British Columbia's Beetle Infested Pine: Biomass Feedstocks for Producing Power

Final Report: April 30th, 2005

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Prepared for the

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Executive Summary

The mountain pine beetle (MPB) has caused extensive damage to trees in British Columbia, threatening the health of the forestry industry and the viability of several communities in some portions of the province. One possible response is to harvest MPB damaged wood and use it as a fuel for the generation of power. This study is a conceptual engineering economic analysis of that option.

Two cases are evaluated in this study, both based on a power plant producing 300 MW of power (net of internal power station usage; gross power production is 330 MW). In this study, the power plant is assumed to be a stand alone base load condensing steam cycle power plant. Note that if a suitable host can be found for low quality heat, the plant could be developed as a cogeneration facility, with improved economics. The critical factor here is identifying a suitable heat sink.

Case 1 is based on harvesting MPB wood over a 20 year period, a "harvest as you go" scenario. Case 2 ("one time harvest") is based on harvesting MPB wood in an intense two year period before the plant is constructed and storing it at the side of logging roads. Stacking patterns would be chosen to maximize natural air circulation to minimize tree rot. Biomass harvested from the forests of Canada prior to January 1 2008 might enable the regrowth to be credited towards Canada's commitments under the Kyoto accord. Of the 500 million m^3 of infected wood, an estimated 200 million m^3 is expected to be unharvested. This study is based on harvesting 68 million m^3 of this otherwise unharvested wood for conversion to electrical power. We note that the most common comment on this study is skepticism that Case 2 can be implemented, due to limitations in harvesting capacity and difficulties in fast tracking permitting to harvest. We nevertheless include this case for completeness.

The 300 MW_e size is comparable to a 240 gross MW_e and 160 MW_{th} wood/peat/coal fired power plant in Pietarsaari Finland. Construction of this plant would place Canada in the forefront of biomass based power plants. Based on previous studies, the 300 MW_e plant is consistent with optimum size; smaller power plants generate increasingly more expensive power because of the loss of economy of scale in capital equipment. The forest areas of British Columbia especially the infested wood provide a secure source of biofuel for the proposed plant.

The assumed location of the plant in this study is Quesnel, B.C., which is relatively central to the areas of MPB damaged wood and adjacent to an existing major high voltage transmission line that approximately parallels Highway 97. The estimated draw area is approximately 90 km by 90 km. Note that the exact location of the plant would be reassessed at the next stage of study based on more precise estimates of the location of MPB stands for which no other use is identified. If the stands are remote from the Highway 97 and BC Hydro transmission corridor, it would be more economic to provide a more remote location for the power plant with connecting dedicated transmission line than haul the trees a longer distance.

The basis of the plant is the direct combustion of wood chips in a conventional stoker boiler; however, a sensitivity study showed that high pressure gasification of wood followed by a combined cycle power plant, i.e. biomass integrated gasification and combined cycle (BIGCC) had competitive economics, and this option should be evaluated in parallel with the direct combustion option at the next stage of conceptual design if this project proceeds.

Based on an analysis of all cost factors, the estimated all-in net cost of power from this project is \$61.88 MWh^{-1} for Case 1 ("harvest as you go") and \$117.07 MWh^{-1} for Case 2 ("one time harvest"). For Case 1, 45.6% of the total cost of power is the delivered cost of wood to the power plant, 38.5% is the recovery of investment in the power plant (over the 20 year life of the plant), and 15.9% is operating and maintenance cost. The delivered cost of biomass includes harvesting (\$10.32 MWh^{-1}), transportation (\$7.62 MWh^{-1}), silviculture (\$3.58 MWh^{-1}), road construction (\$4.06 MWh^{-1}) and whole tree chipping (\$2.61 MWh^{-1}); ash disposal is a very small component of total power cost. Case 2 is less economic than Case 1 because of the carrying cost of the early harvest; total spending in Case 2 for the harvest and field storage of MPB trees, including construction of logging roads and silviculture costs after harvest, are in excess of one billion dollars.

Average monthly power price in the northwestern US has ranged from \$45 to \$55 (US\$). For economic analysis, we assume that the average value of incremental power in Quesnel to Powerex, the exporting arm of BC Hydro, is \$55 (Cdn \$) per MWh, a figure we believe to be conservative. Note that this value does not include a possible Federal subsidy of \$10 MWh^{-1} discussed below. Operation of a MPB wood power plant in off peak hours has the potential to enable storage of water for use in generating power for export sale during peak hours. A critical activity in the next phase of evaluation of this project is a more precise determination of the value of power, including carbon credits discussed below.

In Case 1 ("harvest as you go") the MPB wood power plant would create a carbon credit for displacement in northwestern North America of an incremental base loaded fossil fuel power plant. In this study we assume that the displaced fuel is coal (base load) rather than gas (peak load). In Case 2 the MPB wood power plant would potentially be eligible for two carbon credits, one for removal of carbon from Canada's forest prior to the deadline within the Kyoto agreement, which would allow regrowth to be counted as incremental carbon sequestered, and one for the displacement in northwestern North America of an incremental base loaded fossil fuel power plant. The table below shows the carbon credit, in \$ Cdn per tonne of CO_2, that is required for the power plant to achieve a 10% return on total capital employed. In the last speech from the Throne in Canada the Federal Government signaled its intention to implement a credit of \$0.01 per kWh for biomass based power (\$10 per MWh). Note from the table that if the MPB wood project qualified for this subsidy, it would dramatically reduce the required carbon credit. Leverage through debt financing is not factored into this study; we believe a 10% pre tax return on total capital is reasonable for a merchant power plant secured by a long term power purchase contract.

Some elements of wood power plant are low risk: harvesting and transporting timber, burning mill residues such as sawdust to generate steam power, generating power from steam, and transmitting and exporting power are well understood and widely practiced in B.C. For MPB wood power plant, however, we do not know how the quality of wood affects its fiber quality for timber and pulp and the heat values for heat and power production. We suspect that these quality characteristics are time dependent. It is important we develop models that we can predict the quality of the infested tree. Capital and operating costs of a large wood based direct combustion or BIGCC power plant would need more detailed evaluation if this project proceeds.

Biomass harvesting cost is a critical cost element of the total power cost. It depends on a number of factors such as the type of harvesting system, type of machine, size of the trees, location etc. The economics of utilization of MPB infested wood for power depends significantly on the delivered cost of biomass. Given the range of reported values, one critical component of future evaluation of this project is a detailed cost analysis of all components of the delivery of MPB wood to a power plant.

In summary, Case 1 ("harvest as you go") results are:

Items	**Values**
Size of the MPB wood power plant (direct combustion)	300 MW
Amount of biomass required over 20 years	67,864,000 m^3
Project area from which biomass is drawn	790,000 ha (89 km x 89 km)
MPB power cost	\$61.88 MWh^{-1}
Value of a carbon credit required to achieve 10% return on capital:	
Without proposed federal subsidy	
Case 1, with single carbon credit	\$7.30 per tonne of CO_2
Case 2, with double carbon credit	\$32.94 per tonne of CO_2
With proposed federal subsidy	
Case 1, with single carbon credit	-\$3.31 per tonne of CO_2
Case 2, with double carbon credit	\$27.63 per tonne of CO_2

Key cost elements in the overall cost of MPB wood power for Case 1 are:

Cost element for Case 1: "harvest as you go"	**Cost (\$ MWh^{-1})**
Delivered Biomass Cost Components	
Harvesting cost	10.33
Transportation cost	7.62
Silviculture cost	3.58
Road Construction cost	4.06
Chipping cost	2.61
Total delivered biomass cost	**28.20**
Capital cost recovery	**23.82**
Operation and Maintenance Cost Components	
Storage cost at plant	0.71
Operating cost for plant	1.52
Maintenance cost for plant	6.12
Administration cost for plant	0.95
Ash disposal cost	0.56
Total operation and maintenance cost	**9.86**
Total Power Cost from MPB Killed Wood	**61.88**

Key sensitivities for Case 1 (“harvest as you go”) and their impact on the cost of carbon credit needed to realize a 10% return on capital are shown below:

Factor	MPB Power Cost ($ MWh^{-1})	MPB Power Cost Impact (%)	Carbon Credit Impact (%)
Base Case	61.88	0	0
Biomass yield is 25% higher per gross hectare	60.25	- 2.6	- 23.7
Biomass yield is 25% lower per gross hectare	64.51	+ 4.3	+ 38.2
Biomass harvesting cost is 50% higher	67.06	+ 8.4	+ 75.3
Biomass harvesting cost is 50% lower	56.70	- 8.4	- 75.3
Biomass transportation cost is 25% higher	63.78	+ 3.1	+ 27.8
Biomass transportation cost is 25% lower	59.97	- 3.1	- 27.8
Capital cost of plant 10% higher	64.86	- 4.8	- 43.3
Capital cost of plant 10% lower	58.90	+ 4.8	+ 43.3
Deemed value of power price in BC is \$70 MWh^{-1}	61.88	0	- 218
Deemed value of power price in BC is \$40 MWh^{-1}	61.88	0	+ 218

Acknowledgements

The authors are grateful to BIOCAP Canada Foundation and the BC Government for providing the financial support to carry out this project. The authors thank Mr. Alex Sinclair, Vice President, Western Division, Forest Engineering Research Institute of Canada (FERIC) for his valuable comments on the harvesting, transportation and storage of biomass. The authors would also like to thank Professor Valerie LeMay, Department of Forest Resource Management, University of British Columbia, Professor Vic Lieffers, Department of Renewable Resources, University of Alberta, and Professor Emeritus Gordon Weetman, Department of Forest Sciences, University of British Columbia for providing valuable information on biomass yield. Numerous parties read a preliminary version of this report and provided valuable comments; we thank David Layzell (BIOCAP), Jamie Stephen (BIOCAP), Jack McDonald (FERIC), Tony Sauder (FERIC), Henry Benskin (Ministry of Forests, BC), Dave Spittlehouse (Ministry of Forests, BC), Tony Lempriere (Natural Resources Canada), Joseph Krupski (Ministry of Forests, BC), Christian Wolfe (Ministry of Forests, BC), Dale Draper (Ministry of Forests, BC), Ian Whitworth (Ministry of Forests, BC), Brad Stennes (Canadian Forest Service), Alec McBeath (Canadian Forest Service), Bill Wilson (Canadian Forest Service), Terry Hatton and Peter Graham. Many others in the forestry and engineering community have provided valuable input as noted in the references. However, all the conclusions, recommendations and opinions are solely the authors, and have not been endorsed by any other party.

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1. Background and Overview

The forestry industry of the Province of British Columbia is facing a major problem due to mountain pine beetle (MPB) infestation. According to current estimates the area of infestation in British Columbia was 4.2 million hectares in 2003. This infestation is expected to result in about 500 million m^3 of infected wood biomass over three years. About 40% of this biomass, 200 million cubic meters is forecast to remain unharvested. Some parts of Alberta have also been affected by MPB infestation. 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. Canada has ratified the Kyoto Protocol on Climate Change. The infected pine can be used to generate green power. This would help in mitigation of greenhouse gases emission and will contribute to Canada's efforts to comply with Kyoto Protocol.

Many plants around the world burn biomass to make heat, power or a combination of the two. Many of these plants are based on mill residues, for example bark, sawdust and trimmings, and hence are built at a small size that reflects the source of the biomass. An example of this is the 65 MW plant in Williams Lake that uses about 600,000 tonnes of saw mill residue per year, and numerous smaller power plants throughout Canada. California has 28 direct combustion biomass power plants with a generation capacity of 558 MW and an additional 70 MW of generating capacity from cofiring of municipal waste; many other plants are located across the US. Europe has many biomass power plants, including several using straw as a fuel.

