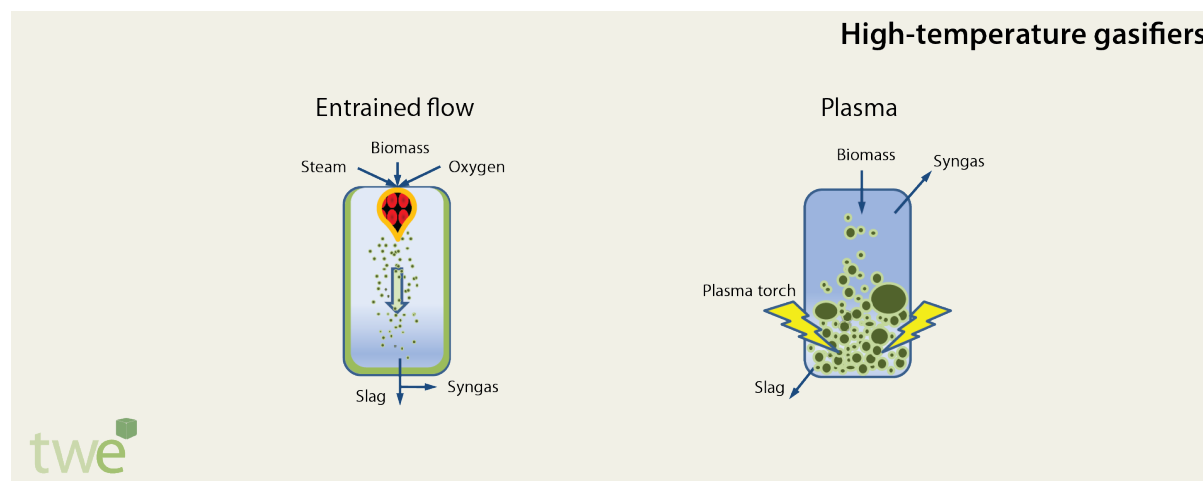
Fluidized beds are attractive for biomass and waste gasification. They are able to process a wide variety of fuels including those with high moisture content and small particle size. They are easily scaled to large sizes suitable for electric power production.

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



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

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 principle 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/m³ 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

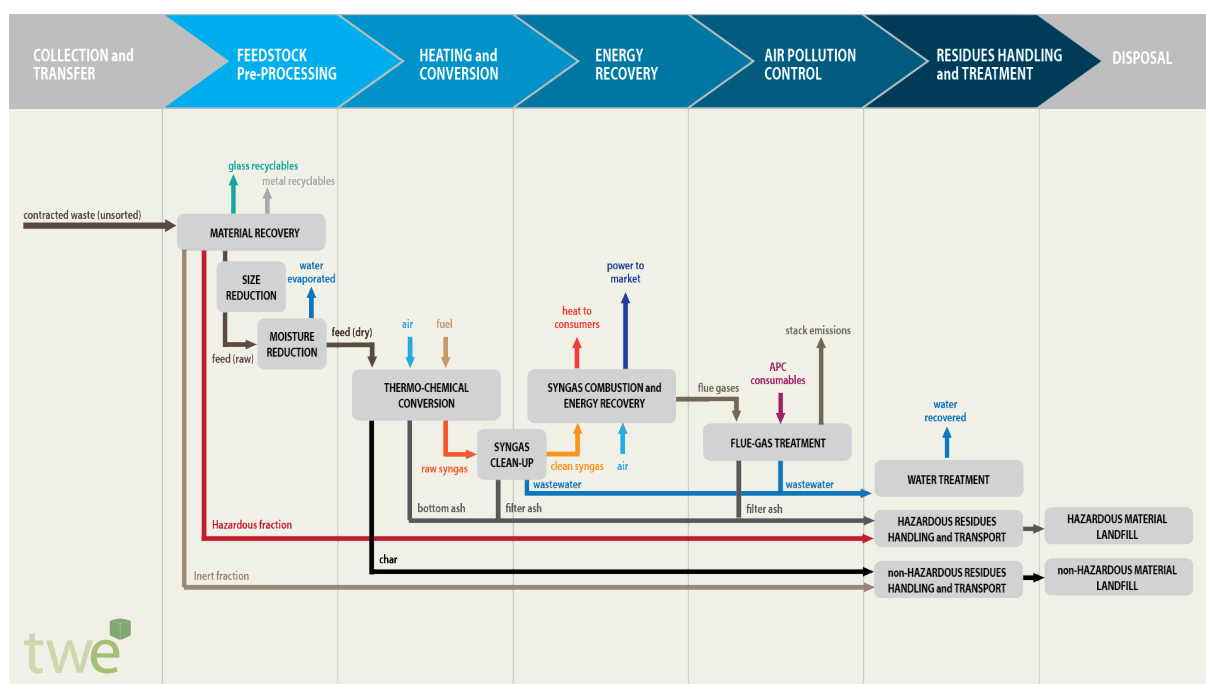
In addition to entrained flow and plasma gasification reactors, where temperatures in excess of 1200 °C can be achieved within the primary reactor chamber, a number of lower temperature processes integrate a secondary, high-temperature 'melting' furnace, where the high temperatures required for melting 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.



