Wood Pellets for UBC Boilers Replacing Natural Gas

By Bernard Chan, Brian Chan, and Christopher Young

University of British Columbia

April 11, 2008

Source: The UBYSSEY

<http://ubyssey.bc.ca/2007/12/04/ubc-professors-seek-to-ease-carbon-footprint/>

“Wood Pellets for UBC Boilers Replacing Natural Gas”

By Bernard Chan, Brian Chan, and Christopher Young

Abstract

This report studies the feasibility of replacing natural gas with wood pellets for UBC boilers. A gasification system is proposed to be installed in the UBC boiler house to convert wood pellets into syngas that can be used to displace the energy required from natural gas to produce steam.

The environmental impact and the cost of implementation between wood pellet technology (case 2) and natural gas technology (case 1) are compared. The environmental impact for the two cases is compared with life-cycle assessment (LCA). The life cycle of natural gas is divided into the following stages: production, transmission, and final use. The life cycle of wood pellets is divided into the following stages: harvesting, transportation, pellet production, and final use. The environmental and human impacts of each stage are evaluated in terms of global warming potential (GWP), smog formation potential (SF), acid rain potential (ARP), and health impact. Moreover, the operating cost of using wood pellet as the energy source is examined. In addition, potential air emission reduction units that help further minimize the emissions from using wood pellets are investigated.

It is found that most local air emissions, especially carbon dioxide, decrease when wood pellet is used. However, when the entire life-cycle is taken into the consideration, the VOC, SO_x, and PM emissions increase significantly. Also, a preliminary economic analysis showed that implementation of the new system which utilizes wood pellets and natural gas for the production of steam generates an annual saving of approximately $2 million. Different valuation methods show that using wood pellets is an improvement over natural gas.

Table of Contents

List of Figures

List of Tables

1.0 Introduction

The need for sustainable, reusable, and environmentally friendly processes are increasingly significant in society nowadays due to stricter regulations, public health concerns, and economic feasibility. The demand for reduction in green house gas (GHG) emissions is the main driver behind the recent push for a broader use of green and carbon neutral processes. The UBC Powerhouse, responsible for providing heat to the entire campus, is currently using natural gas as its main source of fuel. Although natural gas has relatively low air emissions and is quite inexpensive, the unwanted production of CO_2 is a challenge for Canada's goal of being carbon neutral in the future. An alternative method must therefore be adopted. Many European nations such as Sweden and Finland are widely adopting the use of wood pellets in producing heat and energy for residential and commercial use. The bulk of wood pellets consumed in Europe are from Canada. The Canadian government and various corporations are trying to harness the availability of this resource. Gasification of wood pellets followed by combustion of syngas is a feasible and economically sensible way of producing clean steam for heating purposes.

The scope of this project is to environmentally and economically compare the two different energy systems (Case 1 and Case 2). The two systems produce the same amount of energy for comparison. In 2007, UBC consumed 1,018,125GJ of natural gas to produce 726,370 klbs of steam for heating. The energy provided from the steam is about 900,000 GJ. The goal of this project is to use wood pellets technology to generate the same amount of steam. A functional unit of 900,000 GJ delivered heat is chosen which is equivalent to the energy value of the steam produced. This report studies the feasibility of replacing natural gas with wood pellets for UBC boilers through life-cycle assessment (LCA), environmental and health impact analysis, emissions analysis, and cost analysis.

2.0 Life Cycle Assessments

LCA is a systematic method used to evaluate the environmental impacts of a material or product throughout the entire life cycle. A whole life cycle includes all processes from the cradle to the grave. In this report, a life-cycle audit is conducted on each stages of product within the defined boundaries to obtain a life-cycle inventory of emissions and cost for the products.

2.1 Life Cycle Boundaries

The boundary of a process can have significant impact on the ranking of potential pollution prevention modifications. In case 1, the cradle is chosen to be the natural gas field. In case 2, the cradle is the trees in the forests. Figure 1 shows the flowcharts of life cycle of natural gas and wood pellets.

