Application of Thermal Conversion Technologies to Demolition, Land Clearing and Construction (DLC) Waste at the Vancouver Landfill in Delta, British Columbia, Canada

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August 2015
Greenest City Scholars Program 2015

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Table of Contents

Table of Figures

Table of Tables

Executive Summary

Since 2010, the City of Vancouver has worked with University of British Columbia (UBC) graduate students to work on interesting and important sustainability projects to support the City of Vancouver's Greenest City 2020 Action Plan.

Canada, similar to other countries, is coping with an increase of Demolition, Land clearing and Construction (DLC) waste in its large cities including Vancouver. In addition, most countries desire to reduce dependence on landfills and waste exporting, increase the level of recycling and diversion from landfills to reach the "Zero Waste" target and recover energy/fuel from materials not feasibly recyclable for beneficial use. The City of Vancouver owns and operates the Vancouver Landfill, located in Delta, British Columbia, Canada.

This project aims to answer to the following questions:

1. What will the composition and quantity of DLC be in the future at the Vancouver Landfill (VLF)?
2. What is the chemical composition of the treated/painted wood waste at the VLF?
3. What conversion technologies are suitable for the wood waste at the VLF?

In this report, first the future composition and quantity of DLC will be predicted. Then, the chemistry of wood waste at the VLF will be identified. Finally, applicability of common thermal conversion technologies, more specifically, incineration, gasification and pyrolysis, will be assessed for wood waste treatment applicability at the VLF.

Future Composition and Quantity of DLC waste

The sources of DLC waste are mainly from demolition, renovation and new construction at 68%, 26% and 6% respectively. Generally, DLC loads at the Vancouver Landfill are from residential and commercial sources. The quantity of DLC might increase proportionally to population growth rate. Other factors that can cause changes in the magnitude of DLC waste are new bans and regulations as well as permitted or unpermitted activities of demolition, renovation and construction in the city.

According to the Integrated Solid Waste and Resource Management Plan (ISWRMP) established by Metro Vancouver, future DLC diversion goals are to reach from 55% to a minimum of 70% diversion by 2015 and then to 80% diversion by 2020. In addition, the Canada-wide voluntary industry initiative was introduced with a goal of eliminating DLC waste going to landfills across Canada by 2030. On January 2015, Metro Vancouver launched a six-month education program on the new Clean Wood Disposal Ban including residential, municipal, and commercial waste loads at all regional disposal facilities.

The future composition of the wood waste is predicted to change according to incoming bans and regulations. It is expected that the magnitude of the clean wood at the VLF will be close to zero before 2020. Thereafter, the main composition of DLC waste at the VLF will be plywood, treated/painted wood and other materials such as brick, plastic, paper, land clearing, textile, metals, etc.

If no reduction and diversion plan is designed in Metro Vancouver, the magnitude of DLC is predicted to experience an increase of nearly 40% by 2040 to nearly 200,000 tonnes compared to the figure in 2014.

The wood waste constitutes a large amount of DLC, approximately 70%, at the Vancouver Landfill (VLF). The wood waste consists of the clean wood, plywood and treated/painted wood. In 2014, the VLF received approximately 133,000 tonnes of DLC, of which 64,000 tonnes and 27,000 tonnes were clean wood waste and contaminated wood waste, respectively. Due to the larger amount of the wood waste at the VLF, the main focus of this project is on this type of material, in particular, contaminated wood waste.

Maximum and minimum amount of the wood waste coming to the VLF was approximately 28,000 tonnes and 126,000 tonnes between 1993 and 2014. It is predicted that without any reduction and diversion plans, the magnitude of the wood waste will be at an average 77,000 tonnes annually from 2015 to 2040. However, future wood waste will be still annually less than the figures before 2015 due to the new ban on the clean wood waste in Metro Vancouver. The ban on the clean wood waste will significantly influence on the magnitude of the wood waste at the VLF.

Chemical Composition of the Treated/Painted Wood Waste at the VLF

Contaminated wood waste at the VLF is mainly treated and painted. Although, their exact chemistry is unknown, it can be guessed according to the restrictions and bans imposed at the VLF such as *chemical preservatives, pentachlorophenols (PCP), creosote, Ammoniacal copper arsenate (ACA), or the like is prohibited to the VLF. Therefore, it is expected that the VLF's wood waste contains heavy metal contaminations, in particular Chromium, Copper and Arsenic (CCA) as well as formaldehyde from glue materials but not PCP or ACA types.*

CCA-treated wood waste is classified as hazardous in the European Union and subject to stringent requirements. There are currently no economically viable recycling alternatives for CCA-treated wood other than reuse, which simply postpones the time until it is disposed. Although, there may exist many diversion techniques such as chemical extraction, liquefaction, anaerobic digestion, etc. to treat the treated/painted wood waste, however, in this report, only thermal decomposition technologies such as incineration, gasification and pyrolysis will be assessed.

Thermal Conversion Technologies for the Wood Waste at the VLF

Thermal conversion technologies of wood waste, compared to landfilling, have the advantage of providing energy, chemicals and fuel and producing less ash/residues for disposal. However, the environmental concerns associated with this type of materials and their possible impacts on thermal processes and by-products should be recognized and addressed. The author could not find a successful commercialized technology to treat a large amount of the treated/painted wood waste. Benefits and capital costs of the three conversion technologies, niche incineration, gasification and pyrolysis, are summarized in Table E. 1.

Table E. 1 Summary of Advantages, Disadvantages and Capital Costs of Conversion Technologies for Wood Waste at the VLF (100,000 tonnes per year)

Technology	Advantages	Disadvantages	Capital Costs million
Niche Incineration	- Less complexity in the process - No feedstock preparation is required	- High emissions - Fixed, inflexible to a change of mass or volume of the feedstock - Low energy recovery efficiency	$78.5
Gasification	-Moderate to low emissions - Higher energy recovery efficiency - Modular, flexible to a change of mass or volume of the feedstock	- Complications in the process of treated/painted wood waste - High level of toxicity of residues	$101.5
Pyrolysis	- Low emissions - Higher energy recovery efficiency - Modular, flexible to a change of mass or volume of the feedstock	- Complications in the process of treated/painted wood waste - High level of toxicity of residues	$145.5

Applicability of Incineration Technology for the Wood Waste at the VLF

There are facilities such as cement kilns, pulp mills and WTE facilities utilizing a small portion of plywood and treated/painted wood mixed with their normal feedstock such as clean wood, MSW, etc. The main issue related to utilizing a large amount of contaminated wood in their process is that the magnitude of heavy metals released in emissions or retained in ash/residue is unknown. Furthermore, it can cause complexity and difficultly in the combustion process, for instance, combustion of compounds containing atoms such as lead, arsenic, and phosphorous should be considered poisons for most oxidation catalysts (air pollution control system) and if it is not controlled, the catalyst replacement cost can be expensive.

Incineration leads to the release of dioxins and tetra-arsenic hexoxide that requires extensive gas cleaning equipment, since they are very difficult to capture. Furthermore, the arsenic trioxide dust collected in filters still poses problems with respect to occupational health, therefore, the bottom ash needs special handling and treatment.

The main advantage of incineration technology over gasification and pyrolysis is that the feedstock is not required for a pre-processing stage to reduce the size and moisture content as well as remove metals from the wood waste. Gasification and pyrolysis are very sensitive to the size, material type and moisture content. In addition, incineration technology is mature, less expensive and less complicated than gasification and pyrolysis technology.

Applicability of Gasification Technology for the Wood Waste at the VLF

Gasification is more mature than pyrolysis; however, it is not yet proven, even at the pilot scale for this specific input (treated/painted wood waste). Generally, gasification generates less GHG emissions than incineration. The incineration process requires excess volumes of air, which allows contaminants to form, whereas gasification requires very little air. Over 90% of particulates from gasification system can be captured before final syngas combustion. The process is very sensitive to the quality of the feedstock. The quality of the syngas, which is a product of the gasification process, also depends on the quality of the feedstock. Moreover, the critical point is difficulty in transforming all arsenic to the vapor metallic form and then capturing the vapors by appropriate gas cleaning equipment.

Plasma gasification may provide this condition, however, the technology is very expensive and immature. The author thinks that this technology may bring a solution in the future, see “Aside: Interesting Technologies” part in Appendix A 2.

Applicability of Pyrolysis Technology for the Wood Waste at the VLF

Pyrolysis has been proposed a solution to the treatment of CCA-treated wood under certain conditions. Helsen et al., at the University of Leuven in Belgium, examined that *during the pyrolysis process of the CCA-treated wood waste under certain conditions such as at temperature of 370°C or less, residence time of 20 minutes and pressure of 5 bar, most of heavy metals can be captured from the solid or liquid products of the process with minimal air emissions. However, there is no additional advantage of pyrolysis over the other thermal technologies that can be found except the elimination of dioxins and furans formation and possibly easier metal recovery, however, more research is needed to prove this hypothesis.*

Kakitani et al., at Kyoto University in Japan, confirmed that the CCA elements in the pyrolysis residue were highly stable against leaching or extracting; however, the arsenic trioxide formed in the pyrolysis residue is more toxic than arsenic pentoxide (unstable inorganic compound of arsenic). Thus, *landfilling of pyrolysis residues is also a poor solution because of their high levels of toxicity.*

Conclusions

Overall, due to the a combination of expense, maturity of treatment technology and uncertain volumes, it was found that none of the three technologies seemed appropriate for the Vancouver Landfill at this time. The next steps recommended to the City of Vancouver are as follows:

- In the short term, focus on co-combustion of clean and contaminated wood streams acknowledging that CCA-treated wood waste has not been treated separately. As a result of this focus, it is recommended that attention is paid to air emissions compliance; more information can be found in Appendix 15.
- In the long term, keep encouraging recycling solutions in the marketplace and investigate policies that can remove CCA-treated wood in a cost-effective way.
- Keep apprised of developments of solvent extracting processes/technologies to essentially clean the wood.
- Keep apprised of pyrolysis or plasma arc gasification technology developments that may be applicable but are currently immature and expensive as well as an appropriate treatment method must be determined for the process residues.

Acknowledgements

I would like to specially thank Faisal Mirza, the Senior Manager of Operational Improvements at the City of Vancouver, for all his ongoing support and excellent guidance in completing this report. Special thanks go to Scott Stanners from Aeon Energy Solutions, Paul Beauchemin from Envirochem, and Randy Gue from Better Planet Strategies, for providing valuable information for me and their continuous support, which was exceptionally encouraging.

I am grateful to Katie Dolling from UBC and Jennifer Wahl from City of Vancouver for their great support from the beginning to the end of this project. Sincere thanks to following professionals and experts who shared their valuable information with me:

Alan Martin, Clean Energy Consulting
Alexandre Hebert, BCIT
Bahman Ghiasi, PhD Candidate at UBC
Chris Allan, Metro Vancouver
Chris Underwood, City of Vancouver
Cornelius Suchy, Canadian Biomass Energy Research Ltd
Craig Edwards, City of Vancouver
Esther Bérubé, Metro Vancouver
Darcy Quinn, Nexterra
George Twarog, City of Vancouver
Francis J. Ries, Metro Vancouver
Hugo Haley, City of Vancouver
Jerry Sobejko, City of Vancouver
Matthew Grant, Enerkem
Nicole Steglich, City of Vancouver
Philip Scalzo, Biomass Energy Enhancements
Robert Costanzo, City of Surrey
Shahab Sokhansanj, Professor at UBC
Tim Weaver, Envirochem

Glossary of Acronyms

ACA: Ammoniacal copper arsenate
APC: Air Pollution Control
BFB: Bubbling Fluidized Bed Gasifier
CFB: Circulating Fluidized Bed Gasifier
CCA: Chromium Copper Arsenic
CHP: Combined Heat and Power plants
CRI: Construction Resources Initiative
DLC: Demolition, Land Clearing and Construction Waste/Construction, Renovation and Demolition ("CRD") Waste
Dual FB: Dual Fluidized Bed Gasifier
EF: Entrained Flow Gasifier
ELVs: Emission Limit Values
EN: Environment Canada
EPA: Environment Protection Agency
EPR: Extended Producer Responsibility
GHG emission: Greenhouse Gas emission
IRR: Internal Rate of Return
ISWRMP: Integrated Solid Waste and Resource Management Plan
MDF: Medium-density fibreboard
MSW: Municipal Solid Waste
NOx: Nitrogen Oxides
NPV: Net Present Value
ODT: Oven Dried Tonnes
PCDD: Poly-Chlorodibenzo-para-Dioxins
PCDF: Poly-Chlorodibenzo-Furans
PCP: penta-chloro-phenols
PEF: Processed Engineered Fuel
PM: Particulate Matter
RDF (or SRF): Refuse Derived Fuel (or solid recovered fuel/ specified recovered) fuel
SCR: Selective Catalytic Reduction
SNCR: Selective Non-catalytic Reduction
SOx: Sulphur Oxides
TDF: Tire Derived Fuel
TOC: Total Organic Compounds
VLF: Vancouver Landfill
VOCs: Volatile organic compounds
WID: Waste Incineration Directive
WTE: Waste-to-Energy

Introduction

The hierarchy of waste management starts with reducing waste generation as a first step, the reuse of materials of good quality and recycling the rest. Figure 1 illustrates the hierarchy of waste management. While increasing reuse and recycling waste is essential, sustainable alternatives should be used to handle the non-recyclable waste that has been and will be generated in the future. Energy recovery is one solution to dealing with waste streams at Waste-To-Energy (WTE) facilities. Fortunately, there has been great progress in sustainable conversion of waste to energy around the world. Incineration is a mature technology with many successful large-scale facilities operating globally. Some other technologies such as gasification and pyrolysis have not yet been commercialized but there are several pilot scale facilities trying to scale up while dealing with many issues and challenges.

Refuse Derived Fuel (RDF) refers to the segregated high calorific fraction of processed Municipal Solid Waste (MSW). The organic fraction (including paper) of RDF is considered to be a bio-fuel and renewable, therefore, the carbon dioxide released from burning this fraction has a net zero greenhouse gas (GHG) emission effect. However, the overall GHG emissions from RDF are not zero. This is due to carbon emissions from burning the plastics fraction left in RDF. RDF is mainly considered as a substitute to coal in high-energy industrial processes such as power generation, cement making, steel manufacturing, etc. In such processes, substitution of RDF can enhance economic performance while having less environmental impacts.

Due to technical and economic limitations of recycling, product design, inadequate sorting and screening, lack of sufficient markets and immature conversion technologies, some waste has to be landfilled. Sanitary landfills and even unsanitary landfills in most developing countries are the last fate of waste (Earth Engineering Center, Waste-to-Energy Research & Technology Council, Coloumbia University, 2012).

Zero Waste is the recent goal that many industrialized countries are trying to achieve. This goal requires four important key elements in waste management, which are: reduce, reuse, recycle and recover to eliminate a need of waste landfill.

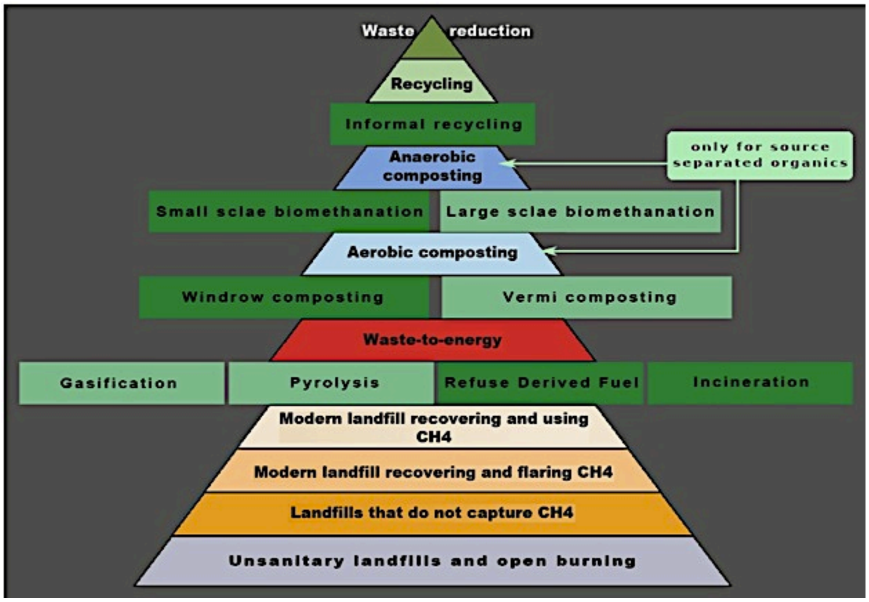


Figure 1 Hierarchy of Waste Management (Earth Engineering Center, Waste-to-Energy Research & Technology Council, Coloumbia University, 2012)

In this project, the main focus is on energy recovery techniques for Demolition, Land Clearing and Construction (DLC) Waste. DLC waste includes mainly wood and soft construction waste. Wood waste, for the purpose of this report, includes clean wood, plywood and painted and treated wood waste. Clean Wood is defined, as solid wood, lumber, and pallets that are unpainted, unstained, untreated, and free of glue. The wood may be pierced with nails or other metal fasteners, such as screws and staples.

Wood waste mainly comes from forestry activities, wood industry, construction and demolition sites and old furniture from households. Figure 2 illustrates different categories of wood waste. In this study, a focus is made on wood wastes from construction and demolition activities.

The City of Vancouver has set Greenest City 2020 Action Plan targets towards a more prosperous, healthy, and resilient future for Vancouver in becoming the greenest city in the world by 2020. The goals are as follows:

- Goal 1: Green Economy
- *Goal 2: Climate Leadership*
- Goal 3: Green Buildings

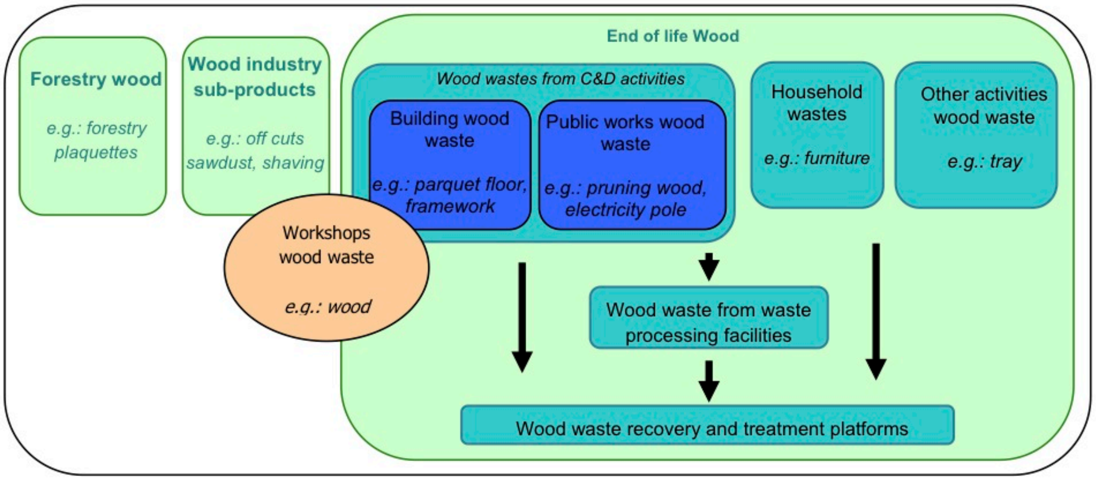


Figure 2 Wood Waste Origins (Rizzo, 2010)

- Goal 4: Green Transportation
- *Goal 5: Zero Waste*
- Goal 6: Access to Nature
- Goal 7: Lighter Footprint
- Goal 8: Clean Water
- Goal 9: Clean Air
- Goal 10: Local Food (City of Vancouver, 2011)

This project is focused on Goal 2 and Goal 5, which are reducing GHG emissions by 33% from 2007 levels and reducing Solid Waste going to the landfill or incinerator by 50% from 2008 levels, respectively.

Overall, some progress has been made across Canada; the sector has increased the volume of DLC diverted from disposal by over 30% in a 10-year period, mainly due to a variety of municipal outreach initiatives to the private sector.In Metro Vancouver, the rate of DLC waste diversion reached 55% in 2010. The 2010 Integrated Solid Waste and Resource Management Plan (ISWRMP) established future diversion goals to reach from 55% to a minimum of 70% diversion by 2015 and then to 80% diversion by 2020. It has been found that demolition, landfill clearing and construction waste contributes considerably to the total volume of waste being disposed at the Vancouver Landfill (City of Vancouver, 2015). Therefore, DLC waste can be considered as a good potential opportunity to achieve the Zero Waste goal.

Total weight of DLC in Metro Vancouver in 2011 was 278,772 tonnes, of which 69% transferred to the Vancouver Landfill and the rest to the Ecowaste Landfill located in Richmond, BC. Quantity of DLC waste from Vancouver Landfill and Ecowaste Landfill is summarized in a table enclosed in Appendix 3. The City of Vancouver arranged a tour for the staff and the author to the Ecowaste Landfill on June 12, 2015. Ecowaste does not have any specific procedures for its contaminated wood waste other than disposal. Figure 3 shows Ecowaste wood waste at its landfill.

Table 1 Quantity of DLC Waste Diverted from Landfill 2000-2010 Canada-wide

	2000	2002	2004	2006	2008	2010	Long Term Change (2000 to 2010)	% Change (2000 to 2010)
Tonnes	494,683	645,931	848,197	715,364	720,076	653,255	+158,572	+32.06

Total DLC produced in Metro Vancouver was approximately 280,000 tonnes in 2011 of which, nearly 26% was unpainted wood waste and 8% treated/painted wood waste. Figure 4 and

Figure 3 Wood Waste at the Ecowaste Landfill, Richmond, BC (Ecowaste, 2014)

Figure 5 show the composition of Metro Vancouver's DLC waste categorized into the type of materials in 2011 by volume and weight, respectively. As can be seen, the main type of materials in the Metro Vancouver's DLC waste was wood waste constituting approximately 57% and 54% by volume and weight, respectively

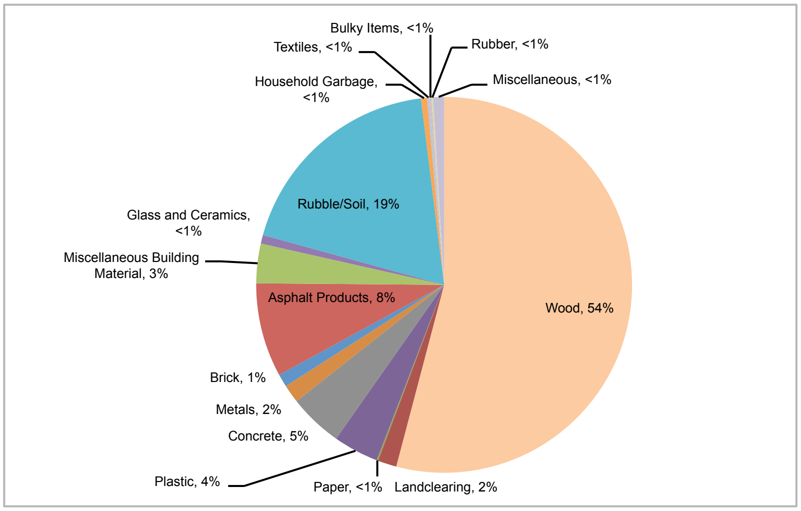


Figure 4 Metro Vancouver's DLC Waste Composition by Volume (AET Consultants, 2011)

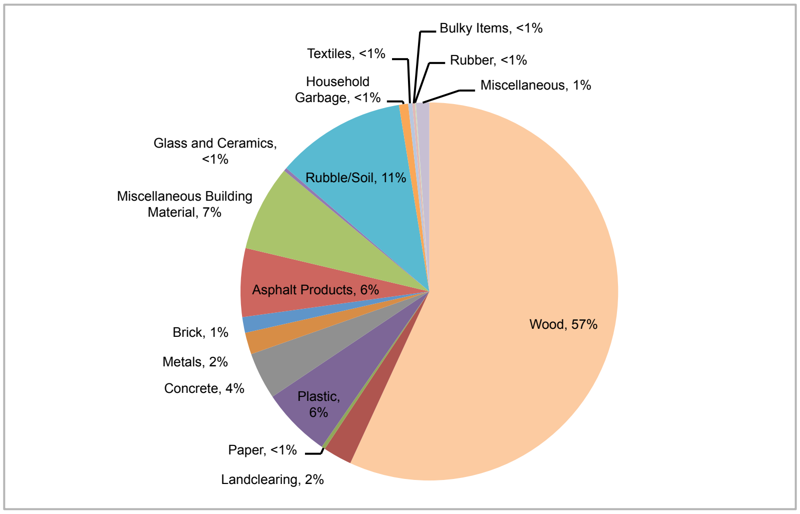


Figure 5 Metro Vancouver's DLC Waste Composition by Weight (AET Consultants, 2011)

DLC Waste at the Vancouver Landfill (VLF)

Wood materials account for the largest fraction in the DLC stream at approximately 66% and 61% by volume and weight, respectively, as shown in Figure 6 and Figure 7 (according to 2011 records). Therefore, the main focus of the City of Vancouver is on recovery of wood waste by reusing, recycling and converting to biofuel or energy.

Clean wood waste, which does not contain any hazardous materials, can be used either for agriculture uses, animal bedding, production of fiberboard and landscaping or as a biomass fuel in pulp and paper plants, cement plants and WTE facilities. Clean wood is ground at the Vancouver Landfill and used in place of wood fines (<3”×3” or demo hog). Concrete, bricks and gravel materials are used as cover materials, fill or road base.

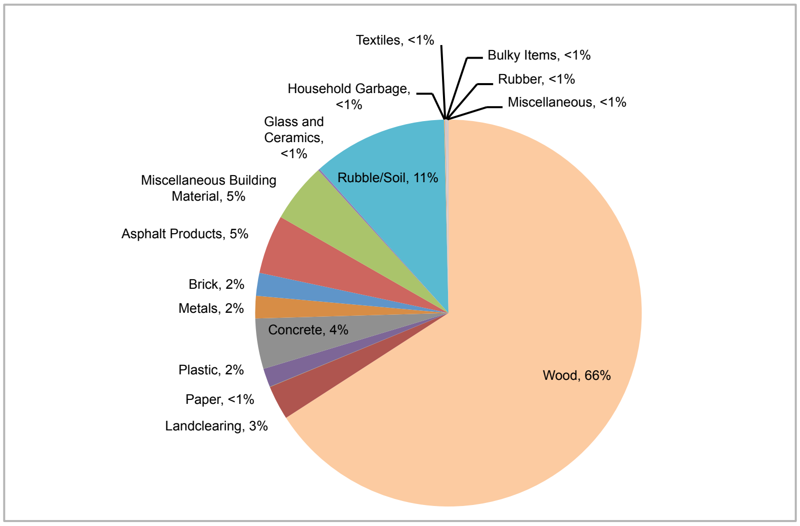


Figure 6 Vancouver Landfill’s DLC Waste Composition by Volume (AET Consultants, 2011)

Treated/painted wood waste was found to be challenging to recover because they are usually contaminated with chemical and toxic materials. They can neither be used as a fuel in the WTE facilities nor used for other applications such as agriculture, landscape chips, animal bedding and garden mulches. There are some facilities that recover energy from railway ties primarily treated with creosote but regulations and emission control standards often restrict this material for use as a fuel.

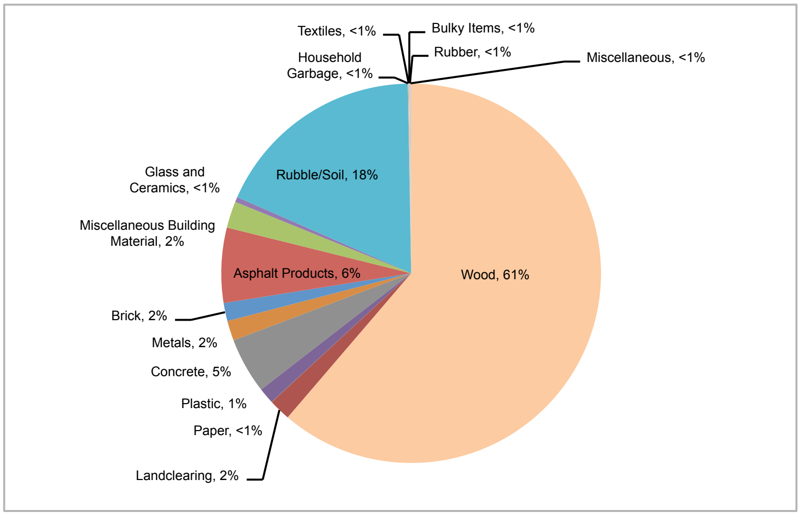


Figure 7 Vancouver Landfill's DLC Waste Composition by Weight (AET Consultants, 2011)

The Enerkem Westbury demonstration facility in Quebec is an example. The feedstock of this facility is 60 tonnes per day of telephone poles and railway ties. The products are syngas, methanol and ethanol but not electricity (Marion County RFP, 2009). However, most facilities that use biomass or MSW as a fuel are either not permitted to use painted and treated wood waste or do not want to accept it as a fuel due to the complexity of chemical compositions.

Table 2 Summary of Current Biomass Fuel Demand (Babcock & Gue, 2014)

Facility	Estimated Tonnage Demand per Year	Quality Criteria
Howe Sound Pulp and Paper	250,000+	All wood acceptable except treated wood*, small proportion of adhesives allowed, no metals, no plastic
UBC Gasification Plant	30,000	Clean wood only, no adhesives, paints or treated wood, no metals, no plastics
Kruger Products	25,000	All wood acceptable except treated wood*, small proportion of adhesives allowed, no metals, no plastic
Lafarge Cement Plant	50,000	All wood types acceptable except treated wood, plastics desired
Lehigh Cement Plant	40,000	All wood types accepted including small proportions of creosote treated woods, plastics desired

***** Treated includes wood that contains creosote, CCA or PCP***

The price of woody biomass depends on the heat value of the fuel, the customer's specifications and supply and demand. Moisture content of the wood waste ranges from 40% to 60%. The moisture content of the VLF's wood waste is assumed to be around 25-30%. Table 2 presents the facilities demanding wood waste. As can be seen, Lehigh Cement Plant is the only facility that accepts treated wood waste containing a small portion of Pentachlorophenol (PCP) and Chromium, Copper & Arsenic (CCA) and creosote (Babcock & Gue, 2014).

Current Bans and Regulations Imposed on DLC Waste and Wood Waste

Canada-wide and BC bans and regulations imposed on DLC waste are as follows:

1. Canada-wide voluntary industry initiative: DLC diversion targets
2. Canada-wide voluntary industry initiative: deconstruction standards
3. Federal Government
4. Province of BC and Metro Vancouver

Canada-wide voluntary industry initiative: Construction Resources Initiative (CRI) Council is a non-profit industry group with a goal of eliminating DLC waste going to landfills across Canada by 2030. This initiative aims to encourage all decision makers on policy, the building and product design, construction practices, purchasing and operations and maintenance, to base their decisions on resource efficiency and reduce DLC waste to landfill with the following targets: 35% diversion by 2015; 50% by 2020; 75% by 2025, and 100% by 2030. Although government policies can target the end of the lifecycle and restrict access to landfills, to complement these regulations or policies, CRI supports strong industry actions that provide a cost-effective means to easily source-separate and reuse or recycle on-site (Giroux , 2014).

Canada-wide voluntary industry initiative: The Canadian Standards Association has developed a "Deconstruction" standard for existing buildings (CSA Z783). This standard applying to existing buildings specifies minimum requirements for procedures related to the deconstruction of buildings at the end of life. However, this Standard does not address procedures for assessing the suitability of deconstruction components or materials for reuse (Giroux , 2014).

Federal Government: Canada Mortgage and Housing Corporation (CMHC) have provided guidance on DLC diversion best practices. Public Works and Government Services Canada together with Environment Canada have also provided a guidance document for environmentally-responsible DLC practices. Environment Canada is undertaking a comprehensive study of DLC waste across Canada and the results are anticipated in 2015. This work will quantify DLC waste that is currently generated, recovered, and disposed and identify recycling and disposal methods and facilities by province/territory (Giroux , 2014).

As of 2013, there are still no mandatory provincial or territorial diversion programs for DLC waste. However, Table 3 indicates which jurisdictions are starting to implement new DLC waste initiatives (Giroux , 2014).

Table 3 Overview of New DLC Diversion Initiatives Jurisdiction-wide (Giroux , 2014)

Canada-wide	BC	AB	SK	MB	ON	QC	PE	NB	NS	NL	NU	NT	YT
✓ Industry outreach Guidance	✓ 2017 EPR	-	-	✓ Strategy	-	✓ 2015 Targets	-	-	✓ Diversion credits	-	-	-	-

Province of BC and Metro Vancouver

In BC, Extended Producer Responsibility (EPR) is an environmental policy approach in which the producer's responsibility for reducing environmental impact and managing the product is extended across the whole life cycle of the product, from selection of materials and design to its end-of-life. EPR shifts responsibility upstream in the product life cycle to the producer, and away from local governments and taxpayers. This approach requires producers to collect and recycle leftover or used products as well as to redesign the products to make them less harmful to the environment and easier to recycle. By utilizing BC's EPR programs, it is possible to reduce materials going to the landfill (Regional District of Bulkley-Nechako, 2012). Summary of regulations, standards or guidelines applicable to solid waste disposal in BC, can be found in Appendix 4.

Some certain criteria defined by Metro Vancouver to accept the demolition waste at the Vancouver Landfill are:

- Loads must be a minimum of 80% wood (City of Vancouver, 2013).
- Soft construction materials such as plastic, carpet, insulation, etc. must be removed prior to delivery of the load (City of Vancouver, 2013).
- Residual quantities of soft construction wastes shall not exceed 2% of the load by volume (City of Vancouver, 2013).
- Recyclables such as concrete, metal (white goods are prohibited), corrugated cardboard

and tires shall be removed to the extent practical (City of Vancouver, 2013).

- Yard trimmings and land clearing waste (unless shredded) are only acceptable in small quantities (City of Vancouver, 2013).
- Roofing materials are acceptable in the loads as long as the other load requirements are met (City of Vancouver, 2013).
- Any soil mixed in with the Demolition Material must meet all requirements for Urban Park use (City of Vancouver, 2013).
- Any wood, which contains chemical preservatives, pentachlorophenols (PCP), creosote or the like, is prohibited (City of Vancouver, 2013).
- Hazardous Wastes as defined in the Environmental Management Act, household garbage, buckets, drums (or any other liquid container) and gypsum, asbestos, putrescible material are prohibited (City of Vancouver, 2013).
- Loads must also not contain any of the materials described in the Landfill's Prohibited Materials list (City of Vancouver, 2013).
- A surcharge of 50% is applied to the tipping fee for waste loads found to contain 5% or more by volume of banned materials (Metro Vancouver).
- On January 1, 2015, Metro Vancouver launched a six-month education program on the new Clean Wood Disposal Ban at all Regional Facilities including residential, municipal, and commercial garbage loads at regional disposal facilities. Come July 1, 2015, a 50% surcharge will be applied to all loads of garbage containing clean wood if the quantity of wood exceeds 10% of the garbage load (Metro Vancouver).
- DLC waste started to be separately recorded from excavation material because it has been accepted for a fee. The construction and demolition disposal rate is $60.00 per tonne as of today, July 2015 (City of Vancouver, 2013).

In addition, Ammoniacal Copper Arsenate (ACA), which is a waterborne salt-type preservative with similar characteristics to CCA, has some limited use in Canada (Canada Plan Service, 2010).

As mentioned previously, Metro Vancouver’s 2010 Integrated Solid Waste and Resource Management Plan (“ISWRMP”) established future diversion goals to reach from 55% to a minimum of 70% diversion by 2015 and then to 80% diversion by 2020.

The main target according to the Metro Vancouver's ISWRMP is to achieve a minimum of 70% waste diversion by 2015. Metro Vancouver has so far achieved a diversion rate of almost 70% by recycling 900,000 tonnes out of 1.3 million tonnes of DLC waste generated annually. Diversion of an additional 155,000 tonnes of DLC waste has been set to level by 2015, with the additional diversion targeted primarily at the wood waste. According to the new Clean Wood Disposal ban introduced by Metro Vancouver, a 50% penalty will apply to garbage loads containing over 10% clean wood. Clean wood waste is defined as unpainted, glue-free and chemical-free, wood waste that can be recycled into compost, fuel, or wood products. This new ban has increased clean wood recycling at Metro Vancouver facilities compared to last year (Sperling Hansen Associates, 2014).

Increasing the processing capacity of blended materials and establishing collection facilities for source-separated wood are effective strategies to achieve the diversion target. Metro Vancouver will continue to monitor markets for clean and treated wood waste. A feasibility study was conducted by FP Innovations for Metro Vancouver in 2012 to evaluate alternatives to convert the wood waste into value added products and biofuel. The study concluded that the condition of the majority of wood waste delivered to disposal, transfer and processing facilities to Metro Vancouver is suitable for fuel, but not for reuse applications. The City of Vancouver has initiatives to encourage construction of LEED buildings as well as deconstruction practices that will extract greater value from wood (Sperling Hansen Associates, 2014).

A number of industries particularly pulp mills and cement kilns require intensive energy. Pulp mills usually provide their energy from burning saw dust and hog fuel contained of low value shredded wood waste and bark. Cement manufacturers typically use coal to accommodate their energy as well as Tire Derived Fuel ("TDF") (Sperling Hansen Associates, 2014).

However, with an expensive carbon tax on coal, oil and natural gas in BC, industries have been motivated to find resources of green energy such as Processed Engineered Fuel ("PEF") to displace carbon intensive fuels. In close proximity to Metro Vancouver, the largest consumers of PEF are Howe Sound Pulp and Paper, Lafarge Cement in Richmond and Lehigh Cement in Delta (Sperling Hansen Associates, 2014).

The Problems

The population growth rate in Metro Vancouver has been estimated approximately 1.7% from 2006 to 2021 annually. Thereafter, Metro Vancouver may expect a total increase of approximately 12.6% in population by 2031 and 8.7% from 2031 to 2041. The percentage of population growth reached a peak at 37.2% in Surrey between 2006 and 2012. This rate in Vancouver is 12.9%. This fact can indirectly indicate that more construction, renovation and deconstruction is expected to occur accordingly. Between 2006 and 2012, the average number of housing construction and demolition was 15,986 and 2,522 respectively (Babcock & Gue, 2014). Moreover, DLC waste is expected to change according to upcoming bans, regulations action plan goals and market drivers.

Vancouver Landfill receives 160,000 to 185,000 tonnes of DLC waste annually, approximately 60% of which is wood waste. Clean wood is now banned for disposal according to the regulation introduced by Metro Vancouver in July 2015. The rest of DLC waste, including treated and painted wood, plywood, concrete, rubber/soil and other materials that are not suitable for recycling, are disposed of. In 2014, approximately 137,000 tonnes of DLC waste were transferred to the VLF and the residuals were landfilled in what is known as the “Western 40” located at the west end of the VLF, see Appendix 5.

The main issues that should be taken into account are:

Firstly, the Western 40 is expected to close by 2018 or earlier and the concern is there may be no other designated place for DLC waste disposal in the area.

Secondly, composition of DLC waste transferring to the VLF is expected to change with upcoming bans and regulatory changes in construction and market drivers. Upcoming bans and regulations will be designed to reach the Metro Vancouver’s ISWRMP goal, DLC waste and mainly the wood waste should be diverted to 80% by 2020.

Thirdly, the type of wood waste coming to the VLF is a problem. This wood waste is mainly contaminated; therefore, special conversion technologies should be applied to deal with them.

To evaluate available options to deal with the above problems, following questions will be answered in this report:

1. What will the composition and quantity of wood waste be in the future at the VLF?
2. What is the chemical composition of the treated and painted wood waste at the VLF?
3. What conversion technologies are suitable for the wood waste at the VLF?

Objectives, Scope and Methodology

In this project, future composition of DLC waste will be predicted and characterized. Predicting future composition of DLC waste transferring to the VLF as well as understanding the type of contamination in the wood waste can determine the most suitable conversion technologies. Also research will be carried out to determine innovative technologies to convert DLC waste to energy and useful co-products and eliminate a need for further landfill air space. A current conversion technology used in many countries is incineration. However, this project also introduces more sustainable conversion technologies that respect the Greenest City Action Plan goals. Assessment will be conducted to identify what services a facility at the VLF would meet and the feasibility of a DLC conversion facility located at VLF and within the City of Vancouver.

A comparison will be done between incineration and other technologies such as gasification being used around the world. The result of this comparison will determine their applicability to the VLF incoming material.

A structured search was undertaken to gather information on technology options using a wide range of sources. This included:

- Review of VanDocs documents (the City of Vancouver's database) and reports
- Review of Internet sources
- Review of recommended reports on technologies, jurisdictions and financial analysis
- Tours to the Vancouver Landfill, Eco-Waste, Recycling Alternative, Nexterra Plant at UBC
- Interview with professionals and experts in technology supplier and user sectors; the list of companies and contact information that were interviewed by the author, can be found in Appendix 19.
- Discussion with technology providers
- Journals, conferences and events

As of the writing of this report, the author was in the process of physically testing samples of the DLC in cooperation with UBC, however, the results were unable to be incorporated due to the August 14th, 2015 deadline for this report.

Project Assumptions

The following factors were considered in the evaluation:

- Throughput capacity
- Quantification of energy generation
- Scalability of the system
- Environmental and health impacts/mitigations/residuals management
- DLC tipping fees
- Capital and operational costs
- Financing options including private/public partnership potential

Energy Generation of WTE Facility with Combined Heat and Power (CHP)

It is important to stress that for the three conversion technologies assessed in this report, cogeneration means to improve energy recovery, especially for small-scale plants. Cogeneration is the simultaneous production of heat and electricity, commonly called combined heat and power (CHP), from a single fuel. Traditionally, a steam turbine is used to produce electricity, although a wood gasification/internal combustion unit can also be a cogeneration unit.

To avoid complications and provide consistent comparison between the three thermal technologies investigated in this study, combination of the technologies with Combined Heat and Power (CHP) is evaluated. Therefore, no research was conducted on other products of gasification and pyrolysis processes. However, there are two other main reasons to consider combination of pyrolysis and CHP; Firstly, the chemistry of the VLF's wood waste and its by-products of the pyrolysis process is unknown, therefore, it may not be possible to produce clean products from the contaminated wood waste in the end. Secondly, there was not reliable information on the possible markets for the products in BC. The lack of standards and regulations for the by-products of the pyrolysis as well as availability of other low price fuels such as natural gas make it very difficult to find a reliable market and price for the products.

Total efficiency of the combined processes is assumed as follows:

- Incineration with CHP up to 50%
- Gasification with CHP up to 60%

- Pyrolysis with CHP up to 65%

Financial Parameters

The following assumptions were made in the development of the project concept and the ensuing financial analysis:

- In all financial analysis on the thermal conversion technologies for the painted and treated wood waste at the VLF, it is assumed that incineration, gasification and pyrolysis technologies can meet all Canadian emissions standards and syngas scrubbing systems and residue treatments are well proven.

