A Conceptual Comparison of Using Bioenergy Options for BC's Mountain Pine Beetle Infested Wood

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Executive Summary

In November 2005, the author issued a report on the feedstock availability and cost of producing electricity from surplus Mountain Pine Beetle (MPB) killed trees in the Province of British Columbia. The report has generated considerable interest and discussion. As a follow-up to this report the author has carried out a preliminary conceptual engineering economic analysis to evaluate the feasibility of producing bio-ethanol and bio-oil from MPB killed wood.

The mountain pine beetle (MPB) infestation has caused considerable damage to the trees in British Columbia affecting approximately 10 million hectares of forest as of the summer of 2005. The infestation is expected to result in approximately 960 million m^3 of killed tree biomass by 2013 according to preliminary estimates. The unharvested killed trees could be used for bioenergy and biofuel production.

This study estimates the cost of production of bio-ethanol and bio-oil using MPB killed trees for two locations in British Columbia: West Road/Nazko River and Quesnel. The analysis includes a detailed estimate of cost components for bio-ethanol and bio-oil production at both locations.

Bio-ethanol can be produced from a variety of biomass feedstocks. A typical bio-ethanol production process consists of feedstock preparation, pretreatment, hydrolysis (releasing of sugar), fermentation, distillation and by-product recovery. This study is based on a two-stage dilute acid hydrolysis process used in production of bio-ethanol from softwood. This process has been evaluated by the National Renewable Energy Laboratory (NREL) in Golden, Colorado, US.

The West Road/Nazko River production site is located approximately 100 km west of Quesnel along the West Road. This area was chosen because it has been identified as having a very high density of MPB killed trees that are forecast to otherwise go unharvested. However, because of the remoteness of the site, the West Road/Nazko River location would incur a premium for plant construction, estimated at 5% higher than Quesnel. The West Road/Nazko River site would also require transporting the bio-ethanol to the main distribution center in Quesnel. The cost of transporting bio-ethanol for 100 km was included in this study. The Quesnel production site is adjacent to Quesnel, B.C. in a region which has a lower density of MPB killed trees but has the advantage of lower plant construction costs. A slightly lower bio-ethanol cost was estimated for the Quesnel location.

Bio-oil is produced from the fast pyrolysis of lignocellulosic biomass. In addition to the production of bio-oil a high quality char and a combustible gas are also produced in the process. Bio-oil has a lower heating value than light fuel oil and diesel. Several research groups and companies have developed technologies for production of bio-oil from woody biomass. This study is based on the pyrolysis of softwood to produce bio-oil using the conversion process proposed by DynaMotive Energy Systems Corporation. As was done in the bio-ethanol analysis, bio-oil production costs were estimated for both the West Road/Nazko River and Quesnel locations. A 10% capital cost premium for the West Road/Nazko River location and a 5% captal cost premium for the Quesnel location are included in production estimates. These premiums are a capital cost penalty for the remoteness of a location from consumers, rail transportation and other related infrastructure. The cost of transporting bio-oil for 100 km from the West Road/Nazko River site to Quesnel is also included. A slightly lower cost is calculated for bio-oil production at the Quesnel site.

In this study, it is assumed that trees are cut, skidded to the roadside and whole trees are chipped. The chips are transported to the plant by a chip van truck where it is used to produce biofuel. In the case of bio-oil production, wood chips are further ground to improve heat transfer and a cost has been added for grinding. Note that only surplus MPB killed trees are harvested for fuel; other species continue to be harvested for existing uses.

Key results of the study:

Bio-ethanol production based on MPB killed tree

- Bio-ethanol cost is estimated for a plant at a capacity of 2,100 dry tonnes of biomass per day for both the West Road/Nazko River and Quesnel locations. The bio-ethanol plant at this size will produce about 190 million liters (50 million gallons) of bio-ethanol per year. A ratio of 0.58 is used in this study for actual yield to theoretical yield of bio-ethanol per unit weight of biomass. Each of these plants will require about 36 million actual m^3 (29 million merchantable m^3) of wood over 20 years irrespective of the two locations. The draw area for West Road/Nazko River and Quesnel locations are 85 km by 85 km and 110 km by 110 km, respectively. These plants will cost about $188 million and $197 million for the Quesnel and West Road/Nazko River locations, respectively.

- Figure S1 shows the cost of production of bio-ethanol as a function of capacity for both Quesnel and West Road/Nazko River locations. The cost of producing bio-ethanol remains fairly constant at a capacity ranging from 4,000 dry tonnes to 10,000 dry tonnes per day. With the increase in size of the plant, the capital cost per unit of capacity decreases and the cost of transportation increases. Hence, there is a capacity at which the total cost of production is minimum and in the case of bio-ethanol there is a wide range in capacity within which the cost of production is at a minimum.
- Table S1 shows cost components for a bio-ethanol plant at two locations in B.C. Capital recovery cost includes a 10% pre tax return on total capital. Cost of bio-ethanol production at the Quesnel site is lower than at the West Road/Nazko River site. Two main reasons: first is the higher capital cost of the West Road/Nazko River location; and, second is the bio-ethanol transportation cost for 100 km from West Road/Nazko River location to Quesnel. A plant at the West Road/Nazko River location will be away from a distribution network and hence bio-ethanol produced at this location is transported to Quesnel which has a developed distribution network. Other cost components for both the locations are the same.

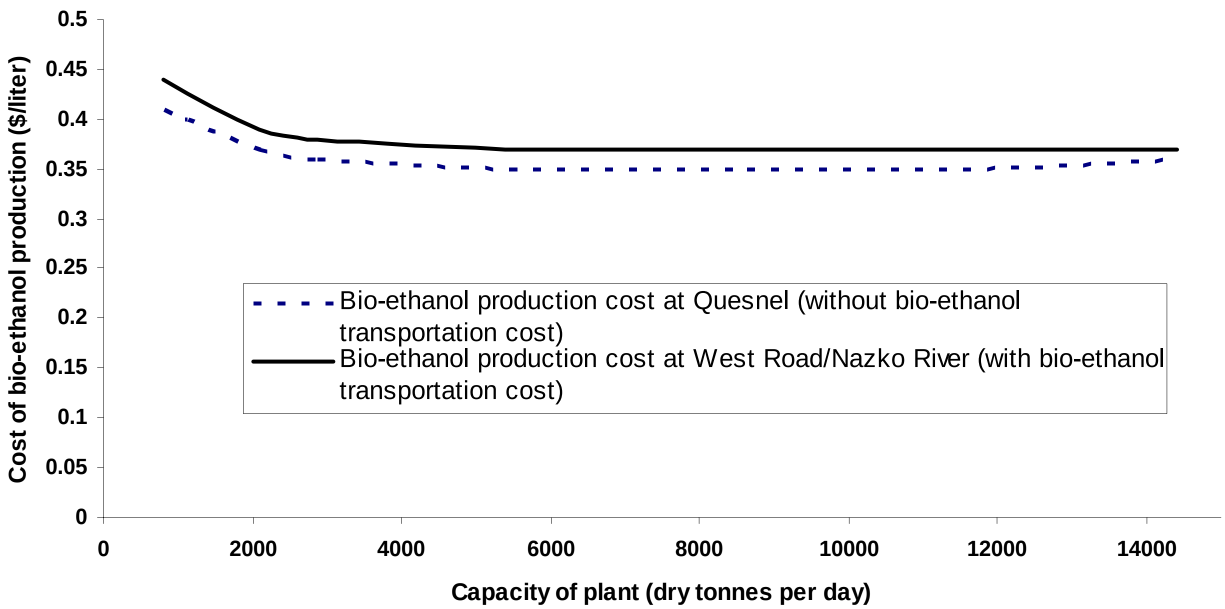

Figure S1: Bio-ethanol cost as a function of capacity for a MPB killed tree based plant.

Table S1: Bio-ethanol cost composition for a MPB killed tree based plant over 20 years

Cost elements	**West Road/Nazko River**	**Quesnel**
	$/liter ($/gallon)	$/liter ($/gallon)
Delivered Biomass Cost Components		
Harvesting cost	0.09 (0.36)	0.09 (0.36)
Transportation cost	0.04 (0.16)	0.04 (0.16)
Silviculture cost	0.02 (0.08)	0.02 (0.08)
Road Construction cost	0.03 (0.10)	0.03 (0.10)
Chipping cost	0.03 (0.11)	0.03 (0.11)
Total delivered biomass cost	***0.21 (0.80)***	***0.21 (0.80)***
Capital cost recovery	***0.07 (0.23)***	***0.06 (0.22)***
Operation and Maintenance Cost Components		
Maintenance cost	0.02 (0.07)	0.02 (0.07)
Operating and administration cost	0.02 (0.07)	0.02 (0.07)
Raw material cost	0.05 (0.20)	0.05 (0.20)
Bio-ethanol transportation cost	0.02 (0.08)	0.00 (0.00)
Total operation and maintenance cost	***0.12 (0.44)***	***0.10 (0.36)***
Total Bio-ethanol Production Cost from MPB Killed Wood	**0.40 (1.51)**	**0.37 (1.40)**

Bio-oil production based on MPB killed trees

- Bio-oil cost is estimated for a plant at a capacity of 220 dry tonnes of biomass per day for both the West Road/Nazko River and Quesnel locations. The bio-oil plant at this size will produce about 40 million liters (10 million gallons) of bio-oil per year. This study uses a yield of 66% (weight basis) of bio-oil per unit weight of biomass. The plant will require about 3.5 million actual m^3 (2.8 million merchantable m^3) of wood over 20 years. This amount of wood is the same for both locations. The draw area for West Road/Nazko River and Quesnel locations are 27 km by 27 km and 35 km by 35 km, respectively. These plants will cost about $18.5 million and $19.4 million for Quesnel and West Road/Nazko River locations, respectively.

- Figure S2 shows the cost of production of bio-oil as a function of capacity for both Quesnel and West Road/Nazko River locations. Bio-oil cost decreases as the capacity of the of the plant increases. Hence a larger plant size will benefit from economies of scale. The bio-oil plants are on a smaller scale as compared to the bio-ethanol plants. The technology is developing and a larger plant may be realized in the future. The curve shows that the optimum size plant is much larger than the size considered in this study.

- Table S2 shows cost components for a bio-oil plant located in the same two locations as the bio-ethanol plants. Capital recovery cost includes a 10% pre tax return on total capital. Cost of bio-oil production at Quesnel is lower than at the West Road/Nazko River location. Two main reasons: first - the high capital cost for West Road/Nazko River location; second - the bio-ethanol transportation cost for 100 km from the West Road/Nazko River location to Quesnel which has a developed distribution network. Other cost components for both locations are the same.

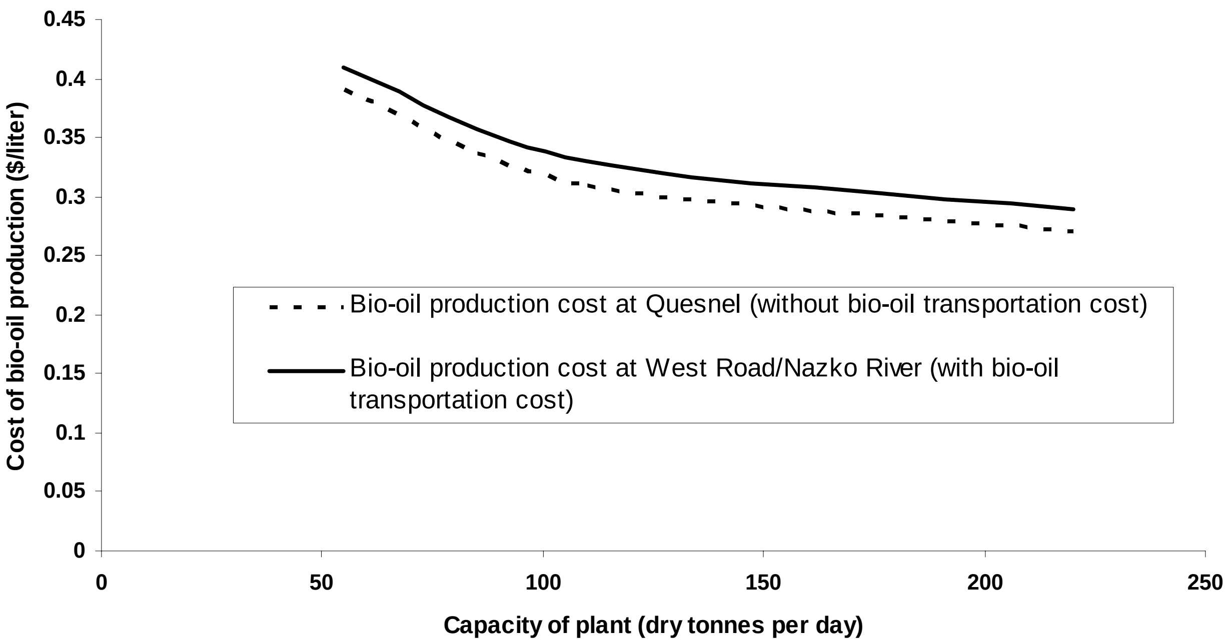

Figure S2: Bio-oil cost as a function of capacity for a MPB killed tree based plant.

