UNIVERSITY OF ALBERTA

Power Generation from Forest Residues

by

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A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfillment of the requirements for the degree of

Master of Science in Engineering Management

Department of Mechanical Engineering

Fall 2011

Edmonton, Alberta

Abstract

Biomass is a renewable energy source and its utilization for power generation could help in the reduction of greenhouse gas emissions. Large amounts of forest residues are generated along the forest from the logging operations of the pulp and lumber industries in Alberta. According to the current practice, these residues are piled and burned to prevent forest fires. These residues could instead be effectively utilized for production of power and could potentially replace coal power in the Province of Alberta. The overall objective of this study is to develop techno-economic models for the assessment of power generation cost and optimum power plant size using forest residues as feedstock in Alberta. At the optimum size of the plant, the cost of generation of power is minimum. In this research two supply chains for utilization of forest residues in a centralized power plant were investigated. In the first option, the residues are collected, piled and chipped along the roadside in the forest. These chips are transported to the power plant using standard chip B-train chip van. In the second option, collected and piled forest residues are compressed and bundled. These bundles are transported to the plant using a standard log haul truck. There bundles are chipped in the plant before their utilization for power generation. The purpose of bundling is to have increased mass of biomass transported per unit distance and utilization of high capacity chippers at the plant. The theoretical optimal size without the constraint of the unit size of the boiler is 524 MW with a power generation cost of $74.20 /MWh for in-wood chipping. Similarly, for the bundling method, the theoretical optimum is 520 MW with power generation cost $87.30 /MWh. At an unit of boiler of 300 MW, the optimum size of the power plant is same as the unit size of the boiler. The power generation costs at this size are $75.50 and $88.50 /MWh for in-wood chipping and chipping at plant option,

respectively. Capital and transportation costs are the major contributor to the power generation cost. Total life cycle emissions in power generation through the two supply options are: 17.56 gCO_2/kWh (in-wood chipping) and 15.8 gCO_2/kWh (chipping at plant) at the optimal size. Biomass based power is currently not economical compared to coal based power in Alberta. At an average price of $60 /MWh coal based electricity generation, the carbon credit required for the biomass based power to be competitive for two options are $28.20 /$tCO_2$ and $29.60 /$tCO_2$at theoretical optimum and 300 MW power plant size for in wood chipping. The same cost was $41.50/$tCO_2$ and $42.90/$tCO_2$ for chipping at plant respectively.

Acknowledgement

The author would like to take this opportunity to express his sincere gratitude to Dr. Amit Kumar, who was the supervisor of this research, for his guidance, advice, assistance, and inspiration throughout the course of this study. It was a great pleasure and valuable experience to work with Dr. Kumar.

The author is also grateful to Dr. Victor Lieffers for providing invaluable advice and annotations regarding forestry in Western Canada, and nutrient replacement related issues in forest harvesting.

The author would like to especially thank Dr. Peter Flynn for his prudent observations and helpful comments.

Lastly, the author would like to thank his colleagues, especially Veena Subramanyam, Shikhar Singh, Arifa Sultana, Ruhul Kabir, Malinga Dassanayake and Arun Bhogal, for their contributions to this study and for making the experience delightful in the *Sustainable Energy Research Laboratory.*

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Abbreviations

ALIS	Alberta learning information service
CFB	Circulating fluidized bed
CRL	Compressed residue logs
ERCB	Energy Resources Conservation Board
FERIC	Forest Engineering Research Institute of Canada
FPAC	Forest Product Association of Canada
gal	US Gallon
GHG	Greenhouse gas
GJ	Gigajoule
Ha	Hectare
HHV	Higher heating value
Hr	Hour
km	Kilometer
kW	Kilowatt
kWh	Kilowatt-hour
LHV	Lower heating value
MW	Megawatt
NREL	National Renewable Energy Laboratory
NYSERDA	New York State Energy Research and Development Authority
odt	Oven dry tonne (0 % moisture content)

PMH	Productive machine hour
SMH	Schedule machine hour
TCI	Total capital investment
TPI	Total project investment

1 Introduction

1.1 Background

Climate change is increasingly becoming a critical issue across the globe. Greenhouse gases (GHGs) are one of the key contributors to climate change. Solar radiations coming to the earth is returned back through the GHG layer after reflection from the earth. When the concentration of the GHG increases, the heat is trapped and causes increase in our atmospheric temperature (IPCC, 2007). CO_2 has the second largest GHG effect. Methane, water vapor, nitrous oxide, ozone, and CFCs are other contributors to GHG effect. After industrialization huge anthropogenic emissions have occurred due to increased use of fossil fuel as a source of energy. Since past 30 years, the rate of global average mean temperature increment is found to be approximately 0.2°C (Hansen et al., 2006). Figure 1-1 gives an overview of net global carbon emission including individual fuel type contribution since 1751 to 2007 (Marland et al., 2007).

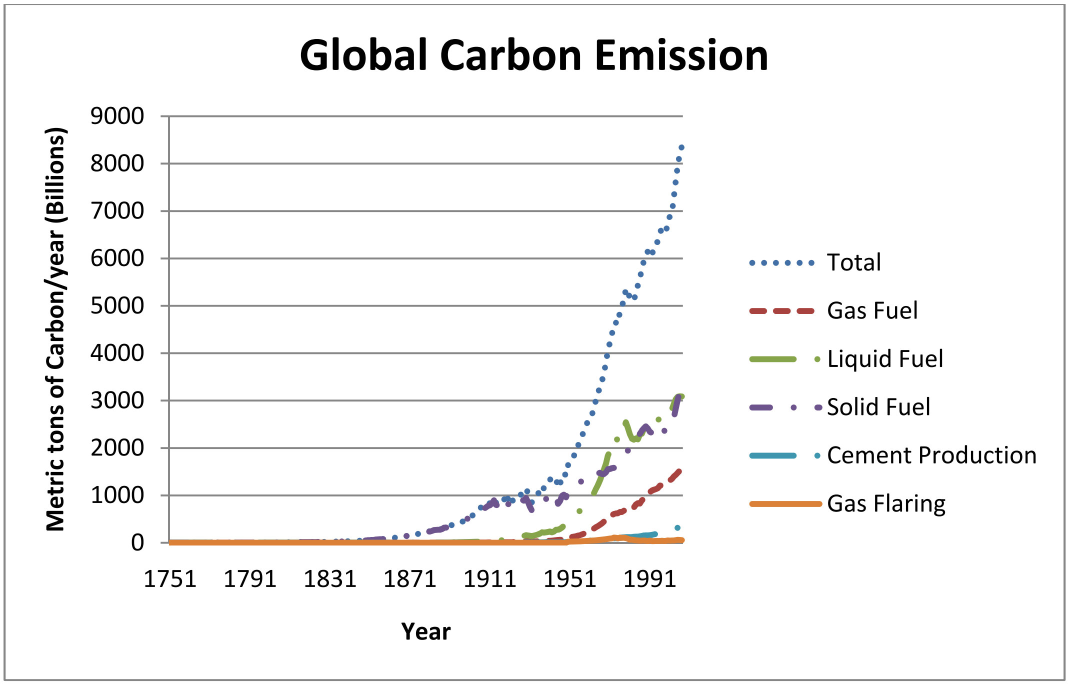

Figure 1-1: Historical global carbon emission (Marland et al., 2007)

Canada was ranked seventh among top ten carbon emitting countries in 2004 (Quadrelli et al., 2007) and eighth in 2005 (Demerse, 2009). Figure 1-2 presents Canada's sector-wise CO_2 emission at four different points of time (Environment Canada, 2010). In case of Canada, approximately 80% of CO_2 emission was contributed by energy sector in 2008 (Environment Canada, 2010).

