What Is the Highest and Best Use of Organic Solid Waste: Production of Compost or Production of Energy?

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1.0 Executive Summary

This project is one of the City of Vancouver 2012 Greenest City Scholars Research Project and falls under the Greenest City Goal 5: "Create Zero Waste". The project attempts to answer the question "What is the highest and best use of organic solid waste: production of compost or production of energy?" As City of Vancouver (hereinafter to be referred as the City) is determined to divert solid waste from going to the landfill or incinerator by 50% from 2008 levels, organic waste diversion is an important strategy in achieving that goal. Composting and anaerobic digestion (AD) are the most common practices to treat organic waste for renewable products and energy. They are both widely applied for municipal organic waste treatment all over the world. To examine whether composting or AD is more suitable for the City, organic waste audit and environmental assessment of composting and AD are conducted in this project.

Three streams of organic waste are analyzed: 1) demolition wood waste, 2) yard waste from various City operated programs, 3) food waste from single families (SF), multi-families (MF), and commercial sectors. Generation of demolition wood waste and yard trimmings drop-offs are assumed to be stable but the implementation of deconstruction permit is accounted and the final disposed waste will drop gradually. Yard trimmings from the residential sector and food waste from both the residential and commercial sectors are assumed to increase by 0.55% annually. This is based on historical data trend and estimated population increase. In line with the Zero Waste Goal, 25% of these waste is expected to be diverted in 2015 and 50% to be diverted in 2020. The table below shows the projections of organic waste generation. More detailed numbers can be referred to in Section 5 below.

Table 1 Organic Waste Generation Projection for 2015 and 2020

Item	Unit	2015	2020
Wood disposed, moderate deconstruction permit implementation	tonne	58,236	53,214
Wood disposed, aggressive deconstruction permit implementation	tonne	42,164	42,164
Yard trimmings from SF collection	tonne	25,296	25,981
Yard trimmings from drop-offs and fall leave program	tonne	31,396	31,396
Food waste from SF collection	tonne	24,727	25,397
Food waste from MF sector	tonne	24,430	25,100
Food waste from Commercial sector	tonne	77,254	79,344

Through the estimated organic waste generation, production of renewable products and energy can be predicted. The following scenarios are established with various combinations of composting and AD operations.

Table 2 Scenarios Set-Up

Scenario Number	Organic Waste Description	Process
0-a	1,000 tonne yard waste	Composting
0-b	1,000 tonne mixed food and yard waste	Composting
0-c	1,000 tonne food waste	Biogas from AD
0-d	1,000 tonne food waste	Heat & power from AD
1-a1	SF mixed food and yard waste, 2015	Composting
1-b1	SF mixed food and yard waste, 2015	Biogas from AD for food waste, Composting for yard waste
1-c1	SF mixed food and yard waste, 2015	Heat & Power from AD for food waste, Composting for yard waste
1-a2	SF mixed food and yard waste, 2020	Composting
1-b2	SF mixed food and yard waste, 2020	Biogas from AD for food waste, Composting for yard waste
1-c2	SF mixed food and yard waste, 2020	Heat & Power from AD for food waste, Composting for yard waste
2-a1	MF and commercial food waste, 2015	Biogas from AD
2-b1	MF and commercial food waste, 2015	Heat & power from AD
2-a2	MF and commercial food waste, 2020	Biogas from AD
2-b2	MF and commercial food waste, 2020	Heat & power from AD

If all compostable waste from SF goes into composting, about 47,000 m^3 compost products would be generated in 2020. If food waste from SF is anaerobically digested while all sources of yard waste is composted, about 800,000 m^3 biogas or 2,000 MWh electricity and around 30,000 m^3 compost could be produced in 2020. For food waste from MF and commercial sectors, AD could produce about 3 million m^3 biogas or 8,000 MWh electricity plus 40,000 tonnes digestate (dewatered digested slurry). Considering 2,600 m^3 natural gas and 10 MWh electricity is consumed by an average household in the City per year (Natural Resources Canada, 2009; BC Hydro, 2012), the production of renewable energy is significant and favourable. However, a recent market study conducted by Metro Vancouver indicates the future supply of compost products will be much higher than local demand and the value of compost is poised to drop dramatically.

Life Cycle Assessment (LCA) is performed to assess the environmental impacts of composting and AD under the various scenarios listed above. LCA is a holistic environmental assessment tool which looks at the entire life cycle of a system from upstream material and energy extraction to downstream product end use and waste disposal. The overall results are summarised in the table below. The relative impact levels are comparable within an impact category only. Quantitative results are shown in Section 6.6.

Table 3 Life Cycle Impact Assessment Results Summary

Technology	Global Warming Impact	Non-Renewable Energy Consumption	Respiratory Effects
Composting	Medium	Low	Low
AD for biogas	Medium	Low	Medium
AD for heat and power generation	Low	Extremely low	Medium

Whether to choose composting or AD or how to combine the two practices would depend on a number of factors. The LCA results provide information on the overall environmental performance but impacts that occur from different stages influence specific regions, stage-wise results should also be reviewed. Also, there can be trade-offs between the impact categories.

Overall, the key findings from the LCA include:

- Global warming impact of composting and AD is similar. Both operations reduce large amount of greenhouse gas (GHG) emissions. Recycling the total organic waste from SF in the City in a year is equivalent to taking away the GHG emissions from about 27,000 km of mid-size car driving.
- Both composting and AD saves non-renewable energy by way of generating renewable product or energy to substitute fossil fuel. The scenario of AD to produce biogas has especially high achievements as the natural gas it substitutes is pure fossil fuel. This scenario has 30 times of non-renewable energy savings compared to the other scenarios and accounts for 2.4 TJ per year which could replace the natural gas use for heating to about 24 households (Natural Resources Canada, 2009).
- Composting saves respiratory impact by producing compost to substitute fertilizers. AD however has positive respiratory impact due to relatively more air pollutions during the digesting process. Overall, the respiratory effects from composting or AD are trivial under the scope of the entire emission inventory in society. Note that the air emissions concentrated on site leading to regional respiratory impact is worth attention.

Recommendations from this project are as follows:

- This study recommends combination of composting and AD practices for the City. Specifically, the City should continue to investigate waste composition, collection pathways, and development of organics processing plants.
- Current in-operation composting sites should remain effective. Expansion or introducing new players to the industry is recommended to consume the increasing organics volume.
- To avoid the flood of compost products, diverting applicable waste (i.e. mainly food waste) to AD is recommended. Renewable energy from AD is an attractive clean energy. However, intensive economic assessment should be in place as AD is more expensive than composting and there is no experience in BC to digest municipal organic waste.
- Additional environmental assessment is recommended along with a more focused LCA method, including on-site assessments.
- Proper economics assessment should be conducted as the lack of data created barriers to carry out the assessment.

- Potential markets outside the local region for compost product and digestate should be explored to consume the abundant supply.
- High level policy in the City or BC influences the realization of the green goals. Funding and other financial support will be crucial for the implementation of these practices.

2.0 Introduction

The City is determined to become the Greenest City in the world by 2020. The Greenest City 2020 Action Plan (GCAP) offers a road map towards a bright green future by identifying ten specific goals, supported by a set of measurable and attainable targets. One of the ten goals is to "Create Zero Waste": reduce solid waste going to the landfill or incinerator by 50% from 2008 levels. Some of the key strategies to reach this target include:

- Nurture a zero waste culture
- Make reducing and reusing a priority
- Capture the compostables
- Be a catalyst for Extended Producer Responsibility (EPR)
- Keep recyclables out of landfills and incinerators
- Reduce, reuse, and recycle more construction, renovation and demolition waste
- Foster a closed-loop economy

Vancouver sends approximately 480,000 tonnes of waste to the landfill or incinerator annually. Among the total waste, about 40% is organic waste such as yard trimmings and food waste. The City has been composting yard trimmings at the Vancouver landfill, and a mixture of yard trimmings and food scraps at the Fraser Richmond Soil and Fibre (hereinafter to be referred as Fraser Richmond). With the aggressive Greenest City goal, the City is currently seeking different ways to effectively divert the large amount of organic waste away from the garbage stream. Composting and AD are the two common practices for organic waste recycling. Composting is the process of aerobically degrading organic matters which generate soil-like product known as compost. Compost is rich in nutrients thus can be used as fertilizer and soil amendment. It is also a good material for landscaping in urban constructions. AD is the process of decomposing organic matters under oxygen-free environment and produces methane-rich biogas. As methane is a fuel similar to natural gas, properly collected and pre-treated biogas is a valuable renewable energy. The slurry from digestion is also a good substitute for fertilizer and can become soil amendment after dewatering. Composting and AD favours slightly different organic waste and requires different operating conditions. Detailed investigation of organic waste composition and holistic assessment of the two technologies are necessary to inform actions taken by the City.

The research question of this project is "what is the highest and best use of organic solid waste: production of compost or production of energy?" The objectives of this project include reviewing available composting and AD technologies and environmental assessment of conducting composting or AD under various scenarios. Specifically, current and estimated organic waste generation and composition are studied with potential outcomes under a variety of treatment technologies summarized. Clean wood waste is particularly researched for their performance in typical composting and digestion practices. Current and potential industry players are catalogued and interviewed so that opportunities of technology transition or introduction can be identified. Resultant products and energy outcomes, along with the gross revenue from the various composting and digestion technologies, are estimated and market demand for these products within the City and/or the lower mainland is briefly evaluated. Environmental Life Cycle Assessment is conducted to quantitatively describe the environmental benefits and impacts of composting and AD. Various scenarios based on the City's situation are established and analyzed.

The deliverables of this project includes:

- Review of composting and AD technologies that are potentially feasible to the City.
- Review of current and potential organic waste industry within the lower mainland.
- Study of requirements of woody wastes as feedstock for composting and AD.
- Estimated organic waste generation in the City and predictions of products and revenue from composting and AD.
- Environmental Life Cycle Assessment of composting and AD under the city scale.
- Recommendations on future practice of organic waste diversion in the City.

3.0 Review of Composting and Anaerobic Digestion

3.1 Overview of Composting Technology

Composting is a biological process which decomposes organic matters under aerobic conditions using appropriate parameters such as carbon to nitrogen ratio, moisture content, oxygen levels, and temperatures. A number of composting technologies and facilities have been developed aiming at waste reduction, profitable production, and odor management. Composting systems can be opened, covered or contained. Aeration includes positive ways such as turning, mixing, or air blowing as well as passive ways such as penetrating with open pipes. Moisture, oxygen levels, and temperature should be monitored when possible. Composting time varies from days to months depending on feedstock composition and process conditions. A curing phase is usually recommended for the finished compost to stabilize. Compost products can be used as fertilizers and soil amendment after screening.

Table 4 Key Composting Parameters

Key Parameters	Desirable Range
Carbon to Nitrogen ratio (C:N)	25:1 to 30:1
Moisture content (W%)	50% to 60%
Oxygen level	> 5%
Particle size	< 5 cm
Temperature	55 ^{o}C to 60 ^{o}C sustained for several days to weeks

Carbon to Nitrogen ratio is an important factor to create compost. It should be assessed and optimized in advance when a mixture of organic waste is to be composted. The C:N ratios of common organic waste is provided below (Composting101, 2006).

Table 5 C:N Ratios of Common Organic Waste

Brown waste, high carbon	C:N	Green waste, high nitrogen	C:N
Ashes, wood	25:1	Alfalfa	12:1
Cardboard, shredded	350:1	Clover	23:1
Corn stalks	75:1	Coffee grounds	20:1
Fruit waste	35:1	Food waste	20:1
Leaves	60:1	Garden waste	30:1
Newspaper, shredded	175:1	Grass clippings	20:1
Peanut shells	35:1	Hay	25:1
Pine needles	80:1	Manures	15:1
Sawdust	325:1	Seaweed	19:1
Straw	75:1	Vegetable scraps	25:1
Wood chips	400:1	Weeds	30:1

The scales of composting range from several liters in a bin to hundreds of thousand cubic meters in engineered systems. A brief overview of various composting systems is presented in the table below and a short description of each type of composting technology follows.

Table 6 Overview of Composting Systems

System	Coverage	Container	Aeration		Cost
			Static	Turning	
Open pile	· None	· None	· Passive · Engineered pipes	· Loader Buckets	· Static: $15~$40/tonne · Turning aeration: $40~60/tonne
Open windrow	· None · Indoor	· None · Mass bed	· Passive · Engineered pipes	· Pull type turners · Self-propelled turner · Turned Mass Beds · Auger turner	· Static: $15~$40/tonne · Turning aeration: $40~$70/tonne
Open bunkers	· None	· Bunkers	· Passive · Engineered pipes	-	· $15~$40/tonne
Covered pile or windrow	· Membrane	· None · Plastic silage bag · Concrete pad · Cells	· Passive · Engineered pipes	-	· $100~$150/tonne
Vertical silo system	-	· In-vessel vertical silos	· Passive	-	· $300~$500/tonne
Container system	-	· (Modular) In-Vessel containers	· Engineered pipes · Fans	· Rotary Drums in tandem	· $300~$500/tonne
Tunnel system	-	· (Modular) Tunnel containers	· Aeration floor	· Auger turner · Rotary Drums in tandem	· $300~$500/tonne
In door agitated bays	-	· Concrete channelled beds	· Aeration floor	· Self-propelled turner	· N/A

3.1.1 Open Systems

A) Open Pile

Open pile is the simplest composting system and consists of a trapezoidal pile of organic wastes with no membrane cover or just a layer of wood chips or finished compost as cover. If a pile is not turned or mixed, it is known as a static pile. Bulking materials like wood chips can enhance the porosity to maintain an aerobic environment. In most cases, aeration is introduced by designed management or facilities. Passive aeration typically refers to inserting open pipes into a pile in order to introduce air. Engineered pipes can be applied with pumps forcing or pulling air through a pile from the side or the bottom. These methods are low in costs and more efficient aeration can be achieved by turning or blending the pile regularly. In small pile composting, manual turning is feasible. For large piles in an open area, a loader or an elevating-face turner is often used. Generally, piles are not turned as frequently as windrows and are primarily used to compost biosolid or feedstock of similar consistency and homogeneity. Therefore it is not an efficient method to break down large particles.

B) Open Windrow

Windrow is similar to open pile except it forms long rows of high volume organics material. The use of larger area enables large and advanced turning equipment to operate such that piles up to 3 to 4 metres high can be handled (Composting Council of Canada). In addition to elevating-face turner, mobile turner is especially suitable for windrow composting. A mobile turner moves slowly over a windrow from one end to the other to turn the compost with its attached mixer. Some turners have a watering attachment to add moisture to the materials while turning. Generally, windrow with good turning achieves more efficient composting than an open pile. Better aeration allows for complex feedstock, quicker and complete decomposition of materials, and higher quality compost products. Nevertheless, windrow can be in small scale as well. Static and passive aeration is also eligible for simple practices.

C) Open Bunkers

Composting piles can be set up in bunkers in order to maintain the shape and avoid erosion by wind in the open air. It is similar to piles but the turning efficiency is limited due to the bunker configuration. Bunkers are not commonly used and are usually for small to medium scale composting with passive turning.

Open systems are not necessarily limited to an outdoor environment and can be housed in buildings. Indoor composting allows for better temperature and air control. It also reduces particulate pollutions to some extent. There are also custom designed mobile turners for indoor windrows resembling a mixer that moves along rails at the side or on the ceiling. It should be noted that indoor composting is different from covered composting as described below.