Table S2: Bio-oil cost composition for a MPB killed tree based plant over 20 years

Cost elements	West Road/Nazko River	Quesnel
	$/liter ($/gallon)	**$/liter ($/gallon)**
Delivered Biomass Cost Components		
Harvesting cost	0.04 (0.17)	0.04 (0.17)
Transportation cost	0.01 (0.04)	0.01 (0.04)
Silviculture cost	0.01 (0.04)	0.01 (0.04)
Road Construction cost	0.01 (0.04)	0.01 (0.04)
Chipping and grinding cost	0.02 (0.08)	0.02 (0.08)
Total delivered biomass cost	***0.10 (0.38)***	***0.10 (0.38)***
Capital cost recovery	***0.05 (0.20)***	***0.05 (0.20)***
Operation and Maintenance Cost Components		
Maintenance cost	0.04 (0.17)	0.04 (0.17)
Operating and administration cost	0.02 (0.08)	0.02 (0.08)
Miscellaneous chemicals and water cost	0.02 (0.08)	0.02 (0.08)
Non production utilities and labor cost	0.01 (0.04)	0.01 (0.04)
Cost of electricity usage	0.01 (0.04)	0.01 (0.04)
Cost of natural gas usage	0.01 (0.04)	0.01 (0.04)
Bio-oil transportation cost	0.02 (0.08)	0.00 (0.00)
Total operation and maintenance cost	***0.14 (0.52)***	***0.11 (0.52)***
Total Bio-oil Production Cost from MPB Killed Wood	**0.29 (1.09)**	**0.27 (1.02)**

Key recommendations:

- Bio-ethanol production in Canada is growing rapidly. Most of the bio-ethanol produced today in Canada is based on corn and wheat. The average cost of bio-ethanol production from grain is in the range of $0.35 - $0.45 per liter. In this study, the cost of bio-ethanol production from a plant using 2,100 dry tonnes of MPB infested pine wood per day is in the range of $0.37 – $0.40 per liter and is competitive with the grain based ethanol production. But the technology for production of bio-ethanol from softwood is still in the developmental stages and there is no large scale commercial plant operating today. With the support of government a demonstration plant for bio-ethanol production based on MPB killed wood is a possibility in the near future.

- This study found that the cost of Bio-oil production ranges from $0.27 to $0.29 per liter for a plant processing 220 dry tonnes of MPB infested wood per day. Bio-oil can be used for production of electricity and a plant at this level of production capacity can support a 10 MW power plant if all the produced bio-oil is used to generate electricity. By extrapolating the estimates reported by Dynamotive Energy Systems Corporation, the calculated cost of electricity production from a bio-oil plant based on MPB infested wood using a gas turbine generator system is above $100 per MWh at a delivered feedstock cost of about $75 per dry tonne for Quesnel and West Road/Nazko River locations. Electricity generation from bio-oil is not competitive with the existing electricity price in BC. The economic viability of alternative uses of bio-oil such as the use of bio-oil for the production of high value chemicals should be explored and evaluated.

Table S3: Comparison of bioenergy options for MPB infested wood

Options	*Economics*	*Status of Technology*	*Comments*
Bio-ethanol	• Cost of production of bio-ethanol from a centralized plant based on MPB infested wood ranges from $0.37 – $0.40 per liter. • Bio-ethanol based on MPB killed tree is competitive with grain based alcohol ($0.35 - $0.45 per liter) • MPB based bio-ethanol is expensive than gasoline.	• No large scale centralized plant based on softwood is operating commercially today. • Technology is still under development.	• Not an option to be implemented immediately.
Bio-oil	• Cost of production of bio-oil from a centralized plant based on MPB infested wood ranges from $0.27 to $0.29 per liter. • Cost of production of electricity (from a gas turbine coupled with a generator) based on bio-oil produced from MPB infested wood is above $100 per MWh at a feedstock cost of about $75 per dry tonne. • Electricity from MPB infested wood based bio-oil is expensive than existing power price in BC.	• No large scale stand alone power plant based on bio-oil from softwood is operating commercially today. • Technology for large scale stand alone power plant based on bio-oil is still under development.	• Not an option to be implemented immediately. • Economics of production of high value chemicals or combined heat and power plant can be evaluated.
Bio-power (evaluated in earlier study by Kumar et al., 2005)	• Cost of electricity production based on direct combustion of MPB infested wood is in the range of $68 to $74 per MWh. • Electricity production from direct combustion of MPB infested wood is expensive than existing power price in BC.	• Large scale biomass power plant operating today (e.g. 240 MW biomass power plant at Pietarsaari, Finland). • Technology for electricity generation from direct combustion of biomass is mature.	• It is a feasible and viable option today with government subsidy for green power. • This technology can be implemented immediately.

In summary, MPB killed wood provides a unique opportunity to convert otherwise wasted biomass in B.C. to useful biofuels and biopower. Conversion of MPB infested wood to bio-ethanol and bio-oil provides more options for utilization of this wood resource, but today, these options are not as mature and lucrative as compared to the electricity generation from direct combustion of MPB wood in a large scale power plant. Production of electricity by direct combustion of MPB infested wood can be implemented immediately, and it can help sustain jobs, contribute to a clean environment, potentially help Canada meet its obligations under the Kyoto accord, and put Canada at the forefront of biomass utilization.

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1. Background and Overview

Mountain pine beetle (MPB) infestation of BC's forest is expected to have a significant detrimental impact on the forest industry. The total area of infestation by summer of 2005 was about 10 million hectares. The infestation is expected to kill approximately 960 million m^3 of tree by 2013 (Clark, 2005). According to the estimates of BC's Ministry of Forests, 200-600 million cu. m of wood would remain unharvested. Regions where the damaged wood is not harvested will experience loss of jobs in the forestry sector and impact on the viability of communities. The unharvested biomass is a fire hazard to regrowing species, and hence there is the risk of even more economic damage. This unharvested wood, if left to decay in the stands, would release carbon into the atmosphere. Utilization of this wood for energy and other bio-based products use will help in reduction of greenhouse gas emissions (GHG) and contribute to Canada's commitment towards the Kyoto Protocol. Among different bioenergy options, it can be used to produce electricity and liquid biofuels such as bio-ethanol and bio-oil.

In a recent study, the author estimated the cost of generating power from MPB killed wood. The cost of power was estimated for two locations in British Columbia (B.C.) namely, West Road/Nazko River and Quesnel. The first location is the West Road/Nazko River area approximately 100 km west of Quesnel along the West Road. These areas were chosen because these have been identified as having a very high density of MPB killed trees that are forecast to otherwise go unharvested. The estimated cost of power for these locations is in the range of $68-$74 per MWh (Kumar et al., 2005a). A 300 MW power plant in these locations would consume about 64 million cu. m of wood over a 20 year lifetime, and hence is a significant sink for otherwise unharvestable wood. But other bioenergy options such as bio-ethanol and bio-oil production need to be evaluated and compared before any final decision is taken.

Bio-ethanol is the name given to the ethanol produced from biomass. Biomass feedstock can include a wide range of materials such as corn, bagasse, agricultural residues (straw or corn stover) or woody biomass (softwood or hardwood). Production of alcohol is not a new concept. Many plants around the world produce ethanol from corn. Annual production capacity of ethanol in the United States is about 4,330 million gallons per year (Ethanol Producers and Consumers, 2006) and additional capacity of 1,750 million gallons is under construction and expansion. In Canada about 63 million gallons of alcohol is produced annually (Agriculture and Agri-Food Canada, 2001). Most of the alcohol produced today is based on grain. Research is in progress in the area of production of bio-ethanol from woody biomass. Several authors have suggested various processes for production of bio-ethanol from woody biomass (Merrick & Company, 2004; Wooley et al., 1999; Wallace et al., 2003; Gregg and Saddler, 1997; Hamelinck et al., 2005; von Silvers and Zacchi, 1994). Bio-ethanol can be blended with gasoline and used as motor fuel. The specific technology used in this study will be discussed in subsequent section.

Bio-oil is an organic liquid which is dark brown in color. It is produced by the fast pyrolysis of biomass. Biomass feedstock can include forest biomass as well as agricultural biomass. Various research groups around the world have studied bio-oil and are developing technologies for its production and utilization (see for example, Grassi and Bridgwater, 1993; Juste and Monfort, 2000; Graham et al., 1994; Luo et al., 2004; CANMET, 2004). Several companies have developed processes to produce bio-oil and are in various stages of demonstration and commercialization (for example, Ensyn Group Inc., 2001; DynaMotive Energy Systems Corporation, 2001). Bio-oil can be combusted to produce electricity and can also be used in manufacturing of specialty chemicals. The specific technology used in this study will be discussed in subsequent section.

The proposed study looks at the alternative use of MPB killed wood in the Province of British Columbia at two locations: Nazko road and Quesnel region. This study is a follow-up work of utilization of mountain pine beetle infested wood for power generation. The objective of this study was to carry out a preliminary techno-economic analysis for using a portion of B.C.'s mountain pine beetle damaged pine for the production of bio-ethanol and bio-oil. The specific objective was to estimate the cost of bio-ethanol and bio-oil production ($/liter) from MPB killed trees based plants in two locations: West

Road/Nazko River and Quesnel. These locations are identified as most appropriate locations for biofuel plant based on the availability of large amount of unharvestable MPB infested wood (Eng, 2005a). This research work estimates the cost of biofuels production from harvesting and transporting a portion of the beetle infested pine wood to a dedicated conversion plant for a period of 20 years.

2. Current biomass feedstock potential and yield

The Province of British Columbia has a total land area of 94 million hectares. Timber productive forest land area is about 55% of the total land area. Timber productive volume for the province is about 10,595 million m^3 (Wood and Layzell, 2003). As of August, 2003, the annual allowable cut for the province was about 74.4 million m^3/yr of wood (Ministry of Forests and Range B.C. (MoFR), 2003). British Columbia's forest consists of both coniferous and deciduous tree species. The coniferous species include lodgepole pine, douglas fir, spruce, hemlock, cedar, and true firs. Among these lodgepole pine is the most susceptible to MPB attack. The extent of infestation is difficult to estimate because of the variability in the rate of infestation and the increase in infestation every year. MPB attacks mature trees that have larger diameters and thick bark, which helps protect the beetles from predators. MPBs attack the trees in a symbiotic relationship with blue stain fungi. Infected trees are typically 80-100 years old and have low resistance to the fungi. Beetles feed on the sapwood and the fungus attacks the tree's resistance mechanisms, resulting in the death of the tree (Pacific Forestry Centre, 2005). This study focuses on the killed lodgepole pine in the interior of B.C.

Current estimates are that at least 200 million m^3 of wood would remain unharvested (MoFR, 2003) and this may increase up to 600 million m^3. The area included in this study is the Quesnel timber supply area (TSA) and specifically locations where the MPB infestation is severe. Two sites within this study area were selected: the West Road/Nazko River area has a very high concentration of surplus MPB killed trees, and the Quesnel area is expected to have lower density but still a large amount of unharvested infested wood situated closer to a community, rail line, major access road and major transmission line. Figure 1 shows the study area. In this study the yield for 60 year or older lodgepole pine stands is estimated using the initial report by MoFR (Eng, 2005a) and also from personal communication with Marvin Eng of MoFR (Eng, 2005b). Actual amounts of MPB killed trees and the fraction of them that are surplus to existing forestry operations is under current re-evaluation within the MoFR, and yield figures may be adjusted in the future.