Several authors have noted that the cost of power from a biomass based plant is dramatically lower for larger plants sizes, greater than 100 to 300 MW (see, for example, Jenkins, 1997; Jenkins, 2005; Kumar et al., 2003; Larson and Marrison, 1997). Because many biomass projects to date are constrained by mill residue supply or by their demonstration nature, only one plant has been built over 100 MW, a 240 MW mixed fuel (fossil plus biomass) plant in Finland near Pietarsaari; the largest North American plant, a US plant burning wood, operates at 80 MW (Wiltsee, 2000; Organization for the Promotion of Energy Technologies, 2004).

The principal diseconomic cost factor for small biomass plants is the high cost of plant capital per unit of output. Power cost per MWh rises dramatically for plants at sizes below 100 MW. As plants get larger, biomass transportation distances increase, and this cost factor eventually overwhelms savings from capital efficiency, but not until significant plant sizes are reached. A highly detailed study by Kumar et al. (2003) identified the optimum size of biomass based power plants in western Canada as being in the range of 200 to 2000 MW. Critical factors in determining optimum size are the tradeoff between plant and transportation costs; the proposed study explores this in detail for beetle infested pine.

The technology for building large scale biomass power plants is well understood; there is no technical hurdle to overcome in the plant design. By building a power plant in the range of 200 to 400 MW for beetle infested pine, Canada and BC would position themselves at the forefront of power generation from biomass at the very time that this technology will undergo intense scrutiny around the world as a means by which countries can meet their Kyoto targets. In addition to the direct benefit of using beetle infested pine to generate power, Canadian firms would be well positioned to design and/or develop projects in other locations around the world. Given Canada's large forestry resource, it makes sense for it to be a leader in power from wood.

The objective of this study was to conduct an initial techno-economic assessment of using a portion of BC's mountain pine beetle damaged pine as a fuel source to generate power. Our assessment estimates the cost of harvesting and transporting a portion of the beetle infested pine wood to support a dedicated wood burning power plant for a period of 20 years. This study estimates the size of the biomass power plant and the cost of producing power from the infested wood. Finally, the value of carbon credit required to make the biomass based power competitive, i.e. achieve a return of 10% on capital in today's power markets, is calculated.

Two cases are evaluated in this study. Case 1 is based on harvesting MPB wood over a 20 year period, a "harvest as you go" scenario. Case 2 ("one time harvest") is based on harvesting MPB wood in an intense two year period before the plant is constructed and storing it at the side of logging roads. We note that the most common comment on this study is skepticism that Case 2 can be implemented, due to limitations in harvesting capacity and difficulties in fast tracking permitting to harvest. Hence the body of the report discusses Case 1 ("harvest as you go") scenario. We have nevertheless included discussion on Case 2 ("one time harvest") for completeness in the Appendix A.

2. Biomass Source and Characteristics

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 BC (MOF), 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 BC. The standing beetle infested pine trees offer a great opportunity as a relatively dense field source of woody biomass which can support a large scale stand-alone power plant.

Current estimates are that 200 million m^3 of wood would remain unharvested (MOF, 2003). The study areas include the Morice Lakes, Prince George, Quesnel, Williams Lake, 100 Mile House and Kamloops timber supply areas and 5 tree farm license areas. Figure 1 shows the study area. One-third of the total timber harvesting land base of the study area is covered by greater than 50% mature pine stands (MOF, 2003). In this study yield for average 90 year old lodgepole pine stands is estimated using the Variable Density Yield Program (VDYP) developed by research branch of the MOF (MOF, 2005).

The average standing yield per net hectare for lodgepole pine is estimated at 241.7 m^3 of delimbed stem volume (including bark).

A critical issue in recovery of wood for power generation is average transportation distance. This requires a conversion from standing yields per net hectare to yields per gross hectare, where gross hectares include all other land uses such as other forest species and non-forest land use. We estimate that 33% of the forest land in the study area is mature lodgepole pine stands and that 10% of land in the study area is not forested (e.g. roads, lakes, communities, agriculture and industry), which gives an equivalent yield of 71.8 m^3 of recovered wood /gross ha (MOF 2005).

In “harvest as you go” case we assume that MPB killed trees are cut and skidded to the roadside. At the roadside 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. This increases the biomass yield to 86.2 m^3 per gross ha.

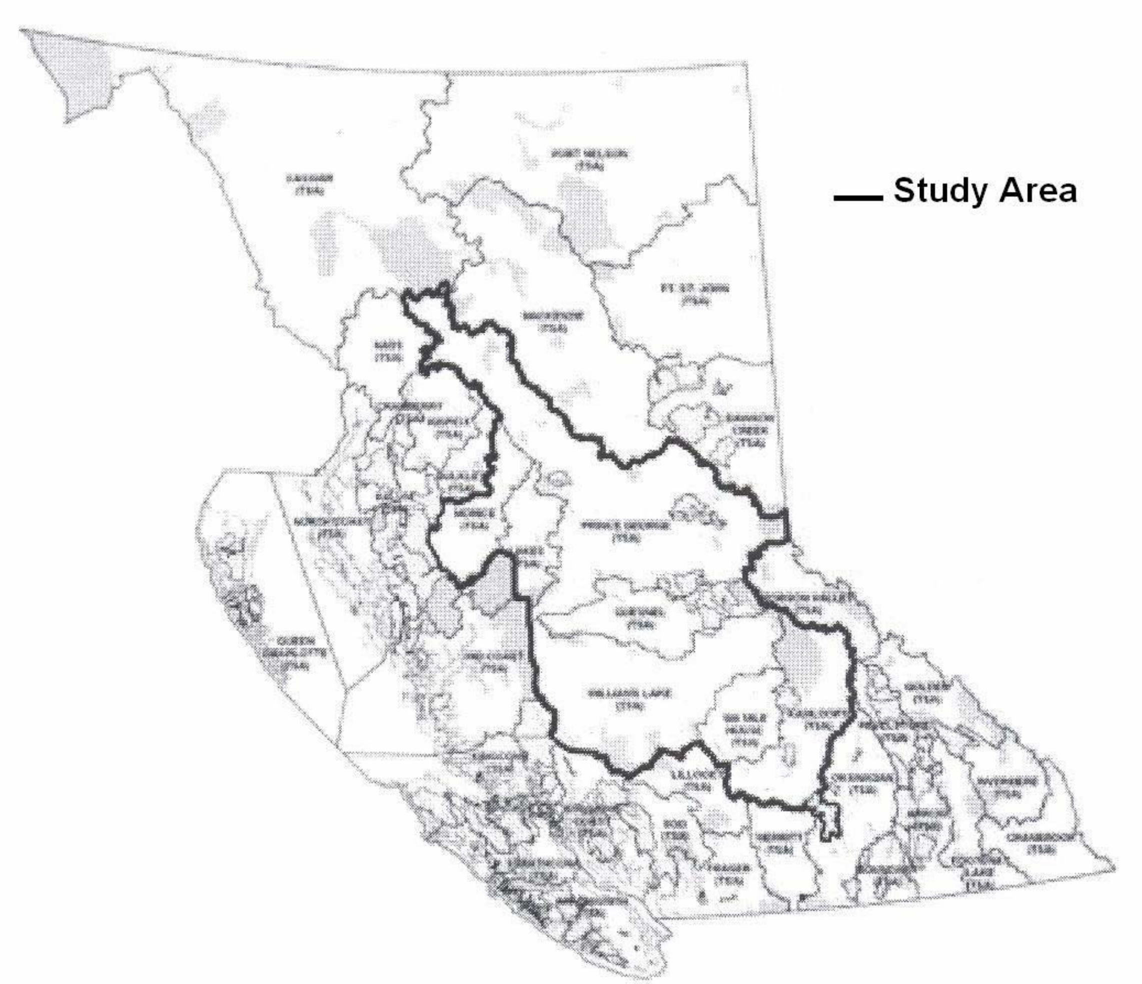

Figure 1: Map of the study region (Ministry of Forests, 2003).

Table 1 summarizes the biomass productivity related parameters. Input to the VDYP model for estimation of yield are given in Table B1 in the appendix. Sensitivity cases for higher and lower yields are included in this study.

Table 1: Biomass productivity related parameters

Items	Value	Comments/Source
Yield of stem volume (including bark) per net hectare, (m^3/ net ha)	241.7	Calculated using VDYP model (MOF, 2005).
Ratio of mature lodgepole pine timber harvesting land base to total timber harvesting land base in the study region	0.33	Derived from earlier study. This is for forest area comprising of more than 50% pine older than 80 years (Ministry of Forest BC, 2005).
Fraction of land covered by roads, lakes, communities, agriculture, industry, etc.	0.1	Assumed.
Fraction of residues in the total tree biomass	0.2	Assumed.
Yield of recovered biomass per gross hectare (m^3/ gross ha)	86.2	Calculated based on above ratios.
Gross volume per average tree (m^3)	0.60	(Wheetman, 2005; LeMay, 2005)
No. of stems per hectare	480	(Wheetman, 2005; LeMay, 2005)
Ratio of usable merchantable volume to gross volume	0.8	(Lieffers, 2002)

3. Fuel Properties

Equilibrium moisture content (EMC) of wood is one of the most important characteristics for its use as fuel. Water in the wood has a tendency to reach equilibrium with the surrounding air. EMC of wood in 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. In this study we estimated the equilibrium moisture content of the wood based on equations developed by William Simpson of United States Department of Agriculture Forest Service (Simpson, 1998). The equations for estimation of EMC are given in Appendix C. 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 fuel properties are given in Table 2.

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

Table 2: Fuel 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 C (Simpson, 1998).
Higher Heating values (MJ/ dry kg)	20	This is the average heating value of softwood (Demirbas, 1997).
Density of logs at given moisture content (kg/ m^3)	455.3	Calculated based on equations given in Appendix D. Density is for lodgepole pine logs at 13% EMC (Simpson, 1993).
Ash in wood (%)	2.5	(McDonald and Sauder, 2005).
Hydrogen content of wood (%, dry basis)	5.98	(National Renewable Energy Laboratory, 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 D) (Simpson and TenWolde, 1999).

4. Scope and Cost

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. MW refers to electrical megawatts unless otherwise noted.

The scope of this study is a dedicated power generation 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 Section 4. Note that for costs affected by scale factor, the costs are reported for a plant capacity of 300 MW.

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. Wood chips are drawn from throughout the harvest area, giving a fixed transportation distance to the power plant over the life of the plant. The study draws on regionally specific detailed studies of the costs of recovering forest biomass performed by Canadian Government, 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 (Puttock, 1995; Sinclair, 1984; Hudson and Mitchell, 1992; Hankin et al., 1995; Hudson, 1995; Perlack et al., 1996; Zundel and Lebel, 1992; Hall et al., 2001; LeDoux and Huyler, 2001; McKendry, 2002; Zundel et al., 1996; Silversides and Moodie, 1985; Zundel, 1986; Mellgren, 1990; MOF, 2001; MOF, 2004; Kuhnke et al., 2002).