3.1.2 Covered Systems

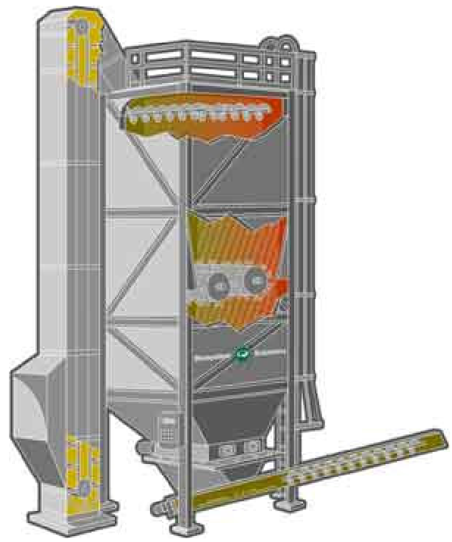
Membrane or other air permeable covers can be applied on piles or windrows for odor control and avoid heavy wind and precipitation. The cover has to be permeable to gaseous substances but retains odour emissions. The cover can be relatively loose but favourably sealed to the ground or containing cells to prevent air from escaping. For the latter case, the air within the system is usually piped to a filter to remove the odor components. The fillings of the filter can be biomass like wood chips, activated carbon, or other chemicals depending on the air purification requirements. There is also a technology that contains the feedstock in large (e.g. 60m) heavy-duty plastic (polyethylene) silage bags. The principle is similar to typical covered systems with the air further contained and controlled. *BioCycle*, Journal of Composting & Organics Recycling labelled this composting method as "enclosed aerated static pile". Covered systems allow better odor treatment and leachate control, thus tend to meet the approval of local air quality regulators and site neighbours. The covered composting practice is typically followed by compost curing in the open air to allow final decomposition and product stabilization.

Overall, open and covered systems require relatively low cost, simple operation, but more space to operate.

3.1.3 In-Vessel Systems

A) Vertical silo

Vertical silo is simple and only allows for passive aeration, thus a moderate efficiency. Original design looks similar to a wire-mesh "cage" that holds the feedstock. Aeration occurs in a way that air is able to flow through the bulking wire-meshes. Current design includes rigid plastic aeration "tubes" running vertically within the silo which is patented as "air-lance". Two silos in batches are common with the first one as a reactor and the second one for curing. Vertical silo can be meters high but is usually only several feet wide. Although the silo requires a small construction area, the efficiency of aeration is limited and decomposition process is slow and could create odor problem.



B) Container

The meaning of container can be confused with vessels but for this report, it specifically refers to fully enclosed static composter with positive aeration and is usually not fixed or built on engineered ground. Containers vary in dimensions and can be modular. In batch container allows flexibility to adjust the starting feedstock mix and to reload the container. A variety of aeration and process control strategies have been developed for this type of system. Typically, air can be blown (positive) into the containers from the bottom and flows up through the feedstock and into a headspace at the top. In other examples, air is drawn (negative) through the material from the top. In both modes, the air will be processed in a filter, usually housed in a separate container. Mechanical aeration in a rotary drum is also applicable for modular container. Rotary drums can be installed for mixing as well as aerating the feedstock. Computer control and monitoring systems have been developed for advanced container composters. Container systems can be located outdoor but for large scale practice, curing is typically needed which often occurs in buildings.

C) Tunnel

Tunnel systems are similar to containers but are usually built on aeration floors. Materials flow in horizontal tunnels and the capacity can vary. Feedstock is loaded from one end and composting occurs in batch mode. At several installations in North

America that use tunnel composting, materials are loaded and unloaded using front-end loaders. After the tunnels are fully loaded, continuous operation can be obtained under proper management. Aeration floors are specially designed with massive air flows that can blow or pull through the floor and the compost mass. Besides static aeration, agitation equipment like augers can be designed on the floors or on the other sides of the tunnels for mechanical aeration. That helps to physically degrade the materials besides introducing air. Rotary drum as described in container systems is also applicable as pre-treatment and aeration facility in tunnel systems. Air filtration and compost curing are also recommended as for other in-vessel systems.

D) Indoor Agitated Bays

In door agitated bays are developed to enhance the tunnel system approach. The feedstock is processed horizontally in long channels/bays with concrete walls and housed in fabricated metal or fabric structures. A turning machine is designed to travel on top of the channels to agitate and move the materials forward. Aeration floor as described in tunnel systems is usually integrated under the channels to optimize aeration. As this system is not in-vessel, primary air control includes hanging plastic curtains around the perimeter of the bays. It also helps to mitigate corrosion of the building by trapping the moisture and ammonia released from composting. Air filters can be applied as well to further treat the air in the building. Compost curing is also commonly deployed. The scale of the channel and the turning frequency determine the composting efficiency. The depth of channels range from 1m to 2m and the widths can be found from 2m to 4m. Channel lengths typically range from about 60m to 90m.

3.2 Local Composting Industry

Local composting industries are reviewed by online searches and interviews. The inventory is shown in Table 7.

Table 7 Inventory of Local Composting Industries

Sites in Operation	Supplier	Technology	Scale	Capacity	Waste source	Power usage	Products
Richmond Composting Facility, Richmond	Fraser Richmond Soil & Fibre Ltd., subsidiary of Harvest Power Canada, Ltd.	Covered Aerated Static Pile (CASP)	~1,000 m^2/cell*10 cells =10,000 m^2 ~8,000 m^3/cell*10 cells =80,000 m^3	Over 200,000 tonnes per year	50%~70% food waste + 50%~70% yard waste, from about 400,000 households in Lower Mainland	1.2E+7 kWh per year (based on 200,000 tonnes)	Screened to soil amender, garden blend, turf blend, and mulch
Vancouver Landfill, Delta	Vancouver Landfill	Open windrow, loader as turner	4.8 hectare	N/A, refer to end product	Residential yard trimmings, food scraps from SF	N/A	16,610 m3 of finished compost (2011)
Richmond Landfill, Richmond	Ecowaste Industries Ltd.	Open positive aeration windrow	~2.5 m (height) * 75 m (length) * 6 m (width)	~5,000 tonnes per year	Local Clean Green® yard waste, residential and	Richmond Landfill, Richmond	Ecowaste Industries Ltd.
Trafalgars Bistro and Sweet Obsession Bakery, Vancouver	GreenGood Composter	Electricity heating container; charcoal filters deodorizer	Main: 187cm x 90cm x 130cm; Deodorizer: 56cm x 84cm x 179cm	40 - 50 tonnes per year	Food waste, raw and cooked	14,400~21,900 kWh per year	Soil amender to Inner City Farms
Mulberry Retirement Community, Burnaby	GreenGood Composter	Electricity heating container; charcoal filters deodorizer	Main: 175cm x 73cm x 117cm; Deodorizer: 56cm X 84cm X 127cm	20 - 30 tonnes per year	Food waste	8,640~13,140 kWh per year	Not specified
Windermere school, Vancouver	Green mountain Technologies	"Earth Tub" container; biofiltration air purification system	3 cubic yards	6.6 - 24.8 tonnes per year (40-150 pounds per day)	food waste from cafeterias, some from the community	~1,080 kWh per year	Not specified
David Thompson school, Vancouver	Green mountain Technologies	"Earth Tub" container; biofiltration air purification system	3 cubic yards	6.6 - 24.8 tonnes per year (40-150 pounds per day)	food waste from cafeterias, some from the community	~1,080 kWh per year	Not specified

Grandview school, Vancouver	Green mountain Technologies	"Earth Tub" container; biofiltration air purification system	3 cubic yards	6.6 - 24.8 tonnes per year (40-150 pounds per day)	food waste from cafeterias, some from the community	~1,080 kWh per year	Not specified
Regional District of Nanaimo, Nanaimo	International Composting Corporation Group	Flow through, in-vessel system (tunnel system)	23,000 ft^2	36,500 tonnes per year	SSO waste, yard & garden waste from 50,000 households in the entire regional district	N/A	Not specified, marketed by Alpine Soil Mart
Minnies Pit landfill, District of Mission	Transform Compost Systems Ltd	Covered positive aeration windrows	12 ft high	10,000 tonnes per year, currently 5,000 tonnes per year	Food Waste and Yard Waste from the District of Mission	N/A	Screened and used in community
Stanhope Farm, Central Saanich, Victoria	Transform Compost Systems Ltd	Indoor positive aeration windrows+ External biofilter	12 ft high	N/A	Food Waste and Yard Waste	N/A	Screened and used for agricultural land
Westcoast Instant Lawns, Delta	Enviro-Smart Organics Ltd.	Indoor positive aeration windrows	N/A	100,000 wet tonnes, 19,000 dry tonnes per year	Yard trimmings, manure, wood and food processing waste	N/A	For sale
Central Landscape Supplies Ltd, Cobble Hill	Central Landscape Supplies Ltd	Open windrow on pad with loader turning	N/A	~4,500 tonnes per year	Only green waste like yard waste	N/A	Screened and used for the soil of themselves
Fisher Road Recycling, Cobble Hill	Fisher Road Recycling	Aeration floor indoor windrow	N/A	N/A	Cobble Hill, Shawnigan Lake, Mill Bay and Cowichan Bay	N/A	Type A Compost

The BioCycle journal published a directory of composting related companies (BioCycle, 2012). A shortened list with companies producing composting equipment is presented in Appendix B. The companies are mostly from North America with a few from Europe and Australia.

3.3 Overview of Anaerobic Digestion Technology

AD is the biological decomposition of organic matters in the absence of oxygen. Unlike aerobic digestion, which completely oxidizes the carbon compounds into carbon dioxide, AD stops the reactions at the stage of intensive methane generation. AD includes the stages of hydrolysis, acidogenesis/acetogenesis and methanogenesis. In this process, biogas is generated with a typical composition of ~60% methane and ~40% carbon dioxide. This biogas can be used as a fuel for heating, generating electricity, or vehicle. The material remaining after digestion, known as digestate, is a stabilized organic slurry which can be used as compost or fertilizer. The digestate can be wholly applied as fertilizer after curing or typically after separation into liquid and solid phase. The liquid phase is a nitrogen-rich fertilizer that is easier to be taken up by plants compared to that in the raw manure fertilizer. The solid phase is rich in phosphorous and potassium nutrient and is frequently used as livestock bedding.

Since AD requires an oxygen free environment, it always has to be in an enclosed system. Covered lagoons on livestock farms can be considered as simple agricultural AD facility but for efficient municipal waste digestion and biogas generation, only sealed vessels are studied. There are several categories to classify anaerobic digesters: the feedstock can be wet or dry, the temperature can be mesophilic (~35°C), thermophilic (55°C~60°C), or psychrophilic (15°C~25°C), the materials can be completely mixed or mixed by flowing through; and the stages of the digestion process can take place in one or multiple vessels. Capacity of AD using municipal waste ranges between 1,000 to 300,000 tonnes per year. Raw biogas usually undergoes upgrading or purification depending on the purpose of the end use. Also, the overall biogas yield depends on the types of digestion feedstock and digester technologies.

Table 8 Overview of AD Systems

AD Systems	Scale	Feedstock Moisture Content	Agitation	Multi-Stage Availability	Retention time
Completely Mixed Digester (CSTR)	· Small · Medium · Large	· Wet · Dry	· Agitator · Liquid circulation	· No	· Long
Fed Batch Digester	· Small · Medium	· Wet · Dry	· Agitator · Liquid circulation	· Yes	· Long
Plug Flow Digester (PF)	· Small · Medium	· Wet	· Feed flow	· No	· Short
Mixed Plug Flow Digester (MPF)	· Medium	· Wet	· Agitator · Feed flow · Vessel rotation	· Yes	· Medium

3.3.1 AD System by Feedstock Moisture Content

A) Wet Digestion

Wet digestion deals with feedstock that contains 10%-15% dry matter. Some organic waste has dry matter content that naturally falls into this range while some feedstock is diluted with water or other liquid to reach this level. Wet digestion is traditionally easier to manage due to its natural tendency to be anaerobic. It allows agitation by feed flow and product gas flow which saves energy consumption. Examples are Up-flow Anaerobic Sludge Blanket (UASB), Plug Flow Digester, and Mixed Plug Flow Digester.

B) Dry Digestion

Dry digestion deals with feedstock that has a dry matter content of up to 20%~40%. Municipal waste is usually much drier than agricultural waste like manure thus it is frequently diluted to dry digestion levels. Dry digestion typically requires an agitator to mix the feedstock in the vessel for desirable reactions. Although the operation of dry digestion consumes more energy, it is the most feasible system for large scale biogas plants. Also, the biogas yield of dry digestion is generally higher than that of wet digestion because of its relation with the solid content in the feedstock.

3.3.2 AD System by Digestion Temperature

A) Mesophilic Digestion

Mesophilic digestion maintains the in-vessel temperature at around 35°C. This is currently the most widely applied temperature that proves to be cost-effective to achieve desirable biogas yield under reasonable retention time.

B) Thermophilic Digestion

Thermophilic digestion requires the temperature during digestion to be about 55°C to 60°C. Generally speaking, the rate of AD increases with temperature. The shortened retention time allows for smaller digester volume and more efficient biogas generation. However, some studies have found the biogas generation is not significant. Thermophilic digestion is more favourable to dry digestion compared to wet digestion. Due to the additional heating requirements, thermophilic digestion is only economically viable at high organic loading rates. It is observed that thermophilic digestion has a benefit of effectively killing the pathogens in the organic waste. This is an advantage when application of the digestate has hygienic concerns.

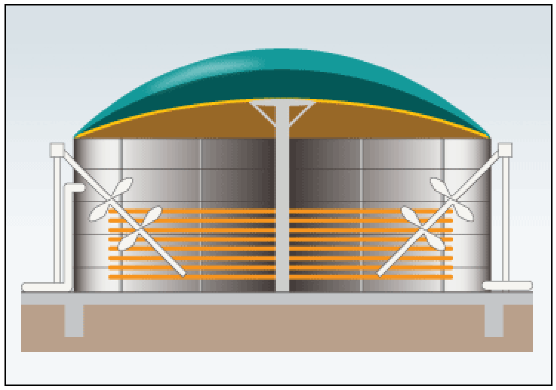
C) Psychrophilic Digestion

Psychrophilic digestion manages to digest organic matters in the temperature range of 15°C-25°C. It is not a commonly used process as only two systems are currently in operation in Quebec and Manitoba. As low temperature slows down the reaction time, longer retention time is required to achieve equivalent gas production and pathogen removal.

3.3.3 AD System by Digestion Agitation

A) Completely Mixed (Completely Stirred Tank Reactor-CSTR)

Completely Mixed digesters use auger-like agitators to mix the materials in tanks. Dry digestion can be realized in such configurations. Fresh feedstock is usually mixed with partially digested materials. The scales can be flexible and almost all of the large scale digesters in operation are completely mixed systems. This technology is mature and is most widely used around the world.



B) Plug Flow (PF)
Plug flow is a common reactor configuration for continuous loading and reaction. It typically consists of long channels in which the materials move along as a plug. Well managed plug flow digesters are able to have continuous and stable biogas generation. As the materials flow, mild agitation occurs. However, this system is not applicable for dry digestion due to its low fluidity. Mixed Plug Flow (MPF) is designed to install agitation equipment into plug flow digesters. That is an improved design that achieves better stability as well as higher efficiency.

C) Rotary Digester
Plug flow digesters can be designed to become rotary to improve agitation. It is similar to the rotary drums for composting but rotates slowly with the materials flowing horizontally similar to the normal plug flow digesters. Such system can be called Rotary Mixed Plug Flow digester.

3.3.4 Stage-Wise Digestion

A) One-Stage Digestion

One-stage digestion refers to the entire AD process occurring in one vessel. Even in series, each vessel has similar inter-environment that does not specify different digestion processes. Therefore, in one stage AD systems, hydrolysis, acidogenesis/acetogenesis and methanogenesis actually take place at the same time. This system has been dominant in the market due to its relative simple design, less frequent technical failures, and lower capital costs.

B) Two-Stage Digestion

Two-stage digestion requires more than one vessel and different vessels house different digestion stages of the hydrolysis, acidogenesis/acetogenesis and methanogenesis processes. Two-stage digestion is able to optimize the environment for acidogenesis and methanogenesis in way of offering different preferred pH conditions. However, experience to date with MSW systems is that the additional costs of the extra tanks and management cannot be made up by the higher gas yield. Hence, this type of digestion system is not as popular as the one-stage digestion.

3.4 Local AD Industry and Potential Suppliers

The use of AD technology to treat municipal solid waste has been slow to penetrate the North American market mostly because of higher costs compared to other options. There are two medium scale digesters running with agricultural waste in Abbotsford but no municipal AD plant is operating in Metro Vancouver. Fraser Richmond is currently building the first digester (High Solid Completely Mixed digester) to treat local municipal organic waste and is expected to be in operation in fall 2012. The City of Surrey has also shown interests in establishing one. Since the information for the City or BC is very limited, the review of AD industry extends to the region of North America.

The two existing agriculture digesters and five upcoming digesters in BC are listed in Table 9 (ADIAC, 2012; Dickson, 2012).