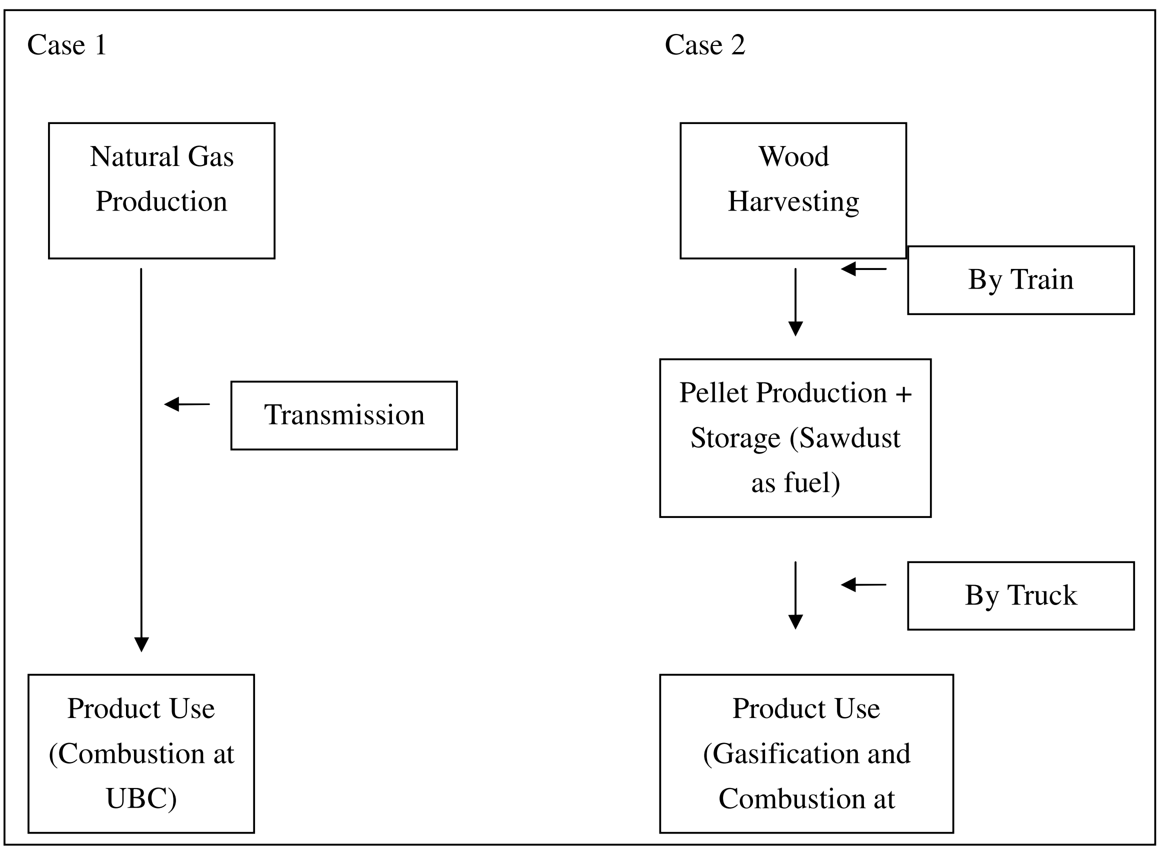

Figure 1. Life Cycles of Natural Gas and Wood Pellets

3.0 Methodology

To evaluate the environmental impact, the emissions from each stage of the cycles are calculated. Average emission factors are obtained from different sources to calculate the emissions. Four environmental impact indicators, global warming potential (GWP), acid rain potential (ARP), human toxicity potential (HTP) and smog formation potential (SFP), are used to quantify the environmental impact.

3.1. Wood Pellet Life Cycle Methodology - (By Jill Craven)

Energy consumption data for the wood pellet life cycle was collected from a various sources. The major upstream stages in the wood pellet life cycle are harvesting, sawmill, pellet mill, storage, and transportation. The final end-of-use stage largely depends on each independent case study.

For the harvesting stage, diesel fuel consumption was taken from and Advantage Journal Article by Sambo published in 2002. The paper, entitled *Fuel consumption for ground-based harvesting systems in Western Canada,* was published by the Forest Engineering Research Institute of Canada FERIC. The fuel consumption data was collected from a study that surveyed several representative harvesting operations. This is considered the best published data available for fuel consumption during harvesting at this time. Currently, FERIC is working on a research project to improve the data for fuel utilization in the harvesting and transportation of wood. Once this data is published, the harvesting stage should be revised for a more complete life cycle analysis. Emission factors for diesel consumption were taken from the US EPA AP 42 document, which can be found online. Since there is no inventory of the exact equipment that is used to harvest and transport wood, the general emission factor of "Diesel industrial Engines" in section 3.3 of the AP 42 document was applied.