- The output of the power plant will be sold to BC Hydro. BC Hydro has defined the range of the electricity potential ($/MWh) for the wood waste based biomass and steps to obtain an electricity generation for Waste-to-Energy facilities, see Appendix 2. The resource options costs are shown as the Unit Energy Cost (UEC) at point of interconnection (POI) for different transmission regions. The costs range from $122-141/MWh. An average cost of $136/MWh ($131.5 at $2013) is assumed for the electricity sale to BC Hydro during the entire life of the facility.

- In another report prepared by ICF International, it was assumed that Metro Vancouver sells its electricity to BC Hydro at a rate of $100/MWh for the first 15 years of operations and further assuming this rate were renegotiated thereafter to $43/MWh (the rate recently negotiated with the existing Burnaby WTE facility) (ICF International, 2014).

The assumptions related to capital cost estimates, O&M cost estimates and revenue estimates are as follows:

- The facility owned and operated by the City of Vancouver, therefore, financing is taken as 100% grant (zero debt & interest) and income tax is zero.
- The life of the plant will be 25 years
- DLC tipping fee is $60 per tonne
- Linear depreciation during the life of the plant
- Electricity rate $136/MWh

- Generally, construction and commission of the facility takes four to five years for all three thermal conversion technologies. If we assume that the construction of the facility will start in 2015, the facility will be ready to run by 2020.

It is also necessary to mention that the costs presented in this report cannot be relied upon because of the following reasons:

- Different sources estimated different costs. For example for incineration technology, there were many experimental formulas to calculate the costs. For example, the capital cost ranges from $60 M to $300 M. To avoid confusion, just one source of information was chosen to obtain all cost estimations for the three technologies.
- For example, capital costs for pyrolysis technology was very unclear because the facilities are still in a pilot scale.
- The cost of air and ash pollution control system suitable is unclear due to uncertainty on chemistry of the wood waste at the VLF.
- The cost breakdowns were unclear; therefore, it is not possible to assure that all costs were considered.
- Fluctuations of dollar values and exchange rates can cause uncertainty on the estimated costs.
- All costs are converted to CDN dollars in 2015 (the original appraised values are given in brackets), so exchange rate and inflation are all rough estimates.

Future Composition of the DLC and Wood Waste at the VLF

The landfill receives between 160,000 and 185,000 tonnes of virgin DLC waste annually, as well as approximately 47,000 tonnes of demo hog material. In 2014, the magnitude of DLC that the VLC received was approximately 133,000 tonnes. The typical composition of DLC materials is comprised of larger wood pieces intermixed with materials such as roofing, fines and other debris. Demo hog has smaller wood fragments intermixed with plastics and other materials.

The Zero Waste Challenge Strategy was developed to implement the ISWRMP and presents opportunities for change and success. This new target will require more bans and regulation to be imposed on all waste including DLC waste and treated and painted wood waste. According to the Canada-wide voluntary industry initiative, reduction of DLC waste to landfill is expected with the following targets: *35% diversion by 2015; 50% by 2020; 75% by 2025, and 100% by 2030.*

As previously mentioned, 70% of DLC waste is woody products. The wood waste consists of clean wood and treated/painted wood. 40% and 16% of the total DLC waste are the clean wood and treated/painted from 1993 to 2010, respectively, and in 2014, the figures slightly increase to 48% and 20%, respectively.

In 2015, Metro Vancouver introduced a new disposal ban on clean wood and it is expected that the percentage of the clean wood coming to the VLF will decrease to zero by 2025.
It is predicted that percentage decreases moderately to 34% for clean wood and 27% for treated/painted wood in 2015. After 2020, treated/painted wood waste is predicted to increase to while clean wood rate decreases to 15%. The treated/painted wood waste will increase to 35% by the end of 2050.

Two scenarios are defined to predict the future composition of the DCL waste in this report, which are as follows:

Scenario 1: if there will be no reduction and diversion plans for DLC waste but still the new disposal ban on the clean wood waste by Metro Vancouver will be considered.

Scenario 2: if there will be reduction and diversion plans for DLC waste plus the disposal ban on the clean wood waste. Figure 8 and Figure 9 illustrate the actual and predicted tonnage of the DLC and wood waste from 1993 to 2050. The actual and predicted annual tonnage of DLC waste and its material types can be seen in Appendix 6.

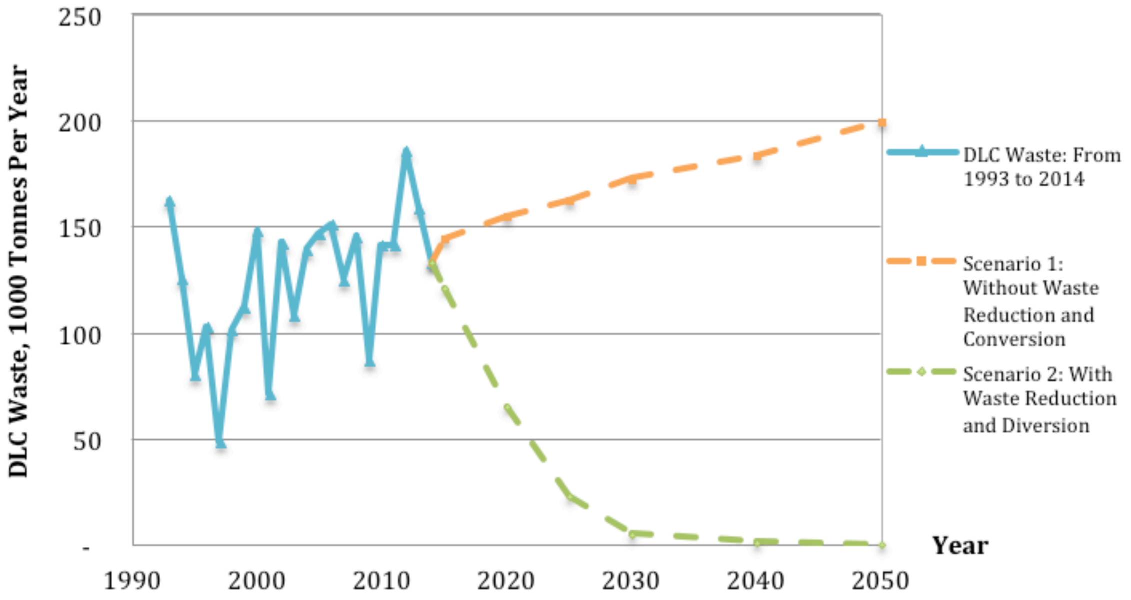


Figure 8 Changes in the Tonnage of DLC Waste at the VLF, without and with Reduction and Diversion Plans

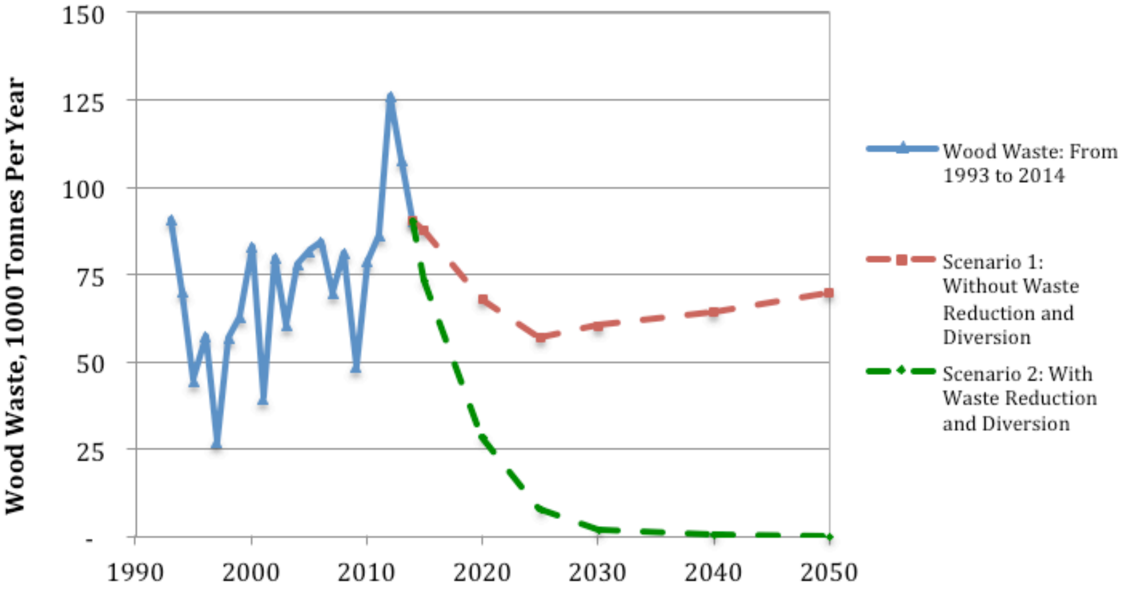


Figure 9 Changes in the Tonnage of the Wood Waste at the VLF, without and with Reduction and Diversion Plans

In *Scenario 1*, DLC waste is assumed to increase according to the population growth in the Metro Vancouver without considering any reduction and diversion plans. The fact is the population growth may represent the rate of construction, renovation and deconstruction in the city. The population growth rate in Metro Vancouver has been estimated to be 1.7% from 2006 to 2021 annually. Therefore, in Metro Vancouver may expect a total increase of approximately 12.6% in population by 2031 and 8.7% from 2031 to 2041. As can be seen Figure 8, DLC waste may increase by 47% from 125,000 tonnes in 2007 to 183,000 tonnes in 2040. The quantity and type of materials of DLC waste can be seen in Figure 10. The figures are summarized in a table in Appendix 7.

While the main composition of the DLC was wood waste before 2015, the concrete, rubber/soil and other materials are expected to be dominant composition of the DLC after 2025. As previously mentioned, the reason is the new ban imposed on the clean wood disposal at the VLF after 2015. The total tonnage of the wood waste is expected to decrease by 8% in 2040 compared to 2007. It is assumed that the VLF will receive nearly 65,000 tonnes of the treated/painted wood waste in 2040, see Figure 9.

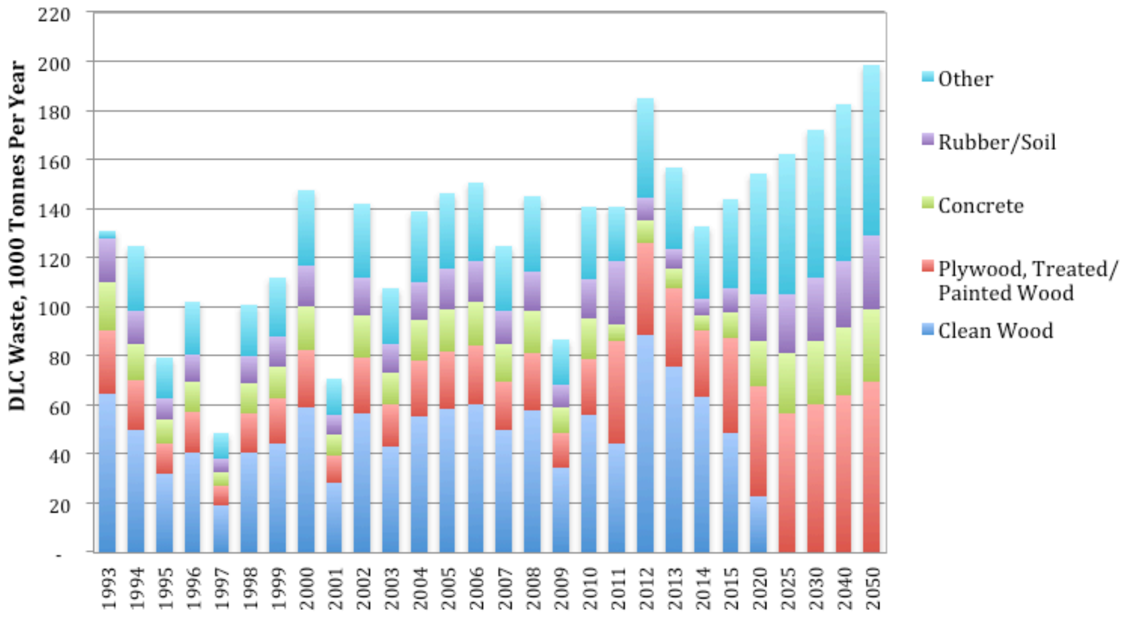


Figure 10 Changes in the Composition of DLC Waste, without Reduction and Diversion Plans

The *Scenario 2* aims to reach the combination of the CRI and ISWRMP goals, as previously mentioned, that set up an increase of diversion rate to 70% by 2015, 80% by 2020 and 100% by 2030 from 2010 levels. As can be seen in Figure 11, the tonnage of DLC waste is expected to reach to nearly zero by the end of 2030. The figures are summarized in a table in Appendix 8. The reduction and diversion plans can be very helpful to reach the "Zero Waste" target.

As also mentioned before, the wood waste constitutes the main composition of DLC waste at around 60%. Reuse and recycle of the wood waste are the first steps of the diversion plans. However, where these procedures are not applicable, conversion technologies can be helpful. The wood waste has inert energy values that can be possible for a sustainable recovery by the state-of-the-art conversion technologies. The fact is conducting research on the conversion technologies for the wood waste and preparing such a report by the author for the City of Vancouver can prove that there will be a great opportunity and horizon as such to stop landfilling the wood waste in the future.

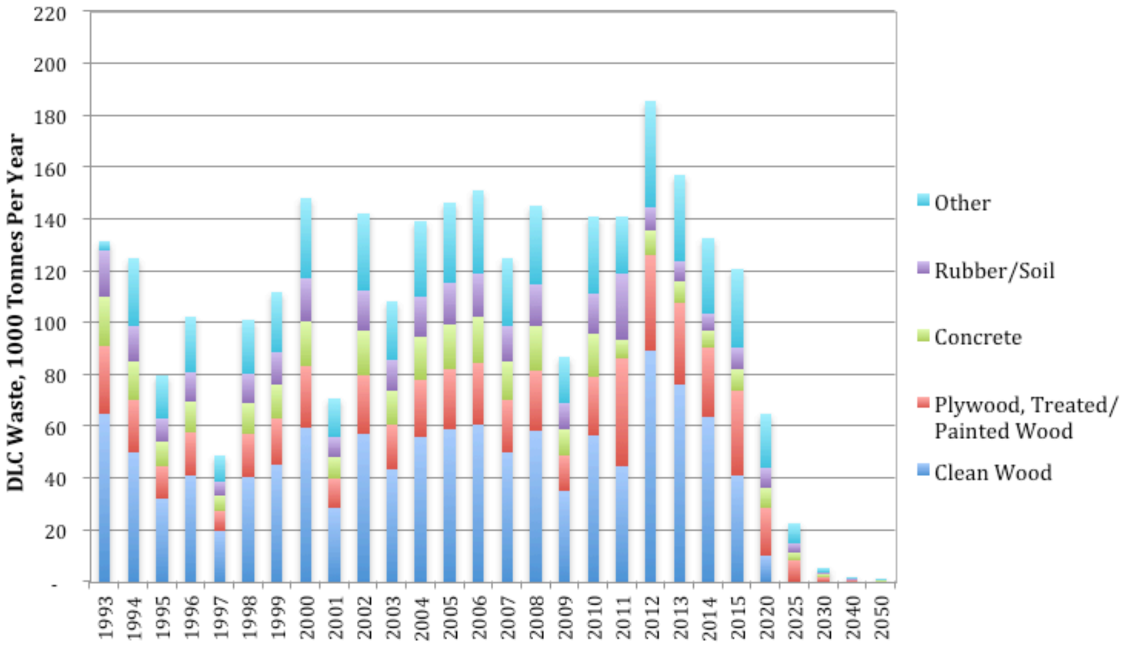


Figure 11 Changes in the Composition of DLC Waste, with Reduction and Diversion Plans

MSW included DLC waste before 1993. Since then, the tonnage and composition of DLC waste has been recorded separately. For those years that the tonnage of DLC waste was combined with the MSW, it was assumed that 25% of the total waste was DLC (Golder Associates, 2008). Metro Vancouver's Solid Waste Management Annual Report 2004 contained information on the composition of total tonnage of MSW, recycled MSW, disposed MSW, total tonnage of DLC, disposed and recycled DLC in Metro Vancouver from 1993 to 2004. For those years that the data includes the combination of the total waste generated within Metro Vancouver from both the Vancouver Landfill and Cache Creek Landfill, it was considered that around 11.29% of the total waste belong to the Vancouver Landfill.

To predict the future composition of DLC waste, the first scenario was considering all current bans and regulations imposed on the waste coming to the Vancouver Landfill plus increase of waste because of the population growth. In this scenario, the trends of MSW generation, disposal and recycling in Metro Vancouver were assumed that current trends would continue unchanged. The second scenario looks at the targets that Metro Vancouver or Canada-wide Voluntary Industry Initiatives have been set by 2020 and further. In this scenario, both waste reduction and diversion are considered. Metro Vancouver's "Zero Waste Challenge: Goals, Strategies, and Actions" document released in March 2009 contained Metro Vancouver's projected capture targets for 2015 for different waste categories. From these numbers, the capture targets were calculated for each of those waste categories as a proportion of the total capture (Ho & et al., 2010) & (AET Consultants, 2011).

As can be seen in Figure 8, if the reduction and diversion occurs according to Metro Vancouver's ISWRMP goal, there will be no DLC waste after 2030. While, if no reduction or conversion for DLC occurs, the tonnage of DLC waste peaks in 2050 at the same rate of 2012.

Wood Waste as a Fuel

Tree species can mainly determine the composition of wood fuel. Typically, wood contains approximately 70% cellulosic material, 25% aromatics (lignin) and 5% extractives (terpines, resin acids, fatty acids, and phenols), and between 0.2 and 3% ash. Four factors are important to consider in burning wood: ash (or incombustibles), chlorine (salt), moisture and the physical size or nature of the fuel.

Typical percentage of chlorine in wood is less than 0.01%. However, if it is exposed to salt water such as seawater, the chlorine content can increase to 0.8%. The presence of chlorine is important because it can form dioxin, which it appears as very fine particulate and therefore, it is very difficult to collect in electrostatic precipitators (EPS), and much of it may be released from the stack.

Type of wood and extent of drying level prior combustion are two factors can determine the moisture content of wood. Typically, values for moisture content can be over 60% for green wood, 55% for wet hog fuels, 30% for hogged scrap wood from sawmills, 10% for planer shavings and sawdust from dried wood, and 4.5% for pellets.

In combustion and energy recovery of wood, moisture contents above 62% can cause low flame temperatures and combustion instability. In addition, wood waste originated from DLC can be expected to contain more non-combustibles such as dirt, drywall, plastic, and metals (e.g., nails). Painted or treated wood fuel may cause additional toxic emissions, such as heavy metals. This kind of wood fuel can be compared to PEF or even more contaminated (Beauchemin & Tampier, 2008).

Classification of wood waste and chemical contamination of wood waste will be discussed in the following paragraphs.

Classification of Wood Waste

Wood wastes are chemically active because of their organic nature. They can be categorized either as non-hazardous or hazardous waste depending on the substances they contain. Raw wood contains natural traces of harmful substances such as heavy metals. However, the main hazardous materials in the wood waste come from substances added during the preservative treatment process and coating of the wood. These added substances can be different depending on the intended usage of wood products. Table 4 presents the potential danger of gluing, fireproofing, preservatives materials, which are considered toxic and carcinogenetic. Two main practices are:

- Surface treatment: the substances only cover the wood surface such as coating and gluing
- Preservative treatment: the substances penetrate the wood fibres to protect against external factors such as fire and wood boring insects and bacterial infections.

Wood waste is divided into three main categories based on their treatment levels:

1. Untreated wood waste
2. Slightly treated wood waste
3. Highly treated wood waste

Untreated wood waste

Untreated wood waste is from raw wood that only received mechanical or thermal treatment but not any kind of chemical preservative treatment. Therefore, they are considered as non-hazardous waste. Untreated wood waste mainly comes from construction sites or workshops including packaging made of wood (pallets, boxes) and sawn raw wood. As this kind of wood waste is non-toxic, with minimal emission treatment, they can be reused, recycled or recovered as energy by direct combustion.

Slightly treated wood waste

Slightly treated wood waste contains small concentrations or low degrees of the preservative substances. Wood that is received coating, gluing, fireproofing and preservation treatments by soaking is considered as slightly treated. Although, the treatment substances are found in low concentrations in wood waste, according to the standards and regulations, they may be placed in a threshold range and the category of hazardous waste. Table 5 presents the classification of slightly treated wood waste.

Table 4 Wood Treatments and Potential Danger of Preservatives (Rizzo, 2010)

Type of treatment	Aim	Preservatives	Potential danger of preservatives
Thermal treatment	Protection	None	None
Coating	Protection and decoration	Non metallic paintings or varnishes	None
		Metallic paintings or varnishes (heavy metals, organic compounds)	
Gluing	Assembling	Mineral glue, animal glue	None
		Synthetic resins (chloroacetate vinyl, Urea-formaldehyde)	Toxic, noxious
Fire proofing	Resistance to fire attack	Metallic salts, isopropanol	Toxic in high concentration
Preservation by soak	Resistance to medium biological attacks	Boron and other heavy metals	Toxic in high concentration
		Diazole, pyrethroide, IPBC	Irritating, mutating, hazardous for reproduction
Preservation by impregnation	Resistance to high biological attacks	CCA, arsenic, organic copper, creosote	Carcinogenic, irritating, toxic

Table 5 Classification of Slightly Treated Wood Waste (Rizzo, 2010)

Type of treatment	Waste origin	Type of wood waste	Examples
Coating	Construction and demolition sites, household dumps, millwork	Recently coated wood used indoor	Furniture, framework, parquet floor, windows, doors
	Demolition sites of old building	Wood coated before 2003 and used indoor	Furniture, parquet floor
Gluing	Construction and demolition sites, household dumps, millwork	Particle board, plywood, laminated wood (MDF, OSB)	Furniture, framework, parquet floor, windows, doors
Fire Proofing	Interior wood	Indoor wood making a barrier against fire	Door, window, framework
Prevention by soak	Construction site and millwork	Raw wood subjected to temporary treatment with bore	Packing, off cut from sawing
	Construction and demolition sites, household dumps, millwork	Outdoor wood with low exposition to soil, sun or humidity	Scaffold, outdoor framework

Highly treated wood waste

Highly treated wood waste is the kind that has been under heavy treatment procedure and has become strong against fire, bacteria and insects attacks, and sun or humidity conditions. Treated wood waste is defined as wood that has been treated with one or more of the following:

- Copper Chromium Arsenic (CCA)
- Copper Organics
- Creosote
- Light Organic Solvent Preservatives (LOSP)
- Micro-emulsion
- Paint/stain
- Varnish

Treatment materials and preservatives contain arsenic, creosote or CCA (chromium, copper, arsenic) that have been penetrated into the deep layer of the wood. Waste wood that has been treated with CCA and creosote is now classified as hazardous waste, so options for these materials will be limited. There are however, many forms of treated wood waste, which are not classified as hazardous for which a greater number of opportunities will be available. Demolition wood waste contains these substances and they usually come from utility poles, railway ties, fences, and outdoor furniture.

Chemistry of Treated/Painted Wood Waste at the VLF

Contamination in wood waste can create an issue for reuse or recycle applications. Wood waste that is most likely to enter final disposal with no form of re-use, recycling and energy recovery consists mainly of painted and preservative treated wood waste along with materials such as Medium-density fibreboard (MDF) and plywood. The wood treatments included in this study are described below (TRADA Technology & Enviros Consulting Ltd, 2005).

The contaminated wood waste at the VLF are mainly treated and painted. Although, the exact chemistry of them is unknown but generally, possible hazardous materials in the wood waste include wood preservatives, varnishes and finishes, solvents/thinners adhesives/glues, latex paint, etc.

Chemical preservatives, pentachlorophenols (PCP), creosote, Ammoniacal Copper Arsenate (ACA), or the like is prohibited to the VLF. Therefore, it is expected that the wood waste at the VLF contains heavy metal contaminations, in particular Chromium, Copper and Arsenic (CCA) as well as formaldehyde from glue materials.

CCA is an inorganic preservative, which consists of a mixture of copper chromium and arsenic salts or oxides of which the ratios can vary which depending upon the application. The wood is typically treated by being immersed in a cylindrical tank where the preservative is forced into the cells under high pressure. The metal salts become highly fixed in the wood and give very effective protection against attack from bacteria, fungi and insects. Traditional applications have been to protect fence-posts, decking, playground equipment and structural timber, especially where it is in contact with concrete or the ground.

Existing and Emerging Technologies for Managing CCA-Treated Wood Waste can be seen in Appendix 9. Chemical, biological and thermal extraction can decontaminate the treated wood. A brief description of four methods is as follows:

1. Chemical Extraction
2. Liquefaction
3. Chelation

4. Thermal Extraction

Chemical Extraction

Several studies have showed that oxalic, citric, acetic, nitric, formic, and sulfuric acids removed varying amounts of metals from CCA-treated wood. CCA components could be completely digested with sulphuric acid under specific conditions of temperature and wood component size (Helsen & Van den Bulck, 2004).

Liquefaction

Liquefaction is used for recycling CCA-treated waste wood. First, the process first converts the waste into a liquid using polyethylene glycol and glycerin, with heat and sulfuric acid as a catalyst. Hazardous components are separated from the liquefied wood by precipitation with complex agents. This method removes 85% of the CCA, which can be recaptured and reused for wood treatment (Helsen & Van den Bulck, 2004).

Chelation

Chelation combines citric acid extraction with the chelating agent, ethylenediaminetetraacetic acid (EDTA). Between 95% and 100% of CCA could be removed (Helsen & Van den Bulck, 2004).

Thermal Extraction

Thermal treatment can be a good option to recover energy from wood waste. However, it must be done with cautions to avoid emission of toxic compounds. Even when a thermal treatment method that ensures no emission of arsenic to the air is developed handling of the residues containing high concentrations of Cu, Cr and As is still a serious matter of concern (Helsen & Van den Bulck, 2004).

The list of conversion technology vendors is summarized in Appendix 10 and Appendix 11.

Emissions Criteria and Control Systems

Typical substances of concern emitted from WTE facilities that are required to be monitored and controlled to specified levels include:

- Total Particulate Matter (including PM10, PM2.5 and ultrafine (nanoparticles))
- Products of incomplete combustion: CO and Organic compounds
- Acidic substances: SOx, NOx, HCl and HF
- Heavy metals: Hg, Cd, Tl, Pb, As, Ni, Co, Cr, Cu, V, Mn, Sb
- Organics: dioxins and furans.

Emission criteria proposed for MSW incineration are enclosed in Appendix 12.

Particulate Matter (PM)

Particulate matter (PM) consists of solid and/or liquid particles that are suspended in the air column. PM is typically grouped into the following categories based on their aerodynamic diameter (in micrometers (μm)):

- Total Particulate Matter (TPM), consisting of all size fractions
- Coarse PM, less than 10 μm (PM10)
- Fine PM, less than 2.5 μm (PM2.5)
- Ultrafine PM, less than 0.1 μm (PM0.1).

In human physiology, coarse particles (those between 2.5 and 10 μm in diameter) are efficiently trapped and removed. They are either filtered out by the hair in the nose, or by impacting on and sticking to moist surfaces in the upper respiratory tract.

Fine particles (those less than 2.5 μm in diameter) are able to penetrate deeper into the respiratory tract. Because of this property, fine particles are believed to be responsible for most adverse health effects associated with particulate matter exposure. Fine particles persist in the atmosphere for long periods and travel long distances. Ultrafine particles (PM0.1) range in size from 0.1 to less than 0.01 μm in diameter (100 to <10 nanometre (nm)). Ultrafine particles are relatively short lived (minutes to hours) (Stantec, 2010).

When wood burns, it produces a variety of particulate matters that are:

- Carbon particles and soot
- Unburned wood dust
- Polyaromatic hydrocarbons (PAH) compounds
- Semi-volatile organic compounds (e.g., tars and condensables)
- Ash (minerals, metals, dirt).

Important to note is that combustion equipment with higher efficiency can produce fewer amounts of larger particles (unburned fuel and wood dust, char and carbon) in the emissions. Therefore, lower and smaller size of PMs is released from modern combustors. In modern combustors, large or small scale, 90% or more of the particles emitted are less than 10 microns in diameter (PM10). Combustors with lower efficiency produce higher and larger size of PMs. Particulate matter control is achieved using an electrostatic precipitator or a fabric filter baghouse with the total efficiency of 98% and 99% for 1 µm particles, respectively (Beauchemin & Tampier, 2008).

Oxides of Nitrogen (NOx)

Oxides of nitrogen (nitric oxide/NO and nitrogen dioxide/NO_2) are formed by the oxidation of nitrogen in the fuel and also in the air but more reactive in the fuel. While, nitrous oxide (N_2O) is important element of global warming emissions, it exists in lesser amounts. The amount of NOx emissions ranges from 303 mg/m3 (95 g/GJ) for wet wood to 674 mg/m3 (211 g/GJ) for dry wood. Greater amount if NOx is produced in higher temperatures of burning dry wood (Beauchemin & Tampier, 2008).

There are two types of NOx control systems normally used in WTE facility APC trains. Namely, these are Selective Catalytic Reduction (SCR) and Selective Non-Catalytic Reduction (SNCR). In SNCR, ammonia is injected into the flue gas stream directly in the furnace at the location where the temperature is around 850oC (Stantec, 2010). Low-NOx burners and/or a Selective Non-catalytic Reduction (SNCR) system are used for reduction of NOx emissions. Selective Catalytic Reduction (SCR) is typical for exhaust gases from reciprocating engines and gas turbines (CH2M HILL Canada Limited, 2009). In SCR, the reaction between NOx and ammonia takes place in a catalytic bed at temperatures normally between 200 and 250°C. In SCR, the catalytic bed is often the last treatment step in the APC, therefore, a preheat system is required. The SCR is used in European countries with strict NOx control regulations (10 mg NOx/m^3) or high NOx tax (Stantec, 2010).

Carbon Monoxide (CO) and Volatile Organic Compounds (VOC)

In an incomplete combustion process, carbon monoxide (CO) and volatile organic compounds (VOC) are produced. Formation of CO is caused by the incomplete combustion of the carbon atoms, while incomplete breakdown of the organic components is responsible for VOCs emissions. The combustion of carbon compounds occurs in two stages: first the carbon is oxidized to carbon monoxide (CO) and second carbon monoxide is then oxidized to CO_2 (Beauchemin & Tampier, 2008).

As higher level of energy is released from oxidation of CO to CO_2, combustors are designed to maximize the second reaction. However, lack of excess air, poor fuel-air contact and low temperature in the combustion zone can cause an incomplete combustion and higher CO emissions (Stantec, 2010).

Sulphur Oxides (SOx)

Wood produces low sulphur oxides (sulphur dioxide). There is no need of flue gas scrubbing, however, it may be present in larger quantities if wood is supplemented with other fuels such as TDF or fuel oils (Beauchemin & Tampier, 2008).

Polyaromatic Hydrocarbons (PAH)

Wood contains of cross-linked aromatics such as primarily phenyl propane terpines, resin acids, fatty acids, and phenols and cellulose (polysaccharides). In case of incomplete oxidation of lignin or extractives during combustion process, they release Products of Incomplete Combustion (PIC) such as PAH (anthracene, benzaldehyde, benzo(a)pyrene, chrysene, ethylbenzene, fluoranthene, etc) (Beauchemin & Tampier, 2008).

Heavy Metals

Heavy metals are usually carried on particulate matter and occur naturally or can be emitted through anthropogenic sources (Beauchemin & Tampier, 2008). Acid gas scrubbers are typically quite efficient in removing large quantities of heavy metals from the flue gas even though this is not their primary purpose. Specifically, wet scrubbers can provide for the significant removal of arsenic, beryllium, cadmium, chromium, lead, manganese and mercury from the flue gas. ESPs and fabric filter baghouses also play an important role in the reduction of heavy metals in the flue gas. They accomplish this because volatilized heavy metals often bind to fly ash particles in the flue gas and large quantities of this particulate matter are captured in an ESP or a fabric filter baghouse. In this way, by removing the particulate matter, large quantities of heavy metals are also captured (Stantec, 2010).

At higher chlorine contents mercury will be primarily in an ionic form, which can be removed by acid gas scrubbers. However, Metallic mercury is much harder to control because it is very insoluble in water. Metallic mercury is normally controlled by being transformed into ionic mercury (by adding oxidants) so that it can then be captured by the wet scrubber; or by direct deposition on activated carbon and captured in a downstream ESP or fabric filter baghouse. A small amount of mercury is released into the atmosphere in a vaporous state during the combustion process, while the majority ends up in the APC residue after treatment. Very little mercury ends up in the bottom ash (Stantec, 2010).

Other heavy metals (e.g. arsenic, beryllium, cadmium, lead, manganese etc.) are converted mainly into non-volatile oxides during the incineration process and bind to particulate matter in the flue gas and are then captured by ESPs and fabric filters (some are also captured by activated carbon). The majority of these heavy metals end up in the APC residue after treatment. Typically, a lesser amount of these heavy metals remain in the bottom ash (Stantec, 2010).

Dioxins / Furans Emissions

Dioxins and furans may form (referred to as de novo synthesis) in catalytic reactions of carbon or carbon compounds with inorganic chlorine compounds over metal oxides (e.g. copper oxide) during the waste incineration process. These reactions generally take place in the temperature range between 250–400°C which occurs as the flue gas cools after leaving the combustion zone of the incinerator. Modern incinerators are designed to ensure that the length of time flue gas spends in that temperature range is minimized, so as to reduce the possibility of de novo synthesis of dioxins/furans.

Important factors in the formation of dioxins and furans include the nature of the fuel, combustion and post-combustion conditions. A decrease in air control efficiency (e.g. Electrostatic Precipitator) and increase in concentration of PAH (e.g. poor combustion) can increase dioxin emissions in the stack (Beauchemin & Tampier, 2008).

These emissions are reduced via an activated carbon injection system. Basically, the gaseous mercury and dioxin/furan compounds are adsorbed onto the surface of the activated carbon particles that are later collected in a baghouse. This type of control system is capable of removing mercury and dioxin/furans from the flue gas to below regulatory concentration limits. The dioxin filter can either be wet or dry. The dry system is the most commonly used (Stantec, 2010).

The overall removal efficiencies of Air Pollution control Systems (APC) depends on the size profile of the emissions leaving the combustion zone, which in turn will depend on the type and operation of the combustion equipment. There are five main types of APC applied to the combustion of wood biomass as follows:

1. Cyclones and/or multi-cyclones
2. Electrostatic precipitators (or Wet ESPs/WESP)
3. Fabric filters or baghouses
4. Scrubbers

Cyclones and/or multi-cyclones: Mechanical collectors use mechanical means to remove particulate matter from the flue gas. A multiple cyclone consists of an array of cyclones in parallel. Overall, multiple cyclones have removal efficiencies of 70–90% (Stantec, 2010)

Electrostatic precipitators (or Wet ESPs/WESP): ESPs use electrical fields to remove particulate matter from flue gas. ESPs have been in common use for a long time. Typically, ESPs have low energy requirements and operating costs (Stantec, 2010). ESPs are capable of removal efficiencies of up to 99.9% with common efficiencies of 99.5% (Stantec, 2010).

Fabric filters or baghouses: Fabric filter baghouses are used to remove particulate matter from the WTE flue gas before it is released into the atmosphere. Flue gases pass through a tightly woven fabric, particulate matter collects on the fabric that prevents it from being released into the atmosphere. Removal efficiency is excellent for PM10 and PM2.5 (Stantec, 2010).

Scrubbers: wet or dry scrubbers use chemical reaction with a sorbent to remove acidic gases including sulfur dioxide (SO2), hydrochloric acid (HCl) and hydrofluoric acid (HF) from the flue gas stream. In addition to acidic gases, scrubbers are also capable of removing particulate matter and heavy metals such as mercury. Both wet and dry scrubbers reduce HCl emissions by 95% and more, and wet scrubbers reduce HF emissions by more than one-third (EPA, 2002).

Wood Waste Properties and Specifications at the VLF

Figure 12 and Figure 13 show that the size and type of the wood waste at the VLF varies from couples of centimetres to a couple of metres, or even larger than this. Therefore, for conversion technologies such as gasification and pyrolysis that are sensitive to the feedstock size, preparation of the feedstock is required. It is predicted that the VLF will be receiving approximately 57,000-90,000 tonnes per year of wood waste by 2040. Therefore, the facility is expected to handle a throughput of around 100,000 tonnes.

The feedstock consists of clean wood and treated/painted wood waste in the earlier years and nearly zero clean wood after 2025. The composition, tonnage and properties of the wood waste at the VLF were discussed in the “Future Composition of the Wood Waste” and “Wood Waste Properties and Specification at the VLF” parts of the report. The size of the feedstock varies from centimetres to couple of metres, and they contain metallic materials at around 1.2%. Therefore, the feedstock should be shredded or grounded to less than 200 mm and metals should be removed by magnets.

Table 6 The Effect of Moisture Content on the Net Heating Value of Wood Compared to that of Other Fuels (FAO Corporate Document Repository, 1990)

Fuel	As fired Gross calorific value MJ/kg	Typical burner efficiency %	Useable Net heating value MJ/kg
Wood at 0% Moisture Content (m.c.)	19.8	80	15.8
10% m.c.	17.8	78	13.9
20% m.c.	15.9	76	12.1
30% m.c.	14.5	74	10.7
40% m.c.	12	72	8.6
50% m.c.	10	67	6.7

The moisture content of the feedstock is assumed to be 25-30%. Therefore, calorific value of the VLF’s wood waste is approximately 15.2MJ/kg. Table 6 presents calorific values of wood waste based on its moisture content. Calorific values for wood waste with moisture contents between20% and 30% are expected to be 15.9 MJ/kg and 14.5 MJ/kg. Therefore, based on the moisture content of the VLF’s wood waste, its calorific value is assumed to be the average of these values.

Figure 12 Various Types of Wood Waste at the VLF

Figure 13 Demo Hog (Wood Fines<3”×3”), the Top Left Picture and Mixture of Tread/Painted Wood Waste, the Top Right and Bottom Pictures

Conversion Technologies

Energy recovery is a method of recovering the chemical energy stored in wastes. It has had great success in both waste separation programs and the technologies advancements around the world. Waste sorting and screening are necessary to separate reusable and recyclable materials as well as materials with high heating value. Figure 14 illustrates Waste-to-Energy Technologies, classifications, procedures and final products.

MSW has been proven to be a good feedstock for WTE facilities. Clean wood waste is also converted to wood chips and pellets and has multiple applications as a fuel. However, plywood, treated and painted wood waste is considered to be challenging in this aspect.

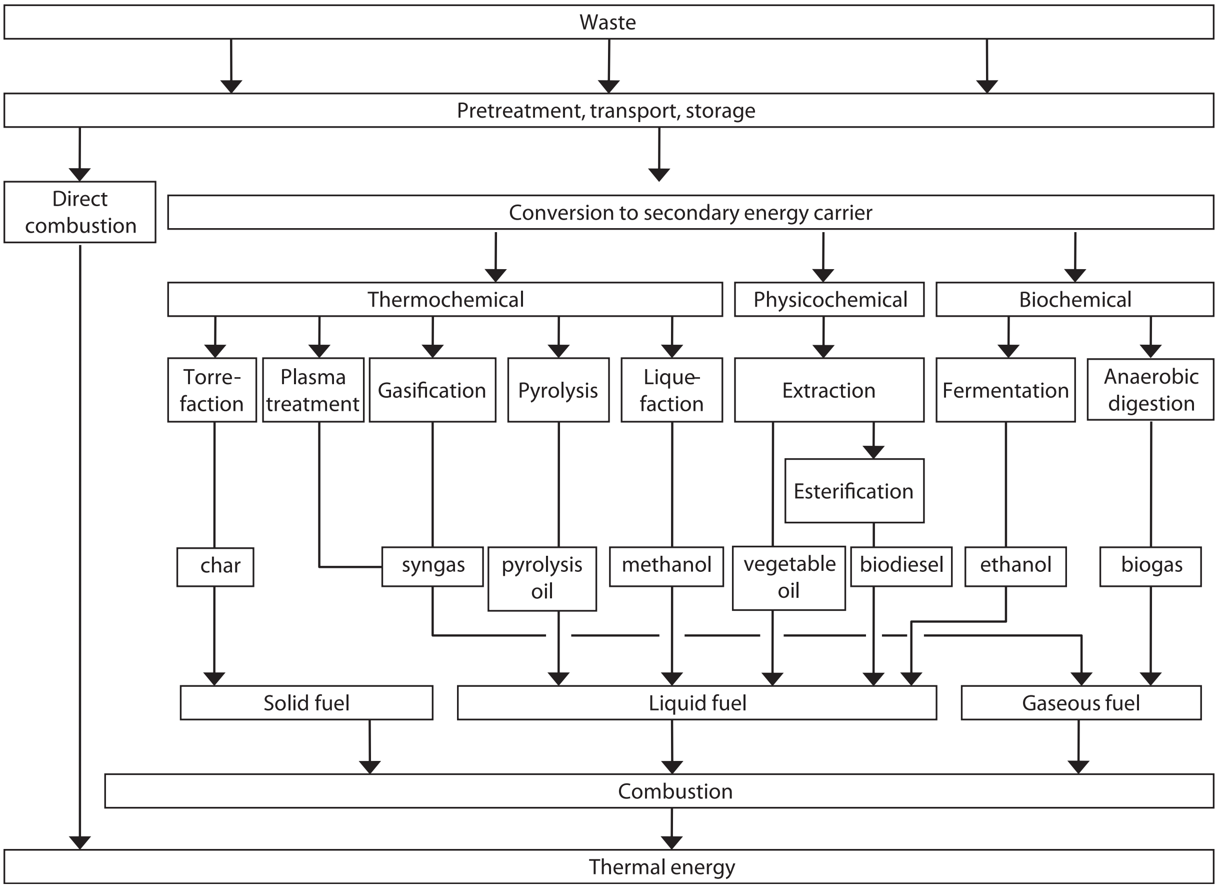


Figure 14 Waste-To-Energy Technologies

Conversion technologies available for wood waste are classified in four categories as follows:

- Re-use
- Recycling / composting

    - Mechanical e.g. chipping
    - Chemical e.g. oxalic acid
    - Biological e.g. composting
- Thermal treatment producing products e.g. pyrolysis and gasification
- Thermal treatments with energy recovery (TRADA Technology & Enviros Consulting Ltd, 2005)

Wood waste, and wood by-products from industry that cannot be recycled or reused, are often recovered for energy use through combustion processes. Contaminated waste wood is mainly landfilled or incinerated. Environment Canada (EC) sets the Emission Limit Values (ELVs) and monitoring requirements for pollutants to air such as dust, nitrogen oxides (NOx), sulphur dioxide (SO2), hydrogen chloride (HCl), hydrogen fluoride (HF), heavy metals and dioxins and furans. At present, clean recovered wood can be burnt outside the restrictions of the EC.