Table 9 Existing and upcoming agriculture digesters in BC

Location	Supplier	Technology	Scale	Capacity	Waste source	Products
Bakerview EcoDairy, Abbotsford	Avatar Energy	Scalable modular plug flow with trickling filter system, mesophilic	-	-	Manure from 50 lactating cows and locally produced whey and bakery by-products	On-farm electricity and heat, cow bedding and fertilizer
Catalyst Power, now known as Fraser Power	PlanET Biogas Solutions	Complete mix, mesophilic	24m diameter tanks by 6m high	200 tonnes/day	Dairy and poultry manure (200 tonnes/day) and food processing waste (40 tonnes/day)	Biogas upgraded to natural gas specifications and digestate used for fertilizer and bedding
Delta	-	-	-	-	Dairy manure	-
Chilliwack	-	-	-	-	Dairy and poultry manure	-
Deroche	-	-	-	-	Dairy manure	-

Rosedale	-	-	-	-	Dairy manure	-
Abbotsford	-	-	-	-	Dairy and poultry manure	-

In Canada, Toronto has two operating AD plants that process municipal waste. The Dufferin Organics Processing Facility uses BTA® technology (a wet-digestion, German technology, Haines, 2008) and is located at the City of Toronto Dufferin Transfer Station in north-west Toronto. The HRL AD facility in Newmarket, Ontario has the capacity to process up to 150,000 tonnes/year of source separated organics and also some mixed waste loads. The facility uses BTA as well.

A summary of commercial AD technologies with large scale reference plants in North America is presented in Appendix C. Data are up to February 2008 (Rapport, 2008).

BC has just begun to promote the use of AD and the BC's Anaerobic Digestion Initiative Advisory Committee (ADIAC) currently has contacts with 14 AD suppliers that have demonstrated interests in providing AD services in BC. All suppliers are from North America more than half of them are from Canada. The information of these suppliers is cited in Appendix D (Ethan, 2012). Although these information was collected targeting the agriculture AD development, most of the technologies are potentially applicable to municipal organic waste treatment when properly designed and modified.

4.0 Woody Waste in Composting and Anaerobic Digestion

Woody waste refers to demolition wood waste, tree branches, and bulking agents as a stream of municipal organic waste and is assessed for composting and AD by literature reviews and interviews. Generally, clean woody material is acceptable and sometimes required for composting with its C:N ratio and physical property. However, it is not easily degradable compared to other organic waste such as grass and food waste. This could be observed in nature as wood takes longer time to rot than fruits and leaves. In practice, woody material is usually screened out from the compost products as it remains the bulk of the volume after composting. For AD, woody material cannot be digested thus it is generally not accepted. However, large scale digesters need bulky material to allow proper percolation. In such case, yard branches can be a good option (Lowell, 2012). The branches are separated out as well after digestion.

As shown in Table 3.1-2, woody waste has extremely high C:N ratio (300:1~400:1) while some food waste are very high in nitrogen content. To reach a balanced C:N ratio, woody waste is required to compost high-nitrogen materials. The MF and commercial sectors intensively generate high nitrogen food waste and yard trimmings become a valuable resource for effective composting. Generally, a rule of thumb in the composting industry is one tonne of wood requires one tonne of food waste (Timmenga & Associates Inc, 2006). Some jurisdictions banned wood waste landfilling to save wood for composting (Corolina Composting Council, 2004) and saving yard trimmings for the winter period are done in some cities. Some studies and partitions also have successful composting experiences using woody waste to mix with animal manure and slaughtered waste (SYLVIS, 2008). Although woody waste can be composted, it has to be cleaned and reduced to smaller size. The wood is usually chipped to 2~3 inches before composting. Also, the wood has to be cleaned and freed of contaminants such as paints, preservative, and other chemicals like pentachlorophenols and creosote. These contaminants will damage the bio-chemical environment for composting. Also, metals such as nails from demolition wood waste can create hazards to chipping machines and are permanent contaminants in the compost product. Occasionally, demolition wood waste is chipped using low speed grinders to reduce the damage from metals. As a result, the preferred woody waste for composting is still yard trimmings. They are generally in smaller sizes and have no chemical contamination. Purchasing wood chips or chipping lumber can significantly increase the cost. Composted woody material will turn dark and soft but not completely smashed. To achieve a finer compost product, woody material is usually screened out or used as mulch (Lapp, 2012).

While composting can degrade woody material slowly, AD is unable to break down the wood at all and the process is extremely slow such that the biogas yield from woody material is very low. The reason is that AD is not strong enough to decompose cellulose and lignin components in the woody material. Limited amount of woody waste can be tolerated but is usually recommended to be removed. Also, wood shavings can cause blockage of pipes. There are ways to increase the biodegradability of lignocelluloses materials by an array of physical/chemical processes. However, this will increase the overall cost hence it is not suitable for practical application. An exception of including woody waste in AD is the tree branches which can be utilized to aid percolation in large digesters. At the end, the branches will not be digested and is separated out after discharged (Monnet, 2003).

Overall, yard trimmings are recommended for composting along with high-nitrogen waste. Demolition waste is expected to be diverted away from the landfill through the implementation of deconstruction permits. The rest of the demolition waste could be chipped for composting but it is not very economical. Although disposing wood waste into incinerators is considered as waste disposal that should be avoided, incinerating bulk wood waste for energy is still a common practice and recommended by some jurisdictions (Allaway, 2012). In the following sections of waste flow analysis in the City, yard trimmings are all modeled to be composted while demolition waste is not included for composting or AD.

5.0 Organic Waste Flows in the City of Vancouver

5.1 Demolition Wood Waste

Construction and demolition waste accounts for about 22% of the total waste that is disposed (City of Vancouver, 2012a). Among them, 30%~50% is wood waste (Kane Consulting, 2011). In 2010, around 82,000 tonnes of wood waste was generated in the City (McDermott, 2012). The quantity is estimated based on the number of issued demolition permits, average areas of building per residential or non-residential permit, and the waste composition factors. Demolition wood waste tends to include contaminants such as paints, preservative, and other chemicals like pentachlorophenols and creosote. Only 50% of the total demolition wood waste could be identified as clean wood and is applicable for composting or incineration (McDermott, 2012). Generation of demolition wood waste is assumed stable in this study (i.e. numbers of 2010 level is applied to all subsequent years until 2020).

Demolition waste used to be disposed into the landfill or the incinerator. Under the Greenest City Goal, the City has launched an advanced permitting process to encourage deconstruction as an alternative to demolition for one & two-family homes. Instead of disposing the demolition waste into the landfill or the incinerator, the City seeks ways to salvage the waste for reuse or recycling. A pilot study conducted last year showed that up to 93% of a house's building materials can be recycled (City of Vancouver, 2012a). With a deconstruction permit, the applicant must divert at least 75% of all building materials. Part of these materials are expected to be reused for constructing a new one or two family dwelling as a requirement for issuing the permit (City of Vancouver Sustainability Group, 2012). Effective in 2012, the City aims to achieve a 5% participation rate for all demolitions to choose the deconstruction permit process in the first year (2012) and increase to 10% for the second year (2013). It is expected to have the deconstruction permit become mandatory in 2014, subject to an updated plan and Council approval (McDermott, 2012). Two scenarios are analyzed in this report. One scenario has the deconstruction permit starting at 5% for 2012 and an incremental increase of 5% until 2020 (to 45%). The other scenario has a more aggressive target which assumes 20% in 2013, 60% in 2014, and 100% (mandatory) in 2015 and thereafter. All deconstruction permits are applied on residential demolition only. For the diversion rate under deconstruction permits, the 75% minimum requirement level is applied. Appendix A lists the data used in the calculations for demolition wood balance.

The estimates of clean demolition wood waste generation from 2012 to 2020 are shown in Table 10.

Table 10 Projections of Clean Demolition Wood Waste Generation

Year	Moderate deconstruction permit implementation			Aggressive deconstruction permit implementation		
	Deconstruction percentage	Wood disposed (tonne)	Clean wood disposed (tonne)	Deconstruction percentage	Wood disposed (tonne)	Clean wood disposed (tonne)
2012	5%	61,250	30,625	5%	61,250	30,625
2013	10%	60,246	30,123	20%	58,236	29,118
2014	15%	59,241	29,620	60%	50,200	25,100
2015	20%	58,236	29,118	100%	42,164	21,082
2016	25%	57,232	28,616	100%	42,164	21,082
2017	30%	56,227	28,114	100%	42,164	21,082
2018	35%	55,223	27,611	100%	42,164	21,082
2019	40%	54,218	27,109	100%	42,164	21,082
2020	45%	53,214	26,607	100%	42,164	21,082

5.2 Yard Waste

5.2.1 Yard Waste from Single-Family (SF) Collection

Yard trimmings from SF properties are collected by the City bi-weekly. MF and non-residential properties that would like to receive City yard trimmings collection can apply to the City and are accepted on a case by case basis. Accepted yard trimmings include 1) leaves and grass clippings, 2) weeds, plants, and flowers, and 3) branches and prunings less than 10 cm in diameter and less than 0.5 m in length. Residents dispose the waste into assigned yard trimmings carts that are serviced using the City's automated trucks equipped with mechanical arms. Four different cart sizes are available ranging from 120 to 360 litres (City of Vancouver Solid Waste Management Branch. 2011).

Since April 22, 2010, residents have been allowed to dispose uncooked fruit and vegetable scraps, coffee grounds and filters, eggshells, and teabags into their yard trimmings cart for composting. This is expected to be an efficient management to divert organics and a requirement by the processor, Fraser Richmond, to mix yard waste and food scraps together. However, for analysis purpose, projection of SF yard waste and food scraps generation are estimated separately instead of the expected total collected altogether. It is worth noting that combined collection of yard trimmings and food scraps will likely continue and expand thus the waste will not be collected separately in practice.

5.2.2 Yard Waste from Multi-Family (MF)

Unlike yard waste from SF, there is currently no yard waste collection provided by the City for MF buildings. The generation amount is estimated by the total waste generation and composition from MF studies by Metro Vancouver. It is reported that 44% of all the total waste generated from MF are compostable and among these, 6% is yard waste (Fournier, 2012). This is slighted lower than the yard waste content found from garbage in SF which is 7% (City of Vancouver. 2012b).

5.2.3 Yard Waste Drop-Offs

Residents can choose to drop-off yard trimmings directly at Vancouver South Transfer Station or Vancouver Landfill. This usually occurs when there are extra or particularly large branches that residents are not able to place into their carts. The ICI sector as well as Park Board drops off considerable amount of yard trimmings each year. The total yard waste drop-offs received by VSTS is around 15,000 tonnes per year and those received by Vancouver Landfill is about 11,000 tonnes per year. These yard waste are composted in open windrows at the Vancouver Landfill.

5.2.4 Fall Leaf Removal Program

The City runs a fall leaf removal program annually from October 1 to January 31. Residents can set out un-limited amount of leaves during that period. Leaves are also swept and removed from City streets. All leaves are currently transferred to the Vancouver Landfill for composting along with the yard trimmings drop-off. The total amount of leaves collected from this program accounts for around 4,000 tonnes per year (City of Vancouver Solid Waste Management Branch, 2011).

5.2.5 Statistics & Estimates

Analyzing the amount of wood waste is one of the tasks in this report and wood composition in yard waste is specifically estimated. Metro Vancouver reports 91% of the yard trimmings is branches and leaves and 9% is grass (Technology Resource Inc. 2011; TRI Environmental Consulting Inc. 2012). Branches and leaves are included as woody waste because leaves have similar carbon nitrogen ratio as wood. Table 11 lists the source of the data used in the calculations.

Table 11 Data in Yard Waste Calculations

	2008	2009	2010	2011	2012	2015	2020	Source
Yard trimmings from SF collection, tonnes	-	-	24,530	25,240	-	-	-	City of Vancouver Solid Waste Management Branch, 2011
Yard trimmings from MF generation, tonnes	4,419	-	-	-	4,505	4,581	4,706	Fournier, 2012
Yard trimmings from drop-off to VSTS, tonnes	15,953	17,705	15,427	14,821	-	-	-	City of Vancouver Solid Waste Management Branch, 2011
Yard trimmings from drop-off to Landfill, tonnes	11,677	11,772	11,364	10,746	-	-	-	City of Vancouver Solid Waste Management Branch, 2011
Fall leaf program, tonnes	4,740	3,240	3,881	4,671	-	-	-	City of Vancouver Solid Waste Management Branch, 2011
Yard waste composition	Large branches: 10%; Small branches and leaves: 81%; Grass: 9%.							Technology Resource Inc., 2011; TRI Environmental Consulting Inc., 2012

The projections of yard waste flow from 2012 to 2020 are shown in Table 12.

Table 12 Projections of Yard Waste Generation

	2012	2013	2014	2015	2016	2017	2018	2019	2020
Yard trimmings from SF collection, tonnes	24,885	25,022	25,159	25,296	25,433	25,570	25,707	25,844	25,981
Yard trimmings from MF generation, tonnes	4,505	4,530	4,555	4,581	4,606	4,631	4,656	4,681	4,706
Yard trimmings from drop-off to VSTS, tonnes	15,977	15,977	15,977	15,977	15,977	15,977	15,977	15,977	15,977
Yard trimmings from drop-off to Landfill, tonnes	11,390	11,390	11,390	11,390	11,390	11,390	11,390	11,390	11,390
Woody waste from yard trimmings (~91%), tonnes	51,648	51,796	51,943	52,091	52,239	52,386	52,534	52,681	52,828
Fall leaf program, tonnes	4,029	4,029	4,029	4,029	4,029	4,029	4,029	4,029	4,029
Total woody waste, tonnes	55,677	55,825	55,972	56,120	56,268	56,415	56,563	56,710	56,857

Note:

-Base amount (as in year 2012) of yard trimmings from SF collection in 2012 is calculated as the average value of 2010 and 2011since there were a significant increase since 2010 though not due to food waste inclusion.

-Base amount (as in year 2012) of yard trimmings from drop-offs to VSTS and landfills is calculated as the average value of 2008 to 2011.

-Projections of MF yard trimming generation of 2015 and 2020 are based on internal estimates in line with Greenest City Goal and with population growth accounted. Estimates of the rest of the years are obtained by interpolation.

-Projection of SF generation applies a same increasing trend as of MF (i.e. annual increase as 0.55% starting from 2012).

-Base amount (as in year 2012) of yard waste from drop-offs and fall leaf program is calculated as the average value of 2008 to 2011. And it is assumed to be stable in the future years as fluctuation is observed in the past years.

-Total woody waste is defined as approximately 91% of branches and leaves in yard trimmings. The rest of the yard trimmings (~9%) are assumed to be grass.

5.3 Food Waste

5.3.1 Food Waste from Single-Family (SF) Collection

Historically, food waste has been disposed of as garbage by SF. Since no specific food waste audit is available, the garbage composition of SF reported by Metro Vancouver is used to estimate the food waste generation. It is reported that 39% of all household garbage consists of food waste (TRI Environmental Consulting Inc., 2012). The total garbage generation from the City is around 63,000 tonnes and food waste accounts for about 25,000 tonnes.

Since April 22, 2010, the City has allowed a limited number of food scraps to be placed into the yard trimming carts. Such food scraps include uncooked fruit and vegetable scraps, coffee ground and filters, eggshells, and teabags. The mixed yard waste and food scraps are composted together. Starting in early 2012, a pilot project involving 2,000 households allows residents to add a wider variety of food scraps to their yard trimmings carts. With more food waste accepted, the yard trimmings carts in the pilot areas are emptied once a week instead of every-other-week. Upon Council approval, the expanded food scraps collection program is expected to be implemented City-wide by early 2013 (Fournier, 2012).

Food waste data is analyzed to assess the potential for composting or AD. Food waste is a high-energy feedstock for AD but yard waste is not able to be digested and only limited amount of branches can be used to aid percolation. As a mixture of yard trimmings and food waste are collected by the City, the mixture will be good for composting but may not be suitable for digestion directly. Thus, the pure food waste option from SF and the subsequent Life Cycle Assessment of digestion scenario are for information only and are probably not suitable for practical use.

5.3.2 Food Waste from Multi-Family (MF) and Commercial Sectors

As MF buildings contract directly with private haulers for garbage collection, food waste from MF is estimated by the total waste generated. It has been reported that about 44% of all the waste from MF are compostable and among these, 32% is food waste (Fournier, 2012). This is higher than the composition found from SF which is about 25% (City of Vancouver, 2012b).