Delivered biomass cost from different sources shows a wide variation as these studies include cost of different operations and systems. This study uses the MOF reported costs for some of the operations. In this study, tree-to-truck cost includes only felling and skidding (obtained by published FERIC reports). The harvesting system is a feller-buncher and a grapple skidder. Loading and unloading costs are included in the hauling cost. The tree-to-truck costs are comparable to other studies but lower than the Ministry of forest, BC, figures (reported in MOF, 2001). MOF, BC has conducted surveys on the logging cost of biomass in this region. Tree-to-truck cost reported by MOF is the average cost of different harvesting method and also includes cost of many operations which are not required in the harvesting model presented in this study such as yarding, bucking, slashing etc. MOF costs also include stumpage values which have not been included in this study. In this study road construction and infrastructure costs also include camp cost and these costs are comparable to MOF costs (MOF, 2004). Cost of overheads in this study is taken from MOF data (MOF, 2004) for the Quesnel region and have been adjusted for suitability to this study as some of the overhead components might not be required for this study (such as, waste and residues surveys cost, etc.) Silviculture cost in this study is the average cost for sub boreal pine/spruce biogeoclimatic zones in BC (MOF, 2004). Table 3 shows the comparison of harvesting cost reported by different sources. Delivered cost of biomass is critical to economics of biomass based power; given the range of reported figures, further detailed cost estimation is required in the next phase of the study.

In addition, a detailed model was developed for chipping of the trees at the roadside. The transported trees would be chipped by 50/48 Morbark chipper (Kowallic, 2002). The large scale chipper is assumed to operate 5000 h per year. Based on this specific case a chipping cost of $4.66 per dry tonne is calculated. This is considerable lower than other reported values in the literature, which range from $13.41 to $23.7 per dry tonne (Desrochers, 2002; MacIntosh and Sinclair, 1988; Wiksten and Prins, 1980; Folkema 1989; Bowater Newfoundland Ltd., 1983; Favreau, 1992; Spinelli and Hartsough, 2001; Asikainen and Pulkkinen, 1998). The lower value in this study arises from the large scale of the chipper (100 green tonnes/h) and the high number of operating hours per year compared to the chippers in earlier studies. 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.

Some cost factors warrant further comment:

- Collection of biomass in the forest: 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 power plant operator contracts out harvesting. We assume that contract harvesting rates cover felling, skidding, and chipping of whole trees at the roadside.
- Transport of biomass to the power plant site: 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.
- Storage of biomass at the plant site: 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 power plant when roads are impassible.

- Combustion of the biomass in a boiler, with use of the steam solely for power generation: Full capital costs are calculated for power generation, and are adjusted for capacity by a scale factor. Note that cogeneration, the use of low-pressure steam exhausted from turbo generators for heating, is not considered in this study. Cogeneration improves the return from power plants but requires a heat sink that matches the operating pattern of the power plant.

  - Scale factor: The base case unit scale factor used in this study was 0.75, where scale factor is an exponent for adjusting the cost of a direct combustion power generation unit from one capacity to another (see equation below).

$$Cost_2 = Cost_1 x (\frac{Capacity_2}{Capacity_1})^{Scale \quad factor}$$

    Scale factors for single boiler biomass power plants from the literature range from 0.7 to 0.8 (Bain et al., 1996; US Department of Energy, 1996; Marrison and Larson, 1995); similar values are reported for coal (Williams, 2002; Silsbe, 2002). Actual cost data is available for a number of straw based plants, although comparison is difficult because the plants use the steam for heat and power, and the relative mix of these varies from plant to plant (Larsen, 1999; Caddet Renewable Energy, 1988a, 1988b, 1998). After modifying the data to adjust for scope, the scale factor is estimated at 0.8, but this reflects plants built in a variety of locations that are always "new" to that location and that are small and built as demonstration units. For that reason, we have assumed that in a large scale facility the scale factor would be lower, particularly since one other large biomass power plant has been recently commissioned.

    Previous studies have shown some disagreement on appropriate range of scale factors; Jenkins (1997) has explored a wide range, from zero to 1.0, while Dornburg and Faaji (2001) argue for a narrower range. Based on discussions with firms that have built major energy facilities, we explore the impact of scale factor in the range of 0.7 to 0.8 for a single unit up to 450 MW size. Over 450 MW, a step change in scale factor occurs: the cost of an additional identical unit is assumed to be 95% (Silsbe, 2002) of the first unit cost, i.e. the cost of building an incremental identical unit saves 5% on the incremental unit only. This is close to Jenkins' assumption that scale factors approach unity as project sizes get very large.

  - Maximum Unit Size: In this study we have assumed that the maximum unit size for a biomass fired boiler is 450 MW. (Although it is possible to build a biomass based single unit plant at 450 MW, this study is based on, and recommends, a plant size of 300 MW, because most of the impact of economy of scale is realized by 300 MW and the unit size is a small extension past the 250 MW existing plant in Finland. However, to illustrate the impact of size we calculate power cost as a function of size for large power plants.)

For any capacity over 450 MW, two or more identical sized units are built, e.g. at 500 MW two units of 250 MW would be built. This assumption reflects two qualitative factors: a judgment re comfort in scale up of existing biomass combustion units, and the maximum unit size that is acceptable in relation to the size of the electrical power market, due to grid stability issues. We note that the one coal fired unit recently commissioned and two planned in the Province of Alberta are all sized at 450 MW, although larger coal fired units have been built in other locations. Optimum plant size is found to be one or more of the maximum sized units, but as noted above, a 300 MW unit achieves enough of the benefit of economy of scale to have a small incremental cost compared to a 450 MW unit. This is discussed further below.

Table 3: Comparison of delivered cost of biomass*

Components	This study[1]	MOF	Northern Forestry Centre, 2002[3] (Average cost)	Northern Forestry Centre, 2002[3] (Subcontractor's cost)	Gingras and Favreau, 1996[4] (FERIC)	Zundel and Lebel, 1992[5]	Folkema, 1989[6] (FERIC)	
							Lower limit	Higher limit
Felling ($/m³)	2.33		2.77	3.68	4.87	5.29		
Skidding ($/m³)	2.13		2.37	3.03	6.78	3.19		
Delimbing ($/m³)	2.23		2.93	3.42	4.11	4.24		
Tree-to-truck ($/m³)	6.69	16.65[2]	8.07	10.13	15.76	12.72	11.38	12.09
Silviculture ($/m³)	3.15	3.45				0.31		
Roads ans infrastructure ($/m³)	3.90	10.76[2]	1.26	1.26			2.13	2.13
Overheads ($/m³)	5.00		2.60	2.60			3.56	4.27
Chipping ($/m³)	1.88	3.27						
Hauling ($/m³)	5.09[7]	7.02	5.10	5.10			7.11	7.82
Total delivered cost ($/m³)	25.71	41.15	17.04	19.10			24.18	26.31

* - All costs have been adjusted to 2004 dollars.
1 - Cost of felling and skidding is estimated based on a merchantable volume of 0.5 m^3 per stem. Note that "harvest as you go" scenario, case 1, doesn't include delimbing as whole tree is chipped for fuel.
2 – Costs are from survey of logging contractors and include stumpage. Tree-to truck cost of MOF includes other operations such as bucking, slashing, yarding etc. Roads and infrastructure cost for MOF also includes overheads.
3 - Hauling cost is estimated using a transportation cost of $0.0354 /t-km and a loading and unloading cost of $3.40/cu.m.
4 - Values are for a full-tree-harvest system in boreal region.
5 - Values are for a full-tree-harvest system.
6 - Values for whole tree chipping system.
7 – Chip hauling cost with a B – train chip van.

- Capital cost: Data were drawn from a variety of actual plant costs and literature sources, and show a wide variability (Broek et al., 1995; Caddet Renewable Energy, 1988a, 1988b, 1998). The value used in this study is \$1596 kW^{-1} for a wood boiler at a size of 300 MW; comparable values for new coal-fired plants in Alberta are \$1260 kW^{-1}. We developed this cost estimate for a power plant based on considering the design differences between a large scale plant using biomass instead of coal, and applying an adjustment to reported values for stand alone coal power plants. Cameron et al. (2004) shows a breakdown of the total estimated cost of a power plant using a low sulfur sub-bituminous coal, the expected differences in scale for biomass vs. coal, and the adjustments to build an estimate for a biomass plant based on a mature coal technology. This value is lower than that extrapolated from many "one of a kind" small demonstration straw based power plants (Kumar et al. 2003), but higher than the reported cost of the one large biomass based power plant, the Finnish Alholmens plant near Pietarsaari with mixed fuel at 240 gross MW (before allowing for consumption of power in the generation plant itself.

  Note that the boiler/power plant cost for wood is higher than comparable capital costs for large coal fired boiler/power plants in western Canada (which use low sulfur coal that does not require sulfur removal from flue gas). Several factors contribute to a higher cost for burning biomass, including higher mass flow rate of solid fuel, lower flame temperature (and hence larger convective to radiant ratio in the boiler) and a more corrosive ash (Miles et al., 1996); these were the factors considered by Cameron et al. (2004). We have run sensitivities on capital cost because of the uncertainty in this value.

- Location: We have assumed Quesnel, BC as the power plant location, although any near location along Highway 97 would be suitable. The location is driven by proximity to existing highways for biomass transportation, proximity to a major power transmission line, and abundant water relative to the need for makeup for evaporation from power plant cooling water. The interior of British Columbia has a cold winter, but also has a workforce and construction industry well used to working productively in cold weather. Hence, no capital cost penalty was applied for climactic conditions. The plant would be sufficiently near to the population centers that construction labor would not need to be housed in a camp, and hence the capital cost has no provision for a camp. However, construction labor would have a daily transportation cost (for example, bus to and from Prince George); to allow for this, overall capital costs are escalated by 5% (Williams, 2002). Figure F1 in Appendix F shows location of Quesnel , BC.

- Disposal of ash: Evidence from two Canadian biomass plants is that once a biomass power plant starts up, a demand develops for ash, in that farmers (and perhaps foresters) will remove ash from the plant at zero cost, and spread it on fields (Matvinchuk, 2002). However, since this takes some time to develop, in this study we have taken a more conservative approach: ash is hauled to fields at an assumed average haul distance of 50 km, and spread, all at full cost to the power plant. For this scenario, spreading cost is a significant portion of total ash disposal cost. Ash content for wood is given in Table 2.

- Connection of the power plant to the existing transmission grid: In this study the location of the power plant is assumed to be at or very near to an existing community and to an existing transmission line. Hence, no net transmission cost is assigned to the power plant.

- Operating costs: For the biomass power plant staff compensation is estimated at \$45 $hour^{-1}$ to cover salary plus benefits.

  - Direct operating labor: A single boiler unit is estimated to require eight operators per shift, and each additional unit requires an additional four operators (Broek et al., 1995; Matvinchuk, 2002). These levels are slightly higher than comparable coal plants, and reflect larger volumes and potential difficulties in the receipt and processing of biomass fuel.

  - Administration costs: The biomass power plant is assumed to be a stand-alone company, and an administration staffing level of 26 is assumed for each case. For this study the staff is sited at the power plant location. If a larger firm owned and operated the biomass power plant, savings in administration costs would be possible. However, these are not a significant cost factor in the overall cost of power.