Treated waste wood includes any wood with a surface coating such as paint, varnish or preservatives. EC requires that combustion of treated wood waste must meet ELVs. In the part that incineration technology is explained, the main requirements of emission control will also be discussed. However, a distinction should be made between carbon of fossil origin and carbon biogenic origin. CO2 released from wood products are carbon neutral and is absorbed by trees during photosynthesis process.

The use of wood waste for energy is high in countries such as the US, Canada and Europe. Typical technology options are as follows:

- Facilities that use small boiler systems for directly heating houses and apartment buildings up to biomass boilers that efficiently supply heat through district heating networks.
- Wood waste, along with other biomass, is also used to generate electricity in Combined Heat and Power plants (CHP). The heat is utilized in local and district heating networks or made available to industry as process heat. It can also be used to produce cooling for industrial purposes, for refrigerated warehouses or for cooling buildings (if combined with CHP, this is called tri-generation).
- Wood waste gasifiers can be used to generate heat and electricity through gasification or pyrolysis processes. The resulting syngas or biochar is then used to produce electricity in

combustion engine systems or gas turbines (Ricardo-AEA Ltd, 2013).

In this project, applicability of three common thermal technologies used for waste treatment are assessed which are as follows:

- Niche incineration
- Gasification
- Pyrolysis

These processes are differentiated by the ratio of oxygen supplied to the thermal process divided by oxygen required for complete combustion. This ratio is defined as the “lambda” ratio and in the case of pyrolysis, it is equal to zero. Gasification is conducted at substoichiometric conditions and full combustion is carried out using a lambda greater than one. Table 7 compares characteristics of current thermochemical conversion technologies.

In this report three thermal conversion technologies are described. The most mature and proven technology is incineration. The other two technologies are gasification and pyrolysis. For each technology, the technology description, feedstock properties and requirements, environmental impacts, policies and restrictions and financial analysis will be explained. In the end of each technology specifications, three facilities will be reviewed.

Table 7 Characteristics of the Main Thermochemical Conversion Technologies (Bosmans, Vanderreydt, Geysen, & Helsen, 2012)

	Pyrolysis	Gasification	Combustion	Plasma treatment
Aim	Maximize thermal decomposition of solid waste into coke, gases and condensed phases	Maximize waste conversion into high calorific fuel gases	Maximize waste conversion into high temperature flue gases	Maximize waste conversion into high calorific fuel gases and an inert solid slag phase
Temperature [°C]	250–900	500–1800	800–1450	1200–2000
Pressure [bar]	1	1–45	1	1
Atmosphere	Inert/nitrogen	Gasification agent: O_2, H_2O	Air	Gasification agent: O_2, H_2O Plasma gas:O_2, N_2, Ar
Stoichiometric ratio	0	<1	>1	<1
Products from the process:				
Gas phase	H_2, CO, H_2O, N_2, hydrocarbons	H_2, CO, CO_2, CH_4, H_2O, N_2	CO_2, H_2O, O_2, N_2	H_2, CO, CO_2, CH_4, H_2O, N_2
Solid phase	Ash, coke	Slag, ash	Ash, slag	Slag, ash
Liquid phase	Pyrolysis oil, water			

Figure 15 shows the level of maturity of conversion technologies and the anticipated cost of that technology. As can be seen, incineration is the most mature and least expensive technology compared to gasification and pyrolysis.

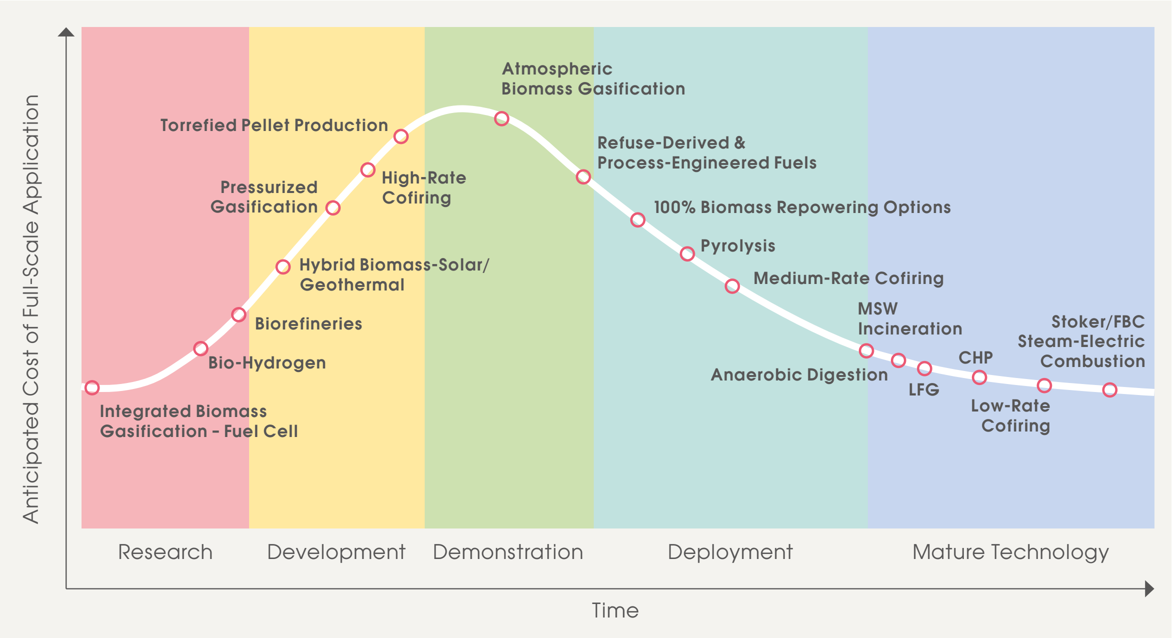


Figure 15 Biomass Power Generation Technology Maturity Status (IRENA, 2012)

Niche Incineration

Waste-to-Energy combustion (WTE) is defined as a process of controlled combustion that produces electricity, steam or other energy as a result by using a device to thermally breakdown the combustible solid waste. The residue of the process is an ash containing little or no combustible material.

"Niche incineration or burning" is a net zero emissions process because of combusting MSW (a bio-fuel) that produces energy as well as WTE combustion decreases the volume of wastes by up to 90%. Such reduction in volume decreases the amount of waste landfilled and prolongs the life of landfills further. However, special concern goes to the treated and painted wood waste. This sort of wood waste is not recommended to use at the WTE facilities because contaminants in the feedstock can produce toxic emissions that are not permitted according to the environment regulations and standards.

Technology Description

Incinerator can be described as a furnace burning the waste. To control emissions from the incinerators, modern facilities are equipped with pollution improvement systems to clean up the flue gases. There are three common kinds of incineration technologies, which are as follows:

1. Moving grate
2. Rotary kiln
3. Fluidized bed

Moving Grate

The furnace is equipped with an inclined moving grate system that keeps the waste moving through the furnace during the combustion process. The modern incinerators use advanced combustion process control measures to optimize the combustion at a temperature over 850^{o}C (to 950^{o}C) with long residence time and high turbulence to ensure complete destruction of organic pollutants. Primary air is supplied from holes in the grate elements to cool the grate. Cooling is important for the mechanical strength of the grate. Moving grates may also be internally water-cooled. Nozzles over the grate supply the secondary air into the boiler. Turbulence can provide a complete combustion of the flue gases by better mixing and ensuring a surplus of oxygen. In the power generating facilities, flue gases are then cooled in super-heaters to heat the steam to 400°C at a pressure of 3.6 MPa in the turbine. Then flue is passed to the flue gas cleaning systems. Figure 16 shows an incinerator with moving grate technology.

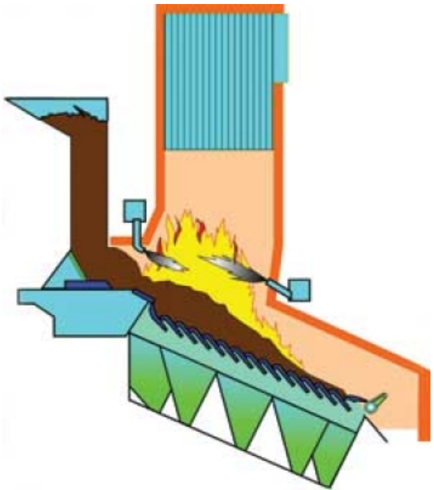


Figure 16 A Diagram of a Moving Grate Incinerator

Rotary Kiln

Industries and municipalities generally use rotary kiln incinerators. Normally, the incinerator has two chambers to perform a two-stage process. It consists of a rotary kiln and a separate secondary combustion chamber. Solid waste is introduced into the upper end of an inclined refractory lined cylindrical tube. While the waste moves through the inclined cylinder with a tumbling action, drying, combusting and ash cooling are performed along the length of cylinder. Typical refractory are capable of maintaining a temperature around 1000°C and the shell temperature needs to be maintained below around 350°C in order to protect the steel from damage (EPD, 2009).

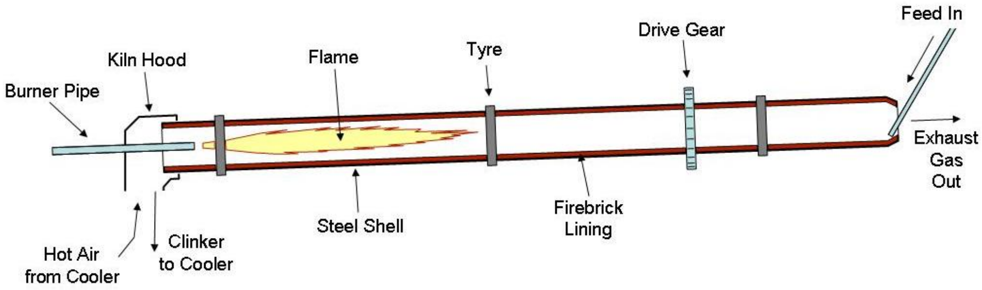


Figure 17 A Diagram of a Rotary Kiln

The secondary chamber completes gas phase combustion reactions. The clinkers spill out at the end of the cylinder. A tall flue gas stack, fan, or steam jet supplies cool air. A rotary kiln incinerator can be seen in Figure 17. Application of rotary kiln incineration to treat mixed MSW is susceptible to numerous technical problems such as thermal shock, ash melting and deposition and corrosion that require intensive maintenance (Stubenvoll, Böhmer, & Szednyj, 2002), (EPD, 2009)

Fluidized Bed

The fluidized bed incinerator consists of a lined combustion chamber loaded with a large granular bed of inert material (e.g. coarse sand or silica) that transfers heat to the waste evenly. During the operation, heated air is blown vertically through the bed at a high flow rate causing the bed of particles to bubble or boil much as a liquid, that allows the waste and the fuel contact each other and facilitates drying and combustion. Figure 18 shows a fluidized bed incinerator.

Fluidized bed combustion is conducted at relatively low temperature from 760°C to 870°C and the average gas residence time is high (over 5 seconds). This can result in an effective combustion even with wet waste (EPD, 2009).

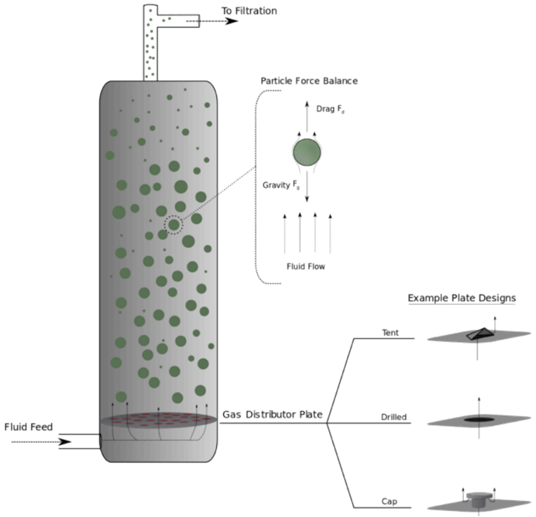


Figure 18 A Diagram of a Fluidized Bed Incinerator

Development Status and Operating Experience

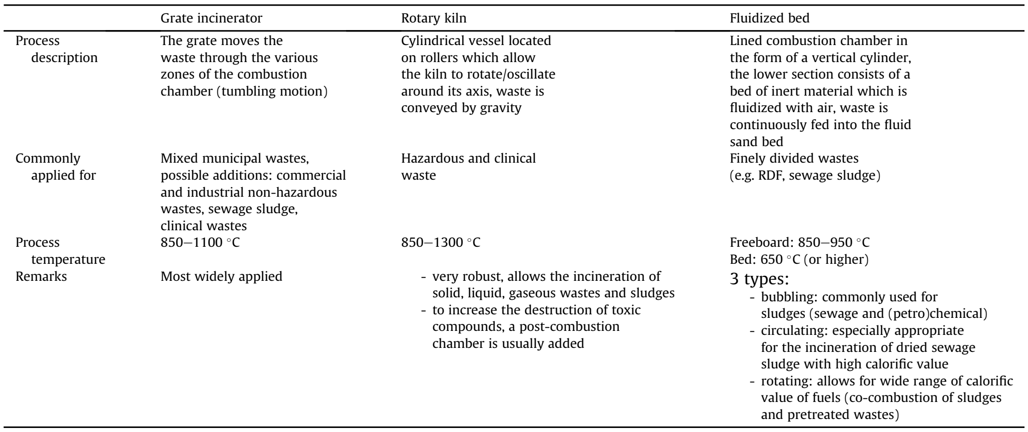
Incinerators are utilized to treat different types of material. Grate incinerators are widely used for incineration of MSW. Rotary kilns are most commonly used for incineration of hazardous and medical waste. The fluidized bed incinerators are applied to finely divided waste (e.g. RDF, sewage sludge). Fluidized bed produces less GHG emissions than the grate type. Table 8 summarizes characteristics of described incinerators.

In Europe, the thermal treatment of waste is governed by the Waste Incineration Directive (WID), which sets emission limit values and monitoring requirements for pollutants to air. Treated waste wood includes any wood with a surface coating such as paint, varnish or preservatives. WID requires that combustion of treated wood waste meets strict emissions limits. Therefore, it is possible to recover energy from treated and contaminated wood, but only where proper pollution control is installed to ensure emissions fall within the WID limits.

The main requirements of WID are:

- Combustion gas must be raised to 850°C for 2 seconds;
- For hazardous waste with more than 1% of halogenated organic substances, expressed as chlorine, the temperature must be raised to 1,100°C for 2 seconds; and
- Residence time and temperature need to be demonstrated.

Table 8 Characteristics of the Three Main Incinerator Types (Bosmans, Vanderreydt, Geysen, & Helsen, 2012)



	Grate incinerator	Rotary kiln	Fluidized bed
Process description	The grate moves the waste through the various zones of the combustion chamber (tumbling motion)	Cylindrical vessel located on rollers which allow the kiln to rotate/oscillate around its axis, waste is conveyed by gravity	Lined combustion chamber in the form of a vertical cylinder, the lower section consists of a bed of inert material which is fluidized with air, waste is continuously fed into the fluid sand bed
Commonly applied for	Mixed municipal wastes, possible additions: commercial and industrial non-hazardous wastes, sewage sludge, clinical wastes	Hazardous and clinical waste	Finely divided wastes (e.g. RDF, sewage sludge)
Process temperature	850–1100 °C	850–1300 °C	Freeboard: 850–950 °C Bed: 650 °C (or higher)
Remarks	Most widely applied	- very robust, allows the incineration of solid, liquid, gaseous wastes and sludges - to increase the destruction of toxic compounds, a post-combustion chamber is usually added	3 types: - bubbling: commonly used for sludges (sewage and (petro)chemical) - circulating: especially appropriate for the incineration of dried sewage sludge with high calorific value - rotating: allows for wide range of calorific value of fuels (co-combustion of sludges and pretreated wastes)

There are also air emissions requirements including limits on the emissions of dust, total organic carbon, Hydrogen chlorine (HCl), Hydrogen fluoride (HF), Sulphur dioxide (SO2), Nitrogen monoxide (NO) and nitrogen dioxide (NO2), heavy metals and dioxins. In the UK, a grading system has been developed to classify wood into high quality (Grade A) and lower quality wood (B to D). WID compliant combustion plants can be used to recover energy from Grades B, C and hazardous waste wood (as well as Grade A), providing an alternative to landfilling for these grades (Ricardo-AEA Ltd, 2013).

Most of the energy produced during combustion is transferred to the flue gases, which are cooled as they pass through the plant allowing for the capture of energy via a heat recovery boiler.

Energy produced by WTE facilities can be used in the:

- Production and supply of heat (as steam or hot water); Reported Potential Thermal Efficiency 80 – 90%
- Production and supply of electricity (by steam turbines); Reported Potential Thermal Efficiency 17 – 30%
- Production of heat and electricity (combined heat and power, CHP); Reported Potential Thermal Efficiency 70-85%

The highest levels of waste energy utilization are normally obtained when the heat recovered can be supplied continuously as district heat (or process steam) or in combination with electricity generation. Electricity only operations are less efficient than those that recover and use district heat (or process steam) but are less dependent on local conditions and therefore are widely employed.

Feedstock Properties and Requirements

In the context of wood waste, “biomass” according to the Metro Vancouver Emission Regulation is defined as wood or wood products that are uncontaminated wood waste, such as mill ends, wood chips, shavings, sawdust, sander dust, clean construction waste, hog fuel, and clean dimensional lumber from deconstruction. This kind of wood waste is allowed to burn but, unless otherwise authorized by the district director, does not include substances containing any of the following:

- Glue, paint or preservative, or foreign substances harmful to humans, animals or plants when combusted
- Wood waste with chloride content greater than 0.05 percent dry basis
- Wood waste with moisture content greater than 60 percent dry basis
- Demolition waste other than clean dimensional lumber from deconstruction
- Other waste containing materials other than uncontaminated wood waste (Metro Vancouver, 2013)

However, there is still no specific guideline available to address the burning of DLC waste. Clearly defined standards and guidelines should be developed to determine the type of wood waste that can be combusted and the best emission controls that are required to meet the emission standards (Tong, Suchy, Linsky, & Hebert, 2012).

The summary of the feedstock properties and requirements based on the combustor types are as follows:

Moving Grate

Typical throughput ranges from 120 to 720 tonnes per day.

Type of materials: The feedstock can be MSW and DLC waste that is left after all possible reusing, recycling and composting of waste or rejected from material recovery and/or composting facilities.

Size of materials: This is the most common type for MSW and other wastes include commercial and industrial nonhazardous wastes, sewage sludge and certain clinical waste that accepts solid waste into the furnace with little pre-processing (EPD, 2009).

Moisture content: it should be less than 50%.

Rotary Kiln

Typical throughput range is 10-350 tonnes per day.

Type of materials: The rotary kiln furnace is used for the treatment of waste plastics, wood chippings, paper cuttings, sludge, waste oil, waste liquid and hazardous waste (Mitsubishi Heavy Industries, 2002), (Stubenvoll, Böhmer, & Szednyj, 2002).

Size of materials: In rotary kiln, pre-processing of MSW is not needed (Stantec, 2010)

Moisture content: The moisture content of the feedstock ranges from 30% to 45%.

Fluidized Bed

Typical throughput range is 36-200 tonnes per day.

Type of materials: Fluidized bed technology is widely applied to treating sewage sludge and MSW (Stantec, 2010).

Size of materials: In rotary kiln, pre-processing of MSW is not needed. Combustion of mixed MSW in a fluidized bed incinerator requires pre-processing of the waste into a homogenous refuse derived fuel and its application is limited (Stantec, 2010). Therefore, large heavy particles of fuel, and waste must be shredded or large particles removed before being fed to the bed.

Moisture content: Feedstock typically contains 20-60% moisture, 40-80% combustibles, and 1-2% ash.

Environmental Impacts

Combustion of wood waste contaminated with organic and inorganic wood protection and wood preservation chemicals has been conducted in BC power boilers over the past two decades. This includes wood contaminated with creosote (railway ties and some structural timber), and pentachlorophenol treated wood (utility poles and some structural timber). *Generally these waste streams have been included on a limited fuel substitution basis in trial burns. While these tests have resulted in acceptable emissions from the facility, other constraints including public concern and waste material handling have prevented adoption of larger programs of fuel substitution with these materials.* Other applications of contaminated wood waste have included the use of wood waste contaminated by other construction and demolition materials (Stantec, 2010).

Substitution and supplementing fuel supply with contaminated wood waste should be acceptable under specific conditions and would require amendment of current facility permits as follows:

- Use of contaminated wood waste as a fuel would likely be considered a major modification to the operations for a given facility and would require permit amendments to address operational changes and revised Emission Limit Values (ELVs).
- Testing of the proposed fuels including mass balance analysis to determine the potential shift in emissions concentrations at various substitution rates would be required. This should be accompanied by fuel trials undertaken to demonstrate the actual shift in emissions concentrations associated with use of the proposed fuels (Stantec, 2010).

Summary

While incineration is a less publicly and environmentally acceptable method to treat materials, this technology is more mature, less complicated and more economically reasonable. Moreover, pre-processing of the feedstock is not required in the incineration process. There are different types of incinerators. Rotary kilns are most commonly used for incineration of hazardous and medical waste, but grate incinerators are widely used for solid waste. The fluidized bed incinerators are applied to finely divided waste (e.g. RDF, sewage sludge). Fluidized bed produces less GHG emissions than the grate type.

The treated/painted wood waste at the VLF might contain heavy metals, therefore, rotary kiln seems to be more suitable. However, the author could not find a commercialized facility to utilize a large amount of the treated/painted wood waste as their throughput. Currently, cement kilns, pulp mills and WTE facilities utilize a small controlled proportion of the contaminated wood such as railway ties and plywood (creosote-contaminated) or even old tires in their throughput. However, treated/painted wood waste contains different contaminations such as heavy metals, in particular arsenic, that make this type of material not suitable for incinerators due to unknown and complexity of the reactions in the process.

Both air emissions and bottom ash of incineration contains high levels of heavy metals. Current Air Pollution Control (APC) systems might capture a large amount of the emissions but it is very expensive and there has not been tested on incineration of a large magnitude of the treated/painted wood waste.

In Appendix A 1, the following facilities, which use incineration technology, are described:

1. Burnaby WTE Facility, British Columbia, Canada
2. Wood Fired Combined Heat and Power Plant, Germany
3. Arnoldstein Plant, Austria

Applicability of Incineration for the Wood Waste at the VLF

The suggested location and the size of the VLF's future facility are determined in a map, which can be found in Appendix 5.

Feedstock specifications and requirements:

It is predicted that the VLF will be receiving approximately 57,000-90,000 tonnes per year of wood waste by 2040. Therefore, the facility is expected to handle a throughput of up to 100,000 tonnes per year. The feedstock consists of clean wood and treated/painted wood waste in the earlier years and nearly zero clean wood after 2025. The size of the feedstock varies from centimetres to couple of metres and they contain metallic materials at around 1.2%. The moisture content of the feedstock is assumed to be 25-30%. Pre-processing of the feedstock is not required in incineration.

Technology:

Technically, incineration by a rotary kiln may be an option to treat the VLF's wood waste. It is more mature and less complicated than the other technologies. However, there may be fundamental issues with the emission control and bottom ash treatment. The author could not find any commercialized facilities that treat a large amount of the treated/painted wood.

Method of energy recovery:

CHP system will be utilized to generate electricity and heat at 30% and 70% of the total produced energy, respectively. The electricity will be purchased by BC Hydro at $136/MW (electricity) and heat will be utilized in district heating at $40/MW (thermal).

Environmental impacts:

As previously mentioned, there is no data available on the chemistry of the wood waste at the VLF. However, it is expected to have heavy metals and formaldehyde contaminations. The level of toxicity of the emissions and bottom ash is unknown. However, an extensive and costly APC system may be required to control heavy metals in the emissions. Bottom ash treatment may be necessary as landfilling of toxic residues is not a permanent and sustainable solution.

Economics details:

The cost of incineration plants depends on the type of the incinerator, APC systems and bottom ash treatment methods. However, all this information may not be available for a precise estimation. The feedstock may consist of compounds containing atoms such as lead, arsenic, and phosphorous, therefore, if the condition is not controlled, it might deactivate the oxidation catalysts and an expensive catalyst replacement may be required. Uncertainty in the costs is also comes from the inflation, location, scale, currency exchange rate and assumptions that have to be made (E4tech, 2009).

All financial parameters and assumptions for an economic assessment of the future incineration plant at the VLF were described in “Project Assumptions” section of this report. Efficiency of incineration with steam CHP is given in Appendix 13. The efficiency of incineration and CHP system is assumed up to 50% due to uncertainties on the feedstock specifications and process complications.

Table 9 illustrates the capital, operational & maintenance costs and revenue estimates. Capital and operating & maintenance costs were derived from experimental curves that were given in a Stantec report, see Appendix 14. The portion of electricity and heat generation is assumed 30% and 70%, respectively. As can be seen, the NPV of the plant is negative at approximately $46 million over 20 years. The breakeven tipping fee for this process is $155 per tonne; more details and calculation parameters can be found in Appendix 16.

Table 9 Incineration Process: Capital, Operational & Maintenance Costs and Revenue Estimates

Financial Parameters	
Interest Rate	6%
Life of the Facility & Amortization Period (years)	20
Nominal System Specifications	
Average Annual Throughput Rate (tonne)	65,608
Electricity Output (MW (electricity) net)	2
Heat Output (MW (thermal) net)	6
Capital Costs	
Direct Capital Costs	$78,308,317
Indirect Costs	-
Contingency (17%)	-
Total Capital Costs	$78,308,317
Annualized Capital Costs	$3,915,416
Operating Costs	
Fixed & Variable Operating Costs	$6,167,197
Assumed Electricity Sales Rate per MWh	$136
Assumed Heat Sales Rate per GJ	$40
Assumed Ferrous Metal Sales	$150
Assumed Non-Ferrous Metal Sales Rate	$1,600
Current DLC Tipping Fee Rate	$60
Predicted Annual Revenue	$12,136,625.53
Net Results	
NPV	($46,264,631.79)
IRR	-6%
Breakeven Tipping Fee, per tonne	$112

Figure 19 illustrates the sensitivity of the NPV to different parameters such as tipping fee, sale price for electricity and heat, throughput rate, generation portions of heat and power, efficiency of the CHP system, capital and operating & maintenance costs. As can be seen, the parameters that influence the NPV are ranked, from the most to the lease important, are as follows:

1. The capital costs
2. Operating & maintenance costs
3. Sale price of heat
4. Efficiency of the Process (Incineration with CHP)

5. Throughput rate
6. Tipping fee
7. Sale price of electricity
8. Percentage of heat and power generation

Therefore, if the capital and operating costs decrease by half, the plant will experience a positive NPV. Double increase of sale price of heat, efficiency of the process, through put rate and tipping fee can make a little amount of positive NPV. However, changes in the other factors might not produce a positive NPV.

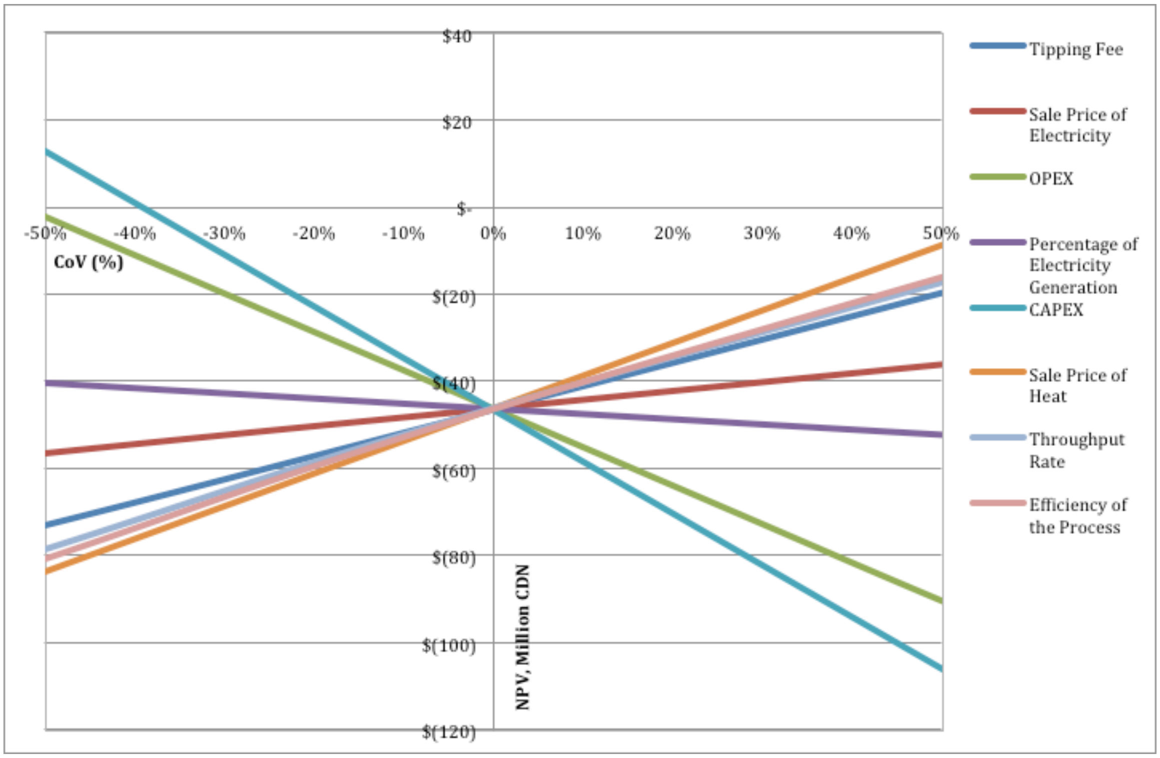


Figure 19 Sensitivity Graph for an Incineration with CHP Plant

Gasification

The gasification process was originally developed in the 1800s to produce town gas. Gasification is a partial combustion of organic substances such as wood products to produce synthetic gas. Gasification takes place at high temperatures (900^{o}C-1400^{o}C) in an oxygen deficient environment, where combustion cannot occur. The carbon content in the material is converted into a syngas containing carbon monoxide, hydrogen and methane, and various hydrocarbons.

The syngas generated is scrubbed to remove some of the particulates, hydrocarbons, and soluble matter. During syngas cleaning, it is separated into clean gas and a liquid product. The liquid product is a fuel containing acetic acids, acetone, methanol and complex oxygenated hydrocarbons (tar). The liquid product can be processed further for use as synthetic oil as a substitute for conventional oil (AECOM Canada Ltd., 2009).

There are several different gasification processes available or being developed that can be suitable to convert municipal wastes, certain hazardous wastes and dried sewage sludge to chemical feedstock to generate electricity or heat in a gas engine or to generate energy in a hydrogen fuel.

Technology Description

As can be seen in Figure 20, gasification processes can be summarized into five thermal steps as follows:

1. Drying process: it occurs at around 100-150°C to remove the moisture in the biomass before it enters Pyrolysis. Typically the resulting steam is mixed into the gas flow and may be involved with subsequent chemical reactions.
2. Pyrolysis process: it is the application of heat (200-500°C) to raw biomass in an absence of air/oxygen. The biomass breaks down into charcoal and various tar gasses and liquids.
3. Combustion process: it is the combination of combustible gases with oxygen to release heat, producing water vapor and carbon dioxide as waste products. It occurs as the volatile products and some of the char react with oxygen to primarily form carbon dioxide and small amounts of carbon monoxide, which provides heat for the subsequent gasification reactions. The reaction is $C + O_2 \Rightarrow CO_2$.

4. Cracking (gasification) process: it is the process of breaking down tar into lighter gases. This process occurs at 800-1200°C. It is necessary to ensure complete combustion and for the production of clean gas that is compatible with internal combustion engines. This basic reaction is C+ $H_2O \Rightarrow H_2$ +CO
5. Reduction process: it is the direct reverse process of combustion. It occurs by passing carbon dioxide (CO_2) or water vapor (H_2O) across a bed of red-hot charcoal (C). Through this process, CO_2 is reduced by carbon to produce two CO molecules, and H_2O is reduced by carbon to produce H_2 and CO that are both combustible gases. Combustion and Reduction are equal and opposite reactions and in most burning processes, they are both operating simultaneously in some form of dynamic equilibrium. The reaction is summarized in Figure 21 (All Power Labs, 2012).

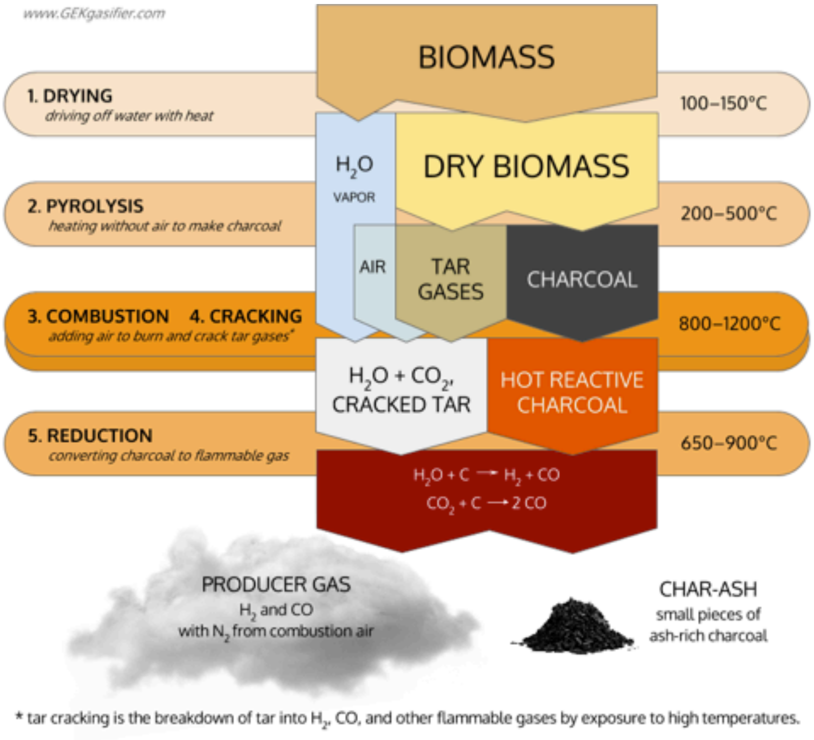


Figure 20 Five Processes of Gasification (All Power Labs, 2012)

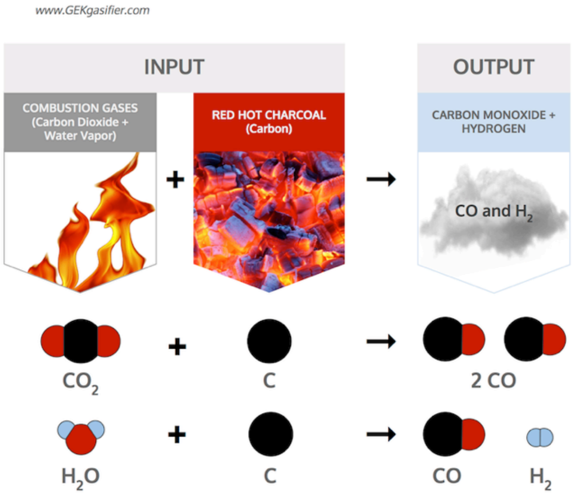


Figure 21 Reduction Reactions, the Heart of Gasification (All Power Labs, 2012)

Figure 22 illustrates the process diagram of an air fed Refuse Derived Fuel (RDF) gasification plant using a heat recovery boiler and stream turbine to generate electricity. The treatment stages are essential to produce clean and high quality of the syngas and the ash generated by the system as well as to minimize the quantity of heavy metals and hazardous constituents in the flue. As previously mentioned, RDF gasification plants perform the five treatment stages: sorting-processing, gasification, combustion of the syngas, electricity generation from steam turbines and treatment of flue gas from the Heat Recovery Boilers (Wilson & et al., 2013).

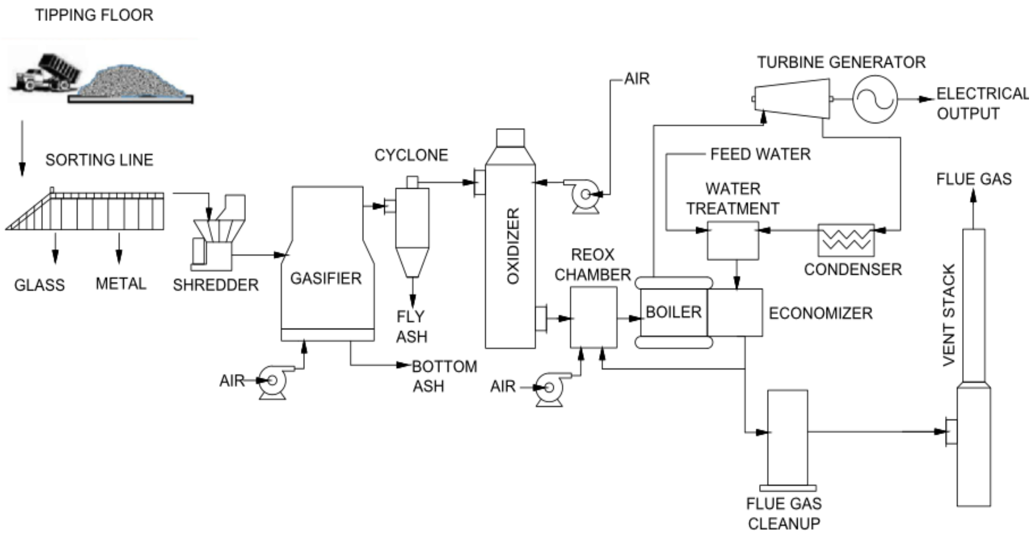


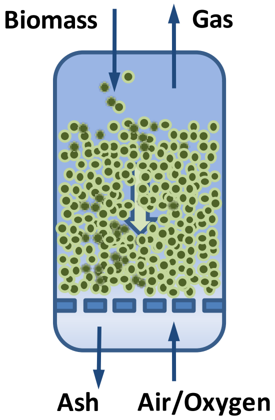
Figure 22 Schematic Diagram of an Air Fed RDF Gasification Power Plant

Plant capacity varies depends on the energy output demand. Most of the available plants are at a pilot scale. There are several types of gasifiers that are commercialized. The list of the principal types are summarized as follows:

1. Updraft Fixed Bed
2. Downdraft Fixed Bed
3. Entrained Flow
4. Bubbling Fluidized Bed
5. Circulating Fluidized Bed
6. Dual Fluidized Bed
7. Plasma

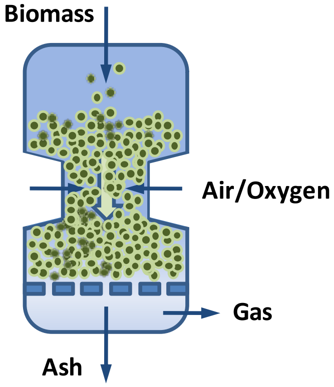
Updraft Fixed Bed

The feedstock is entered from the top of the gasifier and the required air/oxygen or steam intake from the bottom. The biomass and gases move in opposite directions. The product as char burns during the process to provide heat at 1000°C. The methane and tar leaves the gasifier from the top. The ash is collected at the bottom of the gasifier where it drops down from the grate. In the figures, the biomass particles are shown in green, and bed material in blue.



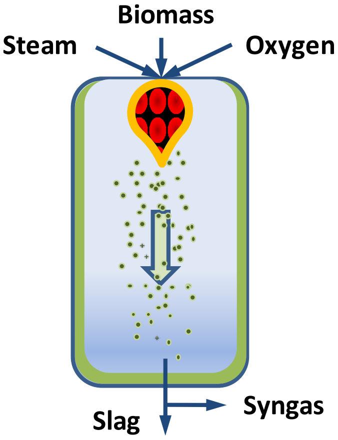
Downdraft Fixed Bed

The same as updraft gasifier, the feedstock is entered from the top but the only difference is the air/oxygen or steam intake enters from the top or the sides. Some of the char produced during the process, falls through the gasifier throat forming a bed of hot charcoal that is acts as a reaction zone. The gases pass through this hot charcoal bed and produce a fairly high quality syngas. Since all tars must pass through a hot bed of char in this configuration, tar levels are much lower than the updraft type. The gas leave the gasifier from the base and ash is collected under the grate at the bottom of the gasifier.



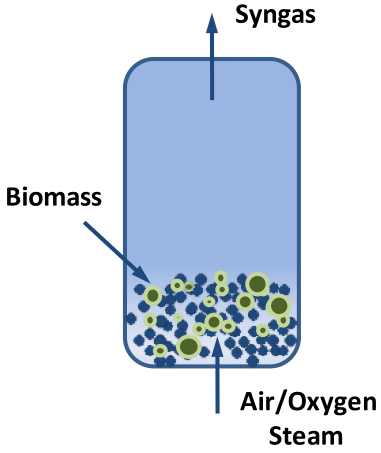
Entrained Flow (EF)

The feedstock in form of powder is entered from the top of the gasifier in the same direction of the air/oxygen or steam intake. The biomass starts burning by a turbulent flame provided at the top. This process produces very high quality syngas at temperature between 1200 and 1500°C that leaves from the bottom of the gasifier. The high temperatures also mean that tar and methane are not present in the product gas. The ash melts and is discharged as molten slag from the bottom. However, some entrained flow gasifiers have an inner water or steam-cooled wall covered with partially solidified slag. These types of gasifiers do not suffer from corrosive slags.



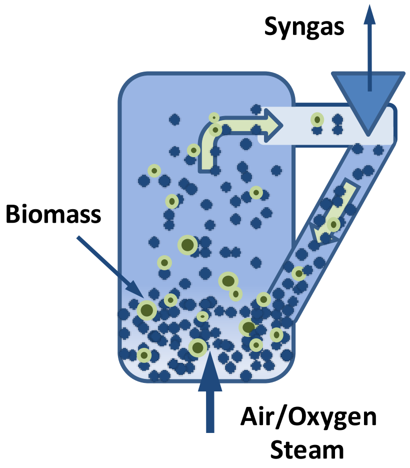
Bubbling Fluidized Bed (BFB)

The feedstock is located at the bottom of the gasifier as a bed of fine materials. The air/oxygen or steam intake is blown upwards thorough the bed (1-3 m/s) to agitate the feedstock. The material is fed from the side and through a combustion process, produces syngas at temperatures below 900°C and leave the gasifier from the top. The ash is removed dry or as heavy agglomerates that is defluidize. Fluidized bed gasifiers are most useful for biomass fuels that generally contain high levels of corrosive ash that would damage the walls of slagging gasifiers.