In this study we assume that MPB killed trees are cut and skidded to the roadside. At the roadside the whole tree is chipped and chips are transported to the plant by a chip van. Thus in this case limbs and tops are also chipped and used as fuel. Typically, the residues (limbs and tops) range from 15% to 25% of the total tree biomass in the forest. In this study we have assumed a value of 20% for the residues, and hence actual yield is 25% higher than merchantable volume. The final average standing yield per gross hectare for lodgepole pine is estimated at 64.1 m^3 for the West Road/ Nazko location and 37.5 m^3 for Quesnel location. Gross hectares include all other land uses such as other forest species and non-forest land use.

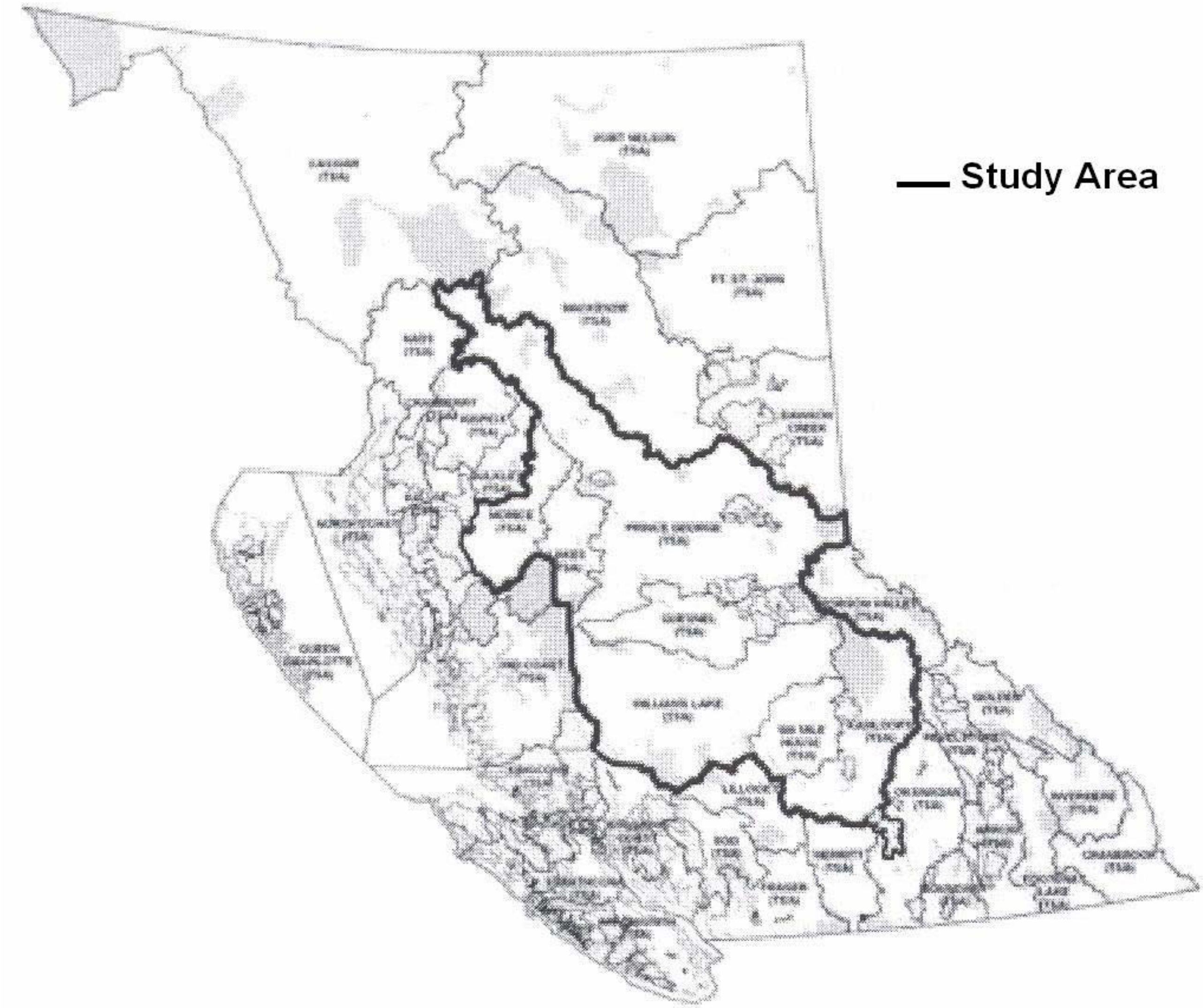

Figure 1: Map of the study region (Ministry of Forests and Range, 2003).

3. Biomass Characteristics and Composition

Equilibrium moisture content (EMC) of wood is one of the most important characteristics for its use as fuel as it has an impact on transportation cost as well as process yield. Water in the wood has a tendency to reach equilibrium with the surrounding air. The EMC of wood stored outdoors is a function of the surrounding temperature and relative humidity of the air. The temperature and relative humidity of air varies with the geographic location and time and hence the EMC varies. This study estimates the equilibrium moisture content of the wood based on equations developed by William Simpson of the United States Department of Agriculture Forest Service (Simpson, 1998). The equations for estimation of EMC are given in Appendix A. In this study EMC is estimated for Williams Lake, which is approximately in the center of the study area; its temperature and relative humidity are assumed to be representative of the study area. A detailed estimation of temperature and relative humidity of each sub-region in the study area is beyond the scope of this study. Average daily temperature and relative humidity data over 20 years for Williams Lake were gathered from Environment Canada (Environment Canada, 2005); the estimated average daily temperature and relative humidity used in this study were 4.2 ^{o}C and 67.6 %, respectively. The calculated value of EMC was 13% (dry basis); other assumed biomass properties are given in Table 1.

The density of logs depends on the equilibrium moisture content of wood and species specific gravity. In this study log density was estimated using the procedure detailed in Simpson (1993) at the calculated EMC. The equations used in this study are given in Appendix B.

Bio-ethanol yield depends significantly on the composition of wood (Aden, 2006). In this study, chemical composition of lodgepole pine (*Pinus contorta*) is assumed to be same as monterey pine (*Pinus radiata*). Chemical composition of monterey pine was used to estimate the theoretical yield of bio-ethanol based on *bio-ethanol yield calculator* developed by National Renewable Energy Laboratory in Colorado, US (Energy Efficiency and Renewable Energy, 2006).

Table 1: Wood properties

Items	Values	Comments/Sources
Average annual equilibrium moisture content (%, dry basis)	13	Based on the average temp. and relative humidity of Williams Lake. Calculated using equations given in Appendix A (Simpson, 1998).
Density of logs at given moisture content (kg/ m^3)	455.3	Calculated based on equations given in Appendix B. Density is for lodgepole pine logs at 13% EMC (Simpson, 1993).
Ash in wood (%)	2.5	(McDonald and Sauder, 2005).
Basic specific gravity for lodgepole pine, G_b	0.38	This value is used to estimate the density of logs at 13% EMC (equations given in Appendix B) (Simpson and TenWolde, 1999).
Monterey Pine (C5 & C6 polymers in weight %)		
• Glucan (%)	41.7	(Energy Efficiency and Renewable Energy, 2006)
• Galactan (%)	2.4	
• Mannan (%)	10.7	
• Xylan (%)	5.9	
• Arabinan (%)	1.5	

Note: all currency figures in this report are expressed in Canadian dollars and are in base year 2004 unless otherwise noted. Costs from the literature have been adjusted to the year 2004 using historical inflation rates; an inflation rate of 2% is assumed for 2005 and beyond.

4. Bio-ethanol Production from MPB Killed Wood – Scope and Cost

The scope of this part of study is a dedicated bio-ethanol production plant operating for 20 years using biomass from infested pine trees. Cost factors are developed for each element of the scope and are included in detail in this section. Note that for costs affected by scale, the costs are reported for plant capacity of about 2,100 dry tonnes per day. This is equivalent to a plant producing about 50 million gallons per year (MMGY) or 190 million liters per year (ML).

This study is based on the existing practices in the forest industry of western Canada. The study assumes clear-cutting throughout the infested pine plots, skidding the whole tree to the roadside, and whole tree chipping at the roadside. Trees are drawn from throughout the harvest area, giving a constant average transportation distance to the bio-ethanol plant over the life of the plant. The study draws on regionally specific detailed studies of the costs of recovering forest biomass performed by the Canadian Forest Service, the Ministry of Forest (British Columbia), the Forest Engineering Research Institute of Canada (FERIC), from other literature, and from personal discussions with researchers and equipment suppliers. Delivered biomass cost from different sources shows a wide variation as these studies include cost of different operations and systems. This study draws on cost studies by FERIC for most of the operations. Harvesting for fuel wood is simpler and involves fewer steps than harvesting for lumber or pulp: trees are not bucked or delimbed, and residues are not left over at the roadside, and trees are not loaded onto trucks but rather left at roadside for chipping. Hence, our costs are at the lower end of the range of FERIC estimates (MacDonald, 2005). The harvesting system in this study is a feller-buncher and a grapple skidder; tree-to-truck cost includes only felling and skidding. Truck loading and unloading costs are included in the transportation cost. Costs for construction of logging roads, and silviculture costs are included for harvesting the infested forest; these are a significant component of overall cost. Biomass cost in this study is thus based on full recovery of all costs associated with harvesting, transportation and chipping, including capital recovery. A detailed literature review and discussion on biomass harvesting and transportation cost is given in an earlier study by the author on the utilization of MPB killed trees for power production (Kumar et al, 2005a). Delivered wood costs used in this study are given in Table 2.

Description of other cost factors:

- <u>Biomass collection in the forest:</u>
  Capital costs for harvesting equipment are not estimated in this study but rather treated as a custom operation cost that includes capital and operating costs; this is equivalent to assuming that the bio-ethanol plant operator contracts out harvesting.

Table 2: Delivered cost of biomass

Components	*This study*[*]
Felling ($/m^3)	6.00
Skidding ($/m^3)	3.00[1]
Silviculture ($/m^3)	3.15[2]
Roads and infrastructure ($/m^3)	3.90[3]
Overheads ($/m^3)	5.00[4]
Chipping ($/m^3)	5.00[5]
Hauling ($/m^3)	5.82[6]
Total delivered cost ($/m^3)	31.87

[*]All the costs have been estimated based on the discussion with personnel from FERIC Western Division (McDonald and Sauder, 2005) and are close to FERIC's lower estimate of biomass delivered cost (McDonald, 2005).
[1] - Skidding distance is assumed to be 150 m. This number is similar to those reported in earlier report by Kumar et al. (2005a).
[2] - Many Canadian provinces require that silviculture treatments be performed shortly after harvesting, so that cut areas are returned to a productive state. This figure is similar to the average silviculture cost for Sub Boreal Pine/Spruce biogeoclimatic zone reported in 2004 Interior Appraisal Manual (MoFR, 2004) and the same as reported in Kumar et al. (2005a).
[3] - This figure is similar to the numbers reported in Favreau (1992); Kumar et al. (2003); Kumar et al. (2005a). Infrastructure cost depends on the amount of labor and machine, and possibly the merchantable volume per hectare.
[4] - These costs include office operations, environmental protection, consultant fees, archaeological surveys engineering etc. This figure is about two-thirds of the overheads reported for Quesnel district in the Interior Appraisal Manual, 2004 and is similar to the figure suggested by FERIC. We have used two-thirds because some of operations included in estimate are not required for the purpose of bio-ethanol production (MoFR, 2004).
[5] - This value is lower than the average value reported in the literature.
[6] – This is based on the formula given in Favreau (1992). Hauling cost for Quesnel location at 2,100 dry tonnes per day where average distance of transport is 47 km with a winding factor of 1.2. Hauling cost for West Road/Nazko location at the same capacity is $5.12 per m^3 for an average transport distance of 36 km with a winding factor of 1.2.