Similar to MF buildings, commercial buildings also contract with private haulers for waste disposal. Food waste from commercial sector is reported as 76,000 tonnes per year (City of Vancouver Administrative Report, 2011). This is up to 3 times higher than the food waste from SF or MF. No other data source for commercial food waste generation is referred thus this estimated number is used for Life Cycle Assessment.

5.3.3 Statistics & Estimates

Table 13 lists the source of the data used in the calculations.

Table 13 Data in Food Waste Calculations

	2008	2009	2010	2011	2012	2015	2020	Source
Food waste from SF collection, tonnes	24,040	24,922	24,469	23,867	-	-	-	City of Vancouver Solid Waste Management Branch, 2011
Food waste from MF generation, tonnes	23,570	-	-	-	24,028	24,430	25,100	Fournier, 2012
Food waste from commercial, tonnes	-	-	-	-	76,000	-	-	City of Vancouver Administrative Report, 2011

Note:

-Food waste from commercial sector did not specify the year and is assumed to be the base level (as in year 2012).

The projections of food waste flow from 2012 to 2020 are as follows.

Table 14 Projections of Food Waste Generation

	2012	2013	2014	2015	2016	2017	2018	2019	2020
Food waste from SF collection, tonnes	24,325	24,459	24,593	24,727	24,861	24,995	25,129	25,263	25,397
Food waste from MF generation, tonnes	24,028	24,162	24,296	24,430	24,564	24,698	24,832	24,966	25,100
Food waste from commercial, tonnes	76,000	76,418	76,836	77,254	77,672	78,090	78,508	78,926	79,344

Note:

-Base amount (as in year 2012) of food waste from SF collection in 2012 is calculated as the average value of 2008 to 2011.

-Projections of MF food waste generation of 2015 and 2020 are based on internal estimates in line with Greenest City Goal and with population growth accounted. Estimates of the rest of the years are obtained by interpolation.

-Projection of SF and commercial generation applies a same increasing trend as of MF, i.e. annual increase as 0.55% starting from 2012.

5.4 Renewable Product and Energy Potential

Under the Greenest City Goal, 50% of the waste that used to be disposed of to the landfill or to the incinerator will be diverted away by 2020. To estimate the diversion potential of organic waste, scenarios of composting and AD are studied based on the city-wide waste flows. Composting is analyzed either as a mixture of food waste plus yard trimmings or just yard trimmings alone. For mixed composting, a rule of thumb is to have the same proportion of weight between food waste and yard waste. In practice, specific parameter analysis is necessary to optimize the properties of feedstock and composting environment. It is also subject to seasonal fluctuations of the availability of yard waste. Table 15 describes the scenarios to recycle organic waste in the City.

Table 15 Scenarios of Composting and AD Production Estimates

Scenarios	Organic waste	Process	Remarks
1-a	SF total organic waste	Composting	Food and yard waste from SF are composted together. Yard waste from drop-offs and fall leaves are composted alone.
1-b	SF total organic waste	AD for biogas+composting	Food waste from SF is digested. All yard waste is composted.
1-c	SF total organic waste	AD for heat and power Composting	Same as 1-b
2-a	MF and commercial food waste	AD for biogas	-
2-b	MF and commercial food waste	AD for heat and power	-

The production of compost from composting and biogas & digestate from AD is estimated under expected waste diversion rates. The generation rate of compost products is 1.48 cubic yard per tonne of feedstock according to information provided by Fraser Richmond (Lowell, 2012). The biogas and digestate generation rates referred to the EcoInvent database used in the LCA study. Economic profit is also estimated and the price of the compost products and digestate are based on Metro Vancouver study (EBA Engineering Consultants Ltd, 2012). However, since huge amount of compost is expected to be generated in Metro Vancouver, the value of compost will most likely drop. An annual price drop of 5% is applied to the economics assessment. This may be unrealistic as the price could drop more substantially when the supply of compost is higher than the demand (Rowan, 2012). Price of purified natural gas is calculated using the price for natural gas ($0.15/purified biogas) (Fortis BC, 2012). Price of electricity from AD is assumed to be the same as current electricity grid ($0.06/kWh electricity) (BC Hydro, 2012). Table 16 shows the prediction of renewable product and energy generations from 2012 to 2020. Gross revenues from these products are estimated in Table 17; all numbers are in unit of 1,000 Canadian dollars.

Table 16 Prediction of Renewable Product and Energy Generations from Composting or AD

	Unit	2012	2013	2014	2015	2016	2017	2018	2019	2020
Waste diversion rate		10%	15%	20%	25%	30%	35%	40%	45%	50%
Diverted yard trimmings from SF	tonne	2,489	3,753	5,032	6,324	7,630	8,950	10,283	11,630	12,991
Diverted yard trimmings from drop-offs	tonne	2,737	4,105	5,473	6,842	8,210	9,578	10,947	12,315	13,683
Diverted fall leaves	tonne	403	604	806	1,007	1,209	1,410	1,612	1,813	2,014
Diverted food waste from SF	tonne	2,432	3,669	4,919	6,182	7,458	8,748	10,051	11,368	12,698
Diverted food waste from MF	tonne	2,403	3,624	4,859	6,108	7,369	8,644	9,933	11,235	12,550
Diverted food waste from Commercial	tonne	7,600	11,463	15,367	19,314	23,302	27,332	31,403	35,517	39,672
Scenario 1-a										
Soil Amender, 100% compost	m3	9,090	13,681	18,302	22,954	27,637	32,350	37,093	41,867	46,672
Scenario 1-b										
Purified biogas	1,000 m3	162	245	328	412	497	583	670	758	847
Digestate product	tonne	1,731	2,610	3,500	4,398	5,306	6,224	7,152	8,088	9,035
Soil Amender, 100% compost	m3	6,347	9,543	12,755	15,983	19,226	22,484	25,758	29,047	32,352
Scenario 1-c										
Electricity	MWh	394	594	797	1,001	1,208	1,417	1,628	1,842	2,057
Digestate product	tonne	1,731	2,610	3,500	4,398	5,306	6,224	7,152	8,088	9,035
Soil Amender, 100% compost	m3	6,347	9,543	12,755	15,983	19,226	22,484	25,758	29,047	32,352
Scenario 2-a										
Purified biogas	1,000 m3	667	1,006	1,348	1,695	2,045	2,399	2,756	3,117	3,482
Digestate product	tonne	7,117	10,734	14,391	18,087	21,822	25,597	29,411	33,264	37,156
Scenario 2-b										
Electricity	MWh	1,620	2,444	3,277	4,118	4,969	5,828	6,696	7,574	8,460
Digestate product	tonne	7,117	10,734	14,391	18,087	21,822	25,597	29,411	33,264	37,156

Table 17 Gross Revenue Prediction of Renewable Product and Energy from Composting or AD

	2012	2013	2014	2015	2016	2017	2018	2019	2020
Scenario 1-a									
Soil Amender, 100% compost	345	509	666	818	964	1,104	1,238	1,366	1,487
Garden Blend, 75% compost, 25% river sand mix	428	631	827	1,016	1,197	1,371	1,537	1,695	1,846
Turf Blend 50% compost, 50% river sand mix	690	1,017	1,333	1,637	1,929	2,209	2,476	2,731	2,974
Scenario 1-b									
Purified biogas	25	37	50	63	76	89	102	115	129
Digestate product	109	162	212	261	309	354	398	440	480
Soil Amender, 100% compost	241	355	464	570	671	768	860	948	1,031
Garden Blend, 75% compost, 25% river sand mix	299	440	577	707	833	953	1,067	1,176	1,280
Turf Blend 50% compost, 50% river sand mix	481	709	929	1,140	1,342	1,535	1,720	1,895	2,062
Scenario 1-c									
Electricity	24	36	48	60	72	85	98	110	123
Digestate product	109	162	212	261	309	354	398	440	480
Soil Amender, 100% compost	241	355	464	570	671	768	860	948	1,031
Garden Blend, 75% compost, 25% river sand mix	299	440	577	707	833	953	1,067	1,176	1,280
Turf Blend 50% compost, 50% river sand mix	481	709	929	1,140	1,342	1,535	1,720	1,895	2,062
Scenario 2-a									
Purified biogas	101	153	205	258	311	365	419	474	529
Digestate product	450	665	873	1,075	1,269	1,456	1,636	1,808	1,973
Soil Amender, 100% compost	345	509	666	768	964	1,104	1,238	1,366	1,487
Garden Blend, 75% compost, 25% river sand mix	428	631	827	953	1,197	1,371	1,537	1,695	1,846
Turf Blend 50% compost, 50% river sand mix	690	1,017	1,333	1,535	1,929	2,209	2,476	2,731	2,974
Scenario 2-b									
Electricity	97	147	197	247	298	350	402	454	508
Digestate product	450	665	873	1,075	1,269	1,456	1,636	1,808	1,973

Soil Amender, 100% compost	345	509	666	768	964	1,104	1,238	1,366	1,487
Garden Blend, 75% compost, 25% river sand mix	428	631	827	953	1,197	1,371	1,537	1,695	1,846
Turf Blend 50% compost, 50% river sand mix	690	1,017	1,333	1,535	1,929	2,209	2,476	2,731	2,974

Note:

-All numbers are in unit of $1,000 Canadian dollars.

-Finished compost can be used as soil amender or further produced into garden blend or turf blend. The current (year 2012) prices of the three types of products are $29/cubic yard for soil amender and turf blend and $27/cubic yard for garden blend (EBA Engineering Consultants Ltd, 2012). This price is for retailing while whole sale price can be much lower. The estimates of the gross revenue from the compost products assume single type of compost product is produced i.e. all compost product is used as soil amender or garden blend or turf blend. In reality a combination of different compost product will be sold depends on the market demand.

5.5 Local Market for Compost Products and Digestate

Metro Vancouver conducted a study for the local recycling market including organic waste recycling. The report identifies the potential increase of compost demand but also observes the on-going efforts to recover organic waste and the expansion of recycling players and facilities. It concludes the generation of compost product will be much higher than the demand. The study covers the Metro Vancouver region but can be applied to the City.

Primary compost users in Metro Vancouver are landscapers, residents, and local government. Landscapers make up over half of the customer base for compost. Residential buyers purchase garden blends and turf blends for home gardening. Local governments apply compost for parks maintenance and building construction. These consumers are relatively stable depending on urban planning and weather conditions. Traditionally, the compost product or digestate is a good source of fertilizer. However, Metro Vancouver already has quite a few animal farms that generate manure fertilizers. Although the agricultural sector currently consumes very little compost, their market share may increase as more organic growers emerge. With the advantages of using compost being more widely perceived, the demand for higher quality compost in organic farms will likely grow. There will be some emerging market opportunities such as storm water green infrastructure services but there have been concerns with the contamination in compost and digestate products. The quality of compost and digestate fluctuates depending on the cleanliness of the feedstock as well as the processing operations. Contaminants such as metal and plastics are often found mixed in with the end products. In such cases, the poor quality of the compost or digestate lowers the competitiveness even for landscaping.

Although the demand of compost will potentially increase, it is not expected to be as significant as the growth of supply. As estimated in the section above, large amount of compost product and digestate will be generated with aggressive composting and AD practice. The estimates are under the assumption that the diversion rate increases gradually to 50% by 2020. However, if the upcoming ban on organic waste is implemented efficiently, more recycled organic products can be expected. Correspondingly, the capacity for processing organic waste will be growing at a fast pace. Current composting capacity in Metro Vancouver is over 300,000 tonnes (EBA Engineering Consultants Ltd, 2012). In 2012, Harvest Power alone will add another 60,000 tonnes. Four companies currently have license applications being considered by Metro Vancouver to process organics in the region and more private companies are also interested in joining the market. Using the estimate of more than 61,000 cubic yards compost produced from SF in the City in 2020 (Section 5.4), about 570,000 cubic yards compost will be generated in Metro Vancouver based on the organic waste ratio (TRI Environmental Consulting Inc, 2012). Over 350,000 cubic yards of compost blended products are sold in the Metro Vancouver region each year (EBA Engineering Consultants Ltd, 2012). Therefore, huge amount of compost products are expected to be surplus.

In the gross revenue estimates in this study, an annual price drop of 5% is applied to the compost products. However, this is a very conservative discount rate according to Staff at Metro Vancouver (Rowen, 2012). It is anticipated that once production of compost and digestate exceeds the demand dramatically, the value may drop to nearly zero. Unless demands from markets in other regions are available, the revenue generated from compost and digestate may be very low.

6.0 Life Cycle Assessment (LCA)

6.1 Introduction to LCA

Life Cycle Assessment (LCA) is a technique for assessing the potential environmental aspects associated with a product or a service. It is "a systematic tool for identifying and evaluating the environmental aspects of products and services from extraction of resource inputs to the eventual disposal of the product or its waste "cradle to grave"" (ISO 14040). LCA typically includes raw material production, manufacture, distribution, consumption and waste disposal including all intervening transportation involved. It avoids misleading conclusion from limited analysis scope and is able to offer a complete picture. LCA has been increasingly applied as a holistic assessment tool for industrial design and various decisions makings. It not only looks at the environmental impacts but can be expanded to social and economic analysis. By selecting a group of environmental aspects or indicators, LCA is able to find the "hot spots" within the life cycles even if some occur at stages that is in the upstream or background and are easily ignored. LCA can be conducted to comprehensively describe a product or service or used for comparisons. LCA is especially effective to analyze environmental impacts that occurred not only at the manufacture or consumption site. Those include non-renewable energy use, GHG emissions, ozone depletion potential etc. For local impacts such as air pollutants and small scale soil and water pollution, specific stages and location could be identified.

The ISO 14000 system of environmental management standards for LCA (ISO 14040) provides guidance for conducting Life Cycle Assessment studies. Four stages are involved in this framework (The Sheltair Group, 2008):

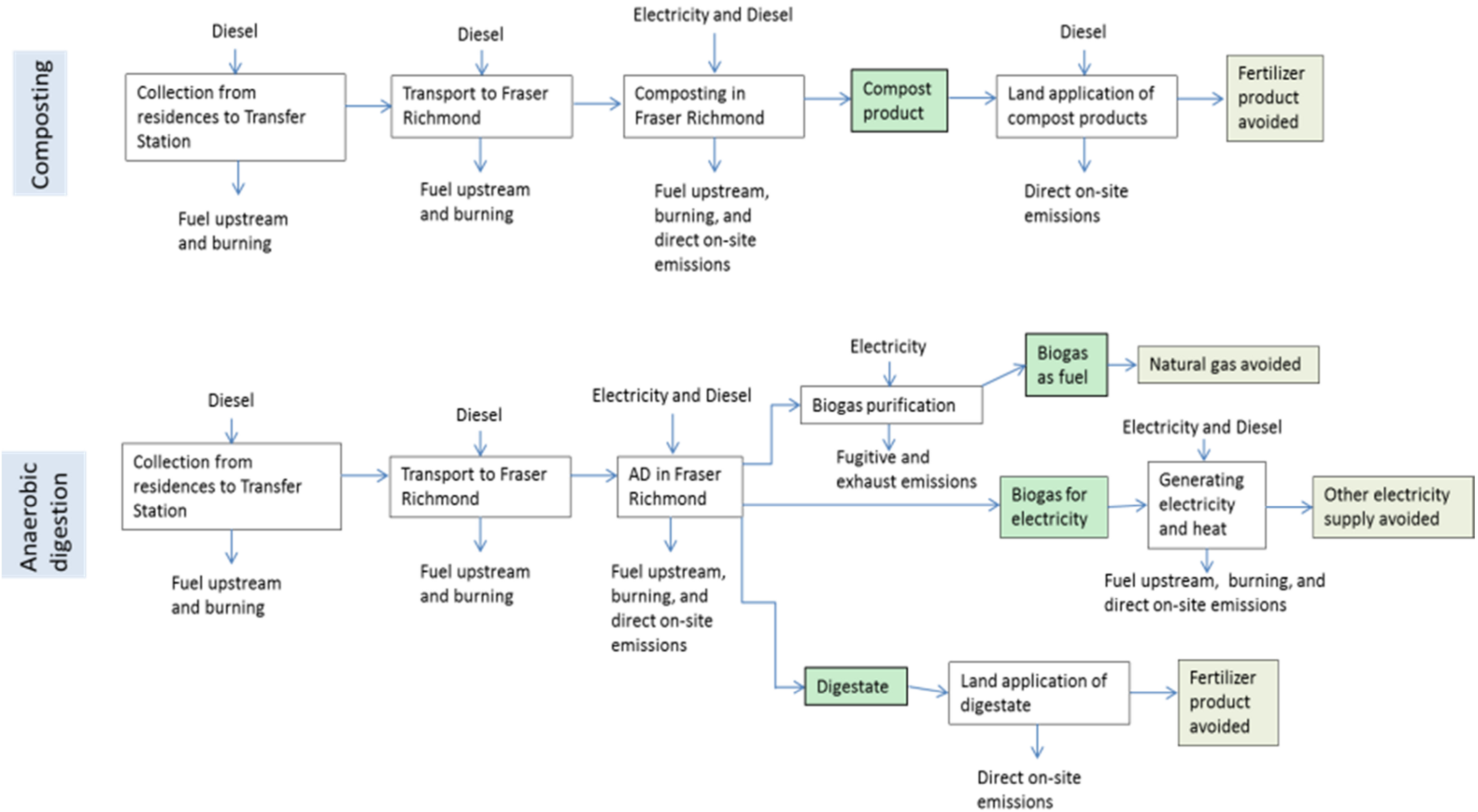
- Goal Definition and Scoping: The process to be studied is described and the boundaries for analysis are established.
- Life Cycle Inventory (LCI): The inputs and outputs of each process are compiled. This includes inputs of energy and raw materials and outputs of wastes, by-products, contaminant, emissions, etc.
- Life Cycle Impact Assessment (LCIA): An assessment is made of the potential environmental burdens, classified according to their category of environmental impact (e.g. global warming, ozone depletion, smog formation potential, etc).
- LCA Interpretation: The results are placed in context and qualified. Limitations on interpretation are made clear, data shortcomings are highlighted, and any subjective assessments are reviewed. In some LCA studies this stage is used to define potential improvements in the process.