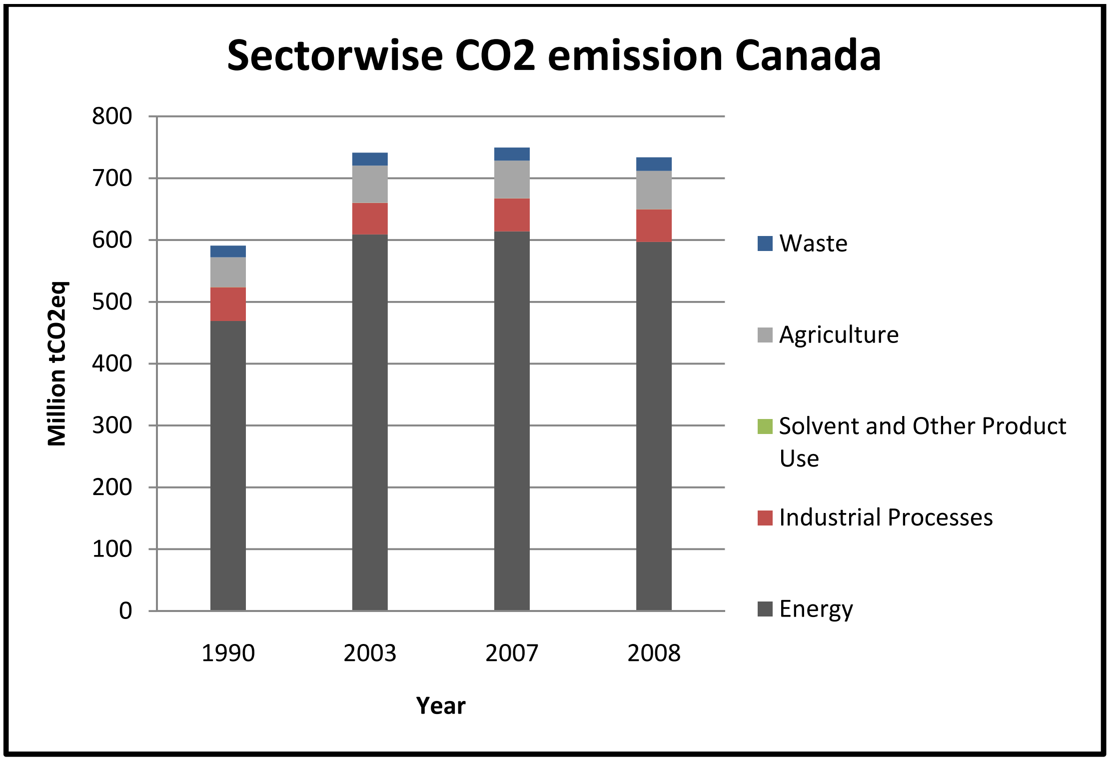

Figure 1-2: Sectorial contribution in CO_2 emission of Canada (Environment Canada, 2010)

Within the energy sector, electricity and heat generation itself accounted for 20%, 22%, 20% and 20% of total CO_2 emission in the year 1990, 2003, 2007 and 2008, respectively. With growing population and energy demand it is projected that by 2020 Canadian GHG emission will rise by 116 million tCO_2 (base year 2008) if no government measures against emission reduction are taken. Figure 1-3 provides information regarding Canada's provincial contribution to total CO_2 emission (Data source: Environment Canada, 2010). From figure 1-3 it can be concluded that Alberta is a major contributor to Canada's total CO_2 emission followed by Ontario.

Utilities and oil sands mining and upgrading contribute to 44.1 % and 21.5% of total Alberta's CO_2 emission, respectively (Alberta Environment, 2010). Alberta's growing population (at the rate of 2.58% per year in 2009, (Government of Alberta-Education, 2009)) and increasing GDP (at the rate of 3.1% per year from 1989 to2009, Government of Alberta, 2009) will keep increasing the demand of utilities and crude oil. At present Alberta's electricity generation capacity is more than 12,000 MW, out of which about 14% comes from renewable sources (e.g., hydro, wind, biomass, solar) and the rest from fossil fuels (Alberta Energy, 2008; AISO, 2009). With increasing demand of electricity (increasing at the rate of 3.3% per annum), Alberta would require about 20,000 MW installed capacity by 2024 to meet the demand (AISO, 2010). Increase in demand of electricity will result in more GHG emissions because fossil fuel will be the primary source of the input fuel. Hence, utilization of renewable energy sources is becoming a critical to reduce environmental loading of GHGs.

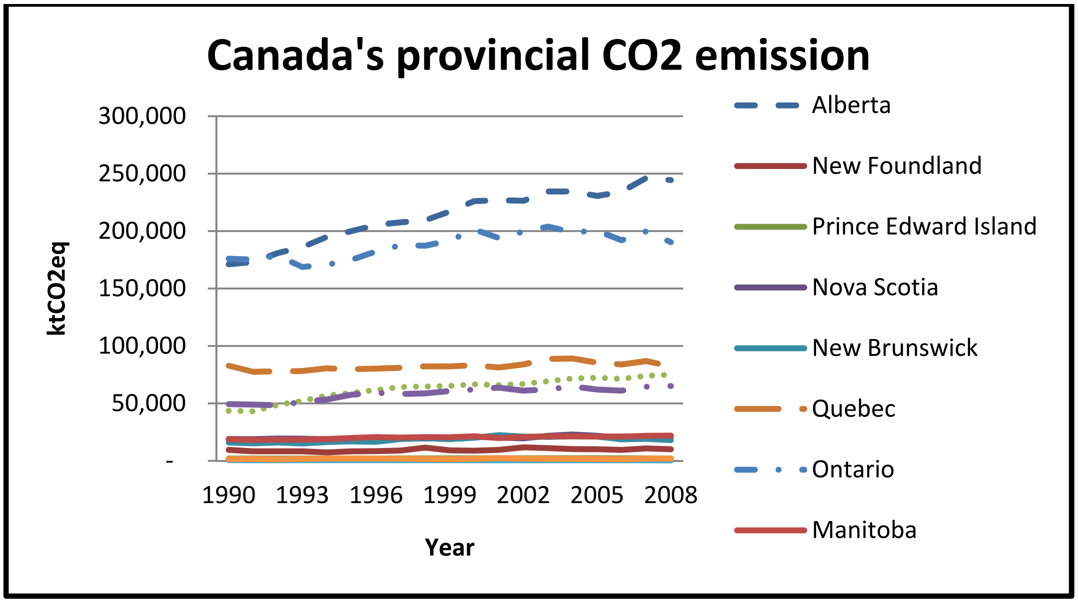

Figure 1-3: Provincial contribution in net CO2 emission of Canada (Environment Canada, 2010)

Alberta has large potential of biomass and it could contribute significantly to the power sector in Alberta compared to other renewable energy sources.

1.2 Biomass Potential in Alberta

Biomass can come from agriculture or from forest. Agricultural biomass includes grains and residues i.e. straw or corn stover. Forest biomass includes the whole tree from the forest, mill residues, dead or dying trees, stumps and harvesting residues. Harvesting residues includes branches and tops generated during the logging operation. In current practice in Alberta, the pulp and lumber companies cut the trees in the stand, drag the trees to the roadside, delimb the trees at the roadside and use the main stem. The residues are piled and burnt to prevent forest fires. These residues can be used in a boiler to generate electricity. Most of the mill residues are used for generating power today. Potential of forest biomass in Alberta's every year is shown in Table 1-1.

Table 1-1: Alberta's electricity generation potential

Source	Oven dry tonnes	Generation potential (MW)[1]
Logging residues	3,500,000	724
Low Quality Trees	1,100,000	227
Deads or Dieing	500,000	103
Mill Processing Residues	724,100	150
Total	5,824,100	1,204

Mill residues are the lowest cost resource compared to roadside residue or standing trees because of low or negligible cost of transportation and processing. Alberta already has 12 MW power plant running from saw mill waste in Drayton Valley (Algonquin Power, 2011). Low quality or dead or dying trees are most expensive when overall fuel supply cost is calculated. The extra cost incur may be due to additional infrastructure required to access the fuel from forest.

