UBC Bioenergy Research and Demonstration Project

Multi-Criteria Decision Analysis of Fuel Supply Options

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1. Introduction

The University of British Columbia (UBC) is committed to reducing the on-campus carbon footprint by 33% in five years. Towards this goal UBC has partnered with Nexterra Energy and General Electric (G.E.) to install a combined heat and power (CHP) plant, the UBC Bioenergy Research and Demonstration Project, that will offset a portion of the natural gas consumed at the central steam plant and electricity purchased from BC Hydro. This unique power plant will be the first commercial demonstration in North America of a CHP utilizing Nexterra's proprietary biomass gasification and syngas cleaning technology with a G.E. Janbacher high efficiency internal combustion (IC) engine. As of spring 2010 significant grant funding has been secured for the Bioenergy Project and it is scheduled to begin operation in 2012. When operational, the CHP plant will convert two-inch wood chips into steam and electricity, which will be used on the UBC Vancouver campus. The actual supplier of the fuel is still being sourced and several options are available. These options include locally sourced green "wood waste", municipal tree trimmings from Vancouver Parks, urban wood waste resulting from building demolition, and mountain pine beetle wood (MPB) from the interior of British Columbia.

Just 10 years ago the term "wood waste" was loosely used in B.C. to describe the over abundance of green wood saw dust, log ends and bark that was created during the lumber and pulp production processes. However during the past decade lumber companies and pulp mills have made significant advances in using this resource more efficiently. For example, B.C. now ships over 1 billion tonnes/yr of wood pellets to Europe and many pulp mills use "wood waste" to offset a portion of their electricity. More recently economic hardships have caused many lumber mills and pulp plants across the province to closedown[7] and the forestry industry has lost 40% of it's Gross Domestic Product (GDP) over the past decade (Fig. 1). This combination of increased demand and reduced supply has caused the price of biofuels to skyrocket, from $10/tonne ten years ago to the current chip prices, which range from $40/tonne[8] to $80/tonne[9]. The volatility in biomass fuels warrants a careful analysis of supply options to mitigate future risks.

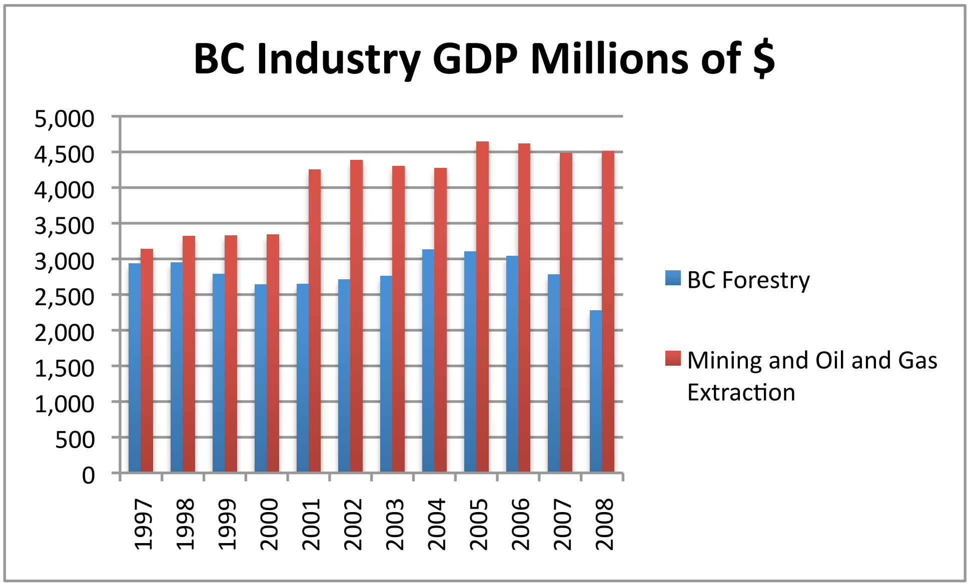


Figure 1. BC forestry industries declining GDP in comparison to the rising GDP of Mining and Energy.

In addition to fuel cost concerns, the point source emissions from burning wood on campus, as well as total air emissions of each fuel source require careful assessment. Emissions limits for small-scale biomass combustion systems around the world appear to be very lenient and focus primarily on Particulate Matter (PM) and Opacity emissions. For example the current Metro Vancouver limits are 18 mg/m^3 PM and 5% Opacity (Table 1). With these limits, Metro Vancouver has some of the most stringent emissions standards in the world. Surprisingly, only the US state of Massachusetts requires small-scale biomass plants to have less PM emissions (16.65 mg/m^3 PM).

Table 1 Summary table of emission limits from various jurisdictions in (mg/m^3)

	EN 303-5 (European standard)	Switzerland OAPC (LRV)		Massachusetts	British Columbia		Metro Vancouver
Boiler	150- 500 kW (highest class boiler)	200-500 kW	> 1 MW < 5 MW	All Boilers	< 25 MW	>= 25 MW	All Boilers
PM	136.22	91.86	115.12	16.65	50.00	20.00	18.00
CO	1089.8	612.40	191.86	13.88	-	-	
OGC (VOC)	72.65	-	30.62	13.88	-	-	
NOx	-	-	-	20.81	-	-	

* All values referenced to 101.3 kPa, 20ºC and 8% O_2 unless states otherwise

** Sources: BC Ministry of Environment "Emissions from Wood-Fired Combustion Equipment", Prepared by Envirochem Services Inc.,June 30, 20
BC Ministry of Environment "Operational Policy Manual Environmental Protection Division (Section 2, Subsection 2.02.25", July 10, 2008
Metro Vancouver (formerly Greater Vancouver Regional District) Boilers and Process Heaters Emission Regulation Bylaw No. 1087, 2008

Table 1 reproduced without modification from Koscher,C. 2010[22].

Considering the pioneering in emissions standards set by the state of California, one might expect that state would have stringent emissions standards for small biomass. However, as shown in Table 2, that assumption would be incorrect (PM = 23 mg/m^3 @ 12% O_2)[22].

Table 2 Summary table of San Joaquin Valley BACT Guideline (1.3.2 B)

Pollutant	BACT Requirements
CO	183 ppmvd @ 3% excess O_2 (0.14 lb/MMBtu), natural gas as auxiliary fuel
NO_x	0.10 lb/MMBtu, ammonia injection and natural gas as auxiliary fuel
PM_{10}	0.045 lb/MMBtu, baghouse. 0.010 gr/dscf @ 12% CO2 (filterable particulates) and 14.08 lb/hr (including condensable particulates).
SO_x	23 ppmvd @ 3% excess O2, limestone injection and natural gas as auxiliary fuel
VOC	0.02 lb/MMBtu, natural gas as auxiliary fuel

Table 2. San Joachim Valley, California. Reproduced without modification from Koscher,C. 2010[22].