  - Maintenance costs: Maintenance is a major source of uncertainty in evaluating biomass plant operating cost. Existing coal power plants in Alberta that pulverize and fire high ash coal have maintenance costs in the range of \$2.04 to \$2.85 MWh^{-1}. Various studies of biomass units show values that are 7 to 10 times higher (Bain et al., 1996; Broek et al., 1995). After some modifying of actual data from a small demonstration straw fired power plant, we estimated maintenance costs at about \$21 MWh^{-1} (Caddet Renewable Energy, 1997). We cannot explain this wide range in terms of difficulty of processing fuel or expected problems in the boiler, and we attribute them in part to the startup and demonstration nature of most existing biomass plants. In this study we have assumed that maintenance costs (parts plus labor) are 3% of the initial capital cost of the plant, which gives a maintenance cost of \$6.12 MWh^{-1}. Actual maintenance costs in large-scale biomass facilities are a critical issue in overall economics of biomass usage; further development of this project should include a reassessment of actual biomass power plant maintenance costs.

- Plant reliability and startup profile: Biomass plants have operating outages that are often associated with solids handling problems. In this study, a plant operating availability of 0.85 is assumed, which is less than levels of 0.90 to 0.95 routinely achieved in coal-fired plants (note that Jenkins (2005) cites an availability of 0.88 for California biomass power plants). Startup of solids based power generation is rarely smooth, and this is accounted for by assuming a plant availability of 0.70 in year 1 and 0.80 in year 2. In year three and beyond the availability goes to 0.85 (Wiltsee, 2000). The plant is assumed to be base load, i.e. operating at full available load 7 x 24 hours, which is a reasonable assumption in BC where plants in the region (Alberta/BC/US Northwest) with a higher net marginal cost (fired by natural gas) provide non-base load power.

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

- Return: Power cost is calculated to give a pre-tax return of 10%. This value is consistent with a plant with a publicly guaranteed return on investment. The impact of rate of return is assessed in a sensitivity case; an alternate case is run at 12%.

- Power price: BC is a net exporter of power to both Alberta and the US Northwest, and the value of power assumed in this study is based on 7x24 average power value in export markets. The US Mid C (Northwest US) power price has ranged from $45 to $55 per MWh (US$), and in this study we assume a value of power at the plant of $55 Cdn per MWh. Note that operation of the biomass power plant during periods when reservoir and turbine capacity allows storage of displaced water at night and generation from the displaced water during the day would in effect realize on peak power price for the incremental power. Full analysis of the value of power requires a more in-depth analysis of reservoir and generation capacity in the BC system and an assessment of the impact of incremental export on regional power pricing.

5. Input Data and Assumptions

Table 4 summarizes the biomass production and delivery data which includes harvesting and transportation costs. Table 5 gives the power plant characteristics and cost data. Table 6 gives the general assumptions for the cost model.

6. Results and Discussion

6.1. Resource requirement and power cost

Table 7 gives the amount of wood required over 20 years to support the biomass power plant, the geographical footprint and the power cost. Note that if all of the assumed available 200 million m^3 of otherwise unharvested MPB wood were to be used for power production, it would support three 300 MW power plants producing, over their life, 143 TWh of electricity.

Figure 2 shows the power cost as a function of plant capacity. The discontinuities in the graph occur when an additional unit is built. In theory, the optimum power plant size would be 450 MW of power generation, but in practical terms a unit of 300 MW would reduce the risk to the project developer, because it is comparable to another large power plant using biomass, and would achieve much of the available economy of scale.

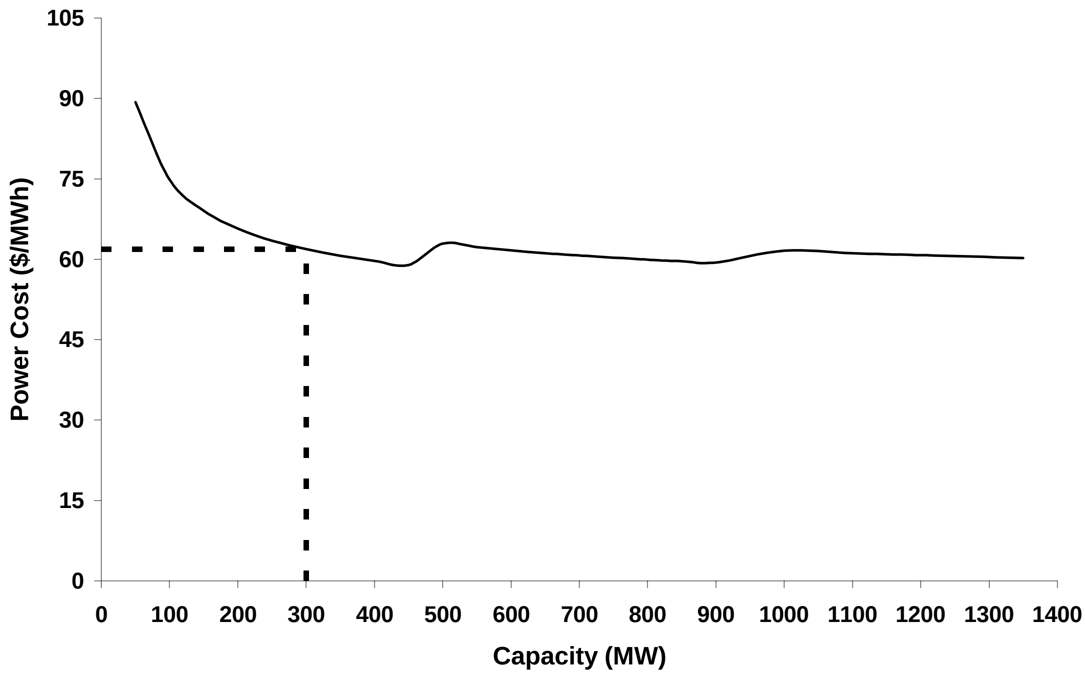

Figure 2. Power cost as a function of capacity for MPB killed wood based plant.

These curves have two characteristics worth noting:

- The profile of power 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. This result is consistent with previous studies of optimum size (Jenkins 1997; Nguyen and Prince, 1996; Overend, 1982; Larson and Marrison, 1997; McIlveen-Wright et al., 2001; Kumar et al., 2003). The flatness of cost vs. capacity for large biomass plants is different than coal projects, where "bigger is better", and the size of a unit is often determined by either the largest available capacity or the largest increment of power generation that the power market can accommodate.

  The result is that biomass to power projects can be built over a wide range of capacities without a significant cost penalty, but not at small plant sizes. For example, the economic optimum sized for MPB killed wood based plant is 450 MW, but the range of capacity for which the power cost is within 10% of the optimum value is 150 MW to 4000 MW. In practice a developer would want a smaller plant to limit risk, and a larger plant size to improve project economics; 300 MW is a reasonable tradeoff between these two factors.

- The assumption of maximum unit size drives the determination of the optimum size: The assumption that the largest single biomass unit that can be built is 450 MW puts a discontinuity in power cost at any multiple of that size, as is seen in Figure 2. This occurs because at 451 MW, two identical 225.5 MW units are built rather than a single unit. However, as noted above, the flatness of the curve suggests that an MPB wood based power plants could be built in any scale from 150 MW to well over 1000 MW with an output power cost predicted to be within 10% of the optimum value.

Table 4: Biomass production and delivery data

Factor	Formulae	Value	Source / Comments
Whole forest harvest cost including skidding to roadside (\$ m^{-3}) • Felling • Skidding	 $1.5015V^{-0.5963}$ $1.6256V^{-0.3676}$	 2.33 2.13	In the formula V stands for mean merchantable volume of per stem. Average merchantable volume is assumed to be 0.8 of the gross volume per tree (Lieffers, 2002). Skidding distance is assumed to be 150 m. Value of V is assumed to be 0.48 m^3 per stem based on the yield of lodgepole pine (Favreau, 1992; Kumar et al., 2003; Wheetman, 2005; LeMay, 2005).
Chips loading, unloading and transport cost (\$ m^{-3})	1.2364*(2.30 + 0.0257D)	5.09	D is the round-trip road distance from the forest to the receiving plant (Favreau, 1992) by a chip van. In this study the cost has been converted to green metric tonnes.
Piling and removing chips from storage piles (\$ m^{-3})		1.90	Basis is that piling and removal cost are 2/3 of truck loading and unloading cost. (Favreau, 1992).
Road construction (\$ m^{-3})	(618.18/VT)	2.56	VT is the mean merchantable volume per hectare, where T is the mean number of merchantable stems per hectare. Value of VT has been assumed to be 241.7 m^3 ha^{-1} for the killed tree areas. The construction cost of roads is \$618.18 ha^{-1} represents the tertiary road network used only during the year of the harvest (Favreau, 1992; Kumar et al., 2003).
Infrastructure cost (\$ m^{-3})		1.24	Infrastructure cost depends on the amount of labor and machine, and possibly the merchantable volume per hectare (Favreau, 1992; Kumar et al., 2003).
Silviculture cost (\$ m^{-3})		3.15	Silviculture cost is \$761.20 ha^{-1}. Many Canadian provinces require that silviculture treatments be performed shortly after harvesting, so that cut areas are returned to a productive state. We have used the average silvivulture cost for Sub Boreal Pine/Spruce biogeoclimatic zone reported in IAM, 2004 (MOF, 2004).
Chipping cost for trees (\$ m^{-3})		1.88	Based on detailed study of Morbark 50/48 whole tree chipper (Kowallic., 2002).

Factor	Formulae	Value	Source / Comments
Overheads ($ m^{-3})		5.00	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. We have used two-thirds because some of operations included in estimate are not required for the purpose of power generation (MOF, 2004).

Table 5: Power plant characteristics and costs

Factor	Value	Source / Comments
Power plant boiler unit size (MW)	450	Maximum unit size assumed.
Plant life (years)	20	Note that the unit could likely run longer than 20 years based on forest harvest residues, mill wastes, or other sources of biomass.
Net plant efficiency (LHV) (%)	34	Internal plant use of power is assumed at 10% of gross (US Department of Energy, 1997; Broek et al., 1995; Wiltsee, 2000; Kumar et al., 2003).
Plant operating factor: • Year 1 • Year 2 • Year 3 onwards	 0.70 0.80 0.85	Estimated based on discussions with industry.
Operating staffing excluding maintenance staff: • 450 MW or below • Above 450 MW, for each additional unit	 8 4	Staffing levels are derived from the literature (Broek et al., 1995; Wiltsee, 2000; Kumar et al., 2003; Williams and Larson, 1996), and discussions with personnel in the power generation industry. For a plant up to 450 MW, operators per shift are fuel receiver (1), fuel handlers (2), control room (2), ash handling plant (1), and other power plant tasks (2). For each additional unit we add one fuel handler, one ash handler, and two staff for other power plant tasks. The assumed staffing is five shifts (10,400 hours per shift position per year), which allows for vacation coverage and training.