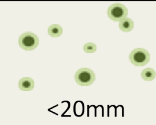

Size reduction

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 requirements¹²

| 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

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.

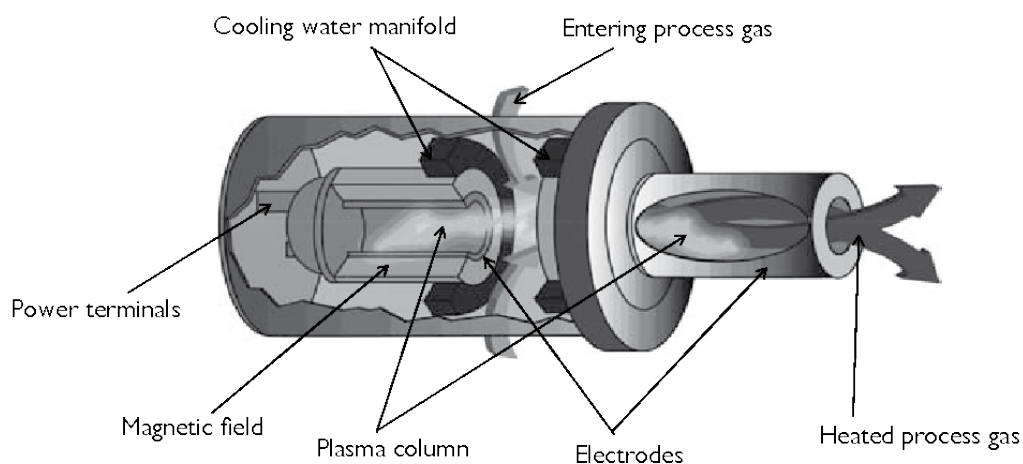
For some technologies, the contactor design is configured to allow multiple waste–gas contact. An example of the latter type of contactor is a circulating fluidized bed (CFB).

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



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:

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 (H₂S) 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, H₂, 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 H₂, 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 (SO₂),
- *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.

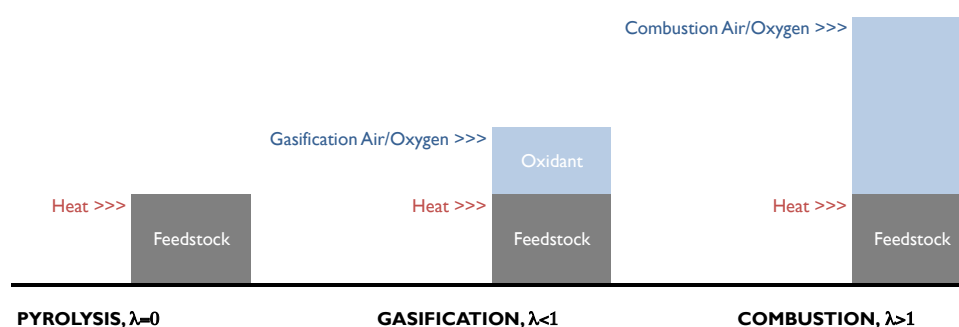
By contrast, in *conversion* facilities, based on pyrolysis or gasification processes, the gaseous products or *syngas intermediates* can be instead cleaned or upgraded prior to

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 Nm³/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

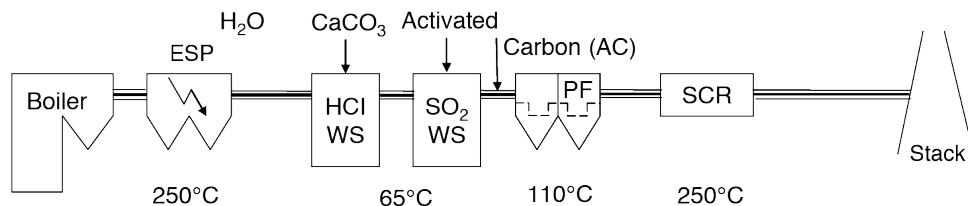
technologies. We describe here typical clean-up system configurations and the key the clean-up steps.

