Report Final

Residual Waste Management Options for the Regional District of Nanaimo

Presented to:
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1. BACKGROUND AND CONTEXT

RDN is looking at additional means of processing and adding value to waste, while keeping it out of the landfill in accordance with the 5R's hierarchy (Figure 1). This is consistent with the RDNs continuous improvement in moving towards "zero waste". Furthermore, there is significant benefit in extending the life of the landfill through diversion of waste as it is likely that some form of landfilling will be necessary for the foreseeable future.

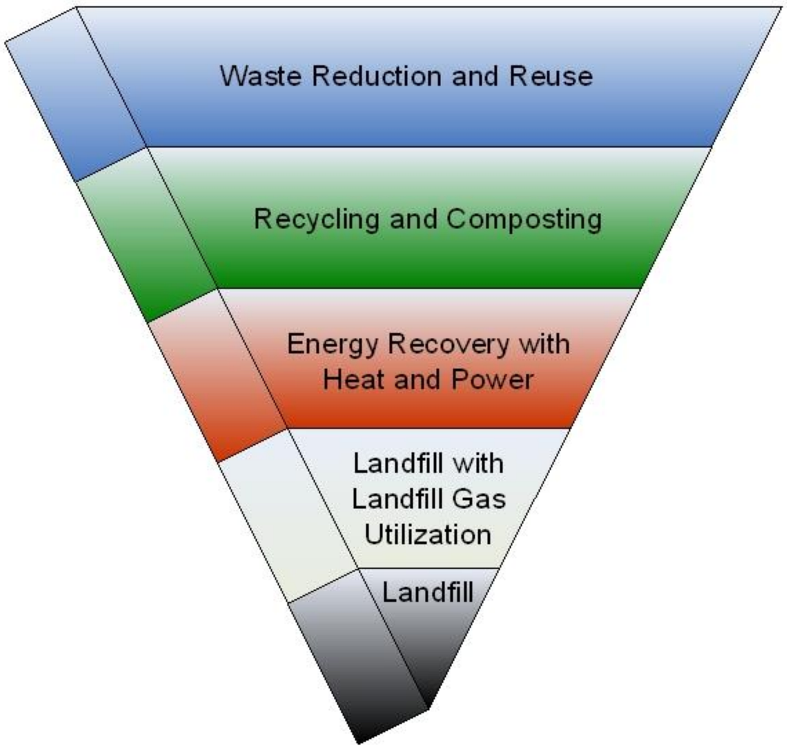


Figure 1: Waste Hierarchy

This study provides a high-level overview and review of technologies that can process what is left over after recycling. The intent is to create value-added products or energy, or both, while minimizing the residual waste going to landfill. The intent is to also to review technologies that can recover energy from organics, which are currently being processed in part using composting.

The technologies that are reviewed in this study are:

- Materials Recovery Facilities for mixed residual waste (dirty MRF)
- Waste to fuels (refuse derived fuels and similar methods to convert specific portions of the residual waste stream after recycling into a secondary fuel that has a net market value)
- Biological waste to energy (in the form of anaerobic digestion (AD), usually combined with composting of the residue), and
- Thermal waste to energy
  - Conventional combustion waste-to-energy (WTE) using mass burn technology,
  - Advanced waste to energy using gasification or pyrolysis, also referred to "conversion".

2. FEEDSTOCK AVAILABILITY

This section provides a summary of waste composition and volumes for two scenarios:

- Scenario 1 with 70% diversion and
- Scenario 2 with 80% diversion.

The residual amounts after recycling for both scenarios 1 and 2 include only those organics that are not already captured for composting. For an assessment of the biological energy recovery technology AD, all of the organic materials will be considered (at the request of the RDN). This will enable a reasonable assessment of AD technology capabilities, since using only the uncaptured organics would result in AD facilities that are too small to be feasible.

Feedstock availability was provided by the RDN from the following documents:

- Regional District of Nanaimo Waste Generation Projections, RDN, Technical Report, March 2015
- Solid Waste Composition Study Report, Maura Walker and Associates, 2012

Furthermore, in the terms of reference for this project it was stipulated that the following organic feedstock amounts should be used for technology evaluations:

- 20,000 tonnes per year of food and yard waste used for composting
- 44,200 tonnes per year of land clearing material, wood waste and some yard waste
- 1,600 tonnes per year of dewatered biosolids

It has been assumed that 20,000 tonnes per year of food and yard waste plus the biosolids (as provided in the terms of reference) would be suitable for AD technologies, and the 44, 200 tonnes per year of land clearing material and wood waste could be added to the residual waste considered for thermal energy recovery and for refuse derived fuels.

The residual waste quantities (what is left after recycling and composting) has been estimated based on RDN projections for 2020. This is the first year a new facility could theoretically be built, given normal planning and construction times. The estimated residual waste amounts for 2020 are shown in Table 1 below. The table also shows the total organics when currently composted amounts are added to the organic portion in the residual waste stream; and it shows the total residuals when land clearing and wood waste are added to the residuals after removal of organics.

Table 1: Estimated residual waste quantities in 2020

Scenario	Residual tonnes	Organics component (35.2% of residual tonnes)	Residual component with organics removed (tonnes)	Total organics with composted organics, yard waste and biosolids (tonnes)	Total residuals including land clearing material and wood waste (tonnes)
Scenario 1 70% diversion	53,326	18,770	35,545	40,370	79,745
Scenario 2 80% diversion	35,551	12,514	23,037	34,114	67,237

The totals identified in the table above will be use as a basis for determining an appropriate size of technology in later sections of the report. It is not envisioned at this time that organics would be processed into fuel or thermal energy and that some form of separate organics processing would remain.

3. RESIDUAL WASTE MANAGEMENT TECHNOLOGY INVENTORY

The following sections provide an overview of the various technologies that were evaluated as part of this study. Each section provides an overview of the technology, information on costs, and a summary of the benefits and disadvantages for each technology.

3.1 Materials Recovery Facilities for Mixed Residual Wastes

Materials recovery facilities (MRF) are used either to separate comingled recyclables (clean MRF), or to separate residual waste after recycling and organics removed at source in order to recover as many of the uncaptured recyclables and organics as possible before the residue goes to landfill (dirty MRF) or mixed waste MRF.

The subject of this report is the mixed waste MRF, since the issue is the diversion of as much of the residuals as possible before landfilling and the capture of energy if feasible. Mixed waste MRF's focus only on the extraction of additional recyclables and organics. They do not recovery energy. Mixed waste MRF's are also called dirty MRF's and more recently are referred to as Mixed Waste Processing Facilities (MWPF).

MWPF consist of mechanical systems, advanced systems using x-rays and optical equipment, and conventional hand picking. There is a large variety of equipment available to choose from by various vendors, ranging in price and ability to separate.

Mechanical systems involve application of standard mechanical separation equipment, suitably configured to recover materials as recyclables and organics, with the rejection of unsuitable materials, typically to landfill.

A good example of a MWPF is operated by the City of Edmonton to separate mixed incoming residential and some ICI waste into the following components:

- Recyclables (fibre, ferrous, non-ferrous metals and plastics)
- Organics, for further processing by an AD plant and compost plant
- Light fraction residuals for further processing into fuel for a gasification plant
- Residuals for landfilling

There are numerous ways to design a MWPF, depending on the desired degree of recycling desired. Optimum performance can be achieved through a system configured as described in Table 2 below.

Table 2: Mechanical System Process for MWPF

SEPARATION TECHNIQUE	DESCRIPTION
Mechanical sorting of oversized items	Removal of large items unsuitable for processing through the plant. Recovery of large pieces of wood and cardboard that can be recycled
Metering system	To ensure a steady and even flow of material to the mechanical system
Primary separation	Typically, the feedstock is split into 3 size fractions as this aids downstream separation. Actual size fractions will depend on the technology supplier's preferences but could be 0-40mm, 40-100mm, 100mm-150mm.
Screening	To separate 3D materials from 2D materials
Air separation	To separate light plastics and papers

Separation Technique	Description
Magnets / Eddy current separators	To recover metals
Optical sorting, or use of other high-tech methods	To remove high value plastics (HDPE / PET) for resale

The primary output from the MWPF plant will be recyclables and an organic component. The organic component, which is derived from mixed waste often has contaminants in it that hinders the making of unrestricted use compost. Recyclables, especially fibres, are often contaminated or wet and are known to be hard to sell to secondary processors.

3.1.1 Process Outputs

Process outputs from MWPF are a direct function of the selected configuration of a given plant, but typically comprise:

- Cardboard
- Fine paper and fibre
- Ferrous and non-ferrous metals
- Plastics
- Organics
- General non-recyclable/recoverable materials for landfill

The quantities of different outputs are directly related to the composition of the incoming waste. A typical example is shown in Figure 2 below:

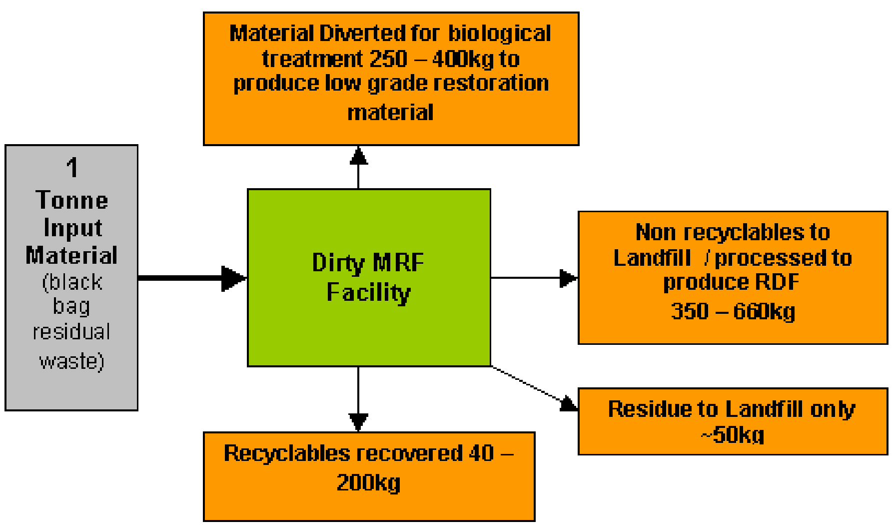


Figure 2: Schematic of Inputs and Outputs of a Typical MWPF (Dirty MRF Process)

3.1.2 MWPF Costs

Capital costs are highly dependent on mechanical system design and degree of sophistication. Most MWPF in North America are owned and operated by private companies and very little data is available on capital and operating costs.