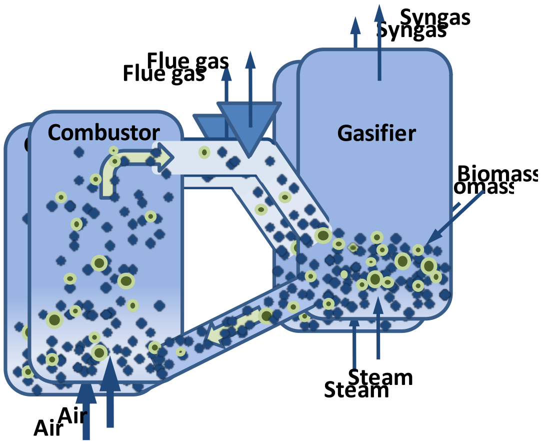
Circulating Fluidized Bed (CFB)

The same as BFB gasifier, the feedstock is located at the bottom of the gasifier as a bed of fine materials. The air/oxygen or steam intake is blown upwards through the bed, a faster than in a BFB gasifier, at 5-10 m/s to agitate the feedstock. The syngas is produced at temperatures below 900°C. The syngas mixed with material particles is separated by a cyclone at the top and the material is returned into the bottom of the gasifier.



Dual Fluidized Bed (Dual FB)

This system includes two chambers, a gasifier and a combustor. The gasifier is the same as CFB/BFB. First, the feedstock is converted to nitrogen-free syngas and char using steam in the gasifier and then the char produced is burnt with existence of oxygen in the CFB/BFB combustion chamber. The bed of hot material is returned to the gasifier to provide the indirect reaction heat. The syngas is separated from the particles at the top of combustion chamber. The temperature of the process is below 900°C.



Plasma

The feedstock is untreated and it can be a mixture of hazardous materials. The feedstock is entered from the top of the gasifier where it contacts with a plasma torch at atmospheric pressure and temperatures of 1,500-5,000°C. High quality syngas produced from the organic materials leaves the gasifier at the top of the gasifier. The inorganic materials are converted to inert slag and collected at the bottom of the gasifier. A plasma arc can be used to clean up the syngas in a subsequent process step.

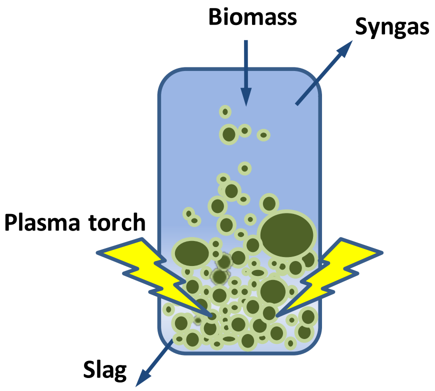


Table 10 presents a comparison of three common types of gasifier. As can be seen, the process in the fluidized bed (FB) gasifiers occurs at the lowest temperatures. Fixed bed gasifiers are small scale and have the simplest construction, however, the feedstock is required to be finely granulated and dried. While FB gasifiers have greater tolerance to particle size and moisture content of the feedstock.

FB gasifiers have a wide range of syngas production capacity. The pressurized BFB, CFB and dual gasifiers have a larger capacity compared to the atmospheric types. EF gasifier is a new type, at a small scale with low levels of tar; therefore, the quality of the syngas is higher than FB types.

Table 10 Process Characteristics of the Three Main Gasifier Types for Waste Treatment

	Fixed bed	Fluidized bed	Entrained flow
Process description	- Downdraft: solid moves down, gas moves down - Updraft: solid moves down, gas moves up	- Bubbling: low gas velocity, inert material stays in reactor - Circulating: inert material is elutriated, separated and recirculate	- Type of fluidized bed - Usually no inert solid, high gas velocity - Can be run as cyclonic reactor
Process temperature (°C)	1000	800-850	1200-1500
Remarks	- Simple and robust construction - Finely granulated feedstock required - Downdraft: low moisture fuels required, low tar content in product gas - Updraft: low exit gas temperature, high levels of tar in product gas	- Greater tolerance to particle size range than fixed beds - Moderate tar levels in product gas - Bubbling: tolerates variations in fuel quality - Circulating: operation more difficult than fixed beds	- Finely granulated feedstock required - Low tar and methane content in product gas - Potential slagging of ash

There are four principal uses of syngas that are currently being explored for production of liquid fuels:

- Fischer-Tropsch synthesis
- Methanol synthesis
- Mixed alcohols synthesis
- Syngas fermentation

Each process has different requirements in terms of the composition of syngas input to the process, and the scale of syngas throughput needed to allow the process to be commercially viable (E4tech, 2009).

Generally, existing gasifiers have lower energy recovery efficiencies than those currently being achieved by modern mass burn incinerators. This is due to the fact that a mass burn process generally results in more complete combustion of the fuel compared to gasification as well as the support fuel/electrical inputs for gasification tend to be higher. The efficiencies of the gasification process depend on how the syngas is used. Efficiencies are in the range of 10% to 20% when the syngas is used to produce electricity using a steam boiler and turbine. It increases to 13%-28% when it is burned in reciprocating engines and in combined cycle gas turbines; they can be as high as 30% and when it is used for district heating (CHP) over 90% of efficiency can be achieved (Stantec, 2010).

A comparison of gasifier types based on feedstock tolerance, syngas quality, development status, scale up potential and costs are summarized in Table 11. Very few plants have been built at the same size. Plants tend to be individually sized according to syngas application and individual site demands or constraints, along with the type and quantity of available feedstock. CFB biomass gasifiers have been commercially mature for heat and power applications but have as yet not progressed to very large scale. BFB plants are built at slightly smaller scale compared to CFB.

Dual fluidized beds have been developed at small scales over a long time, and are expected to be moving to larger scales in the near future.

EF biomass gasification is the newest technology type and currently in small scale, they have been only developed recently for Biomass-To-Liquid (BTL). Plasma gasification plants have mainly been at a small scale in the past, but several much larger plants are planned in the near future for BTL.

Entrained flow and dual fluidized bed gasifiers are the only gasifier types with any pilot or field operating data regarding the production of high quality syngas suitable for liquid fuels. Presents a comparison of gasifier types based on the feedstock tolerance, syngas quality, development status, scale up potential and costs. Plasma gasifiers are very promising in terms of good syngas quality and feedstock flexibility without pre-treatment. However, the technology has so far only been developed for the thermal conversion of wastes for power production, and there is little experience for liquid fuel production (E4tech, 2009).

Table 11 Comparison of Gasifier Types, ● Poor to ●●●● Good (E4tech, 2009)

Gasifier type	Feedstock tolerance	Syngas quality	Development status	Scale up potential	Costs
EF	● Preparation to <1mm, 15% moisture, low ash %, composition unchanging over time	●●● Very low CH_4, C_{2+} and tars, high H_2 and CO	●●● Constructing BTL demos, integration and large scale experience, large industrial players	●●●● Very large gasifiers and plants possible	●●● High efficiency. Expensive pre-treatment if decentralised
BFB	●●● <50-150mm, 10-55% moisture, care with ash	●● C_{2+} and tars present, high H_2 and CO only if O2 blown. Particles	●● Past heat & power applications, modest scale up, some BTL interest	●●● Many large projects planned	●● Possible higher gasifier capital costs and lower efficiency
CFB	●●● <20mm, 5-60% moisture, care with ash	●● C_{2+} and tars present, high H_2 and CO only if O2 blown. Particles	●● Extensive heat & power expertise, research & scale up, but few developers, particularly for BTL	●●● Many large projects planned	●●● Possible higher gasifier capital costs
Dual	●●● <75mm, 10-50% moisture, care with ash	●● C_{2+} and tars present, high H_2, but high CH_4. Particles	● Few and small developers, early stages, only very recent interest in BTL	●● Some projects planned, but only modest scale up	●●● Potential for low syngas production costs
Plasma	●●●● No specific requirements	●●●● No CH_4, C_{2+} and tars High H_2 and CO	●● Several developers, many power applications, early stage of scale-up	● Only small scale, modular systems	● Very high capital costs, low efficiency

Plant size can be determined by the type of the gasifier (see Figure 23). For very large size of facilities (over 100 MW), a pressurized entrained flow gasifier may be the best option but it is very expensive. For the facilities with capacity between 1-10 MW, the best while, less expensive option can be the updraft fixed bed gasifier. Note that the bubbling fluidized bed, dual and plasma gasifiers are not mature for the biomass feedstock (Bosmans, Vanderreydt, Geysen, & Helsen, 2012).

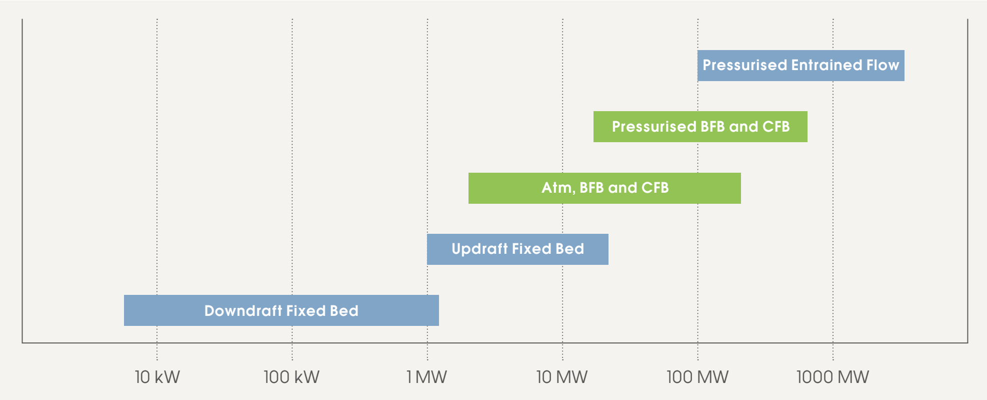


Figure 23 Gasifier Size by Type (IRENA, 2012)

Biomass integrated combined cycle gasification Biomass integrated combined cycle gasification (BIGCC), or biomass integrated gas turbine technology (BIG-GT), as it is sometimes referred to, has the potential to achieve much higher efficiencies than conventional biomass-powered generation using steam cycles by creating a high quality gas in a pressurized gasifier that can be used in a combined cycle gas turbine.

Significant R&D was conducted and pilot-scale plants were built in the late 1990s and the early 2000s. Several demonstration plants were also built. However, performance has not been as good as hoped, and the higher feedstock costs for large- scale BIGCC and the higher capital costs due to fuel handling and biomass gasification has resulted in a cooling of interest. (IRENA, 2012)

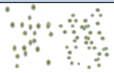
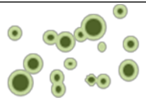
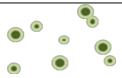
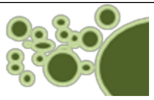
Feedstock Properties and Requirements

Common gasification technologies require extensive front-end processing to provide homogeneous feedstock. The typical application range is 250-500 tonnes per day.

Type of materials: In some gasification technologies, manufactured woods (e.g. plywood), plastic, paper, treated wood or other contaminants are not acceptable.

Size of materials: The requirements of different gasifier types vary considerably: from EF gasifiers requiring small particle sizes, an optimal moisture content and a consistent composition over time, to plasma gasification which can accept nearly all biomass feedstock with minimal or no pre-treatment. CFB and BFB, and Dual systems have intermediate feedstock requirements, being able to accept larger particle sizes and a wider range of moisture contents than EF, but also requiring care over the use of feedstock with low ash melting temperatures, such as agricultural residues.

Table 12 Summary of Feedstock Requirements (E4tech, 2009)

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

The feedstock for the Nexterra Gasification Plant at UBC, utilizing fixed bed gasifier, ranges from 1 to 200 millimeters. Ehsan Oveisi, the PhD Candidate at UBC, advised that the feedstock should be homogenous and the particle size should be small within centimeters.

Table 12 illustrates the feedstock requirements for each gasifier type.

Moisture Content: Feedstock moisture contents above 30% result in a lower gasification thermal efficiency, as energy is needed to evaporate the water, with the resulting steam also affecting the gas composition. Higher moisture contents also reduce the temperatures that are achieved, increasing the proportion of syngas tars in the syngas due to incomplete cracking.

However, drying feedstock to less than 10% requires ever increasing energy inputs, therefore, moisture contents in the range of 10-20% are preferable. Ehsan Oveisi, the PhD Candidate at UBC who is working on the influence of the moisture content of the woody biomass on the gasification process, advised that lower moisture content than 25% in updraft gasifier can result producing small woody dust in the gasifier that is not favorable and can cause technical problems in the process.

Environmental Impacts

Gasifiers release less flue gas than incineration; therefore, air pollution control devices required in gasifiers are smaller and less expensive than incinerators. No gasifier technology is able to directly meet the strict syngas quality requirements for liquid fuels production without gas cleanup, these gases will require cleaning and conditioning to remove contaminants such as tar, particulates, alkali, ammonia, chlorine, and sulfur. However, some gasifiers produce slightly more suitable syngas than others. This can lead to decreased requirements for certain components in the syngas cleanup and conditioning, with corresponding reduced or avoided costs.

As previously mentioned, syngas cleanup is one of the gasification process by which syngas is cleaned by a chemical process that produces residues. Generally, the by-products of burning syngas are similar to those of natural gas, therefore, an additional NOx control may be needed. Nevertheless, available cleanup technologies do not yet meet the needed cost, performance, or environmental criteria needed to achieve commercial implementation (E4tech, 2009), (AECOM Canada Ltd., 2009). Add to this complexity of emission control in gasification, the chemical composition of the wood waste at the VLF is unknown. Therefore, the emissions produced from gasification process of this type of materials still remain unknown.

As mentioned previously in the “Wood Waste as a Fuel” part, ash is the inorganic material in biomass that cannot be gasified and remains as residues at the end of the process. It ranges from less than 1% (on a dry mass basis) in wood to above 20% in some animal manure and herbaceous crops (e.g. rice straw). And it is clear that low-ash content feedstock (<5%) is usually preferable to minimize disposal issues (E4tech, 2009). Chemical composition of ash is very important and it depends on the chemical composition of the feedstock. As the wood waste at the VLF may consist of heavy metals, ash control will become an important issue in the gasification and pyrolysis processes.

The author could not find any gasification plants that utilize a large amount of treated and painted wood as feedstock. In the “Case Study” part in Appendix A 1, examples of gasification plants that utilize RDF, plastics, tires, clean wood and hospital waste will be described.

Summary

Gasification is a partial combustion of organic substances with limited air. Gasification processes are being developed for the treatment of municipal wastes, certain hazardous wastes and dried sewage sludge. Very large gasification plants can use multiple gasifiers as part of a modular system, rather than a single large gasifier. By this feature it is possible to add or take away the mass or volume of organic matter changes, however, it increases in gasifier capital costs, due to the loss of economies of scale. Pre-processing is required and it is important to keep the size, consistency and moisture content (10-25%) within certain predefined limits. Metals can be more of an issue so they should be removed from the feedstock. The MSP materials in entrained flow, fluidized bed or cyclone gasifiers must be finely granulated. Hazardous wastes, on the other hand, may be gasified directly if they are liquid or finely granulated.

The minimum syngas throughput needed to make the facility economically viable helps to determine the most suitable type of gasifier. For the VLF, the final products of the gasification process cannot be easily determined due to unknown feedstock specifications and uncertain volume of the VLF’s wood waste as well as unclear market drivers in the area. Therefore, it is hard to determine the most suitable type of gasifier. Nevertheless, updraft gasifier is robust, simple and suitable for facilities with a capacity of energy output between 1-50 MW that may be suitable for the VLF’s wood waste. However, the main issue is high levels of tar that is produced in the syngas.

The Nexterra Plant at UBC utilizes the updraft gasifier. At this facility they are dealing with high levels of tars and steam in the syngas that significantly reduces the quality of the product. One advantage of this technology compared to incineration is lower emissions and predominant formation of CO rather than CO2. As previously mentioned, the main issues regarding the painted and treated wood are emissions and residues of heavy metals, e.g. arsenic, chromium, copper, lead, zinc and mercury that produced by thermal treatments. Some research has shown that oxygen-deprived processes such as pyrolysis or maybe gasification may release less heavy metals in emissions but mostly captured in the solid and liquid products of the process. Nonetheless, applicability of these technologies for the painted and treated wood waste has not been proven.

While this technology is not fully commercialized in large scale for MSW, the author could not find a gasification plant utilizing a certain amount of the contaminated wood waste as feedstock. The technology suppliers claim that their facilities can handle this type of feedstock but there is no proof for this. The capital and operating costs of gasification is higher than incineration due to the equipment and operation complexity.

In Appendix A 1, the following facilities, which use gasification technology, are described:

1. Nexterra Facility at UBC, Canada
2. Energos Gasification Facility, Norway
3. The Güssing Biomass CHP Plant (Austria)
4. Enerkem Gasification Facility, Edmonton, Canada

Applicability of Gasification for the Wood Waste at the VLF

The suggested location and the size of the VLF's future facility are determined in a map, which can be found in Appendix 5.

Feedstock specifications and requirements:

It is predicted that the VLF will be receiving approximately 57,000-90,000 tonnes per year of wood waste by 2040. Therefore, the facility is expected to handle a throughput up to 100,000 tonnes per year. The feedstock consists of clean wood and treated/painted wood waste in the earlier years and nearly zero clean wood after 2025. The size of the feedstock varies from centimetres to couple of metres and they contain metallic materials at around 1.2%. Therefore, the feedstock should be shredded or grounded to less than 200 mm and metals should be removed by magnets.

The moisture content of the feedstock is assumed to be 25-30%. Except for a plasma gasifier that is not sensitive to the type, size and moisture content of the feedstock, other gasifiers require feedstock preparation. The favorable moisture content for gasification is 10-20%. In this case, drying may/may not be required.

The feedstock preparation phase is expected to be unknown, both from a technical and cost perspective, to the viability of a gasification plant using the treated/painted wood waste as its feedstock.

Technology:

Gasification with updraft gasifier or plasma gasifer may work, however, there is not enough experience of using gasification for a large amount of treated/painted wood waste. There may be fundamental issues with the products of the process and their applicability. The quality of syngas may not be sufficient enough to be used in CHP and residues that are about 15% of the feedstock (by weight), may be contaminated with heavy metals and cannot be used as a fuel, therefore, it might have to be treated and then landfilled. Based on several research conducted and interviews performed with the technology suppliers, the author found out that there has not been enough experience with this process for the VLF's special type of feedstock to be considered commercially proven.

Method of energy recovery:

If gasification process can work for the treated/painted wood waste, as mentioned earlier, there will be still be main issues related to products such as the quality of syngas and toxicity of the residue. Nevertheless, producing electricity and steam by utilizing the syngas into a CHP may be an option. CHP system will generate electricity and heat at 30% and 70% of the total produced energy, respectively. The electricity will be purchased by BC Hydro at \$136/MW (electricity) and heat will be utilized in district heating at \$40/MW (thermal).

Environmental impacts:

As previously mentioned, there is no data available on the chemistry of the wood waste at the VLF. However, it is expected to have heavy metals and formaldehyde contaminations. Although gasification might produce fewer emissions, the level of toxicity of the emissions and the residues is unknown. However, a complicated and costly APC system may be required to control heavy metals in the emissions. Residue treatment may be necessary as landfilling of toxic residues is not a permanent and sustainable solution.

Economics details:

The cost of gasification plants depends on the type of the gasifier in terms of feedstock preparation, scale, fuel synthesis and plant integration. However, all this information may not be available for a precise estimation. Furthermore, immaturity and complexity in the gasification process in a large scale add more uncertainty to the analysis. Uncertainty in the costs also comes from the inflation, location, scale, currency exchange rate and assumptions that have to be made (E4tech, 2009).

Financial parameters and assumptions for an economic assessment of the future gasification plant at the VLF were described in “Project Assumptions” section of this report. Table 13 illustrates the capital, operational & maintenance costs and revenue estimates. The Nexterra UBC plant produces steam and electricity by CHP with an efficiency of up to 60%. Güssing Biomass CHP Plant has an electrical efficiency of 25% and a heat efficiency of almost 50%. Therefore, efficiency of the gasification process is assumed 60% in this report. The portion of electricity and heat generation is assumed 30% and 70%, respectively. The capital and operating

& maintenance costs are derived from case studies (with throughput of 100,000 tonnes per year) in a report under the title of "Review of Alternative Solid Waste Management Methods" prepared by "EarthTech" (now AECOM) in 2005. All costs were converted to the 2015 appraised value.

If the City of Vancouver decides to install a gasification plant for the treated/painted wood waste according to the VLF's feedstock specifications, the NPV and IRR are negative values and the plant is expected to lose money at nearly $58 million over the life of the facility, more details and calculation parameters can be found in Appendix 17. The breakeven tipping fee for this process is $125 per tonne.

Table 13 Gasification Process: Capital, Operational & Maintenance Costs and Revenue Estimates

Financial Parameters	
Discount Rate	6%
Life of the Facility & Amortization Period (years)	20
Nominal System Specifications	
Average Annual Throughput Rate (tonne)	65,608
Electricity Output (MW (electricity) net)	2
Heat Output (MW (thermal) net)	8
Capital Costs	
Direct Capital Costs	$79,000,000
Indirect Costs	$9,000,000
Contingency (17%)	$13,430,000
Total Capital Costs	$101,430,000
Annualized Capital Costs	$5,071,500
Operating Costs	
Fixed & Variable Operating Costs	$7,512,171
Assumed Electricity Sales Rate per MWh	$136
Assumed Heat Sales Rate per GJ	$40
Assumed Ferrous Metal Sales	$150
Assumed Non-Ferrous Metal Sales Rate	$1,600
Current DLC Tipping Fee Rate, per tonne	$60
Predicted Annual Revenue	$15,434,195
Net Results	
NPV	($58,049,697.95)
IRR	-6%
Breakeven Tipping Fee, per tonne	$125

Figure 24 illustrates the sensitivity of the NPV to different parameters such as tipping fee, sale price for electricity and heat, throughput rate, generation portions of heat and power, efficiency of the CHP system, capital and operating & maintenance costs. As can be seen, the important parameters that can influence the NPV of the plant are quite different from those in incineration plants. The parameters that influence the NPV are ranked, from the most to the lease important, are as follows:

1. Operating & maintenance costs
2. The capital costs
3. Sale price of heat
4. Throughput rate
5. Tipping fee
6. Percentage of heat and power generation
7. Efficiency of the Process (gasification with CHP)
8. Sale price of electricity

Interestingly, operating & maintenance costs influence the NPV similar to the capital costs. Due to high capital costs, even if the costs decrease by half, the NPV will not be positive. High capital costs are expected because of the uncertainties regarding to the process and sensitive equipment of the process. The sale price of heat and throughput rate are still two important factors. However, by increasing/decreasing the magnitude of these parameters to double/half, only sale price of heat can produce a positive NPV. Nevertheless, this change might not be realistic due to the low price of natural gas in BC.

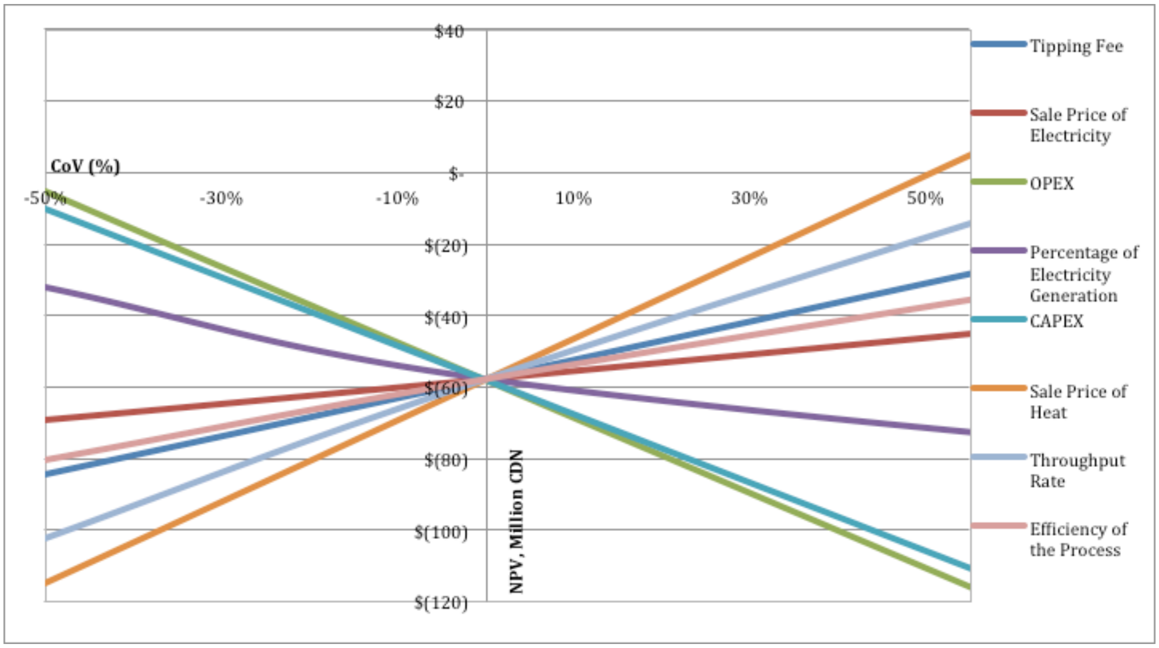


Figure 24 Sensitivity Graph for Gasification with CHP Plant

Pyrolysis

Gasification and pyrolysis are similar except for the source of heat and the products. Pyrolysis system uses an external source to heat to drive the process whereas gasification uses the heat from the waste generated inside the reaction chamber. Gasification is set to produce gaseous fuel while pyrolysis is optimized the production of liquid and solid fuel. Basically, pyrolysis is used in chemical industry to produce charcoal, activated carbon, methanol from wood, etc.

Technology Description

Similar to gasification process but without any air or oxygen input, pyrolysis thermally degrades the waste in the absence of air to produce pyrolysis oil, char and syngas. Pyrolysis reactions occur at temperature range of $400^{o}C$ to $800^{o}C$. Pyrolysis technology constitutes the following steps:

1- Preparation and grinding: Grinding improves and standardizes the quality of the waste presented for processing and promotes heat transfer during the process. Depending on process a separated drying step may be required to improve the LHV of the raw process gases and increase efficiency of gas-solid reactions within the rotary kiln

2- Smoldering process at temperatures between <u>400 and 600°C</u>: Formation of gas from volatile waste particles

3- Pyrolysis process at temperature between <u>500 and 800°C</u>: Thermal decomposition of the organic molecules of the waste resulting in formation of gas and a solid fraction

4- Gasification process at temperature between <u>800 and 1000°C</u>: Conversion of the carbon share remaining in the pyrolysis coke with the help of a gasification substance (e.g. air or steam) in a process gas (CO, H2)

5- Incineration: Depending on the technology combination, the gas and pyrolysis coke are combusted in an incineration chamber for the destruction of the organic ingredients and simultaneous utilization of energy.

The oil produced can be used directly in fuel applications and solid char may be used as a solid fuel, carbon black or upgraded to activated carbon. Most of the waste pyrolysis systems are still at pilot-scales and for specific industrial waste streams like sewage sludge, and hazardous waste such (EPD, 2009). Gasifiers used in pyrolysis technology are the same as gasification. Different types of gasifiers were described previously in the gasification part.

Generally, products of the pyrolysis (charcoal, pyrolysis oil and syngas) may deal with technical, environmental and economic problems. To avoid complications and provide an appropriate tool for comparison, a combination of pyrolysis process and CHP is evaluated in the Financial Analysis part. Generating heat and electricity from the syngas produced by the process may be a better option according to the VLF's wood properties. Figure 25 illustrates a MSW treatment facility constitute a combination of pyrolysis and CHP. This type of facility is described in more detail for the Müllpyrolyseanlage (MPA) MSW Pyrolysis Plant in the Case Study part.

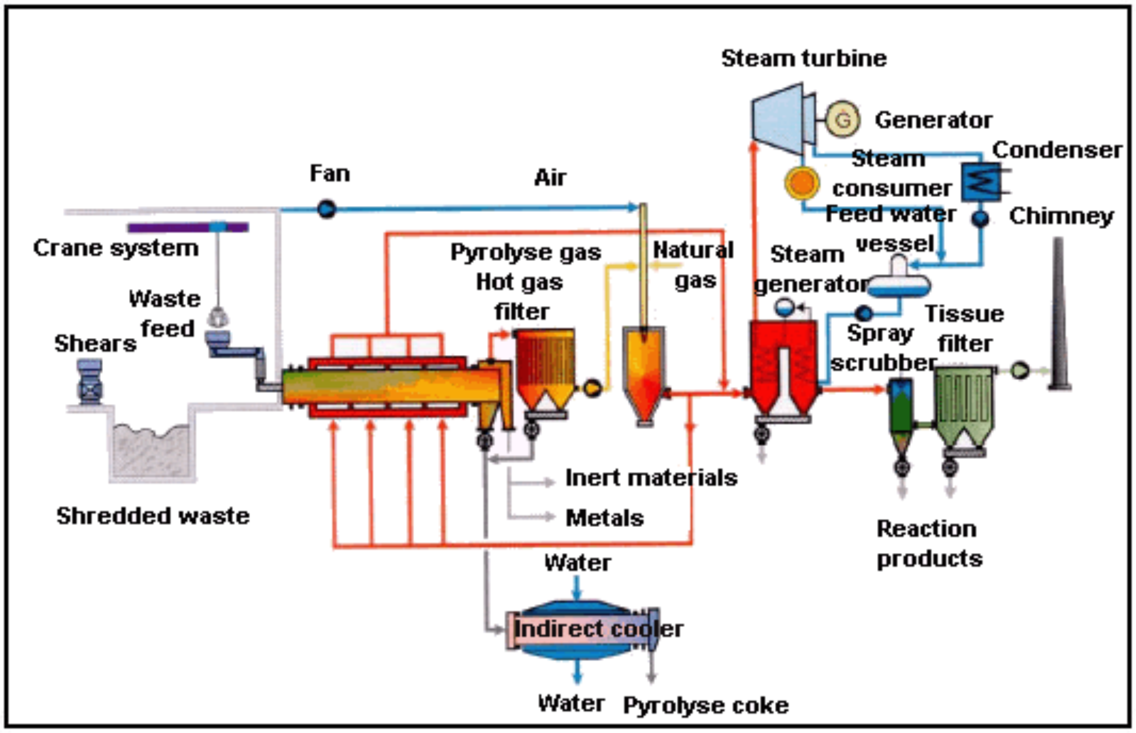


Figure 25 Structure of a Pyrolysis Plant for MSW Treatment

Development Status and Operating Experience

While pyrolysis of biomass continues to be developed on a relatively small scale, no commercial plants for the pyrolysis of MSW or wood waste are operating in North America. Pyrolysis was applied for MSW in the 1970s, but the plants failed to achieve acceptable technical or economic performance, and all have been shut down.

Chartherm process (Thermya, France) can be a candidate for the best available technology to treat chromated copper arsenate (CCA) impregnated wood waste. This technology is described in the Case Study part. This technology can be suitable for the VLF's wood waste. However, it is still in the development stage.

Generally, after reviewing available reports on pyrolysis, it is concluded that this technology is too risky to apply in a large scale. From the technical and economic aspects, even small-scale facilities have been dealing with serious problems and not the least of which is the refining of the various pyrolysis products for commercial use. There is no universally accepted specification or standards for bio oil that is due to insufficient studies on the biological and environmental effects of large-scale bio-oil production by pyrolysis.

Feedstock Properties and Requirements

Similar to the gasification technology, the feedstock is required pre-processing to provide homogenous feedstock and appropriate particle size. The largest facility (located in Japan) processes approximately 150,000 tonnes per year of RDF (or SRF). The typical application range is 10-100 tonnes per day.

Size of materials: The maximum particle size for MSW feedstock is 30 centimeters at the Müllpyrolyseanlage (MPA) MSW Pyrolysis Plant in Germany. However, to control arsenic and other heavy metals that exist in the VLF's wood waste, the particle size is an important factor that will be described in the Environmental Impacts part. However, no exact figure is defined as the most suitable particle size for the contaminated wood waste utilized in pyrolysis.

Type of materials: In addition to the thermal treatment of some municipal wastes and sewage sludge, pyrolysis processes are also used for:

- Decontamination of soil
- Treatment of synthetic waste, used tires, RDF, railway ties, electronics waste and hospital waste
- Treatment of cable tails as well as metal, polyvinyl chloride and plastic compound materials for substance recovery.
- Treatment of wastewater

Moisture Content: There is no exact figure for the moisture content of the feedstock, however, it is around 25% at the Müllpyrolyseanlage (MPA) MSW Pyrolysis Plant in Germany.

Environmental Impacts

As the wood waste at the VLF may contain CCA, zinc and lead, several research studies were done to find out if pyrolysis technology can handle the air and ash pollution produced by the process. Lieve Helsen and her colleagues at the University of Leuven in Belgium have done experimental studies on low-temperature pyrolysis under the name of "Chartherm Process", the detail of which is described in the Case Study part of this section. Helsen investigated the influence of particle size, heating rate, temperature, residence time and pressure on metal retention during pyrolysis, to understand the mechanisms causing heavy metal volatilization and to identify optimal process conditions that minimize heavy metal volatilization while a good quality of charcoal is assured. Their conclusions are summarized as follows:

- Particle size of the feedstock is an important factor to release the metals during the process. Particle size showed a pronounced effect on arsenic and chromium volatilization. Larger particles result in a higher arsenic and chromium retention that is attributed to a higher mass transfer resistance in these particles. Elevated pressure changes the proportions between the different classes of particles only for chromium retentions. This is due to the enhanced heat transfer at elevated pressure, resulting in a reduced thermal lag and thus higher average particle temperature during heating.
- Heating rate mostly can affect chromium retentions primarily through a higher thermal lag of the inner particle temperature at high heating rates.

- Arsenic retentions decreased slightly with increasing temperature till 390 ◦C with a sharp decrease at higher temperatures. Chromium retentions showed an opposite profile with a faster decrease in retention at temperatures lower than 390 ◦C and a limited decrease at higher temperatures.
- Pyrolysis temperature and duration of the pyrolysis process have a great influence on the release of metals and the mass reduction. The optimal results are taken at temperature of at least 370°C during 20 minutes when using a nitrogen low rate of 5Nm^3/h. Under this condition, a minimal loss of metal and high mass reduction can occur. A longer residence time and lower temperature result in a similar wood conversion while reducing chromium and arsenic volatilization, however a lower plant capacity is obtained.
- Elevated pressure causes arsenic retentions to increase by about 5% at 5 bar gage pressure that is attributed to a higher mass transfer resistance at elevated pressure. The effect of elevated pressure on chromium retentions is less clear.
- Chromium is even stronger bound in the pyrolysis residue compared to the original CCA treated wood.

In practice, CCA-treated wood waste after long-term weathering may contain only a small amount of unreacted arsenic compound, because the free arsenic compound may have already been washed or leached out from the treated wood. However, this kind of wood should be handled carefully as there may contain a significant amount of unreacted arsenic compound. Low-temperature pyrolysis is a valuable and promising technique to dispose of CCA treated wood waste. However, arsenic is distributed over the three products (charcoal, bio-oil and pyrolysis gas); no time-temperature threshold found for zero arsenic volatilization. There is no additional advantage of pyrolysis over the other thermal technologies can be found except the elimination of dioxins and furans formation and possibly easier metal recovery, however, more research is needed to evaluate the process.

In another study performed by Kakitani and colleagues, similar results were concluded that the toxic metals in CCA-treated wood were highly stabilized by heating at 300°C for duration of 60 minutes. Immobilization of toxic elements in the residue was promoted by pyrolysis, resulting in the transformation of toxic metals to various types of stable compounds. They also confirm that it is possible to restrain Arsenic via the pyrolysis of CCA-treated wood if the wood contains little unreacted arsenic, and if the wood is carefully pyrolyzed at temperatures around 300-350°C. Under these conditions, almost all of the elements remain in the pyrolysis residue (Kakitani, Hata, Kajimoto, & Imamura, 2004).

The main problem of all three thermal treatment and specially pyrolysis is the residues. Similar to landfilling of the CCA-treated wood waste, landfilling of pyrolysis residue is also a poor disposal method. Landfilling only postpones the collection of the toxic metals, and will lead to many future problems when the toxic elements finally diffuse.

Kakitani et al. confirmed that the CCA elements in the pyrolysis residue were highly stable against leaching or extracting, however, the arsenic trioxide formed in the pyrolysis residue is more toxic than arsenic pentoxide. Thus, the landfilling of pyrolysis residues is also a poor solution because of their high toxicity. The further development of a suitable method of extracting solvents from waste wood may be the best solution to the problem. To the end, additional investigations into the mechanism of immobilization will be needed (Kakitani, Hata, Kajimoto, & Imamura, 2004).

Summary

Pyrolysis is the process of degassing of feedstock in the absence of oxygen to form pyrolysis gas and a solid coke. Pre-processing of the feedstock is required to provide pure and homogeneous waste streams. Similar to gasification plants, pyrolysis plants are made up of small units that can be added to or taken away when the mass or volume of organic matter changes.

The main advantage of this technology is its less air emissions due to the technology specifications but products and residues can be toxic based on the feedstock properties. In this point of view, this technology may be more suitable for the contaminated wood waste at the VLF. As previously mentioned, the main issues regarding the painted and treated wood are emissions and residues of heavy metals, e.g. arsenic, chromium, copper, lead, zinc and mercury that produced by thermal treatments.

Researchers, as such Lieve Helsen at the University of Leuven in Belgium, are still working on the applicability of pyrolysis technology what they call it as the "Chartherm Process" for treatment of the CCA-treated wood. She concluded that under certain conditions such as at temperature of 370°C, residence time of 20 minutes and pressure of 5 bar, most of heavy metals can be captured from the solid or liquid products of the process with minimal air emissions.

Kakitani and colleagues at Kyoto University in Japan, have been conducting research on pyrolysis technology for treatment of CCA-treated wood as well as utilizing strong acid such as sulfuric acid to dissolve and extract CCA compounds from the CCA-treated wood. However, they all confirm that more research is required to be done for a final conclusion.

The technology is still under development and the capital and operating costs are very expensive. Information in regards to capital and operating costs for current pyrolysis plants is scarce, and many projects must be considered on a case-by-case basis to determine their economic feasibility (Stantec, 2010), (Lombardi, Carnevale, & Corti, 2014).

In Appendix A 1, the following facilities, which use pyrolysis technology, are described:

1. Müllpyrolyseanlage (MPA) MSW Pyrolysis Plant, Germany

2. Toyohashi Waste Treatment Recovery and Resource Center, Toyohashi, Japan
3. Hamm Facility, Dortmund, Germany
4. Chartherm Process Plant, Thermya, Bordeaux, France

Applicability of Pyrolysis for the Wood Waste at the VLF

The suggested location and the size of the VLF's future facility are determined in a map, which can be found in Appendix 5.

Feedstock specifications and requirements:

It is predicted that the VLF will be receiving approximately 57,000-90,000 tonnes per year of wood waste by 2040. Therefore, the facility is expected to handle a throughput of up to 100,000 tonnes per year. The feedstock consists of clean wood and treated/painted wood waste in the earlier years and nearly zero clean wood after 2025. The size of the feedstock varies from centimetres to couple of metres and they contain metallic materials at around 1.2%.

Pyrolysis process is sensitive to the size, moisture content and material types of the feedstock. Therefore, the feedstock should be shredded or grounded to less than 200 mm and metals should be removed by magnets.

The moisture content of the feedstock is assumed between 25-30%. The favorable moisture content for pyrolysis process is 10-20% and it should be less than 25%. In this case, drying may/may not be necessary.

The feedstock preparation phase is expected to be unknown, both from a technical and cost perspective, to the viability of a pyrolysis plant using the treated/painted wood waste as its feedstock.

Technology:

Pyrolysis may be the best thermal treatment for the VLF's wood waste due to the lower temperature of the process, heavy metals may retain in the residues instead of being released as emissions. However, there is not enough experience of using pyrolysis for a large amount of treated/painted wood waste. There may be complications in the process and the issues with the quality of products. Similar to gasification, the quality of syngas may not be sufficient enough to be used in CHP and the char/residue that is about 15% of the feedstock (by weight), may be contaminated with heavy metals and cannot be used as a fuel, therefore, it has to be treated and then landfilled.

Method of energy recovery:

If pyrolysis process can work for the treated/painted wood waste, as mentioned earlier, there will be still main issues related to products such as the quality of syngas and toxicity of the residues. Nevertheless, producing electricity and steam by utilizing the syngas into a CHP may be an option. CHP system will be utilized to generate electricity and heat at 30% and 70% of the total produced energy, respectively. The electricity will be purchased by BC Hydro at $136/MW (electricity) and heat will be utilized in district heating at $40/MW (thermal).

Environmental impacts:

As previously mentioned, there is no data available on the chemistry of the wood waste at the VLF. However, it is expected to have heavy metals and formaldehyde contaminations. Although pyrolysis might produce fewer emissions, in a large-scale, the level of toxicity of the emissions and the residues is unknown. Complicated and costly APC system may be required to capture heavy metals from the emissions. Residue treatment is necessary as landfilling of toxic residues is not a permanent and sustainable solution.

Economics details:

Similar to gasification, the cost of pyrolysis plants depends on the type of the gasifier in terms of feedstock preparation, scale, fuel synthesis and plant integration. However, all this information may not be available for a precise estimation. In addition, pyrolysis is less mature than gasification; therefore, complications in the process add more uncertainty to the analysis. Uncertainty in the costs is also comes from the inflation, location, scale, currency exchange rate and assumptions that have to be made (E4tech, 2009).

For the future pyrolysis plant at the VLF, financial parameters and assumptions for an economic assessment were defined in “Project Assumptions” section of this report.

Table 14 illustrates the capital, operational & maintenance costs and revenue estimates. The portion of electricity and heat generation is assumed 30% and 70%, respectively. Therefore, efficiency of the pyrolysis process is assumed 65% in this report. The portion of electricity and heat generation is assumed 30% and 70%, respectively. The capital and operating & maintenance costs are derived from case studies (with throughput of 100,000 tonnes per year) in a report under the title of "Review of Alternative Solid Waste Management Methods" prepared by "EarthTech" in 2005. All costs converted to the 2015 appraised value.

A pyrolysis plant for the treated/painted wood waste at the VLF will be very expensive and not profitable at all. The NPV of the plant is negative and the plant will lose money at approximately $138 million over 20 years, more details and calculation parameters can be found in Appendix 18. The breakeven tipping fee for this process is $215 per tonne.

Table 14 Pyrolysis Process: Capital, Operational & Maintenance Costs and Revenue Estimates

Financial Parameters	
Interest Rate	6%
Life of the Facility & Amortization Period (years)	20
Nominal System Specifications	
Average Annual Throughput Rate (tonne)	65,608
Electricity Output (MW (electricity) net)	2
Heat Output (MW (thermal) net)	9
Capital Costs	
Direct Capital Costs	$117,500,000
Indirect Costs	$8,000,000
Contingency (17%)	$19,975,000
Total Capital Costs	$145,475,000
Annualized Capital Costs	$7,273,750.00
Operating Costs	
Fixed & Variable Operating Costs	$9,247,564.75
Assumed Electricity Sales Rate per MWh	$136
Assumed Heat Sales Rate per GJ	$40
Assumed Ferrous Metal Sales	$150
Assumed Non-Ferrous Metal Sales Rate	$1,600
Current DLC Tipping Fee Rate	$60
Predicted Annual Revenue	$16,285,181
Net Results	
NPV	($138,282,158.81)
IRR	N/A
Breakeven Tipping Fee, per tonne	$215

Figure 26 illustrates the sensitivity of the NPV to different parameters such as tipping fee, sale price for electricity and heat, throughput rate, generation portions of heat and power, efficiency of the CHP system, capital and operating & maintenance costs.