APC configurations

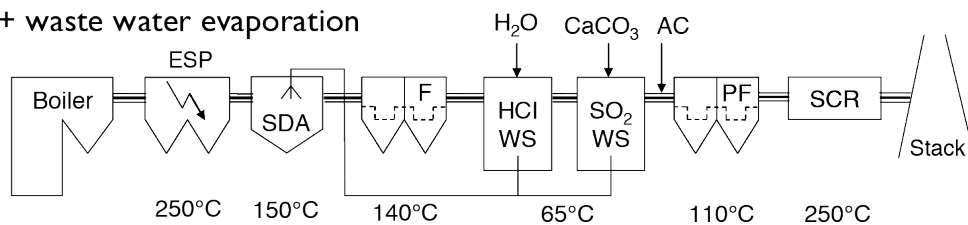
The diagram below presents a process schematic for each of the three configurations for post-combustion APC trains.

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

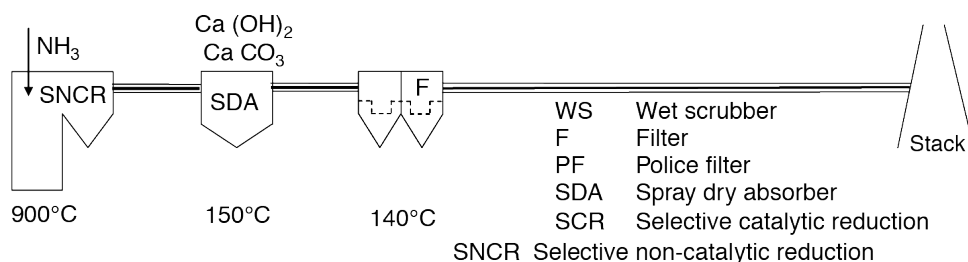
a) Wet clean-up



b) Wet clean-up + waste water evaporation



c) Dry clean-up



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, SO₂), 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

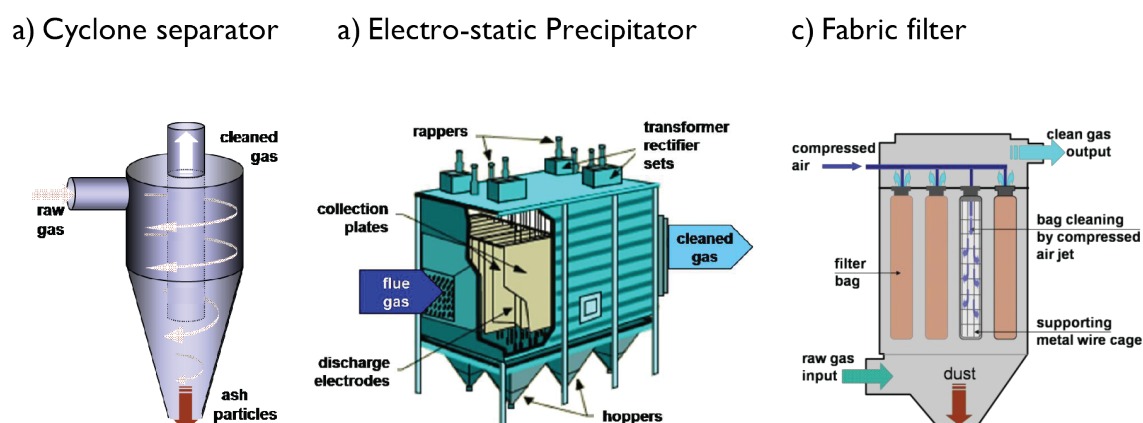
¹⁴ Adapted from (Spliethoff 2010) Fig. 6.45, p. 438.

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 $280\text{ }^\circ\text{C}$.

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, SO₂ and SO₃, 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, SO₂ and SO₃ 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, aqueous lime slurry is finely atomised and completely evaporated.

The good mass transfer between the gas and the liquid in spray drying 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 substoichiometric 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 **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