Dead or dying trees are produced by the forest which is affected by Mountain Pine Beetle (MPB). These trees are not suitable for quality round wood production. Forest in British Columbia has been significantly affected by MPB and several studies have evaluated the utilization of affected trees (Kumar et al., 2008; Kumar, 2009). Smoky,

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[1] Assuming higher heating value 18.5/ODt and 25% plant efficiency

Foothills and Clearwater regions of Alberta are most susceptible regions to Mountain Pine Beetle (MPB) which produces dead or dying trees (Levelton Consultants Ltd, 2008). As of to date no study is available for Alberta which specifically estimates the MPB affected volume of trees and provide techno-economic assessment of its utilization as fuel.

The main potentially available forest biomass in Alberta is roadside logging residues. At present, these residues are piled and burned at the roadside in the forest to prevent forest fire. In European countries these logging residues are fully utilized with much developed fuel supply chain (Junginger et al., 2005). The best example of utilization of these residues is a 240 MW_e Alholmens power plant in Pietarsaari, Finland (Kokko et al., 2003). Figure 1-4 shows a typical forest biomass (harvesting residues) supply chain for cut to length harvesting system. Usually harvesting residues are dispersed along roadside. Hence, these residues are piled before any further processing. As shown in Figure 1-4, two alternate options exist for fuel supply to the plant after piling operation

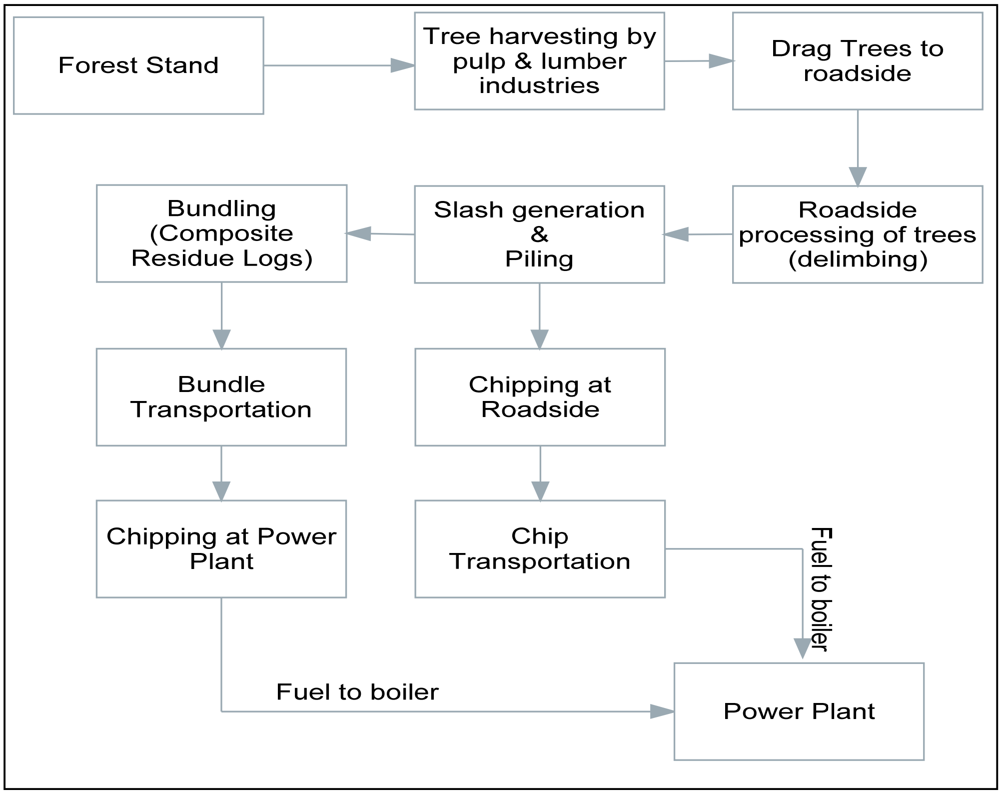

Figure 1-4: Forest biomass supply chain

First, harvesting residues are chipped at landing and chips are transported to power plant. An alternate to this fuel supply chain is a compact form of logging residues known as Composite Residue Logs (CRLs). This method is already used by world's largest biomass-fed power plant in Finland (Cuchetet et al., 2004). In this method, a specifically designed machine (known as bundler) is used to compress the biomass in the bundle form (CRLs). These CRLs are then transported to the plant using standard log haul truck (Cuchetet et al., 2004; Murphy et al., 2003; Andersson, 2000). This methodology was developed to have increased energy transport per unit distance hence lower distance variable cost when compared with chip transportation (Andersson, 2000; Asikainen et al., 2002; Junginger et al., 2005). Another advantage of using this method is chippers with high production capacity can be used which in turn reduces chipping cost (Asikainen et al., 2002).

This study considers both the options of fuel supply for power generation in Alberta. First option considers biomass collection and piling, chipping at roadside, chip transportation. Second option considers biomass collection and piling, bundling of logging residues, bundle transportation and chipping at plant.

1.3 The Objective of This Study

This study is based on utilization of biomass for production of power in Alberta. The overall objective of this study is to conduct a detailed techno-economic analysis of electricity generation using roadside logging residues in western Canada. The specific objectives of this research are the following:

- Identify and analyze various supply chains for utilization of logging residues for power generation.
- Identify and analyze various ways of nutrients import/export from forest which will be harvested for logging residues.
- Development of a model to estimate the nutrient replacement cost through ash recycling ($/tonne) and assessment of advantages and disadvantages of ash for nutrient recycling.

- Development of techno-economic model to determine the optimum size of biomass power plant and corresponding minimum power production cost (\$/MWh).
- Conduct sensitivity analysis to determine the critical parameters in estimation of optimal size and power production cost of a biomass based plant.
- Development of models for estimation of energy input/output (%) ratio for each of the unit processes.
- Development of models for estimation of emission (kgCO_2/kWh) for each of the unit processes.
- Determination of the GHG mitigation cost (\$/tCO_2) required for biomass based power to be competitive with coal based power in Alberta.

Roadside logging residues have been considered as the only fuel input to power plant. These logging residues are generated by pulp and paper and lumber industries which comprise tops, limbs, needle, branches and non valuable trees.

1.4 The Scope and Limitations of This Study

It was assumed that infrastructure built by forest industry will be used to access biomass fuel from forest. Biomass feedstock supply and cost has been evaluated for western Canada, focusing on Alberta. Various costs considered in this research have been taken from different literature. All these cost were adjusted for Alberta and expressed as 2009 Canadian dollar value unless otherwise mentioned.

1.5 The Organization of This Thesis

This thesis contains five chapters including table of contents, list of tables, list of figures, list of abbreviations and appendices. Each chapter of this thesis is a combination of papers which is intended to be read independently.

Chapter 1 of this study includes the background, problem definition, scope and limitations of this study.

Chapter 2 explains impact of harvesting residues removal on forest land. This chapter presents the various ways by which nutrients import-export take place to - and - from the forest. This chapter also estimates nutrient replacement cost using ash recycling including pros and cons of ash recycle on forest land.

Chapter 3 presents the techno-economic assessment of power generation based on harvesting residues. Cost parameters for each unit processes like collection and piling, bundling, transportation, and chipping were estimated. Based on estimated cost this chapter determines the optimum size of the power plant (MW) and corresponding minimum power production cost ($/MWh) for both the fuel supply chain options (chip and bundle transportation).

Chapter 4 presents energy input-output ratios (%) and emission (kgCO_2/kWh) for various unit processes involved in production of power from forest residues. This chapter also presents a comparative analysis of energy input-output ratios and emission for both options of fuel supply. This chapter also estimates the GHG mitigation cost ($/t$CO_2$) required to make biomass project competitive with coal fired power plant.

Chapter 5 provides conclusions and recommendations for future work based on results of this study.

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2 Biomass Residue Utilization and its Impact on Nutrient Balance

2.1 Introduction

Forest has been of great importance to mankind since prehistoric days. It has been a source of a number of products mainly including energy, food, medicine, lumber and paper for mankind. With the development of human civilization more and more economic value has been derived from the forest. Out of total forest area of 748 million hectare of Canada, about 74% is occupied by boreal forest (National Forest Inventory, 2006). This forest land covers Canada's about 45% land; approximately half of it can be harvested for commercial purpose (Porter et al., 2001). Canada's forest sector generates about $57.1 billion of revenue which contributes to approximately 1.9% of country's GDP (FPAC, 2010). Alberta has about 9% of the total forest land (Porter et al., 2001).