Energy consumption data for the sawmill portion was taken from a report produced by The Canadian Industrial Energy End – Use Data and Analysis Centre (CIEEDAC) based out of the Energy and Materials Research Group at Simon Fraser University. The data is complied from statistics Canada, which is a reliable source for the wood pellet life cycle. Emission factors for the fuel consumption of natural gas, heavy fuel oil, middle distillates, propane, and wood waste were applied from the AP 42 document. The emissions associated with electricity consumption were carried out by approximating the electricity mix for British Columbia to be 79 % hydro, 17% coal and 4% natural gas based on how much electricity Canada purchases from the United States and based on how British Columbia produces electricity. Emission factors were applied from the AP 42 document for the coal and natural gas. A journal article by Pehnt provided emission factors for the hydro-electric power.

The pellet mill operation and storage energy consumption data was acquired from a survey of the members of the Wood Pellet Association of Canada. The energy consumed included electricity, wood waste, gasoline, and diesel. The emission factors were applied in the same way as the sawmill operation.

3.2 Natural Gas Life Cycle Methodology

The emission factors for the natural gas upstream cycle were obtained from GHGenius, a model developed for Natural Resources Canada. It provides total emissions over the whole upstream fuel-cycle, per unit of energy delivered to end users. Emission factors for natural gas combustion were taken from the US EPA AP 42 document.

4.0 Environmental and Health Impacts Analysis

Emissions are calculated on each stage of the cycle. The upstream and local environmental impacts of natural gas and wood pellets are compared. Indicators such as global warming potential, smog formation potential and acid rain formation potential are used. Also, the upstream and local health impacts of the two energy sources are compared. Threshold limit values are used to estimate the human health impacts.

4.1 Energy Consumption

In case 1, the goal is to produce 900,000 GJ/year delivered steam by combusting natural gas. The amount of natural gas used per year is 1,018,125 GJ. Saturated steam is produced at a pressure of 162 psi from the natural gas boilers. The total efficiency of the UBC Powerhouse is about 89%.

In case 2, the goal is to produce the same amount of heat as in Case 1 using wood pellets. Synthesis gas is produced from wood pellets in a low-oxygen prolysis process. The gas is then is reformed in the gasifier into a mixture of carbon monoxide, hydrogen and methane. The gas is then combusted with air in order to raise the temperature of the gas. The hot gas is fed into a boiler to generate steam. The efficiency of the system is assumed to be 85%. Wood pellets have an average calorific value of 18 GJ/tonne, and in order to produce 900,000 GJ/year delivered steam, about 60,000 tonnes of wood pellets are needed every year.

4.2 Upstream Fuel-cycle Emissions

The total emissions in the upstream fuel-cycle for the two cases are compared. The upstream cycle in case 1 includes production and transmission of natural gas. It is assumed that the natural gas used in UBC is produced from natural gas fields. GHGenius 2007 provides information about the total emissions over the whole upstream fuel-cycle of natural gas. The emissions for the upstream cycle of natural gas are presented in Table 1.

The upstream cycle in case 2 includes harvesting, pellet production, and transportation. About 60,000 tonnes of wood pellets are required every year for steam production. The emissions for each stage of the upstream cycle of wood pellets are presented in Table 2.

Table 1 Emissions from the Upstream Cycle of Natural Gas (GHGenius 2007)

Constituent	Emission Factor, g/GJ	Emission Rate, kg/year
CO_2	3,306.03	3,365,950
CO	26.95	27,437
CH_4	40.61	41,345
N_2O	0.10	102
NO_x	26.18	26,659
VOCs	1.39	1,415
PM	1.01	1,025
SOx	6.37	6,489

Table 2.Emissions from the Upstream Cycle of Wood Pellets

Stage	Harvest	Truck	Production and Storage*	Train	Total
Constituent	Emission, kg/year	Emission, kg/year	Emission, kg/year	Emission, kg/year	Emission, kg/year
CO_2	277,680	280,500	1,707,841	767,100	3,033,121
CO	8,100	1,590	13,823	2,016	25,529
CH_4	4,602	23	395	0	5,021
N_2O	510	4	16	0	529
NO_X	167	3,282	29,613	14,760	47,822
VOC	80,820	234	362	843	82,259
PM	27,120	157	852	515	28,644
SO_X	51,480	260	7,620	654	60,014

*Sawdust is assumed to be the fuel used for pellets production.

The total emissions from the upstream cycle for the two cases are compared, and the results are presented in Table 3. It can be observed that the CO_2 and CO emissions are slightly lower for case 1. However, the N_2O, VOC, PM and SO_X emissions from the second case are significantly higher. The increase in emissions is mainly due to the harvesting process of wood pellets.