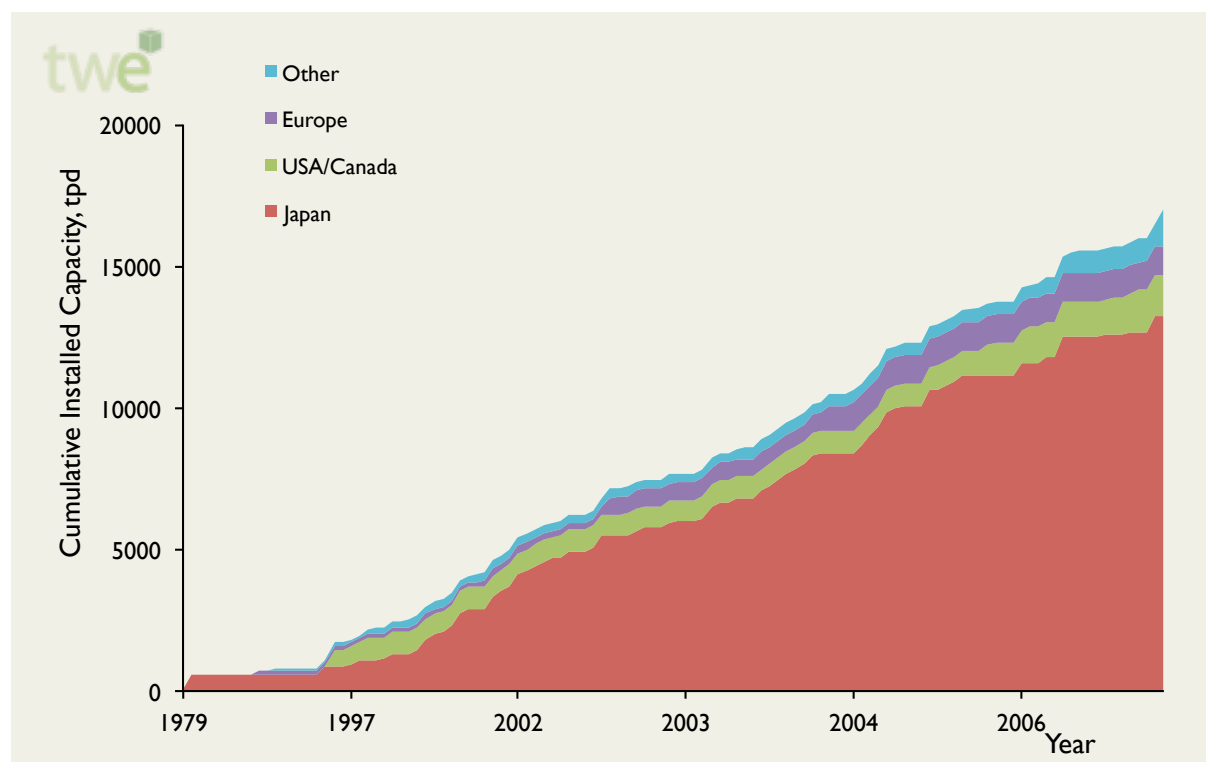
Commercial high temperature conversion + melting technologies include:

- 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, CO₂, CH₄ 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 (SO₂),
- *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 | Japan | US |
|---|--------------------------------------|------------|-----------|-----------|
| | | 2000/76/EC | Japan | 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-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 _{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 | 1.0 | 2.0 | 29.2 | 2.8 | 4.99E-03 | 5.13E-05 |
| Entech - Kuznica - Poland | 0.7 | 5.6 | 174.5 | 37.0 | 5.70E-03 | 1.99E-02 |
| InEnTec - Richland, WA USA | 2.4 | 1.9 | 115.4 | - | 4.77E-04 | 4.77E-03 |
| INEOS Bio - Fayetteville, AK, USA | 1.4 | - | 7.1 | - | 7.12E-05 | 2.14E-03 |
| IES - Romoland, CA, USA | 4.1 | - | 91.9 | 0.3 | - | 4.14E-04 |
| JFE/Thermoselect - Nagasaki, Japan | 3.3 | 8.3 | - | - | - | 1.78E-02 |
| Mitsui R21 - Toyohashi, Japan | 0.7 | 39.7 | 59.0 | 18.4 | - | 3.21E-03 |
| Nippon Steel DMS - Kazusa, Japan | 10.0 | 8.9 | 22.2 | 15.6 | - | 3.21E-02 |
| Plasco, Ottawa, CANADA | 9.1 | 2.2 | 106.8 | 18.5 | 1.42E-04 | 6.58E-03 |
| OE Gasification Heanam, S. Korea | 6.1 | 19.5 | 74.8 | 26.7 | 4.99E-03 | 4.00E-02 |

SOURCE: (CERT 2009), all values normalized to 11% O₂

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 fixed-bed (starved air) **WtGas** gasification technology developed in Australia by **Entech Renewable Energy Systems (Entech-RES)**
- **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 fixed-bed gasification

| INPUTS | | Consumption | | OUTPUTS | | Yield | |
|---|--|-------------|----------------------|----------------------|---------|----------------------|--|
| Stream/component | | kg/h | kg/t _{feed} | Stream/component | kg/h | kg/t _{feed} | |
| TOTAL INPUTS | | 3767.00 | 3767.00 | TOTAL OUTPUTS | 3767.00 | 3767.00 | |
| Feedstocks | | | | Products | | | |
| MSW, as received | | 1000.00 | 1000.00 | Syngas | 3727.00 | 3727.00 | |
| Oxidant | | | | Residues | 40.00 | 40.00 | |
| Air (@ 0.4 eq. ratio) | | 2,467.00 | 2467.00 | | | | |
| Steam (150 °C, 0.35 MPa) | | 300.00 | 300.00 | | | | |
| CONVERSION and RECOVERY PERFORMANCES | | | | | | | |
| Total Residues | | | | | 40.00 | 40.00 | |
| MASS REDUCTION (solids) | | | | | | 96.00% | |