Alberta's boreal forest region comprises 46% softwood, 30% hardwood, 17% mix wood and 7% unclassified (FPAC, 2010) species. Major tree species found are spruce (37%), poplar/aspen (35%) and pine (24%) (FPAC, 2010). Alberta's forest industries generate revenue of about $5.5 billion every year, which is about 10% of total Canadian revenue generated from this industry (FPAC, 2010).

Cut to length is predominantly the practice of wood harvesting in Alberta's boreal forest region. In this method of harvesting, trees are cut and skidded to roadside for further processing to get the round wood for lumber industries. On the roadside the trees are delimbed and the stem is used for pulp and lumber use. Delimbing of the trees generates biomass which consists of branches, tops, bark and leaves which are called forest harvest residues. There is also whole tree biomass from low quality trees. These sources of biomass contribute to the available forest biomass. Utilization of the forest biomass for energy purpose could have some impact on the nutrient level of soil. It is important to understand the nutrient variation in the soil before the forest biomass is utilized for energy. Mostly logging residues (tops, branches, bark and leaves) are used for energy purpose. These parts of the tree are nutrient rich with leaves being the most nutrient rich (Vitousek, 1982). Hence, removal of whole tree or the logging residues from the forest causes the nutrient export from the forest. Nutrient export decreases soil fertility of the forest and the impact is high if forest is in second or higher rotational period (Heilman et al., 1998). It is important to maintain the long term productivity of soil for future tree growth through adequate maintenance of nutrients in the soil.

The current prevailing practice in which biomass is piled and burned, nutrients which are there in ash, accumulates at particular site (along roadside). In this case some nutrients are exported from forest but not replaced back to stands. Also, this may be harmful for soil because of excess nutrient accumulation on the roadside.

Soil is a reservoir of nutrients for trees. During growth, trees take these nutrients from soil. There are 16 elements known to be essential for tree growth and these elements are divided broadly into two categories: macronutrients, and micronutrients. The macronutrients (in order of decreasing amounts in trees) include: carbon, oxygen, hydrogen, nitrogen, potassium, calcium, magnesium, phosphorus and sulfur. The micronutrients (in order of decreasing amounts in trees) include: chlorine, iron, boron, manganese, zinc, copper and molybdenum. Primarily nutrient uptake occurs due to concentration difference between root and soil. Due to variation in components of different biomass and their nutrients concentration, the boreal forest differs greatly in terms of total nutrient storage in various ecosystem components. The forest floor upland forest contains 21% of the above ground organic matter of the boreal forest (Rutkowski et al., 1993). Organic horizon of soil is divided in three categories: Oi, Oe and Oa. (as defined by USDA[2]). In the boreal ecosystem, Oi, Oe and Oa horizons have the largest nutrients content with most of it in the Oa horizon (Rutkowski et al., 1993). The nutrient distribution in trees itself varies depending upon the type of tree. For example, in aspen, the level of potassium in its foliage, wood bark and litter is high relative to other northern tree species (Hendrickson et al., 1987). Table 2-1 shows average nutrient concentration (% dry weight) of aspen tree components.

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[2] O_i: litter or decomposed material whose origin can be identified.

O_e: Partially or well decomposed material whose sources are not recognizable.

O_a: Amorphous, dark and well matted organic layer.

Table 2-1: Nutrient concentration (% dry weight) in aspen tree*

Component	N	P	K	Ca	Mg
Foliage	1.95 (0.14)	0.20 (0.04)	0.15 (0.00)	1.05 (0.01)	0.20 (0.00)
Branch	0.57 (0.07)	0.08 (0.01)	0.15 (0.00)	2.10 (0.04)	0.21 (0.05)
Stem bark	0.33 (0.06)	0.04 (0.01)	0.19 (0.07)	1.08 (0.23)	0.09 (0.02)
Stem wood	0.21 (0.10)	0.03 (0.01)	0.19 (0.01)	0.63 (0.00)	0.08 (0.00)

*Values within parentheses are standard error of the mean.

For coniferous forest, needle constitutes a major proportion of the stand. The nutrient concentration in the needle is very much dependent upon the nutrient composition of organic layer of the soil (Merila et al., 2008). Groundwater table depth is another factor which has significant effect on foliar nutrient concentrations of black spruce (Lieffers et al., 1990). This single factor (groundwater table) can alone explain 52%, 44%, 52%, 59% and 38% of total variance in foliar N, P, K, S and Ca, respectively (Wang et al., 1997). A similar analysis of concentration of 23 elements showed that needle contained the highest concentrations of most of the elements, followed by branches, bark and wood (Rothpfeffer et al., 2007). The concentrations of the macronutrients in wood and bark, except Ca, increases with decreasing stem diameter of the tree (Rothpfeffer et al., 2007). However, foliar N, P and K concentrations decreases with stand age and increases with height and diameter growth of white spruce.

The objective of this chapter is to address issues related to nutrient export due to removal of forest biomass i.e. the logging residues left on roadside. This also includes assessment of cost of nutrient replacement for maintaining the desired nutrient level in the forest ecosystem.

2.2 Nutrient Balance

Nutrient balance along with its concentration is critical for efficient tree growth. As discussed earlier, most of the nutrients taken from ground during the tree growth reside in bark, tops, limbs and leaves. Leaves have the highest concentration of nutrients (Rothpfeffer et al., 2007). During the logging operation in the forest, leaves are a critical part of the residues generated. If these residues are left in the harvesting site for decay, the nutrients go back to soil, allowing them to be taken up again during growth of next generation of forest (Gower, 1992). However, utilizing these biomass residues for energy purpose will cause net export of nutrients from the forest ecosystem. Compared to conventional stem only harvesting, the most intensive harvesting of forest biomass (including harvesting residues) causes significant increase in nutrients export (Rutkowski et al., 1993). This happens because small branches, twigs, and leaves have more nutrients concentration compared to stems. Whole tree harvesting (WTH) experiments have demonstrated decrease in nutrients in the short term (Fahey et al., 1991; Hendrickson et al., 1987). An experiment conducted in Prince Edward Island on white spruce shows a decrease in H^+ concentration in a cut block with WTH as compared to stem only (SO) harvesting (Hendrickson et al., 1987). Similar results were found for nitrate level also in this study. Hendrickson et al. (1987) also demonstrated that the growth of white spruce and pine decreases in the first 6 years after intensive harvesting (WTH). To assess the result on a longer term, British Columbia has initiated a research project called British Columbia's Long Term Soil Productivity (LTSP) project (Powers et al., 1990). The research project is based on a comprehensive model that will provide information about the relative effects of soil compaction and the removal of site organic matter on tree growth.

In order to assess the long-term sustainability of the output and input fluxes of nutrients from and to the system can be measured. A negative balance means export exceeds import and the system will be unsustainable over time. To quantify the effects, nutrient balance approach has been reported by several researchers (Weetman et al., 1972; Huntington, 2000; Watmough et al., 2003). A decrease in the storage of nutrients may not be much critical for nutrient rich soil with a large supply of minerals and extensive cations and anions exchange capacity but a negative balance may affect the soil in the long term over many short rotations.

Nitrogen and sulfur are critical nutrient as these are important for tree growth. After burning the biomass in a power plant these elements are lost in the form of combustion products. Other nutrients could also be lost due to biomass harvesting, if the ash generated during burning of residues is not transported back to the forest. The ash produced during combustion of biomass contains elements like calcium, potassium, magnesium etc. A lot of research is still going-on in the area of usage of ash as a means of nutrient replacement and counteract the soil acidification. At present, some Scandinavian countries are utilizing recycled wood ash as a mean of fertilization (Holmberg et al., 2000; Eriksson, 1998).