Factor	Value	Source / Comments
Power plant capital cost ($ kW^{-1} at 300 MW)	1596	This is for a 300 MW direct combustion biomass power plant determined from the literature (Bain et al., 1996; Broek et al., 1995; Kumar et al., 2003), existing straw plants (Larsen, 1999; Caddet Renewable Energy, 1988a, 1988b, 1998) and existing wood plants (US Department of Energy, 1997; Wiltsee, 2000). Note that this figure is more than 27% higher than comparable figures for coal based power generation. A location specific escalation of 5% is added to this figure to allow for a distributed construction work force that would require daily transportation to the plant site.
Average annual labor cost including benefits ($ hr^{-1}) • Operators • Administration staff	 45.00 45.00	 Estimated based on discussions with industry.
Ash disposal cost • Ash hauling cost ($ dry $tonne^{-1}$ km^{-1}) • Ash disposal cost ($ dry $tonne^{-1}$ ha^{-1}) • Amount of ash disposal (dry tonnes ha^{-1})	 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)
Transmission charge (including capital and operating cost) for remote location ($ MWh^{-1}); note this figure is not used in this study.	1.53	The transmission charge is 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). The cost is for the power plant running at full load at a capacity factor of 0.85. However, a power plant location remote from the existing transmission grid in BC is so unlikely that this transmission charge is not included in this study.
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 6: General assumptions

Factor	Value	Source / Comments
Scale factor • Total direct combustion power plant capacity 20 to 450 MW. • Transmission line capital cost. • Transmission line operating cost.	0.75 0.49 0.50	(Bain et al., 1996; US Department of Energy, 1997). 0.49 is based on fitting a curve to estimates of 300 km transmission lines through remote boreal forest at various capacities. This value is an exponent. 0.5 is an exponent for operating costs and is an estimate based on consultation with the electrical industry.
Cost of an additional equal sized power plant unit relative to the first	0.95	0.95 is based on conversations with Engineering Procurement Construction (EPC) contractors. This value is not an exponent. It states that additional identical power plant units only cost 95% as much as the first unit (Silsbe, 2002).
Factor to reflect capital cost impact for location.	1.05	1.05 is based on discussions with EPC contractors regarding construction in various locations (Williams, 2002).
Transmission loss for remote location.	1% of generated power	The value has been estimated based on consultation with the electrical industry for a base load 100 km line (Xu, 2002). This factor is not used in this study because the location of the power plant is assumed to be adjacent to existing transportation lines.
Annual maintenance cost.	3% of initial capital cost per year	The value has been assumed based on blending data from existing coal-fired units and from studies of biomass power plants (Bain et al., 1996; Broek et al., 1995; Caddet Renwable Energy, 1997; Kumar et al., 2003).
Aggregate pre-tax return on capital (blend of debt plus equity).	10 %	A rate based plant would combine debt at approximately 6.5% and equity at about 10.5%, 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.

Table 7: Resource requirement for MPB killed biomass over 20 years

Items	Values
Total lodgepole pine infested area in the study region[1]	3,300,000 ha
Total infested unharvested wood available[1]	200,000,000 m^3
Size of the direct combustion biomass plant	300 MW
Amount of biomass required over 20 years	67,864,066 m^3
Project area from which biomass is drawn	787,817 ha
Power cost	\$61.88 MWh^{-1}

[1] – (MOF, 2003).

6.2. The composition of power cost from biomass

Table 8 shows the makeup of biomass power cost per MWh. 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 about 45.6% of the total power cost followed by capital cost (38.5%) and operation and maintenance cost (15.9%). Transportation cost is 27.0% 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 2005). In this study, biomass storage cost is not significant component of total cost because it is the cost associated with only three months storage at the plant.

Table 8: Cost of power from MPB killed biomass, year 2004 \$ MWh^{-1}, at full capacity (year 3) and 300 MW size

Cost element	Cost (\$ MWh^{-1})
Delivered Biomass Cost Components	
Harvesting cost	10.33
Transportation cost	7.62
Silviculture cost	3.58
Road Construction cost	4.06
Chipping cost	2.61
Total delivered biomass cost	**28.20**
Capital cost recovery	**23.82**
Operation and Maintenance Cost Components	
Storage cost at plant	0.71
Operating cost for plant	1.52
Maintenance cost for plant	6.12
Administration cost for plant	0.95
Ash disposal cost	0.56
Total operation and maintenance cost	**9.86**
Total Power Cost from MPB Killed Wood	**61.88**

6.3. Economics of MPB killed tree biomass based power

MPB killed tree biomass based power is not directly competitive with the assumed export value of incremental power in BC, which is as discussed above is estimated at $55 per MWh. At this value, in the absence of an emission credit biomass power will not be developed. One critical issue in calculating a carbon credit is how much carbon is displaced.

An MPB wood based power plant is likely to displace a base loaded power plant, i.e. because a biomass based plant is constructed the need for an incremental fossil fuel plant is postponed. In Alberta and portions of the US incremental base load plants burn coal, and that assumption is used in this study, i.e. that the available carbon credit from the MBP wood plant is the assumed displacement of the equivalent amount of coal to generate 300 MW.

Life cycle emissions from biomass power plant

Table 9 shows the relative CO_2 emissions per kWh for the use of MPB killed biomass in this study and a new coal fired power plant located at the mine (in this case it the values have been used for an Alberta based coal power plant). The table uses the values of Spath et al. (1999) for the construction of the power plant and the harvesting of biomass, and incorporates average haul distances for biomass transportation. Transportation of coal has a negligible carbon emission factor because in western Canada the power plant is located adjacent to the mine. Note that the biomass transportation emissions are less than 1% of the emissions of a coal fired plant, per unit of power. Emissions associated with mining coal are included, for both the energy required to move the overburden and recover the coal, and the release of methane. Methane emissions from open pit coal mines reflect not only the methane contained in the mined coal but also methane from the seam near the edge of the pit, which is released to the atmosphere. The approach of Hollingshead (1990) was modified to reflect the large size of a mine supporting a 450 MW coal fired power plant. Methane released from the coal seam is estimated at three times the methane contained in the actual mined coal. From Table 9 it is clear that this assumption does not significantly affect the total estimated carbon credit.

Table 9: Life cycle emissions (g of CO_2 equivalent per kWh) from the power plants

Processes	MPB killed tree biomass	Coal
Production	28.0[a]	11.6[c]
Transportation	2.4[b]	0
Plant construction and decommissioning	12.0[a]	5.0[d]
Energy conversion	0	968.0[e]
Total emissions	42.4	984.6

[a] – (Mann and Spath, 1999).
[b] - based on truck transportation for an average distance of 36 kms, assuming the energy input of 1.3 MJ $tonne^{-1}$ km^{-1} by truck and a release of 3 gC GJ^{-1} km^{-1} (Borjesson, 1996). Most of the coal power plants in western Canada are at a mine, so the transportation distance is very small. The emission during transportation would be negligible as compared to the other components. Hence it has been neglected in this case.
[c] – For Genesee, Alberta coal-field, (Hollingshead, 1990). It includes the contribution from methane emission and also the emission during the mining of coal.
[d] – (Spath et al., 1999).
[e] - The emission factor is calculated based on characteristics of Alberta coal and the new 300 MW coal power plant.

Carbon credit required for MPB killed tree biomass based power to be competitive

From Table 9, the difference in emissions is used to calculate the carbon credit required to make biomass power competitive, i.e. provide a 10% return on capital, with an assumed value of \$55 MWh^{-1}. A carbon credit of \$7.30 $tonne^{-1}$ of CO_2, would be required for displacement of coal fossil fuel based power. Figure 3 shows the carbon credit that would be required to make the biomass cases economic as a function of power price. These values could be used to calculate a variable incentive for a publicly supported biomass power plant if such an incentive were tied to actual power cost.

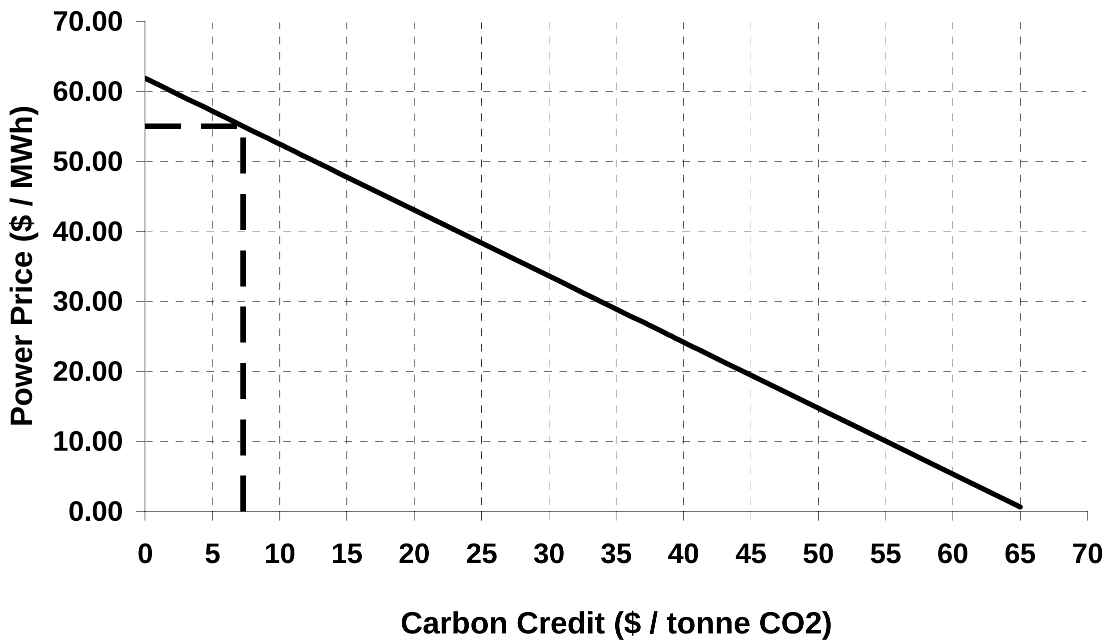

Figure 3. Carbon credit required to make biomass power economic in western Canada as a function of average power price without power subsidy.

The carbon credits shown in Figure 3 do not factor in a potential subsidy for biomass power. In the 2005 budget the Canadian Federal Government announced its intention to apply a support payment to biomass power of \$0.01 per kWh (\$10 per MWh). We do not know if this support payment would be available to a project of the size and scope of the MPB wood power plant proposed in this study. However, if it is available it would have a significant impact on the economics of the project, reducing the effective cost of power to \$51.88 MWh^{-1}. This would make MPB killed wood based power economic at an electricity power price of \$55 MWh^{-1}.

7. Sensitivities

Some key sensitivities are shown in Table 10.

Table 10: Sensitivities for MPB killed tree based biomass power plant for Case 1: "harvest as you go"

Factor	MPB Power Cost ($ MWh^{-1})	MPB Power Cost Impact (%)	Carbon Credit Impact (%)
Base case	61.88	0	0
Biomass production and delivery related sensitivities			
Biomass yield is 25% higher per gross hectare	60.25	- 2.6	- 23.7
Biomass yield is 25% lower per gross hectare	64.51	+ 4.3	+ 38.2
Biomass harvesting cost is 50% higher	67.06	+ 8.4	+ 75.3
Biomass harvesting cost is 50% lower	56.70	- 8.4	- 75.3
Biomass transportation cost is 25% higher	63.78	+ 3.1	+ 27.8
Biomass transportation cost is 25% lower	59.97	- 3.1	- 27.8
Biomass moisture content is 20% (dry basis)	63.41	+ 2.5	+ 22.2
Biomass power plant related sensitivities			
Capital cost of plant 10% higher	58.90	- 4.8	- 43.3
Capital cost of plant 10% lower	64.86	+ 4.8	+ 43.3
Efficiency of power plant is increased from 34% to 35% (LHV)	60.98	- 1.5	- 13.5
Staffing cost is reduced by 25%	61.25	- 1.0	- 9.2
Maintenance cost is reduced by 25%	60.31	- 2.5	- 22.8
Ash disposal has zero cost	61.31	- 0.9	- 8.3
Pretax return on capital is 12% rather than 10%	65.76	+ 6.3	+ 56.4
Power generation technology is BIGCC at 250 MW	57.69	- 6.8	- 60.9
Deemed value of power price in BC is $70 MWh^{-1}	61.88	0	- 218
Deemed value of power price in BC is $40 MWh^{-1}	61.88	0	+ 218

8. Discussion and Recommendations

Biomass harvesting cost is a critical cost element of the total power cost. It depends on a number of factors such as the type of harvesting system, type of machine, size of the trees, location etc. The economics of utilization of MPB infested wood for power depends significantly on the delivered cost of biomass. Given the range of reported values, one critical component of future evaluation of this project is a detailed cost analysis of all components of the delivery of MPB wood to a power plant.