As can be seen, similar to gasification, the important parameters that can influence the NPV of the plant are quite different from those in incineration plants. The operating and capital costs and the sale price of heat are more important factors. However, by changing the value of all parameters by -50% or +50%, the NPV will be still negative. Capital costs are very expensive and this makes the plant impossible to be profitable. Combination of changes in the parameters that were assessed might provide a positive NPV for the plant. A detailed financial assessment is required to find the best changes to obtain a positive NPV.

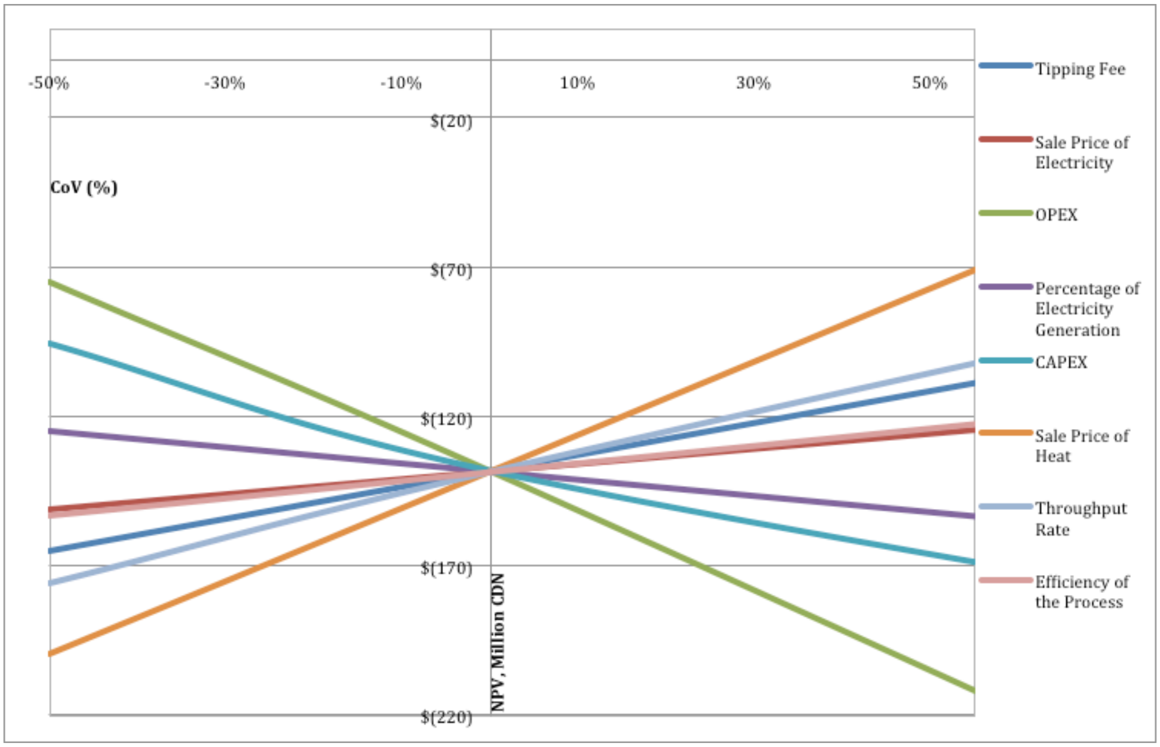


Figure 26 Sensitivity Graph for a Pyrolysis with CHP Plant

Discussion and Evaluation

For three thermal conversion technologies discussed above, five parameters, summarized in Table 15, will be assessed to find the most suitable conversion technology for the VLF's wood waste these are as follows:

Table 15 Summary of Thermal Conversion Technologies and Five Assessment Parameters

	Incineration	Gasification	Pyrolysis
Suitability of the feedstock	**Yes**	**No**	**No**
Applicability of the technology	**Yes**	**Unknown**	**Unknown**
Efficiency of energy recovery (CHP)	**Low**	**Low-Moderate**	**Moderate**
Environmental Impacts			
Air emissions (without special APC)	**High**	**Unknown**	**Unknown**
Air emissions (with special APC)	**Unknown**	**Unknown**	**Unknown**
Ash/biochar/Residues	**Moderate-High**	**High**	**High**
Profitability For the VLF	**Low**	**Low**	**Low**

1. Suitability of the VLF's Wood Waste as Feedstock

It is predicted that the VLF will be receiving approximately 57,000-90,000 tonnes per year of wood waste by 2040. Therefore, the facility is expected to have a capacity of around 100,000 tonnes. The feedstock consists of clean wood and treated/painted wood waste in the earlier years and nearly zero clean wood after 2025.

The size of the wood waste at the VLF varies from a couple of centimetres to a couple of metres or greater. The moisture content is assumed to be between 20% and 30%.

Incineration can handle the size, moisture content and the magnitude of the VLF's wood waste. The moisture content and the magnitude of the feedstock may be suitable for gasification and pyrolysis process. However, gasification and pyrolysis are sensitive to the feedstock size and preparation of the feedstock such as size reduction and drying is required.

2. **Applicability of the Technology**

All three technologies can handle woody feedstock provided it meets the requirements. However, the feedstock preparation phase is expected to be unknown, both from a technical and cost perspective, to the viability of a gasification and pyrolysis process using the treated/painted wood waste as its feedstock.

Incineration with a rotary kiln may be more suitable for the treated/painted wood waste. This type of combustor is utilized in cement plants to reduce emissions. According to the research that the author conducted on a couple of cement and pulp mill plants located in BC, their feedstock can be combination of clean wood and a contaminated wood, plastics, RDF, tires and other combustible materials, however, they do not use a large amount of treated/painted wood as feedstock. The technology is mature and there might not be any complications in the process.

Gasification with a fixed bed updraft gasifier or plasma gasifer may work, however, there is not enough experience of using gasification for a large amount of treated/painted wood waste. There may be fundamental issues with the products of the process and their applicability. The quality of syngas may not be sufficient enough to be used in CHP (Combined Heat and Power) system. Residues may also be contaminated with heavy metals, which cannot be used as a fuel, therefore, it has to be landfilled.

Pyrolysis also may work but similar to gasification, the quality of the products and residue contamination are significant. Gasification is not as mature as incineration. Both pyrolysis and gasification processes might encounter serious technical and financial complications.

Based on several research conducted and interviews performed with the technology suppliers, the author found out that there has not been enough experience with all these processes for the VLF's special type of feedstock to be considered commercially proven.

3. **Efficiency of Energy recovery and Quality of the Product**

The calorific value of the wood waste is considered approximately 12.6 GJ/tonne. The moisture content has an important influence on the net calorific value. It is assumed that the moisture content of the VLF's wood waste is around 25%.

The product of an incineration process is steam and power. Gasification process can produce syngas, ethanol and other fuels. Pyrolysis products are biochar, pyrolysis oil and gas. However, due to the unknown toxicity levels of the treated/painted wood waste at the VLF, the quality of all products is unknown. It may be possible to produce a good quality of products but it cannot be assured. To avoid complications, steam and power are assumed to be the final products of all three thermal technologies discussed in this report.

Combined Heat and Power (CHP) is a high efficiency system to produce heat and electricity. All three technologies can be adapted to this system. Efficiency of combined pyrolysis-CHP is the highest and combined incineration-CHP is the lowest but the quality of syngas cannot be assured. The efficiencies of the combined CHP systems are assumed to be 50%, 60% and 65% for incineration, gasification and pyrolysis, respectively. The author also found couple of sources indicating very high efficiency for the CHP system, however, unknown feedstock properties and technology applicability may be an obstacle to gain a very high efficiency.

4. Environmental impacts

There is no data available on the chemistry of the wood waste at the VLF. However, it is expected to have heavy metals and formaldehyde contamination. Thus, application of thermal conversion technologies may be problematic because of the susceptibility to having heavy metals in emissions, products and residues. Therefore, environmental impacts should be assessed for air emission and ash/residue contaminations. Helsen et al., from the University of Leuven in Belgium, clearly showed that the mechanism of metal volatilization (particularly arsenic) during the thermal decomposition of CCA-treated wood is not yet completely understood. While the CCA preservative chemicals are relatively simple, inorganic reactions during the wood preservation process produce complicated inorganic compounds and complexes and the thermal decomposition of them is unknown and difficult to determine.

Pyrolysis process may produce less toxic emissions than incineration due to the process specifications. Similar to pyrolysis, gasification is cleaner than incineration due to a cleanup

process used for syngas. In addition, modern and expensive Air Pollution Control (APC) systems can capture most pollutants and discharge it as residues. Combination of ACS such as dry, semi-wet and wet scrubbers, Selective Catalytic Reduction/Selective Non-catalytic Reduction (SCR/SNCR) Electrostatic Participators (ESP), baghouses, and the addition of activated carbon and lime can control Particulate Matter (PM), NOx, SOx, HCL, heavy metals and dioxins/furans.
Several studies have been conducted to reduce heavy metals in emissions only by changing specific parameters of the pyrolysis process, such as temperature, residence time and pressure to reduce the ACS costs, however, the results have not yet been proven.

Residues may be the main problem related to the treated/painted wood waste and all three thermal treatments, especially pyrolysis. The residues produced by the process and APC systems require special treatment and handling. The author found out that full treatment of the residues contaminated with heavy metals might not be possible. In addition, landfilling the residue is a poor disposal method and it only postpones the retention of the toxic metals, and will lead to many future problems when the toxic elements finally diffuse into the leachate.

5. Profitability

According to the financial analysis conducted, none of these technologies are profitable. However, due to a large number of uncertainties, the results of the financial analysis might not be reliable. The capital and operational costs of these technologies are very high. Incineration plant requires a capital expenditure of approximately \$80 million and an average annual operating and maintenance costs of \$7 million. The project is predicted to lose \$47 million over 20 years of operation. The Internal Rate of Return (IRR) is -6%.
For a gasification plant, capital and average annual expenditure is approximately \$102 million and \$8 million, respectively. The project may lose \$60 million over 20 years of operation with an IRR of -6%.

The capital and operational costs of a pyrolysis plant are approximately \$146 million and \$10 million, respectively. The project loss is predicted \$138 million over 20 years of operation.
The main parameters that influence the profitability of the projects are: tipping fee, capital and operating costs, throughput rate, sale price of electricity and heat, production rate of electricity and heat and efficiency of the energy recovery. For example, the net result at breakeven is for

the “tipping fee” to be increased to $112/tonne in an incineration plant and $125/tonne and $215/tonne in gasification and pyrolysis plants, respectively. The detail information on capital and operational & maintenance costs and revenue estimates.

Location of the facility

The facility will take around 7 to 10 acres. One option is to build the facility in the west end of the VLF where the “Western 40” is located. The plant can be located to the west end of the Western 40, the proposed location of the facility at the VLF can be found in Appendix 5.

Generally, construction and commission of the facility takes four to five years for all three thermal conversion technologies. If we assume that the construction of the facility will start in 2015, the facility will be ready to run by 2020.

Conclusions

Overall, there is no proven technology available to treat a large amount of treated/painted wood waste. However, if it is assumed that the project is profitable, the ranking of the technologies based on the technical and environmental aspects are as follows:

1. Incineration: this technology is mature and most aspects of the technology have been known now. A rotary kiln can handle the feedstock and complicated and expensive APC systems can be applied to capture heavy metals. However, due to complicated inorganic compounds and complexes in the treated/painted wood, thermal decomposition of this type of materials is unknown and difficult to determine.

2. Pyrolysis: this technology is less mature than gasification and many aspects of the technology have not been identified yet. However, due to a lower temperature of the process compered to gasification, retention of the heavy metals in the residues is higher. The emissions might contain less heavy metals and can be captured by a proper APC system but residue treatment is required. Similar to incineration, thermal decomposition of the treated/painted wood waste is unknown and very complicated to determine.

3. Gasification: this technology deals with technical complications. Calorific value, moisture content and type of woody materials and contaminations of the VLF's wood waste can influence on the quality of the syngas produced by the process. Plasma gasification was not fully covered in the "Gasification" section due to immaturity of the technology, however, it is discussed in the "Aside: Interesting Technologies" section of the report. This technology might handle heavy metals contaminations; however, it is very expensive. Similar to pyrolysis and incineration, thermal decomposition of the treated/painted wood waste is unknown.

Identifying the best thermal technology and profitability of the facility might not be possible. The main reasons are as follows:

- Chemistry of the treated/painted wood waste at the Vancouver Landfill is unknown; accordingly, the composition of the emissions and ash/residues is unknown. Therefore, identifying suitable APC systems and ash/residue treatment methods might not be possible.
- Emission control and ash/residue treatment must be considered differently from case to case for the different thermal methods.
- A few research have been conducted on applicability of pyrolysis for treating the treated/painted wood, therefore, it is not a proven technology to treat this type of materials.

Conclusions and Recommendations

Main parameters that were assessed to evaluate the three conversion technologies, incineration, gasification and pyrolysis:

- Suitability of the VLF's wood waste;
- Applicability of technologies for the VLF's wood waste;
- Efficiency of energy recovery (with combined CHP);
- Environmental impacts (air emission and ash/biochar/residues); and
- Profitability for the VLF.

None of the proposed technologies will be profitable over 20 years of the facility life. The main financial parameters that influence the NPV of the facility are capital and operating & maintenance costs that are very expensive and unpredictable due to immaturity of the process or required extensive air pollution control systems and ash/residue treatment stage.

Overall, the author concludes that although, incineration, gasification and pyrolysis processes may cause unpredictable and unsolvable problems when the CCA-treated wood waste is used, new developments in these technologies might provide suitable and beneficial solutions to air pollution and ash/residue contamination in the future.

The author offers her recommendations to the followings:

- City of Vancouver
- BC Government
- UBC

Recommendations to the City of Vancouver:

Short Term:

- Detail identifying chemistry of the treated/painted wood waste at the VLF
- Identify thermal and physical properties of the treated/painted wood waste at the VLF
- Cooperate with cement and pulp mill plants as they may be interested in this type of

materials as a fuel

- Require residential and commercial customers a better segregation for the wood waste from the other DLC materials otherwise, they receive a fine. Regulation can be more effective than incentives on the public, research on behavioral factors that also can be applied to energy saving shows that an individual gets more upset if he/she loses $50 than gets happy to win $50. This concept is referred to as loss aversion.
- Cooperate with residential and commercial construction, renovation & demolition sector as well as wood & furniture industry to participate in properly segregating and the wood waste and utilizing green materials in construction
- Properly sort and screen the wood waste and recording the magnitude of the treated/painted wood waste
- Cooperating with other municipalities and private recyclers such as Ecowaste and Harvest Power to find the best solutions

Mid Term:

- Take the next steps tougher and more determined to find the best way to treat this type of materials
- Conduct more research on alternative diversion technologies such as recycling, chemical extraction, liquefaction, chelation and anaerobic digestion to treat the treated/painted wood waste at the VLF
- Cooperate with UBC to conduct more research on the thermal technologies, particularly on emission control and residue treatment for decomposing of the treated/painted wood waste
- Be more proactive, participating or conducting national and international conferences on this topic

Long Term:

- Fund, loan and incentives from the government to attract the private sectors
- Conduct a proper financial analysis to determine a feasible tipping fee for the DLC
- Ask for credits or funds from the government for thermal or other diversion technologies for the VLS's wood waste
- Ask for more $/kwh for the electricity produced by WTE facility from BC Hydro

- Explore possible markets with a higher sale price for heat and steam produced by the thermal facility
- Larger facilities are more feasible than smaller ones, combining the treated/painted wood waste across Metro Vancouver can provide larger magnitude of feedstock for a facility that can make the project more feasible (economies of scale indicate that larger facilities tend to have lower capital and operating costs per annual design tonne)
- Explore decontamination methods and market for by-products of pyrolysis or gasification process

Recommendation to the BC Government:

Short Term:

- Make regulations on sorting and segregating according to the types of wood waste
- Connect all municipalities as well as private sectors in Metro Vancouver to record and identify the exact magnitude and chemistry of the contaminated wood waste being produced in Metro Vancouver to get insight understanding about this type of waste

Mid Term:

- Allocate funds and incentives on conducting research at academic institutions
- Identify new guidelines and standards based on detailed scientific proofs for diversion methods of treated/painted wood waste
- Take the leadership in treating the contaminated wood waste; definitely, diversion of the contaminated wood waste is one important step towards Zero Waste goal.
- Invite national and international experts and professionals to share their ideas and find solutions, holding national and international conferences may be an effective approach
- Create one proactive group of experts to work together and share their knowledge and suggestions

Long Term:

- Negotiate with electricity and heat generating organizations such as BC Hydro and

Fortis BC for higher sale prices of the electricity and heat produced by WTE facilities

- Cooperate with private sector and allocating funds and loans to participate in this field
- If BC succeeds in managing the contaminated wood waste, it will be the only one in Canada or even the world. This is a great opportunity to introduce this province to hit a record not just for its beautiful scenery but also for its great wood waste management. This will be a great example for other provinces in Canada and other countries around the world. In this case, new businesses and investment areas may be created in BC.

Recommendations to UBC

Fortunately, UBC possesses excellent academic staff and hard-working and curious students; thus, this place can give a great opportunity to conduct more research on this topic and participate in finding an innovate solutions to this widespread issue. The author recommends the followings to UBC for taking the leadership in this area:

- Allocate funds and loans to work on this field can help Vancouver to reach the "Greenest City" goals. The author can see a great chance for UBC to be a leader in this way.
- Find private and public organizations and institutions to invest in this area
- Allocate a group of experts and students to conduct research on this topic
- Conduct national and international conferences and invite all professional around the world to share their ideas, identify possible solutions and divide the tasks if it was needed

Appendices

Appendix 1

Appendix A 1 Case Study

1. Incineration
2. Gasification
3. Pyrolysis

Incineration

- Burnaby WTE Facility, British Columbia, Canada
- Wood Fired Combined Heat and Power Plant, Germany
- Arnoldstein Plant, Austria

Burnaby WTE Facility, British Columbia, Canada

The WTE facility is owned by Metro Vancouver and is operated and maintained by Covanta Burnaby Renewable Energy, ULC in Burnaby. This facility started operating in 1988. The Facility receives its feedstock (MSW) primarily from the Cities of Burnaby, New Westminster and the North Shore at approximately 280,000 tonnes annually (Metro Vancouver, 2015).

Feedstock properties and requirements:

MSW is the main feedstock. There may be a minimal pre-processing on waste such as shredding of large items but there is no separation process.

Technology:

The waste is transferred from a bunker to a combustion chamber. Three Martin GmbH mass burn boilers provide steam at 3.6 MPa/350°C superheater outlet conditions with the capacity of about 280,000 tonnes per year. The tipping and bunker area is maintained under negative pressure and air to control odor. Electronic combustion systems are implemented into all grate systems to ensure a complete combustion is achieved. Secondary air is also added to the system to provide sufficient oxygen for combustion process (AECOM Canada Ltd., 2009) (Covanta, 2014).

The temperature inside the furnace is more than 1,000° Celsius (Metro Vancouver, 2015). The heat from combustion process boils water and steam produced drives a turbine to generate electricity. This facility generates 470 kWh of electricity and 760 kWh of steam per tonne of waste. Bottom ash (residue of combustion) can be processed to extract metals and is used as cover material in landfills and roadbed construction. However, as of the writing this report, the Vancouver Landfill was burying it with the MSW. The residue from plastics is considered to be very little with no emissions in the landfill (AECOM Canada Ltd., 2009).

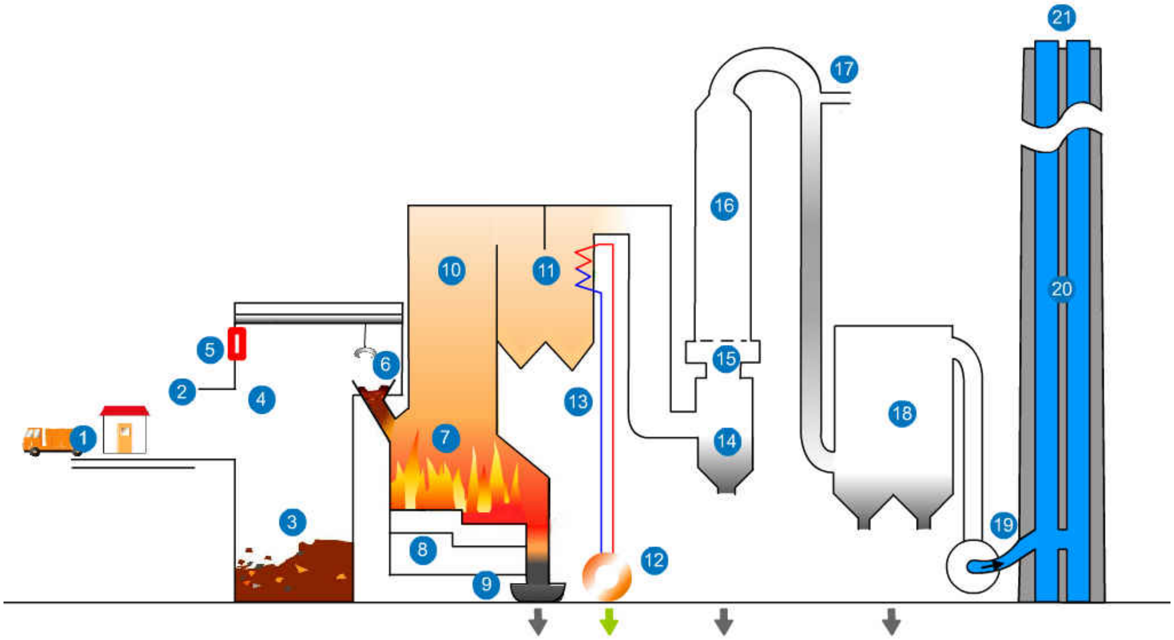
All gases are collected, filtered and cleaned with a modern technology before being released into the atmosphere. The air pollutants are controlled by Flakt Dry Absorption Reactor and Flakt Pulse Jet Baghouse. Lime and activated carbon are added to the cooled flue gas to react with acid gases and vaporous metals for capturing them. After this stage, the flue gas is passed through fabric filter baghouse to capture acids, metals and particulate matter (PM) (Covanta, 2014), (Metro Vancouver, 2015). Figure A. 1 presents a schematic of the WTEF-process.

Method of energy recovery:

This facility generates electricity for about 25,000 homes (470 kWh) and 760 kWh of steam per tonne of waste. Electricity is sold to British Columbia Hydro (BC Hydro) and the steam was sold to the neighbouring paper recycling facility (Metro Vancouver, 2015). “From its commissioning in 1988 to 2011, the facility had provided steam to a neighboring paper mill which shut down due to the sale of the mill property. The Facility could also provide district heating needs to the surrounding industrial park and the Fraser Lands Development, nearly 5 km away” (Adema, 2013).

Environmental impacts:

Baghouse filters typically have a particulate collection efficiency of 99% or better, even when particle size is very small. The last stage is the filtered gas exits through a stack with a continuous air emissions monitoring. Metro Vancouver’s WTEF produces no process liquid discharge (Covanta, 2014), (Metro Vancouver, 2015).



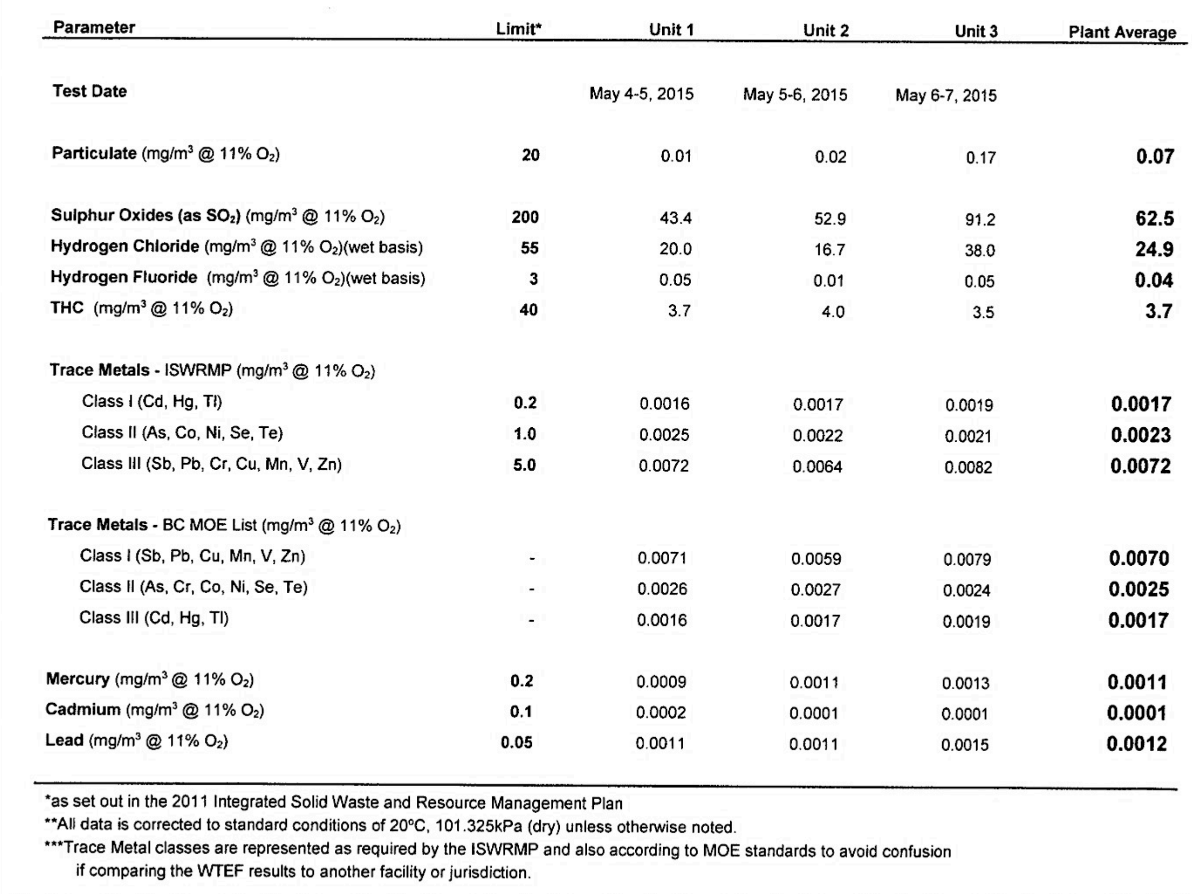
Legend:

1. Scale and visual inspection of waste
2. Tipping hall
3. Waste bunker/storage
4. Overhead crane
5. Fire detection system
6. Waste feed hopper and system
7. Combustion chamber
8. Grate
9. Ash discharge and quench
10. NOx control
11. Heat exchanger
12. Steam turbine generator
13. Steam condenser
14. Cyclone coarse dust removal
15. Reagent injection for neutralization of acid gases
16. Absorber tower
17. Activated carbon injection
18. Baghouse filter
19. Induced draft fan
20. Stack
21. Emissions monitoring system

Figure A. 1 Cross-Section of WTEF in Burnaby, British Columbia

Metro Vancouver is required to perform an emission survey on a regular basis at a Waste-To-Energy Facility by the provincially approved Integrated Solid Waste and Resources Management Plan (2011). This survey includes particulate matter (PM), trace metals, Volatile organic compounds (VOCs), acid gases and ammonia. *The result of the survey was all Units were in compliance with limits as set out in the provincially approved Integrated Solid Waste and Resources Management Plan* (A. Lanfranco and Associates Inc., 2015). The lab result of emissions from the WTE Facilities in Burnaby can be found in Table A. 1. The Facility operates under the Metro Vancouver Solid Waste Management Plan, and as such the MV bylaw, mentioned previously in the Environmental Impacts part, does not apply to the Burnaby Incinerator (Stantec, 2010). According to the emission lab results, all sources were below the regulated limits established in the ISWRMP for all emission parameters measured on the test dates.

Table A. 1 Comparison of Emission Test Results from Burnaby WTE facilities with Limits



Parameter	Limit*	Unit 1	Unit 2	Unit 3	Plant Average
Test Date		May 4-5, 2015	May 5-6, 2015	May 6-7, 2015	
Particulate (mg/m^3 @ 11% O_2)	**20**	0.01	0.02	0.17	**0.07**
Sulphur Oxides (as SO_2) (mg/m^3 @ 11% O_2)	**200**	43.4	52.9	91.2	**62.5**
Hydrogen Chloride (mg/m^3 @ 11% O_2)(wet basis)	**55**	20.0	16.7	38.0	**24.9**
Hydrogen Fluoride (mg/m^3 @ 11% O_2)(wet basis)	**3**	0.05	0.01	0.05	**0.04**
THC (mg/m^3 @ 11% O_2)	**40**	3.7	4.0	3.5	**3.7**
Trace Metals - ISWRMP (mg/m^3 @ 11% O_2)					
Class I (Cd, Hg, Tl)	**0.2**	0.0016	0.0017	0.0019	**0.0017**
Class II (As, Co, Ni, Se, Te)	**1.0**	0.0025	0.0022	0.0021	**0.0023**
Class III (Sb, Pb, Cr, Cu, Mn, V, Zn)	**5.0**	0.0072	0.0064	0.0082	**0.0072**
Trace Metals - BC MOE List (mg/m^3 @ 11% O_2)					
Class I (Sb, Pb, Cu, Mn, V, Zn)	-	0.0071	0.0059	0.0079	**0.0070**
Class II (As, Cr, Co, Ni, Se, Te)	-	0.0026	0.0027	0.0024	**0.0025**
Class III (Cd, Hg, Tl)	-	0.0016	0.0017	0.0019	**0.0017**
Mercury (mg/m^3 @ 11% O_2)	**0.2**	0.0009	0.0011	0.0013	**0.0011**
Cadmium (mg/m^3 @ 11% O_2)	**0.1**	0.0002	0.0001	0.0001	**0.0001**
Lead (mg/m^3 @ 11% O_2)	**0.05**	0.0011	0.0011	0.0015	**0.0012**

*as set out in the 2011 Integrated Solid Waste and Resource Management Plan

**All data is corrected to standard conditions of 20°C, 101.325kPa (dry) unless otherwise noted.

***Trace Metal classes are represented as required by the ISWRMP and also according to MOE standards to avoid confusion if comparing the WTEF results to another facility or jurisdiction.

The Burnaby Incinerator is one of the approved disposal facilities. Expansion of WTE utilization (up to 500,000 tonnes per year of new WTE capacity) and development of new WTE capacity through new projects can maximize the environmental, financial, and social benefits in the region (Stantec, 2010).

Economic details:

This facility was built at approximately $394 million ($2014). Operating expenditures totalled $20.60 million with an additional $1.53 million in debt charges in 2014. Metro Vancouver's portion of energy revenues from electrical sales totalled $5.47 million ($2014). Based on a throughput tonnage of 275,260 tonnes, the net unit cost per tonne for operation and maintenance of the WTEF in 2014 was $60.53 per tonne.

Wood Fired Combined Heat and Power Plant, Germany

In 2001, a new biomass fired combined heat and power (CHP) plant fuelled by forestry and wood residues from sawmills was commissioned in the town of Pfaffenhofen, Germany (population approximately 22,000).

Feedstock properties and requirements:

The plant was originally designed to combust forest and sawmills residues, using an initial ratio of 30 per cent wood chips and 70 per cent sawmill residues. However, by 2003 this ratio was reversed because changes in pricing and improved fuel logistics. Since 2004 the plant uses exclusively forest residues (90 per cent) and woodchips from landscape protection and management (10 per cent). This was due to a subsidy for electricity produced in plants exclusively using wood and other replenishing raw materials that was introduced in 2004.

Technology:

Fired Combined Heat and Power (CHP)

The plant produces process steam, process heat, district heat, and space and process cooling, as well as electricity and was regarded as one of the most innovative and advanced plants in Germany.

The plant supplies a newly erected district-heating grid with steam and hot water. The maximum thermal power output is 32.5 MW, supplying heat via a district heating network to a hospital, schools, and other public and private buildings. Furthermore, the plant delivers process steam for a large biological baby food factory. The plant supplies 6.1MW electricity for the grid and the calorific value of the fuel is 9.07 MJ/kg (moisture content 45%).

Environmental impacts:

Annual CO2 savings has been calculated around 65,000-70,000 tonnes and 90% of ash is reused in the agricultural and forest sector as a fertilizer (Ricardo-AEA Ltd, 2013).

Economic details:

Financial Total investment costs was $76 million (€49 M, €2001) and were financed by a combination of private finance, equity, government investment grants and bank loans. In 2000 the Federal Government adopted the new Renewable Energy Sources Act. The Act provides guaranteed, absolute minimum feed-in tariffs that the grid operator has to pay for a period of 20 years after commissioning the plant. The introduction of this new law improved the cost effectiveness of the plant significantly. When the plant was commissioned in 2001 it was eligible for a feed in tariff of $0.14/kWh (9.3 Eurocents, €2001). The amendments to the Renewable Energy Sources Act in 2004 saw further bonuses to be paid on top of the regular feed-in tariff provided the electricity is exclusively produced from wood and other replenishing raw materials. The ability of the plant to secure heat customers and sell almost all of the residual heat to domestic and commercial users further improved the project economics.

Arnoldstein Plant, Austria

The Arnoldstein plant is located in the town of Arnoldstein with a population of 560,000 inhabitants in Austria. The plant serves the whole state processing almost 27% of the state's waste. The plant commenced operations during the spring of 2004. It was constructed by Martin GmbH, Siemens, Austrian Energy and Environment and PORR Technobau und Umwelttechnik. The plant has technical and managerial staff of 29 persons, allocated into 3 shifts, with 8000 operational hours per year (Kalogirou, 2010).

Feedstock properties and requirements:

The feedstock is approximately 90,000 tonnes per year of MSW.

Technology:

The combustion process in the facility includes the following steps:

- The combustion chamber consists of a single line with two moving grates of MSW with a lower heating value of 10 MJ/kg
- The combustion process takes place with air enriched in oxygen at percentages of 24-35% (Syncom Process/Martin Technology)
- Flue gas temperature is 1100^{o}C-1200 ^{o}C. There is a recirculation of flue gases for better combustion
- Due to the enriched air by oxygen the combustion is more efficient and there is almost a complete destruction of dioxins. Dioxin monitoring is done online.

Method of Energy Recovery:

The plant produces steam of 400^{o}C, at pressure 40 bar and 10-13 tonnes per hour. The steam has a market for teleheating and for hot water usage. The gross power is rated at 7 MW (electricity) and the net power is rated at 5.2 MW (electricity). Self-consumption of recovered energy is higher than normal because of the oxygen production (~95%) to enrich the combustion air. Energy production is 500 KWh per tonne.

Environmental Impacts:

The air control system utilizes semi-dry scrubbers with hydrated lime to reduce SO_2, HCl and Hydrogen fluorides. Filters are used to reduce dust particles, heavy metals and organic pollutants. Activated carbon filters are used to control mercury and heavy metals. Selective catalytic reduction (SCR) is used to reduce NOx in the flue gases.

The process produced bottom ash around 25% in a good quality due to high combustion efficiency. In order to avoid leaching the bottom ash is compressed with heat. The Bottom ash is landfilled in an ash monofill at a price of $66 per tonne (€50, €2010). Fly ash is stabilized with lime and cement within the landfill area and then it is landfilled.

Economic details:

The total capital cost was $99 million (€75, €2010).

Gasification

- Nexterra Facility at UBC, Canada
- Energos Gasification Facility, Norway
- The Güssing Biomass CHP Plant (Austria)
- Enerkem Gasification Facility, Edmonton, Canada

Nexterra Facility at UBC, Canada

Feedstock properties and requirements:

The feedstock is around 12,000-50,000 tonnes per year (35 – 140 tonnes per day) of a range of woody biomass such as wood residuals and clean construction debris as well as biosolids that it is planned (Nexterra, 2013). The size of the feedstock is up to 80 millimetres (see Figure A. 2). There is a pre-processing of the feedstock to adjust the size and moisture content of the feedstock. Metallic materials are also removed by magnets.

The moisture content of the feedstock varies 6 – 60% but 25% is more favorable. It should not be less that 10% to avoid producing dust that make problem with the gasification process and the equipment.

Figure A. 2 The feedstock of the Nexterra Gasification Plant at UBC, Canada

Technology:

The method is conventional gasification. The type of the gasifier is fixed bed updraft. The process is similar to the gasification process that was described in the “Technology Description” of the “Gasification” section. The facility utilizes a NG boiler to produce steam (see Figure A. 3).

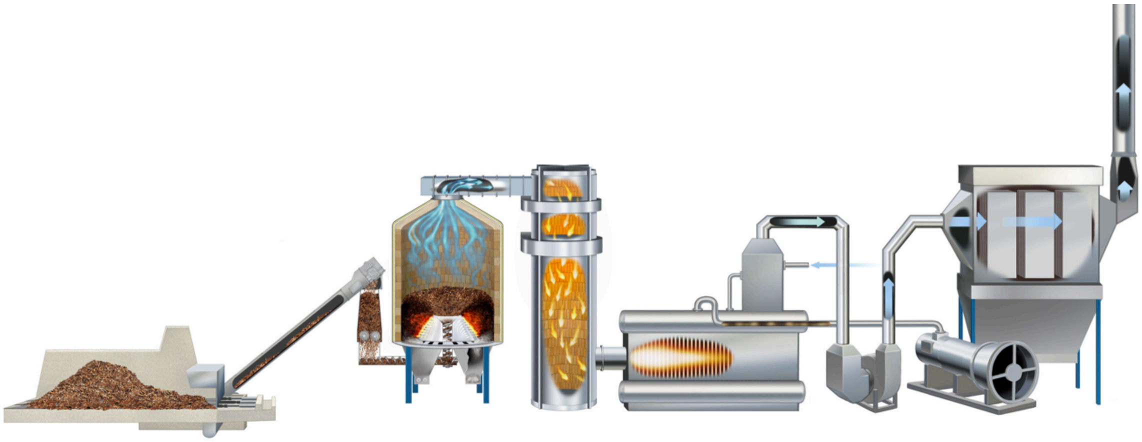


Figure A. 3 Schematic diagram of the gasification process in the Nexterra Facility at UBC, Vancouver

The summery of the steps of the process are feedstock preparation, gasification, oxidization of the syngas, combustion, electricity and steam generation and ESP for emission control (Nexterra, 2013).

Method of Energy Recovery:

The plant produces steam and electricity by CHP with an efficiency of up to 60%. The capacity of the facility is 2 MW of electricity and 3 MW of thermal energy (Nexterra, 2013). The author had a discussion with Ehsan Oveisi, PhD Candidate, about the future product of the facility. It is expected that the facility provides hot water for the building in the area. In this case the efficiency will increase to some levels.

Environmental Impacts:

The air control system of the facility is ESP. The author could not find enough information on the emissions levels. However, it is claimed that the plant meets the emission criteria according to the BC standards.

Economic details:

There is not enough information available on the economics of the facility in detail. However, the capital cost of the facility is approximately $29 million ($27 M, $2011), (Platt, 2012).

Energos Gasification Facility, Norway

This facility is an example of a proven Small-scale, Energy from Waste. Energos is part of the ENER-G group, headquartered near Manchester, UK. This technology was developed in Norway in the 1990s in order to provide an economic alternative to mass-burn WTE with equally low emissions to the atmosphere and flexibility in feedstock.

Feedstock properties and requirements:

All operating plants treat MSW plus additional streams of commercial or industrial waste. The current operating plants range in capacity from 10,000 to 78,000 tonnes per year. The feedstock to an Energos plant is post-recycling MSW mixed with a smaller amount of other waste streams. These include industrial wastes and residues from materials recovery facilities (MRF). The waste is pre-treated to ensure a sufficiently high surface-to-volume ratio and a low content of metals. Fuel bulk density requirements after shredding and mixing are as greater than 150 kg/m^3 and less than 500 kg/m^3. The different waste fractions have to be shredded to ensure particle size is 90% less than 150 mm and100% less than 200 mm. The content of other metals such as steel, stainless steel, iron and brass are < 0.5 % in weight, and maximum particle size < 40 mm after shredding (Stein & Tobiasen, 2004).

Technology:

This technology is well developed with six operating plants in Norway. The schematic diagram of the Energos process can be seen in Figure A. 4. The process can be described as follows:

- Energos furnace unit is horizontally divided into a primary chamber on the bottom and a secondary chamber on top of the primary chamber
- Thermal treatment process consists of two stages: first, partial oxidation and gasification of the waste in the primary chamber on a moving grate at sub-stoichiometric oxygen conditions (air to fuel ratio=λ=0.5-0.8). Second, the volatile gases generated in the gasification chamber are then combusted fully in the secondary chamber and the heat in the combustion gases is transferred to steam in a heat recovery system.
- Temperatures reach up to 900^{o}C in the gasification chamber and up to 1000^{o}C in the oxidation chamber.

The schematic diagrams of the gasifier and thermal oxidizer, and heat recovery Steam generation units are shown in Figure A. 5 and Figure A. 6, respectively.