One example that might be used is a single stream clean MRF recently built in London, ON. The major difference with a mixed waste MRF is that there is no separation of the organic component of the waste, so actual costs of a mixed waste MRF could be higher than for a clean MRF. The MRF in London cost $22.4 million for a capacity of 75,000 tonnes per year, or about $300 per tonne of installed capacity.

Information was also taken from a recent study "Mixed Waste Processing Economic and Policy Study" by Burn McDonnell, September 2015. Based on a 300,000 tonne per year facility, capital costs would be about $200 per tonne of installed capacity. However, the RDN application requires a facility of about a quarter of that size, so the smaller economies of scale could easily add 30 to 50% to that cost, bringing it into the $260 to $300 per tonne of installed annual capacity range.

Operation and maintenance costs for MWPF are also directly related to throughput and complexity of equipment. Operating costs for MWPF are not generally public information. The above reference study by Burn McDonnell calculated a cost of $36 per tonne for a 300,000 tonne per year facility. Generally net operating costs, after sales of recyclables, can be in the $30 to $50 range, although a Metro Vancouver report (May 29, 2013) indicated potential costs of over $100 per tonne. For this study, we will use $30 to $50 per tonne.

3.1.3 Advantages and Disadvantages of MWPF

Advantages of MWPF

- Good way to increase recycling rates in combination with source segregated recycling programs
- Can reduce the residual waste by 15% through recycling and up to 50% when organics removal is included
- Non-recycled residue can be further processed into refuse derived fuel

Disadvantages of MWPF:

- Equipment is expensive and complex. Actual cost for the extraction of a tonne of recyclables can be well above $400 per tonne
- Recyclables may be contaminated and difficult to sell
- Compost made from organics coming from mixed waste is generally contaminated with plastics and glass and not suitable for unrestricted use

3.2 Refuse Derived Fuel and other emerging Waste to fuels technologies

3.2.1 Refuse Derived Fuel

Refuse Derived Fuel (RDF) or Solid Recovered Fuel (SRF), in its more refined form, is produced from waste which has undergone some level of mechanical and sometimes biological processing.

Whilst both RDF and SRF fall under the banner of fuels derived from waste, the fuels are generally distinguished by reference to quality and end user as follows:

- **RDF** is made from domestic waste which includes biodegradable material as well as plastics, and has a lower calorific value than solid recovered fuel. Refuse derived fuel is used in combined heat and power facilities, many of them in Europe where they produce electricity and hot water for communal heating systems in the local area.

- **Solid recovered fuel** is a high quality alternative to fossil fuel produced from commercial waste including paper, card, wood, textiles and plastic. It can be produced to a range of specifications to meet customer requirements. With a moisture content of less than 15%, solid recovered fuel has a high calorific value and is used in facilities such as cement kilns.

Since this study deals with mixed MSW, efforts will focus on RDF only.

There are generally two methods of producing RDF:

- Mechanical processing (with or without thermal drying)
- Mechanical Biological Treatment incorporating mechanical separation and bio-drying

Around 50-70% of the RDF produced from a RDF production plant is of biomass origin, and can contribute to the generation of renewable and carbon-neutral energy. The actual proportion of biomass in the outputs from a given facility varies according to the plant feedstock and processes used to produce the RDF.

RDF can be used as a fuel in Energy from Waste plants using the conventional mass burn approach or gasification/pyrolysis technologies. However given the costs of preparing RDF there is no current market incentive to prepare such material for mass burn. In North America there has been very limited use of RDF to date other than:

- as a supplement in coal fired power plants, or other industrial boilers, which can handle up to 10% RDF without a requirement for significant refinement of emissions control equipment, or
- as part of a fuel mix used in cement kilns, which are however very sensitive to Chlorine content and require careful front-end removal of PVC products in particular.

Table 3 below gives an indication of the comparative fuel qualities of typical raw MSW, RDF and coal.

Table 3: Comparative fuel properties of RDF

Fuel type	Heating Value, as received (KJ/Kg)	Moisture Content (%)	Ash Content (%)
Raw MSW	11,000 – 12,000	30 - 40	25 - 35
RDF	12,000 – 16,000	15 - 20	10 - 22
Coal	21,000 – 32,000	3 - 10	5 - 10

***Source**:* CalRecovery

3.2.2 General Process Options

Mechanical Systems

Mechanical systems for RDF production involve application of standard mechanical separation equipment, suitably configured to recover materials either as recyclables or RDF and rejection of unsuitable materials, typically to landfill. Depending on the nature of the feedstock and the specific technical requirements of the subsequent thermal processing stage it may also be necessary to include an element of drying to reduce moisture content. This not only increases the calorific value (CV) but also improves separation efficiency in the mechanical equipment, due to reduced clogging and adhesion by accumulated fine-grained material.

A good example of an RDF production unit in Western Canada is the plant operated by the City of Edmonton to produce feedstock for the adjacent Enerkem gasification facility which will produce biofuels.

There are numerous ways to design an RDF plant, depending on the desired quality of the fuel and degree of recycling desired. Optimum performance can be achieved through a system configured as described in Table 4 below.

Table 4: Mechanical System Process for RDF production

Separation Technique	Description
Mechanical sorting of oversized items	Removal of large items unsuitable for processing through the plant. Recovery of large pieces of wood and cardboard that can be recycled
Metering system	To ensure a steady and even flow of material to the mechanical system
Primary separation	Typically, the feedstock is split into 3 size fractions as this aids downstream separation. Actual size fractions will depend on the technology supplier's preferences but could be 0-40mm, 40-100mm, 100mm-150mm. A shredder may also be employed at this stage to help with size reduction
Screening	To separate 3D materials from 2D materials
Air separation	To separate light plastics and papers
Magnets / Eddy current separators	To recover metals
Optical sorting	To remove high value plastics (HDPE / PET) for resale, or problem plastics (PVC)

The primary output from the RDF plant will be a relatively fine fuel or fluff. In addition there will be residuals which need to go to landfill, recyclables and an organic component which can be treated further with AD to generate gas, or to produce a low grade soil amendment or it can be dried and also used as a bio-fuel.

Bio-drying

Bio-drying involves using the heat generated through microbial action (similar to composting) to dry organic waste to increase its calorific value for use as a fuel. The fuel is then used in other applications such as cement kilns or industrial boilers where it offsets the use of fossil fuels, thus providing a substantial environmental benefit. This is an alternative to the use of organic material in AD, where a significantly smaller proportion of the inherent fuel value of the material is generated as biogas.

The large scale composting of household and commercial organics in Europe led to a very large amount of finished compost for which there were few established markets. At the same time, there was a growing market for bio-fuels, from sources such as wood and purpose planted crops. These bio-fuels are used to replace fossil fuels such as coal or natural gas, greatly reducing the fossil fuel generated CO_2.

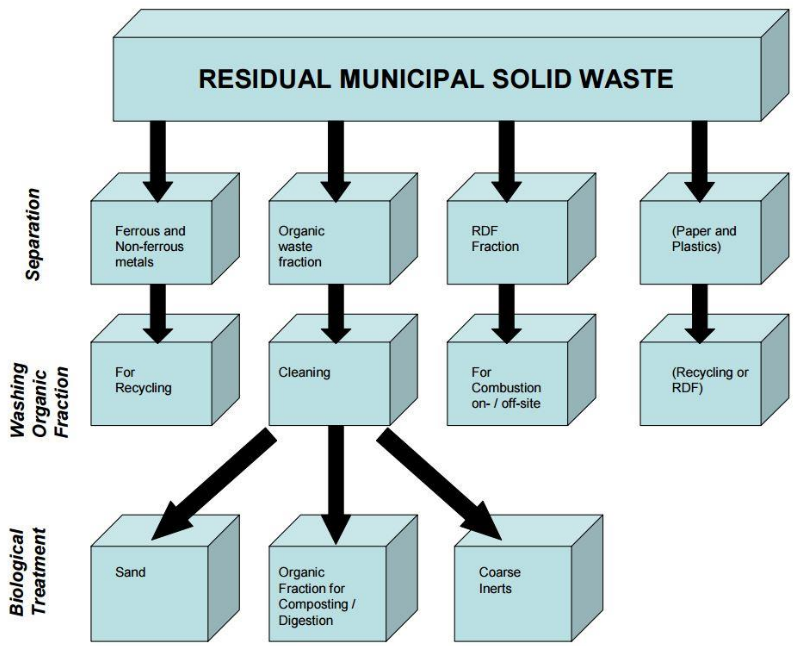
Since the biological activity of composting generates a large amount of heat, technologies were developed to use this heat for drying the organics (instead of composting them fully), thus generating an additional source of bio-fuel for which there are ready markets. Bio-drying can handle the entire organic waste stream, including biosolids. Several compost system suppliers now offer their technology for either composting or bio-drying.