The Quesnel location assumes access to MPB wood. The next stage of the project would better identify stands of MPB wood suitable for harvesting for fuel. If the best site is remote from Highway 97 and the transmission line, the plant location would be shifted to the wood, since it is cheaper to build a remote power plant with a transmission line than it is to move the wood. We compared a case of transporting wood to a power plant three times the distance of the base case to a case of transmitting power to 100 km at a line loss of 1%. In case of longer transportation distance of wood, the cost of power was 7.1% higher than the case of transmitting power though a transmission line for a distance of 100 km.

Ash removal cost is based on the conservative assumption of no credit for the nutrient value of the ash; as noted above, there is evidence that once a biomass plant starts operation that a demand for the ash emerges and that growers will haul it away at no charge to the plant. This is evaluated in a sensitivity case. In the next phase of the study exact location of ash disposal can be identified.

This study is based on production of electrical power only. Use of low pressure steam for heating helps the economics of any thermal power plant; we note, however, that finding a suitable “sink” for the heat is not an easy task. This could be looked at in the next phase of the study.

For a given source of biomass three factors have a strong impact on the cost of biomass utilization: the end product (e.g. power, heat, ethanol), the technology of conversion, and the scale. The feedstock cost has a significant impact on technology selection when a lower efficiency technology with a lower capital cost per unit of output is compared to a higher efficiency technology with a higher capital cost per unit output. This study is based on the direct combustion of biomass in a boiler and then power generation through a steam turbine. Direct combustion of biomass has a lower efficiency and lower heat rate than gasification, which has higher efficiency and higher capital cost per unit output. Biomass gasification combined cycle (BIGCC) is in the early stages of development. Today the maximum size of single unit gasifier based BIGCC plant is 250 MW (Shilling, 2004). The MPB killed tree biomass based power generation using BIGCC technology at a capacity of 250 MW is evaluated as a sensitivity case assuming all the parameters remain the same as direct combustion except capital cost of plant and power generation efficiency. Power cost from BIGCC is \$57.69 MWh^{-1} (at a capital cost of \$1915 kW^{-1} at 250 MW and LHV efficiency 45% (Cameron et al., 2004)). This clearly indicates that at present cost BIGCC and direct combustion have very similar costs. As expected there is decrease in the delivered cost of biomass (\$20.98 MWh^{-1} for gasification vs. \$28.20 for direct combustion) because of the decrease in the quantity of biomass required. On the other side, the capital cost of the plant per unit output goes up (\$26.48 MWh^{-1} for gasification vs. \$23.82 MWh^{-1} for direct combustion) because of the higher capital cost. Selection of a power generation technology between direct combustion and BIGCC would need further detailed assessment in the next stage and is beyond the scope of this study. A sensitivity in carbon credit for this case is shown in Table 10.

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. An accurate assessment of the yield would be required if the project is developed further. We have calculated the sensitivity in power cost and carbon credit for higher and lower yields.

Higher moisture content of the fuel reduces the efficiency. 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. Note that higher moisture content lowers the LHV of the wood, and more biomass would be required to generate the same amount of power. A higher moisture content case has been estimated as a sensitivity.

9. Conclusions

The cost of generating power using MPB wood in a 300 MW direct combustion power plant is for "harvest as you go" case is \$61.88 MWh^{-1}. Delivered cost of biomass is about 45.6% of the total power cost, followed by capital cost (38.5%) and operation and maintenance cost (15.9%). A carbon credit of \$7.30 per tonne of CO_2 is required to provide an adequate return on capital with an assumed existing value of incremental export power of \$55 MWh^{-1}; the range arises from the amount of carbon reduction credited to the project.

Total estimated MPB killed wood that would otherwise remain unharvested is about 200,000,000 m^3. A 300 MW direct combustion MPB killed tree based power plant would require about 67,864,000 m^3 of wood over 20 years. The total projected area from which biomass would be drawn is about 787,820 ha.

MPB killed wood provides a unique opportunity to convert otherwise wasted biomass in BC to useful electrical power, a project that would create 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

Case 2: "One time harvest"

In this case we assume that MPB killed trees are cut and skidded to the roadside. These trees are delimbed at the roadside and the stems are stacked in storage piles. Trees are transported from storage to the power plant as required over the 20 year life of the plant. At the plant trees are chipped and fed to the boiler. The whole process from felling to storage in piles would ideally be completed before January 2008 to prevent the killed trees from being considered as source of carbon under the Kyoto Protocol – Article 3.4.

Storage is at the side of logging roads in long piles readily accessed from the road. Delimbed logs are stored in piles with a honeycomb like structure to maximize air circulation and minimize fungal attack of the trees. Trees would likely be topped (cut) to 15 meters, with piles for storing uniform length material separated from piles storing irregular lengths. However, this detail would be assessed in the next stage of design. 3% of the biomass going into storage is assumed to be lost to rot and other factors; this value will require further confirmation.

Each pile is 15 m deep and 5 m in height, and would run up to 1 km in length. A typical area suggested for piles is roughly 2 ha (Pischedda et al., 2003). The honeycomb like configuration with additional open space at the bottom from sacrificial foundation logs will help maintain proper circulation of air and give natural drying of wood. Previous studies have shown that the lower heating value of wood stored in piles over longer period of time does not change significantly (Nurmi, 1995). There is some loss of bark in the storage, and the foundation logs in contact with the ground would likely rot. Different organisms can attack stored wood, including fungi, bacteria, insects and marine borers. Fungi, bacteria and insects are active at mild temperatures and high moisture content. These are normally active at temperatures above 10 ^{o}C and a moisture content above 19 % (Jirjis, 1995; Highley, 1999). Based on the calculated equilibrium moisture content of the piled wood in the study region, significant decay of wood should not occur. Marine borers are normally active in salt and brackish water (Highley, 1999), and are not relevant to the study area. These issues could be further investigated in detail in the next stage of the study.

The case assumes clear-cutting throughout the infested pine plots with distributed storage; wood is drawn from storage throughout the harvest area, giving a fixed transportation distance to the power plant over the life of the plant. In this case, the storage area is distributed at the edge of logging roads. Each pile covers an area of about 0.75 ha, based on the configuration discussed earlier. This would result in loss of land area for tree stands and hence, loss in royalty for the government and loss of operating income for timber companies over 20 years. In this study we calculate a charge paid by the power project to compensate for the estimated annual value of lost royalty and income, and include this as a component of storage cost. A model has been developed to calculate the land area required for 20 years of storage and the total cost of storage. This study assumes a stumpage fee of \$23.04 m^{-3} based on the average stumpage rates in British Columbia – Interior for timber sales (MOF, 2002). A value of \$23.04 m^{-3} is also assumed for loss of operating income for timber companies. A ratio of 0.8 is used in study for usable merchantable volume to gross volume (Lieffers, 2002). Piling of wood into storage and removing of wood from storage is included in storage cost. This is calculated as the loading and unloading cost of the trees; a value of \$2.84 m^{-3} is used in this study (Favreau, 1992). Additional input parameters required for this case are given in the Table A1.

Table A1: Additional input parameters

Items	Cost	Comments/Sources
Average stumpage rate for BC – interior timber sales (\$ m^{-3})	23.04	(MOF, 2002)
Average loss of operating income for lumber companies (\$ m^{-3})	23.04	Assumed
Ratio of usable merchantable volume to gross volume	0.8	(Lieffers, 2002).
Percentage of volume occupied in each pile by wood (%)	50	Calculated based on the length, width and height of the pile and volume of stem.
Loss of material in storage (%)	3	This based on the assumption that some material at the bottom of the pile would be infected or will decay during storage.
Logs loading, unloading and transport cost (\$ m^{-3})	1.2364*(3.44 + 0.0285D)	D is the round-trip road distance from the forest to the receiving plant (Favreau, 1992) by a 48-foot trailer. In this study the cost has been converted to green metric tonnes.
Delimbing	$1.4270V^{-0.6071}$	Value of V is assumed to be 0.50 m^3 per stem based on the yield of lodgepole pine (Favreau, 1992; Kumar et al., 2003; Wheetman, 2005; LeMay, 2005).
Piling and removing logs from storage piles (\$ m^{-3})	2.84	Basis is that piling and removal cost are 2/3 of truck loading and unloading cost. (Favreau, 1992).

The cost of power in this case is \$117.07 MWh^{-1}. This is clearly not competitive with the existing power price of \$55 MWh^{-1} in BC. There are two potential carbon credits that arise from an MPB wood based plant in the "one time harvest" case: regrowth of forest biomass and displacement of fossil fuel. A credit for regrowth of forest biomass can arise under the Kyoto Accord if Canada uses its forests in carbon calculations and if the MBP wood is harvested prior to January 1 2008. In this case, every tonne of CO_2 equivalent removed in the tree trunks transported to the plant would be credited to Canada over the period of regrowth. An MPB wood based power plant is likely to displace a base loaded power plant, i.e. because a biomass based plant is constructed the need for an incremental fossil fuel plant is postponed. In Alberta and portions of the

US incremental base load plants burn coal, and that assumption is used in this study, i.e. that the available carbon credit from the MBP wood plant is the assumed displacement of the equivalent amount of coal to generate 300 MW. At a power price of \$55 MWh^{-1}, for this case it MPB based power would need a double credit of \$32.94 per tonne of CO_2. If federal subsidy of \$10 MWh^{-1} is available, double credit value would be \$27.63 per tonne of CO_2.

Appendix B

Table B1: Input to the VDYP model for estimation of biomass yield from lodgepole pine stands

Items	Values	Comments/Sources
Species composition (%)[a]	100 – Lodgepole Pine	Killed trees mostly belong to this species.
Site Index at BHA (breast height age)[a]	15.1 m	This is the top height at breast height age 50 years and is an indicator of site productivity.
Volume adjustment factor[a]	1	This factor helps to localize the volume predictions if necessary.
Stocking class[a]	0	This stocking class indicates no decrease in yield.
Forest Inventory Zone[a]	H, I, J	These are the geographical zones developed to provide broadly based ecological classification of the forest land in British Columbia. For this study it has been assumed based on the area under consideration.
Crown Closure[a]	100 %	This the percentage of the ground covered by tree crown as assessed from aerial photos.
Utilization level[a]	12.5+ cm	This indicates the maturity of the trees and infested lodgepole pine trees are in this range.

[a] These input assumptions have been established in discussion with the Professors of the department of forestry at the University of British Columbia (LeMay, 2005; Wheetman, 2005).