Table 3. Comparison of Upstream Emissions for the Two Energy Sources

Emissions	Natural Gas, kg/year	Wood Pellets, kg/year	% Change
CO_2	3,365,950	3,033,121	-10
CO	27,437	25,529	-7
CH_4	41,345	5,021	-88
N_2O	102	529	419
NO_X	26,659	47,822	79
VOC	1,415	82,259	5713
PM	1,025	28,644	2695
SO_X	6,489	60,014	825

4.3 Local Emissions

The local environmental impacts of the two energy sources are examined and the expected emission rates on campus are calculated.

In Case 1, the fuel consumption of natural gas is 1,018,125 GJ/year. With a heating value of 1000 Btu/ft^3 (0.039 GJ/m^3) for natural gas, about 26,000,000 m^3 of natural gas was consumed last year. The emission coefficients for the combustion of natural gas were obtained from AP42. The emission coefficients and the emission rates are presented in Table 4.

In Case 2, the amount of wood pellets required is estimated to be 60,000 tonnes/year. The expected emission coefficients during gasification and combustion of synthesis gas were obtained from Nexterra Energy Corp. The emission coefficients and the expected amounts of emissions during gasification and combustion are presented in Table 5.

Table 4. Emissions during Natural Gas Combustion (AP 42)

Constituent	Emission Factor, kg/10^6 m^3	Emission, kg/year
CO_2	1,920,000	50,028,057
CO	1344	35,020
CH_4	36.8	959
N_2O	10.24	267
NO_x	2,240	58,366
VOC	88	2,293
PM	121.6	3,168
SO_x	9.6	250
TOC	176	4,586

Table 5. Expected Emissions during Gasification and Syn-gas Combustion (Nexterra.Energy)

Constituent	Emission factors, lbs/MMBtu input	Emission factors, kg/tonne of wood	Emission, kg/year
CO_2	205	1495.630	89,737,827*
CO	0.05	0.365	21,887
CH_4	Trace only	Trace only	Trace only
N_2O	Trace only	Trace only	Trace only
NO_x	0.15	1.094	65,661
VOC	0.0043	0.031	1882
PM	0.008	0.058	3,502
SO_x	Trace only	Trace only	Trace only
TOC	0.0085	0.062	3721

*CO_2 emitted from the combustion of biomass is considered to be carbon neutral.

The local emissions from the two systems are compared, and the results are presented in Table 6. It can be observed that, by replacing natural gas with wood pellets, the CO_2, NO_x, PM, emissions increase. Since the ratio of C to H is almost double for wood to natural gas, the CO_2 emission is higher, but CO_2 emitted is considered to be carbon neutral. Since wood pellet is biomass, and when they are burned, the carbon dioxide is essentially “recycled” back into the environment. In theory, the burning of wood pellets does not result in net emission of CO_2. The NO_x and PM emissions in case 2 can be further reduced by installing different treatment units. This is discussed in section 5 of this report. Also, since wood biomass has very low sulphur content, the SO_x emission is lower.

Table 6. Comparison of Local Emissions for the Two Energy Sources

Emission	Natural Gas, kg/year	Wood Pellet, kg/year	% change
CO_2	50,028,057	89,737,827*	79
CO	35,020	21,887	-38
CH_4	959	N/A	N/A
N_2O	267	N/A	N/A
NO_X	58,366	65,662	13
VOC	2,293	1,882	-18
PM	3,168	3,502	11
SO_X	250	N/A	N/A
TOC	4,586	3,721	-19

*CO_2 emitted from the combustion of biomass is considered to be carbon neutral.

4.4 Total Emissions from Natural Gas and Wood Pellets

The total emissions for the two cases are presented in Table 7. As expected, the amount of CO_2 decreases when wood pellets are used as the energy source. Also, the study shows a reduction of CO, CH_4 and TOC. However, some other important emissions increase, such as VOC, PM and SO_X. These emissions depend very much on the wood harvesting stage.

Table 7. Comparison of the Total Emissions for the Two Energy Sources

	Total		
Emissions, kg/year	Natural Gas	Wood Pellets	% change
CO_2	53,394,007	29,93,280	-94
CO	62,457	46,913	-25
CH_4	42,304	4,943	-88
N_2O	369	524	42
NO_X	85,025	112,791	33
VOC	3,708	84,070	2167
PM	4,193	32,146	667
SO_X	6,739	60,014	791
TOC	4,586	37,21	-19

The total emissions for the two cases are presented in Table 7. As expected, the amount of CO_2 decreases when wood pellets are used as the energy source. Also, the study shows a reduction of CO, CH_4 and TOC

4.5 Environmental and Human Impacts

In order to understand the environmental impacts of the two systems, the environmental impacts are evaluated in terms of global warming potential (GWP), acid rain potential (ARP), and smog formation potential (SF). Also, the human health impact is evaluated using threshold limit values (TLV). An overview of the environmental and human health impacts of the two energy sources is provided in Table 8.