While LCA is powerful to capture the entire picture, it can be weak to identify spatial and temporal details unless specific procedure is designed. Spatial details of upstream and downstream processes are usually hard to be recognized in LCA. Unlike the manufacturing or consumption of a product which typically takes place in a confined area, upstream source and energy extraction and downstream waste disposal can be dispersed far away. Although LCA manages to sum up all the associated environmental burdens, the real impacts relating to the specific spatial environment are hard to capture. Similarly, it was pointed out that LCA is less effective to assess toxic and hazardous substances because the effects depend on the specific environment and human intake (Stevels, 1999). Also, LCA can only reflect the static situation of a system; it is not able to take care of the dynamic changes in the future. Overall, high uncertainty can be involved in a LCA study. Since numerous data are aggregated in a life cycle inventory which is afterwards calculated into impact results, uncertainties from the data source are carried on. Environmental burdens such as pollution emissions are quite uncertain from the natural occurrence as well as human measurements. Second-hand management of these data often involves conversion and assumption. Different impact assessment methods are developed with various algorithms. All these limitations of LCA method should be made aware of and care should be taken when the results are used for decision making.

The LCA in this study is conducted in Simapro LCA software version 7.3.3. The software compiles the environmental inventories of a project's processes that the user assembles. It is also able to analyze the impacts with a group of impact assessment methods built in. This allows the translation of environmental interactions of a project into the specific impacts or the environment and human health.

6.2 Project Boundary

The life cycles in this study start from waste collection by the City (for SF) or by private haulers (for MF and commercial). All waste is assumed to be transported via an average distance from the center of the City to VSTS and subsequently to Fraser Richmond. Composting and AD is assumed to take place on site at Fraser Richmond. Necessary post-treatments of the bio-product such as curing of the compost, purifying biogas, and dewatering digestate are also modeled. After the operation, land application of compost product and digestate is the last stage with the application operation and direct emissions counted within the boundary. Transport of compost and digestate from the plant to application sites is not included due to high uncertainty. The figure below illustrates the life cycles of composting and AD in this study. Specifically, infrastructure is not included in this study because there were no complete or consistent data gathered.



Schematic of the life cycles of composting and AD

6.3 Scenarios

LCA scenarios are in line with the scenarios for renewable product estimates in Section 5.4. Four reference scenarios to compare composting and AD of 1,000 tonnes of organic waste are first analyzed. This is to evaluate the environmental performance of the different options on the same amount of waste. Six scenarios analyze the diverted SF organic waste plus yard waste drop-offs (including fall leaf program) in the City. Three modeled for year 2015 and the other three for year 2020. The amount of each type of organic waste in 2015 or 2020 is based on the estimates in Section 5. Finally, another four scenarios are established for digesting food waste from MF and commercial sectors. Table 18 below shows the set-up of all the scenarios.

Table 18 Scenarios Set-Up

Scenarios	Organic waste	Process	Remarks
0-a	1,000 tonne yard waste	Composting	-
0-b	1,000 tonne mixed waste	Composting	1:1 Food waste + Yard waste
0-c	1,000 tonne food waste	AD for biogas	-
0-d	1,000 tonne food waste	AD for heat and power	-
1-a1	SF total organic waste, 2015	Composting	Food and yard waste from SF are composted together. Yard waste from drop-offs and fall leaves are composted alone.[1]
1-b1	SF total organic waste, 2015	AD for biogas+composting	Food waste from SF is digested. All yard waste is composted.[2]
1-c1	SF total organic waste, 2015	AD for heat and power Composting	Food waste from SF is digested. All yard waste is composted.
1-a2	SF total organic waste, 2020	Composting	Same as 2-a
1-b2	SF total organic waste, 2020	AD for biogas+composting	Same as 2-b
1-c2	SF total organic waste, 2020	AD for heat and power Composting	Same as 2-c
2-a1	MF and commercial food waste, 2015	AD for biogas	-
2-b1	MF and commercial food waste, 2015	AD for heat and power	-
2-a2	MF and commercial food waste, 2020	AD for biogas	-
2-b2	MF and commercial food waste, 2020	AD for heat and power	-

Note:

[1] Diverted yard waste from SF happens to be of similar amount as food waste.

[2] This is not very practical as food waste is collected along with yard waste in the City.

6.4 Goal and Scope

This study is to describe the environmental performance of city-wide composting and/or AD. The waste system is modeled at a regional scale with the site of Fraser Richmond assumed to be the plant location. Local reports and studies combined with literature review provide data source for the life cycle inventories. This LCA study can serve to partly inform decision making in terms of environmental impacts of organic waste recycling. However, this LCA is not intended to define the 'best' solution.

Economic and social factors are not addressed in this study. Also, the environmental evaluation is not complete as well since LCA method also has limitations. In the same way, the 'best' scenario shown in the result of this study cannot be defined as the optimal practice. The waste system as well as the operation technology and scale are simplified simulation and modified and hybrid operation will be more appropriate in real application.

6.5 Life Cycle Inventory (LCI) Building

As described in Section 6.1, building a Life Cycle Inventory is to compile the inputs and outputs of each process (unit process) in a life cycle. This includes inputs of energy and raw materials and outputs of wastes, by-products, contaminant emissions, etc. Most of the unit processes are stages of a life cycle, either in foreground or background. Another type of unit process refers to avoided product which may not be a physical portion of a life cycle. That is when the system produces a product to substitute (avoid) the production of another product that has the same function. Environmental burden of producing these avoided products are counted as negative.

The main unit processes in this study are summarized in Table 19. Data available from Vancouver or BC are preferred but for those that are not available with specific local information, commercial LCA database and literature report data are used.

Table 19 Main Unit Processes in this LCA Study

Unit process	Data source	Region of data origin
Heavy Duty Vehicle transport	GHGenius v 4.01	BC, Vancouver
Composting and curing	Boldrin 2009, Solano.., Komilis_2004	US, Vancouver
AD and digestate dewatering	EcoInvent database v 2.2	Switzerland, US
Biogas purification	EcoInvent database v 2.2	Switzerland, US
Co-generation of electricity and heat using biogas	EcoInvent database v 2.2	Switzerland, US
Application of compost product	Boldrin 2009, Solano.., EcoInvent database v 2.2	US
Application of digestate	EcoInvent database v 2.2	Switzerland, US
Electricity generation mix in BC	GHGenius v 4.01	BC
Diesel production in BC	GHGenius v 4.01	BC
Natural gas production in BC	GHGenius v 4.01	BC
Fertilizer production (N,P,K)	EcoInvent database v 2.2	European average

Specifically, the energy consumptions involved in this project are summarized in Table 20.

Table 20 Energy Consumption in this Project

Operations	Item	Value	Unit	Source
Trucks	Diesel	2.09	MJ/km	GHGenius v 4.01
Trimming grinder	Diesel	47.58	MJ/tonne	Komilis, 2004; GHGenius v 4.01
Forklift	Diesel	25.30	MJ/tonne	EcoInvent database v 2.2
Composting	Electricity	60	kWh/tonne	Geesing, 2012 (Fraser Richmond)

Digestion	Electricity	30	kWh/tonne	EcoInvent database v 2.2
Digestate dewatering	Electricity	10	kWh/tonne	EcoInvent database v 2.2
Biogas purification	Electricity	0.5	kWh/m3	EcoInvent database v 2.2

Detailed environmental inventories and descriptions of unit processes are in Appendix E.

6.5.1 LCI of 1,000 Tonne Organic Waste Reference Scenarios

With all the data of unit processes collected, life cycle inventories of different scenarios can be built up. The four reference scenarios are first analyzed to look at different treatments of 1,000 tonnes of organic waste. Table 21 shows the life cycle emissions of GHG and key air pollutants. Waterborne emissions are not analyzed because not all unit processes have data available.

Table 21 LCI of 1,000 Tonne of Organic Waste Reference Scenarios

	Unit	Scenario 0-a	Scenario 0-b	Scenario 0-c	Scenario 0-d
CO_2, biogenic	tonne	778	321	763	939
CO_2, fossil	tonne	-1.4	-2.92	27	-5.5
CH_4, biogenic	tonne	1.82	0.91	10	8.59
CH_4, fossil	kg	8.21	6.1	-60	-69
CO, biogenic	kg	2.97	2.99	3.81	127
CO, fossil	kg	-3.37	-4.87	-9.12	-5.96
NMVOC	kg	-1.53	-2.11	3.9	5.48
N_2O	kg	135	128	83	90
NH_3	kg	30	36	313	313
NOx	kg	-18	-23	-45	21.1
H_2S	kg	-0.06	-0.06	246	245
SO_2	kg	-178	-149	36	45
SOx	kg	6.56	5.12	-15	-2.38
PM_{10}	kg	0.44	0.47	0.57	-1.58
$PM_{2.5}$	kg	-5.75	-5.39	-1.7	-3.8
PM, unspecified	tonne	2.63	1.47	730	731

Note:
-PM_{10}: Particular matters with diameter less than 10 µm
-$PM_{2.5}$: Particular matters with diameter less than 2.5 µm

Biogenic CO_2 emissions are a large portion of total CO_2 emissions because bio-waste is processed. Most of the biogenic CO_2 emissions occur during composting process or digestion process and also biogas purification and burning for heat and electricity. Biogenic CO_2 and CH_4 emission from yard waste composting is much higher than that from mixed waste composting, which attributes to higher carbon content in woody waste compared to food waste. N_2O and NH_3 emissions mainly occur during composting and land application of compost products. Generally, the difference of composting the two types of waste is small (Table 21). Transport of the waste from residences to composting/digestion site contributes large amount of fossil CO_2 emissions as well as some amount of fossil CH_4, fossil CO, NOx, SOx, and PMs. These are mostly from the diesel fuel production. The rest of the emissions mainly occur exclusively in the background processes and the avoided products production. There is no significant difference for fuel and electricity uses for composting with different feedstock. Therefore, the rest of the emissions are similar in the two scenarios. Negative emissions are results of avoided products such as replacing products like fertilizers, natural gas, and electricity If such emission saving is significant in the entire life cycle, net negative emissions are observed for the entire life cycle.

Emissions of the two AD scenarios are generally higher than composting. Substantial higher emissions of biogenic CH_4, NMVOC, NH_3, and H_2S occur during AD compared to composting. Another significant emission contributor is the electricity consumption for biogas purification process in the first AD scenario. Digesting 1 tonne of organic waste consumes less electricity (40 kWh) than composting 1 tonne of organic waste (60 kWh). However, purifying the biogas generated from 1 tonne of feedstock (100 m^3 biogas) consumes even more electricity (50 kWh) than digestion. This adds on significant fossil emissions and air pollutants which include fossil CO_2, fossil CO, SO_2, and PMs. Heat and power generation causes large amount of biogenic CO_2 and CO emissions as the biogas is burned in the biogas engine. The model in this study does not require biogas purification before feeding the engine which means high tolerance of impurities is achieved in such biogas engine. Normally, biogas has to be upgraded to some extent to meet the requirement of the engine. That will actually incur some energy consumption as well as emissions. Besides, the avoided natural gas or the electricity and heat from AD are even more notable. The savings of emissions and environmental impacts can influence or determine the life cycle results. In particular, natural gas saving is more significant than electricity generation saving because the electricity portfolio in BC is already clean with about 93% from hydro power. If BC's electricity is generated by the average practice in North America or the world, switching to AD electricity would have higher environmental achievement.

6.5.2 LCI of Scenarios for All Organic Waste in the City

As described in Section 6.3, three scenarios are modeled for annual organic waste diversion from SF in the City in 2015 and 2020 respectively. The LCI results of the city scale scenarios are consistent with the reference scenarios in Table 21. The AD scenarios for SF waste considered some yard waste to be composted. Generally, the emissions in 2020 are a little more than twice the emissions in the corresponding scenarios in 2015.

Table 22 LCI Results of SF Scenarios in the City

	Unit	Scenario 1-a1	Scenario 1-b1	Scenario 1-c1	Scenario 1-a2	Scenario 1-b2	Scenario 1-c2
CO_2, biogenic	ktonne	10	16	17	21	32	35
CO_2, fossil	tonne	-48	148	-54	-97	304	-110
CH_4, biogenic	tonne	26	88	79	52	179	161
CH_4, fossil	kg	141	-256	-313	286	-530	-646
CO, biogenic	kg	61	66	827	123	134	1697
CO, fossil	kg	-87	-104	-85	-178	-212	-172
NMVOC	kg	-38	2.45	12	-78	5.69	26
N_2O	tonne	2.66	2.42	2.46	5.41	4.92	5

NH_3	tonne	0.69	2.36	2.36	1.4	4.84	4.84
NOx	kg	-432	-533	-122	-880	-1087	-242
H_2S	kg	-1	1517	1513	-2	3117	3108
SO_2	tonne	-3.26	-2.3	-2.25	-6.63	-4.65	-4.54
SOx	kg	115	-1.12	78	234	-5.06	158
PM_{10}	kg	9.07	9.8	-3.45	18	20	-7.27
$PM_{2.5}$	kg	-113	-92	-105	-229	-187	-213
PM, unspecified	tonne	39	42	42	79	85	85

Digesting diverted food waste from MF and commercial sectors is also analyzed for 2015 and 2020 level. Life cycle emissions of GHG and key air pollutants are shown in Table 23. Since these scenarios only dealt with food waste in AD, the results are proportional to the reference data in Table 21. Although the diverted food waste of MF and commercial sectors is more than 4 times the waste (food and trimmings) from SF (Table 16), the overall emissions are not 4 times as high as SF waste.