Appendix C

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

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

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 D

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 E
Reviewers' Comments on Preliminary Report Issued on March 15th, 2005

Comments	Reponses
Jack McDonald, Tony Sauder and Alex Sinclair (FERIC)	
The cost calculations are very sensitive to the power plant efficiency, therefore, predicting the feedstock moisture content accurately will be crucial. The biomass is assessed at 13% moisture content (dry basis), a value that I consider too low for a year-round average. 13% (wet basis) is achievable during the summer months, but not year-round. 30% MC (wet basis) is more appropriate. On the other hand, harvesting trees that have been standing dead for several years may achieve such low moisture contents.	We have done a sensitivity for moisture level in the wood; the critical value is the annual average moisture level. A 50% higher moisture level (20% annual average) increases the power cost and carbon credit by ~$1.53. This is not likely to be a killer.
The stated size of the study block is 100 km square (1,000,000 ha). I wonder whether the required volume of MPB-killed timber within 50 km of Quesnel is sufficient to sustain the plant since that particular geographic area contains a significant portion of younger stands and urban and agricultural land. None of these will contribute volume to the plant. A location west of Quesnel may be more likely to achieve the required volume of timber within the stated radius from the plant. Accordingly, some of the assumptions about construction costs and ready access to existing power lines may be inappropriate.	The specified yield of MPB wood assumes that 10% of land is non-forest (agriculture and industry), and that of the 90% that is forested, only one third is mature MPB. The study contains a sensitivity of a 25% lower yield, and this increases the power cost and carbon credit by ~$2.63. If less MPB wood is available near Highway 97, two choices would emerge: one is to locate the power plant remotely, and the other is to just drive the wood a further distance. A remote power plant requires higher investment for two reasons: construction cost would be an estimated 5% higher due to the need to locate workers in a camp, and a transmission line would be required. A further cost is that line loss on the transmission line would likely be 1% per 100 km. We have addressed this in discussions.
It is not clear what harvesting schedule is being considered. On the one hand, there are comments about harvesting by 2008 to	We have addressed this by presenting two cases: "harvest as you go" case and "one time harvest "case. We have addressed

Comments	Reponses
avoid being considered as a carbon source under the Kyoto Protocol, and there is mention of storing large amounts timber on sacrificial logs at roadside. This makes me think the proponents are considering a "hit it early, hit it hard" strategy. On the other hand, it is impractical to harvest the full volume of MPB-killed timber, and store it for up to 20 years (lifespan of the plant), but if the harvesting is to occur over the lifespan of the plant, what is the relevance of the 2008 Kyoto deadline? Clarification, please.	the impracticality of “one time harvest” case in the Appendix. Note that if the MBP wood is not harvested in 2006 and 2007, the prospect of a double carbon credit disappears.
In addition, if the logs are to be harvested continually over the life of the plant, will they actually sustain a 3% volume loss, and will they require the specialized storage techniques mentioned in the proposal (which incidentally will increase harvesting costs)?	I agree. We don’t know this and we don’t have any way to confirm this. Our base case results “harvest as you go” case is not affected by this.
The proposal allows for roadside storage of the logs, but only minimal storage at the plant. The two-week allowance for plant-side storage is insufficient to carry the plant through spring breakup when logging roads are impassible. Two to three months of supply is more appropriate. There would be a cost associated with such plant-side storage that has not been considered in the analysis.	The comment that more storage is required at the plant site is correct, and we havel adjusted the estimate for this. We have included a storage of 3 months at the plant site.
The 13% moisture content value generated a wood density of 455 kg/m3. I consider that number to be too low -- dry logs are more typically in the 650-700 kb/m3 range. However, this point may be irrelevant since log trucks typically achieve their volume capacity before they reach their weight capacity when hauling dry logs (low bulk density). I think that the cost equation that was used for transportation is more appropriate for green logs -- the costs for dry logs will be higher than shown in the analysis.	
Solving for the value of D in Table 3: it must be 75 to achieve a transportation cost of 6.90. Since D is expressed as round-trip	The transportation cost formula is per cubic meter, not per tonne. We agree that a truck transporting low moisture content wood will

Comments	Reponses
distance, the one-way haul distance is 37 km . I presume this value was derived as an average haul distance from the original stated size of the study block (100 km by 100 km, or 50 km on each side of the plant location). Accordingly, the 6.90 value shown in Table 3 may be appropriate for green logs with a round-trip distance of 75 km, but it is too low for dry logs, or for longer distances.	reach a volume limit before a weight limit, but we think that a formula based on volume applies to dry and wet wood. The comments on derivation of distance are correct; we use a distance weighted transportation cost, so lower yield, for instance, gives higher average driving distance and our calculations increase the transportation cost. We have explained it in the text.
The 1% ash figure is too low -- 2-3% is more appropriate. While the cost for disposing the ash was considered, the availability of suitable sites for disposing significant quantities of ash was not examined.	We have increased the ash content to 2.5 %, but ash disposal is a very minor cost factor (56 cents per MWh). It doesn't affect the outcome significantly.
The cost calculations for falling, skidding, and delimbing seemed reasonable. Two components in the cost calculations were questionable: the average tree size appeared too large (0.6 m3 / tree seems more appropriate) and the net recoverable volume ratio appears too low for trees will not be cut into lumber. However, these two differences tend to cancel each other, so the net effect on cost calculations is zero.	We have decreased the average tree size to 0.6 m^3 per tree and recoverable volume ratio to 0.8.
Dave Spittlehouse (Ministry of Forests, BC)	
The assumption of possible forest sequestration credits should be removed. There are four reasons. 1. There is insufficient time between >now and 1 January 2008 for much harvesting and piling of wood to take place. The project needs public consultation, determination of a tenure agreement, final approval, finding the land, building of roads and then harvest. Will be lucky if anything much is done on the land prior to 2008. 2. The new forest on the harvested lands will grow slowly. In the first commitment period and probably more, there will still be a	Our base case is for "harvest as you go" case, so there is no carbon credit because of forest sequestration. We have included the "one time harvest" case along with forest sequestration carbon credit in the appendix A for completeness.

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carbon loss from the site because of decay of residues and soil carbon will release more carbon than sequestered in tree growth. 3. Crediting from growth assumes Canada chooses the forest management option (3.4) in Kyoto. In this case, any credits/debits would be subject to the national treasure claim. If Canada does not choose forest management then there are no credits/debits. 4. Biomass is considered carbon neutral because it is assumed to cycle back into tree growth. Thus claiming a double credit violates the accounting, at least in spirit, and would not look good internationally.	
Much of the dead pine is mixed in with live pine and other species. It would be difficult to harvest only the pine and stockpile for the future. Need to integrate supply within the harvesting process supplying live wood.	We agree. This should be studied in detail in the next phase of the study.
Under 3.4 forest management any loss of carbon from the land is a debit to the owner. The owner must replace this with offsets purchased or with other forest growth on the owner's land. These units of carbon have value; thus the wood for biomass energy is no longer "free". What are the economics in this case? Even if Canada has not chosen to include forest management in the first commitment period	This should be addressed in the next phase of the study.
What is the possible fuel stock for the plant after all the MPB wood is gone? Maintaining a future supply needs to be addressed early in the life of the plant.	The future supply of biomass could come from other sources such as agricultural residues, hybrid plantations, herbaceous crops. This should be evaluated in the next phase of the study.
Jamie Stephen (BIOCAP)	
Need a better map – clarity	We have increased the size of the picture to make it more clear.
Need a second map that hightlights where the proposed plant would be located, with areas of harvest surrounding the plant.	The area of harvest will be mostly in the study region shown in Figure 1. We have also included a map showing the location of

Comments	Reponses
Also, show transmission line.	Quesnel , BC (Appendix F).
Need to discuss demand for power somewhat – you mention there BC is a net exporter, but is there enough demand to justify another plant? Would adding another 300MW impact the price at all?	Consumption of power in Western North America is about 30 GW. So there is no problem for demand.
Need to reference table #7 (costs) in pages 16-18. Perhaps by each title you could put the presumed cost of the total to keep a running tally.	These are calculated values from the model using all the input values.
Under 'Maintenance costs' please explain 'manipulation'. Would the maintenance cost be somewhat lower than with straw due to the lower ash content of wood?	We have addressed by making it more clear. Maintenance cost would be lower than the straw because of the low content of alkali and halides in wood. These are corrosive on combustion.
I think we need to show ROI with no carbon credits. Even if this doesn't look that great, I think it may be necessary and would highlight the importance of carbon credits. There should also be a mention of the cost of leaving (see below)	We do not feel it is necessary in the context of this project.
What is the average transportation distance? What is the maximum? (perhaps I missed this)	For a circular area of biomass collection, the radius is 50 km.
I would like to see a more clear explanation of where figure 2 comes from (ie. some preliminary figures showing a breakdown of the individual components – pictures are worth a thousand words)	Figure 2 is plotted after calculating cost of power at different capacities using the model. Breakdown of the individual components is given in Table 8.
I would like to see a bar graph with a breakdown of the individual components that make up the price per MWh	Table 8 gives the breakdown of the costs in $/MWh, a bar graph would be duplication of information.
I would like it more clear in the Executive Summary that this is a 20 year project. Also 'storage of water' needs to be clarified and put in context.	We have included this in the Executive Summary. "Storage of water" in the section 'Scope and Cost' under Power Price.
It may be beyond the scope of this report, but it would be nice to see a comparison to the costs of simply leaving the biomass in place (eg. forest fires, etc). This could significantly benefit the economic case. Perhaps a project for later or for the Gov't?	Agreed it is beyond the scope of this project.
Just a visual thing, but I am not crazy about the cover.	We have addressed this by removing the cover pictures.
Table 8 – LCA – this has to be labelled with g of what (CO2e or	We have included CO_2 label.

Comments	Reponses
C). This is something we run into all the time.	
Tony Lempriere (Natural Resources Canada)	
I also had a quick read. Not knowing anything about the various details, it nevertheless seems like a thorough study that has covered a lot of ground and indicated key areas of uncertainty.	We appreciate these comments.
My only criticism is the calculation of the carbon credits, which is probably incorrect (it appears as if a very simplistic approach is taken). This may be a serious problem, as it is the carbon value which appears to make the project economic. The authors describe two C credits 1) assuming all biomass needed is harvested prior to 2008, then the authors suggest a credit for the re-growth equivalent to the amount harvested To get an accurate picture of the carbon credit, would need to consider: a) the carbon stock changes in the baseline of no harvest and slow decay over time from 2008 onward, plus what ever regeneration occurs b) the carbon stock changes due to regeneration from 2008 onward over time, after the harvest has occurred c) carbon accounting rules require assessing carbon stock changes as they occur, and credits would be provided for what has occurred, not what will happen in the future - so the correct value of the credits is the net present value of the difference between a) and b), over time, starting in 2008 2) fossil fuel displacement this calculation seems conceptually fine, with the key issue of	We have addressed in the report. Our base case is for “harvest as you go” case, so there is no carbon credit because of forest re-growth in this case.. We have included the “one time harvest” case along with forest re-growth carbon credit in the appendix A for completeness as most of the comments on this case suggest its impracticality and it is uneconomic too.