Nutrient Fluxes

In the whole forest ecosystem a balance, shown below in equation 2.1, exists between uptake and decomposition of nutrients (Ulrich, 1987):

$$aCO_2 + xM^+ + yA^- + (y-x)H^+zH_2O + energy \\ \leftrightarrow \left(C_aH_{2z}O_zM_xA_y\right)_{org.matter} + (a+\cdots)O_2 \qquad (2.1)$$

Where a, x, y, and z are constants, M^+ are cations (Ca^+, Mg^+, K^+,) and A^- are anions (NO_3^-, $H_2PO_4^-$).

The above cycle is not completely closed because small amounts of nutrients are deposited from the atmosphere and losses take place due to leaching or biomass removal from forest. The fluxes of nutrients can be summarized through mass balance equation as shown below in equation 2.2:

$$\Delta biomass + \Delta soil + \Delta atmosperiflux + \Delta runoffflux = 0 \qquad (2.2)$$

Regionally, various balance accounts have been developed using the above equation with consideration of biomass removal effect (Ulrich, 1987).

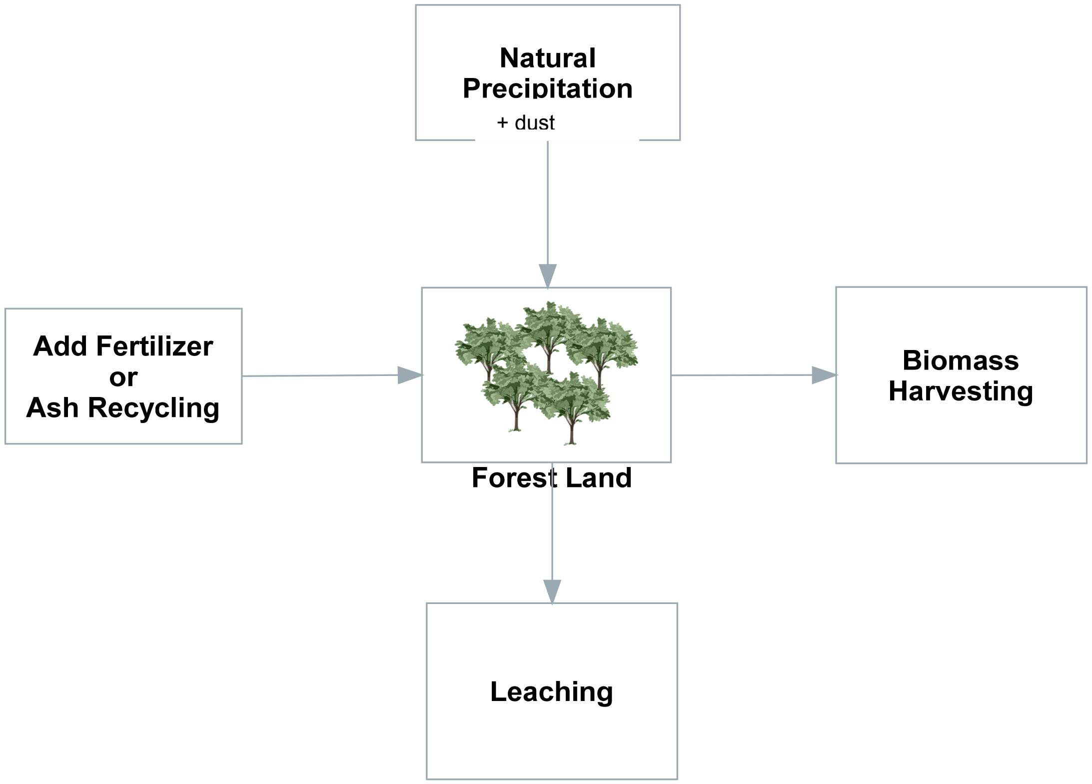

Figure 2-1: Flow of nutrient to and from a forest ecosystem

Nutrient export from forest ecosystem through biomass harvesting has already been discussed in the nutrient distribution section. Nutrient import through fertilization/ash recycling will be described in a subsequent section on ash disposal.

Deposition

Atmospheric deposition is a source of nutrient's input to the forest ecosystem. Depending upon the climatic condition, it has a capability to replace nutrients even if intensive harvesting is done. There are two types of depositions, dry deposition and wet deposition. Dry deposition of gases depends upon the height of the source, wind speed, surface resistance, and atmospheric stability, length of surface roughness and compensation points (Asman, 1998). An experiment conducted to evaluate spatial and temporal patterns of atmospheric deposition of P and N in the north – temperate lakes of Alberta indicates that the total phosphorus and total nitrogen deposition is very much dependent on rainfall and sources of nutrients to the atmosphere (Shaw et al., 1989). Overall in Canada, atmospheric deposition of nitrogen in the form of ammonium and nitrate has steadily increased since the 1900s. In the 1990s it was estimated that the supply was at an average of 2.5 kilograms of nitrogen per hectare per year to forest (Chambers et al., 2004). Other factors that affect the dry deposition are cleanliness of the area as well as structure of the landscape. On the other hand, wet deposition depends upon both the amount of precipitation and concentrations of the elements in the precipitation. Deposition that reaches the forest floor and thus enters the soil consists of throughfall[3] plus stream flow. Trees tend to act as particle collectors, so for those elements which occur in dry deposition, concentration may be higher in throughfall than in bulk deposition. Especially for potassium, canopy leaching is an important pathway in forest soils (Langusch et al., 2003).

Sulfuric acid or sulphur dioxide deposition is relevant to nutrient cycling because of its acidifying effect. An assessment done near a sour gas processing plant in Alberta shows that the soil subjected to the highest S deposition contained 25.9 k mol S/ha (in the uppermost 60 cm of the soil layer) compared to 12.5 k mol S/ha or less at the analogues receiving low S deposition (Prietzel et al., 2004).

However, nitrogen and sulfur deposition cannot be solely seen as a supply of nutrients but it also results in acidification. Soil acidification can lead to significant loss of base cations from the soil. Alkalinity is a measure by which soil resists any change in pH or capacity of soil to neutralize acids. Addition of wood ash can help to increase alkalinity of soil due to presence of base cations. Another source of base cations in deposition can be related to anthropogenic emissions, dust inputs or sea salts. Knowledge of these factors helps in identifying source of base cations in the given region. Sea salt input may be particularly important for magnesium and micronutrients like boron. This kind of deposition is highest in the coastal areas. Heavy metal’s deposition is one source of heavy metals in biomass, and spreading of ash from wood-based combustion is recommended as a means of counter acting acidification and nutrient removals due to harvesting.

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[3] Throughfall - Process of precipitation through above ground trees.

Leaching

Major natural export of nutrients from the forest ecosystem is through leaching which occurs due to the seepage of water out of the rooting zone. In addition, harvesting also affects nutrient export through leaching. Thus, leaching is critical when calculating nutrient balances. Output nutrient fluxes depend on both water fluxes through the soil profile and nutrient concentrations in the water seepage.

It has been assumed that unpolluted old-growth temperate forests should exhibit minimal net uptake or accumulation in biomass (Hedin et al. 1995). Thus, leaching losses should be roughly equal to input in deposition. This has been found to be the case for base cations and inorganic nitrogen (Hedin et al., 1995). On the other hand developing forests tend to retain added nutrients so that losses in leaching are reduced. This applies specially for nitrogen, as this is the main limiting factor for forest growth. In forest that is not saturated with nitrogen, leaching of inorganic nitrogen is insignificant, while in nitrogen saturated system it can be significant (Gundersen et al., 2006). Leaching of base cations is influenced by both natural weathering rates and deposition patterns. Unlike nitrogen, leaching of base cations is influenced by both soil pH and deposition. Leaching of nitrogen as well as other nutrients may increase temporarily as a result of harvesting. To what extent compensation using fertilizers or wood ash is necessary after harvesting will depend on the ability of weathering and deposition together to replace nutrient losses in both harvesting and leaching.

Nitrogen Fixation

Loss of nitrogen during burning of biomass can be compensated through nitrogen fixation. In this method, atmospheric nitrogen is biologically converted into a form which plant can use. Figure 2-2 shows examples of nitrogen fixing bacteria (Deacon, 2011).