Table 23 LCI Results of MF and Commercial Food Waste Scenarios in the City

	Unit	Scenario 2-a1	Scenario 2-b1	Scenario 2-a2	Scenario 2-b2
CO_2, biogenic	ktonne	19	24	40	49
CO_2, fossil	tonne	688	-140	1414	-287
CH_4, biogenic	tonne	255	218	523	449
CH_4, fossil	tonne	-1.53	-1.76	-3.15	-3.63
CO, biogenic	kg	97	3227	199	6.63
CO, fossil	kg	-232	-152	-476	-311
NMVOC	kg	99	139	204	286
N_2O	tonne	2.11	2.28	4.33	4.69
NH_3	tonne	7.95	7.95	16	16
NOx	tonne	-1.15	0.54	-2.37	1.1
H_2S	tonne	6.24	6.23	13	13
SO_2	tonne	0.93	1.14	1.9	2.35
SOx	kg	-387	-61	-794	-125
PM_{10}	kg	14	-40	30	-82
$PM_{2.5}$	kg	-43	-97	-89	-198
PM, unspecified	tonne	19	19	38	38

6.6 Life Cycle Impact Assessment (LCIA)

The inventories of energy consumption and emissions are further translated into impacts on the environment and human health. For example, fossil fuels like oil and gas are non-renewable and the consumption is depleting the limited resource. GHG emissions aggravate global warming which is an urgent issue that draws the world's attention. Air pollutants can harm people's respiratory system and can be toxic or carcinogenic to human. All kinds of impacts are categorised in a LCIA and respectively assessed for a project. In this study, four impact categories are analyzed: global warming, non-renewable energy consumption, respiratory effect caused by inorganic compounds, and respiratory effect caused by organic compounds. This covers the most important indicators under the available data source. Ecosystem and human toxicity are not assessed due to limitation of data and time.

For each impact category, one consistent unit substance is defined to measure the impact. For example, non-renewable energy consumption is measure by joule of primary fossil energy. Global warming impact is measured by the mass of CO_2-equivalent (CO_2-eq) emission. In such case CO_2 is called a benchmark compound. Other GHG have relevant global warming potentials compared to CO_2 for conversion to CO_2-eq. Similarly, the benchmark compound for respiratory effect caused by inorganic substances and organic substances is $PM_{2.5}$ and C_2H_4, respectively. Thus the respiratory effects are measured in units of kg $PM_{2.5}$ and kg C_2H_4.

Simapro software has a group of impact assessment methods built in. Once the user has modeled a project's life cycle, it is able to calculate the environmental impacts based on the life cycle inventory. The method of IMPACT 2002+ (Jolliet, 2003) version 2.10 is selected in this study. It is one of the best developed LCIA methods that can analyze 15 impact categories. The four impact categories in this study are all covered by IMPACT 2002+. The global warming potentials are modified to 100-year time horizon values based on IPCC's 2006 report instead of the original 500-year values. This is because 100-year time horizon values are more widely used and well recognized in most studies. IMPACT 2002+ also allows normalization calculations to reflect the magnitude of the impacts relative to the total environmental burdens generated within a certain region. Canadian normalization factors (Lautier, 2010) are used to aggregate the overall impacts into unitless indicator in the sensitivity analysis in Section 6.8.

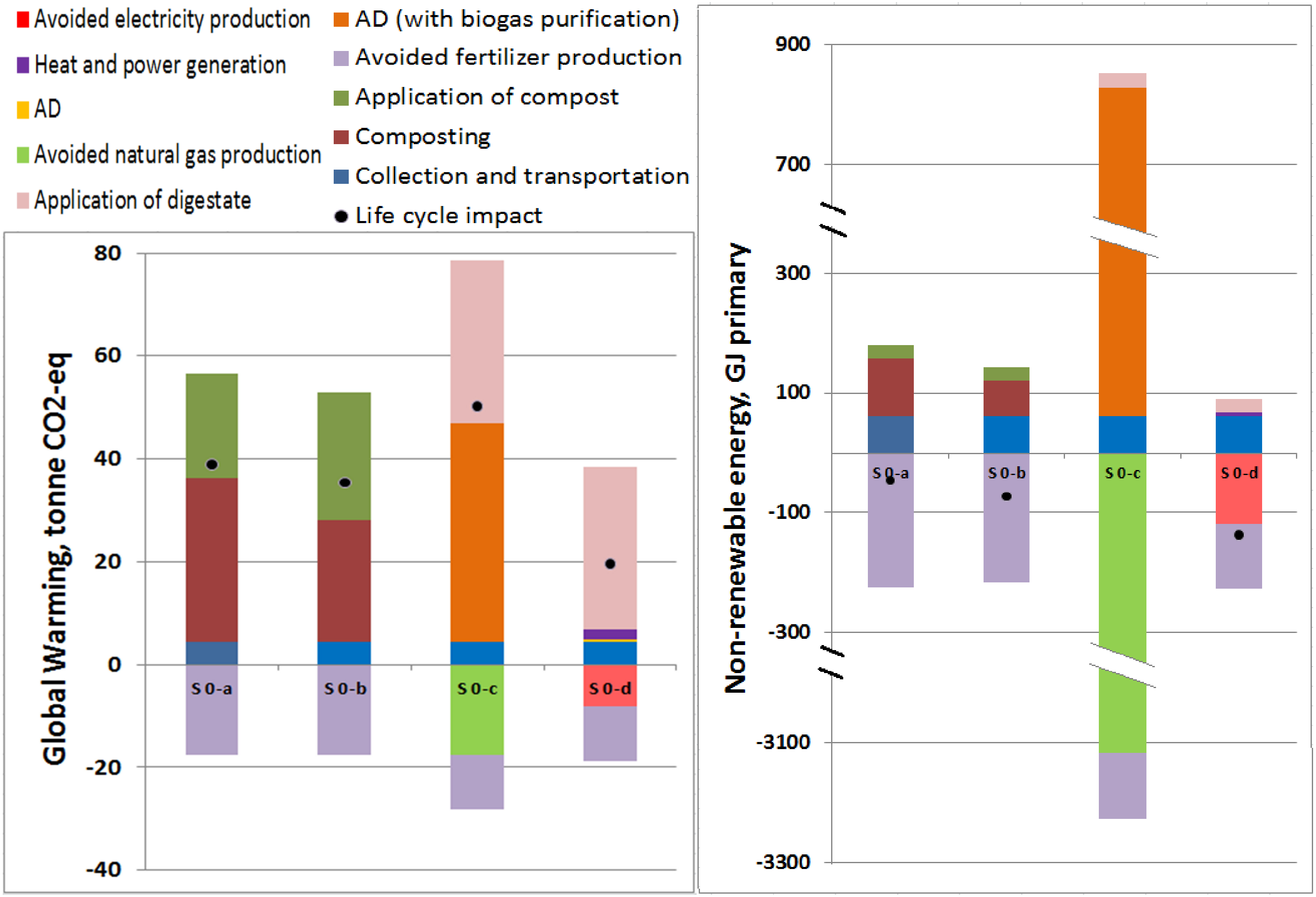
6.6.1 LCIA Results of 1,000 Tonne Organic Waste Reference Scenarios

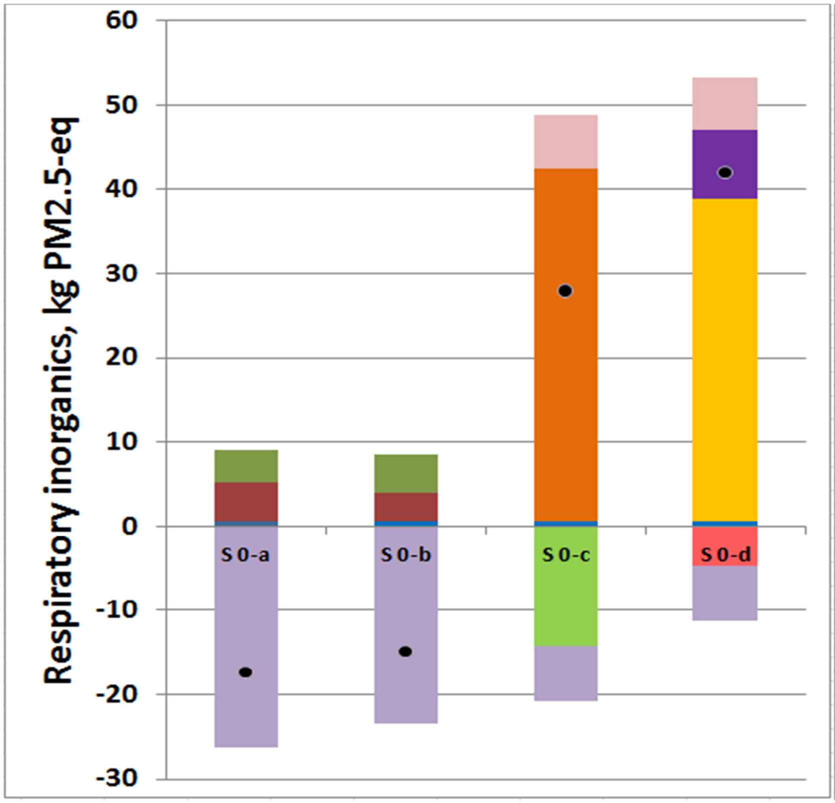
In line with the LCI building, impact assessment is first conducted on composting or digesting 1,000 tonnes of organic waste for reference. The results provide life cycle comparison between composting and AD of a certain amount of waste. The table below shows the LCIA results.

Table 24 LCIA of 1,000 Tonne of Organic Waste Base Scenarios

	Unit	Scenario 0-a	Scenario 0-b	Scenario 0-c	Scenario 0-d
Global warming	tonne CO_2-eq	39	35	50	20
Non-renewable energy consumption	GJ primary energy	-45	-73	-2,375	-137
Respiratory inorganics	kg $PM_{2.5}$-eq	-17	-15	28	42
Respiratory organics	kg C_2H_4-eq	-1.23	-1.59	0.62	8.96

The impacts are broken down by life cycle stages as illustrated in the charts below. The numerical values are presented in Appendix F.





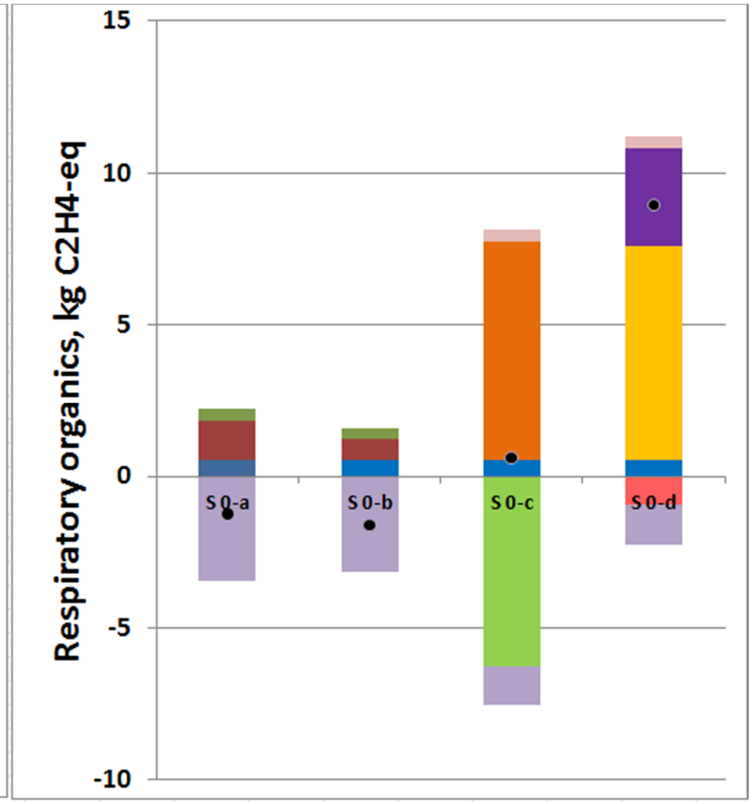


Figure 6.6.1 Stage-wise LCIA results of reference scenarios

6.6.2 LCIA Results of Scenarios for All Organic Waste in the City

The life cycle impacts of composting or digesting the estimated organic waste from SF and food waste from MF and commercial sectors are analyzed for year 2015 and 2020. The tables below show the results. Since scenarios for year 2020 generally deal with twice the waste (similar waste composition) compared to year 2015, the LCIA results for year 2020 are about twice of 2015 with no pattern change for each impact category. Thus, only the results for 2015 are referred to in the following discussions. Also, as SF waste treatment involves a combination of composting of yard waste and food waste or combination of composting and AD, stage-wise break down is not further investigated.

Table 25 LCIA Results of SF Scenarios in the City

	Unit	Scenario 1-a1	Scenario 1-b1	Scenario 1-c1	Scenario 1-a2	Scenario 1-b2	Scenario 1-c2
Global warming	tonne CO_2-eq	749	863	673	1,522	1,755	1,365
Non-renewable energy	TJ primary	-1.27	-15.33	-1.49	-2.59	-31.46	-3.04
Respiratory inorganics	kg $PM_{2.5}$-eq	-322	-44	-3.50	-654	-83	0.13
Respiratory organics	kg C_2H_4-eq	-30	-1.27	-0.64	-60	-2.09	-0.79

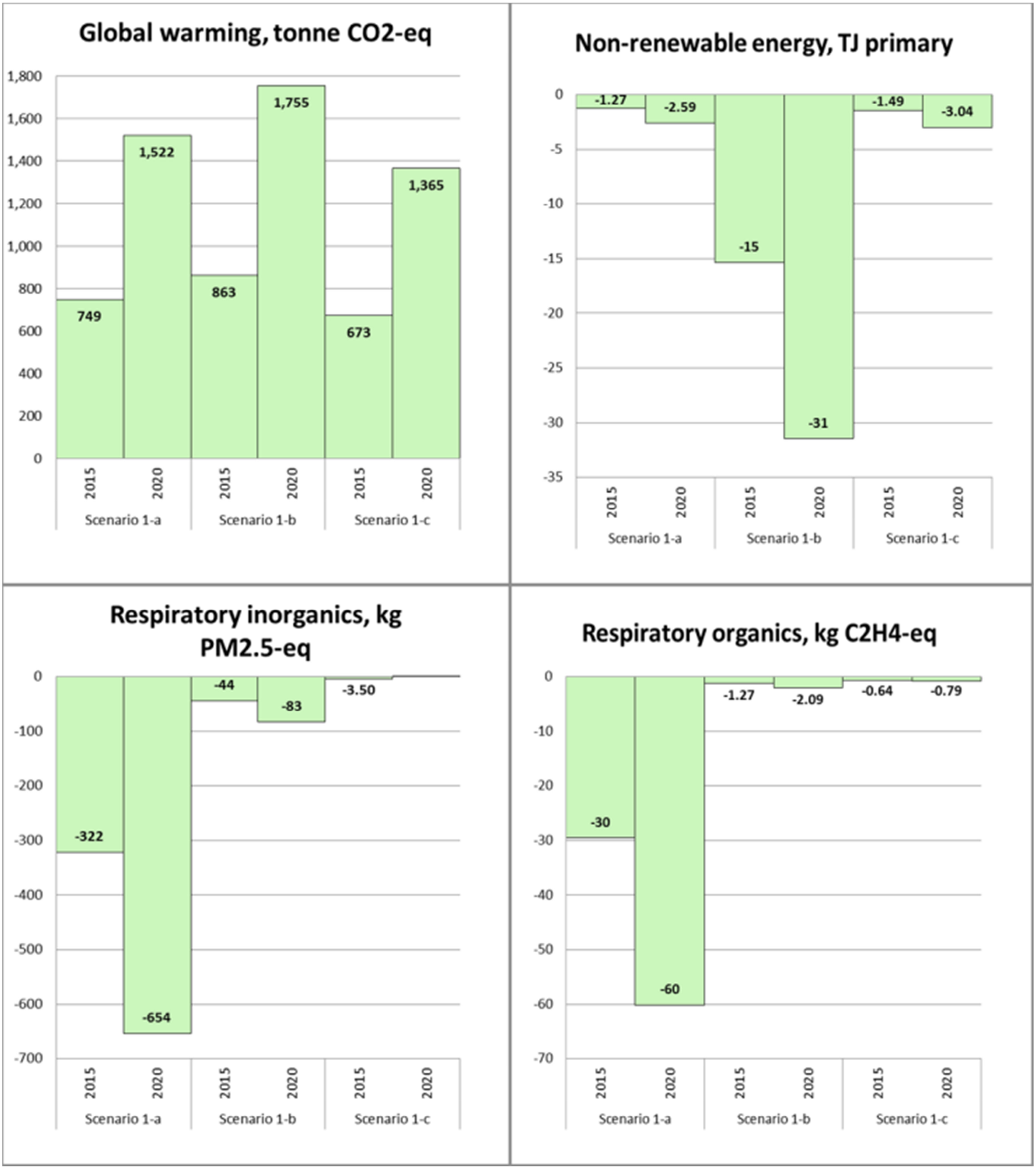
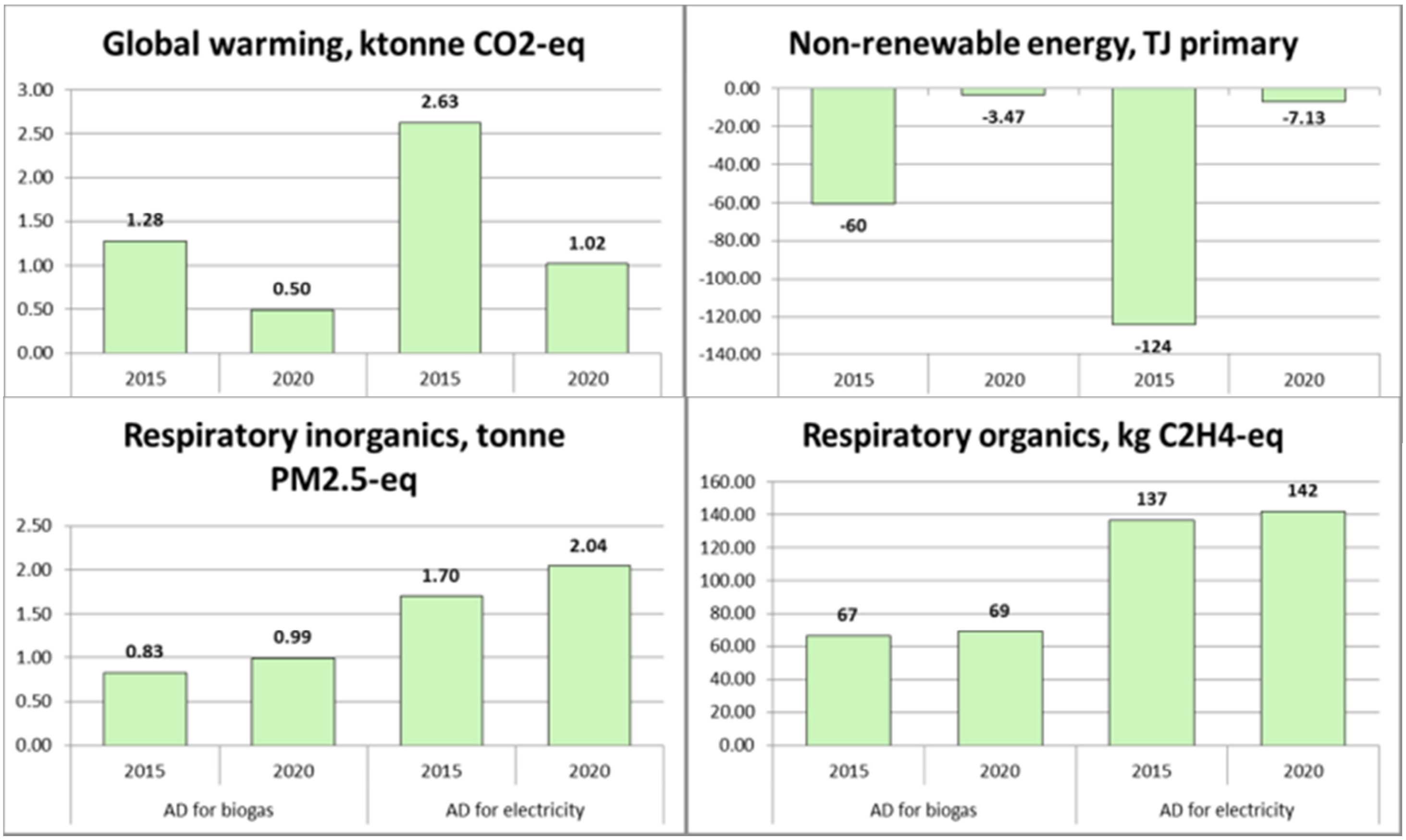