Table 8. Environmental and Health Impacts for the Two Energy Sources

	Upstream Fuel-Cycle			Local			Total		
	Natural Gas	Wood Pellets	% Change	Natural Gas	Wood Pellets	% Change	Natural Gas	Wood Pellets	% Change
GWP, kg eq CO_2/year	5,553,434	5,557,435	0	52,540,516	2,674,459	-95	58,093,950	8,231,893	-86
ARP, kg eq SO_2/year	25,150	93,490	272	41,106	45,963	12	66,257	139,453	110
SF, kg eq ORG/year	5,007	255,077	4,995	2,298	1,882	-18	7,304	256,960	3418
Health* Impact, kg/hr/ppm	13,905	47,689	243	31,001	22,770	-27	44,906	70,459	57

* Health impact is evaluated based on TLV.

Taking into consideration impacts to the local community, using wood pellets as the energy source decreases global warming impact, smog formation and human health impact. However, when the whole life-cycle is taken into consideration, smog formation, acid rain potential, and health impact are comparatively higher.

5.0 Regulations and Air Emission Reduction Units

In order to meet the regulations under the *Environment Management Act* with regards to air emissions, treatment units must be implemented to improve the air quality of the flue gas prior to release. Using the expected local emission released without control in Table 6 as a basis, and comparing these results to Table 9; it was found that the pollutants such as PM and NO_x emissions would require further control to meet the current *Air Quality Management Laws*. One would like to further control the particulate emissions and NO_x as the reduction of the system's carbon footprint is a priority of UBC.

Table 9. Emission Limits for Boilers and Heaters in GVRD

Contaminant / Parameter	Emission Limit	
	Natural gas or propane* (new or modified)	Biomass** (new or existing)
Particulate matter, filterable (mg/m3)	5	15 ***
Particulate matter, condensable (mg/m3)	10	15
Nitrogen oxides (mg/m3)	60	120 ****
Carbon monoxide (ppmv)	400	400
Opacity (%)	5	5

5.1 PM Control Technologies

Due to the unique design of the gasifier, the bulk of the ash and PM are captured through the hopper and removed. The ESP is hence used to collect the remaining ash and PM.

Electrostatic precipitator (ESP) is a particulate control device that uses electrical forces to move particles flowing within an exhaust stream onto surrounding collection surfaces. It will be the main unit in capturing and controlling PM of the flue gas. Electrodes in the center of the flow lane are maintained at high voltage and generate an electrical field that forces particles to the collector walls. Dust and ash particulates are stuck to the surface of such walls; gentle shaking or pulsing forces enacted on these surfaces cause these particles to gently fall down into the collecting hopper. Typical new equipment design efficiencies are between 97 and 99.9%. ESP size is the most important factor in determining the collection efficiency. Assuming 99% treatment efficiency, the calculated PM emission released into the environment is found to be 35 kg/year.

The unit size determines "treatment residence time; the longer a particle spends in the ESP, the greater its chance of being collected. Maximizing electric field strength will maximize ESP collection efficiency. Some factors that affect the collection efficiency are dust resistivity, gas temperature, chemical composition, and particle size distribution" (Cheremisinoff, 418). In addition, ESPs generally have a low pressure drop and a minor affect on the gas flow; hence the energy requirements and operating costs are relatively low. The flowing figure shows the components of an ESP.

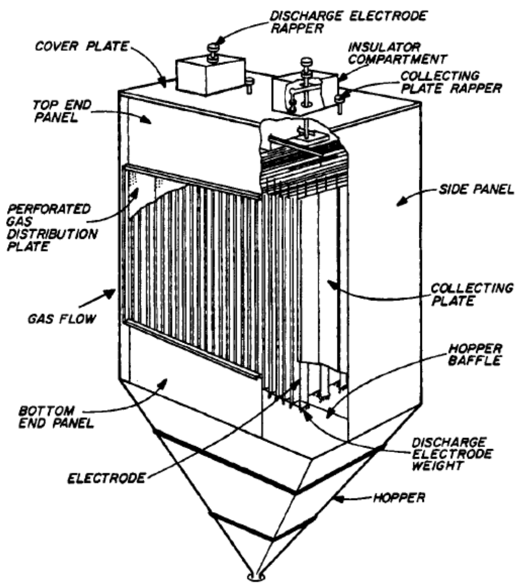

Figure 2. Design components of an ESP

5.2 NO_x Control Technologies

There are three ways to capture and reduce nitrogen oxides prior to release: absorption, selective non-catalytic reduction, and selective catalytic reduction (SCR). The most suitable choice for the UBC boiler house would be the use of SCR units. This SCR type will not require the use of ammonia; a reduction in cost and the elimination of a hazardous material is therefore an added advantage. The catalyst in use will be composed of ferric-zeolite reacting in a fixed bed or fluidized bed reactor. The reaction (eq. 1) uses the injection of hydrocarbons to thermodynamically favor the yield of N_2 and CO_2.