SOURCE: (Hyder 2013)

Table 5. Low-Temperature Conversion, representative energy balance for fixed-bed gasification

| INPUTS | | | | OUTPUTS | | | |
|-------------------------------------|--|----------------------|------|----------------------|----------------------|--------|--|
| Stream/component | | GJ/t _{feed} | MW | Stream | GJ/t _{feed} | MW | |
| TOTAL INPUTS | | 24.57 | 6.83 | TOTAL OUTPUTS | 24.57 | 6.83 | |
| Feedstocks | | | | Products | | | |
| MSW, as received | | 18.15 | 5.04 | Syngas | 13.93 | 3.87 | |
| | | | | Heat | 4.67 | 1.30 | |
| Auxiliary thermal inputs | | | | Losses | | | |
| Steam (150 °C, 0.35 MPa) | | 0.83 | 0.23 | Conversion losses | 5.97 | 1.66 | |
| Fuel (unspecified) | | 5.60 | 1.55 | | | | |
| ENERGY RECOVERY PERFORMANCES | | | | | | | |
| Syngas energy @ ambient temperature | | | | | 13.93 | 3.87 | |
| HOT GAS EFFICIENCY, HHV basis | | | | | | 75.70% | |
| COLD GAS EFFICIENCY, HHV basis | | | | | | 56.69% | |

SOURCE: (Hyder 2013)

High-Temperature Conversion

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

| INPUTS Stream/component | Consumption | | OUTPUTS Stream/component | Yield | |
|---|----------------|----------------------|-----------------------------|----------------|----------------------|
| | kg/h | kg/t _{feed} | | 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 Stream/component | | | OUTPUTS Stream | | |
|--------------------------------------|----------------------|--------------|----------------------|----------------------|--------------|
| | GJ/t _{feed} | MW | | 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 | | | | | |
| Additives | | | | Recoverable by-products | | | |
| Coke | 1250.00 | 40.00 | Aggregate (slag and metal) | 9550.00 | 305.60 | | |
| Limestone | 3209.00 | 102.69 | | | | | |
| Oxidant | | | | Residues | | | |
| Air | 2345.00 | 75.04 | Char solids | 142.60 | 4.56 | | |
| Oxygen | 10169.00 | 325.41 | Other residues | 901.40 | 28.84 | | |
| 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