3.2.3 Process Outputs

Process outputs from mechanical separation systems are a direct function of the selected configuration of a given plant, but typically comprise:

- Wood and cardboard
- Oversize rejects
- Recovered metals
- Valuable plastics (if desired)
- Fuel
- Grits (fine-grained materials which often include a relatively high organic content)

The quantities of different outputs are directly related to the composition of the incoming waste. A block diagram showing the flow of waste and its conversion into RDF is shown in Figure 3 below:



Source: European Commission – Directorate General Environment Refuse Derived Fuel, Current Practice And Perspectives (B4-3040/2000/306517/Mar/E3)

Figure 3: Schematic of Inputs and Outputs of a Typical RDF Process

The organic fraction can be used either for composting/digestion as shown in the figure above, or can be converted to fuel using bio-drying, which converts it to almost 100% RDF.

3.2.4 Mechanical Systems Costs

Capital costs are highly dependent on mechanical system design and degree of sophistication. One example is the City of Milwaukee, which investigated the possible capital cost requirements for a 60,000 tonnes per annum mechanical separation facility (~30 tonnes per hour on single shift, 5 day working), in 2012. The total costs of all process equipment, installation, engineering design, construction, administration and contingencies were estimated to be between US$9.8M and US$11.7M, depending on the choice of process equipment vendor. These figures equate to a range of CAD$14.2 – 17.0M, or CAD$240 to 280 per tonne of installed annual capacity.

Operation and maintenance costs for MRF's are also directly related to throughput and complexity of equipment. In the City of Milwaukee study, outlined above, indicative O&M costs (2012) are US$ 1.1M, or about CAD$27 per tonne. This excludes contingencies, transport and disposal of residues.

3.2.5 Bio-drying Costs

There is very little cost information available for bio-drying in Canada, since it is a fairly new concept in North America. In a recent personal conversation with a senior executive of a German company involved in composting and bio-drying (Ulf Harig, UTV), he indicated that bio-drying in Germany using the GORE covers (typically used for composting but with a different membrane) has been very successful. The throughput is doubled for the same capital cost because the process is twice as fast as composting. It is safe to assume that costs would be about half of those of a compost system. In addition, it would require less space, since curing of the finished product would not be required. The decision of whether it is more cost effective to compost, or to bio-dry depends on the availability of markets for compost or bio-fuel. In some regions, composting is the preferred technology because there is a local desire to return the organics back to the soil.

Some typical capital costs for a GORE compost system with a capacity of 20,000 tpy are in the order of $300 per tonne of installed capacity. Given that the throughput of a bio-drying facility would be double a conventional composting process, then the capital costs would be about half of that. Other bio-drying processes and technologies are expected to be more expensive but may provide the benefit of being fully enclosed.

Operating costs for GORE technology composting and other composting facilities in the 20,000 tonne per year range are generally in the order of $60 to $100 per tonne. Bio-drying costs can be expected to be about half that, or $30 to $50 per tonne.

3.2.6 Advantages and Disadvantages of RDF

Advantages of RDF

- Fuel made from waste that would otherwise be landfilled
- Fuel would normally be 50%+ biogenic coming from mixed waste
- Process increases heating value and decreases moisture content of waste
- Proven technology and well understood
- Fuel can be transported and stored, and used in other locations
- Could off-set fossil fuel coal
- Cement industry may be interested in alternate fuels to replace coal

Disadvantages of RDF:

- Limited application on a commercial scale, very few facilities in North America
- Markets for RDF not established in BC
- Complex technologies are high maintenance when operating with waste
- RDF may not receive environmental approvals as fuel, rather as waste and require more stringent scrubbers when combusted

- May not be competitive with natural gas (at current price level)
- Becomes very costly if pelletization of the RDF is required

3.2.7 Emerging Technologies

Hydrothermal Carbonization (HTC) Process

There are several emerging technologies that offer alternative methods of recovering energy from waste. One of the more promising is hydrothermal carbonization. This is described for interest only and as a "technology to watch".

Hydrothermal Carbonization (HTC) is the carbonization of organic materials that mimics what happens in nature over the course of millions of years. With HTC, organic materials are subjected to heat and pressure in a water bath and in the course of 2 to 12 hours a biogenic coal (biocoal) is produced that has a variety of uses either as a green fuel, as a soil conditioner, or as chemical feedstock.

HTC can convert wet input material into carbonaceous solids at relatively high yields and opens up applications for feedstocks such as kitchen waste, biosolids, animal manures and even yard and garden waste. These feedstocks are generated on a regular basis in large quantities and present challenges and high costs when approached using other methods.

There are many advantages of using HTC as a tool for managing solid waste. Since the largest fraction of the carbon in the waste remains integrated in the biocoal, the successful carbonization of waste has the potential to reduce GHG emissions when compared to landfilling, composting and traditional/thermal waste to energy. This can be achieved by replacing fossil coal in coal fired boilers while at the same time avoiding the generation of methane from organics in landfills. Biocoal produced from waste also has the potential to be a carbon sink when applied to land as soil amendment.

HTC from waste is also a potential alternative strategy for the production of biogenic fuels. The HTC process substantially increases the energy density of the organic wastes, bringing them to the equivalent of lignite coal. This can have major benefits for the storage, transportation and combustion of the fuel.

Processing waste with HTC helps to break-down and destroy compounds such as pharmaceuticals, personal care products, and endocrine disrupting compounds, which are problematic in landfills and composting operations.

In summary, HTC has the potential to provide many advantages compared to current methods of treating organic wastes. Since it is relatively new area of research, there are few companies involved, and only one so far has been identified as having a commercial scale facility which has been built in Germany, but is still in commissioning so there is no final operating or cost data available at this time. Other firms include a local BC company working out of Vancouver, another Vancouver based firm building a demonstration facility in Alberta, and a firm in China that is testing a pilot facility.

3.3 Biological Waste to Energy - Anaerobic Digestion (AD)

AD is the biological conversion of organic materials in the absence of oxygen. For comparison, composting is the biological conversion of organic materials in the presence of oxygen. The two processes rely on different micro-organisms and processing steps, and produce different end-products. The AD process is carried out by anaerobic micro-organisms that convert carbon-containing compounds to biogas, which is a gas consisting primarily of methane (CH4) and carbon dioxide (CO_2), with trace amounts of other gases. For the process to take place efficiently, six key process parameters must be carefully controlled. These are pH, temperature, carbon to nitrogen ratio (C:N), organic loading ratio, retention time and reaction mixing.

Two possible temperature ranges are employed in AD processes, and the temperature range utilized in the process will also dictate the type of bacteria that will be utilized. “Mesophilic” bacteria operate in an optimum temperature range of 35-40°C, while “Thermophilic” bacteria prefer warmer conditions, in the range of 50-55°C. Since AD processes are themselves not exothermic (heat producing), heat must be added and precise temperature control must be incorporated into plant design to maintain desired temperature ranges.

An optimum C:N ratio of between 20:1 and 30:1 in the feedstock promotes the production of methane; as a result, feedstock mixes must be carefully monitored to achieve this range and avoid digester inhibition or lower biogas production. The organic loading rate is a measure of the biological conversion capacity of the AD system. Loading a digester above its ideal organic loading rate will result in lower biogas yield due to the accumulation of inhibiting substances in the digester. In terms of retention time, sufficient time in the digester is required to achieve effective biological degradation. While retention times will depend on the process design and feedstock characteristics, typical hydraulic retention times are 12-30 days. The hydraulic retention time is chosen as a balance between throughput and gas recovery, since a longer retention time will yield more gas. Finally, physical mixing of the feedstock is important as it provides improved contact between the organic material and bacteria.

The solid content within the AD process depends on the type of technology used – wet or dry. A basic AD flow diagram is shown in Figure 4 below.

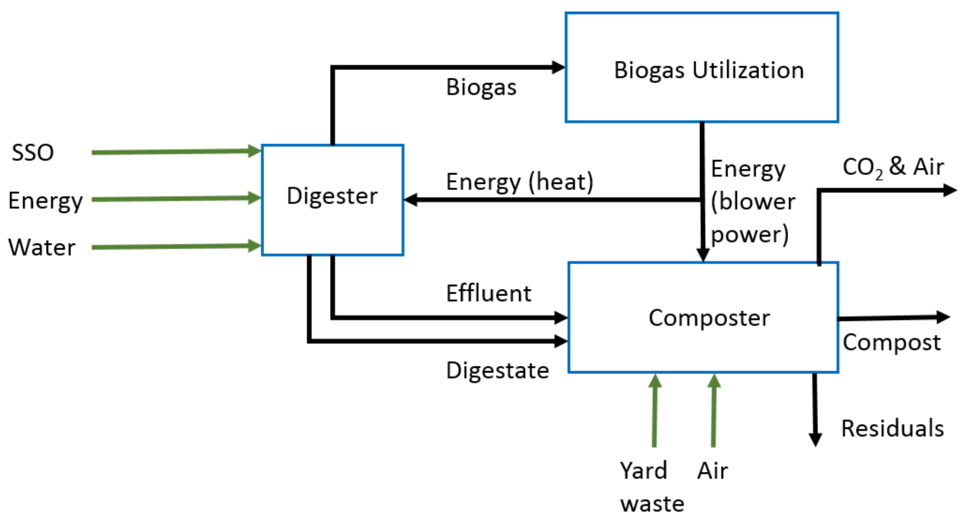


Figure 4: Basic AD Block Flow Diagram

3.3.1 General Process Options

Anaerobic digestion technologies can be grouped by the number of digestion stages – single or two/multiple. There are also two general types of processes, wet and dry AD, which are discussed later. Production of biogas from anaerobic digestion involves a series of biological processes of which acidification and methanogenesis are the primary stages. In single stage AD systems, these two processes take place in the same digester. In two-stage AD systems, these processes are performed in separate digesters.

The majority of AD plants in operation today that process SSO utilize single stage (batch or continuous flow) AD systems. The large number of single-stage AD systems is due primarily to the systems' relatively simple design and therefore lower cost, compared to two-stage systems.