Global warming, tonne CO2-eq
1,800
1,600
1,400
1,200
1,000
800
600
400
200
0
749
1,522
863
1,755
673
1,365
2015
2020
Scenario 1-a
Scenario 1-b
Scenario 1-c
Non-renewable energy, TJ primary
0
-5
-10
-15
-20
-25
-30
-35
-1.27
-2.59
-15
-31
-1.49
-3.04
Respiratory inorganics, kg PM2.5-eq
-100
-200
-300
-400
-500
-600
-700
-322
-654
-44
-83
-3.50
Respiratory organics, kg C2H4-eq
-40
-50
-60
-70
-30
-60
-1.27
-2.09
-0.64
-0.79

Table 26 LCIA Results of MF and Commercial Food Waste Scenarios in the City

	Unit	Scenario 2-a1	Scenario 2-b1	Scenario 2-a2	Scenario 2-b2
Global warming	ktonne CO_2 eq	1.28	2.63	0.50	1.02
Non-renewable energy	TJ primary	-60	-124	-3.47	-7.13
Respiratory inorganics	tonne $PM_{2.5}$ eq	0.83	1.70	0.99	2.04
Respiratory organics	kg C_2H_4 eq	67	137	69	142

Figure



6.7 Discussions

The comparison between scenarios of 1,000 tonnes of waste shows that AD has higher impacts on global warming and respiratory effect but also saves tremendous amount of non-renewable energy by generating biogas. Respiratory impact of AD mainly comes from digestion process as well as cogeneration process. Biogas purification causes significant global warming impact and consumes non-renewable energy. Land application of digestate also has higher impacts on global warming compared to land application of compost. It is worth noting that the LCIA results do not identify foreground and background processes and some impacts such as energy production and compost product application actually occur outside the City. Thus these results are not adequate to address how much impact directly influences the City. The LCIA results of the SF scenarios are discussed per impact category below. MF and commercial food waste scenarios are not specifically discussed but can be referred to the reference scenarios of food waste AD.

6.7.1 Global Warming

Global warming impact ranges from 20 to 50 tonne CO_2-eq per 1,000 tonne of organic waste processed. AD for biogas emits more GHG than composting while AD for heat and power has lower global warming impact. The largest portion of AD to biogas scenario is from digestion plus biogas purification. This is mostly due to the electricity consumption rather than direct on-site emissions because direct CO_2 and CH_4 emissions are biogenic which have no global warming potential. If biogas purification is improved with lower energy consumption, AD for biogas can potentially perform better than composting. For on-site GHG emissions, composting process has significant generation as shown in the figure. GHG emissions from land application of compost products and digestate are similar. Fertilizer substitutes from digestate are less than that from compost products. However, AD is able to supplement natural gas or electricity which saves more GHG emissions by avoiding the production of natural gas or regular electricity. Overall, AD for heat and power has the least global warming impacts which is 20 tonne CO_2-eq per 1,000 tonne food waste. On the electricity generation basis, the generation of 1 kWh bio-electricity comes to a total GHG emission of 0.034 kg CO_2-eq while generating 1 kWh electricity under the current BC grid emits about 0.04 kg CO_2-eq (life cycle value) in this study. It is widely perceived that 0.02~0.03 kg CO_2-eq is emitted to generate 1 kWh electricity in BC excluding background processes like infrastructure and fuel extractions (MacDonald, 2012).

When looking at the city scale SF scenarios that combine composting and AD according to the waste composition, the differences of global warming impact are not very significant between scenarios. GHG emissions from processing SF organic waste range from 673 to 863 tonnes in 2015 and from 1,365 to 1,755 tonnes in 2020. For reference, a rough estimate of GHG emission rate of solid waste landfilling in Vancouver was about 0.43 (=220,000/508,000) tonne CO_2-eq per tonne waste disposed in 2008. The life cycle GHG emission rate of composting or digesting is 0.03~0.04 tonne CO_2-eq per tonne waste processed. Thus recycling the organic waste instead of landfilling potentially reduces GHG emissions by an order of magnitude. Even if excluding the emission savings from supplementing fertilizers, natural gas, and electricity, the reduction will still increase by 50% to 100% than landfilling. Driving a mid-size car for 1,000 km emits roughly 0.3 tonnes CO_2-eq (Carbon Credit Canada, 2012). Applying composting or AD to the 20,000 tonnes of organic waste from SF (2015 diversion rate, Table 16) can reduce around 8,000 (=20,000*(0.43-0.035)) tonnes CO_2-eq compared to landfilling. This equals to taking away 27,000 km of car driving to reduce GHG emissions.

6.7.2 Non-Renewable Energy Consumption

Non-renewable energy consumed in this system is natural gas, diesel, and oil. However, the LCIA results are actually negative of all scenarios due to substituting fertilizer, natural gas, and electricity. Diesel is consumed for the transport of organic waste as well as off-road facility operations. BC electricity mix is partly made up of non-renewable energy such as natural gas and oil. Similar to global warming impact, consumption of electricity for AD and biogas purification adds on significant burden to the scenario of AD for biogas. This, nevertheless, can be compensated by the tremendous savings of natural gas with biogas produced. Overall, composting and AD to cogeneration respectively achieves about 60 and 136 GJ non-renewable energy savings per 1,000 tonne of waste processed. By producing biogas as end product, substituting natural gas equals to 2,400 GJ non-renewable energy savings per 1,000 tonne of waste processed.

For the city scale SF scenarios, 1.3~1.5 TJ of non-renewable energy could be saved by composting or digesting for heat and power with SF organic waste under 2015 diversion level. About 15 TJ non-renewable energy could be saved if food waste is digested for biogas generation. These are life cycle values which include savings result from fertilizer substitute as well. To have direct benefit of saving non-renewable energy, only AD provides renewable energy such as biogas and bio-electricity. If this renewable energy is supplied, Vancouver could obtain notable fossil energy savings.

6.7.3 Respiratory Effects

Air contaminates including inorganic and organic compounds can have impact on human's respiratory system. Inorganics air pollutants are aggregated by the hazardousness compared to $PM_{2.5}$ and organic pollutants are aggregated with C_2H_4 as a benchmark substance. The common inorganic pollutants that have respiratory effects are NH_3, NOx, SOx, H_2S, and PMs. Organic pollutants consist of a longer list with the most common pollutant referred to as volatile organic compounds (VOCs). AD process along with biogas purification and cogeneration has higher inorganic air pollutant emissions. However, the AD for biogas scenario avoids production of natural gas which saves on impacts to respiratory effects and results in a much lower life cycle value compared to AD for cogeneration scenario. The CH_4 emissions as well as electricity consumption during AD and its following operations contribute significant organic air pollution. Overall AD has higher impacts on respiratory effects compared to composting. With significant fertilizer substitute, composting has negative life cycle impact on both inorganic and organic air pollutions.

The respiratory effects reported are absolute values which require normalization. Canadian air pollution inventory is referred to for comparison. It is reported that inorganic air pollutants generated in Canada is 153 kg $PM_{2.5}$-eq/person/year (Lautier, 2010). Data for organic pollutants are currently not available. Since the population of the City is about 600,000 people, the air pollution reduction (negative life cycle value as above) from scenario 1-a1 for example is 0.001 kg $PM_{2.5}$-eq/person/year. Therefore, respiratory effect of composting or AD is actually fairly trivial regardless of the positive impact in certain stages or the negative impact during the entire life cycles. However, it is worth noting that human health impacts are sensitive to location which means for most air pollution, only the local population bears the impacts. For this report, the main concern is with the composting and AD process. The on-site emissions should be separately reviewed to illustrate local impacts. Impacts related to upstream energy and material productions typically occur outside the City. Nevertheless, aiming at a life cycle reduction of environmental and health impact is always necessary.

6.8 Sensitivity Analysis

Sensitivity analysis is conducted to test the influence of some parameters from the life cycle impact results. The tested factors include transport of the waste, on-site emission rates, biogas yield of AD, normal electricity use instead of self-supplied bio-electricity use for biogas cogeneration, electricity generation rate from biogas, and fertilizer substitute rate. Base cases are the scenarios of city-wide organic waste treatment under 2015 level as described in Section 6.3. All factors are fluctuated by ±20% except for the normal electricity use (applied to replace bio-electricity in base cases). Rather than presenting the impact results by each impact categories as in Section 6.7, the impacts in sensitivity analysis are aggregated into a unitless score. Each impact result of a certain category is normalized by the Canadian average level with an example to discuss respiratory effects. No further localized data are available thus Canadian average is used. A total of the normalized results from the four impact categories are obtained as a unitless score to evaluate the environmental performance of the system. Therefore, the higher the score, the more environmental impact the system has. Table 27 shows the sensitivity analysis results.

Table 27 Sensitivity analysis results of the LCA study

Parameter to be tested	Change	Composting	Result change	AD for biogas	Result change	AD for electricity	Result change
Base case	-	34.55	-	22.30	-	45.82	-
Transport of waste	+20%	36.03	4%	23.78	7%	47.30	3%
Transport of waste	-20%	33.07	-4%	20.82	-7%	44.34	-3%
Biogas yield	+20%	-	-	11.05	-50%	-	-
Biogas yield	-20%	-	-	33.45	50%	-	-
Electricity yield	+20%	-	-	-	-	45.03	-2%
Electricity yield	-20%	-	-	-	-	46.35	1%
Fertilizer supplement	+20%	27.80	-20%	21.21	-5%	44.65	-3%
Fertilizer supplement	-20%	40.98	19%	23.29	4%	46.73	2%
On-site emission	+20%	38.68	12%	22.65	2%	46.08	1%
On-site emission	-20%	30.10	-13%	21.86	-2%	45.29	-1%
Non-bio electricity use	n/a	-	-	-	-	69.00	51%

The sensitivity analysis shows that the life cycle assessment results are not sensitive to transportation process of waste, electricity generation rate from biogas, fertilizer substitute in AD, or on-site emissions in AD. Composting scenario is moderately sensitive to fertilizer substitute amount and on-site emissions. AD scenario is very sensitive to biogas yield and whether to consume normal grid electricity or bio-electricity. The sensitivity analysis helps identify the “hot spots” of a life cycle that have high impacts.

6.9 Limitation

This LCA study manages to evaluate the life cycle environmental impacts of conducting composting and AD in the City but there are limitations to both the LCA method and this report. For this report, environmental data collection was restricted to air emissions; waterborne and soil emissions are not available hence no thorough assessment was applicable for human health and the ecosystem. Also, the data used in this study are mostly from the commercial LCA database and literature reviews which increase the uncertainty of the analysis. Ideally, environmental data should be collected from on-site measurements to correctly evaluate the system. This is a common issue for most LCA studies but the LCA could be improved when first hand data is available. In addition to the natural uncertainty in the dataset, it is worth noting that the composting and AD system are only modeled by selected technologies.

Practical application can turn out to use different technologies for large scale collection. Also, environmental performance can vary accordingly and a thorough scrutiny of all types of technology was not available in this study. In addition, LCA can be conducted for economic performance which is called Life Cycle Costing (LCC) but this was not included due to time constraints.

7.0 Conclusion and Recommendation

Whether to choose composting or AD or how to combine the two practices depends on a number of factors. The LCA results provide information on the overall environmental performance of different scenarios. However, as the impacts from different stages influence specific regions, stage-wise results should also be reviewed. Also, there can be trade-offs between the impact categories. For example, the non-renewable energy saving by producing biogas from AD can be very attractive although its life cycle GHG emission is higher than composting. In practice, economic assessment is also very important and was not included in this study. Revenue estimate of compost product may become uncertain due to the anticipated increase of compost products in the region. The prices of biogas/natural gas and electricity fluctuate and studies have shown that strong subsidiary has to be in place to support AD.

Overall, this study recommends a combination of composting and AD practice for the City of Vancouver. Composting is readily available with large sites in operation for years. It is generally the optimal choice when yard waste is collected separately or when the mixture of yard waste is much higher than food waste. However, to avoid the tremendous surplus of compost production, diverting food waste to AD is recommended to generate renewable biogas or electricity. Fraser Richmond is currently building a large scale high solid anaerobic digester. Digestion has environmental benefit in ways of replacing fossil source energy. However, AD requires higher costs to start-up as well as to operate and sufficient funding and government subsidiary have to be in place to ensure operation is feasible. Thus, policy environment will significantly influence the circumstances. For wood waste from demolition, deconstruction is an optimal choice. Other ways to reuse wood waste face obstacles as demolition wood is usually not clean enough. Chipping clean wood is acceptable for composting but not economically attractive. Although feeding wood into incinerator is considered waste disposal, it is still a common and effective practice for district energy.