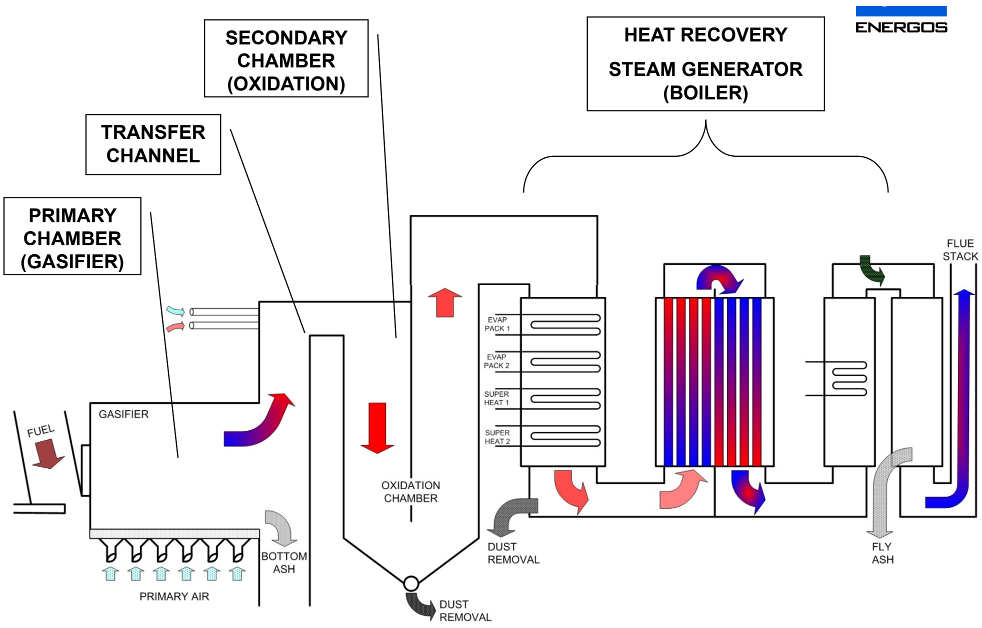


Figure A. 4 The Energos Process

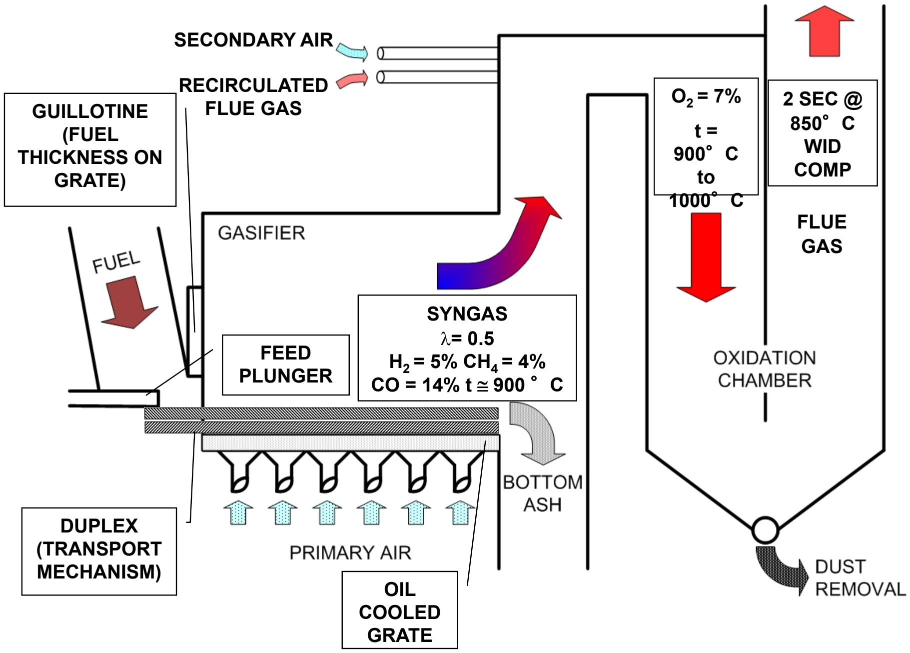


Figure A. 5 Energos Gasifier and Thermal Oxidizer

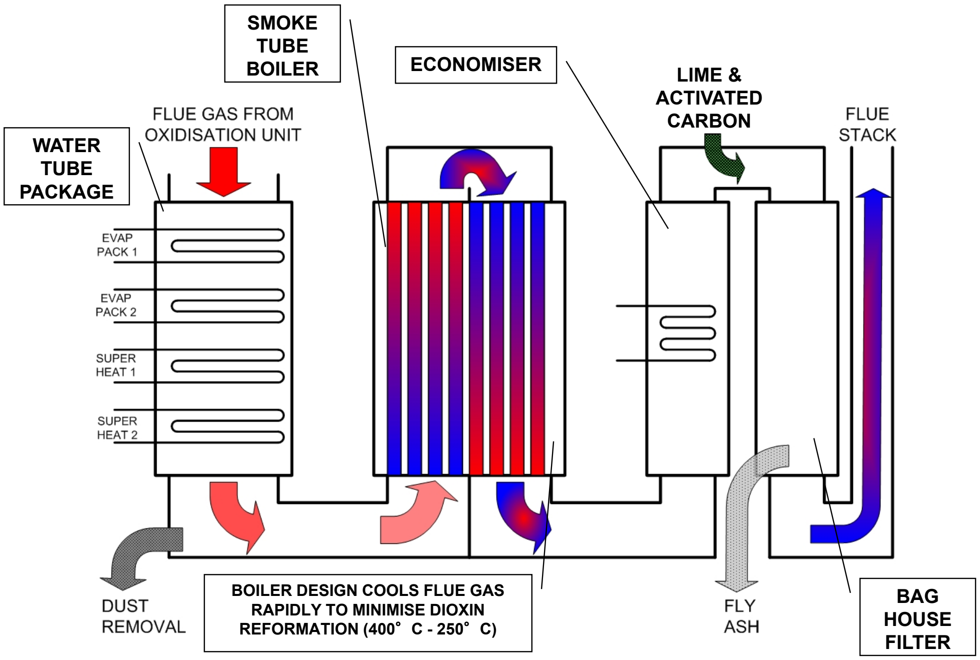


Figure A. 6 Energos Heat Recovery and Steam Generation System (HRSG)

Method of Energy Recovery:

Energos is a CHP energy recovery plant. Power production is done by steam turbines. Two such plants are in operation at present and another two double line CHP plants are presently in the engineering phase (Stein & Tobiasen, 2004).

Environmental Impacts:

A standard Energos plant is equipped with a dry flue-gas cleaning system. Lime and activated carbon is injected in the flue-gas upstream of a bag-house filter. Lime will absorb acid components (SO2, HCL and F) in the flue gas while activated carbon will absorb Total Organic Compounds (TOC), heavy metals and dioxins. Dust/particles, lime and activated carbon will be separated from the flue-gas by the bag house filters. Emissions are monitored continuously.

Table A. 2 illustrates emission measurements at the facility and the EU standard emissions limits. As can be seen, all components are less than the EU standard emissions. Formation of NOx is stabilized relatively low (at about 15 % of the EU limit) and any dioxins in the feed are destroyed in the combustion chamber, and the rapid cooling achieved in the energy recovery system minimizes formation of dioxins. Good burnout of bottom ashes causes a low content of some heavy metals.

The metals will pass through the primary combustion chamber and end up in the bottom ash, partly oxidized. Most of the metals will have a negligible vapor pressure at the certain temperatures in the primary chamber. Therefore, some of them, such as lead and zinc, may chemically react with substances with increased vapor pressure, and may be mixed with the flue gas and the flue gas cleaning system will generally retain their small particles. Mercury and cadmium are more volatile. The mercury will tend to vaporize and goes to the flue gas. When the flue gas is cooled, more than 95% of the mercury, and more than 99% of the cadmium, will condense or adsorb on dust and lime, and will thus be retained in the flue gas cleaning system.

It is estimated that the fractions of components present in the feed eventually end up as emissions to the air. These components are Mercury: 2–5 %, Cadmium: < 0.01 %, Arsenic: < 0.03 %, Cobalt: < 0.05 %, Nickel: < 0.03 % and All other metals: < 0.01 %.

The distribution of these components between bottom ash and filter ash may be manipulated by changing the temperature of the primary combustion chamber. Higher temperatures lead to less of the components in the bottom and more in the filter (Ellyin, 2012), (Sandquist, 2011) & (Stein & Tobiasen, 2004).

Table A. 2 Energos Emissions Summary (Stein & Tobiasen, 2004)

Component	**Symbol**	**Energos Emissions [mg/Nm3]**	**EU Standard Emissions [mg/Nm3]**	**% of EU Standard**
Dust	-	0.3 -0.7	10.0	3.0%
Mercury	Hg	0.001-0.007	0.03	3.0%
Cadmium & Thallium	Cd & TI	0.00004	0.05	0.1%
Heavy Metals	-	0.0008	0.5	0.2%
Carbon Monoxide	CO	1.0-10.0	50.0	2.0%
Hydrogen Fluoride	HF	0.04-0.2	1.0	4.0%
Hydrogen Chloride	HCL	0.3-2.0 10.0	10.0	3.0%
Total Organic Compounds	-	0.0.-0.6	10.0	0.0%
Sulphur Dioxide	SO2	9.0-40.0	50.0	18.0%
Nitrogen Oxides	NOx	30.0-120.0	200.0	15.0%
Ammonia	NH3	0.04	10.0	0.4%
Dioxins(1)	-	0.008-0.037	0.1	8.0%

(1) unit: ng TEQ/Nm3

Process residues:

- Water from boiler blow down is used in the slag discharge basin.
- Shredder rejects from waste pre-treatment are recycled.
- Slag is used as topsoil at existing landfills.
- Filter dust is landfilled as hazardous waste (Stein & Tobiasen, 2004).

Stack emissions:

- Emissions to air through the stack consist of 10% carbon dioxide, 15% water, 5% oxygen and 70% nitrogen.
- Less than 0.1% of the emissions consist of harmful components and pollutants. These emissions are well below the new EU standard emissions limits. Emissions also do not show insignificant impact on soil quality, flora and fauna in the surrounding areas of the plant (Stein & Tobiasen, 2004).

Economic details:

For the Type 42 plant (double-line), the total capital cost is approximately $51 million (€35M, €2004) and $4.5 million (€3.1M, €2004) for the first year. The payback period of the plant is 6 to 7 years with the total revenue of approximately $12 million (€8.2M, €20024) (Stein & Tobiasen, 2004).

The Güssing Biomass CHP Plant (Austria)

The Güssing Biomass CHP Plant is located in in the city of Güssing, Austria. It started operation in 2002.

Feedstock properties and requirements:

The plant uses agricultural and forestry residues and wood from the region. The quantity of fuel consumed is approximately 20,000 tonnes per year (2,300 kg/hour). Moisture content of the feedstock is 20-30%.

Technology:

The plant consists of a dual fluidized bed steam gasifier, a two-stage gas cleaning system, a gas engine with an electricity generator and a heat utilization system nitrogen-free biogas for electricity generation and district heating distribution, a detailed flow sheet is shown in Figure A. 7.

(x) flue gas filter, and
(xi) flue gas (gas engine) cooler.

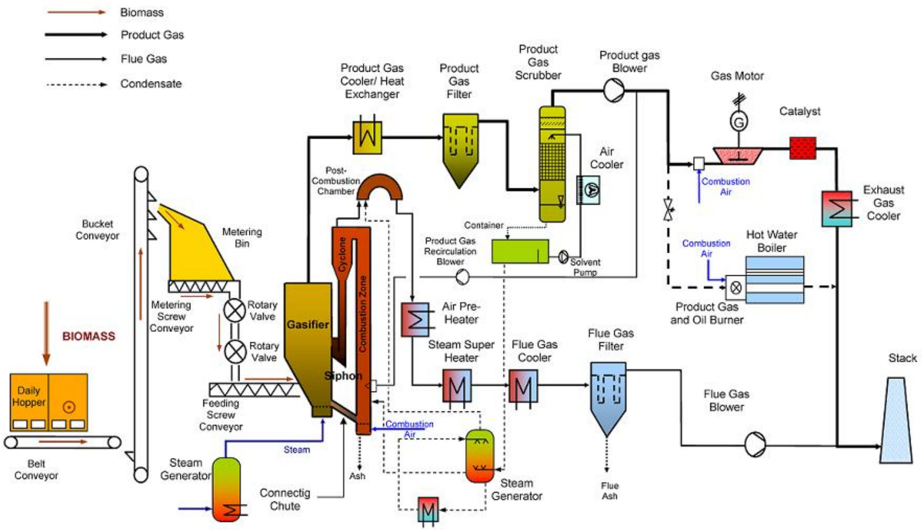


Figure A. 7 Schematic diagram of the gasification process in the Güssing Biomass CHP Plant

Biomass chips are fed into the fluidized bed reactor via a rotary valve system and a screw feeder. The fluidized bed gasifier consists of two zones, a gasification zone and a combustion zone. The gasification zone is fluidized with steam that is generated by waste heat of the process to produce a nitrogen free producer gas.

The combustion zone is fluidized with air and delivers the heat for the gasification process via the circulating bed material. The producer gas is cooled and cleaned by a two stage cleaning system. A water-cooled heat exchanger reduces the temperature from 850°C – 900°C to about 160°C – 180°C. The first stage of the cleaning system is a fabric filter to separate the particles and some of the tar from the producer gas. These particles are returned back into combustion zone of the gasifier.

In a second stage, a scrubber liberates the gas from tar. Spent scrubber liquid saturated with tar and condensate is vaporized and introduced into the combustion zone of the gasifier. The scrubber is used to reduce the temperature of the clean producer gas to about 40 °C which is necessary for the gas engine. The clean gas is finally fed into a gas engine to produce electricity and heat. If the gas engine is not in operation the whole amount of producer gas can be burned in the boiler to produce heat. The flue gas of the gas engine is catalytically oxidized to reduce the CO emissions. The heat of the engine´s flue gas is used to product district heat.

The sensible heat of the flue gas for the combustion zone is used for preheating of the air, superheating the steam and also to deliver heat to the district heating system. A gas filter separates the particles before the flue gas is released via a stack to the environment.

Method of Energy Recovery:

The plant achieves an electrical production of 2 MW from 8 MW of input biomass, through a biomass gasifier coupled with an Internal Combustion (IC) gas engine with an electrical efficiency of 25% and a heat efficiency of almost 50%. The gasification plant produces 4.5 MW of heat for the local district-heating network.

The district heating system is 27 km in length and services 300 houses, 50 building public buildings and 10 industrial applications. Electricity is sold to the local electrical grid operator for which a feed-in tariff is received. The plant produces enough electricity to meet the entire needs of the city. The energy framework in Austria ensures the economic efficiency of the plant. Whilst fuel costs are high, this is offset by the high feed in tariffs for electricity.

Environmental Impacts:

Most of the tar and some ammonia are removed by a scrubber. This scrubber uses a solvent that gives excellent results for tar removal. The spent solvent together with tar components is fed into the combustion zone und combusted. The temperature of the gas is further reduced to about 40 – 50°C in the scrubber which is necessary for the gas engine. Therefore most of the steam condenses there. This condensate is evaporated and fed into the after burning chamber of the combustion zone. This is a main advantage of the process as no wastewater problem arises. The measurements at the demonstration plant were similar to those at the 100 kW pilot plants. The clean producer gas has a very low tar content (10-40 mg/Nm3 dry gas) that is no problem for the operation of the gas engine, see Table A. 3.

Table A. 3 Producer Gas Quality

Component	Raw gas	Clean gas	Dimension
tar	1,500 - 4,500	10 - 40	mg/Nm^3
particles	5,000 – 10,000	<5	mg/Nm^3
ammonia	1000 - 2000	<400	ppm
hydrogen sulfide	n.m.	20 - 40	ppm

n.m. not measured

The flue gas from the gas engine and the flue gas from the combustion zone are mixed together and released via the stack to the environment. Results of emission measurements are shown in Table A. 4. All measurements are below the emission limits that were set by the local authorities. The condensate from the scrubber is evaporated and fed into the combustion zone where the organic matter is combusted. The only solid residue is the fly ash from the combustion zone. Therefore the carbon content in this fly ash is very low (<0.5 w-%) and can be handled similar to an ash from biomass combustion. This is an essential advantage compared to the most other gasifiers. The CHP plant Güssing is characterized by excellent environmental performance:

- Low gaseous emissions
- No liquid emissions
- Ash only from the combustion zone (very low carbon content)

Table A. 4 Emissions from CHP-plant Güssing

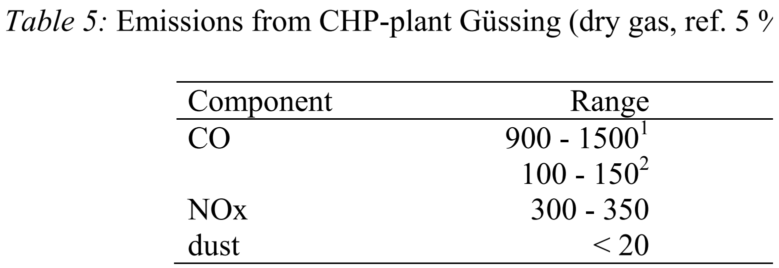


Table 5: Emissions from CHP-plant Güssing (dry gas, ref. 5 %

Component	Range
CO	900 - 1500[1]
	100 - 150[2]
NOx	300 - 350
dust	< 20

Economic details:

The cost of the demonstration plant was approximately \$15 million (€10M, €2002), with \$9 million (€6M, €2002) funded nationally and by the European Union. Operation costs are approximately 15% of the investment costs (Hofbauer, Rauch, Klaus, Koch, & Aichernig, 2002)

Enerkem Gasification Facility, Edmonton, Canada

Enerkem Gasification Plant is located in the City of Edmonton in Alberta, Canada. Enerkem has another demonstration plant in Westbury, Quebec. Construction of the Edmonton facility was set to begin in 2010 and operations was planned to begin in 2011.

Feedstock properties and requirements:

The feedstock is approximately 80,000-85,000 tonnes per year of MSW in form of RDF. It is designed around the typical Enerkem module of 100,000 T/Y of dry RDF, with the intention of supplementing the currently available waste with additional waste from other sources in the future (Stantec, 2010), (CBCL, 2011). The biofuel is limited to a maximum of 5 cm (1.96 inch) with a maximum moisture content of 20-25% (Fischer Tropsch, N/A).

Technology:

The conventional gasification in Enerkem facility includes four steps as follows:

1- Pre-treatment of the feedstock that involves drying, sorting and shredding of the materials.
2- Feedstock is fed into the gasifier. The bubbling fluidized bed gasifier converts the residues into synthetic gas and operates at a temperature of approximately 700°C.
3- Synthetic gas cleaning and conditioning, which includes the cyclonic removal of inerts, secondary carbon/tar conversion, heat recovery units, and reinjection of tar/fines into the reactor.
4- Conversion of syngas into biofuels. Enerkem intends to produce approximately 360 litres of ethanol from 1 tonne of waste (dry base) (Stantec, 2010)

Method of Energy Recovery:

The Edmonton plant produces liquid fuel (ethanol) as its final product at approximately 36 million litres annually. The reason for this is entirely financial, and not environmental or socially driven. Because it was not feasible to construct a plant to only generate electricity in Alberta as the rate for sale of electricity generated is only $0.05/kWh (CBCL, 2011).

Environmental Impacts:

The syngas is cleaned by a cyclone system to remove 90-95% of the solid particles. Both the washing and filtration system can be used to purify the gas further. The typical composition of the syngas by volume is 16% CO_2, 12-30% CO, 2-10% H_2, and 55% N_2. The syngas also contains small percentages of light hydrocarbons, oxygen, solid particles, tar, and other elements (Fischer Tropsch, N/A).

Economic details:

The capital cost of Edmonton project is approximately $85 million ($80 M, $2011) that some $21.2 million ($20 M, $2011) of this was provided as a grant from the Alberta government. Enerkem built, owns and operates the plant, and receives all revenues from the sale of the ethanol product. Edmonton will be responsible for feedstock handling and treatment, providing a RDF to the gasification plant that meets Enerkem's specifications, and will also pay a tipping fee of $53 ($50, $2011) per tonne to Enerkem (CBCL, 2011).

Pyrolysis

- Müllpyrolyseanlage (MPA) MSW Pyrolysis Plant, Germany
- Toyohashi Waste Treatment Recovery and Resource Center, Toyohashi, Japan
- Hamm Facility, Dortmund, Germany
- Chartherm Process Plant, Thermya, Bordeaux, France

Müllpyrolyseanlage (MPA) MSW Pyrolysis Plant, Germany

The (MPA) MSW Pyrolysis Plant is located two miles outside the City of Burgau in Germany. This plant treats the waste for about 120,000 residents from all the county of Günzburg (294 square miles). The area of the plant is about three acres and it is adjacent to the County Council's Landfill. The plant started operating in 1984 and in 1987, the plant was owned by the County of Günzburg (Lacitysan, 2004).

Feedstock properties and requirements:

The plant processes about 38,580 tons per year of MSW including residual domestic waste, commercial waste, bulky waste, and sewage sludge at 45% organic and 30% inorganic. The moisture content of the feedstock is 25%. No sorting or segregating of the MSW feedstock is required, however, all material must be shredded into maximum size of 30cm. Heating value of feedstock is an average 8.5 GJ per tonne (max 14 GJ per tonne & min 5 GJ per tonne).

Technology:

The conversion technology is pyrolysis (kiln). The technology supplier is WasteGen UK Ltd. and the technology is designed by TechTrade. The facility has two-unit plant including refuse treatment, two rotary kilns, dust separation, combustion chamber, waste heat boiler, steam turbine generator, bag house filter in addition of sodium bicarbonate and activated carbon and induced draft fan and stack. The schematic flow sheet of the MPA MSW Plant can be seen in Figure A. 8 (Lacitysan, 2004).

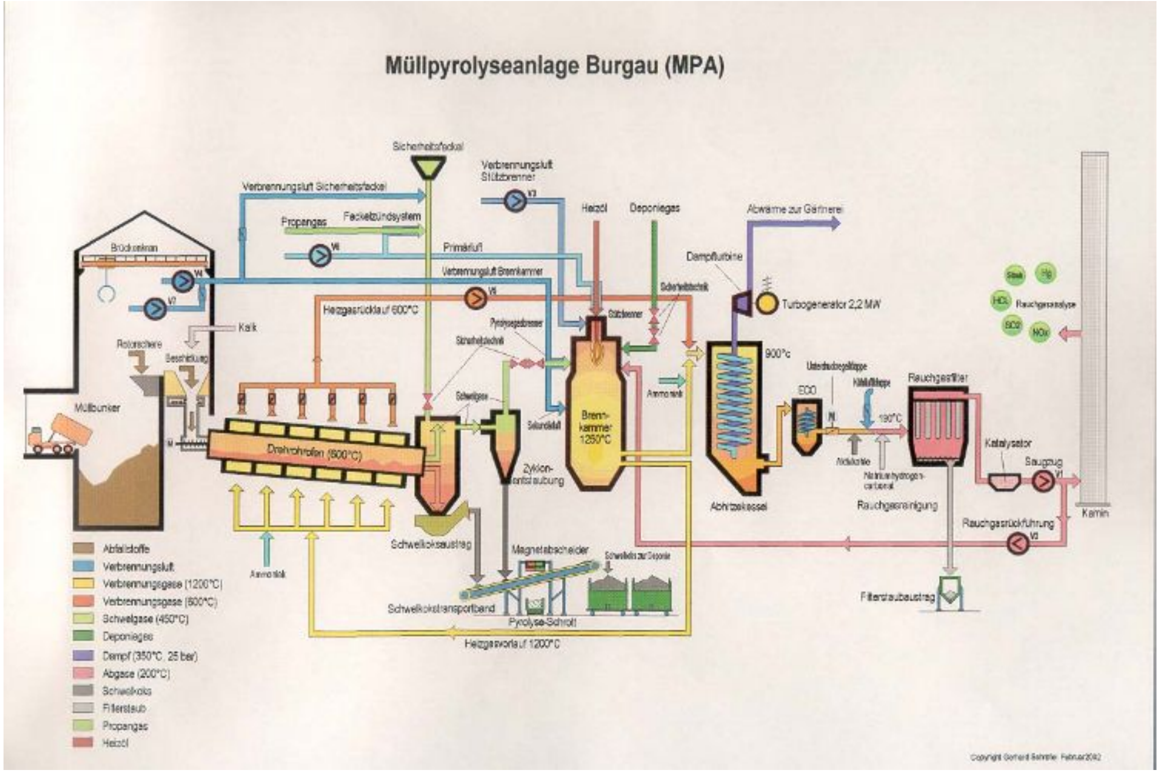


Figure A. 8 Simplified Flow Sheet of the MPA MSW Plant

There are two 33-ton/hour shredders (one operating/one standby). The shredder cuts the waste into a maximum size of 30cm. The shredded waste is then dumped into below grade storage area adjacent to the delivered MSW storage area. The shredded waste is fed into the pyrolysis feed chutes. Lime is added (8 kg/tonne of MSW) for removal of SO2 in the syngas.

A slide gate is used to feed the waste into the screw feeder, and it provides a seal from outside air and a constant feed to the kiln. The screw feeder moves the waste into the inlets of two 2.64 tonnes/hr (TPH) rotary pyrolysis kilns. Part of the hot flue gas from the combustion chamber (at about 1,260°C) flows through the jacketed portion of the kiln. The outside walls of the kilns are then heated indirectly from the hot flue gas in the combustion chamber. The outside of the kiln reaches 700°C, and the inside of the kiln reaches 500°C, resulting in pyrolysis of the organic portion of the MSW and producing the syngas. The residence time in the kiln is 1 hour.

The cooled flue gas exits at the top of the kiln through insulated pipes, and is returned to the top of the boiler, where it is mixed with the hot flue gas from the combustion chamber. Solids from the kiln (carbon char, minerals, glass) are discharged through a water bath, which provides a seal against air entering the kiln and a quench for the hot residues. The char and ash are removed by a wet slag remover and it is transferred into the conveyor belt. The ferrous metal from the residue is extracted by a magnetic separator and sell it to the users. The remained residue is landfilled as inert waste. This residue contains aluminum oxide, silicic acid, calcium oxide, iron oxide, carbon and anions (sulfates, carbonates, etc.). The quantity of the landfilled residue is about 300 kg/tonne of the MSW.

The pyrolysis gas also contains 40-60% steam and approximately 15% organic condensation products (tars and oil). Syngas is produced at a rate of 700 m^3/tonne of refuse annually. The syngas contains hydrogen (H_2), carbon monoxide (CO), carbon dioxide (CO_2), methane (CH_4) and hydrocarbons. The heating value varies 10-14 MJ/ m^3 depending on the quality of the feedstock.

The hot, dirty syngas passes through a hot gas cyclone, which removes most of the particulate matter (PM). The PM collected in the hot gas cyclone is discharged onto the solid residue conveyor for disposal in the landfill. The combustion chamber burns the syngas, along with the landfill gas, using air drawn from the tipping hall (for odor control), at temperatures in excess of 1,250°C. At the top of the combustion chamber, parts of cooler flue gases from the pyrolysis kiln outlets are used to help control the flue gas temperature. Typically, 80% of the hot flue gas goes to the boiler and 20% of the hot flue gas exits the combustion chamber and flows back to the pyrolysis kilns to provide indirect heat for pyrolysis.

The flue gas passes through a baghouse filter that removes the remaining PM. Sodium bicarbonate and activated carbon are injected into the flue gas stream, absorbing gaseous pollutants (SO2 and HCl) and mercury. The ash falls into a small bucket and the ash material is very grainy. It is taken to a salt mine for disposal. The fan creates an induced draft in the system and moves the flue gas to the stack. The flue gas is discharged through a 30m high stack (Lacitysan, 2004).

Method of Energy Recovery:

Steam is produced from the boiler at temperature of 1,250°C, and drives a 2.2 MW steam turbine generator for power generation. Over the last 18 years, the heating value of the MSW has increased from 6 GJ/tonne to approximately 10 GJ/tonne (more plastics). As a result, more, high heating value syngas was being produced. The boiler did not have enough heat transfer surface and was limiting gas throughput. A new boiler was retrofitted last year and solved the problem. Residual steam/condensate is piped to a nearby greenhouse. In the greenhouse, four crops of cucumbers and tomatoes are grown each year (Lacitysan, 2004).

Environmental Impacts:

The flue gas cleaning system consists of a fabric filter baghouse that come before a superposed dry sorption and a downstream catalyzer. For the absorption of acid gases and mercury, lime hydrate, sodium bicarbonate and active carbon are supplied to the process. While the fabric filter is operating with lower energy consumption and therefore is significantly cheaper, it is more efficient and it reduces emissions significantly (BWF Envirotec, 2010).

Pollutants that are monitored in the flue gas include Particular Matter (PM), hydrochloric acid (HCl), sulfur dioxide (SO2), carbon, cadmium/thallium, mercury, dioxins and furans. The actual measured emission values are lower than the permitted values (Lacitysan, 2004).

Economic details:

Capital cost of this plant is unknown. The operating cost is over \$232 per tonne (\$2015). The labor costs in Germany are very high and this is over 35% of the total budget. This cost also includes capital recovery for improvements that were made to the facility (Earth Tech Canada Inc., 2005).

Toyohashi Waste Treatment Recovery and Resource Center, Toyohashi, Japan

There were a total of six pyrolysis plants operating in Japan based on the information available as of March 2010. Toyohashi pyrolysis facility is located at the Toyohashi Waste Treatment Recovery and Resource Center, Toyohashi in Japan. The facility was commissioned in 2002. The recovery and resource center also has a grate-fired mass burn facility to process MSW. Overall, it was found that the grate-fired plant has been more reliable and flexible with higher availability in comparison with the pyrolysis plant (Stantec, 2010).

Feedstock properties and requirements:

The facility consists of two 200-tonnes/day units that process MSW, or approximately 120,000 tonnes/year. Incoming waste is shredded to 15x15 cm and has an average heat value of 9.2 MJ/kg. The facility runs approximately 6,900 hours per year for line 1 and 7,400 hours per year for line 2 or over 80%. Scheduled and unscheduled downtime is required to repair the refractory lining of the reactor (Stantec, 2010).

Technology:

The process involves low temperature pyrolysis (400°C) followed by a high temperature secondary combustion stage. Pyrolysis generally takes place at lower temperatures than used for gasification that results in less volatilization of carbon and certain other pollutants, such as heavy metals and dioxin precursors. Recovery of metal is higher because of the relatively low temperature during the pyrolysis process and before entering into the high temperature chamber. Aluminum and iron are removed after the pyrolysis drum. Residues are bottom ash 12.4%, with recovery of iron and aluminum (Stantec, 2010).

Method of Energy Recovery:

Due to the pre-treatment of waste and the fuel burned in the high temperature chamber, the electrical output from the pyrolysis process is almost balanced with the internal energy consumption. The facility produces annually 41 GWh electricity, with 90% used for internal consumption and pre-treatment. Only 4.46 GWh is sold. Heat produced is used to heat a public swimming pool (Stantec, 2010).

Environmental Impacts:

The APC train includes: quenching, fabric filter baghouse for PM removal, SCR for NOx, and flue gas recirculation (Stantec, 2010).

Economic details:

The overall capital cost for the pyrolysis plant was approximately $230 M ($165 million USD, $1998) (Stantec, 2010).

Hamm Facility, Dortmund, Germany

The power station is owned and operated by RWE Energie, the waste and power-generation company that owns Thames Water and Innogy in the UK.

Feedstock properties and requirements:

The pyrolysis plant has a capacity of 100,000 tonnes of MSW per year. Pre-processing of the feedstock is required. The waste gets shredded to the size of 200 mm. Input waste is around 13,000 kg/h.

Technology:

The waste is pre-treated and shredded to 200 mm and goes to an intermediate storage area; any oversized material goes back through the shredder. A conveyor to the pyrolysis plant operating at 95% availability transports the waste. There are two rotary kilns in the plant. The waste material passes a sluice and enters into one of the rotary pyrolysis kilns by a screw feeder. The rotary pyrolysis unit runs at negative pressure and is heated by natural gas burners. The process can also use syngas heat source. In the absence of air/oxygen the waste is heated and decomposed at the temperature of approximately 500^{o}C, with a residence time of around 1 hour. The ferrous and non-ferrous metals, sand and grit residues are separated by a magnetic separator.

In the event of an emergency boiler shut down the syngas is incinerated in a burning chamber including a stack.

Method of Energy Recovery:

The pyrolysis plant produces approximately 75 MW of gas energy, that is around 15 MW (electrical) at a normal steam turbine conversion efficiency (20%). The quantity of syngas is around 10,300 kg/hr producing 55.3 MW of energy. The quantity of pyrolysis char is 2,500 kg/h producing 8.3 MW of energy.

Environmental Impacts:

A cyclone de-dusts the pyrolysis gas, after that the deposited dusts and carbon particles are added to the pyrolysis coke. Emission data are not available.

Economic details:

There is no exact capital and operating costs available, the cost is estimated to be approximately $120M (£50m, 2005).

Chartherm Process Plant, Thermya, Bordeaux, France

The Chartherm process aims to capture metals, carbon and energy contained in CCA-treated wood waste. The combination of low temperatures (around 370°C) and elevated pressures at the bottom of the wood column results in a relatively fast thermochemical conversion despite the low temperatures used (Helsen, 2008).

Feedstock properties and requirements:

The CCA-treated wood waste and contaminated wood waste, at a rate of 1500 kg per hour, 10,000 MT per year (Hery, N/A).

Technology:

The Chartherm process includes the following steps:

1) Crushing: the crusher reduces the wood from its original size to five centimeters long splinters.

2)''Chartherization" (thermochemical conversion): At first, the whole reaction column (ideally 10m high) is filled with crushed wood and during the operation, extraction of hot charcoal at the bottom occurs simultaneously with the supply of cold wood at the top of the reactor. This procedure can ensure a continuous operation of the system. During chartherization, the crushed wood is heated in the reaction column by subjecting it to a flow of hot gases in counter flow regime meaning that the wood is exposed to low temperatures at the top of the column and heated while moving downwards. For a reaction column of 10m high, the residence time of the wood in the column is at least 8 hours depending on the type of wood input and the hot gas flow rate.

The wood is dried and decomposed, releasing volatile combustible vapors and producing a coal-type residue that captures the metals and minerals. The vapors, released by thermal decomposition of the wood (370°C), flow upward where part of them is condensed due to the cooling effect of the wood column. These condensed compounds are cracked when they arrive again in the hot zone at the bottom of the column, and so on. Thus, the process is characterized as a sequence of evaporation, cooling, condensation, heating, cracking, etc. where the wood column acts both as a condenser and as a filter. The combustible vapors are washed in a water scrubber and subsequently burnt in a gas burner that supplies energy to the system (autothermal operation), see Figure A. 9 for more details of the process.

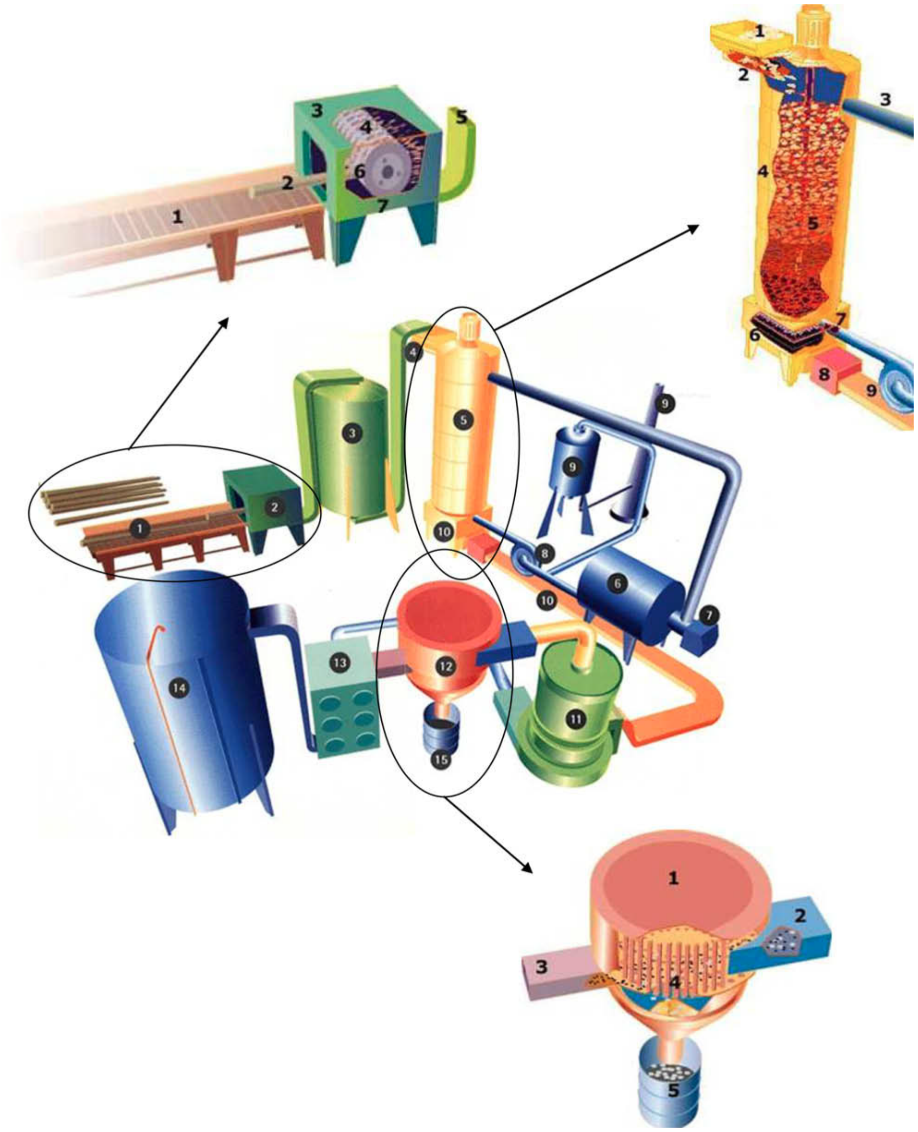


Figure A. 9 Schematic presentation of the Chartherm process:

(1) chain conveyor, (2) crusher, (3) crushed wood silo, (4) feed hopper, (5) reactor, (6) hot gas generator, (7) afterburner, (8) compressor, (9) flue gas scrubber and chimney, (10) solid product extractor and conveyor, (11) mill, (12) pneumatic centrifugal separator, (13) carbon product collector, (14) carbon product storage, (15) metals conditioning. Detail of crusher: (1) chain conveyor, (2) pole, (3) crusher, (4) inertia drum, (5) wood shreds output, (6) wood crushing, (7) metal scrap collector. Detail of reactor: (1) hopper, (2) crushed wood input, (3) gas output, (4) reactor, (5) crushed wood at different levels of chartherisation, (6) grate, (7) hot gas input, (8) carbon product extraction, (9) carbon product output. Detail of separation: (1) pneumatic centrifugal separator, (2) carbon product input, (3) clean carbon output, (4) venting drum, (5) heavy metals and minerals.

3) Separation (or refining): The mineral residue is extracted from the bottom of the column, is cooled, compressed and grounded to powder and fed to the subsequent separation stage. Centrifugal separation can separate carbon from the other minerals (Helsen, 2008).

Method of Energy Recovery: Pyrolysis with auto-combustion process (heat generation for the system from hot gases with a temperature of 370°C) and producing “clean graphitic carbon powder" at a minimum rate of 425 kg per hour, 3000 MT per year (Hery, N/A), (Helsen, 2008).

Environmental Impacts:

As previously mentioned, in studies performed by Helsen, arsenic is identified as the problematic compound with respect to volatilization. The goal of low temperature and elevated pressures in Chartherm process is to keep all metals in the solid product (coal type residue) without any metals present in the vapor. The synchar product contains all minerals and metals that were originally present in the wood. The subsequent separation of the synchar in a pure carbon product and a rich metal product is performed in a mechanical way by using a centrifugal separator, after milling.

However, the metal behavior during chartherization is not yet completely understood and needs more fundamental research percentages of metals volatilized depend strongly on the operating conditions of the process. Therefore, it may be possible to limit arsenic release by choosing the operating conditions very carefully.

To get the chlorine in free form, high temperatures are needed while the reactor temperature never exceeds 400°C. As long as dioxins are not present in the input to the process, they will not be present in the product streams of the process. (Helsen, 2008)

Economic details:

There is no information available on the capital and operating costs of the industrial level plant.

Appendix A 2 Aside: Interesting Technologies

It is expected that more research will be conducted on the pyrolysis and gasification of the treated/painted wood waste. The technologies that are now immature, however, under developments are described below.

1. Plasma Arc Gasification (Plasco)
2. Combined Slow Pyrolysis and Gasification (Thermoselect High Temperature Recycling)

Plasma Arc Gasification

Plasma arc gasification may be a better conversion technology because its byproduct is vitrified slag and it does not leachate. This byproduct can be used to produce rock wool, floor tiles, roof tiles, insulation and landscape blocks. However, pyrolysis and gasification produce ash and char that cleanup process is required before disposal at the landfill. Plasma arc gasification also shows a higher net conversion efficiency (Plasco: 32.2%) compared to gasification (Enerkem: 29.7%) and pyrolysis (JBI: 25.7%). On the other hand, the maturity level of gasification technology is higher than the other two with the lowest for plasma arc gasification technology (Tan, 2013).

Plasma arc gasification is an expensive technology compared to gasification and pyrolysis.

Figure A. 10 illustrates the schematic diagram of a process of plasma arc gasification. Plasma arc gasification processes are characterized by:

- High reaction temperatures and energy densities in the reactor
- Capability to safely dispose of hazardous wastes including asbestos, munitions, medical waste, toxic chemical agents, etc.
- High parasitic power loads required operate the torches
- Production of inert vitrified solid (after cooling) from inorganic components in the fuel
- Requirement for a low moisture fuel that is consistent in composition (Stantec, 2010)

The facility is modular and multiple modules can be accommodated on a single site with some sharing of infrastructure. Plasma gasification applies a high temperature plasma arc under an oxygen-starved environment to break down waste to produce syngas for energy recovery. The operating temperature of plasma gasification can be as high as 2,700^{o}C to 4,400^{o}C or even up to 10,000^{o}C. At these temperatures, waste is broken into basic elemental components in a gaseous form, complex molecules are separated into individual atoms, and inorganic materials such as glass are transformed into a vitrified slag. The technology is mainly adopted for treating industrial and hazardous wastes such as MSW ash, contaminated soils, military waste, used activated carbon and radioactive wastes. Application for treating mixed MSW is rare and mainly limited to refuse derived fuel treatment. Emission from a plasma gasification plant is low, and there are no ash residues requiring landfill disposal. Since the process requires significant amount of energy input, the overall energy recovery rate is lower (EPD, 2009). The residue is estimated to be >1 to 10% but varying due to the nature of the waste and efficiency of the conversion process. The landfill capacity is reduced by up to 99%. The electricity production is between 0.3 and 0.6 MWh/annual tonne of MSW.

Plasma arc facilities tend to consume more energy to operate than other types of facilities. Plasma arc gasification is not commercially proven to treat MSW. The primary reason appears to be the high capital and operational costs for such facilities. The capital cost of the technology is $1,440/tonne (+/-40%). Operating and maintenance cost is $135/tonne (+/-50%). The wear on the plasma chamber is very high and to keep the process operating redundant plasma chambers are needed. Two technologies that are currently being tested in Canada are the Alter NRG process and the Plasco process (Stantec, 2010). Nevertheless, the author could not find any example of thermal treatment of the treated/painted wood waste with this technology. Therefore, applicability of this technology, the emission control and residue treatment for the treated/painted wood waste is unknown. The Plasco Plasma Arc Gasification plant is described below.