There is little difference in the overall processing capacity or the biogas production rate when comparing single or two-stage AD systems, even though two-stage systems have a theoretical advantage. For SSO, both single and two-stage AD systems would be appropriate however, with the performance being similar, the additional capital and operating costs for a two-stage system could be difficult to justify.

Historic market penetration in Europe of the wet and dry two-stage digesters is very moderate. The advantage of having a faster degradation during the digestion stage is usually not enough to compensate for the higher capital cost of the hydrolysis-stage. Therefore, two-phase digestion has been decreasing.

3.3.2 Wet and Dry Options

Typically SSO have a solid content anywhere between 20-30% for food waste, and 40%+ for yard and garden waste. The higher solid content feedstock makes it most suitable for dry AD systems.

Dry AD systems, also referred to as high solids digesters are designed to process organic feedstock with a solids content between 25% and 40%. Unlike wet digesters that process pump-able slurries, dry AD systems can process solid substrates without the addition of water. There are two key types of dry AD systems, which are the continuous vertical plug flow and batch tunnel horizontal digesters. Continuous horizontal units also exist but have largely fallen out of favour. Continuous vertical plug flow digesters are vertical, cylindrical tanks that are continuously fed from the top, and the materials moves downward by gravity during the digestion process. A tunnel-like chamber with a gas-tight door is used in batch tunnel digesters. Mixing is not usually used in either of the systems but they need structural material to operate. Pretreatment is limited to contaminant removal, since contaminants affect the quality of the digestate and subsequently the compost.

Wet AD systems dilute the food waste organics to a solid content between 10-15% by adding water. This diluted mixture is pulped to obtain the consistency of a thick soup.

Wet AD systems work best with a consistent and wet feedstock, adding water if needed to achieve a slurry with a solids content of 10-15%. However, SSO waste is often varied and its composition is ever changing. This could be a disadvantage in that the wet slurry in the digester can separate into layers of material with a floating scum at the top of the digester, which could prevent proper mixing and result in heavier particles at the bottom of the digester. This can then cause damage to the digesters pumps and ancillary equipment, and ultimately settle out causing blockage and reduced digester volume. This striation of material in digesters occurs in extreme cases and vendors have methods in place to manage this issue. The advantage of the separation of material in wet AD systems is that it is used to effectively remove impurities from the time the material is raw feedstock to when it is pulped and being processed.

Wet AD technology is well established, especially for biosolids and agricultural manures. For SSO,there are two wet AD plants in Canada, both in Ontario. Vendors of wet AD technologies include Canada Composting Inc. (BTA process), Clarke Energy (Haase process) and RosRoca (Biostab process). Wet AD works well for food waste and biosolids, however, is not that suitable for yard and garden waste because it does not break down lignocellulosic materials well, which comprise a substantial part of yard and garden waste. Also yard and garden waste requires much more intensive shredding before it can be fed into a wet process.

There are well over 120 AD plants in Europe processing food waste. While most of these still use the wet AD technology, there is a growing interest in dry AD systems in North America because they are more forgiving on the type of collection required (i.e. many municipalities like to collect yard and food waste combined). A recent study by Imperial College London (Angelonidi & Smith 2014), indicated that dry AD produced generally lower yields at higher costs than wet AD. There are three dry AD plants in western Canada, one is currently operational (Richmond, BC) and two are under construction (Surrey, BC and Edmonton, AB). The City of Edmonton is currently building a 45,000 tpy dry AD facility using Bioferm technology. City of Surrey has designed a $50 million dollar AD facility which will accept 115,000 tpy. This is a P3 project using Orgaworld's BIOCEL technology, which is a mesophilic batch process requiring minimal pretreatment.

3.3.3 Feedstock Requirements

An AD facility would accept and process residential source separated organics (SSO - kitchen scraps plus yard and garden organics) and organic waste from the industrial/commercial/institutional (ICI) sectors. Figure 5 shows a typical load of mixed SSO from the residential and ICI sectors as it would be received at an AD facility.

Note that for wet AD systems, plastic bags for the collection of kitchen waste are generally not acceptable and would need to be removed during pre-processing. This includes compostable bags, since they would not degrade quickly enough and they would interfere with the wet AD process.

Figure 5: Typical SSO

Feedstock requirements for the dry AD process are more forgiving and plastic bags and other contaminants, if not too excessive, are generally passed through the digester. However, the contaminants then reduce the quality of the digestate and resulting compost, making it more difficult to sell/use and also limiting its applications.

Since AD works only on the organic fraction of the waste stream, separation of the organics from other waste and contaminants is required. In general, source separation is used, but despite that, some contaminants still prevail in the SSO. Especially for wet AD, but also, to a smaller degree, for dry AD, pre-processing methods are required to:

- remove non-digestible materials which take up unnecessary space in the digester;
- create a uniform small particle size in the feedstock to promote efficient digestion;
- protect the plant and equipment from waste components that may cause physical damage; and
- remove materials which may adversely affect the quality of the digestate.

Pre-processing commonly involves mechanical processes including the use of:

1. trommels/screens for the removal of the oversized fraction;
2. de-packaging equipment if commercial food waste that is still in containers needs to be processed;

3. mostly for wet AD systems, hammer mill (or similar) is required for size reduction of the SSO feedstock because it needs to be converted into a slurry; and
4. shredding/mixing equipment (or use of a Hydropulper as a pre-treatment process for wet AD systems to break down the organics and separate out the heavy and light non-organic fractions).

3.3.4 Process Outputs

The main AD process outputs are gas, digestate and residue. The main purpose of AD is to generate gas, since it has the most environmental (GHG offsets) and financial (available energy markets). Based on a literature review, the average gas generation of most common and installed technologies is fairly consistent and approximately 90 to 120 m3 per tonne of feedstock as received. The actual amount will depend on the quality and type of the feedstock and the specific technical process used. Most gases recovered consist of about 60% methane, resulting in a gross energy equivalent of about 2 331 MJ or 648 kWh per tonne of feedstock. If this gas is converted to electricity in a reciprocating engine at an assumed 37% efficiency, then each tonne of feedstock could produce about 240 kWh of electricity, which is about 40% of what an average household in Alberta uses per month (600kWh). A certain portion of the gas energy/electricity, typically about 20%, will be used for internal process consumption and the balance can be sold.

Biogas must usually be cleaned of impurities before it can be utilized. For direct combustion in a boiler, the removal of moisture is usually all that is needed. If the gas is going to be used to generate electricity in a gas engine, then H2S must be removed because it is corrosive. In addition, siloxanes (silicon compounds) must be removed because they create additional friction and wear in the engine. If the biogas is upgraded to natural gas quality, then in addition to moisture, H2S and siloxanes, the most of the CO2 and O2 need to be scrubbed out before the gas can be injected into the grid.

The material remaining after the AD process is a partially stabilized organic material called digestate. Typically, about 30% by weight of the feedstock will end up as dewatered (30% solids) digestate. If the process is thermophylic, then the digestate only needs to be dewatered and matured, since the high temperatures in the process will have resulted in adequate pathogen kill, and the end product can be sold as soil amendment. Mesophilic processes require a complete composting treatment or some other form of heat/pasteurization (e.g. 1 hour at 70oC) to achieve pathogen kill before the product can be used. If the AD process is wet, then the digestate will be liquid and will need to be dewatered to about 30% solids, which can then be composted or land applied. An alternative option which is increasingly used in Europe where land application is undesirable is to use the biosolids as a bio-fuel. This requires dewatering, which can be achieved physically through presses, thermally through drying with heat, or biologically by employing bio-drying (a process similar to composting). The residual liquid fraction, if not reusable in the process, is disposed of as wastewater, or in some cases can be used as liquid fertilizer.

Feedstock contamination, based on experience at existing AD plants in Canada and Europe can be high and as much as 20% of the incoming feedstock if it is SSO. This residue must be removed before, during and after the process and is usually sent to landfill.

3.3.5 AD Costs

The capital costs of AD facilities vary widely, depending on size, location, type of technology and efficiency. In Table 5 below examples of capital costs from known Canadian facilities are shown and average at close to $500 per tonne of installed annual capacity. European facility costs are less reliable due to very different local cost structures, exchange rates, etc. and are thus presented for comparison only. However, the average cost per tonne for the European facilities is also in this range. For calculating potential costs for AD, the Surrey capital cost figure of $609 is the most realistic figure to use because it was most recently tendered and is most likely to be reasonably representative for AD plants built on Vancouver Island, as well.

Table 5: Approximate Capital Costs for AD Plants

Vendor	Technology Type	Annual Incoming Tonnage Processed	Estimated Capital Costs	Estimated Capital Cost/Tonne of Capacity
Canada Composting (BTA)	Wet	4,000	$18,500,000	$411
Canada Composting (BTA)	Wet	28,000	$10,500,000	$380
Pembrokeshire, S Wales, UK	Wet	13,600	$10,000,000	$735
Consett, Durham, UK	Wet	14,700	$9,000,000	$612
Anglesey, N Wales, UK	Wet	30,000	$12,000,000	$400
Newton Aycliffe, Durham, UK	Wet	53,000	$13,200,000	$249
North London, UK	Wet	54,000	$24,600,000	$456
Orgaworld **Surrey, BC 2015**	Dry	115,000	$70,000,000	$609
Valorga **Barcelona 2004**	Dry	120,000	$82,000,000	$684
Veolia **Winterthur 2014** **Backnang 2011**	 Dry Dry	 23,000 36,000	 $19,600,000 $22,100,000	 $853 $615
BIOferm **Oshkosh 2013** **Lochhead 2013**	Dry Dry	10,000 40,000	$3,500,000 $30,000,000	$350 $750

Most AD plants are privately operated, so reliable operating costs are difficult to obtain. Data from 2007 for the Dufferin AD facility in the City of Toronto indicates that operating costs at that time were $112 per tonne (BioCycle August 2007, Vol. 48, No. 8, p. 51), excluding digestate treatment and disposal and excluding utilities or energy revenue. This seems high compared to the operating costs of European AD plants, which are generally around $60 per tonne. However, the European costs may be low because they often include a heavily subsidized feed-in tariff for the sale of the green energy. A reasonable preliminary assumption for study purposes is approximately $90 per tonne.