- <u>Transport of biomass to the bio-ethanol plant site:</u>
  The cost of building logging roads is charged to the project. Biomass projects have a transportation cost that varies with plant capacity. This arises because the area from which biomass is drawn is proportional to plant capacity, and the haul distance is proportional to the square root of that area.

Biomass economics are thus sensitive to biomass yield: higher yields per unit area reduce the area required to sustain a given project size. We explore this effect as a sensitivity.

- <u>Storage of biomass at the plant site:</u>
  Trees are chipped at the roadside in the forest and transported to the plant by a chip van. A small reserve of biomass is stored on plant site (equivalent to about three months operation) to sustain the bio-ethanol plant when roads are impassible.

- <u>Bio-ethanol production technology:</u>
  Bio-ethanol can be produced from a variety of biomass feedstock. A typical bio-ethanol production process consists of feedstock preparation, pretreatment, hydrolysis (releasing of sugar), fermentation, distillation and by-product recovery. Several studies have been carried out on the conversion of lignocellulosic biomass feedstock to bio-ethanol (see for example, Aden et al., 2002; Saddler et al., 2004; Gregg and Saddler, 1995; Wooley et al., 1999; Shell et al., 2004; Itoh et al., 2003). Softwood is difficult to convert to bio-ethanol because of their lignin content and the nature of lignin. Several authors have studied the process of conversion of softwoods to bio-ethanol (see for example, von Sivers and Zacchi, 1995; Alkasrawi et al., 2003; Saddler et al., 2004; Gregg and Saddler, 1995; Kadam et al., 2000; Merrick & Company, 2004; Gregg and Saddler, 1996; Pye et al., 2004; Nguyen et al., 1999; Nguyen et al., 2000).

  This study is based on a two-stage dilute acid hydrolysis process used in production of bio-ethanol from softwood. This process has been evaluated by National Renewable Energy Laboratory, Golden (NREL), Colorado, US (Merrick & Company, 2004; Kadam et al., 2000). This study draws on previous design work by NREL of an bio-ethanol plant processing 800 dry tonnes per day of softwood (Merrick & Company, 2004), and on another previous study of conversion of corn stover to bio-ethanol (Aden et al., 2002). Full capital costs are calculated for bio-ethanol production, and are adjusted for capacity by a scale factor.

  <u>Scale factor:</u> The NREL study (Merrick & Company, 2004) includes a specific analysis of scale factors by equipment type, which allows an assessment of the impact of scale for portions of the bio-ethanol plant. The scale factor for each equipment was used to evaluate the costs at various capacities. Wherever scale factor was not given, it was assumed to be 1.

  <u>Capital cost:</u> Capital costs were calculated for two locations in B.C. At a plant capacity of 2,100 dry tonnes per day (190 million liters per year) plant, capital costs for Quesnel and West Road/Nazko River are $188 million and $197 million, respectively for stand alone plant. This capital cost includes the cost of all the equipment from fuel handling plant to the power plant for utilization of lignin.

  <u>Location:</u> This study analyzes two locations based on the availability of majority of unharvested infested wood. These locations are: West Road/Nazko River and Quesnel, B.C. The choice of location is driven by availability of infested wood, proximity to existing highways for biomass transportation, and abundant water relative to the need for water in the bio-ethanol plant. The interior of British Columbia has a cold winter, but also has a workforce and construction industry accustomed to working productively in cold weather. The plant would be sufficiently near to the population centers that construction labor would not need to be housed in a camp for the Quesnel location, and hence the capital cost has no provision for a camp in Quesnel. However, some construction labor might have a daily transportation cost (for example, bus to and from Prince George); to allow for this, overall capital costs are escalated by 5% for a plant located near consumer. A bio-ethanol plant located in the West Road/Nazko River location would need a camp for construction labor. Hence, a capital cost penalty of 10% relative to a plant located near consumers, equivalent to a 5% premium compared to Quesnel, is applied. Map in appendix C shows the two locations.

- Disposal of ash:
  Ash would be generated from the power plant burning lignin and producing power for in-plant use and for sale. In this study ash is hauled to disposal fields at an assumed average haul distance of 50 km, and spread, all at full cost to the bio-ethanol plant. For this scenario, spreading cost is a significant portion of total ash disposal cost. Ash content for wood is given in Table 1. This is a very small portion of the total cost of bio-ethanol production (less than one cent per liter).

- Connection of the lignin based power plant to the existing transmission grid: Quesnel is near to a major existing high voltage power line which runs almost parallel to Highway 97. A lignin based power plant in this location would not need a new dedicated transmission line to connect to the existing grid. A plant located in West Road/Nazko River will need a new dedicated transmission line. Capital and operating costs for a 100 km long transmission line are included for West Road/Nazko River case and 1% line loss of power in this connection line is also included in the analysis. Power transmission cost is a very small portion of the total cost of bio-ethanol production (less than one cent per liter).

- Operating and administration costs:
  For bio-ethanol plant, a total of 70 staff is assumed. This is based on earlier studies by NREL (Aden et al., 2002; Merrick & Company, 2004; Kadam et al., 2000). This staffing level consists of one plant manger, one plant engineer, one maintenance supervisor, one lab manger, five shift supervisors, two lab technicians, eight maintenance technicians, twenty shift operators, thirty two yard employees, one general manger and five clerks and secretaries. Salary for each staff is assumed based on the data given in these reports.

- Plant reliability and startup profile:
  Biomass handling plants have operating outages that are often associated with solids handling problems. In this study, a bio-ethanol plant operating availability is 0.95. Startup of solids based plants is rarely smooth, and this is accounted for by assuming a plant availability of 0.85 in year 1 and 0.90 in year 2. In year three and beyond the availability goes to 0.95 (Merrick & Company, 2004).

- Bio-ethanol transportation by truck:
  A bio-ethanol plant located in West Road/Nazko River will be remote from the existing highway and distribution infrastructure. In this study it is assumed that bio-ethanol produced from a plant in West Road/Nazko River location is transported to Quesnel at a cost of 2 cents/liter by trucks (Borjesson, 1996). This cost is not attributed for Quesnel case as the produced bio-ethanol is already near the distribution infrastructure.

- Reclamation:
  A site recovery and reclamation cost of 20% of original capital cost, escalated, is assumed in this study, spent in the 20th year of the project. Because the charge occurs only in the last year, it is an insignificant factor in the cost of bio-ethanol.

- Return:
  Bio-ethanol cost is calculated to give a pre-tax return of 10%. This value is consistent with a plant with a secured fuel supply and bio-ethanol sale agreement. The impact of rate of return is assessed in a sensitivity case; an alternate case is run at 12%. Note that an actual plant would be financed by a mix of debt and equity that would be specific to the project developer, hence no attempt is made to calculate a return on equity.

4.1. Input Data and Assumptions

Table 3 gives the bio-ethanol plant characteristics and cost data. Table 4 gives the general assumptions for the cost model.

4.2. Bio-ethanol Results

4.2.1. Resource requirement and bio-ethanol cost

Table 5 gives the amount of wood required over 20 years to support the bio-ethanol plant, the geographical footprint and the bio-ethanol production cost for two locations. Note that if all of the minimum assumed available 200 million m^3 of otherwise unharvested MPB wood were to be used for bio-ethanol production, it would support five 190 million liters bio-ethanol plants, over their life, producing 3.8 billion liters of bio-ethanol.

Figure 2 shows the bio-ethanol cost as a function of plant capacity. A plant of 2,100 dry tonnes per day (190 million liters per year) capacity would reduce the risk to the project developer and would achieve much of the available economy of scale.

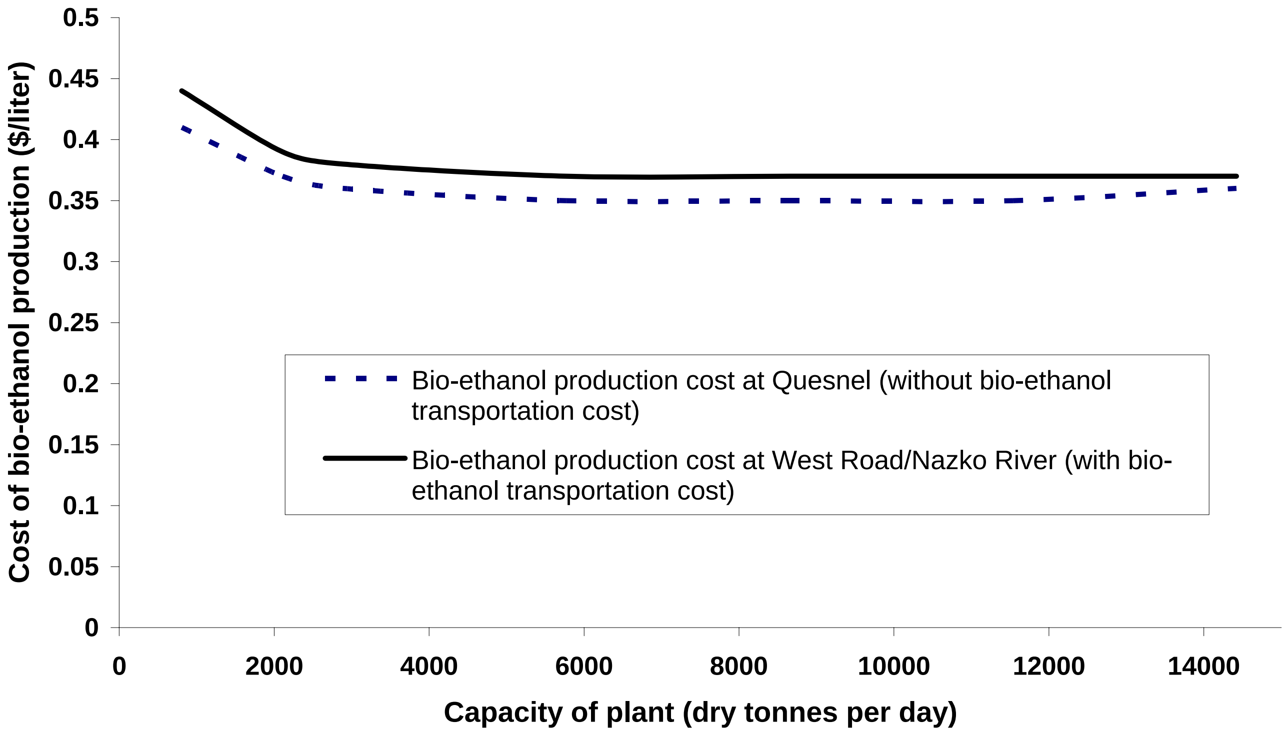

Figure 2. Bio-ethanol cost as a function of capacity for MPB killed wood based plant.

Table 3: Bio-ethanol plant characteristics and costs

Factor	Value	Source / Comments
Bio-ethanol plant size (million liters/yr)	190	This is equivalent to 50 million gallons per year bio-ethanol plant.
Biomass consumption (dry tonnes per day)	2,100	This is equivalent to a biomass consumption of 0.73 million dry tonnes per year.
Plant life (years)	20	Note that the plant could likely run longer than 20 years based on forest harvest residues, mill wastes, or other sources of biomass.
Theoretical bio-ethanol yield (liters/dry tonne)	450	This is based on the assumption that composition of lodgepole pine is same as monterey Pine (composition given in Table 1). Yield is estimated using bio-ethanol yield estimator developed by National Renewable Energy Laboratory, Golden, Colorado, US (Energy Efficiency and Renewable Energy, 2006).
Ratio of actual yield/theoretical yield	0.58	Wooley et al., 1999; Kadam et al, 2000.
Plant operating factor: • Year 1 • Year 2 • Year 3 onwards	 0.85 0.90 0.95	A start-up profile for first two year is based on experience of a solid handling plants. For third year it is taken from literature (Kadam et al., 2000; Merrick & Company, 2004) and is consistent with typical oil refinery.
Bio-ethanol plant capital cost for 2 cases (million dollars) • Quesnel • West Road/Nazko River	 188 197	These are for whole bio-ethanol plant and have derived from literature (Merrick & Company, 2004; Kadam et al., 2000). A location specific escalation of 5% is included in the cost for Quesnel to allow for a distributed construction work force that would require daily transportation to the plant site, and an escalation of 10% is included for West Road/Nazko River for a camp based remote construction site.
Average annual operating and administration cost (million dollars)	4	It includes all the operating and administrative staff salaries.
Ash disposal cost • Ash hauling cost ($/dry tonne/km) • Ash disposal cost ($/dry tonne/ha) • Amount of ash disposal (dry tonnes/ha)	 0.186 25.90 1	Hauling distance for the ash is assumed to be 50 km for the three cases. (Zundel et al., 1996) (Zundel et al., 1996) (Zundel et al., 1996)
Raw material cost (million dollars)	10	This is the cost of raw material for third year of operation when plant is running at full capacity. This figure includes cost of all the chemicals (sulfuric acid, calcium oxide, ammonia, cellulose complex etc.), other fuel source and water required for conversion of wood to bio-ethanol. This is estimated based on data provided in NREL report (Merrick & Company, 2004; Kadam et al., 2000) and is adjusted for a 2,100 dry tonne per year plant.