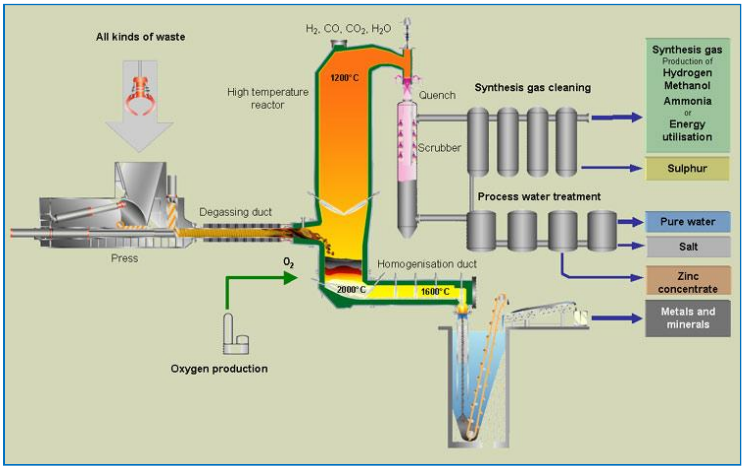


Figure A. 10 Schematic Diagram of Plasma Arc Gasification Process

Plasco Plasma Arc Gasification Plant, Ottawa, Canada

Plasco Energy Corp. (Plasco) has also developed a plasma arc gasification technology to treat MSW. Plasco built entered into an agreement with the City of Ottawa to develop a demonstration facility on City-owned property next to the City‘s Trail Road Landfill in April 2006. Construction began in June 2007, and the first waste was received at the facility in January 2008 (Stantec, 2010).

Feedstock properties and requirements:

The plant is permitted to process 85 tonnes per day of MSW. The plant processed approximately 2,000 tonnes of MSW in the first year of operations (2008), operating for 890 hours or approximately 37 days (Stantec, 2010).

Technology:

Pre-processing of MSW is required to ensure that the waste received is suitable for the conversion chamber. Figure A. 11 presents a conceptual overview of the Plasco process. The process includes complex reaction, scheduled and unscheduled downtime. In the Plasco process, the syngas produced in the primary conversion chamber is refined and cleaned (Stantec, 2010).

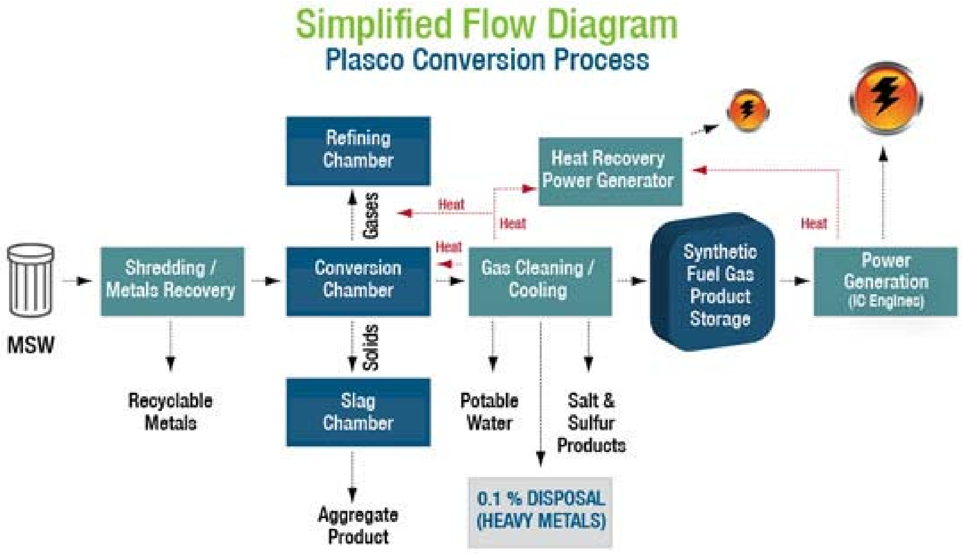


Figure A. 11 Plasco Conversion Process, Simplified Flow Diagram

Method of Energy Recovery:

The process would produce 1,150 kWh of power per tonne of waste when fully operational process 85 tonnes per day (Stantec, 2010).

Environmental Impacts:

No emissions to air are generated during the creation of Syngas from MSW. The emissions to air from the process are associated with the combustion of the Syngas in gas engines to produce electricity. These emissions must meet requirements in the operating permit that are more stringent than those set out in Ontario guidelines for PM, Organic matter, HCl, NOx, mercury, cadmium, lead and dioxins/furans (Stantec, 2010).

Economic details:

The adjusted base capital cost of $89.5 million and operating and maintenance cost of $10 million for a 300 Tonnes per day plant (Clark & Rogoff, 2010).

Combined Slow Pyrolysis and Gasification (Thermoselect High Temperature Recycling)

The development of the Thermoselect HTR (High Temperature Recycling) process began in 1989. A demonstration plant was built at Fondotoce in Italy and was operated for semi-commercial scale from 1994 to 1999. The plant at Karlsruhe, Germany (1999) uses three trains of the Thermoselect system to process 204,119 tonnes per year (225,000 tonnes/yr) of MSW and produce 50 MW (thermal) of heat for the district-heating network. The plant at Ansbach, Germany (2000), has one train to process 75,000 tonnes per year of MSW, and a second train is scheduled to be added later (Fischer Tropsch, N/A).

Feedstock properties and requirements:

Many improvements have been made to the Thermoselect gasifier including increased throughput from 10-12.5 tonne per hour (Fischer Tropsch, N/A)

Technology:

The process combines slow pyrolysis with fixed-bed oxygen-blown gasification and residue melting. The first stage of the process uses a high-pressure press to compact the feedstock to increase its bulk density, squeeze out entrained air, and homogenize the material by dispersal of liquids. The second stage involves the pyrolysis of the compacted material by indirect heating while it flows down the pyrolysis channel. The temperature varies from 100-200°C at the entrance to over 800°C at the transition point from the pyrolysis channel to the gasification reactor. A residence time of 1-2 hours is needed to convert the material to syngas and char.

Further reaction takes place in the gasification reactor with a residence time of 2-4 seconds and a syngas discharge temperature of 1,200°C. Oxygen is fed to the gasification reactor at a pressure of 100 kPa. All the carbon char is converted to syngas comprising mostly H2 and CO. The inorganic components such as metals and mineral materials are maintained in a molten stage between 1600-2000°C with additional fuel gas. Slag in molten state is water quenched to form mineral chip and iron rich metal pellets for recycling. The syngas can be used as a fuel source for power generation (Fischer Tropsch, N/A).

Method of Energy Recovery:

Thermoselect plant at Hanau, Germany, uses two trains to process 90,000 tonne per year of MSW. The syngas is used for offsite power generation of 10.3 MW (electricity). A facility was built in Chiba, Japan, in 1999 with two trains to process 136.1 metric ton/day (150 ton/day) of MSW (Fischer Tropsch, N/A).

Environmental Impacts:

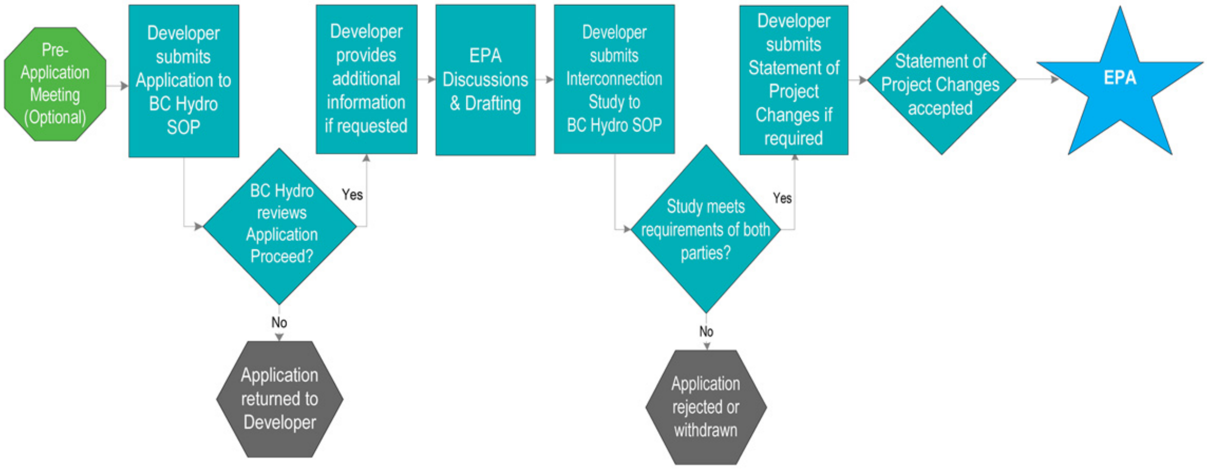
The syngas from the gasification reactor is water quenched to below 70°C. Acid gases such as HCl and HF are removed by conventional scrubbing while H2S is converted catalytically to elemental sulfur. The syngas is further processed to remove water vapor and passed through an activated carbon filter to comply with regulatory limits (Fischer Tropsch, N/A).

Economic details:

They found that the Thermoselect facility is the most capital intensive at about $237 million for 1,587 tonnes/day plant and also has the highest operating cost at $86.11/tonnes. On the other hand, it has the highest net heat rate at 13.55 MJ/kWh (Fischer Tropsch, N/A).

Appendix 2 Summary of Wood Based Biomass Potential and Steps to Obtain an Electricity Generation Permit for WTE Facilities (BC Hydro, 2013)

Transmission Region	Number of Projects	Installed Capacity (MW)	DGC (MW)	Annual Energy (GWh/yr)	Annual Firm Energy (GWh/yr)	UEC at POI Range ($2013/MWh)
Standing Timber						
Peace River	1	46	46	368	368	241
North Coast	2	221	221	1,762	1,762	205 - 276
Vancouver Island	1	246	246	1,962	1,962	232
Lower Mainland	1	246	246	1,962	1,962	232
Sub-Total	5	759	759	6,054	6,054	205 - 276
Roadside Debris & Woodwaste						
Peace River	1	56	56	446	446	132
North Coast	3	38	38	301	301	122 - 137
Central Interior	1	41	41	325	325	137
Kelly Nicola	1	60	60	476	476	141
Vancouver Island	1	89	89	707	707	132
Lower Mainland	1	89	89	707	707	133
Selkirk	1	66	66	530	530	131
East Kootenay	1	28	28	225	225	139
Sub-Total	10	467	467	3,718	3,718	122 - 141
Total	**15**	**1,226**	**1,226**	**9,772**	**9,772**	**122 - 276**



Appendix 3 Quantity of DLC Waste Diverted from Two Landfills 2010-2011 Metro Vancouver (AET Consultants, 2011)

	Ecowaste and Vancouver Landfill Combined		
Material Categories - By Material Type	% by Volume	% by Weight	Total Estimated Annual Weight (Tonnes)
Wood	**56.9%**	**54.1%**	**150,823**
Dimensional Lumber (unpainted)	29.6%	25.6%	71,380
Dimensional Lumber (painted/treated)	9.0%	8.2%	22,797
Pallets	0.1%	0.1%	315
Wood Flooring (e.g. Hardwood, Laminate)	0.6%	0.5%	1,347
Wood Shakes and Shingles	1.1%	0.8%	2,194
Composite	16.4%	18.9%	52,790
Landclearing	**2.5%**	**1.6%**	**4,518**
Large yard waste (branches > 15 cm diam. Or 1m long	1.8%	1.3%	3,639
Small yard waste, green waste	0.7%	0.3%	879
Paper	**0.3%**	**0.1%**	**341**
Cardboard	0.1%	0.0%	64
Miscellaneous paper (office, kraft, etc.)	0.2%	0.1%	277
Plastic	**6.0%**	**3.9%**	**10,871**
Sheet or film plastic	1.4%	0.1%	141
Styrofoam packaging	1.9%	0.1%	396
Miscellaneous plastic (rigid plastics, pipes, vinyl siding)	2.7%	3.7%	10,334
Concrete	**4.0%**	**4.6%**	**12,906**
Poured with rebar	0.5%	0.5%	1,486
Poured without rebar	1.9%	2.2%	6,112
Preformed blocks	1.7%	1.9%	5,307
Metals	**1.9%**	**1.6%**	**4,377**
Ferrous	0.6%	0.8%	2,283
Non-Ferrous	0.1%	0.1%	301
Mixed metals (plumbing, electrical, flashing, siding, furniture)	1.2%	0.6%	1,793
Brick	**1.3%**	**1.1%**	**3,081**
Asphalt Products	**5.9%**	**8.1%**	**22,519**
Pavement	0.1%	0.1%	337
Asphalt shingles and tarpaper	5.4%	7.1%	19,923
Tar and gravel roofing	0.4%	0.8%	2,258
Miscellaneous Building Material	**7.3%**	**3.4%**	**9,488**
Carpet	1.7%	1.1%	3,051

	Ecowaste and Vancouver Landfill Combined		
Material Categories - By Material Type	% by Volume	% by Weight	Total Estimated Annual Weight (Tonnes)
Underlay	1.0%	0.7%	1,901
Linoleum Flooring	0.3%	0.4%	1,015
Drywall	0.9%	0.6%	1,573
Lath and Plaster	0.2%	0.1%	328
Stucco wall finishing	0.5%	0.3%	867
Ceiling tiles	0.2%	0.1%	371
Insulation (i.e. fiberglass, cellulose, foam)	2.7%	0.1%	381
Glass and Ceramics	**0.3%**	**0.7%**	**2,063**
Glass	0.0%	0.0%	64
Porcelain (i.e., bathroom fixtures)	0.0%	0.0%	126
Indoor tile (i.e., wall finishing, flooring)	0.1%	0.4%	1,024
Outdoor tile (i.e., roofing)	0.1%	0.3%	848
Rubble/Soil	**11.1%**	**18.8%**	**52,289**
Household Garbage	**0.8%**	**0.5%**	**1,438**
Textiles	**0.3%**	**0.2%**	**638**
Bulky Items	**0.2%**	**0.1%**	**411**
Rubber	**0.1%**	**0.1%**	**409**
Tires, tubing	0.0%	0.0%	96
Rubber roofing	0.1%	0.1%	312
Miscellaneous	**1.1%**	**0.9%**	**2,601**
Total	**100.0%**	**100.0%**	**278,772**

Appendix 4 Jurisdictional Reviews in British Columbia

Jurisdictional Reviews: Regulations, Standards or Guidelines Applicable to Solid Waste Disposal (Giroux , 2014)

Title & Description of Regulations, Standards, or Guidelines for Disposal	Category	Sector	Voluntary or Mandatory
British Columbia			
Environmental Management Act (EMA) and the Waste Discharge Regulation require site specific authorization for waste disposal, in a municipal landfill or incinerator	Landfills and Incineration	All Sectors	M
Wood Residue Burner and Incinerator Regulation under the EMA established the phase-out dates (Dec 2016) and operating conditions for all types of specified burners used in BC and sets emission limits and fees for the discharge of associated particulate matter for all burner facilities in the province. There is a supporting Code of Practice for this Regulation targeting ICI sector.	Incineration	ICI wood	M
Open Burning Smoke Control Regulation restrict open burning of: tires, treated lumber, plastics, drywall, demolition waste, rubber, domestic waste, paint, asphalt products, hazardous waste, fuel, and debris burning from land clearing and harvesting.	Open Burning	All Sectors	M
The Landfill Criteria for Municipal Solid Waste document addresses the siting, design, operation and performance requirements for three classifications of landfills: sanitary landfills; modified sanitary landfills; and selected waste landfills. Mandatory if included in a site-specific landfill authorization.	Landfills	MSW	V/M
Landfill Gas Management Regulation: province-wide criteria for LFG capture from municipal solid waste landfills, and identification of opportunities to increase LFG recovery. The regulation phases in new requirements for LFG capture that take into account economic and technical feasibility requirements and associated implications for landfill owners.	Landfill gas	MSW	M
Code of Practice for Industrial Non-Hazardous Waste Landfills Incidental to the Wood Processing Industry (including logging operations, manufacturing lumber, wood or millwork products). The code of practice is a results-based regulation requiring all landfills to register their facility, provide financial security and prepare a conceptual closure plan, an annual report and a final closure plan, while large wood waste landfills are also required to prepare a waste characterization report, a design plan and an operation plan.	Landfills	ICI wood	M
Concrete and Concrete Products Industry Code of Practice - establishes province-wide standards for waste discharge from this industry. It includes the management of waste solids — as well as registration, monitoring, record keeping and enforcement.	Landfills	ICI concrete	M
The Combustion of Municipal Solid Waste FactSheet provides guidance on emission limits and other operating parameters.	Incineration	All Sectors	V
Considerations for the Inclusion of Waste-to-Energy Facilities (WTE) in Solid Waste Management Plans information sheet provides guidance regarding an efficiency threshold that distinguishes between disposal and energy recovery.	Incineration	All Sectors	V

Appendix 5 Location of the "Western 40" and Suggested Location for the WWTE Facility at the VLF

The area inside of the blue rectangular is the location of the Western 40 (40 hectares). The VLF's future Wood Waste-To-Energy (WWTE) Facility can be constructed in the area inside of the red rectangular (~3 hectares)

Appendix 6 Real Annual DLC Waste and The Material Types 1993-2014 at the VLF

	1993	1994	1995	1996	1997	1998	1999	2000	2001
Clean Wood	64,800	49,994	31,880	40,920	19,380	40,480	44,732	59,157	28,322
Plywood, Treated/Painted Wood	25,920	19,997	12,752	16,368	7,752	16,192	17,893	23,663	11,329
Concrete	19,440	14,998	9,564	12,276	5,814	12,144	13,420	17,747	8,497
Rubber/Soil	17,820	13,748	8,767	11,253	5,330	11,132	12,301	16,268	7,789
Other	34,020	26,247	16,737	21,483	10,175	21,252	23,484	31,057	14,869
Total DLC Waste	**162,000**	**124,984**	**79,700**	**102,300**	**48,450**	**101,200**	**111,830**	**147,892**	**70,806**
Total Wood Waste	**90,720**	**69,991**	**44,632**	**57,288**	**27,132**	**56,672**	**62,625**	**82,820**	**39,651**

	2002	2003	2004	2005	2006	2007	2008	2009	2010
Clean Wood	56,879	43,167	55,682	58,461	60,248	49,883	58,017	34,704	56,293
Plywood, Treated/Painted Wood	22,752	17,267	22,273	23,384	24,099	19,953	23,207	13,882	22,517
Concrete	17,064	12,950	16,705	17,538	18,074	14,965	17,405	10,411	16,888
Rubber/Soil	15,642	11,871	15,313	16,077	16,568	13,718	15,955	9,544	15,481
Other	29,861	22,663	29,233	30,692	31,630	26,189	30,459	18,220	29,554
Total DLC Waste	**142,197**	**107,918**	**139,205**	**146,151**	**150,619**	**124,709**	**145,042**	**86,760**	**140,734**
Total Wood Waste	**79,630**	**60,434**	**77,955**	**81,845**	**84,347**	**69,837**	**81,224**	**48,586**	**78,811**

Appendix 6 Continued

	2011	2012	2013	2014
Clean Wood	44,190	88,952	76,026	63,706
Plywood, Treated/Painted Wood	42,079	37,063	31,677	26,544
Concrete	6,688	9,266	7,919	6,636
Rubber/Soil	25,536	9,266	7,919	6,636
Other	22,239	40,770	33,261	29,199
Total DLC Waste	**140,734**	**185,316**	**158,387**	**132,721**
Total Wood Waste	**86,270**	**126,015**	**107,703**	**90,250**

Appendix 7 Predicted Annual DLC Waste and The Material Types, Without Reduction and Diversion Plans at the VLF

	2015	2020	2025	2030	2040	2050
Clean Wood	48,888	23,158	0	0	0	0
Plywood, Treated/Painted Wood	38,823	44,773	56,749	60,256	64,036	69,582
Concrete	10,065	18,527	24,321	25,824	27,444	29,821
Rubber/Soil	10,065	18,527	24,321	25,824	27,444	29,821
Other	35,947	49,405	56,749	60,256	64,036	69,582
Total DLC Waste	**143,789**	**154,389**	**162,140**	**172,160**	**182,960**	**198,804**
Total Wood Waste	**87,711**	**67,931**	**56,749**	**60,256**	**64,036**	**69,582**

Appendix 8 Predicted Annual DLC Waste and The Material Types, With Reduction and Diversion Plans at the VLF

	2015	2020	2025	2030	2040	2050
Clean Wood	40,955	9,729	0	0	0	0
Plywood, Treated/Painted Wood	32,523	18,810	7,945	1,750	438	109
Concrete	8,432	7,783	3,405	750	188	47
Rubber/Soil	8,432	7,783	3,405	750	188	47
Other	30,114	20,755	7,945	1,750	438	109
Total DLC Waste	**120,455**	**64,861**	**22,701**	**5,000**	**1,250**	**313**
Total Wood Waste	**73,478**	**28,539**	**7,945**	**1,750**	**438**	**109**

Appendix 9: Existing and Emerging Technologies for Managing CCA-Treated Wood Waste

(Helsen & Van den Bulck, 2004)

management option	**barriers**	**prognosis**
reuse	wood waste is bulky and inefficient to transport; contaminated sawdust may be generated	good for industrial products but of limited potential for residential treated products
• used as garden borders, posts, land piling, retaining walls, …	high contamination with nails and other fasteners; high cost to dismantle; low quality wood	
• remanufacture – fence components	high contamination with nails and other fasteners; high cost to dismantle; low quality wood	material would have to be refinished to even out differences in weathering discoloration
• salvage and reuse through waste exchange	high cost of handling sorting, transportation and storage	limited potential
refining for recycling		
• wood based composites	issue of using metal containing and contaminated wood and loss of ownership of treated wood (product should be identified as one containing treated wood); landfill disposal is only deferred, not avoided; CCA tends to interfere with the adhesives	the market is not in favour of using CCA wood in conventional wood composite manufacturing, questions about safety of workers and environmental problems
– wood-cement composites	CCA wood fibre cement products are unlikely to be used since pulping of treated wood releases the CCA components into the spent pulping liquor, unless it is mechanically pulped; slow process due to long curing time of the composite; potential for hexavalent chromium release	excellent potential for the development of new composite products; benefit from inclusion of decay resistant wood fibre; stabilisation of metals within a cement matrix; improvement in bending strength and stiffness, internal bond strength, water absorption and thickness swelling performance
– wood-polymer composites	leaching, recyclability, decay resistance, emissions during processing and impacts on physical and mechanical properties should be evaluated	benefit from inclusion of decay resistant wood fibre; low cost and high strength to weight ratio
– thermosetting adhesives bonded composites, particleboard	it makes little sense to use CCA wood since the decay hazard is too low to justify it, except in the presence of termites; in that case the identification of the amount and distribution of CCA particles is required; an addition of 50% CCA wood does not significantly affect the board properties	unproven and unlikely to be a significant factor in the near term
– wet processed fibreboard and MDF	it makes little sense to use CCA wood since the decay hazard is too low to justify it; use of CCA wood would complicate the cleanup of process water	unproven and unlikely to be a significant factor in the near term
– exterior flakeboard products, oriented strand board (OSB)	OSB is made from high quality flakes; lumber products can not be flaked properly; the presence of CCA lowers all property values substantially; however, physical and mechanical properties were enhanced by spraying the flakes with a primer just before spraying and blending of the resin	unproven and unlikely to be a significant factor in the near term
• biodegradation by fungi	part of the contaminants left in the wood and loss in fibre quality; absence of end use for extracted wood and chemicals; problems with contamination of the system by other organisms	not economically feasible
• extraction of CCA components	not 100% effective and slow; recycling of CCA components is not proved; not cost-effective at this time; high cost of size reduction	some potential for treatment of minor amounts of treated wood such as that produced as a by-product of milling
– biological	almost complete extraction, only if combined with solvent extraction = dual remediation; several constraints that limit efficiency and cost-effectiveness	technically feasible but slow and expensive (high cost of the nutrient culture medium)
– chemical	huge amounts of chemicals are used; multistage extraction is required to ensure complete removal of CCA; technology to recover CCA chemicals is not disclosed (re-oxidation + elimination of extracting compounds), but mixing of recovered solution and fresh CCA solution is promising	more research and development is needed to improve, optimise and evaluate the process; effects of extraction on combustion characteristics of wood residue are not reported; extraction has negative effect on the properties of particleboard prepared from extracted wood; economic feasible for surface removed treated wood or sawdust by-products of a re-sawing operation to recycle CCA chemicals
– steam explosion	does not increase the extractability of	not economically feasible

Appendix 9: Continued

	the chemical components if used as a pre-treatment prior to extraction; leave some residual material in the extracted wood (only 90% removal of CCA)	
– electro-dialytic	no field tests performed (pilot scale is now being tested); expected cost is high; after treatment the metals are distributed over the electrolyte solution, the membrane and as a precipitate on the electrode; total removal of metals not achieved, Cu/Cr/As ratio in the electrolyte differs from the ration in the fresh CCA solution	not yet economically feasible; difficult to compete with solvent extraction
• use for mulch, compost or animal bedding	more leaching due to increased surface area (less than 0.1% CCA wood causes a mulch to exceed risk-based direct exposure standard for arsenic); CCA chemical is dispersed into the environment; products will become untraceable	clear policies and regulations that prohibit inclusion of CCA wood in mulch should be developed
treatment and destruction		
• wood liquefaction	only initial lab-scale experiments; only 85% of the CCA is removed	much more research is needed to improve, optimise and evaluate the process
• thermal destruction	advantage of energy recovery and significant reduction of waste volume, but ash is considered as hazardous waste and arsenic compounds are volatile (modifications, controls and monitoring are needed to meet air quality standards); chipping or grinding is required increasing the energy consumption and cost	potential if the metals collected in the ash are dealt with and arsenic is trapped from the flue gas; most common method in Europe but strong resistance in Canada; more favourable climate for this option is expected in the future
– controlled environment incineration / combustion / cogeneration	cost of grinding dirty material; presence of arsenic in the emissions; collection of metals in the ash where it must be collected and dealt with (metal stabilisation or metal extraction through chemical or electrochemical processes or cyclone melting); general resistance in some countries to consider these options for disposal	some potential, but requires further development; lessens the dependence on fossil fuels; metal concentrations can be diluted by mixing with other waste streams (such as household waste) or fuels (such as coal)
– cement kilns	Portland cement standards have limitations on metal levels, chromium being the limiting element; cost of collection, transport, removal of metal contaminants, getting a permit	potential is limited to a fraction of wood generated; appropriate for milling residues and low retention residential wood
– controlled pyrolysis	arsenic is distributed over the three products (charcoal, bio-oil and pyrolysis gas); no time-temperature threshold found for zero arsenic volatilisation	besides elimination of dioxins and furans formation and possibly easier metal recovery, no additional advantages over the other thermal destruction methods
– high temperature gasification in a metallurgical furnace	high cost of pure oxygen; removal of pure metallic arsenic in the vapour not yet proven on a large scale; arsenic emissions during start-up and shutdown	pilot plant tests still have to be performed; more research is needed to evaluate the process
• energy and raw materials recovery by metallurgical processes	plant has to be well designed to scrub all volatile and particulate arsenic from the stacks; relatively low CCA concentrations in the lumber make CCA recycling economically infeasible; not yet all metal products are transformed to usable forms	excellent potential if infrastructure for collection and transportation of CCA wood waste is developed; further research is needed to examine the maximum amount of CCA wood that can be mixed with copper concentrates without interfering the process
landfill disposal	CCA chemical can leach from CCA wood (both unburned and as ash) in quantities that exceed regulatory thresholds; monofill results in the highest metal concentrations in the leachate compared to C&D debris landfill and MSW landfill; cost of landfilling (hazardous waste sites, lined landfills); shortage of landfill space	not a preferred option because it does not recover any value from the used product; may not be acceptable at individual landfill sites (by 2005 no organic wastes will be accepted at landfills in the EU)

Appendix 10 List of Conversion Technology Vendors: Gasification, Biological Processing and Aerobic Digestion/Composting

Thermal Processing

Gasification

- Bioengineering Resources, Inc./New Planet Energy/Ineos Bio
- CBES Global, LLC
- Crystal Creek Energy
- Dynecology
- Ebara Corporation
- Ecosystems Projects
- EcoTech Fuels, LLC
- Enerkem
- Entech Solutions
- Envirepel Energy, LLC
- Global Alternative Green Energy
- Global Energy Solutions
- Global Recycling Group
- Green Energy Corporation
- Holloway Environmental/Entech
- ILS Partners/Pyromex
- Interstate Waste Technologies (Thermoselect)
- KAME/DePlano
- MaxWest Environmental Systems
- Mustang Renewable Power Ventures (Waste 2 Energy)
- Primenergy
- Princeton Environmental Group
- Taylor Biomass
- Taylor Recycling Facility
- Thermogenics
- Urbaser, Inc. (Energos AS)
- Waste Gasification Systems / Allan Environmental
- Waste to Energy, LLC/BioEnergy Design, LLC
- World Waste Technologies
- Ze-Gen
- Zeros Technology Holding
- Zero Waste Energy Systems

Biological Processing

Anaerobic Digestion

- ArrowBio
- Arrow Ecology and Engineering
- Bekon
- BioFERM
- Biogas Energy, Inc.
- Canada Composting
- CCI BioEnergy
- Clean World Partners
- CR&R, Inc. with Organic Waste Systems (DRANCO)
- Ecocorp
- Harvest Power
- KAME/DePlano
- Mustang Renewable Power Ventures (Bekon)
- New Bio
- Orgaworld
- Ros Roca Envirotec
- Strategic Management Group w/ Entec Biogas USA
- Urbaser, Inc. (Valorga)
- Vagron
- Waste Recovery Systems, Inc. (Urbaser/Valorga)
- Zero Waste Energy, LLC (Kompoferm)

Aerobic Digestion/Composting

- Civic Environmental Systems
- Conporec
- Mining Organics Management

Appendix 11 List of Conversion Technology Vendors: Plasma Gasification, Pyrolysis, Chemical and Mechanical Processing

Plasma Gasification
AdaptiveARC
Alter NRG Corporation / Westinghouse
BioGold Fuels Corporation / Alter NRG
Environmental Energy Resources/ SNC-Lavalin
EnviroArc Technologies / Nordic American Group
Global Environmental Technologies
GSB Technologies
InEnTec
NRG Energy, Inc.
Peat International / Menlo Int.
Plasco Energy Group
Solena Group
Startech Environmental
Technip USA, Inc.

Pyrolysis
Bioconversion Technology LLC (Emerald Power)
Eco Waste Solutions
Entropic Technologies Corporation
GEM America
Pan-American Resources
Pyrogenesis Canada, Inc.
Recycled Energy Corporation/Pyrolysis "Plus" Technology
Renewable Energy Resources, Inc.
International Environmental Solutions

Steam Reformation
Synterra Energy

Chemical Processing

Hydrolysis
Arkenol Fuels/Blue Fire Ethanol
Biofine / BioMetics
Genahol
Masada OxyNol
RCR International

Other
Changing World Technologies
Innovative Energy Solutions, Inc.
Terrabon, Inc. w/ Waste Management California

Mechanical Processing

CES Autoclaves
Cleansave Waste Corporation
Comprehensive Resources
EnerTech Environmental
Herhof Gmbh
Recycled Refuse International
Ros Roca Envirotec (MBT)
Tempico
Vorus Biopower
WET Systems
World Waste Technologies
WSI Management, LLC

(1) Highlighted companies submitted responses to the County of Los Angeles Department of Public Works Request for Expression of Interest, Conversion Technology Providers distributed in June 2011.

Appendix 12 Proposed Revisions to Emission Criteria for Municipal Solid Waste Incineration in British Columbia

Contaminant	Concentration Units	RECOMMENDED EMISSION LIMITS (Facilities Processing >400 kg/h)					CURRENT EMISSION LIMITS (1991)		
		C: Continuous P: Periodic [1]	Daily Average	Average Period and Monitoring Method	Half Hourly Average	Average Period and Monitoring Method	Facilities processing >400 kg/h	Average Period	Monitoring Method
Total Particulate Matter (TPM)	mg/Rm^3 @ 11% O_2	**P (C optional)**	**10**	Calculated as the arithmetic average of a minimum three individual stack tests per stack conducted in accordance with standard methods, or as the arithmetic average of 24 hours of data from a continuous emissions monitoring system.	**20**	1/2 hour average as determined by a continuous emissions monitoring system	20	To be monitored over the approved sampling and monitoring period	Methods to be approved by Regional Manager
Carbon Monoxide (CO)	mg/Rm^3 @ 11% O_2	**C**	**50**	Calculated as the arithmetic average of a minimum three individual stack tests per stack conducted in accordance with standard methods, or as the arithmetic average of 24 hours of data from a continuous emissions monitoring system.	**100**	1/2 hour average as determined by a continuous emissions monitoring system	55	4-hour rolling average	Continuous Monitoring
Sulphur Dioxide (SO_2)	mg/Rm^3 @ 11% O_2	**C**	**50**	Calculated as the arithmetic average of a minimum three individual stack tests per stack conducted in accordance with standard methods, or as the arithmetic average of 24 hours of data from a continuous emissions monitoring system.	**190**	1/2 hour average as determined by a continuous emissions monitoring system	250	To be monitored over the approved sampling and monitoring period	Methods to be approved by Regional Manager
Nitrogen Oxides (NO_x as NO_2)	mg/Rm^3 @ 11% O_2	**C**	**190**	Calculated as the arithmetic average of a minimum three individual stack tests per stack conducted in accordance with standard methods, or as the arithmetic average of 24 hours of data from a continuous emissions monitoring system.	**350**	1/2 hour average as determined by a continuous emissions monitoring system	350	To be monitored over the approved sampling and monitoring period	Methods to be approved by Regional Manager
Hydrogen Chloride (HCl)	mg/Rm^3 @ 11% O_2	**C**	**10**	Calculated as the arithmetic average of a minimum three individual stack tests per stack conducted in accordance with standard methods, or as the arithmetic average of 24 hours of data from a continuous emissions monitoring system.	**60**	1/2 hour average as determined by a continuous emissions monitoring system	70	8-hour rolling average	Continuous Monitoring
Hydrogen Fluoride (HF)	mg/Rm^3 @ 11% O_2	**P/C**	**1**	Calculated as the arithmetic average of a minimum three individual stack tests per stack conducted in accordance with standard methods, or as the arithmetic average of 24 hours of data from a continuous emissions monitoring system.	**4**	1/2 hour average as determined by a continuous emissions monitoring system	3	To be monitored over the approved sampling and monitoring period	Methods to be approved by Regional Manager
Total Hydrocarbons (as CH_4)[2]	mg/Rm^3 @ 11% O_2	**N.D.**	N.D.		N.D.		40	To be monitored over the approved sampling and monitoring period	Methods to be approved by Regional Manager
Organic Matter (as CH_4)	mg/Rm^3 @ 11% O_2	**C**	N.D.		**70**	Calculated as a 1/2 hour average at the outlet of the secondary chamber before dilution with any other gaseous stream, measured by a CEMS	N.D.		
VOCs (reported as Total Organic Carbon)	mg/Rm^3 @ 11% O_2	**C**	**10**	Calculated as the arithmetic average of 24 hours of data from a continuous emissions monitoring system.	**20**	1/2 hour average as determined by a continuous emissions monitoring system	N.D.		
Arsenic (As)	µg/Rm^3 @ 11% O_2	**P**	**4**	Calculated as the arithmetic average of a minimum three individual stack tests per stack conducted in accordance with standard methods.	N.D.		4	To be monitored over the approved sampling and monitoring period	Methods to be approved by Regional Manager
Cadmium (Cd)	µg/Rm^3 @ 11% O_2	**P**	**14**	Calculated as the arithmetic average of a minimum three individual stack tests per stack conducted in accordance with standard methods.	N.D.		100	To be monitored over the approved sampling and monitoring period	Methods to be approved by Regional Manager
Chromium (Cr)	µg/Rm^3 @ 11% O_2	**P**	**10**	Calculated as the arithmetic average of a minimum three individual stack tests per stack conducted in accordance with standard methods.	N.D.		10	To be monitored over the approved sampling and monitoring period	Methods to be approved by Regional Manager
Lead (Pb)	µg/Rm^3 @ 11% O_2	**P**	**100**	Calculated as the arithmetic average of a minimum three individual stack tests per stack conducted in accordance with standard methods.	N.D.		50	To be monitored over the approved sampling and monitoring period	Methods to be approved by Regional Manager
Mercury (Hg)	µg/Rm^3 @ 11% O_2	**P or C [3]**	**20**	Calculated as the arithmetic average of a minimum three individual stack tests per stack conducted in accordance with standard methods, or as the arithmetic average of 24 hours of data from a continuous emissions monitoring system.	N.D.		200	To be monitored over the approved sampling and monitoring period	Methods to be approved by Regional Manager
Chlorophenols	µg/Rm^3 @ 11% O_2	**P**	**1**	Calculated as the arithmetic average of a minimum three individual stack tests per stack conducted in accordance with standard methods.	N.D.		1	To be monitored over the approved sampling and monitoring period	Methods to be approved by Regional Manager
Chlorobenzenes	µg/Rm^3 @ 11% O_2	**P**	**1**	Calculated as the arithmetic average of a minimum three individual stack tests per stack conducted in accordance with standard methods.	N.D.		1	To be monitored over the approved sampling and monitoring period	Methods to be approved by Regional Manager
Polycyclicaromatic Hydrocarbons	µg/Rm^3 @ 11% O_2	**P**	**5**	Calculated as the arithmetic average of a minimum three individual stack tests per stack conducted in accordance with standard methods.	N.D.		5	To be monitored over the approved sampling and monitoring period	Methods to be approved by Regional Manager
Polychlorinated Biphenyls	µg/Rm^3 @ 11% O_2	**P**	**1**	Calculated as the arithmetic average of a minimum three individual stack tests per stack conducted in accordance with standard methods.	N.D.		1	To be monitored over the approved sampling and monitoring period	Methods to be approved by Regional Manager
Total Dioxins and Furans (as PCDD/F TEQ)	ng/Rm^3 @ 11% O_2	**P**	**0.08**	Calculated as the arithmetic average of a minimum three individual stack tests per stack conducted in accordance with standard methods.	N.D.		0.5	To be monitored over the approved sampling and monitoring period	Methods to be approved by Regional Manager
Opacity	%	**P (C optional)**	N.D.		**5**	1/2-hour average from data taken every 10 seconds, measured by a CEMS	5	1-hour average from data taken every 10 seconds	Continuous Monitoring

NOTES:

Concentration units: Mass per reference cubic metres corrected to 11% oxygen. Reference conditions: 20°C, 101.3 kPa, dry gas

N.D. = Not Defined

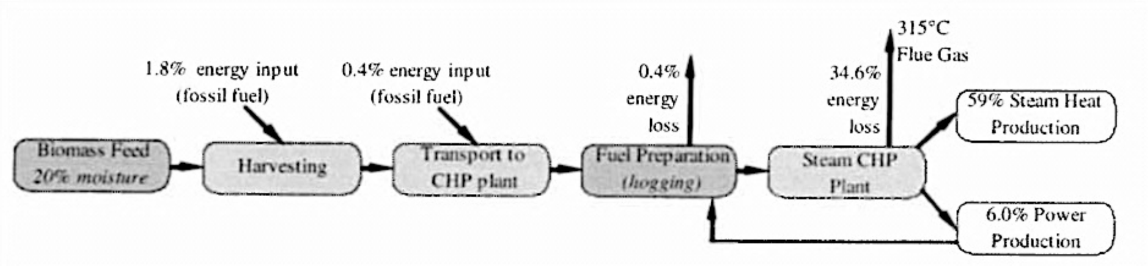
[1] Where Periodic stack test measurements (P) are indicated, the daily averaging period applies. For Continuous monitoring (C), the 1/2 hour averaging period applies. P/C indicates both technologies are available; ELV will be linked to sampling method.

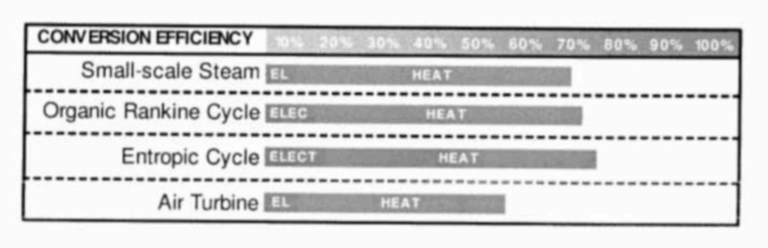
[2] No limit for Total Hydrocarbon is proposed for the revised criteria. This parameter is addressed by the proposed limit on organic matter.

[3] Daily Average ELV for mercury applies regardless of monitoring method

Appendix 13 Steam CHP Energy Balance and Conversion Energy Comparison

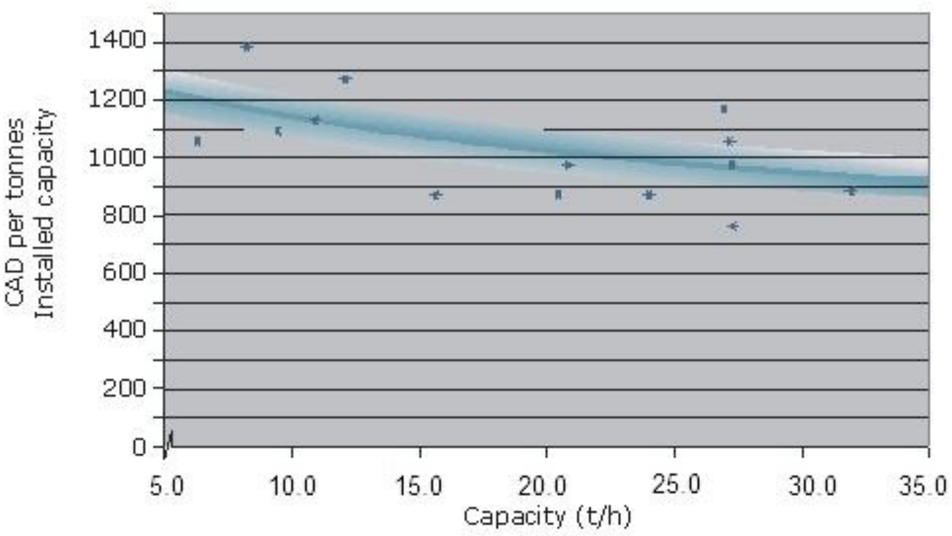
As can be seen, the energy efficiency of small-scale incineration plant with CHP is expected to be up to 65%. In this report, due to uncertainty on the feedstock quality and process complications, the efficiency of the system is assumed up to 50%.



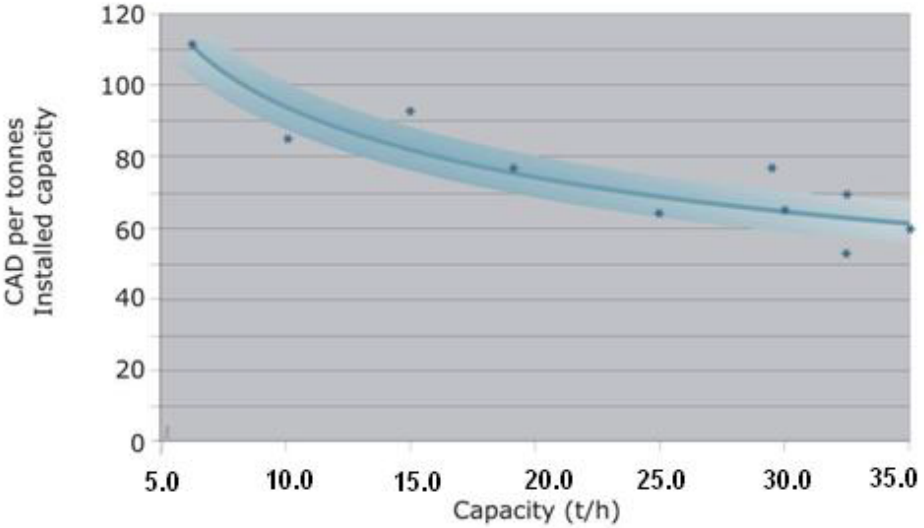


Appendix 14 Range of Capital and Operating & Maintenance Costs for WTE Facilities per Installed Capacity

Capital costs



Operating & Maintenance costs



Source: Ramboll. 2007. Memo to MacViro during the Durham/York Environmental Assessment (Stantec, 2010)

Average throughput for the proposed facility is assumed 7.5 tonnes per hour, therefore, from the curves above, the capital cost is around $1195 ($1050, $2007) per tonne of wood waste and $96 ($85, $2007) per tonnes of wood waste for operating & maintenance cost.