Further economic analysis is necessary to assess the feasibility of promoting composting and AD. On-site environmental monitoring and measurement is recommended to describe the direct emissions and environmental impacts along with the model data in this study. Also, as composting and digestion sites deal with waste from multiple jurisdictions besides the City of Vancouver, more practical details will need to be addressed.

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9.0 Appendix

Appendix A: Data in demolition wood waste calculations

Item	Value	Source
Number of demolition permits in the City	762 Residential, 112 Non-residential	McDermott, 2012
Average areas of buildings	2000 ft^2 per home, 17,382 ft^2 per non-residential building	McDermott, 2012
Demolition waste generation factors	115 lb/ft^2 Residential, 155 lb/ft^2 Non-residential	Kane Consulting, 2011
Demolition waste composition	49.45 % Residential, 31.00 % Non-residential	Kane Consulting, 2011
Clean wood content	50% of total wood waste	McDermott, 2012
Regional wood recycling rate	24%	McDermott, 2012
Diversion rate requirement for deconstruction holder	75%	City of Vancouver Sustainability Group, 2012

Appendix B: Directory of composting equipment and Systems

Aerated Composting Floors, Aeration Systems	BacTee Systems Inc.
	BuildWorks Systems Inc.
	FPZ, Inc.
	MAF Composting Systems
	O2 Compost
Aerated Containers/In-Vessel	BacTee Systems, Inc.
	Christiaens Group
	Compost Systems GmbH
	Double T Equipment Ltd.
	ECS-Engineered Compost Systems
	Green Mountain Technologies, Inc.
	HotRot Composting Systems
	Renewable Carbon Management LLC
	ROS ROCA Envirotec
	TAIM WESER
	Tidy Planet Limited
	Transform Compost Systems Ltd.
	VCU Europa Ltd.
	XACT Systems Inc.
Cover Systems, Enclosed Aerated Static Piles	BacTee Systems Inc.
	Biosolids Recycling, Inc.
	Conporec, Inc.
	ECS-Engineered Compost Systems
	GORE Cover Systems
	Managed Organic Recycling, Inc.
	Scarab Manufacturing
Horizontal Agitated Beds	BACKHUS North America Inc.
	Conporec, Inc.

	Farmer Automatic of America
	IPS Composting Systems,
	Siemens Water Technologies
	Transform Compost Systems Ltd.
Rotary Drums	A-C Equipment Services Corp.
	BW Organics Inc.
	Conporec, Inc.
	DTEnvironmental
	Environmental Products & Technologies Corporation
	Keppel Seghers, Inc.
	Nioex Systems Inc.
	Stearns & Wheler GHD

Appendix C: Commercial AD suppliers with large scale reference plants in North America

Process System Name	No. of Plants	Capacity (tons/y)	No. of Stages		Feedstock moisture content		Operating Temperatures	
			1	2	Wet	Dry	~35°C (95°F)	~55°C (130°F)
AAT	8	3,000 to 55,000	X		X		X	
APS	3	NA			X			
ArrowBio	4	90,000 to 180,000		X	X		X	
BTA	23	1,000 to 150,000	X	X	X		X	X
Biocel	1	35000	X			X	X	
BioConverter	2	NA			X			
Biopercolat	1	100000		X		X	X	
Biostab	13	10,000 to 90,000	X		X			X
DBA-Wabio	4	6,000 to 60,000	X		X		X	
DRANCO	17	3,000 to 120,000	X			X		X
Entec	2	40,000 to 150,000	X		X		X	
Haase	4	50,000 to 200,000		X	X		X	X
ISKA	4	20,000 to 50,000				X		
Kompogas	38	1,000 to 110,000	X			X		X
Linde-KCA/BRV	8	15,000 to 150,000	X	X	X	X	X	X
Preseco	2	24,000 to 30,000						
Schwarting-Uhde	3	25,000 to 87,600		X	X			X
Valorga	22	10,000 to 270,000	X			X	X	X
Waasa	10+	3,000 to 230,000	X		X		X	X

Appendix D: AD suppliers that show interest in the market in BC

Company Name	Description
Andgar Corporation (Rep. GHD Digesters)	Andgar Corporation specializes in all facets of construction and Project Management. Partnered with GDH Inc, a US technology provider, Andgar markets, constructs and general contracts GHD□s mixed plug-flow anaerobic digester across the Pacific Northwest. Andgar Corporation is in the business of turning animal and other organic waste into profits for owners, while improving the environment for everyone.
Avatar Energy	Avatar Energy was founded in 2005 with the goal of creating a sustainable digester system for any size farms. Our digesters have specific design features to enable inexpensive maintenance and straightforward operation. They efficiently operate in extreme climates of the dairy farms across the United States and Canada.
Bio-En Power Inc.	Bio-en Power is a renewable energy company specializing in AD facilities to turn biodegradable waste to energy. We will design build AD facilities from farm size to industrial scale plants. The biogas can be used in CHP units, cleaned to gas grid quality or for vehicle fuel.
Bio-Methatech	Established in 2006, Bio-Methatech Canada is a full service AD company that designs, builds, commissions and provides full customer support and service around the LIPP design AD systems. Working with our partners LIPP GmbH, who have over 700 AD systems in operation worldwide, allows us to respond to clients□ complete AD project requirements.
BIOFerm Energy Systems	BIOFerm Energy Systems is a technology provider for both dry and wet AD systems. Wholly owned by the Viessmann Group, a $2.5 billion company in Germany, BIOFerm has over 250 installations in Europe and is currently constructing its first North American facility in Wisconsin.
Catalyst Power Inc.	Catalyst Power is now in its 5th year of operation. The members of the team come from a diverse background in business, agriculture and banking. We were deeply involved in the development of the initial guidelines for farm based AD, and the first passes through all regulating bodies.
CH-Four Biogas Inc.	CH-Four Biogas is a progressive developer of AD technology. We are active in all aspects of project development including economic and technical feasibility assessments, complete system design, construction management and system optimization. We are particularly specialized in the co-digestion of variable feedstocks.
Electrigaz	Electrigaz is the only technology independent biogas engineering firm in Canada specialized exclusively in the design, planning and realization of biogas solutions for farms, agro-food industries and municipalities. With our German partner K&F, we cumulate over 20 years of biogas experience and over 100 biogas plants built worldwide.
PlanET Biogas Solutions	PlanET specializes in the design, construction, and service of on-farm AD systems for converting agricultural and off-farm waste to electricity. PlanET systems are designed to fit with existing farm operations and are optimized to maximize biogas yield. PlanET currently has 7 installations in Canada and almost 300 worldwide.

RCM International LLC	RCM has over 80 on farm AD systems in-operation around the US on pig and dairy farms; the first was built in 1982 at a dairy in California and is still in operation. RCM builds round, heated mixed tanks with soft covers and provides turn-key and design/bid/ procurement services.
UTS Residual Processing, LLC	UTS Residual Processing belongs to Anaergia, Inc., an international group of companies with over 1,500 biogas plants. We provide engineering and proven technology for management of residuals, conveyance to final process solutions: AD, pipeline conveyance, bio-methane utilization (energy + heat, vehicle and pipeline), and solid/liquid by-products (composting, bedding and water).
Valbio Canada	Valbio Canada provides turnkey AD systems for several markets including agricultural, industrial and municipal. Valbio offers a full complement of services: from design to implementation and technical support and surveillance of the installations. With expertise in energy efficiency, Valbio also integrates the energy of the biogas into the customer's operations.
Yield Energy Inc.	Yield Energy Inc. is a Canadian-owned company formed in 2006. Yield offers a full range of services for new biogas plant owners from biological and financial feasibility studies, plant design and engineering, project and construction management, commissioning, project financing, off-farm feedstock supply and on-going biological support services.

Appendix E: Life Cycle Inventory (LCI) of unit processes

Appendix E-1: Environmental inventory of diesel production and consumption in HDV and off-road facilities

Resource input for 1 MJ diesel at usage				
Energy, from oil	1.292 MJ			
Energy, from biomass	0.026 MJ			
Air emissions				
Emissions	**1 MJ Diesel for High Duty Vehicle**		**1 MJ Diesel for off-road facilities**	
	Upstream	**Consumption**	**Upstream**	**Consumption**
CO_2, fossil, g	43.073	67.556	16.707	68.283
CH_4, g	0.247	0.004	0.113	0.001
N_2O, g	0.001	0.003	0.001	0.029
CO, g	0.028	0.012	0.012	0.067
NMVOC, g	0.019	0.007	0.009	0.025
NOx, g	0.112	0.026	0.046	0.255
SOx, g	0.119	0.003	0.050	0.001
PM total, g	0.008	0.001	0.003	0.041

--Source: GHGenius database v4.01, 2012

Appendix E-2: Environmental inventory of electricity generation in BC

Emissions	1 MJ electricity from hydro	1 MJ electricity from natural gas			1 MJ electricity from oil		1 MJ electricity from biomass (wood)	
	Fuel cycle	Fuel upstream	Electricity generation, boiler	Electricity generation, turbine	Fuel upstream	Electricity generation	Fuel upstream	Electricity generation
CO_2, fossil, g	1.510	5.122	133.364	120.809	20.472	192.811	0.323	0.000
CH_4, fossil, g	0.091	0.048	0.003	0.009	0.156	0.002	0.000	0.000
N_2O, g	0.000	0.000	0.000	0.003	0.001	0.000	0.000	0.015
CO, fossil, g	0.000	0.006	0.095	0.085	0.013	0.039	0.013	0.000
NMVOC, g	0.000	0.002	0.010	0.002	0.011	0.006	0.005	0.030
NOx, g	0.000	0.024	0.192	0.202	0.052	0.213	0.003	0.367
SOx, g	0.000	0.008	0.001	0.001	0.060	0.626	0.001	0.359
PM total, g	0.000	0.000	0.009	0.007	0.004	0.038	0.000	0.133

Source: GHGenius database v4.01, 2012

Appendix E-3: Environmental inventory of natural gas generation (for industry rather than electricity generation)

Emissions	1 MJ natural gas to industry
CO_2, fossil, g	5.127
CH_4, fossil, g	0.069
N_2O, g	0.000
CO, fossil, g	0.006
NMVOC, g	0.002
NOx, g	0.024
SOx, g	0.008
PM total, g	0.000

Source: GHGenius database v4.01, 2012

Appendix E-4: Environmental inventory of composting and curing

Unit process--Composting, with curing included. For 1 tonne feedstock				
	Yard waste	1:1 Food waste + Yard waste	Unit	Source
Electricity consumption	60	60	kWh	Geesing, 2012
Diesel consumption for grinding	47.58	19	MJ	Komilis, 2004
Compost yield	1.475	1.475	yd3	Lowell, 2012
CO_2 emission, biogenic	787	320	kg	Boldrin 2009
CH_4 emission, biogenic	1.82	0.91	kg	Boldrin 2009
N_2O emission	83.2	65	g	Boldrin 2009
NH_3 emission	9	9	g	RTI International, 2000

Avoided N fertilizer (as N)	1.95	2.4	kg	Boldrin 2009
Avoided P fertilizer (as P_2O_5)	3.89	3.38	kg	Boldrin 2009
Avoided K fertilizer (as K_2O)	7.95	6.33	kg	Boldrin 2009

Note:
-For mixed food and yard waste composting, assume 80% of the yard waste requires grinding.

Appendix E-5: Environmental inventory of AD and digestate dewatering

Unit process--AD, with digestate dewatering included. For 1 tonne feedstock			
	Value	**Unit**	**Source**
Electricity consumption for digestion	30	kWh	EcoInvent v2.2
Electricity consumption for dewatering	10	kWh	EcoInvent v2.2
Heat consumption	594	MJ	EcoInvent v2.2
Biogas yield	100	m3	EcoInvent v2.2
Digestate yield (after dewatering)	0.71	tonne	EcoInvent v2.2
CO_2 emission, biogenic	704	kg	EcoInvent v2.2
CH_4 emission, biogenic	8.53	kg	EcoInvent v2.2
H_2S emission	245	g	EcoInvent v2.2
NH_3 emission	274	g	EcoInvent v2.2
Avoided N fertilizer (as N)	2.650	kg	Boldrin 2009
Avoided P fertilizer (as P_2O_5)	0.258	kg	Boldrin 2009
Avoided K fertilizer (as K_2O)	0.316	kg	Boldrin 2009

Appendix E-6: Environmental inventory of biogas purification

Unit process--Biogas purification. For 1 m3 purified biogas		
	Value	**Unit**
Raw biogas input	1.5	m3
Electricity consumption	0.5	kWh
CO2 emission, biogenic	866	g
CH4 emission, biogenic	22.2	g
H2S emission	0.003	g
SO2 emission	0.5	g
Avoided natural gas	1	m3

Source: EcoInvent database v2.2

Appendix E-7: Environmental inventory of co-generation with biogas

Unit process--Co-generation of electricity and heat. For 1 m3 biogas			
	Electricity	**Heat**	**Unit**
Energy generation	2.02 kWh	12.5 MJ	-
CO_2 emission, biogenic	1.47	0.43	kg
CO emission, biogenic	0.84	0.25	g
CH_4 emission, biogenic	0.4	0.12	g

N_2O emission	0.04	0.01	g
NMVOC emission	0.04	0.01	g
SO_2 emission	0.37	0.11	g

Source: EcoInvent database v2.2
Emissions are allocated to electricity generation and heat generation for purpose of LCA calculations. They do not separate in reality. Allocation is based on the energy values of heat and electricity.

Appendix E-8: Environmental inventory of compost and digestate application

Unit process--Application of 1 tonne compost or digestate				
	Yard waste compost	**1:1 Food waste + Yard waste compost**	**Digestate**	**Unit**
Diesel consumption for forklift	25	25	25	MJ
NH_3 emission	38	57	63	g
N_2O emission	92	139	140	g
Cl emission, to water	2.9	2.9	0.0006	kg
PO_4 emission, to water	14	2	0.8	g
Fe emission, to water	5	1	0.3	g
Cu emission, to water	3	3	8	g
Zn emission, to water	11	11	27	g

Source: Compost product application: RTI International, 2000; Boldrin, 2009. Digestate application: EcoInvent database v2.2

Appendix E-9: Environmental inventory of fertilizer production

Unit process--Production of fertilizers. For 1 kg fertilizer produced.				
	N, as N	**P, as P2O5**	**K, as K2O**	**Unit**
Electricity consumption	0.157	0.752	0.122	kWh
CO_2 emission, fossil	2.48	1.4	1	kg
CO emission, fossil	2	1.4	0.78	g
CH_4 emission, fossil	5.9	2	2	g
N_2O emission	9.5	0.03	0.05	g
NMVOC emission	0.8	0.5	0.4	g
SOx emission	0.004	0.02	0.003	g
NOx emission	8.5	5.9	3.1	g
NH_3 emission	3.1	0.03	0.01	g

Source: EcoInvent database v2.2

Appendix F: Numerical values of the stage-wise LCIA results

	Scenarios	Collection and transport	Composting	Application of Compost	Avoided Fertilizer Production	Anaerobic Digestion (with biogas purification)	Anaerobic Digestion	Electricity and Heat Generation	Application of Digestate	Avoided Natural Gas Production	Avoided Fertilizer Production	Avoided Electricity Production	Life Cycle Impact
Global Warming, tonne CO2-eq	S 0-a	4.4	32	20	-18								39
	S 0-b	4.4	24	25	-18								35
	S 0-c	4.4				43			31	-18	-11		50
	S 0-d	4.4					0.5	1.9	31		-11	-8.1	20
Non-renewable energy, GJ primary	S 0-a	61	97	22	-225								-45
	S 0-b	61	60	22	-216								-73
	S 0-c	61				768			23	-3118	-109		-2375
	S 0-d	61					1.4	5.3	23		-109	-118	-137
Respiratory inorganics, kg PM 2.5-eq	S 0-a	0.7	4.5	3.9	-26								-17
	S 0-b	0.7	3.3	4.6	-23								-15
	S 0-c	0.7				42			6.2	-14	-7		28
	S 0-d	0.7					38	8	6		-6.6	-4.6	42
Respiratory organics, kg C2H4-eq	S 0-a	0.5	1.3	0.4	-3.4								-1.2
	S 0-b	0.5	0.7	0.4	-3.2								-1.6
	S 0-c	0.5				7.2			0.4	-6.2	-1.3		0.6
	S 0-d	0.5					7.1	3.2	0.4		-1.3	-0.9	9.0