Factor	Value	Source / Comments
Transmission charge (including capital and operating cost) for remote location, West Road/Nazko River (cents/liter)	0.30	This charge is for transmission of surplus power from lignin based power plant and is only attributed to the bio-ethanol plant located at West Road/Nazko River. The transmission charge are derived from earlier study assuming 100 km of dedicated lines carrying 300 MW at a total capital cost of $31 million at 10% capital recovery plus an operating cost of $128,000 excluding line loss (Kumar et al., 2003). However, a lignin based power plant location near existing transmission grid in Quesnel, B.C. would not incur this transmission charge, and hence this cost is not included in this study for this location.
Power generation using lignin (MWh/yr)	187,700	This is the amount of power available for sale from a 2,100 dry tonne plant (Merrick & Company, 2004; Kadam et al., 2000).
Sale price of electricity (cents/kWh)	5	Typical power price in B.C.
Spread of costs during construction (%) • Year 1 • Year 2 • Year 3	 20 35 45	Plant startup is at the end of year 3 of construction. Estimated based on discussions with industry.

Table 4: General assumptions for a bio-ethanol plant

Factor	Value	Source / Comments
Scale factor • Transmission line capital cost. • Transmission line operating cost.	0.49 0.50	This cost is estimated to transmit the surplus power from the lignin based power plant at West Road/Nazko location to Quesnel. 0.49 is based on fitting a curve to estimates of 300 km transmission lines through remote boreal forest at various capacities (Kumar et al., 2003). This value is an exponent. 0.5 is an exponent for operating costs and is an estimate based on consultation with the electrical industry.
Factor to reflect capital cost impact for location. • Quesnel • West Road/Nazko River	1.05 1.10	
Annual maintenance cost.	2% of initial capital cost per year	Merrick &Company, 2004; Kadam et al., 2000.
Aggregate pre-tax return on capital (blend of debt plus equity).	10 %	A bioethanol plant would combine debt and equity, and hence a blended value of 10% return on capital is conservative.
Site recovery and reclamation costs.	20% of initial capital cost	The reclamation cost is escalated and is assumed to be in the 20^{th} year of operation.
Bio-ethanol transportation cost ($/liter)	0.02	This is the cost of transportation of bio-ethanol from West Road/Nazko River location to Quesnel for distribution. This is for transportation of 100 km by trucks and is derived from Borjesson (1996).

Table 5: Resource requirement and cost composition for a MPB killed tree biomass based bio-ethanol plant over 20 years

	West Road/Nazko River	Quesnel
Capacity of plant (dry tonnes/day)	2,100	2,100
Capacity of plant (million liters/yr) [million gallons/yr]	190 [50]	190 [50]
Amount of biomass required over 20 years (actual m^3)	35,931,000	35,931,000
Amount of biomass required over 20 years (merchantable m^3)	28,744,800	28,744,800
Project draw area (km x km) Note: only the surplus MPB killed trees within this area are used for fuel.	85 by 85	110 by 110
Cost elements		
Delivered Biomass Cost Components	$/liter ($/gallon)	$/liter ($/gallon)
Harvesting cost	0.09 (0.36)	0.09 (0.36)
Transportation cost	0.04 (0.16)	0.04 (0.16)
Silviculture cost	0.02 (0.08)	0.02 (0.08)
Road Construction cost	0.03 (0.10)	0.03 (0.10)
Chipping cost	0.03 (0.11)	0.03 (0.11)
Total delivered biomass cost	***0.21 (0.80)***	***0.21 (0.80)***
Capital cost recovery	***0.07 (0.23)***	***0.06 (0.22)***
Operation and Maintenance Cost Components		
Maintenance cost	0.02 (0.07)	0.02 (0.07)
Operating and administration cost	0.02 (0.07)	0.02 (0.07)
Raw material cost	0.05 (0.20)	0.05 (0.20)
Bio-ethanol transportation cost	0.02 (0.08)	0.00 (0.00)
Total operation and maintenance cost	***0.12 (0.44)***	***0.10 (0.36)***
Total Bio-ethanol Production Cost from MPB Killed Wood	**0.40 (1.51)**	**0.37 (1.40)**

The curve in Figure 2 shows that the profile of bio-ethanol cost vs. capacity is flat at large plant size, and very steep at low plant size. In biomass projects, two cost factors compete: fuel transportation costs rise in approximate proportion to the square root of capacity, while capital costs per unit capacity decrease. Because the variable component of fuel transportation cost becomes a significant cost factor as biomass yields drop, the result is a very flat profile of cost vs. capacity at large capacities. This result is consistent with previous studies of optimum size of bio-ethanol plants (Nguyen and Prince, 1996; Aden, 2002; Wooley et al., 1999; Marrison and Larson, 1995; Kumar et al., 2005b). Biomass to bio-ethanol projects can be built over a wide range of large sizes, without a significant cost penalty, but not at small plant sizes. A 2100 dry tonnes per day (190 million liters per year) is a reasonable tradeoff between reducing the risk from a new large plant and gaining the benefit of the economy of scale.

4.2.2. Composition of bio-ethanol cost

Table 5 shows the makeup of bio-ethanol cost in $/liter and $/gallon. Note that costs are for the first year of operation at full capacity (year 3), but are deflated back to the base year 2004. Delivered cost of biomass is in the range of 54% - 57% of the total bio-ethanol cost, followed by operation and maintenance cost (27% - 31%) and capital cost (16% - 18%). Transportation cost is about 19% of the biomass delivered cost which is close to the figures reported in other studies (Aden et al., 2002; Perlack and Turhollow, 2002; Glassner et al., 1999, Kumar et al., 2003 and 2005b). In this study, biomass storage cost and ash disposal costs are less than one cent per liter of bio-ethanol and hence are not shown in Table 5. For West Road/Nazko River location, transmission charge to Quesnel for transmitting surplus power from lignin based power plant is also less than one cent per liter of bio-ethanol produced and hence is not shown in Table 5. Bio-ethanol produced at West Road/Nazko River location is transported by trucks to Quesnel for distribution. This cost of bio-ethanol transportation is about 5% of the production cost. The difference in the cost of bio-ethanol for two locations is due to the high capital cost of West Road/Nazko River plant and cost of transportation of bio-ethanol produced at the West Road/Nazko River location by truck to Quesnel.

4.2.3. Sensitivities

Some key sensitivities are shown in Table 6.

Table 6: Sensitivities for a MPB killed tree based bio-ethanol plant for West Road/Nazko River and Quesnel locations.

Cost element	Quesnel	West Road/Nazko River
Base case bio-ethanol production cost - $/liter ($/gallon)	**0.37 (1.40)**	**0.40 (1.51)**
	% Change	**% Change**
Biomass production and delivery related sensitivities		
Biomass yield is 25% higher per gross hectare	- 0.55 %	- 0.50 %
Biomass felling and skidding cost is 50% higher	+ 8.60 %	+ 8.10 %
Biomass transportation cost is 25% higher	+ 3.05 %	+ 2.60 %
Bio-ethanol plant related sensitivities		
Capital cost of plant 10% higher	+ 3.32 %	+ 3.42 %
Staffing cost is reduced by 25%	- 1.10 %	- 1.30 %
Maintenance cost is reduced by 25%	- 1.10 %	- 1.30 %
Pretax return on capital is 12% rather than 10%	+ 4.70 %	+ 4.70 %

5. Bio-oil Production from MPB Killed Wood – Scope and Cost

The scope of this study is a dedicated bio-oil production plant operating for 20 years using biomass from infested pine trees. Cost factors are developed for each element of the scope and are included in detail in this section. The costs are reported for a plant having capacity of about 220 dry tonnes per day. This is equivalent to a plant producing about 10 million gallons per year (MMGY) or 40 million liters per year (ML).

The biomass production and delivery cost for a bio-oil production plant is same as shown in Table 2 except the transportation cost. Transportation cost depends on the capacity of the plant as the transportation distance change with capacity. The biomass hauling costs for bio-oil producing plants at West Road/Nazko River and Quesnel locations are \$3.56 and \$3.78 per m^3, respectively.

Description of other cost factors:

- Biomass collection and transportation in the forest:
  Assumptions in estimating the collection cost is same as for the bio-ethanol plant. Formula for estimating transportation cost is same as used for bio-ethanol case and has been derived from Kumar et al. (2005a).

- Storage of biomass at the plant site:
  The storage time is assumed to be three months similar to bio-ethanol case for the time when roads are impassable. Trees are chipped at the roadside in the forest and transported to a plant by a chip van.

- Grinding of biomass at the plant site:
  Biomass received at the plant is in the form of chips of size 2-3 inches. For bio-oil production it is further ground to a size of 0.04 inches which helps in high heat transfer (DynaMotive Energy Systems Corporation, 1999). A cost of \$6.80 per dry tonne is included in this study for grinding (Mullaney et al., 2002).

- Bio-oil characteristics and production technology:
  Bio-oil can be produced from a variety of biomass feedstock. Bio-oil is produced from the fast pyrolysis of lignocullulosic biomass. In addition to production of bio-oil in the process, a high quality char and a combustible gas is also produced. Bio-oil is not a petroleum-based product and is insoluble in petroleum-based materials such as #2 fuel oil or gasoline. However, recently Natural Resources Canada has developed BDM process to produce a mixture of bio-oil and diesel (CANMET, 2004). Bio-oil contains about 30% water and hence has a low heating value than light fuel oil and diesel by about 55% (Cole Hill Associates, 2004).

  Several companies have developed technologies for production of bio-oil from woody biomass (see for example, DynaMotive Energy Systems Corporation, 2000; Freel and Graham, 2000; Biomass Technology Group, 2004). Various research groups around the world have also studied bio-oil and are developing technologies for its production and utilization (see for example, Grassi and Bridgwater, 1993; Juste and Monfort, 2000; Graham et al., 1994; Luo et al., 2004; Mullaney et al., 2002).

  A typical bio-oil production process consists of feedstock preparation which includes grinding, drying if the moisture content of the biomass is high, fast pyrolysis of biomass in a fluidized bed, decomposition of biomass in solid char, gas and vapors, separation of char by a cyclone, condensation of the vapors to get bio-oil. This study is based on the pyrolysis of softwood to produce bio-oil. This process is same as proposed by DynaMotive Energy Systems Corporation

(DynaMotive Energy Systems Corporation, 1999, 2000). This study draws on previous techno-economic work by Mullaney et al. (2002) for a bio-oil plant. Full capital costs are calculated for bio-oil production, and are adjusted for capacity.

Capital cost: Capital costs were calculated for two locations in B.C. At a plant capacity of 220 dry tonnes per day (40 million liters per year), capital costs for Quesnel and West Road/Nazko River are about $18.5 million and $19.4 million, respectively. The capital costs for Quesnel and West Road/Nazko River are different because of the remote location factor which is discussed below. The study done by Mullaney et al., (2002) includes capital cost for three different size plants and these reported costs are used in this study.