AD plants generate revenue from the sale of electricity (or gas, if it is upgraded to pipeline quality) produced with the bio-gas that is recovered through the process. A very efficient wet AD facility might be able to generate up to 260 kWh of electricity per tonne of feedstock and after internal usage sell 210 kWh per tonne of feedstock (Dry AD facilities generally produce about 20% less gas). Assuming the electricity could be sold for $0.10 per kWh, this could result in revenue of $21 to $17 per tonne of feedstock; which is only adequate to offset some, but not all of the operating costs.

It can be assumed that in conjunction with the AD plant, composting of the digestate could be carried out for $40 per tonne, so that after adding the cost of composting and subtracting the revenue from the sale of energy, the minimum break-even tipping fee (without profits or contingencies) would be approximately $110 per tonne.

3.3.6 Advantages and Disadvantages of AD

Advantages of AD:

- Proven for SSO in Canada
- Generates 100% green energy
- Good odour control possible due to in-vessel and in-building process
- Minimal residues if digestate composted, cleaned and land applied
- Secure markets for energy.

Disadvantages of AD:

- Treats and recovers energy only from the organic portion of the waste stream
- Most of the references are for module sizes that are greater than 10,000 tpy (smaller sizes may be harder to procure and more expensive to build)
- Needs good feedstock source control and some pre-processing
- No secure markets for compost from digestate, and contamination from poor segregation at sources carried through the process resulting in contaminated compost
- Considerably more expensive than landfilling and somewhat more expensive than composting

3.4 Thermal waste to energy

This section is separated into conventional waste to energy using combustion technology, and advanced waste to energy using gasification of pyrolysis, also referred to “conversion”.

3.4.1 Combustion technology

The main components of a conventional waste to energy facility are illustrated in Figure 6.

Following some form of feedstock preparation, the combustion process is used to release the heat, which is then converted to steam or hot water. The steam in turn can be converted to electricity or used in industrial processes. The gases, after the heat has been extracted, are then cleaned before being vented to the atmosphere. Two forms of ash come from the process: bottom ash from the actual burning of the feedstock, and fly ash from the flue gas cleaning process.

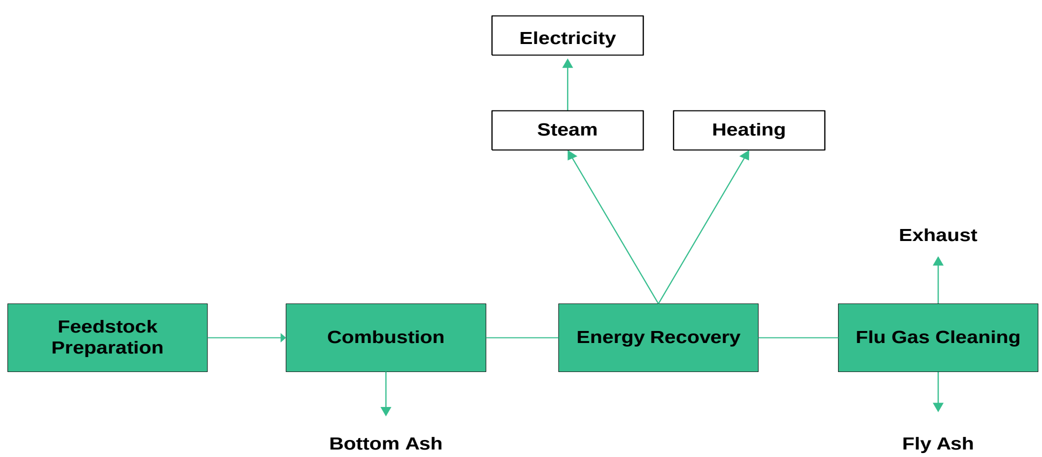


Figure 6: Main Components of a Conventional Waste to Energy System

There are several technologies that have been developed and are commonly used. They employ a conventional combustion approach. The major classifications are:

- mass burn: used for large applications, usually over 200 tonnes per day or 70,000 tonnes per year;
- controlled air, starved air, or modular systems (sometimes also called close coupled gasification systems): for applications up to 300 tonnes per day, or 100,000 tonnes per year;
- fluidized bed technologies: for preprocessed waste with capacities up to about 200 tonnes per day (70,000 tonnes per year); and
- rotary kilns: usually used for specialty waste that requires a high degree of agitation and containment, such as hazardous or medical waste (these systems are highly specialized, costly, and not normally used for MSW. They will not be discussed further in this report).

Following waste presorting or preprocessing, waste enters the actual furnace area, where it is converted into heat through combustion. As the waste travels through the system, it is slowly reduced to ash and inerts. These are removed at one end of the process. The ash, inerts and metals are then collected and sent either for recycling (metals) or disposal (ash, slag). Many plants in Europe now process the ash into low grade building materials, thus recycling it. WTE facilities generally generate 20 to 25% residue by weight and 5 to 10% residue by volume. This means that less than 10% of the volume of material entering a conventional WTE plant will need to be landfilled (if the ash is not recycled).

In larger WTE facilities, the boiler section is an integral part of the combustion area. In smaller units, the boiler is often a separate unit. Steam can be produced for industrial processes or to drive a steam turbine generator set for the production of electricity. A larger WTE facility is the same as a wood or biomass fired power plant, except that municipal solid waste is burned instead of wood. Combustion of waste, however, requires adherence to much stricter emission standards than for the burning of wood or biomass.

MSW contains heat energy, principally in the form of its constituent organic carbon molecules. Unprocessed MSW typically has a heat value of approximately 10,500 to 12,800 kilo-joules/kg (4,500 - 5,500 Btu/lb). At this heating value, a WTE facility can supply, after in-plant consumption, at least 450 to 700 kWh of electricity from each tonne of waste burned. Actual heat values depend on the specific composition of the waste, including the circumstances of its collection and delivery to a facility, as well as the extent to which the waste is pre-processed at the facility to remove inert and high moisture content materials. The anticipated composition of the RDN waste stream includes plastics, fines, and textiles, that all have high heating value. The system is not dependent on paper and food waste, which are expected to be diverted to recycling and composting systems. Wet waste can make a system operate less efficiently.

The solid residue remaining after thermal treatment/destruction is typically termed 'bottom ash'. This material is mechanically collected, cooled (typically water quenched then drained) magnetically/ electrically screened to recover recyclable ferrous/aluminum materials (although these metals can be recovered during the MSW in-feed preparation) and removed for final disposal, typically placed in MSW landfill sites. The material can, depending upon its chemical composition, physical state, and regulatory requirements, be utilized as a form of aggregate substitute. Bottom ash from a WTE facility is typically 5 to 10% by volume and 20 to 25% by weight of the incoming waste stream to a thermal treatment/destruction facility.

Air pollution control systems generate the other solid residue from a facility. Termed 'fly ash', this material is comprised of the fine particulate contaminants captured from the flue gas and the reagents (e.g., lime) used to effect capture. Fly ash may be classified as hazardous waste (higher propensity to leach contaminants in hazardous concentrations) as it contains the contaminants removed from the exhaust gases and is usually managed via further chemical stabilization and/or ultimate disposal in secure hazardous waste landfill sites.

It is possible to add on to any process the treatment of ash through vitrification. This employs extremely high temperatures to convert ash into inert vitrified substances, which can be ground and used as aggregate, thus fully recycled. There are no known applications of ash vitrification on a large commercial scale for MSW combustors in North America, mainly due to the high energy costs required to vitrify the ash.

Due to its heterogeneous nature, the burning of municipal solid waste produces emissions, which must be tightly controlled. Modern combustion systems address this issue in two ways: (1) the combustion program is optimized so that as few pollutants as possible are generated in the first place, and (2) very extensive air pollution controls systems are integrated into the process so that ultimate emissions meet all regulatory standards. Modern WTE emission standards, including BC standards are among the most stringent for any combustion device.

Air pollution control systems include equipment to continuously and/or periodically monitor emissions performance and to report performance for process control and regulatory compliance purposes. Modern air pollution control systems are interlinked to the waste in-feed control, thermal treatment/destruction units and energy recovery/conversion units of a facility, so that trends in emission performance are discerned and appropriate adjustments in the facility's unit functions are automatically made to ensure that emissions meet or are better than regulatory standards.

Compared to landfill disposal, thermal processing usually results in a net reduction of greenhouse gas (GHG) emissions in most jurisdictions. In BC, with its relatively green electricity, this may not necessarily be the case, although if heat from the WTE plant is also utilized and offsets fossil fuels, then this will benefit the GHG balance. The reductions are generated by the avoided methane emissions from landfilling (from anaerobic decomposition of organics), and from avoided carbon dioxide emissions from burning fossil fuels to produce electricity and heat. The WTE process does generate some GHG emissions from the combustion of fossil-fuel derived products such as plastics. However, the combustion of biogenic waste (food waste, yard waste, wood waste etc.) does not contribute to anthropogenic emissions of carbon dioxide, since the carbon contained in those materials is part of the active carbon cycle.

In a thermal treatment facility, virtually all of the organic materials are converted to carbon dioxide and water. When considering GHG emissions, only the carbon dioxide from the non-renewable portion of the waste stream is generally counted. The amount of organic waste is either determined on a case-by-case basis or by a general countrywide rule. In some European countries, for example, it is assumed that half of the energy produced in a WTE facility is from renewable sources.

3.4.2 Landfill Avoidance and Space Savings

Thermal processing does not eliminate the need for landfills. It can, however, significantly reduce the amount of landfill space required. This translates into savings by avoiding or deferring the development of new landfill space and avoiding the use of land, which could be used for agriculture or industrial development.