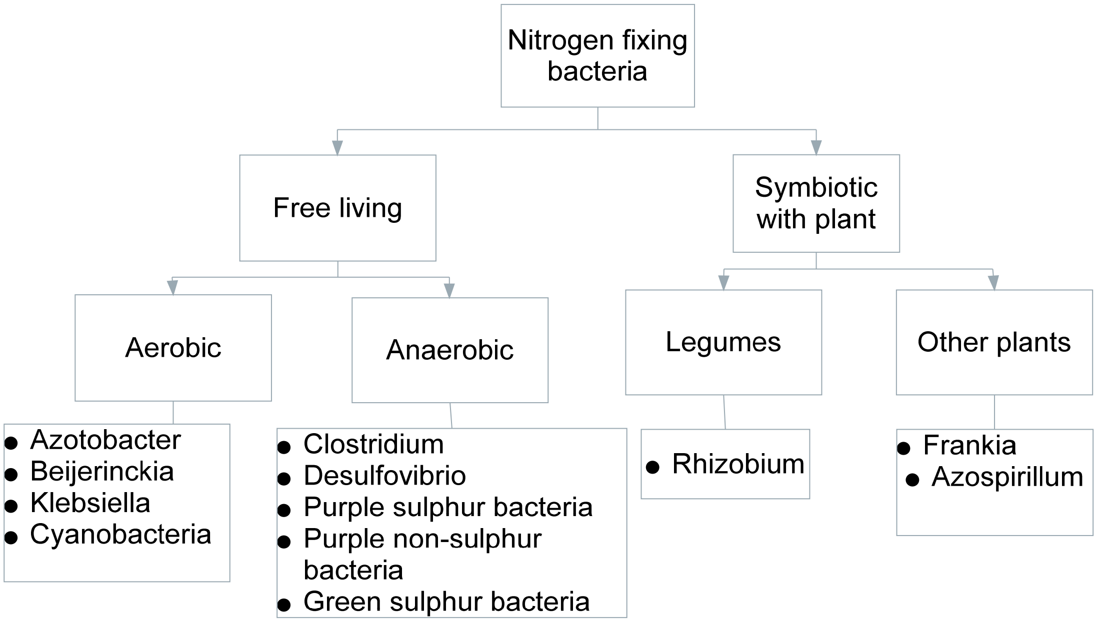

Figure 2-2: Examples of nitrogen fixing bacteria

Biological nitrogen fixation takes place through following equation (Postgate, 1998):

$$N_2 + 8H^+ + 8e^- \rightarrow 2NH_3 + H_2 \qquad (2.3)$$

Mostly microorganisms that fix atmospheric nitrogen are Cynobacteria, Rhizobia and Frankia (Berman-Frank et al., 2003; Sellstedt et al., 1986; Pagan et al., 1975). There are several factors such as the placement of the nodules on the legume root system, the amount of soil mineral nitrogen and phosphorus fertilizer applied and the temperature have an impact on the amount of nitrogen fixed by the plant (Hardarson et al., 2011).

2.3 Ash Disposal

Intensive harvesting of residues will cause export of nutrients from the forest. Nutrients are a small proportion of the total weight of the trees. Increased transport of forest nutrients due to increased use of forest fuel is not negligible. Also soil acidity is another concern because these residues are the major source of cations.

Solid residual left after the burning of wood is known as ash. Today, in Alberta, this ash is not spread back to the stands. Wood ash contains all the major plant nutrients except nitrogen. Recycling of wood ash to the forest is a possible way to close the nutrient cycle and counteract increased soil acidity. One way to do this is to return the ash back to the forest to balance the nutrients. However, if the ash is going to be recycled to the forest ecosystem it is important to know that there are negative impacts that might outweigh the positive effects.

Major components of wood ash are calcium, potassium, magnesium, silicon, aluminium, iron and phosphorus (Steenari et al., 1999).

Table 2-2: Wood fly ash composition for different tree species (%)

Element	Pine	Aspen	Poplar
Calcium	29.05	21.17	25.67
Potassium	16.24	11.25	7.93
Magnesium	7.03	3.55	9.09
Sulfur	1.07	0.70	1.02
Phosphorus	0.84	1.18	0.95
Manganese	4.04	0.14	0.45
Zinc	0.36	0.34	0.04
Iron	0.58	0.26	0.32
Aluminium	0.47	0.14	0.35
Sodium	0.06	0.06	2.30
Silicon	Not Available	0.11	Not Available
Boron	0.06	0.05	0.05
Copper	0.04	0.03	0.03

Other trace elements found are arsenic barium, boron, cadmium, copper, chromium, silver, molybdenum, mercury, nickel, vanadium and zinc (Steenari et al., 1999). However, elemental composition of ash can vary considerably between tree species. Environmental factors such as soil type and climate as well as plant operations such as combustion temperature and ash collection systems will influence the elemental composition (Etiégni et al., 1990; Misra et al., 1993). Table 2-2 shows a typical composition of wood fly ash of different tree species when combusted at 600 ^{o}C (Misra et al., 1993).

Wood ash reacts easily with water and oxides to form hydroxide. Hydroxide dissolves in water to give hydroxide ions. Thus, ash has capability to neutralize acidity of the soil (acid-base reaction). Approximately three tons of wood ash has a liming effect (increase in soil pH) equivalent to one ton of CaO. Some other factors which may cause variation in concentration of elements in ash are the type of wood burner, burning conditions, contamination of fuel and storage conditions. In particular, charcoal (elemental C) due to incomplete combustion causes large variation in elemental concentration in ash (expressed as per unit weight). Different element in the ash has different solubility and solubility of potassium is highest followed by magnesium, calcium and phosphorus (Eriksson, 1998b). There is a risk of contamination in the ash and use of contaminated ash for nutrient recycling can damage the soil. There is a high probability of contamination when harvesting residues is burned in the plant with scrap wood from construction, pressure treated wood or other sources. It is recommended to precondition the ash before it is recycled. During storage of ash its property will change because of its reaction with air moisture (Steenari et al., 1999). The hardened ash is less reactive and cause reduced solubility of elements. Stabilization and agglomeration methods used today usually involve the addition of water to the ash. These then either undergoes pelletization, granulation or spontaneous stabilization combined with crushing (Steenari et al., 1998).

Two major impacts on soil by using wood ash are change in soil acidity and microbiological action in the soil. In terms of soil acidity the effect in the upper part of the soil (in forest soil usually the organic horizon) is significant and depends upon both type of ash and the amount of ash applied in Baltic countries (Ozolincius et al., 2005b). The effects of wood ash on the acidic properties of soil seem to last over a long period of time. Ash doses around 5 tons per hectare have been shown to cause changes in pH of +1.4 to +2.0 units over 10-19 years after their application in south Sweden (Bramryd et al., 1995). The transport of alkalinity down through the profile is slow and the effects deeper down in the profile are found to be small and usually visible after a considerable time (>10 yrs) of application of the ash (Bramryd et al., 1995). Effect of wood ash application also depends upon the type of soil on which it has been dispersed (Matsi et al., 1999; Saarsalmi et al., 2001).

2.4 Nutrient Replacement Cost

There are various factors that have to be considered before nutrients are replaced back to forest. The whole process of ash recycling can be subdivided in three major parts as shown in fig 2-3.