Location: This study analyzes two locations based on the availability of majority of unharvested infested wood. These locations are: West Road/Nazko River and Quesnel, B.C. The location is driven by availability of infested wood and proximity to existing highways for biomass transportation. Capital costs for Quesnel and West Road/Nazko River have been escalated by 5% and 10%, respectively. The reason is the same as explained for escalation of capital costs for two location for a bio-ethanol plant.

- Operating and administration costs:
  For a bio-oil plant, a total of 15 staff is assumed. This is based on earlier studies by Mullaney et al. (2002). This staffing level consists of one plant manger, one supervisor, four shift breakers, four field operator, four Forklift operator and one administrative staff responsible for accounting, bookkeeping and purchasing. Salary for each is assumed based on the data given in these reports.

- Plant reliability and startup profile:
  Biomass handling plants have operating outages that are often associated with solids handling problems. In this study, a bio-oil plant operating availability of 0.95 is used. Startup of solids based plants is rarely smooth, and this is accounted for by assuming a plant availability of 0.85 in year 1 and 0.90 in year 2. In year three and beyond the availability goes to 0.95.

- Bio-oil transportation by truck:
  A bio-oil plant located in West Road/Nazko River will be remote from the existing highway and distribution infrastructure. In this study it is assumed that bio-oil produced from a plant in West Road/Nazko River location is transported to Quesnel at a cost of 2 cents/liter by trucks (Borjesson, 1996). This cost is not attributed for Quesnel case as the produced bio-oil is already near the distribution infrastructure.

- Reclamation:
  A site recovery and reclamation cost of 20% of original capital cost, escalated, is assumed in this study, spent in the 20th year of the project. Because the charge occurs only in the last year, it is an insignificant factor in the cost of bio-oil.

- Return:
  Bio-oil cost is calculated to give a pre-tax return of 10% similar to the bio-ethanol plant. Note that an actual plant would be financed by a mix of debt and equity that would be specific to the project developer, hence no attempt is made to calculate a return on equity.

5.1. Input Data and Assumptions

Table 7 gives the bio-oil plant characteristics and cost data.

5.2. Bio-oil Results

5.2.1. Resource requirement and bio-oil cost

Table 8 gives the amount of wood required over 20 years to support the bio-oil plant, the geographical footprint and the bio-oil production cost for two locations. Note that if all of the minimum assumed available 200 million m^3 of otherwise unharvested MPB wood were to be used for bio-oil production, it would support 57 bio-oil plants each of capacity 40 million liters per year, over their life, producing 800 million liters of bio-oil. Figure 3 shows the bio-oil cost as a function of plant capacity.

Similar to bio-ethanol plant, large size bio-oil plants are also benefited by the economy of scale. The capacities that are considered are in range of what has been proposed by the typical bio-oil companies. The optimum size at which bio-oil production cost is minimum is not yet reached and there is possibility of increasing the capacity of the plant provided the technology permits.

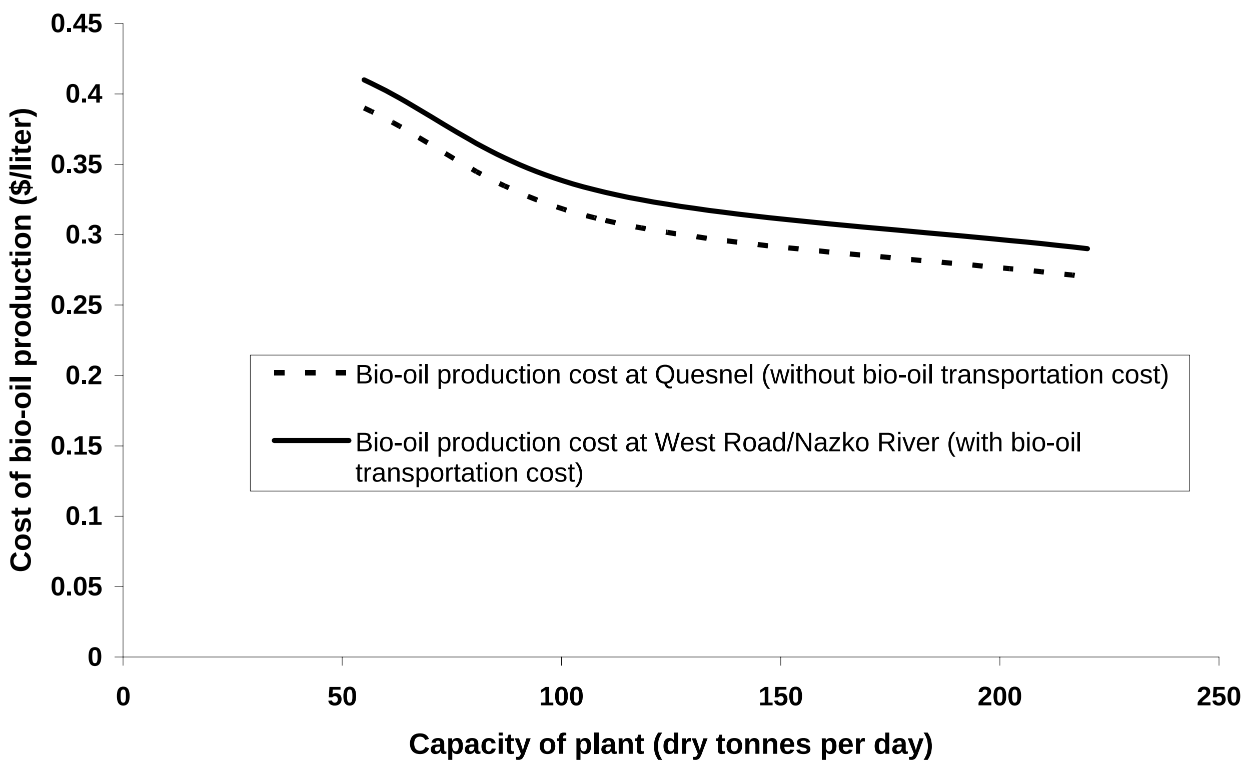

Figure 3. Bio-oil cost as a function of capacity for MPB killed wood based plant.

5.2.2. Composition of bio-oil cost

Table 9 shows the makeup of bio-oil cost in $/liter and $/gallon. Note that costs are for the first year of operation at full capacity (year 3), but are deflated back to the base year 2004. Operation and maintenance cost is in the range of 44% - 48% of the total bio-oil cost, followed by delivered cost of biomass (34% - 37%) and capital cost (17% - 18%). Transportation cost is a small component because of smaller transportation distances. Cost of storage of biomass at the plant is less than one cent per liter and hence is not shown in Table 9. Bio-oil produced at West Road/Nazko River location is transported by trucks to Quesnel for distribution. This cost of transportation is about 7% of the bio-oil production cost. The difference in the cost of bio-oil for two locations is due to the cost of transportation of bio-oil produced at the West Road/Nazko River location by truck to Quesnel.

Table 7: Bio-oil plant characteristics and costs

Factor	Value	Source / Comments
Bio-oil plant size (million liters/yr)	40	This is equivalent to about 10 million gallons per year bio-oil plant.
Biomass consumption (dry tonnes per day)	220	This is equivalent to a biomass consumption of 72,300 dry tonnes per year.
Plant life (years)	20	Note that the plant could likely run longer than 20 years based on forest harvest residues, mill wastes, or other sources of biomass.
Theoretical bio-oil, char and gas yield (weight %) o Bio-oil o Char o Combustible gases	 66 21 13	This is derived from DynaMotive Energy Systems Corporation (2000) and Mullaney et al. (2002).
Plant operating factor: • Year 1 • Year 2 • Year 3 onwards	 0.85 0.90 0.95	
Bio-oil plant capital cost for 2 cases (million dollars) • Quesnel • West Road/Nazko River	 18.5 19.4	These are for whole bio-oil plant and are derived from Mullaney et al. (2002). A location specific escalation of 5% is included in the cost for Quesnel to allow for a distributed construction work force that would require daily transportation to the plant site, and an escalation of 10% is included for West Road/Nazko River for a camp based remote construction site.
Average annual operating and administration cost (million dollars)	1	It includes all the operating and administrative staff salaries and an overhead of 30% adopted from Mullaney et al. (2002).
Chemicals and water cost (million dollars)	1	This is the cost of chemicals and water for third year of operation when plant is running at full capacity (Mullaney et al., 2002).
Cost of non production utilities and labor (million dollars)	0.3	(Mullaney et al., 2002)
Cost of natural gas for pyrolysis ($/GJ)	8	Assumed. This cost of natural gas is used in the model based on DynaMotive data that heat requirement is approximately 2.5 MJ per kg of bio-oil produced. Out this 1 MJ per kg of bio-oil produced is required from natural gas (DynaMotive Energy Systems Corporation, 2000)
Cost of electricity requirement (kWh/hr)	1,800	This is electricity consumption level per operating hour for a 220 dry tonne plant (Mullaney et al., 2002).
Spread of costs during construction (%) • Year 1 • Year 2 • Year 3	 20 35 45	Plant startup is at the end of year 3 of construction. Estimated based on discussions with industry.

Factor	Value	Source / Comments
Factor to reflect capital cost impact for location. • Quesnel • West Road/Nazko River	 1.05 1.10	
Annual maintenance cost.	10% of initial capital cost per year	Mullaney et al. (2002).
Aggregate pre-tax return on capital (blend of debt plus equity).	10 %	A bio-oil plant would combine debt and equity, and hence a blended value of 10% return on capital is conservative.
Site recovery and reclamation costs.	20% of initial capital cost	The reclamation cost is escalated and is assumed to be in the 20th year of operation.
Bio-oil transportation cost ($/liter)	0.02	This is the cost of transportation of bio-oil from West Road/Nazko River location to Quesnel for distribution. This is for transportation of 100 km by trucks and is derived from Borjesson (1996).

Table 8: Resource requirement and cost composition for a MPB killed tree biomass based bio-oil plant over 20 years

	West Road/Nazko River	**Quesnel**
Capacity of plant (dry tonnes/day)	220	220
Capacity of plant (million liters/yr) [million gallons/yr]	40 [10]	40 [10]
Amount of biomass required over 20 years (actual m^3)	3,556,140	3,556,140
Amount of biomass required over 20 years (merchantable m^3)	2,844,900	2,844,900
Project draw area (km x km) Note: only the surplus MPB killed trees within this area are used for fuel.	27 by 27	35 by 35
Cost elements		
Delivered Biomass Cost Components	**\$/liter (\$/gallon)**	**\$/liter (\$/gallon)**
Harvesting cost	0.04 (0.17)	0.04 (0.17)
Transportation cost	0.01 (0.04)	0.01 (0.04)
Silviculture cost	0.01 (0.04)	0.01 (0.04)
Road Construction cost	0.01 (0.04)	0.01 (0.04)
Chipping and grinding cost	0.02 (0.08)	0.02 (0.08)
Total delivered biomass cost	***0.10 (0.38)***	***0.10 (0.38)***
Capital cost recovery	***0.05 (0.20)***	***0.05 (0.20)***
Operation and Maintenance Cost Components		
Maintenance cost	0.04 (0.17)	0.04 (0.17)
Operating and administration cost	0.02 (0.08)	0.02 (0.08)
Miscellaneous chemicals and water cost	0.02 (0.08)	0.02 (0.08)
Non production utilities and labor cost	0.01 (0.04)	0.01 (0.04)
Cost of electricity usage	0.01 (0.04)	0.01 (0.04)
Cost of natural gas usage	0.01 (0.04)	0.01 (0.04)
Bio-oil transportation cost	0.02 (0.08)	0.00 (0.00)
Total operation and maintenance cost	***0.14 (0.52)***	***0.11 (0.52)***
Total Bio-oil Production Cost from MPB Killed Wood	**0.29 (1.09)**	**0.27 (1.02)**

5.2.3. Sensitivities

Some key sensitivities are shown in Table 9.

Table 9: Sensitivities for a MPB killed tree based bio-oil plant for West Road/Nazko River and Quesnel locations.