As a general rule, if thermal processing is employed, a minimum of 10% of the input material by volume (or 25% by weight) will still need to be landfilled. This would be in addition to a non-combustible waste that would require disposal. Furthermore, thermal plants require a constant source of feedstock, so that they are usually built to capture only a certain percentage of the total waste stream and provide a margin of safety, should the availability of waste change (for example through increased recycling or composting).

Therefore, landfill capacity will still be required for:

- the ash/residue from a thermal facility,
- non-combustible wastes,
- wastes that are generated over and above the thermal processing capacity (the plant should always be undersized to allow for fluctuations in the waste stream and additional recycling/diversion),
- future growth in waste, and
- a back-up management method for when the thermal processing plant and other waste processing facilities, such as compost plants, have scheduled and unscheduled shut downs.

3.4.3 Costs of conventional combustion/WTE

With a worldwide inventory of over 600 conventional combustion or WTE facilities, there is a lot of statistical information on the costs of this technology. Of course there are many local factors to be considered, but for comparative purposes, the average known costs can be very helpful. In the figures below (Figure 7 and Figure 8) the costs, based on capacity have been plotted for different capacities of plants. As can be seen, the average capital costs for a 50,000 tonne per year facility for example are about $1,200 per tonne of installed capacity and the operating costs would be in the range of $115 per tonne. Since these figures are from 2007, an escalation of about 15% should be applied.

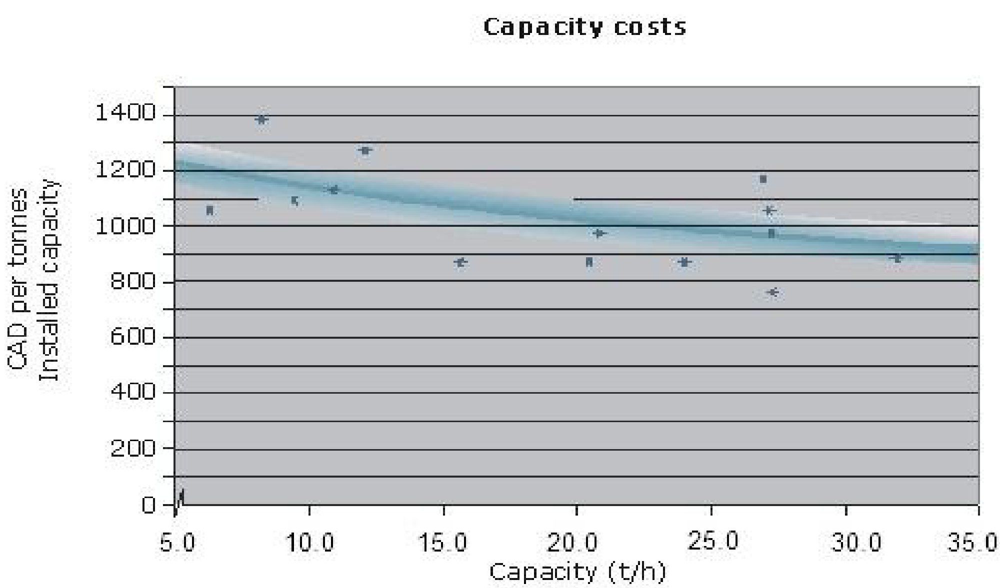


Figure 7: Cost of capital for conventional combustion/WTE versus capacity

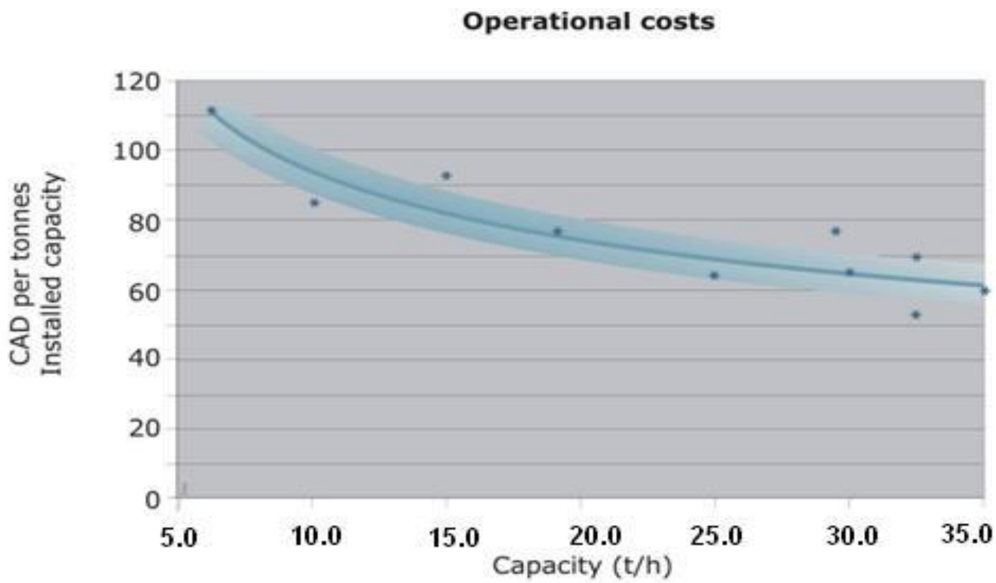


Figure 8: Typical operational costs for conventional combustion/WTE versus capacity

Source: Ramboll. 2007. Memo to MacViro during the Durham/York Environmental Assessment

3.4.4 Advantages and disadvantages of conventional thermal WTE

There is considerable technical and emotional debate about the advantages and risks of conventional combustion systems. Experience from the past, before modern emission standards and controls were in place, has caused waste incineration to receive a bad name.

Advantages of conventional waste to energy systems:

- It is well established worldwide. More than 36 million people in 29 countries dispose of their MSW at waste to energy facilities;
- There are many examples of well-operated waste to energy facilities in the developed world. Modern WTE facilities have no significant impact on the environment and generally a positive greenhouse gas balance;
- Conventional combustion is relatively simple and costs less to build and operate than most advanced systems, such as gasification and pyrolysis;
- Other wastes, such as biosolids and biomedical materials can be destroyed; and
- The technology is reliable.

Disadvantages of conventional waste to energy systems:

- Public perception and opposition can be significant;
- It does not represent an advanced form of waste management, but is rather one of the traditional technologies available;
- Fly ash may be hazardous, which requires some form of treatment or stabilization before disposal;
- Electrical energy generated may not be recognized as “green”; and
- In the eyes of some regulators and the public, WTE plants are not considered recycling but a form of waste disposal.

3.5 Gasification

3.5.1 General

Gasification is a generic term used to describe a process of partial combustion of carbonaceous fuel to generate syngas. It involves the thermal break-down of solid materials into a gaseous constituent (syngas), and an ash residue. In principle, if solid materials are subjected to a large quantity of oxygen (air) and heat, they will combust. If the air is reduced to less than what is needed for combustion, it results in gasification. When waste is heated with zero air in an enclosed chamber, then the process is termed pyrolysis.

Gasification of solid materials is a process that has been around for over a century and was historically used to gasify coal and wood to make gas while producing coke and charcoal. Only in the second half of the last century has gasification been viewed as a potential method of obtaining a relatively clean energy product from waste materials and been applied to municipal solid waste, or organic materials derived from the waste stream.

The impetus to apply the gasification technology to MSW grew out of concern about the mounting problems associated with MSW disposal, including diminishing landfill volumes, groundwater contamination from landfill leachates and the technical problems associated with the early combustion technologies applied to the incineration of MSW. The production of energy from MSW gained favour in the mid-1980's as it was believed that the days of cheap and abundant energy were over.

The gasification process requires some form of external energy which is usually taken from limited combustion of the volatiles in the feedstock under sub-stoichiometric (less oxygen than needed for complete combustion) conditions in a reactor. This means that only partial combustion occurs due to limiting the quantity of oxygen available for the reaction. The remainder of the un-combusted volatiles in the feedstock are then “gasified” and converted to syngas, which can be cleaned and burned in an internal combustion engine, gas turbine, or in a boiler. Syngas can also be used as feedstock in a chemical processes such as in methanol and ethanol production.

Pyrolysis works in much the same way as gasification, except that the feedstock is contained in a sealed environment without oxygen and heat is applied from the outside. Pyrolysis can provide, in addition to gas, a synthetic oil, which can also be further refined as fuel or chemical feedstock. Both processes leave a carbon rich char, which can be discarded, or further processed and combusted to recover the remaining heating value.

Gasification and Pyrolysis are described together because of their similarities. However, later in the report they are evaluated separately because gasification is much more widely used for MSW than pyrolysis and therefore the maturity of the technology is different.

It is important to consider the complete system when evaluating and comparing gasification and pyrolysis systems, since they do not consist of a single step, but rather a combination of steps, such as feedstock pre-processing, thermal separation (gas, liquid, char), high-grading and removal of contaminates from gas and liquids produced, and finally the combustion of products for the recovery of energy. Several of these steps may be combined and provided as a single unit by the supplier. The complete process is demonstrated in Figure 9.