Expected emission from the UBC Bioenergy Demonstration Project are 5 mg/m^3 @ 8% O_2, well below the Metro Vancouver standard. One of the downfalls of this approach to measuring pollution is that it does not account for the total annual accumulation of pollutants. A better way to measure pollutants is to base them on kg/yr or tonne/yr to account for accumulation. This revised method has been employed in this report.

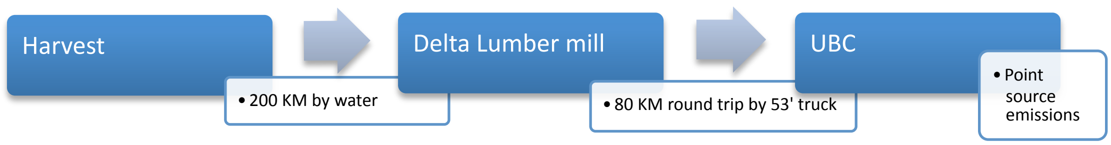
Using a life cycle air emissions analysis I compare the four possible fuel supply options. The findings are then included in a weighted scoring decision analysis incorporating the net present value of the fuel switching savings and localized truck traffic concerns. The results suggest that urban wood waste is the best source for fueling UBC's biomass needs.

2. Life Cycle Air Emissions Assessment

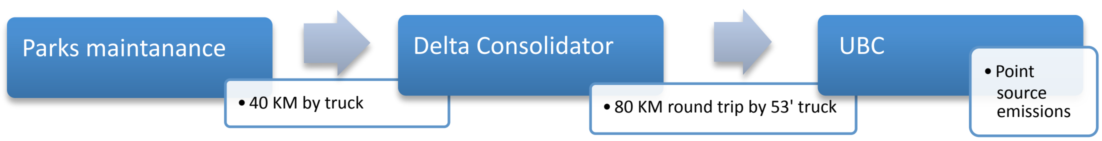
The primary drivers for the life cycle air emissions assessment are fuel moisture content, quantity delivered, distance traveled and the percentage of harvesting, trucking and chipping that can be attributed to the UBC Bioenergy Project. Mountain pine beetle wood is assumed to have zero commercial value except for bioenergy. As a result of this lack in commercial value all emissions from harvesting, chipping, delivery and combustion will be attributed to the Bioenergy Project. This is not the case for the other fuel source options, which are derived from the existing infrastructures of municipal parks maintenance operations and building demolition. For these sources I have not included emissions from the harvesting stage in the air emissions assessment. To analyze the local green wood waste sourced from local lumber mills a weight based allocation method is used to assign a percentage of the total air emissions during harvest and transportation to the lumber mill.

2.1. LCA Boundaries Diagrams

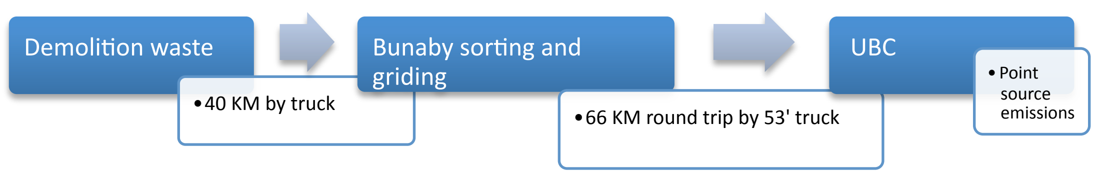
Local Green Wood Waste



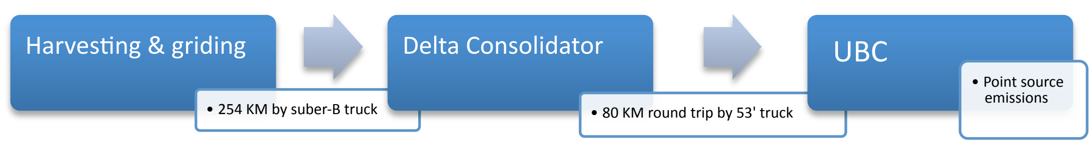
City of Vancouver Parks



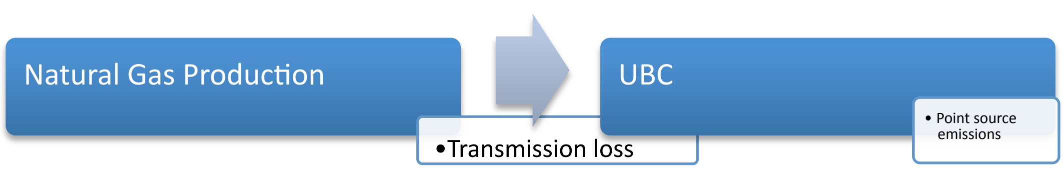
Urban Wood Waste



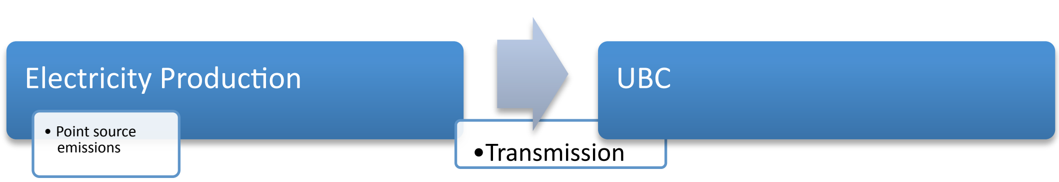
Mountain Pine Beetle (MPB)



Natural Gas Life Cycle



BC electricity Life Cycle



2.2. LCA Methodologies

To evaluate the overall environmental impact of each option the emissions from each process stage are calculated using average emission factors obtained from each wood source option. The emissions are then assessed using four environmental impact indicators: global warming potential (GWP) in carbon dioxide CO_2 equivalent, acid rain potential (ARP) in sulfur dioxide SO_2 equivalent, human toxicity potential (HTP) using threshold limit values for chemicals emitted, and smog formation potential (SFP) in organic compound ORG equivalents (Tables 1-5). It is noteworthy that this life cycle analysis includes the upstream emissions from the production of diesel fuel, natural gas, and coal in all relevant analyses.

2.2.1. Harvesting Stage

For the harvesting stage, diesel fuel consumption estimates are based on data presented by the Forest Engineering Research Instituted of Canada (FERIC) in 2002[3]. This article provides average fuel consumption data per unit tonne of biomass removed from the forests of Canada. Diesel emissions factors for heavy-duty equipment, which were assumed to be the source of all diesel emissions in harvesting of wood, were taken from the EPA AP 42[1] document. See Appendix A1 for the spreadsheet calculations.