Cost element	Quesnel	West Road/Nazko River
Base Case bio-oil production cost - $/liter ($/gallon)	**0.27 (1.02)**	**0.29 (1.11)**
	% Change	**% Change**
Biomass felling and skidding cost is 50% higher	+ 3.7 %	+ 6.9 %
Capital cost of plant 10% higher	+ 3.7 %	+ 3.5 %
Staffing cost is reduced by 25%	- 3.7 %	- 3.5 %
Maintenance cost is reduced by 25%	- 7.4 %	- 6.7 %

5.2.4. Electricity production from bio-oil

Bio-oil can be used for the production of electricity. Electricity can be generated by bio-oil in three ways: in a gas turbine coupled with a generator; in a combined cycle mode with exhaust from gas turbine used to produce steam which is then used to run a steam turbine; and, in combined heat and power generation (DynaMotive Energy Systems Corporation, 2000). The cost of production of electricity is different for the three modes and depends significantly on the delivered biomass cost. Detailed electricity generation cost is reported by DynaMotive Energy Systems Corporation using bio-oil from a simple gas turbine (DynaMotive Energy Systems Corporation, 2000). A plant producing 40 million liter per year of bio-oil can provide fuel for 10 MW power plant. Based on the reported cost, it is estimated that the cost of power generation from MPB infested wood based bio-oil is above $100 per MWh at a delivered feedstock cost of about $75 per dry tonne for Quesnel and West Road/Nazko River locations. The electricity produced at the West Road/Nazko location will have to be transmitted to Quesnel where the main BC Hydro grid exists. This will add further cost to the total cost of electricity delivery. At this cost, electricity generation from bio-oil is not competitive with the existing electricity price in B.C. A combined cycle plant for electricity generation or combined heat and power generation plant might improve the economics.

6. Discussion

This study does not take any credit or subsidy into account in calculating the cost of bio-ethanol or bio-oil. Government incentive can help in improving the economics of both the biofuels.

Biomass yield in this study has been estimated for a healthy lodgepole pine stand. MPB killed trees might have a different yield than the healthy stands. The ratio of merchantable volume to total volume of the tree is also an important parameter to estimate the amount of biomass available for fuel purposes as it impacts the yield of biomass per unit area. In this study we have used a ratio of 0.8; the impact of this ratio on bio-ethanol and bio-oil costs is shown in Figure 4 and 5 for both the locations. One future step is confirmation of MPB wood yields based on whole tree chipping.

Higher moisture content of the fuel reduces the lower heating value. This study doesn't include any drying operation. The equilibrium moisture content of wood estimated in this study is for a particular region, and is averaged over a year. EMC varies with relative humidity and temperature, and the impact of varying conditions over the year on both EMC and the energy content of the wood can be evaluated in more detail if the project proceeds. Higher moisture content will increase the biomass transportation cost for both bio-ethanol and bio-oil cases. In case of bio-oil production, it is assumed that char produced from the process will be used to dry the biomass. As the estimated moisture content for this study is low, there might be surplus char left.

Ratio of actual yield to theoretical yield in case of bio-ethanol production is a critical ratio. This is high for corn stover. This study uses a ratio of 0.58. There is significant potential of improving this ratio. Impact of this ratio on the bio-ethanol production cost is shown in Figure 6.

In this study bio-oil is transported from West Road/Nazko River location to Quesnel for distribution. At Quesnel bio-oil can used for the production of electricity or chemicals. Electricity production by a centralized stand alone plant is not competitive with existing power price in B.C. Use of bio-oil for production of high value chemicals can be further evaluated.

This study does not include any revenue which can be generated by selling char. If surplus char is left after drying of the biomass, it can be sold and that can improve the economics of bio-oil.

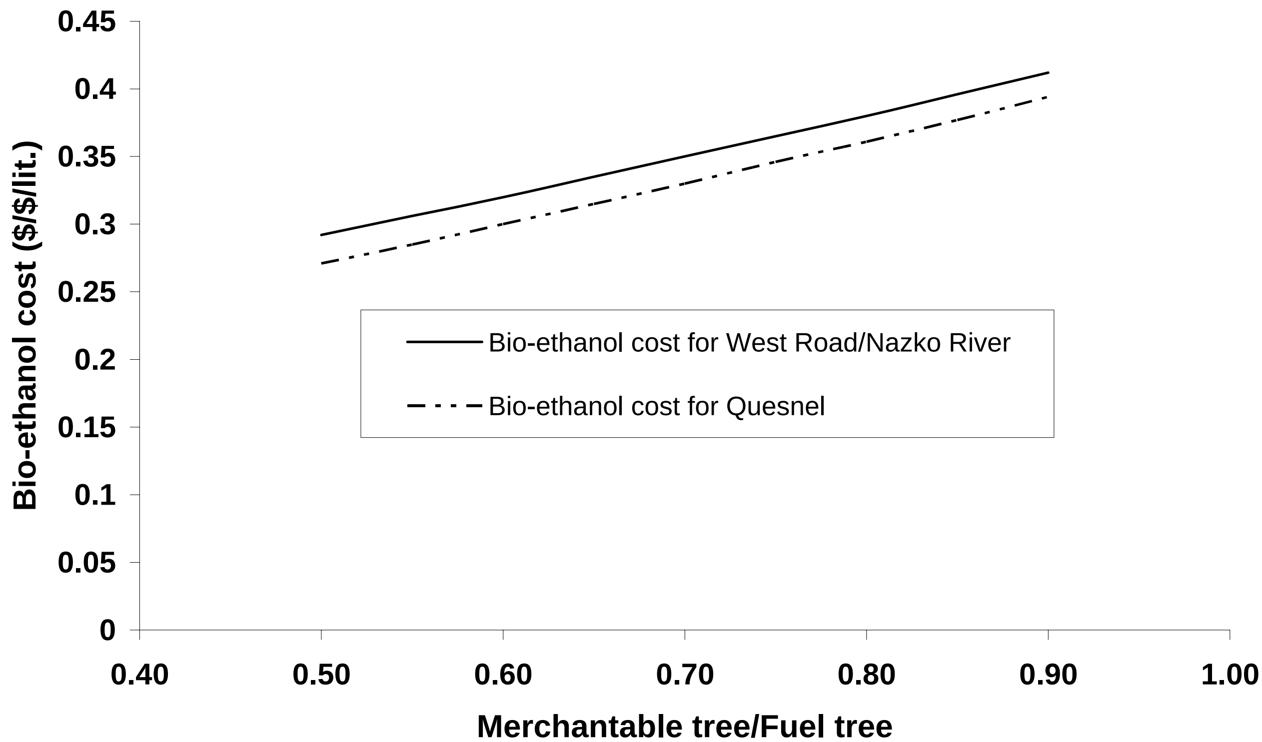

Figure 4: Impact of ratio of merchantable volume to total volume of a tree on bio-ethanol production cost for West Road/Nazko River and Quesnel locations at a plant capacity of 2,100 dry tonnes per day.

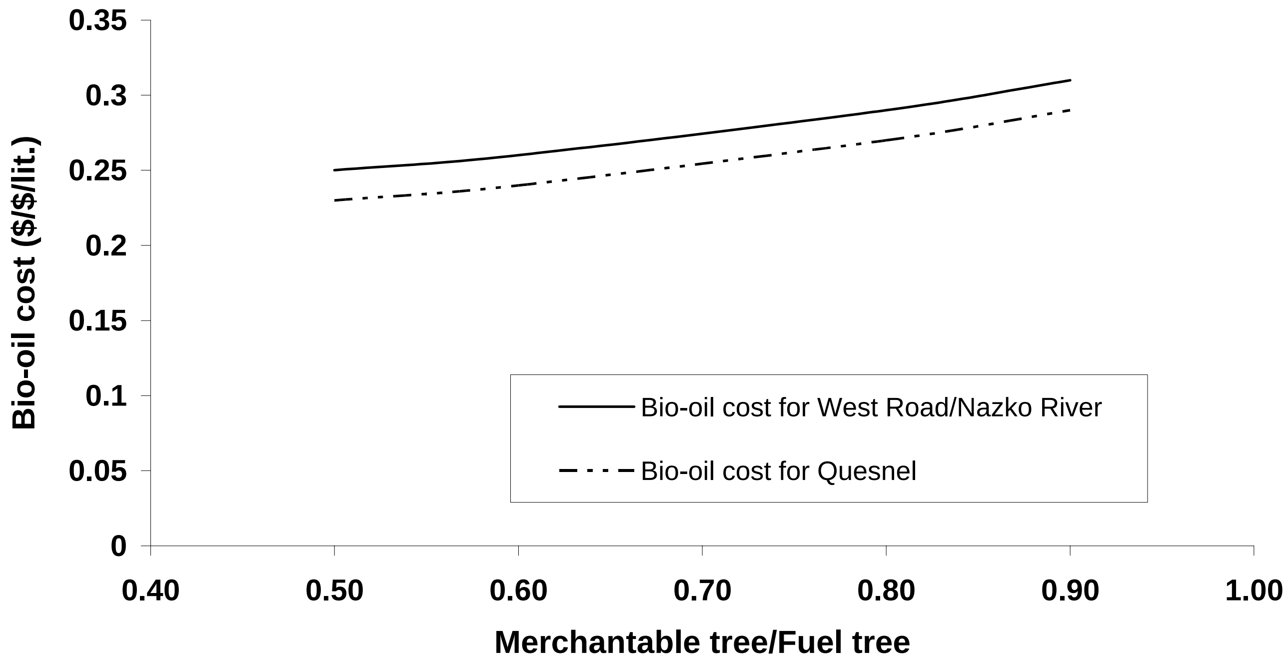

Figure 5: Impact of ratio of merchantable volume to total volume of a tree on bio-oil production cost for West Road/Nazko River and Quesnel locations at a plant capacity of 220 dry tonnes per day.

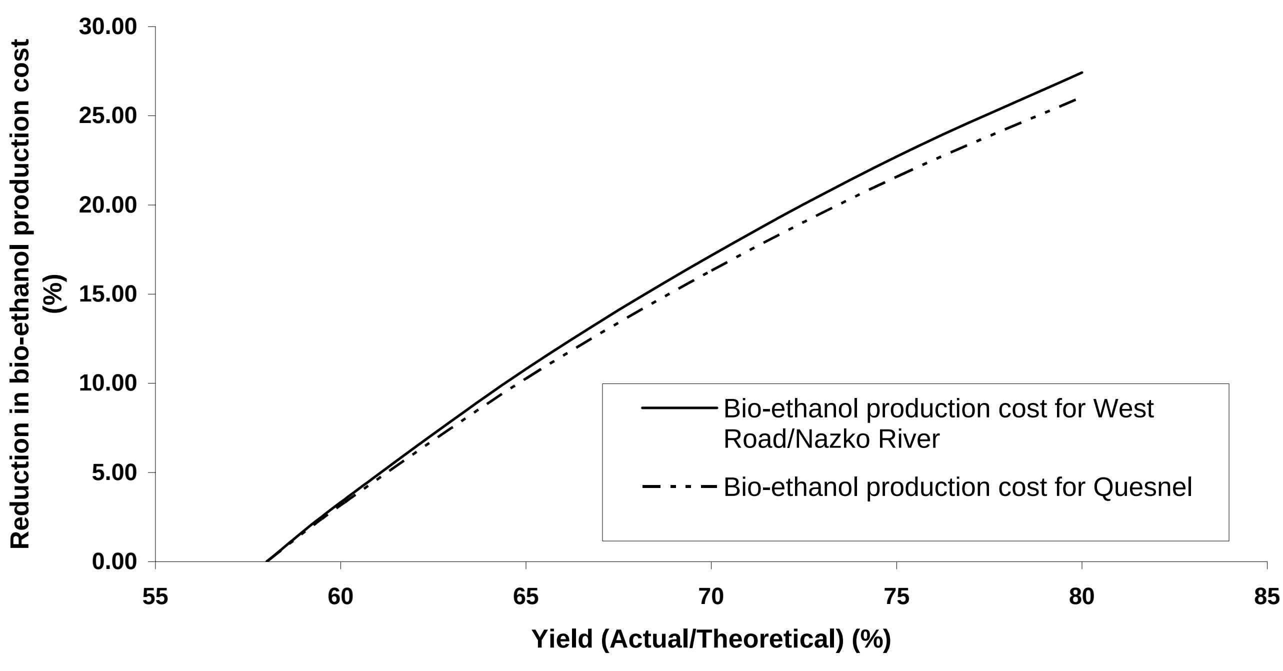

Figure 6: Impact of ratio of actual yield to theoretical yield on bio-ethanol cost for West Road/Nazko River and Quesnel locations at a plant capacity of 2,100 dry tonnes per day

7. Conclusions

The cost of generating bio-ethanol using MPB killed wood in a 2,100 dry tonnes per day plant is $0.40 per liter ($1.51 per gallon) for plant located in West Road/Nazko River with a transportation cost of bio-ethanol to Quesnel and $0.37 per liter ($1.40 per gallon) for plant located in Quesnel without any transportation cost of bio-ethanol. Delivered cost of biomass is in the range of 54% - 57% of the total bio-ethanol cost, followed by operation and maintenance cost (27% - 31%) and capital cost (16% - 18%). The cost of bio-ethanol from Quesnel location is lower than the bio-ethanol cost at West Road/Nazko River location. Two main reasons for this are: bio-ethanol transportation cost; and, a higher capital cost premium for West Road/Nazko River location plants. Hence, a Quesnel location is recommended based on current estimates of available surplus MPB killed trees. Total amount of wood to support this size bio-ethanol plant over 20 years is about 36 million actual m^3 (29 million merchantable m^3). For West Road/Nazko River location, an area of 85 km by 85 km is required while at Quesnel an area of 110 by 110 km is required to support this size plant.