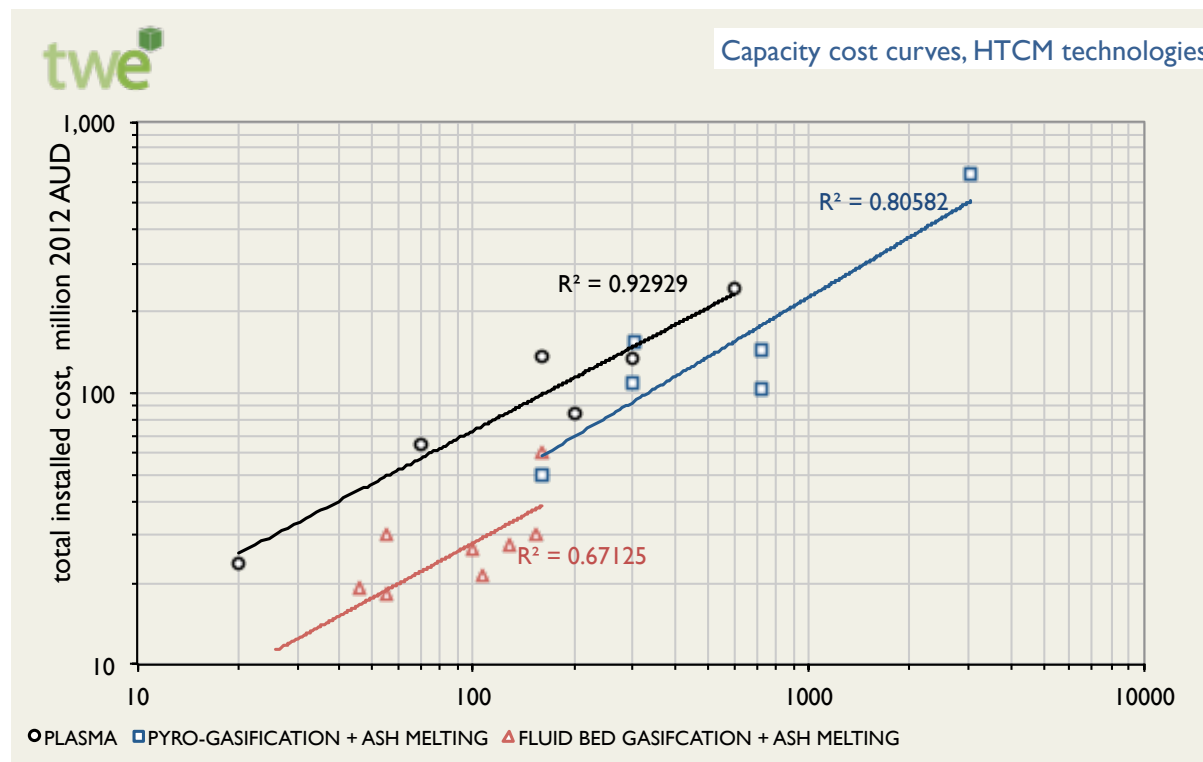
| INPUTS | | | | OUTPUTS | | | |
|--|----------------------|--------------|-----------------------|----------------------|--------|--------------|---------------|
| Stream/component | GJ/t _{feed} | MW | Stream | GJ/t _{feed} | MW | | |
| TOTAL INPUTS | | 15.15 | 119.24 | TOTAL OUTPUTS | | 15.15 | 119.24 |
| Feedstocks | | | Syngas | | | | |
| MSW | 12.31 | 101.13 | Energy content | 9.83 | 80.30 | | |
| Tyres | 1.67 | 0.77 | Sensible heat | 1.79 | 15.54 | | |
| Additives | | | Latent heat | 0.49 | 4.22 | | |
| 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



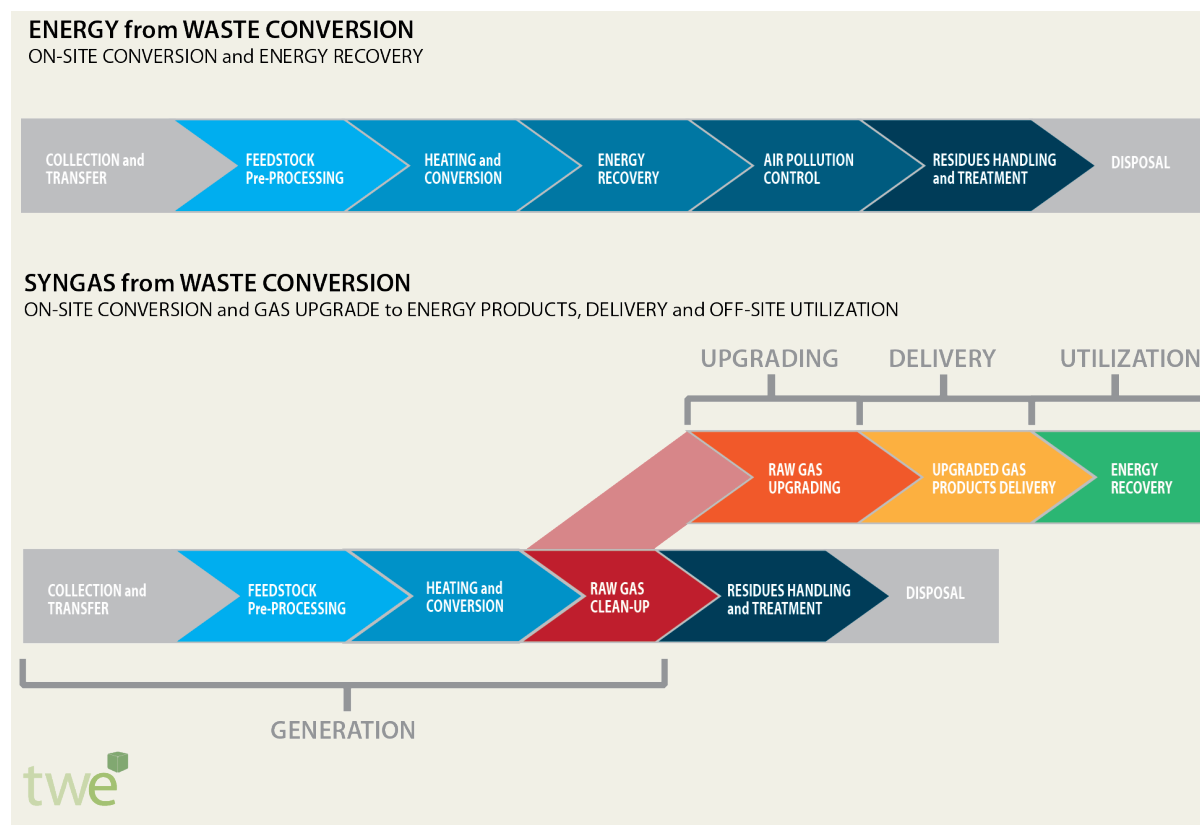
Pictured: Syngas cleaning at Kymijärvi II gasification facility, Lahti, Finland.
Credits: Metso Power, 2012