2.2.2. Chipping Stage

Numerous technologies with varying degrees of efficiency are currently employed to reduce whole logs or limbs into 3 inch minus wood chips. To calculate the life cycle for the chipping stage an average chipping machinery efficiency of 44 KJ/KG is assumed[8]. It is also assumed that all mountain pine beetle wood and 50% of the Vancouver Parks wood are chipped using trailer mounted chippers, which require diesel fuel to operate. The same diesel fuel emissions factors and assumptions used in the harvesting calculations are used to calculate emissions for chipping and upstream processing. For urban wood waste and local green wood waste all chipping is assumed to run on electricity. Chippers running on diesel are assumed to be 30% efficient and 80% efficient for electricity. See appendix A2 for the spreadsheet calculations.

2.2.3. Trucking Stage

The wood fuel for the Bioenergy Plant will be brought to UBC along Southwest Marine Drive, the established trucking route to campus, in 53' walking floor trucks (Fig. 2). Heavy-duty diesel trucks are assumed to provide all of the transportation requirements. For in-city transportation 53' walking floor trucks are assumed to have an average fuel economy of 2.2 km/liter and 25 tonnes/load[6]. Highway transportation, only necessary for the MPB wood source, is assumed to utilize B-train trucks, which have an average fuel economy of 1.7 KM/Liter and 37 tonnes/load[6]. An allocation percentage is used to quantify the amount of travel that is attributed to hauling MPB wood. This is due to the fact that, open-top B-train trucks are currently used to haul municipal solid-waste to Cache Creek, often times returning to Vancouver empty. These empty trucks can be used to haul wood chips to Vancouver for ultimate delivery to UBC. By synergizing the hauling of municipal waste to Cache Creek with the hauling of wood chips from Merrit to Delta, the location of a wood waste consolidator, significant energy and cost saving can be realized. As such the MPB wood chip source option has an assumed highway trucking distance of 254 km[13]. To this is added the same 80 km round trip in-city truck transportation calculation assumed for the local green wood and Vancouver Parks fuel source options. These sources would all be trucked to UBC from the Delta consolidator. The urban wood waste will be trucked to UBC from a Burnaby consolidator, as such a trucking distance of 66 km is assumed for this fuel source option. See appendix A3 for Spreadsheet calculations.

Figure 2. Keith's 53' walking floor truck trailer with truck. The trailer is shown during loading by a wood chipper. www.wilkens-ind.com/inventory/amtphoto.ashx?id=2131691&img=1

2.2.4. Biomass Combustion at UBC

Localized air emission calculations are based on data provided by Nexterra Energy using expected performance emissions numbers[4]. For the cogen mode a biomass belt dryer is required to reduce fuel moisture content to acceptable levels (<25%) for use in the IC engine. The use of the belt dryer contributes to the total air emissions of the plant. When the belt dryer is operating, the plants thermal output is reduced by 40%, and significant increases in the release of particulate matter (PM) and volatile organic compound (VOC) are expected. Wood fuel with moisture levels below 25% are considered to be dry enough for direct use by the IC engine, removing the parasitic load of the belt dryer from the system. One of the main objectives of this LCA is to compare the Bioenergy Plant efficiency and emissions when using wood fuel with moisture content bellow the requirement of the belt dryer (sourced from MPB wood and urban wood waste) to the use of wood fuel with a high moisture content (locally sourced green wood and municipal tree trimmings) which require the dryer. See appendix A4 for point source air emissions calculations.

2.2.5. Natural Gas Offsets

During Cogen mode the Bioenergy Plant is expected to deliver 9,600 LBS/hr steam which is 12% of the average steam requirements on campus and 1.94 MW of electricity. When the dryer is not in operation the out-put of the plant increases an additional 4 MMBTU/hr. The UBC central steam plant currently burns natural gas to produce steam and operates at a seasonally adjusted efficiency of 85%[5]. Upstream air emissions for natural gas production and transportation are obtained using GHGenius, a free software program from Natural Resources Canada[2]. This software provides total emissions over the whole upstream fuel-cycle process including production and transmission losses. The EPA AP-42 document[1] was used to calculate the point source emissions from the UBC steam plant. It is noteworthy that recently a third party hired by UBC Utilities found that the actual PM emissions from the steam plant are reasonably consistent with EPA standards[5,1]. See appendix A5 for life cycle natural gas air emissions.

2.2.6. Electricity Offsets

This is a frequently debated topic that inevitably leads to “GHG Headache”, a phrase coined by BC Hydro to describe the lack of consensus when quantifying electricity offsets. On one hand BC Hydro’s electricity mix is currently generated from 90% clean renewable sources and according to BC Hydro it will be GHG free by 2016[19]. On the other hand BC is connected to the North American power grid, which is largely coal based and one could argue that any new power generated will offset dirty power from imports. For the purpose of this document, and to avoid GHG headache, I have assume 90% of BC Hydro’s power is clean and renewable and the remaining 10% is derived from coal burning power plants with an average efficiency of 32%[10]. Emissions factors for coal-generated electricity are obtained from the EPA AP 42[1] document on bituminous coal and Pamala L. Spath's analysis of the subject: *Life cycle assessment of coal power production*[10]. See appendix A6 for the electricity mix calculations.

3. LCA Results

3.1. Air Emissions Analysis

3.1.1. Local green wood waste

Basran and Canadian Oversea's Log and Lumber are two local vendors that could easily fulfill UBC's biomass needs at a cost of $45/tonne[15]. Alternatively, an exciting opportunity exists to collaborate with UBC's Malcom Knapp Research Forest (MKRF), a self sufficient, sustainable forestry located near Maple Ridge and managed by UBC's forestry department. Approximately 3,000 green tonnes/yr waste wood are produced by the MKRF lumber activities. Considering the fuel moisture content of 45% in green wood waste, the Bioenergy Plant will require approximately 23,000 tonnes/yr to meet the energy and heat generation goals. While the remaining 20,000 tonnes/yr can be provided by local vendors, it is reasonable to assume that the portion available from MKRF will increase over time, as the forest expands production to meet future increases in market demand for lumber and/or biofuel crops[11].

Local Green wood	Energy consumption GJ/yr	Fuel Type	GWP tonnes CO2 eq	ARP tonnes SO2 eq.	SFP tonnes ORG eq.	TLV kg/hr
Harvesting	3912	Diesel	574	5.9	2.1	0.8
Chipping	1265	Electric	43	0.3	0.1	0.4
Transportation	1281	Diesel	188	1.9	0.7	0.3
UBC point gray	230000	Residual	-6878	25.1	3.8	3.4
Total	**236458**		**-6074**	**33**	**6.8**	**4.9**

Table 3. Life cycle energy and air emissions analysis for locally sourced green wood waste. Emissions from water-based wood transportation are included in the harvesting stage.