$NO + HC + O_2 => N_2 + CO_2 + H_2O$…… (1)

The reduction efficiency is in the range of 75 - 90%. Assuming 80% treatment efficiency, the new NO_x emission would be 13,132 kg/yr. However, some challenges of using this technology is having a low selectivity, and a potential for catalyst poisoning in the presence of water. This treatment method is currently not required for today's air emission standards; however, it is a good recommendation for implementation when such standards become stricter.

6.0 Implementation

In the initial stage, it would be more economical to size the gasification system for partial implementation. This means that wood pellets would only be used to supply a fraction of the energy required to generate the steam needed for sufficient heating. This was a suggestion made by Mr. Dejan Sparica, VP and Chief Engineer of Nexterra Energy Corporation. The biomass gasification system is to be retro-fitted into the natural gas boilers which run the existing UBC heating system. Wood pellets will be used to generate syngas in the gasifiers, which will then be combusted in the existing boilers to generate steam.

The UBC Powerhouse 2007 year end report indicates the difference in natural gas usage (in GJ) throughout the year. The 2007 annual report broken down by month and organized by decreasing natural gas consumption is summarized in the plot below:

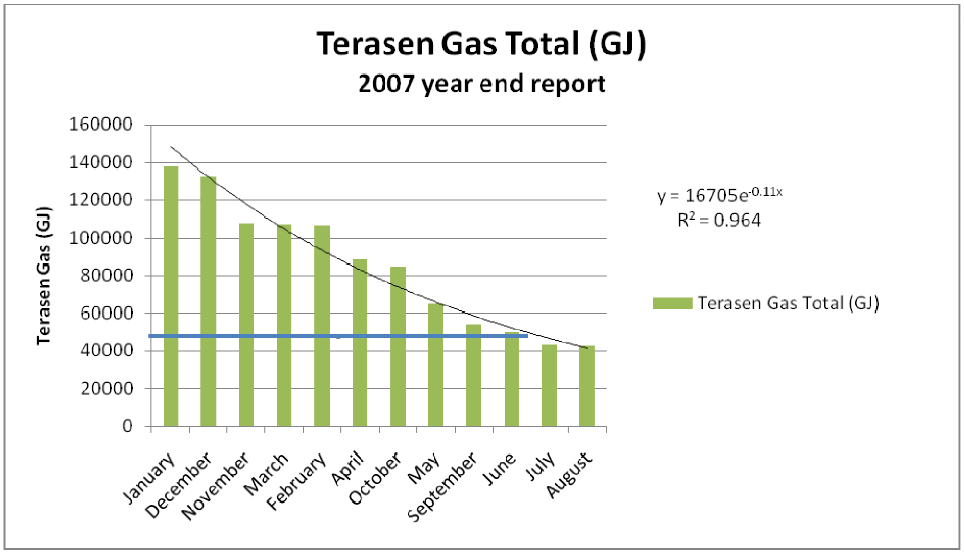

Figure 3. UBC 2007 Natural Gas Consumption

As expected, the natural gas consumption is highest during the winter. To project the monthly energy consumption, an exponential curve was fitted to the 2007 energy consumption data. As mentioned above, a partial implementation of the gasification system is proposed. This means that the gasifier will run at around 100% capacity throughout the year. The blue line shown in Figure 3 is the cut off point at around 50,000 GJ of natural gas. Thus area under the blue line in the plot above indicates the energy that is going to be supplied by wood pellets while the area above the line indicates the energy supplied by natural gas.

Approximately 34,700 ton/yr of wood pellets is required to replace the 594,000 GJ/yr of natural gas needed to generate the annual steam requirement. The mass of wood pellets used per year will generate around 420,000 klbs/yr of steam and the natural gas requirement per year will become 458,000 GJ compared to the original 1,053,000 GJ per yr.

6.1 Economic Analysis

An economic analysis was conducted to estimate the cost difference of implementing the gasification system. A preliminary analysis indicates that the new system, which combines the use of wood pellets and natural gas as fuel, results in annual savings of approximately $2.0 million. The following is a breakdown of the economic analysis.