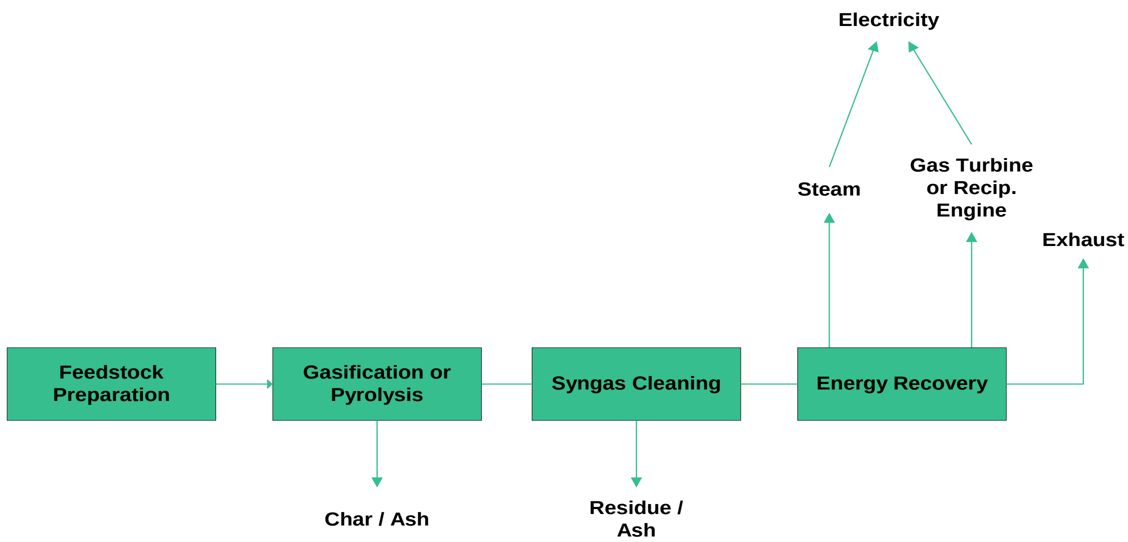


Figure 9: Process Flow for Conversion Technologies

3.5.2 True Gasification versus Staged Gasification

True gasification is when the recovered syngas is used as a gas after cleaning and refining, either as a feedstock for a chemical process, or as a fuel for a reciprocating engine or gas turbine. Generally, separate air pollution cleaning equipment is not required or very little is required when the gas is combusted, since the syngas is cleaned before combustion.

Staged gasification is when the syngas is combusted in a close-coupled second vessel without any additional cleaning. Air pollution control equipment is required after combustion, similar to conventional waste to energy combustion facilities. This is a much more forgiving process and there are reputable companies selling staged gasification technology, however, for the purpose of this study we will not be considering these since they differ very little from conventional combustion technologies which are not part of this study.

3.5.3 General Process Options

Gasification

Gasification is a thermal upgrading process in which the majority of the carbon in the waste is converted into the gaseous form (syngas), leaving an inert residue (char). The upgrading process involves the partial combustion of a portion of the fuel in the reactor with air, pure oxygen, and oxygen enriched air or by reaction with steam. The energy content of the waste is therefore transferred into the gas phase as chemical energy, which can be utilized to generate power. The components in syngas also make it potentially suitable for use as chemical feedstock.

Relatively high temperatures are employed: 900 to 1 100 °C with air and 1,000 to 1,400 °C with oxygen. Air gasification is the cheaper of the two options, but results in a relatively low energy gas, containing up to 60 % nitrogen, with a heating value of 4 to 6 MJ/Nm^3. Oxygen gasification gives a better quality gas of 10 to 18 MJ/Nm^3 but requires an oxygen supply, which increases complexity and cost. The advantages and disadvantages of using oxygen from an economic and technical perspective are complex and have to be considered on a project-by-project basis. As an example, the Enerkem gasification facility in

Edmonton is being run initially with air, but will be converted to an oxygen operation, since it was determined that the increased efficiency will cover the additional cost and increase revenues and profits.

In waste gasification the aim usually is to maximize the levels of CO and H_2 in the syngas, which increases the flexibility in utilizing the syngas as a source of energy and as chemical feedstock. Operating conditions such as temperature and pressure are manipulated to optimize the yield and composition of the syngas for its end use. Thus, there is a delicate balance, unique to each process, to maximize certain parameters while minimizing costs.

Plasma Gasification

A variation of gasification uses electrical energy in the form of a high temperature plasma (greater than 2,000 °C). The high temperature of the electric arc breaks down the organic parts of the waste into elemental gas. The main advantage of using plasma to heat the waste is that a clean syngas is created, mostly without the tars that have to be meticulously cleaned from the traditionally created syngas. Sometimes a plasma is used only for syngas cleaning after a more traditional gasification process, in order to save energy costs. The main drawback of plasma gasification is the high cost of input energy.

Pyrolysis

Pyrolysis is the thermal degradation of carbonaceous materials, typically at temperatures between 400°C and 600 °C either in the complete absence of oxygen, or with such a limited supply, that gasification does not occur to any appreciable extent. Such processes de-volatilize and decompose solid organic materials by heat; consequently, no combustion is possible. The products of pyrolysis always include gas, liquid and solid char with the relative proportions of each depending on the method of pyrolysis and the reaction parameters, such as temperature, heating rate, pressure and residence time. In general, lower temperatures produce more liquid product and high temperatures produce more syngas. When operated at 800 °C or greater, the main product is syngas.

The main difference between pyrolysis and gasification is how the energy is applied to the process in absence of oxygen. Typically, heat is applied indirectly through the walls of the reactor. Often this heat can be created by using some of the syngas produced in the process.

It should be noted that the site area requirements for a gasification facility can vary significantly, depending on the type of process used and the selection of the constituent elements of the system.

3.5.4 Feedstock Requirements

Gasification and pyrolysis systems typically require homogeneous feedstock necessitating front-end processing of MSW. The degree of pre-processing depends on the actual process. This significantly raises costs and requires energy inputs into the process. In most cases, extensive shredding and classification is required, sometimes combined with pelletization.

3.5.5 Process Outputs

Gasification creates a syngas and ash or slag. The quality of the syngas differs between processes, which is a result of the initial waste calorific value and the gasifying agent (air, steam or O_2) used. The syngas can be utilized for energy generation or as a chemical feedstock. Extraction of hydrogen from the syngas for fuel cells is one of the newer applications for syngas currently being researched. Some gasification processes produce a slag that may be reused as a civil engineering raw material, but the ash produced in many gasification processes is landfilled.

Pyrolysis processes produce char, oil and syngas. The syngas can be used in a similar way as the syngas from gasification. Pyrolysis oils are high in heavy organics and could be used as fuel oil or distilled to lighter fuels or chemical products. The char from some pyrolysis reactors has a high heating value and could be combusted to recuperate some of its energy value

Once cleaned, the syngas can be burned in an internal combustion engine, gas turbine, or in a boiler under excess-air conditions. Alternatively, the syngas can be used in chemical processes such as ethanol production. The syngas has an energy content about one fifth to one third that of natural gas.

There are numerous firms that offer gasification and pyrolysis systems for MSW, however, many are at a demonstration or pilot scale, and very few plants have actually been built. Therefore, actual operating experience and performance data is not readily available. Some information can be taken from the only large scale gasification plant in North America that is currently being commissioned in Edmonton by Enerkem. Other performance have been summarized by the International Solid Waste Association (ISWA) in a white paper from 2013, showing that in general, conversion technologies (pyrolysis/gasification) are less efficient in producing electricity per tonne of waste (that can be sold to the grid) than conventional mass burn combustion. Examples of vendors of technologies in this category include Enerkem (gasification, Enerkem process), Harvest International New Energy / Alter NRG (plasma gasification, Westinghouse Plasma Gasification process), Nexterra (gasification, Nexterra process – primarily wood and biosolids) and Powerhouse Energy (gasification, Pyromex process).

3.5.6 Gasification and Pyrolysis Costs

The Enerkem gasification facility in Edmonton is the only conversion technology in North America for which capital costs are known. For a capacity of 100,000 tonnes of feedstock per year year (or about 14 tonnes per hour), the capital costs are projected at $100 million for the plant itself, plus $40 million for converting feedstock into refuse derived fuel (RDF). This results in capital cost of about $1,400 per tonne of installed annual capacity.

It can be assumed that conversion technologies, like most waste processing facilties, benefit from economies of scale, similar to conventional WTE technologies. For conventional WTE plants, a wealth of statistics are available and were provided in the previous section. Comparison of conventional WTE with the Enerkem facility costs indicates that gasification technologies may cost about 20% more than conventional WTE plants.

Similar to capital costs, there are few reference facilities providing any kind of reliable costs. Given that conversion technologies and the associated RDF preparation steps are far more complex and costly than conventional WTE, it can be safely assumed that operating costs for gasification or pyrolysis would be higher, if not substantially higher than WTE costs. Examples of typical WTE operating costs, dependent on the size of the plant, are shown in the section on WTE. For gasification, $40 per tonne for feedstock preparation should be assumed and added to conventional WTE operations costs.

3.5.7 Advantages and Disadvantages of Gasification and Pyrolysis

Advantages of Gasification and Pyrolysis:

- Energy recovery from waste that would otherwise be landfilled
- One commercial scale facility being commissioned in Canada (All other full scale operating plants in Japan)
- Potentially lower emissions than from conventional WTE

- Can create a non-leachable residue suitable for other applications if combined with plasma heating

Disadvantages of Gasification and Pyrolysis:

- Very few commercial facilities worldwide and only one in Canada (still in commissioning)
- Needs substantial pre-processing
- Considerably more expensive than landfilling
- Lower energy recovery in practice than from conventional WTE
- Higher costs than conventional WTE
- Technologies are too new and may not be able to obtain financing
- Module sizes small enough for RDN may not be available or unproven
- High costs of new technology and smaller units may discourage development

4. RANKING OF TECHNOLOGIES USING SELECTION CRITERIA

4.1 Methodology for evaluation

The purpose of this evaluation is to compare the identified technology categories and rank them in accordance with their desirability for application in the RDN. The evaluation criteria are divided into individual sub-categories, and each of these sub-categories is assigned a score between 1 and 3. These scores can be modified and updated in the future or as priorities change.

All technologies under consideration are proven, commercially available technologies, with the exception of HTC, which is provided more for information and will not be ranked separately. Most of the technologies have the ability to recover energy from the residual waste and they all result in a reduction of waste going to landfill to varying degrees, while providing some GHG reduction benefits compared to landfilling.