3.1.2. Vancouver Parks

The University of British Columbia has just entered into a Memorandum of Understanding (MOU) with the City of Vancouver. As part of this MOU the city of Vancouver has agreed to supply UBC with "free wood" waste from the city's parks maintenance, which Vancouver officials estimate to be on the order of 100,000 tonnes/yr of fresh green wood. This fresh green wood has a moisture content of approximately 50%[4]. This high moisture content requires significant drying and in total the Bioenergy Plant will require 26,000 tonne/yr of this type of wood. 50% of the wood is assumed to be chipped in trailer mounted diesel powered chippers while the remaining 50% will require large industrial whole log electric powered chippers. This has been taken into consideration for the life cycle analysis (Table 4). While the idea of “free wood” sounds great, the devil is in the details. UBC is not interested in owning or operating large chipping equipment or storing biomass on campus. Also current design drawings for fuel receiving bays at the plant do not accommodate tipping trucks. As a result a fuel broker such as Basran or Canadian Overseas log and lumber will need to be engaged to assure the quantity, quality and availability of fuel. This is likely to add significant costs to the “free wood”. As such to calculate the NPV for this section I have arbitrarily assumed Vancouver Parks derived fuel is delivered at a cost of $28/tonne.

Vancouver Parks	Energy consumption GJ/yr	Fuel Type	GWP tonnes CO2 eq	ARP tonnes SO2 eq.	SFP tonnes ORG eq.	TLV kg/hr
Harvesting	N/A	N/A	N/A	N/A	N/A	N/A
Chipping	2323	Diesel/Elctric	210	2.1	0.7	0.6
Transportation	1470	Diesel	216	2.2	0.8	0.3
UBC point gray	250800	Green Wood	-6878	25.1	3.8	3.4
Total	**254594**		**-6453**	**29**	**5.4**	**4.3**

Table 4. Life cycle energy and air emissions analysis for Vancouver Parks green wood waste.

3.1.3. Mountain Pine Beetle Wood

With approximately 30% of British Columbia’s total area affected by the MPB there is no shortage in B.C. for beetle-killed pine trees. Merrit, at 254 KM from Vancouver, is the closest source for MPB wood to UBC. At this time there is at least a 10 year supply of wood. After 10 years the beetle-killed trees will likely have decomposed significantly and no longer be unusable for bioenergy[20]. A number of green houses in the lower mainland are already utilizing MPB wood and Trace Resources LTD has recently constructed a B-train truck transfer facility in Delta for distribution to the lower mainland[21]. The main advantage to using MPB wood chips is their low moisture content (20%), which results in reduced fuel requirements and truck trips to the Bioenergy Plant. Specifically the plant will require approximately 15,000 tonnes/yr of MBP wood to operate, this more that 10,000 tonnes/yr less than the requirement of Vancouver Parks green wood (Table 5). Additionally, MPB wood will not require a drying stage, and the belt dryer will not need to be operated. This will result in an increased thermal output of 4

MMBTU/hr, that is a 40% increase, and reduce VOC and PM emissions by 55% and 77% respectively compared to using fuel requiring the belt dryer. See appendix A4 for direct comparison results.

Mountain Pine Beetle	Energy consumption GJ/yr	Fuel Type	GWP tonnes CO2 eq	ARP tonnes SO2 eq.	SFP tonnes ORG eq.	TLV kg/hr
Harvesting	8637	Diesel	1266	13	5	1.82
Chipping	2158	Diesel	316	3	1	0.45
Transportation	3070	Diesel	450	5	2	0.65
UBC point gray	220680	Biomass	-9744	25.11	1.46	0.77
Total	**234545**		**-7711**	**46**	**9.0**	**3.7**

Table 5. Life cycle energy and air emissions analysis for MPB wood source.

3.1.4. Urban Wood Waste

Urban Wood Waste Recyclers in Burnaby accepts demolition waste at a fraction of the cost of landfills. The biomass is sorted and freed from contaminates, chipped and then sold back onto the market. Clean white wood is their most highly valued product at 20% moisture content and $40 tonne[12]. It is promised to be free of all chemical contaminates such as paints, glues, metals and plastics, however this is not always the case and trance plastics and particles are found in the product stream. Nexterra's Dockside Green Facility in downtown Victoria is currently running on a similar type of fuel. A proximal analysis is of this wood waste was not available for this report and to my knowledge Nexterra has not conducted dioxin or heavy metal emissions testing at their Victoria facility. To analyze the potential environmental impacts of this type of wood fuel, I have based the point source emissions calculations on those described in the previous paragraph for MPB wood, which has similar moisture content. Due to the trace contaminants in this wood source, this analysis incorporates the emissions factors for the gasification of municipal solid waste[1], by assuming it accounts for 2% of the total mass of the required wood fuel, 15,000 tonnes/yr (Table 6). This affects the point source Human Toxicity Potential most dramatically causing local air emissions to increase by 14%. Because demolition waste would normally be sent to a landfill, air emissions from the harvesting stage have been neglected.

Urban Wood Waste	Energy consumption GJ/yr	Fuel Type	GWP tonnes CO2 eq	ARP tonnes SO2 eq.	SFP tonnes ORG eq.	TLV kg/hr
Harvesting	N/A	N/A	N/A	N/A	N/A	N/A
Chipping	809.16	Electricity	27.5	0.2	0.1	0.3
Transportation	676	Diesel	99.1	1.0	0.4	0.1
UBC point gray	220680	Woodwaste	-9744	25.11	1.46	0.88
Total	**222165**		**-9617**	**26**	**1.9**	**1.3**

Table 6. Life cycle energy and air emissions analysis for urban wood waste source.

3.2. Net Present Value Summary

The net present values highlighted in yellow below indicate the operational savings over a period of 15 years (capitol cost are excluded). The savings are based on hedging the future price of biomass fuel compared to natural gas including carbon tax liabilities. Additionally in order to finacially justify the cogen operation of the Bioenergy Plant, for all fuel source options it is assume that the electricity generated is sold at a premium of $0.12 kWh. This high price requires a power purchase agreement from BC Hydro for which negotiations are currenlty ongoing. Significantly the results show that the urban wood waste has twice the NPV of the locally sourced green wood (Table 7).

UBC Renewable Energy Demonstration Project						
Operational Scenarios - Summary						
Scenario			Co-Gen Local Green wood	Co-Gen Vancouver parks	Co-Gen Mountain Pine Beetle	Co-Gen Urban wood waste
Scenario Parameters						
A	Electricity price per kWe		$0.120	$0.120	$0.120	$0.120
B	Electricity load		100%	100%	100%	100%
C	Steam MMBtu/hr		9.6	9.6	9.6	9.6
D	Hot Water MMBtu/hr		0	0	4	4
Net present value of costs less expenses						
10 Years			4,439,191	5,779,509	5,565,246	9,192,576
15 Years			5,855,619	7,593,693	7,441,953	12,145,737
20 Years			6,865,513	8,235,395	8,780,019	14,251,300
Discount rate	7%					

Table 7. Net present value results for each fuel source option

3.3. Local Trucking Traffic Management

The designated truck route to campus is via South West Marine Drive and passes through one of highest income neighborhoods in Vancouver. Neighborhood residents have complained in the past about the number of trucks bound for campus and several years ago UBC committed to limiting this number to 150 truck trips/day. Current counts put UBC’s truck traffic at just over this number and UBC’s Office of Campus and Community Planning are actively exploring ways to reduce truck traffic. As mentioned above, the moisture content of wood plays a significant role in dictating the annual tonnage of fuel required, and also determines the number of trucks required to transport the fuel to campus. As Table 8 shows truck trips for MPB and urban wood waste are significantly reduced over higher moisture content options.