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course being that all the feedstock is removed prior to 2008, which the authors stress. In my comments above I am thinking in the context of the likely offset credit system rules - of course, if other mechanisms are used to provide a value for carbon then these criticisms of the analysis may be less relevant.	
Joseph Krupski and Christian Wolfe (Ministry of Forests, BC)	
Overall, this seems to be a very good and complete analysis.	
Storage: • Is there basis for the assumption of 3% biomass loss? How much of the biomass lost would be due to rotten foundation logs, and how much would be to general decay? • Although average moisture and temperature may be conducive to storage, it is possible that seasonal differences will not. One could imagine that moisture levels and temperatures in the spring would be high enough to cause significant decay.	• This assumptions doesn't affect the "harvest as you go" case which is the main focus of the report. This could be further investigated in the next stage of the study. • We agree. But in the "harvest as you go" case there is no long term storage of the wood, so base case results are not affected by this assumption.
Availability, Accessibility and harvest of biomass: • If the 64 Mm^3 come from unharvested 200 Mm^3 MPB-killed trees, then where is this 200Mm^3 located and why is it not harvested (access, processing capacity, low grade, etc.)? What are the BC MoF assumptions to arrive at this volume? Can the 64 Mm^3 be found in the study area (95km x 95 km) around Quesnel? I believe that other users (7 saw-, pulp and paper mills in Quesnel) would also be harvesting MPB killed trees in this area and could be given priority to harvest the most accessible timber (distance and road access).	• Figure 1 shows the region where this 200 million m^3 of wood is located. We have selected Quesnel for three reasons: access to a transmission line; access to highway 97 for transportation and it is approximately in the center of the study region. In the next stage of the study a more detailed location of the plant could be identified. This is addressed in the discussion.

<table>
<tr><th>Comments</th><th>Reponses</th></tr>
<tr><td>Is it realistic to assume that all 64 Mm³ will be harvested and stock piled by the end of 2008 given that harvesting 300 Mm³ MPB trees will also require considerable amount of resources?</td><td>Most of the review comments we have received, shows the skepticism of harvesting all wood in two years. So we have changed out report and addressed “harvest as you go” case as the main scenario in the report. Appendix includes the “one time harvest” case for completeness.</td></tr>
<tr><td>Carbon credits:
We would like more explanation on the 1st carbon credit, re harvest before 2008. Does this credit apply to forestland or only to afforested areas?
We would like more explanation on the 2nd carbon credit, re. replacing electricity produced with fossil fuel with electricity from biomass (bioenergy). Is this the current situation in BC? The report indicates that BC Hydro could store water in reservoir by using electricity generated in Quesnel.</td><td>This is not the current situation in BC, but in future when the carbon credit market develops, it could occur. BC Hydro could store water to generate electricity in peak hour.</td></tr>
<tr><td>Net volume and slash:
Ratio of usable merchantable volume to gross volume (0.6) seems low considering that they are planning full-length harvest. Why would the trees be cut at 15 meters?
Full-length harvest will generate a considerable amount of slash at the roadside. Can this be used to feed the power plant? For example, Timberjack has patented a continuous bundling machine (1490D) that bundle tops and branches that can easily be transported and stored for use as biomass fuel. If not used for energy production, what then?</td><td>We have changed the gross volume to 0.6 m^3. In the “harvest as you” trees would not be delimbed or topped. Whole tree would be chipped and chips would be transported. For the ”one time harvest” case trees would be cut to 15 m to facilitate in storage in the described configuration.
There would be no slash in the “harvest as you go” scenario. For “one time harvest” case this could be further investigated.</td></tr>
<tr><td>Assumption of maximum unit size:
It is indicated that flatness in the curve (Figure 2) suggests that an MPB-wood-based power plants could be built in any scale</td><td>We agree that transportation costs rise with capacity and the feedstock costs would be large for large plant. Figure 2 in the report does take into account delivered material costs. The</td></tr>
</table>

Comments	Reponses
from 200 MW to well over 1000 MW. Given that fuel transportation costs rise approximately in proportion to the square root of capacity, one would expect that feedstock costs to feed a large power plant (over 450 MW) would be prohibitive. Are these curves not including delivered material costs?	capital cost per unit output goes down with the increase in size because of economy of scale. At larger size the increase in transportation cost is offset by the benefits in capital cost. Hence giving a flat curve.
Ash disposal: • The study indicates that demand will develop for ash, mainly from farmers. Is there enough agriculture activity in and around Quesnel to spread the volumes of ash generated (50-km radius)? • How does the Williams Lake power plant gets rid of its ash?	• We have addressed this in discussion and this can be evaluated in further detail in the next phase of the study.
Steam and Cogeneration: • There are seven or so mills (saw-, pulp and paper) in Quesnel. Should there be some consideration given to the possibility of selling residual steam (Cogen) to one or a few mills operating in Quesnel? Could there be a mill interested in accessing steam/heat generated from this power plant? • The report also raises concerns on the humidity level of the feedstock; would it be economically feasible to use the generated steam to dry the feedstock (and thus increasing the burning value) prior to combustion?	• We have addressed this in discussion. Cogeneration will improve the economic of the plant. Proper sinks could be identified in the next phase of the study. • Wood moisture content is low in case of the killed mountain pine beetle trees. We don't think that drying is required at this moisture content.
Brad Stennes and Tony McBeath (Canadian Forest Service)	
The Biocap study is quite interesting and raises some good points. I would defer to their expertise for the costing of a biomass facility, and the BIGCC would certainly be more efficient than the wood fired facilities we examined (from NREL studies).	We agree that BIGCC is more efficient. We have addressed it in the discussion with a sensitivity. We have calculated the cost of producing power from BIGCC and it is lower than the direct combustion but the difference not significant. This could be

Comments	Reponses
	evaluated in the next phase of the study.
I have some major problems with their assumptions on the feedstock supply and especially costs. Unfortunately this is also the least developed part of their analysis (and the most critical). We did spend a good bit of time on this aspect of the analysis. Here are a few points: 1. They use $6.89/m3 as the tree to truck logging cost. We use $16.65/m3, which is from the BC MoF and represents average tree-to-truck costs in the PG region. Why did they not use Ministry numbers for this? 2. They use $247/ha as the silviculture costs. We use PG region estimates for basic silviculture costs, again from the MoF, at approximately $1,200/ha. 3. They use $3.80/m3 as the other indirect costs (roads and overhead), we use $10.76/m3. The differences are: Stennes/McBeath Kumar et al. ($/m3) Logging Costs (tree to truck + indirect + Silviculture) 30.86 11.72 Hauling 7.02 6.90 Chipping 3.27 1.88 Stacking 0.0 4.25 Delivered and Chipped 41.15 24.75 In terms of final electrical generation costs, they estimate the portion attributable to feedstock costs at $34.87/MWh and we	We have addressed the difference in the feedstock cost in the report in section 4. We have included Table 3 on the comparison of feedstock cost. We have adjusted our silviculture cost. We have also included an overhead component of cost. We have included a discussion on the MOF costs in section 4. We agree that delivered cost of biomass is a critical component of biopower cost. The uncertainty in the feedstock could be evaluated in the next phase of the study.

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estimate $75.80/MWh.	
The whole concept of stacking logs for 20 years?? I asked one of our entimologists if this is feasible and he said that this would almost certainly speed up decay rather than slow it down. The question then is why do this? In addition, with these piles of rather dry wood going on for a km at a time, the added risk of fire would be tremendous. Log piles at sawmills can result in huge fires.	The body of the text is based on “harvest as you go” case. This doesn’t need storage. The “one time harvest” (in the appendix A) is impractical based on the feedback and not economic as compared to “harvest as you go” case. We have just included it for completeness.
I think that assuming a 20-year supply of feedstock is a major problem. After the beetle finishes up and the reductions in wood supply gain hold (10 to 12 years hence), there is going to be some severe shortages of fibre in this region. A massive plant like this would have to draw away supply from many other competeing sources if it was to stay in business.	The future supply of biomass could come from other sources such as agricultural residues, hybrid plantations, herbaceous crops. This should be evaluated in the next phase of the study.
In this type of accounting should they not examine the deforestation implications of stacking >60 million m3 of logs at the roadside?	This is a good point but it is beyond the scope of this study. This could be addressed in next stage.
We had the same question about the double-accounting of carbon credits?	

Appendix F - Map

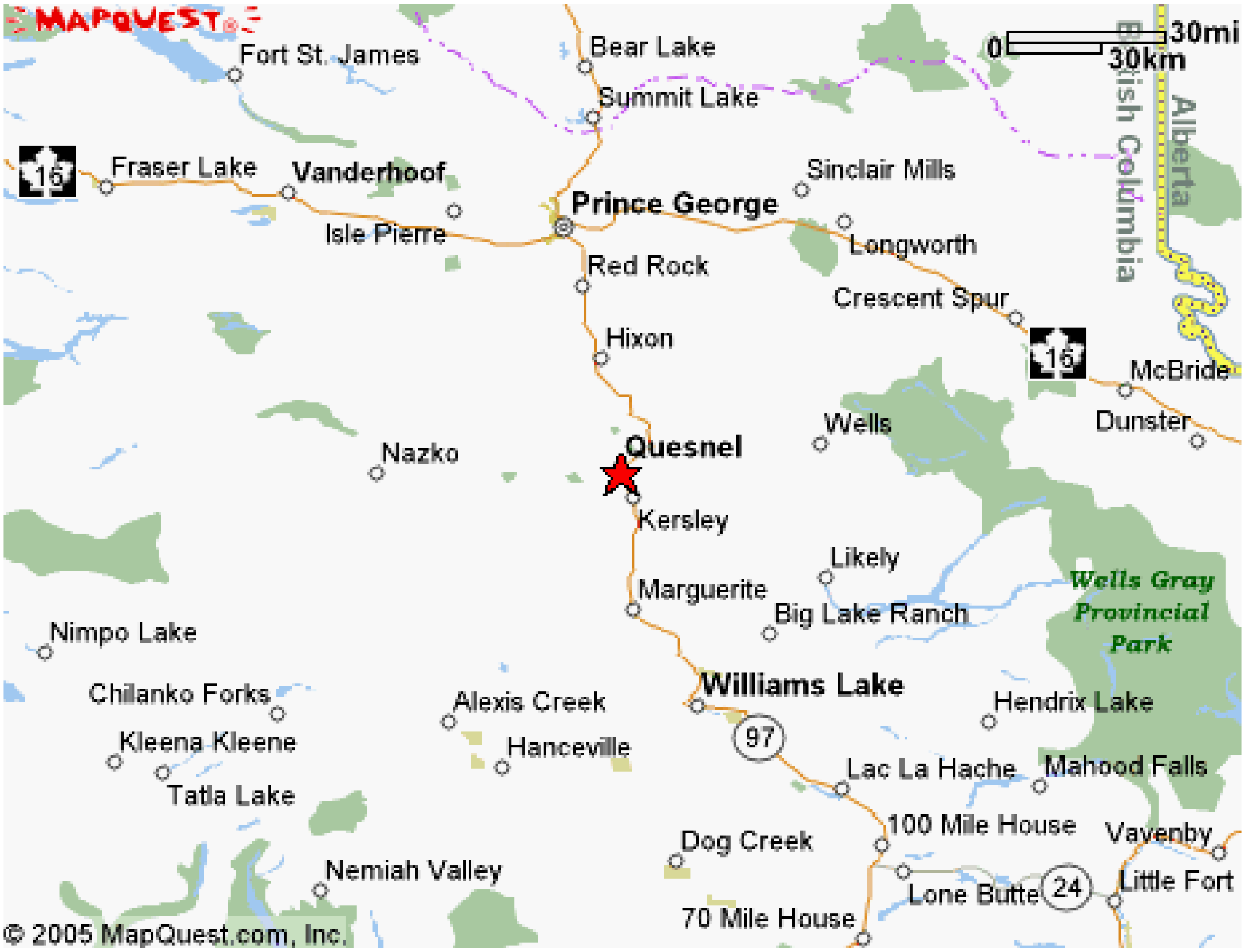

Figure F1. Location of Quesnel, BC and Highway 97 (Source: MapQuest.com)