Appendix 15 Co-combustion

It is a variation of incineration technology where two different types of materials are combusted in the same combustion system. One of the examples is the use of certain waste (e.g. waste oil, animal meal, used tires and rubber) or fraction of MSW with high heating value (e.g. refuse derived fuel produced from Mechanical and Biological Treatment Plants) as a fuel for direct feeding to the cement kiln and is burnt together with the cement raw material to produce cement. However, the waste needs to be specially prepared from mixed MSW so as to ensure the compliance with stringent standards.

Figure A. 12 illustrates a schematic diagram of the proposed eco-co-combustion process is given. The technology of an Eco-co-combustion system is considerably more efficient than conventional co-combustion process adopted worldwide. The proposed system burns the MSW in a separate rotary kiln system and the waste heat generated is utilized in the “front-end” cement making calcination process. The pre calcinerated materials hence produced is then used for cement production in the existing rotary kiln of the cement plant.The ash residues generated from MSW burning in the rotary kiln is to be re-used as feed materials into the cement making process.

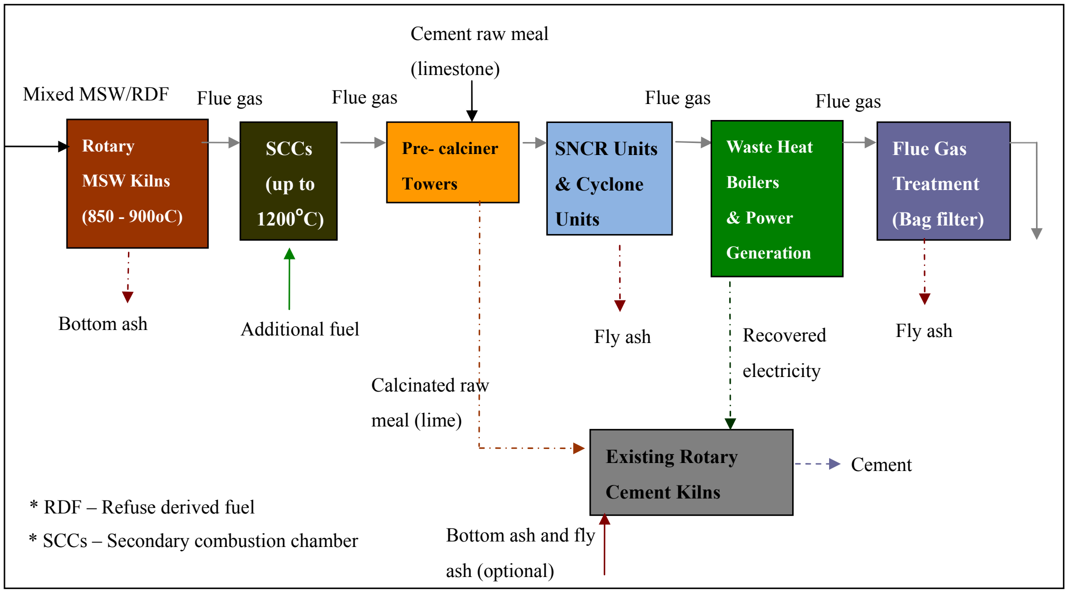


Figure A. 12 Schematic Diagram of the Proposed eco-co-combustion System

Appendix 16 Financial Details and Calculations for Incineration Technology

WTE FACILITY DATA	2015	2020				2025					2030					2035					2040
YEAR	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Throughput Rate (t/yr)		100,000	100,000	72,876	67,931	65,695	63,458	61,222	58,985	56,749	57,450	58,152	58,853	59,555	60,256	60,634	61,012	61,390	61,768	62,146	64,036
Production of electricity MWH		17,733	17,733	12,923	12,046	11,650	11,253	10,857	10,460	10,063	10,188	10,312	10,437	10,561	10,685	10,752	10,819	10,887	10,954	11,021	11,356
Production of heat (GJ/yr)		223,440	223,440	162,835	151,786	146,789	141,791	136,794	131,797	126,800	128,367	129,934	131,502	133,069	134,636	135,481	136,325	137,170	138,015	138,859	143,082
Metal Recovery		226,284	228222	230159	232097	234034	221659	209285	196910	184535	172160	170877	169594	168311	167027	165744	166386	167027	167669	168311	182960
Ferrous Metal Recovery (t/yr)		2,320	2,340	2,360	2,380	2,400	2,273	2,146	2,019	1,892	1,765	1,752	1,739	1,726	1,713	1,699	1,706	1,713	1,719	1,726	1,876
Non-Ferrous Metal Recovery (t/yr)		339	342	345	348	351	332	314	295	277	258	256	254	252	251	249	250	251	252	252	274
Wood Waste Payable																					
Payable Wood		$ 6,000,000	$ 6,000,000	$ 4,372,580	$ 4,075,879	$ 3,941,690	$ 3,807,501	$ 3,673,312	$ 3,539,123	$ 3,404,934	$ 3,447,020	$ 3,489,107	$ 3,531,194	$ 3,573,281	$ 3,615,367	$ 3,638,047	$ 3,660,726	$ 3,683,406	$ 3,706,085	$ 3,728,765	$ 3,842,163
Payable Electricity, Sale to Grid		$ 2,411,733	$ 2,411,733	$ 1,757,583	$ 1,638,322	$ 1,584,384	$ 1,530,446	$ 1,476,508	$ 1,422,570	$ 1,368,632	$ 1,385,549	$ 1,402,466	$ 1,419,383	$ 1,436,300	$ 1,453,217	$ 1,462,333	$ 1,471,449	$ 1,480,565	$ 1,489,682	$ 1,498,798	$ 1,544,379
Payable Heat		$ 8,937,600	$ 8,937,600	$ 6,513,395	$ 6,071,429	$ 5,871,541	$ 5,671,653	$ 5,471,765	$ 5,271,877	$ 5,071,989	$ 5,134,682	$ 5,197,374	$ 5,260,066	$ 5,322,759	$ 5,385,451	$ 5,419,235	$ 5,453,018	$ 5,486,801	$ 5,520,585	$ 5,554,368	$ 5,723,285
Payable Metals		$ 891,120	$ 898,750	$ 906,381	$ 914,011	$ 921,641	$ 872,909	$ 824,176	$ 775,443	$ 726,711	$ 677,978	$ 672,924	$ 667,871	$ 662,817	$ 657,764	$ 652,710	$ 655,237	$ 657,764	$ 660,291	$ 662,817	$ 720,508
Payable Ferrous Metals		$ 348,038	$ 351,019	$ 353,999	$ 356,979	$ 359,959	$ 340,926	$ 321,893	$ 302,859	$ 283,826	$ 264,793	$ 262,819	$ 260,846	$ 258,872	$ 256,898	$ 254,925	$ 255,911	$ 256,898	$ 257,885	$ 258,872	$ 281,404
Payable Non-Ferrous Metals		$ 543,081	$ 547,732	$ 552,382	$ 557,032	$ 561,682	$ 531,983	$ 502,283	$ 472,584	$ 442,884	$ 413,185	$ 410,105	$ 407,025	$ 403,945	$ 400,866	$ 397,786	$ 399,326	$ 400,866	$ 402,406	$ 403,945	$ 439,104
Revenue before Tax		$ 18,240,453	$ 18,248,084	$ 13,549,938	$ 12,699,642	$ 12,319,257	$ 11,882,509	$ 11,445,761	$ 11,009,014	$ 10,572,266	$ 10,645,229	$ 10,761,872	$ 10,878,514	$ 10,995,157	$ 11,111,799	$ 11,172,325	$ 11,240,431	$ 11,308,536	$ 11,376,642	$ 11,444,748	$ 11,830,334
Operation Expenditure	$/tonne																				
Base O&M ($/tonne)	$ 60	$ 6,000,000	$ 6,000,000	$ 4,372,580	$ 4,075,879	$ 3,941,690	$ 3,807,501	$ 3,673,312	$ 3,539,123	$ 3,404,934	$ 3,447,020	$ 3,489,107	$ 3,531,194	$ 3,573,281	$ 3,615,367	$ 3,638,047	$ 3,660,726	$ 3,683,406	$ 3,706,085	$ 3,728,765	$ 3,842,163
Direct O&M*	$ 30	$ 3,000,000	$ 3,000,000	$ 2,186,290	$ 2,037,940	$ 1,970,845	$ 1,903,750	$ 1,836,656	$ 1,769,561	$ 1,702,467	$ 1,723,510	$ 1,744,554	$ 1,765,597	$ 1,786,640	$ 1,807,684	$ 1,819,023	$ 1,830,363	$ 1,841,703	$ 1,853,043	$ 1,864,382	$ 1,921,081
Enhanced O&M Cost**	$ 4	$ 400,000	$ 400,000	$ 291,505	$ 271,725	$ 262,779	$ 253,833	$ 244,887	$ 235,942	$ 226,996	$ 229,801	$ 232,607	$ 235,413	$ 238,219	$ 241,024	$ 242,536	$ 244,048	$ 245,560	$ 247,072	$ 248,584	$ 256,144
Total O&M Cost	$ 96	$ 9,400,000	$ 9,400,000	$ 6,850,375	$ 6,385,544	$ 6,175,314	$ 5,965,085	$ 5,754,855	$ 5,544,626	$ 5,334,396	$ 5,400,332	$ 5,466,268	$ 5,532,204	$ 5,598,140	$ 5,664,075	$ 5,699,607	$ 5,735,138	$ 5,770,669	$ 5,806,200	$ 5,841,732	$ 6,019,388
Total costs																					
Inflation- Tipping fee	2%	$ -	$ 120,000	$ 174,903	$ 244,553	$ 315,335	$ 380,750	$ 440,797	$ 495,477	$ 544,789	$ 620,464	$ 697,821	$ 776,863	$ 857,587	$ 939,995	$ 1,018,653	$ 1,098,218	$ 1,178,690	$ 1,260,069	$ 1,342,355	$ 1,460,022
Inflation- Metal recovery	2%	$ -	$ 17,975	$ 36,255	$ 54,841	$ 73,731	$ 87,291	$ 98,901	$ 108,562	$ 116,274	$ 122,036	$ 134,585	$ 146,932	$ 159,076	$ 171,019	$ 182,759	$ 196,571	$ 210,484	$ 224,499	$ 238,614	$ 273,793
Inflation- Electricity Rate	1%	$ -	$ 24,117	$ 35,152	$ 49,150	$ 63,375	$ 76,522	$ 88,590	$ 99,580	$ 109,491	$ 124,699	$ 140,247	$ 156,132	$ 172,356	$ 188,918	$ 204,727	$ 220,717	$ 236,890	$ 253,246	$ 269,784	$ 293,432
Inflation- Heat Rate	1%	$ -	$ 89,376	$ 130,268	$ 182,143	$ 234,862	$ 283,583	$ 328,306	$ 369,031	$ 405,759	$ 462,121	$ 519,737	$ 578,607	$ 638,731	$ 700,109	$ 758,693	$ 817,953	$ 877,888	$ 938,499	$ 999,786	$ 1,087,424
WTE Inflation- O&M	2.50%	$ -	$ 235,000	$ 342,519	$ 478,916	$ 617,531	$ 745,636	$ 863,228	$ 970,310	$ 1,066,879	$ 1,215,075	$ 1,366,567	$ 1,521,356	$ 1,679,442	$ 1,840,825	$ 1,994,862	$ 2,150,677	$ 2,308,268	$ 2,467,635	$ 2,628,779	$ 2,859,209
Capital Expenditure																					
Base CAPEX		$ 78,308,317																			
Owner Costs***																					
Additional Cost&Contigency Amount****		-																			
Total Additional Costs (CHP Plant)		-																			
Total CAPEX		$ 78,308,317																			
EBITDA		$ (8,840,453)	$ (8,864,552)	$ (6,733,622)	$ (6,365,868)	$ (6,213,715)	$ (5,999,935)	$ (5,784,273)	$ (5,566,729)	$ (5,347,303)	$ (5,359,143)	$ (5,421,427)	$ (5,483,488)	$ (5,545,326)	$ (5,606,940)	$ (5,642,687)	$ (5,688,075)	$ (5,733,553)	$ (5,779,120)	$ (5,824,777)	$ (6,066,408)
Interest	0%																				
Tax	0%																				
Depreciation & Amortization	Linear (25 years)	$ 3,915,416	$ 3,915,416	$ 3,915,416	$ 3,915,416	$ 3,915,416	$ 3,915,416	$ 3,915,416	$ 3,915,416	$ 3,915,416	$ 3,915,416	$ 3,915,416	$ 3,915,416	$ 3,915,416	$ 3,915,416	$ 3,915,416	$ 3,915,416	$ 3,915,416	$ 3,915,416	$ 3,915,416	$ 3,915,416
Cash In		$ 18,240,453	$ 18,499,552	$ 13,926,516	$ 13,230,328	$ 13,006,560	$ 12,710,655	$ 12,402,356	$ 12,081,664	$ 11,748,579	$ 11,974,550	$ 12,254,262	$ 12,537,048	$ 12,822,907	$ 13,111,840	$ 13,337,156	$ 13,573,890	$ 13,812,489	$ 14,052,955	$ 14,295,288	$ 14,945,005
Cash Out		$ 91,623,733	$ 13,550,416	$ 11,108,310	$ 10,779,875	$ 10,708,262	$ 10,626,136	$ 10,533,499	$ 10,430,351	$ 10,316,691	$ 10,530,823	$ 10,748,251	$ 10,968,976	$ 11,192,997	$ 11,420,316	$ 11,609,885	$ 11,801,230	$ 11,994,353	$ 12,189,251	$ 12,385,927	$ 12,794,013
Cash Flow		$ (73,383,279)	$ 4,949,136	$ 2,818,206	$ 2,450,452	$ 2,298,299	$ 2,084,519	$ 1,868,857	$ 1,651,313	$ 1,431,887	$ 1,443,727	$ 1,506,011	$ 1,568,072	$ 1,629,910	$ 1,691,524	$ 1,727,271	$ 1,772,659	$ 1,818,137	$ 1,863,704	$ 1,909,361	$ 2,150,992
Discounted Cash Flow		$ (69,229,509)	$ 4,404,713	$ 2,366,220	$ 1,940,988	$ 1,717,423	$ 1,469,503	$ 1,242,897	$ 1,036,054	$ 847,532	$ 806,170	$ 793,348	$ 779,284	$ 764,165	$ 748,163	$ 720,730	$ 697,801	$ 675,191	$ 652,937	$ 631,069	$ 670,690
Cumulative Cash Flow		$ (69,229,509)	$(64,824,795)	$ (62,458,575)	$ (60,517,588)	$ (58,800,165)	$ (57,330,662)	$ (56,087,765)	$ (55,051,711)	$ (54,204,179)	$ (53,398,009)	$ (52,604,661)	$ (51,825,377)	$ (51,061,212)	$ (50,313,049)	$ (49,592,319)	$ (48,894,518)	$ (48,219,327)	$ (47,566,390)	$ (46,935,321)	$ (46,264,632)
NPV																					
	($46,264,632)																				
Discount rate 6%																					
IRR	-6%																				

*Direct costs include: ash management, stack testing, insurance, treatment chemicals, water supply/wastewater disposal, purchased electricity and natural gas.

** Enhanced costs include air pollution control

***Owner costs includes planning, permitting, design and construction monitoring

****Additional costs may include enhanced architecture, marine transport facilities for out-of-region locations, electrical interconnection costs, onsite improvements, offsite roadway improvements and offsite community improvements.

**** Contingency: 17% of capital costs.

Technical and Financial Parameters and Assumptions:

DLC tipping fee	60	$/tonne ($2015)	Capacity Factor	85%	
Recovered Ferrous Metal Price	150	$/tonne ($2015)		209422	GJ/yr
Recovered non Ferrous Metal Price	1600	$/tonne ($2015)		58173	MWh
Non-ferrous metal in DLC waste	0.15%		Capacity	8	MW
Ferrous metal in DLC waste	1.03%			887	kWh/tonne
Gross Calorific Value	15.2	GJ/tonne		7.4	GJ/tonne
Calorific Value of the wood waste	10.64	GJ/tonne	Electricity share	30%	
Moisture Content	25%		Heat Share	70%	
Efficiency of the boiler	70%				

Appendix 17 Financial Details and Calculations for Gasification Technology

WTE FACILITY DATA	2015	2020				2025					2030					2035					2040
YEAR	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Throughput Rate (t/yr)		100,000	100,000	72,876	67,931	65,695	63,458	61,222	58,985	56,749	57,450	58,152	58,853	59,555	60,256	60,634	61,012	61,390	61,768	62,146	64,036
Production of electricity MWH		20,267	20,267	14,770	13,767	13,314	12,861	12,408	11,954	11,501	11,643	11,785	11,928	12,070	12,212	12,289	12,365	12,442	12,518	12,595	12,978
Production of heat (GJ/yr)		340,480	340,480	248,129	231,293	223,678	216,063	208,448	200,833	193,219	195,607	197,995	200,383	202,772	205,160	206,447	207,734	209,021	210,308	211,595	218,030
Metal Recovery		226,284	228222	230159	232097	234034	221659	209285	196910	184535	172160	170877	169594	168311	167027	165744	166386	167027	167669	168311	182960
Ferrous Metal Recovery (t/yr)		2,320	2,340	2,360	2,380	2,400	2,273	2,146	2,019	1,892	1,765	1,752	1,739	1,726	1,713	1,699	1,706	1,713	1,719	1,726	1,876
Non-Ferrous Metal Recovery (t/yr)		339	342	345	348	351	332	314	295	277	258	256	254	252	251	249	250	251	252	252	274
Wood Waste Payable																					
Payable Wood		$ 6,000,000	$ 6,000,000	$ 4,372,580	$ 4,075,879	$ 3,941,690	$ 3,807,501	$ 3,673,312	$ 3,539,123	$ 3,404,934	$ 3,447,020	$ 3,489,107	$ 3,531,194	$ 3,573,281	$ 3,615,367	$ 3,638,047	$ 3,660,726	$ 3,683,406	$ 3,706,085	$ 3,728,765	$ 3,842,163
Payable Electricity, Sale to Grid		$ 2,756,267	$ 2,756,267	$ 2,008,666	$ 1,872,368	$ 1,810,725	$ 1,749,081	$ 1,687,438	$ 1,625,794	$ 1,564,151	$ 1,583,485	$ 1,602,818	$ 1,622,152	$ 1,641,486	$ 1,660,819	$ 1,671,238	$ 1,681,656	$ 1,692,075	$ 1,702,493	$ 1,712,912	$ 1,765,004
Payable Heat		$ 13,619,200	$ 13,619,200	$ 9,925,173	$ 9,251,702	$ 8,947,111	$ 8,642,519	$ 8,337,928	$ 8,033,337	$ 7,728,746	$ 7,824,277	$ 7,919,808	$ 8,015,339	$ 8,110,870	$ 8,206,402	$ 8,257,881	$ 8,309,361	$ 8,360,840	$ 8,412,320	$ 8,463,799	$ 8,721,197
Payable Metals		$ 891,120	$ 898,750	$ 906,381	$ 914,011	$ 921,641	$ 872,909	$ 824,176	$ 775,443	$ 726,711	$ 677,978	$ 672,924	$ 667,871	$ 662,817	$ 657,764	$ 652,710	$ 655,237	$ 657,764	$ 660,291	$ 662,817	$ 720,508
Payable Ferrous Metals		$ 348,038	$ 351,019	$ 353,999	$ 356,979	$ 359,959	$ 340,926	$ 321,893	$ 302,859	$ 283,826	$ 264,793	$ 262,819	$ 260,846	$ 258,872	$ 256,898	$ 254,925	$ 255,911	$ 256,898	$ 257,885	$ 258,872	$ 281,404
Payable Non-Ferrous Metals		$ 543,081	$ 547,732	$ 552,382	$ 557,032	$ 561,682	$ 531,983	$ 502,283	$ 472,584	$ 442,884	$ 413,185	$ 410,105	$ 407,025	$ 403,945	$ 400,866	$ 397,786	$ 399,326	$ 400,866	$ 402,406	$ 403,945	$ 439,104
Revenue before Tax		$ 23,266,587	$ 23,274,217	$ 17,212,799	$ 16,113,960	$ 15,621,167	$ 15,072,010	$ 14,522,854	$ 13,973,697	$ 13,424,541	$ 13,532,760	$ 13,684,658	$ 13,836,556	$ 13,988,454	$ 14,140,352	$ 14,219,876	$ 14,306,980	$ 14,394,085	$ 14,481,189	$ 14,568,293	$ 15,048,871
Operation Expenditure	$/tonne																				
Base O&M ($/tonne)	$ 90	$ 9,000,000	$ 9,000,000	$ 6,558,870	$ 6,113,819	$ 5,912,535	$ 5,711,251	$ 5,509,968	$ 5,308,684	$ 5,107,401	$ 5,170,531	$ 5,233,661	$ 5,296,791	$ 5,359,921	$ 5,423,051	$ 5,457,070	$ 5,491,089	$ 5,525,109	$ 5,559,128	$ 5,593,147	$ 5,763,244
Direct O&M*	$ 22.50	$ 2,250,000	$ 2,250,000	$ 1,639,717	$ 1,528,455	$ 1,478,134	$ 1,427,813	$ 1,377,492	$ 1,327,171	$ 1,276,850	$ 1,292,633	$ 1,308,415	$ 1,324,198	$ 1,339,980	$ 1,355,763	$ 1,364,268	$ 1,372,772	$ 1,381,277	$ 1,389,782	$ 1,398,287	$ 1,440,811
Enhanced O&M Cost**	$ 2	$ 200,000	$ 200,000	$ 145,753	$ 135,863	$ 131,390	$ 126,917	$ 122,444	$ 117,971	$ 113,498	$ 114,901	$ 116,304	$ 117,706	$ 119,109	$ 120,512	$ 121,268	$ 122,024	$ 122,780	$ 123,536	$ 124,292	$ 128,072
Total O&M Cost	$ 117	$ 11,450,000	$ 11,450,000	$ 8,344,340	$ 7,778,136	$ 7,522,058	$ 7,265,981	$ 7,009,904	$ 6,753,826	$ 6,497,749	$ 6,578,064	$ 6,658,380	$ 6,738,695	$ 6,819,010	$ 6,899,326	$ 6,942,606	$ 6,985,886	$ 7,029,166	$ 7,072,446	$ 7,115,726	$ 7,332,127
Total costs																					
Inflation- Tipping fee	2%	$ -	$ 120,000	$ 174,903	$ 244,553	$ 315,335	$ 380,750	$ 440,797	$ 495,477	$ 544,789	$ 620,464	$ 697,821	$ 776,863	$ 857,587	$ 939,995	$ 1,018,653	$ 1,098,218	$ 1,178,690	$ 1,260,069	$ 1,342,355	$ 1,460,022
Inflation- Metal recovery	2%	$ -	$ 17,975	$ 36,255	$ 54,841	$ 73,731	$ 87,291	$ 98,901	$ 108,562	$ 116,274	$ 122,036	$ 134,585	$ 146,932	$ 159,076	$ 171,019	$ 182,759	$ 196,571	$ 210,484	$ 224,499	$ 238,614	$ 273,793
Inflation- Electricity Rate	1%	$ -	$ 27,563	$ 40,173	$ 56,171	$ 72,429	$ 87,454	$ 101,246	$ 113,806	$ 125,132	$ 142,514	$ 160,282	$ 178,437	$ 196,978	$ 215,907	$ 233,973	$ 252,248	$ 270,732	$ 289,424	$ 308,324	$ 335,351
Inflation- Heat Rate	1%	$ -	$ 136,192	$ 198,503	$ 277,551	$ 357,884	$ 432,126	$ 500,276	$ 562,334	$ 618,300	$ 704,185	$ 791,981	$ 881,687	$ 973,304	$ 1,066,832	$ 1,156,103	$ 1,246,404	$ 1,337,734	$ 1,430,094	$ 1,523,484	$ 1,657,027
WTE Inflation- O&M	2.50%	$ -	$ 286,250	$ 417,217	$ 583,360	$ 752,206	$ 908,248	$ 1,051,486	$ 1,181,920	$ 1,299,550	$ 1,480,064	$ 1,664,595	$ 1,853,141	$ 2,045,703	$ 2,242,281	$ 2,429,912	$ 2,619,707	$ 2,811,666	$ 3,005,790	$ 3,202,077	$ 3,482,760
Capital Expenditure																					
Base CAPEX	$ 79,000,000	$ 79,000,000																			
Owner Costs***	$ 9,000,000	$ 9,000,000																			
Additional Cost&Contigency Amount****	$ 13,430,000	$ 13,430,000																			
Total Additional Costs (CHP Plant)	$ -	$ -																			
Total CAPEX	$ 101,430,000	$ 101,430,000																			
		$ -																			
EBITDA		$ (11,816,587)	$ (11,839,697)	$ (8,901,078)	$ (8,385,580)	$ (8,166,282)	$ (7,885,403)	$ (7,602,685)	$ (7,318,130)	$ (7,031,737)	$ (7,063,830)	$ (7,146,353)	$ (7,228,638)	$ (7,310,687)	$ (7,392,498)	$ (7,438,847)	$ (7,494,829)	$ (7,550,893)	$ (7,607,039)	$ (7,663,268)	$ (7,960,177)
Interest	0%																				
Tax	0%																				
Depreciation & Amortization	Linear (25 years)	$ 5,071,500	$ 5,071,500	$ 5,071,500	$ 5,071,500	$ 5,071,500	$ 5,071,500	$ 5,071,500	$ 5,071,500	$ 5,071,500	$ 5,071,500	$ 5,071,500	$ 5,071,500	$ 5,071,500	$ 5,071,500	$ 5,071,500	$ 5,071,500	$ 5,071,500	$ 5,071,500	$ 5,071,500	$ 5,071,500
Cash In		$ 23,266,587	$ 23,575,947	$ 17,662,634	$ 16,747,076	$ 16,440,547	$ 16,059,631	$ 15,664,074	$ 15,253,876	$ 14,829,036	$ 15,121,958	$ 15,469,327	$ 15,820,474	$ 16,175,400	$ 16,534,105	$ 16,811,365	$ 17,100,422	$ 17,391,725	$ 17,685,275	$ 17,981,071	$ 18,775,064
Cash Out		$ 117,951,500	$ 16,807,750	$ 13,833,057	$ 13,432,996	$ 13,345,764	$ 13,245,729	$ 13,132,889	$ 13,007,246	$ 12,868,798	$ 13,129,629	$ 13,394,474	$ 13,663,336	$ 13,936,214	$ 14,213,107	$ 14,444,018	$ 14,677,093	$ 14,912,333	$ 15,149,736	$ 15,389,303	$ 15,886,387
Cash Flow		$ (94,684,913)	$ 6,768,197	$ 3,829,578	$ 3,314,080	$ 3,094,782	$ 2,813,903	$ 2,531,185	$ 2,246,630	$ 1,960,237	$ 1,992,330	$ 2,074,853	$ 2,157,138	$ 2,239,187	$ 2,320,998	$ 2,367,347	$ 2,423,329	$ 2,479,393	$ 2,535,539	$ 2,591,768	$ 2,888,677
Cumulative Cash Flow		$ (89,325,390)	$ 6,023,671	$ 3,215,387	$ 2,625,062	$ 2,312,601	$ 1,983,690	$ 1,683,383	$ 1,409,564	$ 1,160,262	$ 1,112,506	$ 1,093,006	$ 1,072,032	$ 1,049,818	$ 1,026,580	$ 987,811	$ 953,934	$ 920,758	$ 888,310	$ 856,613	$ 900,703
		$ (89,325,390)	$ (83,301,719)	$ (80,086,332)	$ (77,461,270)	$ (75,148,669)	$ (73,164,978)	$ (71,481,596)	$ (70,072,032)	$ (68,911,771)	$ (67,799,264)	$ (66,706,258)	$ (65,634,226)	$ (64,584,408)	$ (63,557,828)	$ (62,570,017)	$ (61,616,083)	$ (60,695,324)	$ (59,807,014)	$ (58,950,401)	$ (58,049,698)
NPV																					
	($58,049,698)																				
Discount rate 6%																					
IRR	-6%																				

*Direct costs include: ash management, stack testing, insurance, treatment chemicals, water supply/wastewater disposal, purchased electricity and natural gas.

** Enhanced costs include air pollution control

***Owner costs includes planning, permitting, design and construction monitoring

****Additional costs may include enhanced architecture, marine transport facilities for out-of-region locations, electrical interconnection costs, onsite improvements, offsite roadway improvements and offsite community improvements.

**** Contingency: 17% of capital costs.

Technical and Financial Parameters and Assumptions:

DLC tipping fee	60	$/tonne ($2015)	Capacity Factor	85%	
Recovered Ferrous Metal Price	150	$/tonne ($2015)	Capacity	239340	GJ/yr
Recovered non Ferrous Metal Price	1600	$/tonne ($2015)		558459	MWh
Non-ferrous metal in DLC waste	0.15%			9	MW
Ferrous metal in DLC waste	1.03%			1013	kWh/tonne
Gross Calorific Value	15.2	GJ/tonne		8.3	GJ/tonne
Calorific Value of the wood waste	12.2	GJ/tonne	Electricity share	30%	
Moisture Content	25%		Heat Share	70%	
Efficiency of the boiler	80%				

Appendix 18 Financial Details and Calculations for Pyrolysis Technology

WTE FACILITY DATA	2015	2020				2025					2030					2035					2040
YEAR	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Throughput Rate (t/yr)		100,000	100,000	72,876	67,931	65,695	63,458	61,222	58,985	56,749	57,450	58,152	58,853	59,555	60,256	60,634	61,012	61,390	61,768	62,146	64,036
Production of electricity MW		22,293	22,293	16,247	15,144	14,646	14,147	13,648	13,150	12,651	12,808	12,964	13,120	13,277	13,433	13,517	13,602	13,686	13,770	13,854	14,276
Production of heat (GJ/yr)		366,016	366,016	266,739	248,639	240,454	232,268	224,082	215,896	207,710	210,277	212,845	215,412	217,980	220,547	221,931	223,314	224,698	226,081	227,465	234,382
Metal Recovery		226,284	228222	230159	232097	234034	221659	209285	196910	184535	172160	170877	169594	168311	167027	165744	166386	167027	167669	168311	182960
Ferrous Metal Recovery (t/yr)		2,320	2,340	2,360	2,380	2,400	2,273	2,146	2,019	1,892	1,765	1,752	1,739	1,726	1,713	1,699	1,706	1,713	1,719	1,726	1,876
Non-Ferrous Metal Recovery (t/yr)		339	342	345	348	351	332	314	295	277	258	256	254	252	251	249	250	251	252	252	274
Wood Waste Payable																					
Payable Wood		$ 6,000,000	$ 6,000,000	$ 4,372,580	$ 4,075,879	$ 3,941,690	$ 3,807,501	$ 3,673,312	$ 3,539,123	$ 3,404,934	$ 3,447,020	$ 3,489,107	$ 3,531,194	$ 3,573,281	$ 3,615,367	$ 3,638,047	$ 3,660,726	$ 3,683,406	$ 3,706,085	$ 3,728,765	$ 3,842,163
Payable Electricity, Sale to Grid		$ 3,031,893	$ 3,031,893	$ 2,209,533	$ 2,059,605	$ 1,991,797	$ 1,923,989	$ 1,856,182	$ 1,788,374	$ 1,720,566	$ 1,741,833	$ 1,763,100	$ 1,784,367	$ 1,805,634	$ 1,826,901	$ 1,838,362	$ 1,849,822	$ 1,861,282	$ 1,872,743	$ 1,884,203	$ 1,941,504
Payable Heat		$ 14,640,640	$ 14,640,640	$ 10,669,561	$ 9,945,580	$ 9,618,144	$ 9,290,708	$ 8,963,273	$ 8,635,837	$ 8,308,402	$ 8,411,098	$ 8,513,794	$ 8,616,490	$ 8,719,186	$ 8,821,882	$ 8,877,222	$ 8,932,563	$ 8,987,903	$ 9,043,244	$ 9,098,584	$ 9,375,286
Payable Metals		$ 891,120	$ 898,750	$ 906,381	$ 914,011	$ 921,641	$ 872,909	$ 824,176	$ 775,443	$ 726,711	$ 677,978	$ 672,924	$ 667,871	$ 662,817	$ 657,764	$ 652,710	$ 655,237	$ 657,764	$ 660,291	$ 662,817	$ 720,508
Payable Ferrous Metals		$ 348,038	$ 351,019	$ 353,999	$ 356,979	$ 359,959	$ 340,926	$ 321,893	$ 302,859	$ 283,826	$ 264,793	$ 262,819	$ 260,846	$ 258,872	$ 256,898	$ 254,925	$ 255,911	$ 256,898	$ 257,885	$ 258,872	$ 281,404
Payable Non-Ferrous Metals		$ 543,081	$ 547,732	$ 552,382	$ 557,032	$ 561,682	$ 531,983	$ 502,283	$ 472,584	$ 442,884	$ 413,185	$ 410,105	$ 407,025	$ 403,945	$ 400,866	$ 397,786	$ 399,326	$ 400,866	$ 402,406	$ 403,945	$ 439,104
Revenue before Tax		$ 24,563,653	$ 24,571,284	$ 18,158,054	$ 16,995,075	$ 16,473,273	$ 15,895,107	$ 15,316,942	$ 14,738,777	$ 14,160,612	$ 14,277,929	$ 14,438,925	$ 14,599,922	$ 14,760,918	$ 14,921,914	$ 15,006,341	$ 15,098,348	$ 15,190,355	$ 15,282,362	$ 15,374,369	$ 15,879,461
Operation Expenditure	$/tonne																				
Base O&M ($/tonne)	$ 113	$ 11,276,060	$ 11,276,060	$ 8,217,578	$ 7,659,976	$ 7,407,789	$ 7,155,601	$ 6,903,414	$ 6,651,227	$ 6,399,040	$ 6,478,135	$ 6,557,230	$ 6,636,326	$ 6,715,421	$ 6,794,516	$ 6,837,139	$ 6,879,762	$ 6,922,384	$ 6,965,007	$ 7,007,629	$ 7,220,742
Direct O&M*	$ 28.19	$ 2,819,015	$ 2,819,015	$ 2,054,395	$ 1,914,994	$ 1,851,947	$ 1,788,900	$ 1,725,854	$ 1,662,807	$ 1,599,760	$ 1,619,534	$ 1,639,308	$ 1,659,081	$ 1,678,855	$ 1,698,629	$ 1,709,285	$ 1,719,940	$ 1,730,596	$ 1,741,252	$ 1,751,907	$ 1,805,186
Enhanced O&M Cost**	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Total O&M Cost	$ 143	$ 14,095,075	$ 14,095,075	$ 10,271,973	$ 9,574,970	$ 9,259,736	$ 8,944,502	$ 8,629,268	$ 8,314,034	$ 7,998,799	$ 8,097,669	$ 8,196,538	$ 8,295,407	$ 8,394,276	$ 8,493,145	$ 8,546,424	$ 8,599,702	$ 8,652,980	$ 8,706,258	$ 8,759,537	$ 9,025,928
Total costs																					
Inflation- Tipping fee	2%	$ -	$ 120,000	$ 174,903	$ 244,553	$ 315,335	$ 380,750	$ 440,797	$ 495,477	$ 544,789	$ 620,464	$ 697,821	$ 776,863	$ 857,587	$ 939,995	$ 1,018,653	$ 1,098,218	$ 1,178,690	$ 1,260,069	$ 1,342,355	$ 1,460,022
Inflation- Metal recovery	2%	$ -	$ 17,975	$ 36,255	$ 54,841	$ 73,731	$ 87,291	$ 98,901	$ 108,562	$ 116,274	$ 122,036	$ 134,585	$ 146,932	$ 159,076	$ 171,019	$ 182,759	$ 196,571	$ 210,484	$ 224,499	$ 238,614	$ 273,793
Inflation- Electricity Rate	1%	$ -	$ 30,319	$ 44,191	$ 61,788	$ 79,672	$ 96,199	$ 111,371	$ 125,186	$ 137,645	$ 156,765	$ 176,310	$ 196,280	$ 216,676	$ 237,497	$ 257,371	$ 277,473	$ 297,805	$ 318,366	$ 339,157	$ 368,886
Inflation- Heat Rate	1%	$ -	$ 146,406	$ 213,391	$ 298,367	$ 384,726	$ 464,535	$ 537,796	$ 604,509	$ 664,672	$ 756,999	$ 851,379	$ 947,814	$ 1,046,302	$ 1,146,845	$ 1,242,811	$ 1,339,884	$ 1,438,065	$ 1,537,351	$ 1,637,745	$ 1,781,304
WTE Inflation- O&M	2.50%	$ -	$ 352,377	$ 513,599	$ 718,123	$ 925,974	$ 1,118,063	$ 1,294,390	$ 1,454,956	$ 1,599,760	$ 1,821,975	$ 2,049,134	$ 2,281,237	$ 2,518,283	$ 2,760,272	$ 2,991,248	$ 3,224,888	$ 3,461,192	$ 3,700,160	$ 3,941,792	$ 4,287,316
Capital Expenditure																					
Base CAPEX	$ 117,500,000	$ 117,500,000																			
Owner Costs***	$ 8,000,000	$ 8,000,000																			
Additional Cost&Contigency Amount****	$ 19,975,000	$ 19,975,000																			
Total Additional Costs (CHP Plant)	$ -	$ -																			
Total CAPEX	$ 145,475,000	$ 145,475,000																			
EBITDA	$(129,189,819)	$ (10,468,578)	$ (10,438,532)	$ (7,841,222)	$ (7,361,531)	$ (7,141,027)	$ (6,861,319)	$ (6,582,150)	$ (6,303,522)	$ (6,025,433)	$ (6,014,549)	$ (6,053,349)	$ (6,091,166)	$ (6,128,001)	$ (6,163,853)	$ (6,170,263)	$ (6,185,905)	$ (6,201,227)	$ (6,216,229)	$ (6,230,912)	$ (6,450,223)
Interest	0%																				
Tax	0%																				
Depreciation		$ 7,273,750	$ 7,273,750	$ 7,273,750	$ 7,273,750	$ 7,273,750	$ 7,273,750	$ 7,273,750	$ 7,273,750	$ 7,273,750	$ 7,273,750	$ 7,273,750	$ 7,273,750	$ 7,273,750	$ 7,273,750	$ 7,273,750	$ 7,273,750	$ 7,273,750	$ 7,273,750	$ 7,273,750	$ 7,273,750
Cash In		$ 24,563,653	$ 24,885,984	$ 18,626,794	$ 17,654,624	$ 17,326,737	$ 16,923,883	$ 16,505,808	$ 16,072,511	$ 15,623,993	$ 15,934,193	$ 16,299,021	$ 16,667,810	$ 17,040,560	$ 17,417,270	$ 17,707,935	$ 18,010,495	$ 18,315,399	$ 18,622,648	$ 18,932,241	$ 19,763,467
Cash Out		$ 166,843,825	$ 21,721,202	$ 18,059,322	$ 17,566,843	$ 17,459,460	$ 17,336,315	$ 17,197,408	$ 17,042,739	$ 16,872,309	$ 17,193,394	$ 17,519,422	$ 17,850,394	$ 18,186,309	$ 18,527,168	$ 18,811,422	$ 19,098,340	$ 19,387,922	$ 19,680,168	$ 19,975,078	$ 20,586,994
Cash Flow		$(142,280,172)	$ 3,164,782	$ 567,472	$ 87,781	$ (132,723)	$ (412,431)	$ (691,600)	$ (970,228)	$ (1,248,317)	$ (1,259,201)	$ (1,220,401)	$ (1,182,584)	$ (1,145,749)	$ (1,109,897)	$ (1,103,487)	$ (1,087,845)	$ (1,072,523)	$ (1,057,521)	$ (1,042,838)	$ (823,527)
Cumulative Cash Flow		$(134,226,577)	$ 2,816,645	$ 476,461	$ 69,531	$ (99,178)	$ (290,748)	$ (459,953)	$ (608,733)	$ (738,877)	$ (703,131)	$ (642,892)	$ (587,708)	$ (537,172)	$ (490,909)	$ (460,447)	$ (428,226)	$ (398,297)	$ (370,496)	$ (344,671)	$ (256,780)
		$(134,226,577)	$(131,409,932)	$(130,933,471)	$(130,863,941)	$(130,963,119)	$(131,253,867)	$(131,713,820)	$(132,322,553)	$(133,061,430)	$(133,764,561)	$(134,407,454)	$(134,995,161)	$(135,532,333)	$(136,023,242)	$(136,483,689)	$(136,911,915)	$(137,310,212)	$(137,680,708)	$(138,025,379)	$(138,282,159)
NPV																					
	($138,282,159)																				
Discount rate 6%																					
IRR	#NUM!																				

*Direct costs include: ash management, stack testing, insurance, treatment chemicals, water supply/wastewater disposal, purchased electricity and natural gas.

** Enhanced costs include air pollution control

***Owner costs includes planning, permitting, design and construction monitoring

****Additional costs may include enhanced architecture, marine transport facilities for out-of-region locations, electrical interconnection costs, onsite improvements, offsite roadway improvements and offsite community improvements.

**** Contingency: 17% of capital costs.

Technical and Financial Parameters and Assumptions:

DLC tipping fee	60	$/tonne ($2015)	Capacity Factor	85%	
Recovered Ferrous Metal Price	150	$/tonne ($2015)	Capacity	239340	GJ/yr
Recovered non Ferrous Metal Price	1600	$/tonne ($2015)		66483	MWh
Non-ferrous metal in DLC waste	0.15%			9	MW
Ferrous metal in DLC waste	1.03%			1013	kWh/tonne
Gross Calorific Value	15.2	GJ/tonne		8.5	GJ/tonne
Calorific Value of the wood waste	12.2	GJ/tonne	Electricity share	30%	
Moisture Content	25%		Heat Share	70%	
Efficiency of the boiler	80%				

Appendix 19 List of Technology Suppliers and Users: Incineration, Gasification and Pyrolysis

REMOVED DUE TO CONFIDENTIALITY

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