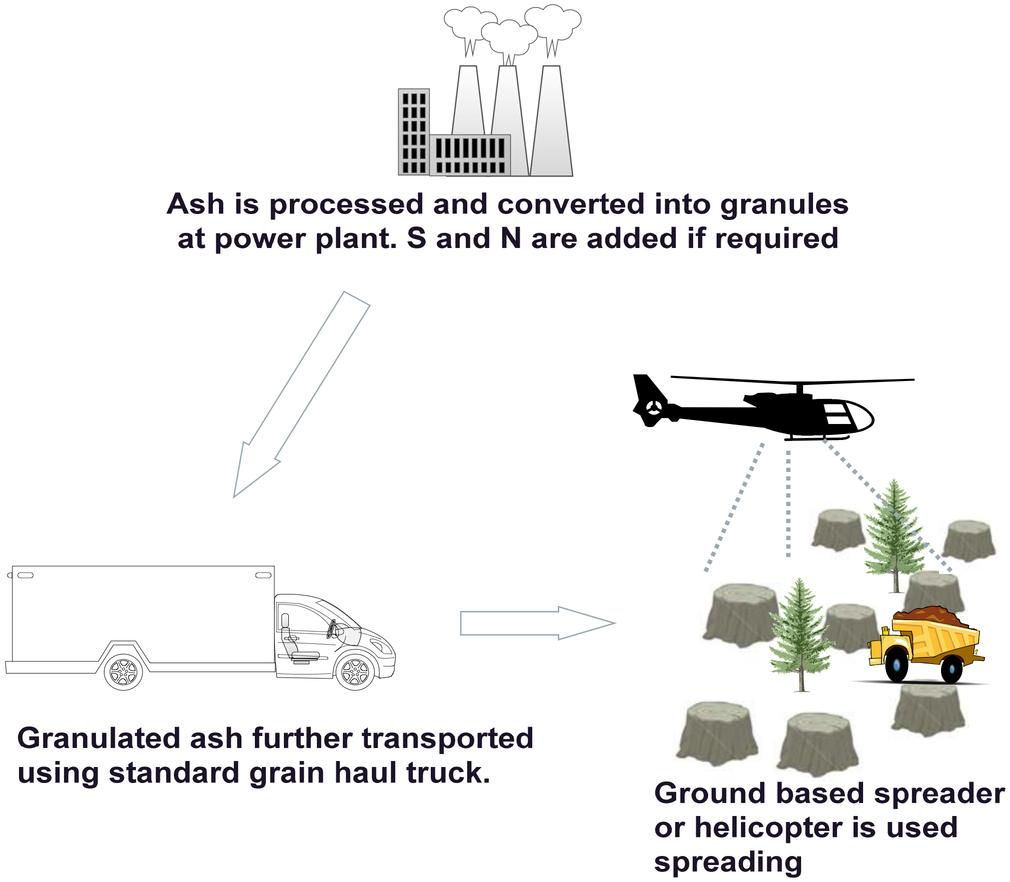

Figure 2-3: Process of ash recycling from a power plant

Ash from the power plant is loaded on to the truck for transportation to the cut block. At each of the three stages shown in Figure 2-3, there are a number of unit operations which incur some cost. The scope of nutrient and the cost estimation are shown in the Figure 2-4.

During the process of burning of biomass, N, S and some amount of P are lost as these are oxidized. Hence, the cut block which requires fertilization to replace these nutrients, there is an extra cost of adding these nutrients during ash processing. The total cost of nutrient replacement C_T can be represented as:

$$C_T = C_{Ash} + C_{Fert} \qquad (2.4)$$

Where, C_{Ash} is the total cost of ash utilization for nutrient replacement and C_{Fert} is the cost of fertilization. The methodology to estimate the C_{Ash} is detailed in Figure 2-4. C_{Ash} is estimated considering all the activities within the dashed line as shown in Figure 2-4. The ash utilization cost can be further divided as shown in equation 2.5.

$$C_{Ash} = C_{CB} + C_T + C_P \qquad (2.5)$$

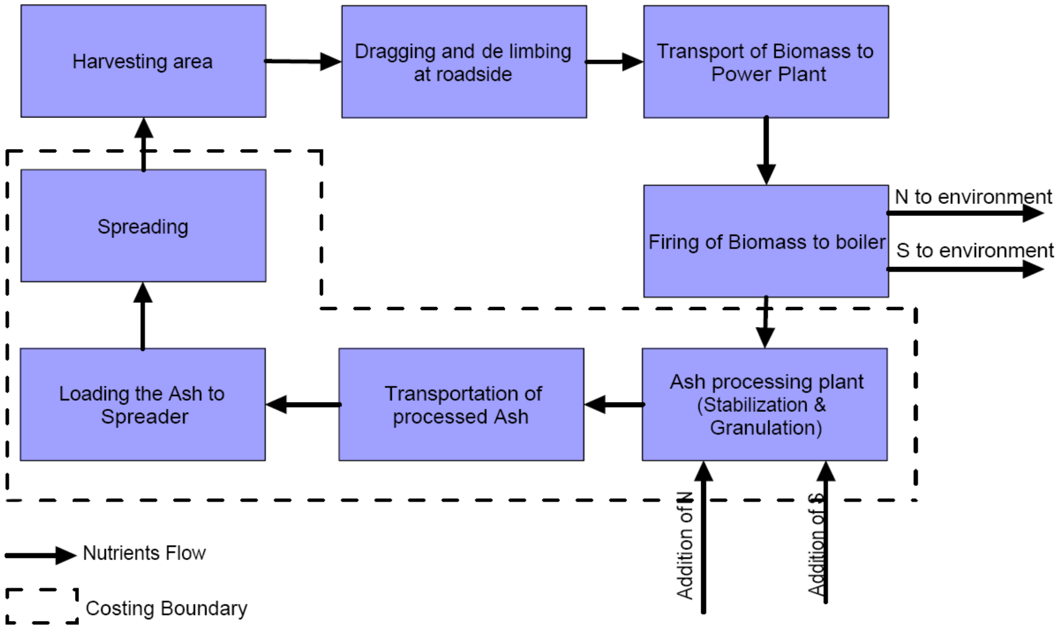

Figure 2-4: Scope of cost estimation for ash recycling

In equation 2.5, C_{CB} is the cost that occurs at the cut block in loading and spreading of ash, C_T is the cost that occurs in transportation and C_P is the cost of ash processing at the plant. The key objective of this study is to estimate C_{Ash} ($/MWh of electricity generation). The study also aims to identify the effect of moisture content on fertilization cost in wood ash recycling.

Cost at the power plant (C_P)

The ash processing plant is assumed to be located near the power plant. This key assumption is based on the difficulty to handle the unprocessed ash and to avoid any extra cost of transportation to a remotely located ash processing plant. It would be advantageous economically to transport densified ash compared to the unprocessed ash. There are numerous processing activities which need to be performed at the power plant before ash is finally transported to cut block for spreading. At the plant, ash is processed chemically and mechanically for stabilization. Ash stabilization is done to prevent any harmful effect on the soil. Chemical stabilization, also called hardening, includes hydration and carbonation of ash. Hydration is followed by subsequent carbonation which leads to lower solubility of calcium and reduces the alkalinity (Steenari et al., 1998). Mechanical stabilization is done by forming agglomerates using different techniques like granulation or roller pelleting (Amu et al., 2005). This helps ash to be stable for longer period of time and better suited for newly harvested areas. Additives are used during agglomeration process and selection is done based upon the ash type. Binders used for wood ash are cement, lignosulfonate and molasses (Borjesson, 1992). Limestone and dolomite powder can also be used as binder for wood ash and it is best suited for soil with acidic nature (Sarenbo et al., 2004).

Two major components of plant operational cost are staff and energy costs. This also includes cost of material handling within the plant. Plant operation requires operating labor and administrative staff. For this analysis it was assumed that two persons will be required for plant operation, one person will be required for ash handling yard, and one person will be dedicated for granule handling and storage. Operating labor will work on eight hours shift basis. One administrative staff will be involved in managing the activities in the plants. It was assumed that plant availability will be

90%. Since the process of wood ash granulation is similar to the process of asphalt mixing plant (Emilsson, 2006), a typical asphalt mixing plant consumes energy in the form of LPG, heavy fuel oil, diesel fuel, waste oil, electricity and natural gas (Natural Resource Canada, 2010). Data as given by Natural Resource Canada (NRC, 2009) for energy consumption of asphalt plant was used to estimate energy cost of ash granulation. Table 2-3 provides details of energy consumption per unit of asphalt production with corresponding energy prices. Input parameters for development of techno-economic model to estimate the annual granulated ash production and its costs are given in Table 2-4. All the cost parameters are in 2009 Canadian dollars.