Similarly, the cost of producing bio-oil from MPB wood in a 220 dry tonnes per day plant is $0.29 per liter ($1.11 per gallon) for plant located in West Road/Nazko River with a transportation cost of bio-oil to Quesnel and $0.27 per liter ($1.02 per gallon) for plant located in Quesnel without any transportation cost of bio-oil. Operation and maintenance cost is in the range of 44% - 48% of the total bio-oil cost, followed by delivered cost of biomass (34% - 37%) and capital cost (17% - 18%). The cost of bio-oil from Quesnel location is lower than the bio-oil cost at West Road/Nazko River location mainly because of the transportation cost of bio-oil. The plant will require about 3.5 million actual m^3 (2.8 million merchantable m^3) of wood over 20 years. The draw area for West Road/Nazko River and Quesnel locations is 27 km by 27 km and 35 km by 35 km, respectively.

8. Recommendations

- Bio-ethanol production in Canada is growing rapidly. Most of the bio-ethanol produced today in Canada is based on corn and wheat. The average cost of bio-ethanol production from grain is in the range of $0.35 - $0.45 per liter (Agriculture and Agri-Food Canada, 2001). In this study, the cost of bio-ethanol production from a plant using 2,100 dry tonnes of MPB infested pine wood per day is in the range of $0.37 – $0.40 per liter and is competitive to the grain based alcohol. But the technology for production of bio-ethanol from softwood is still under development stage and there is no large scale commercial plant operating today. A demonstration plant with the support of government can be considered for bio-ethanol production based on MPB killed wood in near future.

- Bio-oil production cost in this study ranges from $0.27 to $0.29 per liter for a plant processing 220 dry tonnes of MPB infested wood per day. Bio-oil can be used for production of electricity and a plant at this level of production capacity can support a 10 MW power plant if all the produced bio-oil is used to generate electricity. By extrapolating the estimates reported by Dynamotive Energy Systems Corporation, the calculated cost of electricity production from bio-oil plant based on MPB infested wood using gas turbine generator system is above $100 per MWh at a delivered feedstock cost of about $75 per dry tonne for Quesnel and West Road/Nazko River locations. Electricity generation from bio-oil is not competitive with the existing electricity price in BC. Alternative use of bio-oil for the production of high value chemicals can be explored and detailed economics should be evaluated.

- This study assumes the yield of bio-ethanol and bio-oil (liters per dry tonne) from mountain pine beetle infested wood to be same as healthy pine wood. The yield of biofuels from an infested tree might be different than values used in this study. Future research is required to determine the characteristics of infested wood and its impact on biofuels yield.

- Transportation of bio-ethanol and bio-oil from West Road/Nazko River location to Quesnel is assumed to be by trucks. A techno-economic analysis of pipeline transport of bio-ethanol and bio-oil should be carried and compared with the economics of transportation by trucks.

- In this study, we have used a two-stage dilute acid hydrolysis process for the production of bio-ethanol from mountain pine beetle killed trees. There are other processes such as lignol process (Pye at al., 2004) which should be evaluated and compared to select the best technology.

- A bio-oil production plant can be located near a heat sink and it can be used in combined heat and power generation mode. This type of system should be evaluated for Quesnel location.

- Table 10 is a summary of the comparison of the three different options of utilization of MPB infested wood.

Table 10: Comparison of bioenergy options for MPB infested wood

Options	Economics	Status of Technology	Comments
Bio-ethanol	• Cost of production of bio-ethanol from a centralized plant based on MPB infested wood ranges from \$0.37 – \$0.40 per liter. • Bio-ethanol based on MPB killed tree is competitive with grain based alcohol (\$0.35 - \$0.45 per liter) • MPB based bio-ethanol is expensive than gasoline.	• No large scale centralized plant based on softwood is operating commercially today. • Technology is still under development.	• Not an option to be implemented immediately.
Bio-oil	• Cost of production of bio-oil from a centralized plant based on MPB infested wood ranges from \$0.27 to \$0.29 per liter. • Cost of production of electricity (from a gas turbine coupled with a generator) based on bio-oil produced from MPB infested wood is above \$100 per MWh at a feedstock cost of about \$75 per dry tonne. • Electricity from MPB infested wood based bio-oil is expensive than existing power price in BC.	• No large scale stand alone power plant based on bio-oil from softwood is operating commercially today. • Technology for large scale stand alone power plant based on bio-oil is still under development.	• Not an option to be implemented immediately. • Economics of production of high value chemicals or combined heat and power plant can be evaluated.
Bio-power (evaluated in earlier study by Kumar et al., 2005)	• Cost of electricity production based on direct combustion of MPB infested wood is in the range of \$68 to \$74 per MWh. • Electricity production from direct combustion of MPB infested wood is expensive than existing power price in BC.	• Large scale biomass power plant available (e.g. 240 MW biomass power at Pietarsaari, Finland). • Technology for electricity generation from biomass is mature.	• It is a feasible and viable option today with government subsidy for green power. • This technology can be implemented immediately.

- In summary, MPB killed wood provides a unique opportunity to convert otherwise wasted biomass in B.C. to useful biofuels and biopower. Conversion of MPB infested wood to bio-ethanol and bio-oil provides more options for utilization of this wood resource, but today, these options are not lucrative as compared to the electricity generation from direct combustion of MPB wood in a power plant. Production of electricity by direct combustion of MPB infested wood can be implemented immediately and it can help sustain jobs, contribute to a clean environment, potentially help Canada meet its obligations under the Kyoto accord, and put Canada at the forefront of biomass utilization.

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Appendix A

Equations for Calculation of Equilibrium Moisture Content (Simpson, 1998)

$$EMC = \frac{1800}{W} x[\frac{Kh}{1-Kh} + \frac{(K_1Kh + 2K_1K_2K^2h^2}{1+K_1Kh+K_1K_2K^2h^2}]$$

Where,
W, *K*, K_1, and K_2 are the coefficients of an adsorption model and can be calculated by using equations given below. These coefficients depend on the surrounding air temperature *T* (^oC).

h in the above equation is the relative humidity of surrounding air (%/100).

$$W = 349 + 1.29T + 0.0135T^2$$

$$K = 0.805 + 0.000736T - 0.00000273T^2$$

$$K_1 = 6.27 - 0.00938T - 0.000303T^2$$

$$K_2 = 1.91 + 0.0407T - 0.000293T^2$$

Appendix B

Equations for Calculation of Density (Simpson, 1993)

$$G_m = \frac{G_b}{(1-0.265aG_b)}$$

Where,
G_m is the specific gravity based on volume at moisture content M.

G_b is the basic specific gravity (based on green volume). For lodgepole pine it is 0.38.

$$a = \frac{(30-M)}{30}$$

Where,
$M < 30$.

$$\rho = 1000 * G_m * (1 + M/100)$$

Where,
ρ is the density in kg/m^3.

Appendix C - Map

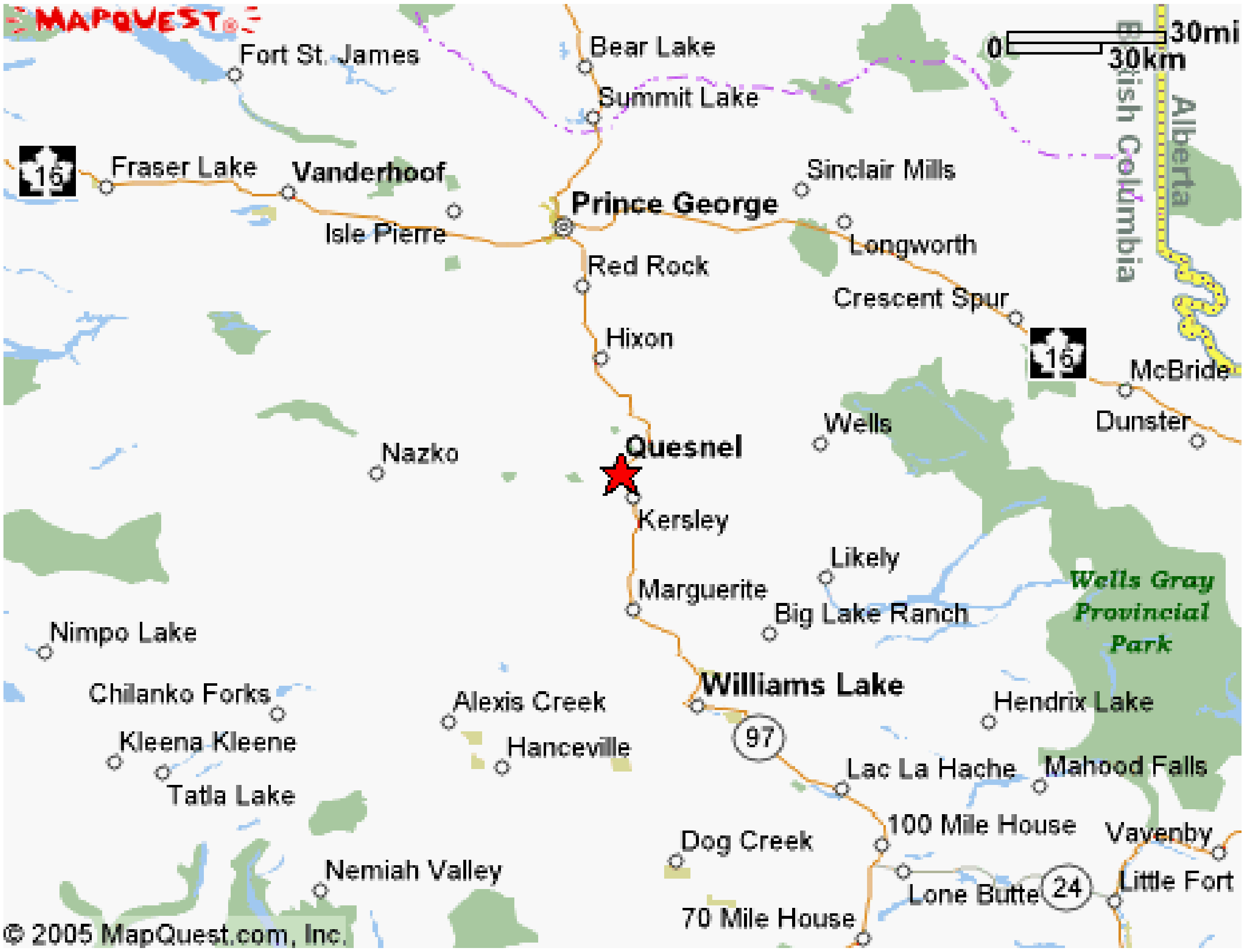

Figure C1. Location of Nazko and Quesnel in B.C. and Highway 97 (Source: MapQuest.com)