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

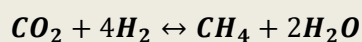
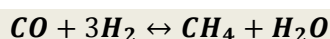
Substitute Natural Gas (SNG)

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:

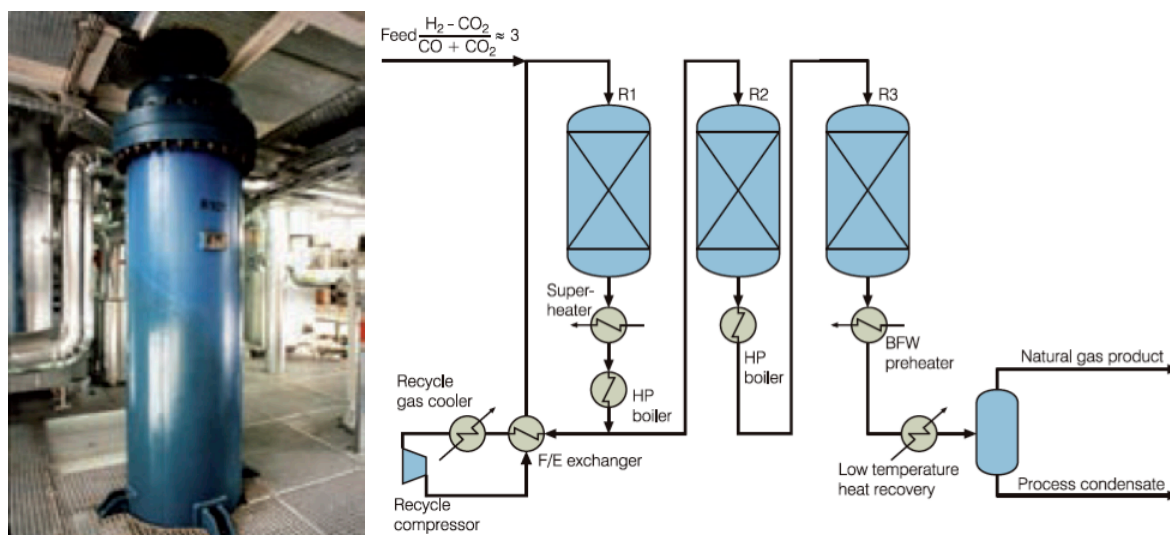


(3)

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 Nm³/h unit, and a schematic of the process are shown in the figure below.

Figure 18. Haldor-Topsøe 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 H₂ and CO) is first treated in a series of *water-gas conversion shift* (WGS) reactors (for conversion of CO, into CO₂ and further H₂) 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).