Truck traffic management	MPB Wood	Urban Wood Waste	Vancouver Parks Wood	Local Green Wood
UBC trips per day	1.61	1.61	2.89	2.52

Table 8. Estimated truck trips to campus per day for various fuel supply options.

4. Decision Analysis

To compare the four potential wood fuel sources, a weighted scoring method was used. Prior to applying the weighted score, the results of each environmental category (i.e. Smog Formation Potential) were normalized to the wood source with the highest (worst) emissions impact score in that category. For example, MPB wood was found to have the highest acid rain potential (Table 5) as such all the other wood source acid rain potential values were normalized to the MPB value. This approach ensured that a reduction in environmental or human health impact resulted in a lower than 1 numerical score. In contrast, to normalize NPV of savings, the values for each wood source were normalized to the source with the lowest (worst) savings potential, locally sourced green wood (Table 3). This ensured that wood sources with increased savings were reflected as numerical values less than 1, allowing for direct comparison to the environmental impact analyses. A similar normalization method was used for the local truck transportation category. Categories were assigned arbitrary weighted value as shown in Table 9.

The results from the decision analysis (Table 9) indicate that urban wood waste supplied by Urban Wood Waste Recyclers is clearly the best biomass fuel option for the UBC Bioenergy Plant. Urban wood waste has the lowest score in almost every category. This means that altering the arbitrary weighting in the weighted scoring method will not to change the outcome. However if local air emissions are the only concern, and all other categories are ignored, including NPV savings, then Mountain Pine Beetle wood is the better option. While this report focuses on the Cogen mode only a similar out come is expected for the thermal mode which has not be assessed in this report due to the added complexity.

Weighted scoring method	Weight	Mountain Pine Beetle	Urban Wood Waste	Vancouver Parks	Local Green Wood
Global Warming potential savings	20%	0.79	0.63	0.94	1.00
Acid Rain Potential	5%	1.00	0.57	0.64	0.72
Smog Formation Potential	10%	1.00	0.21	0.60	0.75
Human Toxicity Potential	30%	0.75	0.26	0.88	1.00
NPV of savings	25%	0.77	0.48	0.77	1.00
Local Truck traffic management	10%	0.56	0.56	1.00	0.87
Total Ranking Lowest score = best	100%	**0.78**	**0.43**	**0.84**	**0.95**

Table 9. Normalized weighted scoring method used to compare various criteria based on arbitrary weighted values assigned by me.

Appendix

Appendix A1 Harvesting

Nexterra fuel requirements	tonne/yr	Density when harvested kg/M3	M^3/year	weight based allocation factor	Diesel fuel used Liters/ M^3	Liters diesel consumed/ yr	GJ consumed/ yr
Mountain Pine Beetle	14712	465	31639	100%	7.1	223303	8637
Local Green Residual	23000	610	37705	38%	7.1	101125	3912
Urban Wood Waste	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Vancouver Parks	N/A	N/A	N/A	N/A	N/A	N/A	N/A

MPB wood	Kg/MJ total	MJ/yr	KG/yr	GWP (CO2 eq.)	ARP (So2 eq.)	SFP (ORG eq.)	TLV mg/M3 TWA	GWP GHG eq	ARP	SFP	TLV Kg/hr
CO_2	8.62E-02	8637368	7.45E+05	1	0	0	9000	7.45E+05	0.00E+00	0.00E+00	9.44E-03
NMVOC	1.68E-04	8637368	1.4499E+03	3.4	0	3.1	0	4.93E+03	0.00E+00	4.49E+03	0.00E+00
CH_4	1.37E-04	8637368	1.1853E+03	21	0	0.015	0	2.49E+04	0.00E+00	1.78E+01	0.00E+00
CO	4.47E-04	8637368	3.8609E+03	1.9	0	0.054	29	7.34E+03	0.00E+00	2.08E+02	1.52E-02
N_2O	1.12E-05	8637368	9.6355E+01	310	0	0	0	2.99E+04	0.00E+00	0.00E+00	0.00E+00
Nox	1.95E-03	8637368	1.6845E+04	27	0.7	0	5.6	4.55E+05	1.18E+04	0.00E+00	3.43E-01
SOx	1.55E-04	8637368	1.3381E+03	0	1	0	5.2	0.00E+00	1.34E+03	0.00E+00	2.94E-02
PM	1.38E-04	8637368	1.1922E+03	0	0	0	0.096	0.00E+00	0.00E+00	0.00E+00	1.42E+00
							Total	**1266466**	**13130**	**4721**	**1.82**

Mill Residual	LCA Kg/MJ total	MJ/yr	KG/yr	GWP (CO2 eq.)	ARP (So2 eq.)	SFP (ORG eq.)	TLV mg/M3 TWA	GWP GHG eq	ARP	SFP	TLV Kg/hr
CO_2	8.62E-02	3911508	3.37E+05	1	0	0	9000	3.37E+05	0.00E+00	0.00E+00	4.28E-03
NMVOC	1.68E-04	3911508	6.5659E+02	3.4	0	3.1	0	2.23E+03	0.00E+00	2.04E+03	0.00E+00
CH_4	1.37E-04	3911508	5.3677E+02	21	0	0.015	0	1.13E+04	0.00E+00	8.05E+00	0.00E+00
CO	4.47E-04	3911508	1.7485E+03	1.9	0	0.054	29	3.32E+03	0.00E+00	9.44E+01	6.88E-03
N_2O	1.12E-05	3911508	4.3635E+01	310	0	0	0	1.35E+04	0.00E+00	0.00E+00	0.00E+00
Nox	1.95E-03	3911508	7.6285E+03	27	0.7	0	5.6	2.06E+05	5.34E+03	0.00E+00	1.56E-01
SOx	1.55E-04	3911508	6.0597E+02	0	1	0	5.2	0.00E+00	6.06E+02	0.00E+00	1.33E-02
PM	1.38E-04	3911508	5.3988E+02	0	0	0	0.096	0.00E+00	0.00E+00	0.00E+00	6.42E-01
							Total	**573531**	**5946**	**2138**	**0.82**