The cost of natural gas and wood pellets were initially compared. From the Terasen Gas website, the average natural gas cost was marked as $6.95/GJ not including transportation cost. The cost of wood pellet is $110/ton, quoted by Peter Brand, Marketing VP at Pinnacle Pellet Incorporated. Comparing the current heating system (only natural gas as energy source) and the proposed system, an additional cost of $1.6 million would be required for the proposed system.

The transportation cost of wood pellets from interior BC to Vancouver by rail is estimated to be $20/ton. This estimate was provided by Staffan Melin, Research Director for the Wood Pellet Association of Canada. The delivery and midstream charge of natural gas is $2.75/GJ and $1.33/GJ respectively. The emission costs also need to be taken into consideration. Table 10 lists the emission costs imposed by Metro Vancouver for various air pollutants. Note that not all air contaminants were included in the new pricing regulation section. Therefore, for the unlisted air contaminants, the existing emission fees for general air contaminants were used. After taking into account transportation cost and emission costs, it was found that implementing the new system would generate annual savings of around $2 million. Several factors were not taken into account in this economic analysis. The additional equipment costs were not taken into consideration because it was difficult to get an exact quote for the gasification system. The account for these costs could significantly influence the outcome of this economic analysis. In addition, the costs

Table 10. Emission fees for air contaminants

Air Contaminant	Proposed Emission Fee (per tonne of air contaminant)	Change from proposal in issue paper	Existing Emission Fee (per tonne of air contaminant)
Particulate Matter (PM), from combustion sources (includes filterable and condensable)	$300	Combustion particulate matter defined to include filterable and condensable portions.	$60 for all contaminants, except odour
Particulate Matter (PM), from other than combustion sources	$30	No change	
Nitrogen Oxides (NOx)	$50	No change	
Volatile Organic Compounds (VOC)	$30	No change	
Sulphur Oxides (SOx)	$100	No change	
Total Reduced Sulphur (TRS)	$150	No change. TRS is defined to include, but not be limited to, hydrogen sulphide, dimethyl sulphide, dimethyl disulphide and methyl mercaptan.	
Air toxics (and metals)	$1,000	Emission fee increased and definition of air toxics broadened.	
Other (not otherwise specified)	$30	No change. "Other" contaminants include any contaminants specified in permits and not listed or specified elsewhere in this table.	
Odour	$50 (fee per billion odour units)	No change	$0

associated with emission control equipment were ignored in this analysis. Another major factor that was not taken into consideration is the fluctuation of fuel cost. In fact, the cost of natural gas fluctuates quite frequently so it will have a significant effect on the overall cost.

7.0 Conclusion

A biomass gasification system is proposed to be implemented into the existing natural gas boilers that generate steam for the UBC heating system. The environmental impacts of the two energy sources are compared. It can be observed that the amount of carbon dioxide emitted has significantly decreased when the wood pellet gasification system is implemented. Thus, there is a large reduction in global warming potential. However, other emissions such as NOx, VOC, PM and SOx have increased. The amount of PM and NOx when burning wood pellets can be further reduced by using electrostatic precipitator and selective catalytic reduction method. The majority of VOC and SOx emissions are mainly from the machines used to harvest woods. A more environmental-friendly wood harvesting method should be developed to reduce VOC and SOx emissions.

In the initial stage of implementation, the gasification system, which gasifies wood pellets into syngas, will only provide a fraction of the energy required to generate the annual steam requirement while the rest of the energy requirement is fulfilled by natural gas. The mass of wood pellets required for this plan is 34,700 tons/yr. The amount of steam generated from biomass is approximately 420,000 klbs/yr. A preliminary economic analysis showed that implementation of the new system which utilizes wood pellets and natural gas for the production of steam generates an annual saving of approximately $2 million. The factors taken into account for this analysis include fuel cost, transportation cost and emission costs. The additional costs for new equipment such as the gasifiers and emission control equipment were not taken into consideration.

Reducing the university's carbon footprint is a primary goal. Since gasifying wood pellets sharply cuts greenhouse gas production and also costs lower, it is a feasible and economically sensible method to deliver heat in UBC.

References

Allen, David T., and David R. Shonnard. Green Engineering: Enviornmentall Conscious Design of Chemical Processes. Upper Saddle River: Prentice Hall PTR, 2002.