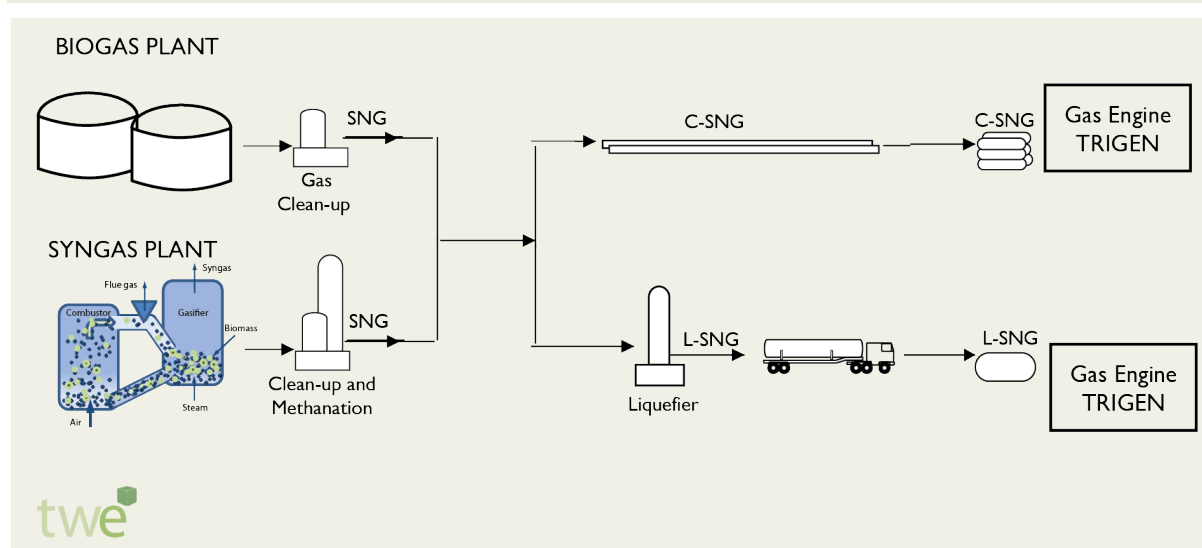
Renewable gas delivery

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 Trigenation 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’ applications, 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 Nm³ 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 m³ 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

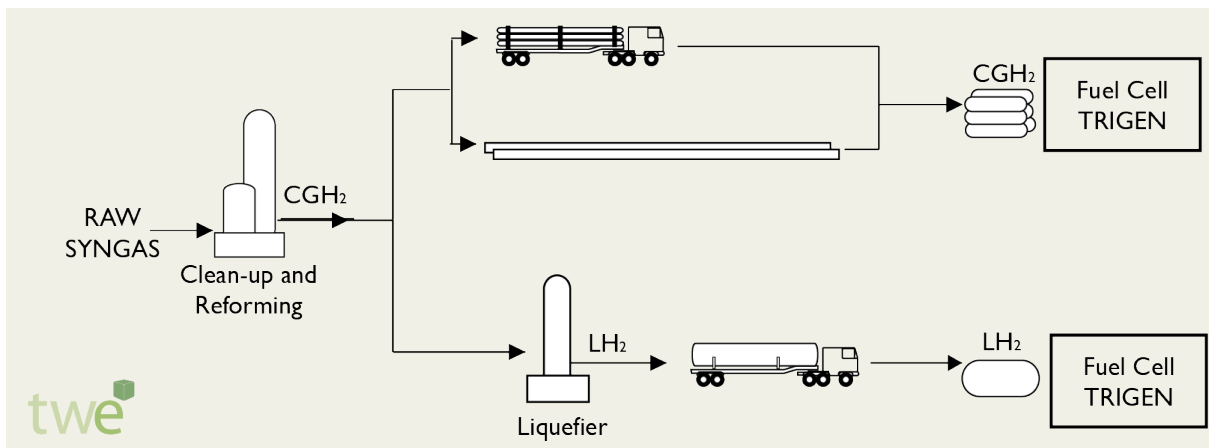
Hydrogen-based pathways

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

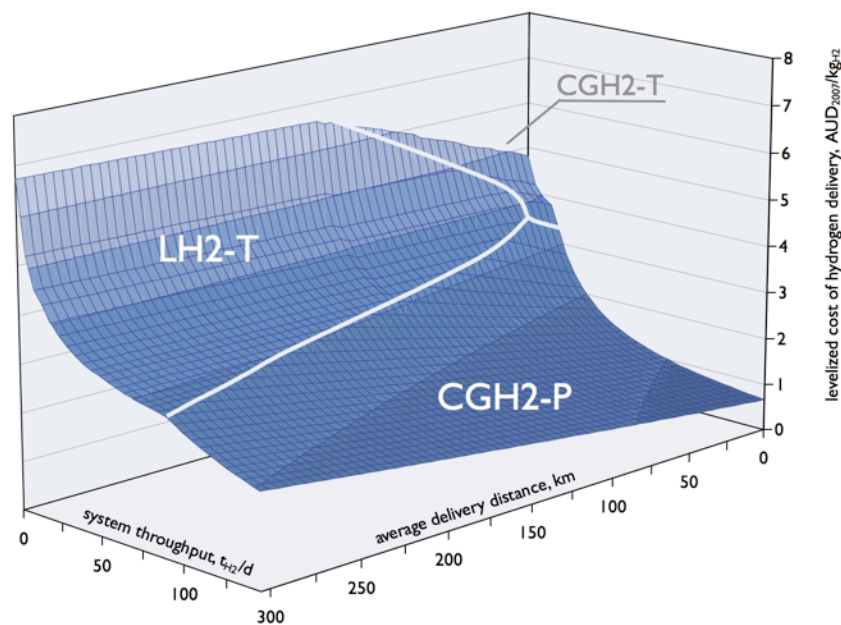


The liquid and gas paths transport pure hydrogen in its molecular form (H_2) via truck, pipeline, rail, or ship/barge. Liquid or gaseous truck and gas pipelines are the primary methods by which industrial hydrogen is delivered today.

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 distance¹⁵



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