Appendix A2 Chipping

Brand	Type of chipper	KG/S	KW	KJ/KG
Nickolson WFP 3A	Trailer mounted	13.7	450	33
ERJo	Trailer mounted	6.2	412	67
Evolution 910R	Drum	11.5	267	23
MOHA	Drum	4.7	229	49
Morbark 1200	Hammermill	10.0	481	48
			Average =	44

Whole log chipping	Biomass required tonne/yr	Moisture content	MJ Required / tonne	GJ/YR	Fuel type	Assumed eff.	Total GJ/yr
MPB Wood	14712	20%	44	647	Diesel	30%	2158
Vancouver Parks	26400	50%	44	1162	Diesel/Electric	50%	2323
Urban wood waste	14712	20%	44	647	Electric	80%	809
Local Green	23000	45%	44	1012	Electric	80%	1265

MPB wood	Diesel emissions factor Kg/MJ total	MJ/yr	KG/yr	GWP (CO2 eq.)	ARP (So2 eq.)	SFP (ORG eq.)	TLV mg/M3 TWA	GWP GHG eq	ARP	SFP	TLV Kg/hr
CO_2	8.62E-02	2157760	1.86E+05	1	0	0	9000	1.86E+05	0.00E+00	0.00E+00	2.36E-03
NMVOC	1.68E-04	2157760	3.6220E+02	3.4	0	3.1	0	1.23E+03	0.00E+00	1.12E+03	0.00E+00
CH_4	1.37E-04	2157760	2.9611E+02	21	0	0.015	0	6.22E+03	0.00E+00	4.44E+00	0.00E+00
CO	4.47E-04	2157760	9.6453E+02	1.9	0	0.054	29	1.83E+03	0.00E+00	5.21E+01	3.80E-03
N_2O	1.12E-05	2157760	2.4071E+01	310	0	0	0	7.46E+03	0.00E+00	0.00E+00	0.00E+00
Nox	1.95E-03	2157760	4.2082E+03	27	0.7	0	5.6	1.14E+05	2.95E+03	0.00E+00	8.58E-02
SOx	1.55E-04	2157760	3.3428E+02	0	1	0	5.2	0.00E+00	3.34E+02	0.00E+00	7.34E-03
PM	1.38E-04	2157760	2.9782E+02	0	0	0	0.096	0.00E+00	0.00E+00	0.00E+00	3.54E-01
							Total	**316385**	**3280**	**1179**	**0.45**

Vancouver Parks Trimmings	Diesel emissions factor Kg/MJ total	MJ/yr	KG/yr	GWP (CO2 eq.)	ARP (So2 eq.)	SFP (ORG eq.)	TLV mg/M3 TWA	GWP GHG eq	ARP	SFP	TLV Kg/hr
CO_2	8.62E-02	1161600	1.00E+05	1	0	0	9000	1.00E+05	0.00E+00	0.00E+00	1.27E-03
NMVOC	1.68E-04	1161600	1.9499E+02	3.4	0	3.1	0	6.63E+02	0.00E+00	6.04E+02	0.00E+00
CH_4	1.37E-04	1161600	1.5940E+02	21	0	0.015	0	3.35E+03	0.00E+00	2.39E+00	0.00E+00
CO	4.47E-04	1161600	5.1924E+02	1.9	0	0.054	29	9.87E+02	0.00E+00	2.80E+01	2.04E-03
N_2O	1.12E-05	1161600	1.2958E+01	310	0	0	0	4.02E+03	0.00E+00	0.00E+00	0.00E+00
Nox	1.95E-03	1161600	2.2654E+03	27	0.7	0	5.6	6.12E+04	1.59E+03	0.00E+00	4.62E-02
SOx	1.55E-04	1161600	1.7996E+02	0	1	0	5.2	0.00E+00	1.80E+02	0.00E+00	3.95E-03
PM	1.38E-04	1161600	1.6033E+02	0	0	0	0.096	0.00E+00	0.00E+00	0.00E+00	1.91E-01
							Total	**170321**	**1766**	**635**	**0.24**

Vancouver Parks rounds	Electricity Emissions factor Kg/MJ	MJ/yr	KG/yr	GWP (CO2 eq.)	ARP (So2 eq.)	SFP (ORG eq.)	TLV mg/M3 TWA	GWP GHG eq	ARP	SFP	TLV Kg/hr
CO_2	3.04E-02	1161600	3.53E+04	1	0	0	9000	3.53E+04	0.00E+00	0.00E+00	4.48E-04
NMVOC	2.78E-05	1161600	3.23E+01	3.4	0	3.1	0	1.10E+02	0.00E+00	1.00E+02	0.00E+00
CH_4	2.11E-05	1161600	2.45E+01	21	0	0.015	0	5.15E+02	0.00E+00	3.68E-01	0.00E+00
CO	8.03E-06	1161600	9.32E+00	1.9	0	0.054	29	1.77E+01	0.00E+00	5.03E-01	3.67E-05
N_2O	9.93E-07	1161600	1.15E+00	310	0	0	0	3.57E+02	0.00E+00	0.00E+00	0.00E+00
Nox	9.96E-05	1161600	1.16E+02	27	0.7	0	5.6	3.12E+03	8.10E+01	0.00E+00	2.36E-03
SOx	1.99E-04	1161600	2.31E+02	0	1	0	5.2	0.00E+00	2.31E+02	0.00E+00	5.08E-03
PM	2.74E-04	1161600	3.18E+02	0	0	0	0.096	0.00E+00	0.00E+00	0.00E+00	3.78E-01
							Total	**39408**	**312**	**101**	**0.39**
						Vancouver Parks Total		**209729**	**2078**	**736**	**0.63**

Urban Wood Waste	Electricity Emissions factor Kg/MJ	MJ/yr	KG/yr	GWP (CO2 eq.)	ARP (So2 eq.)	SFP (ORG eq.)	TLV mg/M3 TWA	GWP GHG eq	ARP	SFP	TLV Kg/hr
CO_2	3.04E-02	809160	2.46E+04	1	0	0	9000	2.46E+04	0.00E+00	0.00E+00	3.12E-04
NMVOC	2.78E-05	809160	2.25E+01	3.4	0	3.1	0	7.66E+01	0.00E+00	6.98E+01	0.00E+00
CH_4	2.11E-05	809160	1.71E+01	21	0	0.015	0	3.59E+02	0.00E+00	2.56E-01	0.00E+00
CO	8.03E-06	809160	6.49E+00	1.9	0	0.054	29	1.23E+01	0.00E+00	3.51E-01	2.56E-05
N_2O	9.93E-07	809160	8.03E-01	310	0	0	0	2.49E+02	0.00E+00	0.00E+00	0.00E+00
Nox	9.96E-05	809160	8.06E+01	27	0.7	0	5.6	2.18E+03	5.64E+01	0.00E+00	1.64E-03
SOx	1.99E-04	809160	1.61E+02	0	1	0	5.2	0.00E+00	1.61E+02	0.00E+00	3.54E-03
PM	2.74E-04	809160	2.22E+02	0	0	0	0.096	0.00E+00	0.00E+00	0.00E+00	2.63E-01
							Total	**27451**	**218**	**70**	**0.27**