GVRD, Jan 08. "Proposed Amendments to the Air Quality Management Bylaw". http://www.gvrd.bc.ca/air/pdfs/Prop_Amend_to_AQ_Mngmt.pdf

Nicholas P. Cheremisinoff, 2002. "Handbook of air pollution prevention and control" Elsevier Science, USA.

Nyboer, John. "A Review of Energy Consumption and Related Data in the Canadian Wood Products Industry: 1990, 1995 to 2006." Canadian Industrial Energy End-Use Data and Analysis Centre, Simon Fraser University. March 2008 <http://www.cieedac.sfu.ca/CIEEDACweb/pubarticles/Industry%20-%20Forest%20Products/Wood%20Products%20Report%202007%20_2006%20data_%20Final.pdf>.

Sambo, Stephanie. "Fuel consption for ground-based harvesting systems in western Canada." Advantage 3.29 (2002): 1-12.

Pehnt, Martin. "Dynamic life cycle assessment (LCA) of renewable energy technologies." Renewable Energy. 31(2006): 55- 71.

US EPA. AP 42: Compilation of Air Pollutant Emission Factors. 5.1 Office of Air Quality Planning and Standards, Office of Air and Radiation, U. S. Environmental Protection Agency, 1995. <http://www.epa.gov/ttn/chief/ap42/index.html>.

Acknowledgements

Mr. Dejan Sparica, PEng., VP and Chief Engineer of Nexterra Energy Corp.

Jill Craven, graduate student from the Biomass and Bioenegy Research Group

Dr. Yan Li, Product Development Engineer of Nexterra Energy Corp.

Appendix - Sample Calculations

1. Heat produced from the UBC Powerhouse

Amount of steam produced = 726,370 KLBS = 329481432 kg

Saturated Steam at 160 psi, heating value of steam = 2,780 kJ/kg

Heat delivered = 329,481,432 kg x 2780 kJ/kg = 915,958 GJ ≈ 900,000 GJ

2. Efficiency of the UBC Powerhouse

Amount of natural gas required = 1,018,125 GJ

Efficiency = 915,958/1,018,125 = 0.89

3. Amount of wood pellets required to generate 900,000 GJ

Heating value of wood pellets = 18GJ/ton

85 % efficiency is assumed

Amount of wood pellets = 900,000/18/0.85 = 58,823 tons ≈ 60,000 tons

4. Cut off point of natural gas

Exponential fit for Terasen Gas 2007 year end report
(Arranged in order of magnitude by month)

$E_{NG} = 16705 \times e^{-0.11(month)}$ Where, E_{NG} = GJ of Terasen Gas

	2007 Year end steam generation	
Month	**Total Line Steam (KLBS)**	**Terasen Gas Total (GJ)**
January	100320	137663
December	96072	132406
November	76986	107322
March	75359	106830
February	76125	106589
April	63545	88522
October	60990	84653
May	46974	64804
September	38271	53776
June	36055	49793
July	27610	43075
August	28063	42693

Generation of steam in klbs/GJ of NG consumed:

$$Y_{steam} = \frac{\overline{M}_{steam}}{\overline{E}_{NG}}$$

$$Y_{steam} = \frac{60530.8 klbs}{84843.8 GJ} = 0.707 klbs/GJ$$

Cut off line at 50,000 GJ of natural gas

5. Mass of wood pellet required to substitute cut off point of natural gas:

E_{NG} (July) = 49814 GJ/month

E_{NG} (August) = 44625 GJ/month

E_{NG} (other months) = 50000 GJ/month

$$M_{steam} = 50000 GJ/month \times 0.707 klbs/GJ$$
$$M_{steam} = 35369 klbs/month$$
$$E_{steam} = M_{steam} \times H_{steam}$$

Where, H_{steam} = 1.26 GJ/klbs

$$E_{steam} = 35369 klbs/month \times 1.26 GJ/klbs$$
$$E_{steam} = 44631.2 GJ/month$$

Gasifier + Boiler efficiency ($\eta_{overall}$) was assumed to be 85% in terms of GJ of steam per GJ of wood pellet

Heating value for wood pellet (H_{pellet}) = 18 GJ/ton

$$M_{pellet} = \frac{E_{steam}}{\eta_{overall} \times H_{pellet}}$$
$$M_{pellet} = \frac{44631.2 GJ/month}{0.85 \times 18 GJ/ton}$$
$$M_{pellet} = \underline{\underline{2917.1 ton/month}}$$
$$M_{pellet(10months)} = 2917.1 ton/months \times 10 months$$
$$M_{pellet(10months)} = \underline{\underline{29171 tons}}$$

The same is done individually for July and August because their energy requirements from NG are lower than 50.000 GJ.