Evaluation criteria are outlined in Table 6 below and applied in a separate evaluation spreadsheet to MWPF, RDF, AD, conventional combustion/WTE, and gasification/pyrolysis.

Table 6: Evaluation Criteria

Evaluation Criteria		Guidance on Scoring
Technology Performance	Technology maturity	1. Uncommon technology with only one or two commercially operating facilities 2. Common technology in some countries, but not in North America 3. Well established commercial technology in North America
	Suitability	1. Not appropriate for RDN residual waste stream 2. Can handle a portion of the waste stream, but does not result in maximum diversion 3. Can take all of the residual waste and process it for energy recovery and maximized diversion
	Energy recovery efficiency/ potential	1. Low energy production (up to 100kWh per tonne of feedstock) 2. Moderate energy recovery (100 to 250 kWh per tonne of feedstock) 3. High energy recovery (over 250 kWh per tonne of feedstock)
Technology Operations	Operational flexibility	1. Technology can accept only designed throughput, no flexibility for higher or lower volumes of feedstock 2. Moderate flexibility, can operate efficiently with plus/minus 20% of design capacity 3. Highly flexible, up to 50% more or less feedstock can be handled
	Feedstock quality requirements	1. Very strict quality requirements requiring extra processing 2. Moderate processing required 3. Can take waste with minimal processing
	Expected availability and reliability	1. Questionable reliance 2. Moderate reliance, availability of 80% expected 3. Proven High reliability and availability of 90% achievable
Environmental	GHG benefits	1. Low or no potential GHG benefits

Evaluation Criteria		Guidance on Scoring
		2. Moderate GHG benefits expected 3. Maximum GHG benefits
	Process ash or discards to landfill (per tonne input)	1. High (more than 20% by weight) 2. Medium (5% to 20% by weight) 3. Low (under 5% by weight)
	Total diversion potential of residual waste from landfill	1. Low (less than 50%) 2. Medium (50 to 80%) 3. High (over 80%)
Social	Public/social acceptance of potential odours, noise, traffic and visual impacts	1. Prevalent fears in community about odours or emissions 2. Could be accepted by community with some assurances 3. No concerns by community
	User convenience	1. Organics require careful separation at source, low tolerance for contamination 2. Organics separation improves efficiencies, process can tolerate some contamination 3. Separate collection of organics not required
	Siting and permitting	1. Difficult to site, lengthy permit process expected 2. Standard siting procedure, some opposition possible 3. Easy to site, general acceptance, simple permitting
Economics/ Affordability	Capital costs ($/tonne of installed annual capacity)	1. High, more than $800 per tonne 2. Medium, $400 - $799 per tonne 3. Low, under $400 per tonne
	Operating costs ($/tonne), excluding capital but including profits from product or energy sales	1. High, over $120 per tonne 2. Medium, $50 - $119 per tonne 3. Low, under $50 per tonne
	Markets for end products	1. Quality product moderate with questionable markets 2. Good market potential but not yet established 3. Firm markets already exist

4.2 Comparison and ranking of technologies

Each of the evaluation criteria is assigned a weighting. If the weighting is equal for each criterion (20%) then the following summary rating occurs: (see Table 7)

This table indicates that in order of preference, the technologies rank as follows:

1. Refuse derived fuel
2. Mixed waste processing facility
3. Anaerobic digestion
4. Conventional combustion
5. Gasification.

Table 7: Evaluation Scores with Equal Weighting

Evaluation Area	Allocated Weighting (%)	MIXED WASTE MRF	REFUSE DERIVED FUEL	ANAEROBIC DIGESTION	CONVENTIONAL COMBUSTION WTE	GASIFICATION
Technology Performance	20	2.00	3.00	2.33	3.00	2.67
Technology	20	2.67	2.67	2.00	2.33	1.33
Environmental	20	2.00	2.67	2.33	2.00	2.67
Social	20	2.67	2.33	2.67	2.00	2.33
Economics/Affordability	20	2.67	2.00	2.33	2.00	1.67
	100	2.40	2.53	2.33	2.27	2.13

If the weighting is changed to reflect priorities on technology and economics, the technology ranking remains the same: (see Table 8)

1. Refuse derived fuel
2. Mixed waste processing facility
3. Anaerobic digestion
4. Conventional combustion
5. Gasification

Table 8: Evaluation scores with emphasis on performance, environment and economics

Evaluation Area	Allocated Weighting (%)	MIXED WASTE MRF	REFUSE DERIVED FUEL	ANAEROBIC DIGESTION	CONVENTIONAL COMBUSTION WTE	GASIFICATION
Technology Performance	25	2.00	3.00	2.33	3.00	2.67
Technology	15	2.67	2.67	2.00	2.33	1.33
Environmental	10	2.00	2.67	2.33	2.00	2.67
Social	10	2.67	2.33	2.67	2.00	2.33
Economics/Affordability	40	2.67	2.00	2.33	2.00	1.67
	100	2.37	2.52	2.32	2.30	2.13

With an extreme priority on Environment and social (Table 9), the following ranking occurs:

1. Refuse derived fuel
2. Anaerobic digestion or Gasification
3. Mixed waste processing facility
4. Conventional combustion

Table 9: Evaluation scores with priorities on environment and costs

Evaluation Area	Allocated Weighting (%)	MIXED WASTE MRF	REFUSE DERIVED FUEL	ANAEROBIC DIGESTION	CONVENTIONAL COMBUSTION WTE	GASIFICATION
Technology Performance	10	2.00	3.00	2.33	3.00	2.67
Technology	10	2.67	2.67	2.00	2.33	1.33
Environmental	50	2.00	2.67	2.33	2.00	2.67
Social	20	2.67	2.33	2.67	2.00	2.33
Economics/Affordability	10	2.67	2.00	2.33	2.00	1.67
	100	2.27	2.57	2.37	2.13	2.37

From this analysis and sensitivity, it can be concluded that the preferred technology for the RDN is RDF, followed by MWPF, and AD. Conventional combustion and gasification are less preferred except when there is a high priority on environmental and social criteria (third sensitivity). In this case AD is rated higher than before because it makes such a clean energy, and gasification is rated highly because it almost eliminates the need for a landfill (but not quite).

5. SUMMARY AND CONCLUSIONS

5.1 Technical Summary

Primary outputs and performance from the various technologies described in this report are summarized in the following Table 10.

Table 10: Primary outputs of reviewed technologies

TECHNOLOGY/ PERFORMANCE	MIXED WASTE PROCESSING FACILITY	REFUSE DERIVED FUEL	ANAEROBIC DIGESTION	CONVENTIONAL COMBUSTION	GASIFICATION/ PYROLYSIS
Capital Costs, in $ per tonne of annual capacity (typical cost based on existing facilities)	$300	$260 fuel prep only, does not include burning	$610	$1,400	$1,700
O&M costs in $ per tonne processed (typical costs)	$30 to $50	$30 to $50 fluff only, no pellets	$110	$130	$170
Net energy recovered for sale in kWh per tonne of feedstock (typically achievable)	none	800 kWh of electricity or 2,600 kWh of heat, when used as fuel by others	170kWh of electricity for dry AD	700kWh of electricity	500kWh of electricity
Value of energy in $/ tonne of feedstock	$0	$0 to $50	$20	$70	$50
% of residual waste removed from landfilling (by weight)	50%	85% Up to 95% if used by cement kiln	45%	75%	70% with conventional gasification 95% with plasma

In the above cost and performance summary, the energy recovery is compared on the basis of electricity production for AD, conventional combustion and gasification. These processes can also produce heat, or heat combined with electricity, further enhancing their efficiency. In the case of AD, it is also possible to produce a pipeline quality bio-gas that can be used as fuel. Comparing on the basis of electricity, however, provides a good comparative view of how much energy can be recovered per tonne of input material. Mixed waste processing does not produce any energy.

In the case of RDF, the electricity values and heat values are theoretical only, since they will depend on where the fuel will ultimately be burned, what the efficiency of the boiler is, and whether they will be burned for heat, electricity, or both. The electricity value is if the RDF were burned in a dedicated power plant, and the heat is if it were used in an industrial boiler or at a cement kiln. The capital and operating costs of the RDF plant are only for fuel preparation and do not include the combustion component. Thus RDF is not truly comparable with conventional combustion, where the costs include the entire plant, including burning area, power production and air pollution control equipment.

5.2 Conclusions and Recommendations

From the evaluation in Section 4 it can be seen that RDF is the preferred technology. This is primarily because of its low cost, it high energy recovery, and its high diversion potential from landfill. It must be clearly understood that having established and secure long term markets for RDF are absolutely essential, otherwise the technology is not viable, and the RDF would have to be landfilled.

Mixed waste processing is the second choice because it is relatively low cost and environmentally friendly (no emissions). However, it only reduces waste by about 50% and there are reports in the literature about problems with finding uses for the compost contaminated with plastics and glass, and for recycled fibres and plastics that can also be contaminated and not always meet recycling industry standards.

AD has good environmental benefits, and is less costly than conventional combustion and gasification. However, its weak point is that it is limited to the processing of organics, which represent less than half of the total waste stream.

Conventional combustion is expensive for the size required in the RDN and suffers from a poor public image and potential siting and permitting issues. It does, however, reduce the amount of waste going to landfill by 75% by weight and more importantly, 90% by volume.

Gasification is even more expensive than conventional combustion, and is much less proven. If combined with plasma technology, it can reduce waste going to landfill by over 95%. However, the gasification facilities that exist appear to have a lower energy recovery efficiency than conventional combustion.

In conclusion, RDF is the preferred technology for processing waste residuals after recycling. It may be advantageous to combine RDF with AD as two separate streams working in parallel, thus achieving the greatest diversion from landfill combined with high environmental benefits. RDF is only preferred if markets for the final product are secure.