Local Green Wood	Electricity Emissions factor Kg/MJ	MJ/yr	KG/yr	GWP (CO2 eq.)	ARP (So2 eq.)	SFP (ORG eq.)	TLV mg/M3 TWA	GWP GHG eq	ARP	SFP	TLV Kg/hr
CO_2	3.04E-02	1265000	3.84E+04	1	0	0	9000	3.84E+04	0.00E+00	0.00E+00	4.87E-04
NMVOC	2.78E-05	1265000	3.52E+01	3.4	0	3.1	0	1.20E+02	0.00E+00	1.09E+02	0.00E+00
CH_4	2.11E-05	1265000	2.67E+01	21	0	0.015	0	5.61E+02	0.00E+00	4.00E-01	0.00E+00
CO	8.03E-06	1265000	1.02E+01	1.9	0	0.054	29	1.93E+01	0.00E+00	5.48E-01	4.00E-05
N_2O	9.93E-07	1265000	1.26E+00	310	0	0	0	3.89E+02	0.00E+00	0.00E+00	0.00E+00
Nox	9.96E-05	1265000	1.26E+02	27	0.7	0	5.6	3.40E+03	8.82E+01	0.00E+00	2.57E-03
SOx	1.99E-04	1265000	2.52E+02	0	1	0	5.2	0.00E+00	2.52E+02	0.00E+00	5.53E-03
PM	2.74E-04	1265000	3.46E+02	0	0	0	0.096	0.00E+00	0.00E+00	0.00E+00	4.12E-01
							Total	**42915**	**340**	**110**	**0.42**

Appendix A3 Trucking

IN CITY TRUCKING 53'	Biomass required tonne/yr	Truck capcity tonnes/ load	Truck trips/yr	Round trip in city distance traveled per load KM	Allocation factor	Average in city Fuel eff. Diesel trucks KM/Liter	Annual Liters consumed	MJ/yr
MPBK	14712	25	588.5	80	100%	2.2	21185	819447
Local Green Residual	23000	25	920	80	100%	2.2	33120	1281082
Vancouver Parks	26400	25	1056	160	50%	2.2	38016	1470459
Urban wood waste	14712	25	588.5	132	50%	2.2	17478	676043
HIGHWAY TRUCKING SUPER-B								
MPBK	14712	37	398	508	50%	1.74	58174	2250156

Emission Factors for Energy Consumed			
Diesel:			Units
Pollutant	Amount	Units	Kg/MJ
CO_2	164	lb/MMBtu	7.0520E-02
TOC	0.36	lb/MMBtu	1.5480E-04
CH_4	0.133	g/L	3.4590E-06
CO	0.95	lb/MMBtu	4.0850E-04
N_2O	0.4	g/L	1.0403E-05
NOx	4.41	lb/MMBtu	1.8963E-03
SOx	0.29	lb/MMBtu	1.2470E-04
PM 10	0.31	lb/MMBtu	1.3330E-04
Aldehydes	0.7	lb/MMBtu	3.0100E-04

Upstream Emission Factors for Energy Produced GHGenius				
Emissions of the Production of Highway Diesel from Oil in grams per unit of energy delivered to end users:				
Pollutant	Amount	Units	Amount	Units
CO_2	15689	g/GJ	1.5689E-02	Kg/MJ
NMOC	13	g/GJ	1.3061E-05	Kg/MJ
CH_4	134	g/GJ	1.3377E-04	Kg/MJ
CO	39	g/GJ	3.8504E-05	Kg/MJ
N_2O	1	g/GJ	7.5272E-07	Kg/MJ
NO_2	54	g/GJ	5.3965E-05	Kg/MJ
SOx	30	g/GJ	3.0220E-05	Kg/MJ
PM	5	g/GJ	4.7236E-06	Kg/MJ

MPB wood	Kg/MJ total	MJ/yr	KG/yr	GWP (CO2 eq.)	ARP (So2 eq.)	SFP (ORG eq.)	TLV mg/M3 TWA	GWP GHG eq	ARP	SFP	TLV Kg/hr
CO_2	8.62E-02	3069603	2.6E+05	1	0	0	9000	2.65E+05	0.00E+00	0.00E+00	3.36E-03
NMVOC	1.68E-04	3069603	5.2E+02	3.4	0	3.1	0	1.75E+03	0.00E+00	1.60E+03	0.00E+00
CH_4	1.37E-04	3069603	4.2E+02	21	0	0.015	0	8.85E+03	0.00E+00	6.32E+00	0.00E+00
CO	4.47E-04	3069603	1.4E+03	1.9	0	0.054	29	2.61E+03	0.00E+00	7.41E+01	5.40E-03
N_2O	1.12E-05	3069603	3.4E+01	310	0	0	0	1.06E+04	0.00E+00	0.00E+00	0.00E+00
Nox	1.95E-03	3069603	6.0E+03	27	0.7	0	5.6	1.62E+05	4.19E+03	0.00E+00	1.22E-01
SOx	1.55E-04	3069603	4.8E+02	0	1	0	5.2	0.00E+00	4.76E+02	0.00E+00	1.04E-02
PM	1.38E-04	3069603	4.2E+02	0	0	0	0.096	0.00E+00	0.00E+00	0.00E+00	5.04E-01
							Total	**450085**	**4666**	**1678**	**0.65**

Mill Residual	Kg/MJ total	MJ/yr	KG/yr	GWP (CO2 eq.)	ARP (So2 eq.)	SFP (ORG eq.)	TLV mg/M3 TWA	GWP GHG eq	ARP	SFP	TLV Kg/hr
CO_2	8.62E-02	1281082	1.1E+05	1	0	0	9000	1.10E+05	0.00E+00	0.00E+00	1.40E-03
NMVOC	1.68E-04	1281082	2.2E+02	3.4	0	3.1	0	7.31E+02	0.00E+00	6.67E+02	0.00E+00
CH_4	1.37E-04	1281082	1.8E+02	21	0	0.015	0	3.69E+03	0.00E+00	2.64E+00	0.00E+00
CO	4.47E-04	1281082	5.7E+02	1.9	0	0.054	29	1.09E+03	0.00E+00	3.09E+01	2.25E-03
N_2O	1.12E-05	1281082	1.4E+01	310	0	0	0	4.43E+03	0.00E+00	0.00E+00	0.00E+00
Nox	1.95E-03	1281082	2.5E+03	27	0.7	0	5.6	6.75E+04	1.75E+03	0.00E+00	5.09E-02
SOx	1.55E-04	1281082	2.0E+02	0	1	0	5.2	0.00E+00	1.98E+02	0.00E+00	4.36E-03
PM	1.38E-04	1281082	1.8E+02	0	0	0	0.096	0.00E+00	0.00E+00	0.00E+00	2.10E-01
							Total	**187840**	**1947**	**700**	**0.27**

Vancouver Parks	Kg/MJ total	MJ/yr	KG/yr	GWP (CO2 eq.)	ARP (So2 eq.)	SFP (ORG eq.)	TLV mg/M3 TWA	GWP GHG eq	ARP	SFP	TLV Kg/hr
CO_2	8.62E-02	1470459	1.3E+05	1	0	0	9000	1.27E+05	0.00E+00	0.00E+00	1.61E-03
NMVOC	1.68E-04	1470459	2.5E+02	3.4	0	3.1	0	8.39E+02	0.00E+00	7.65E+02	0.00E+00
CH_4	1.37E-04	1470459	2.0E+02	21	0	0.015	0	4.24E+03	0.00E+00	3.03E+00	0.00E+00
CO	4.47E-04	1470459	6.6E+02	1.9	0	0.054	29	1.25E+03	0.00E+00	3.55E+01	2.59E-03
N_2O	1.12E-05	1470459	1.6E+01	310	0	0	0	5.09E+03	0.00E+00	0.00E+00	0.00E+00
Nox	1.95E-03	1470459	2.9E+03	27	0.7	0	5.6	7.74E+04	2.01E+03	0.00E+00	5.85E-02
SOx	1.55E-04	1470459	2.3E+02	0	1	0	5.2	0.00E+00	2.28E+02	0.00E+00	5.00E-03
PM	1.38E-04	1470459	2.0E+02	0	0	0	0.096	0.00E+00	0.00E+00	0.00E+00	2.41E-01
							Total	**215608**	**2235**	**804**	**0.31**

Urban wood waste	Kg/MJ total	MJ/yr	KG/yr	GWP (CO2 eq.)	ARP (So2 eq.)	SFP (ORG eq.)	TLV mg/M3 TWA	GWP GHG eq	ARP	SFP	TLV Kg/hr
CO_2	8.62E-02	676043	5.8E+04	1	0	0	9000	5.83E+04	0.00E+00	0.00E+00	7.39E-04
NMVOC	1.68E-04	676043	1.1E+02	3.4	0	3.1	0	3.86E+02	0.00E+00	3.52E+02	0.00E+00
CH_4	1.37E-04	676043	9.3E+01	21	0	0.015	0	1.95E+03	0.00E+00	1.39E+00	0.00E+00
CO	4.47E-04	676043	3.0E+02	1.9	0	0.054	29	5.74E+02	0.00E+00	1.63E+01	1.19E-03
N_2O	1.12E-05	676043	7.5E+00	310	0	0	0	2.34E+03	0.00E+00	0.00E+00	0.00E+00
Nox	1.95E-03	676043	1.3E+03	27	0.7	0	5.6	3.56E+04	9.23E+02	0.00E+00	2.69E-02
SOx	1.55E-04	676043	1.0E+02	0	1	0	5.2	0.00E+00	1.05E+02	0.00E+00	2.30E-03
PM	1.38E-04	676043	9.3E+01	0	0	0	0.096	0.00E+00	0.00E+00	0.00E+00	1.11E-01
							Total	**99126**	**1028**	**370**	**0.14**

Appendix A4 Point source biomass air emissions.

Nexterra Cogen emissions tonnes/yr	Nexterra Cogen mode (Expected emissions)	UBC Steam plant offsets	Total
CO_2 X 1000	19.15	6.07	-6.07
Nox	35.87	7.08	28.79
PM Filterable Combustion	1.54	0.10	1.44
PM Filterable Non-Combustion	5.21	0.00	5.21
CO	71.44	4.25	67.19
CH_4	0	0.12	-0.12
TOC	13.42	0.56	12.86
VOC	9.78	0.28	9.50
Sox	0	0.03	-0.03

Nexterra Cogen ***no dryer*** emissions tonne/yr	Nexterra Cogen mode (Expected emissions)	UBC Steam plant offsets	Total
CO_2 X 1000	19.15	8.60	-8.60
Nox	35.87	10.04	25.83
PM Filterable Combustion	1.54	0.14	1.40
PM Filterable Non-Combustion		0.00	0.00
CO	71.44	6.02	65.42
CH_4	0	0.16	-0.16
TOC	13.42	0.79	12.63
VOC	4.36	0.39	3.97
Sox	0	0.04	-0.04
Note: C02 from Nexterra is assumed to be Carbon Neutral			

Appendix A5 UBC Steam Plant point source and life cycle air emissions

UBC Power House Emissions 1,020,000 GJ Natural Gas	Natural Gas Emissions factors as per EPA AP-42	Metric Equivalent	UBC Power House Emissions/yr	Upstream emissions GHGenius	Total LCA emissons
Contaminate	LB/10^6 SCF	KG/GJ	tonnes/yr	tonnes/yr	Tonnes /Yr
CO_2	120000	5.0E+01	50605	3372	53977
Nox	140	5.8E-02	59.0	26.8	85.84
PM Filterable	1.9	7.9E-04	0.8	1.0	1.83
PM Filterable Non-Combustion	0	0.0E+00	0.0	0.0	0.00
CO	84	3.5E-02	35.4	27.5	62.91
CH_4	2.3	9.5E-04	1.0	41.4	42.39
TOC	11	4.5E-03	4.6	0.0	4.64
VOC	5.5	2.3E-03	2.3	1.4	3.74
Sox	0.6	2.5E-04	0.3	6.5	6.75

Appendix A6 BC Hydro Electricity Mix Calculations

Coal: LCA EMISSIONS				
Pollutant	Amount	Units	g/MJ	
CO_2	1,093.5	g/kWh	303.76	
CH_4	0.8	g/kWh	0.21	
N_2O	0.0	g/kWh	0.01	
CO	0.3	g/kWh	0.08	
NMOC	1.0	g/kWh	0.28	
NO_2	3.6	g/kWh	1.00	
SOx	7.2	g/kWh	1.99	
PM	9.9	g/kWh	2.74	
Total emissions for electricity including 7% line losses				
Souce:	http://www.nrel.gov/docs/fy99osti/25119.pdf			

BC Electriy Mix with 10% Coal				
Pollutant	Amount	Units	kg/MJ	
CO_2	109.4	g/kWh	3.04E-02	
CH_4	0.1	g/kWh	2.11E-05	
N_2O	0.0	g/kWh	9.93E-07	
CO	0.0	g/kWh	8.03E-06	
NMOC	0.1	g/kWh	2.78E-05	
NO_2	0.4	g/kWh	9.96E-05	
SOx	0.7	g/kWh	1.99E-04	
PM	1.0	g/kWh	2.74E-04	
Total emissions for electricity including 7% line losses				

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