Table 2-3: Asphalt plant energy consumption (per tonne of production)

Fuel type (unit)	Fuel consumption	Per unit price	Data source
LPG	0.52 (L)	63.25 (cents/L)	Natural Resource Canada, 2009
Heavy fuel oil	0.72 (L)	81.45 (cents/L)	Natural Resource Canada, 2009
Diesel fuel	1.24 (L)	1.01 ($/L)	Average 2009 diesel fuel price in Canada (NRC, 2009)
Waste (used) oil	2.95 (L)	3.00 (cents/L)	Sanders, 2010
Electricity	2.12 (kWh)	4.78 (cents/kWh)	AESO, 2009
Natural gas	4.66 (m^3)	7.05 ($/MJ)	National Energy Board, 2010

Table 2-4: Granulation station cost components

Cost Components	**Value**	**Reference/Comments**
Capital investment (million $)	1.93	This is the approximate cost given in (Vesterinen, 2003).
Labor cost ($/hour)	36	ALIS, 2009
Number of labor staff	4	Assumed
Number of administrative staff	1	Assumed
Fuel cost ($/tonne)	1.22	Estimated based on Table 2-3 data.
Maintenance cost ($/tonne)	1.00	(Lee, 2010).
Total annual production (tonne)	15,428[4]	This is the station capacity as reported in an earlier study (Vesterinen, 2003).
Amount of binder required (% of total mass)	50	This amount is reported for slow nutrient release from granules (Holmberg et al., 2000; Sarenbo et al., 2004).
Market price of dolomite binder($/tonne)	46.82	Average of import - export prices given by Market Research Services (2010).
Cost of sulfur addition ($/tonne)	77.81	Yu, 2005.
Cost of nitrogen addition ($/tonne)	871	Canadian Fertilizer Institute, 2008.

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[4] For annual ash production by power plant above this size, it was assumed that two identical units will be built with capacity factor 1.

Cost of Transportation (C_T)

Transportation cost is divided in two parts: distance fixed cost and distance variable cost. Distance fixed cost comprise of loading and unloading cost whereas distance variable cost is function of distance from ash granulation plant to forest. The distance variable cost includes the cost of labor, fuel, maintenance etc. Limited research has been conducted to estimate the transportation cost ($/t-km) of ash granules. Jacobson (1997) reported the cost for transportation of granules for 80 km and its spreading cost in the forest is in the range of 38-61 (1997 US$ /tonne). The stabilized ash is in the form of granules and less dusty as compared with the original ash from the biomass boiler. Hence, the trucks used for grain transportation can also be used to transport granules. To estimate distance variable cost in the base case, cost given by Transport Canada (2005) for medium truck utilization (160,000 km/year) with 10% profit margin were used. It was assumed that granule will be transported using 5 axle semi unit van with capacity of 22 tonnes (Transport Canada, 2005) and transportation is assumed to be subcontracted. The adjusted cost is 172.15 cents/km which gives distance variable cost 7.8 cents/tonne/km. A loading and unloading cost of $5 per tonne is considered which is cost of loading and unloading for bulk material (Kumar et al, 2007; Bernhofen et al., 2011).

Cost of Spreading (C_{CB})

Once the processed ash is transported, it is unloaded on the roadside. The equipment required for this operation are forwarder[5] with a changeable spreader and special grapple for ash loading. The spreading may be affected by the type of soil. For example, peat lands are soft and it is difficult for tractor to move. For this analysis, a forwarder with a disc spreader and scoop system having 6 tonnes capacity is considered. Operational and financial parameters for ground spreading system are given in Table 2-5.

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[5] An equipment used in wood harvesting for small distance transportation

Table 2-5: Spreading cost parameters

Items	Value	Reference/Comments
Capacity per load (tonnes)	6	(Väätäinen, 2010).
Forwarder life (years)	10	(Doler et al., 2001).
Spreader life (years)	10	(Doler et al., 2001).
Annual operating hours (hours/year)	2000	Considering one shift of 8 hours and 5 days in a week.
Forwarder cost ($)	240,000	Average price from different manufacturers (Vaatainen et al., 2010).
Disc spreader and scoop cost ($)	30,000	(Vaatainen et al., 2010)
Operation and maintenance cost (% of capital cost)	31	Operation and maintenance cost for forwarder calculated based on the methodology given in earlier studies (Vaatainen et al., 2010; Jirousek et al., 2007).
Labor cost ($/hour)	20.66[6]	ALIS, 2009.

Based on the parameters given in Table 2-5, a data intensive techno-economic model was developed. The output of this model gives a cost of spreading in the base case to be $20.10 per tonne. For peat lands, ground based spreading is difficult and helicopter is required for this operation. If helicopter is used, the spreading cost will be higher than ground based spreading. This study does not consider the case where helicopter is used for analysis.

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[6] Average wages of Alberta's logging machinery operators.

2.5 Results and Discussions

Based on estimated cost parameters, the cost of ash processing, transportation and spreading are given in Table 2-6.

Table 2-6: Cost estimated at each unit process

Cost Parameters	Value	Unit
Ash processing and granulation (C_P)	68	\$/ODt
Transportation (C_T)	7.80	cents/ODt/km
Spreading (C_{CB}) (ground based)	20.10	\$/ODt
Total cost of ash recycling (for plant size 50 – 500MW range)[7, 8]	1.50 -1.63	\$/MWh

The total cost of ash recycling depends on the area harvested to supply biomass to the power plant. This is because larger harvesting area means larger transportation distance. This is a key reason for variation in dollar per MWh cost with change in plant size.

To evaluate the total cost including fertilization cost associated with nutrient's balance, information regarding the atmospheric deposition of sulfur and nitrogen is required. Atmospheric depositions of sulfur and nitrogen are site specific. Studies show that over 20 – 100 years atmospheric deposition of sulfur ranges from 0.06 – 0.16 g/m^2/yr in Alberta's peat lands (Turetsky et al., 2000). The same study also reported that atmospheric nitrogen deposition rate in northern Alberta ranges from 0.7 to 0.8 g/m^2/yr. The biomass yield of 0.247 Odt/hectare (Kumar et al., 2003) was used to estimate harvesting area required to generate 1 MWh of electricity. Fertilization cost will be incurred if nutrients' (N and S) export is more than the import. This is because if the amount of nutrients removed during power production

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[7] Range of plant size considered because higher plant size means larger area will be covered for biomass. Hence larger distance will be covered during spreading ash.

[8] Conversion of cost in terms of \$/MWh is based on chapter 3 base case data assumption.

is compensated by atmospheric deposition then there is no need to replace these nutrients. The only source of nutrients (N and S) import is atmospheric deposition. Table 2-7 describes the summary of findings. A detail calculation table is shown in appendix B.

Table 2-7: Summary of results

Items	Nitrogen	Sulfur	Comments/Remarks
N and S distribution in biomass	2.58 - 3.12% (as shown in Table 1)	758 – 872 mg/kg	Sulfur distribution for whole tree (Asman, 1998). Only branches have been considered.
Nutrient export (kg/MWh)[9] - N_e	15.88	0.45	Assuming 85% capacity factor for power generation.
N and S atmospheric deposition (g/m^2/yr)	0.75	0.11	Average of the maximum and minimum taken from (Turetsky et al., 2000)
Nutrient import (kg/MWh)[10] - N_I	26.59	3.9	Area estimated for atmospheric deposition was equated with area harvested at 47% moisture content.
Fertilization cost ($/MWh) ($N_I$ – N_e)	0	0	If import > export, cost considered is zero.

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[9] This is calculated by method of total annual nutrients (N & S) removal divided by total annual power production.

[10] This is estimated by (Area harvested per year times N or S deposition rate)/Annual power production.

Impact of moisture content of wood on fertilization cost

To study the effect of moisture content of wood on fertilization cost, Figure 2-5 shows the plot of net nutrient import minus export (i.e., (N_I – N_e)) vs. moisture content (MC). Appendix B shows detailed calculation method at moisture content of 47%. Changing moisture content will change the area harvested at 300 MW. A larger area will increase the natural deposition of N and S. Hence, it shows that for the range of moisture content between 1 to 57%, fertilization cost remains zero as import is greater than export for both N and S. Increase in net deposition of N and S can be explained as increase in moisture content increases the area harvested for power generation means higher atmospheric deposition per MWh. Nutrient export per MWh remains constant because amount of dry biomass do not change.

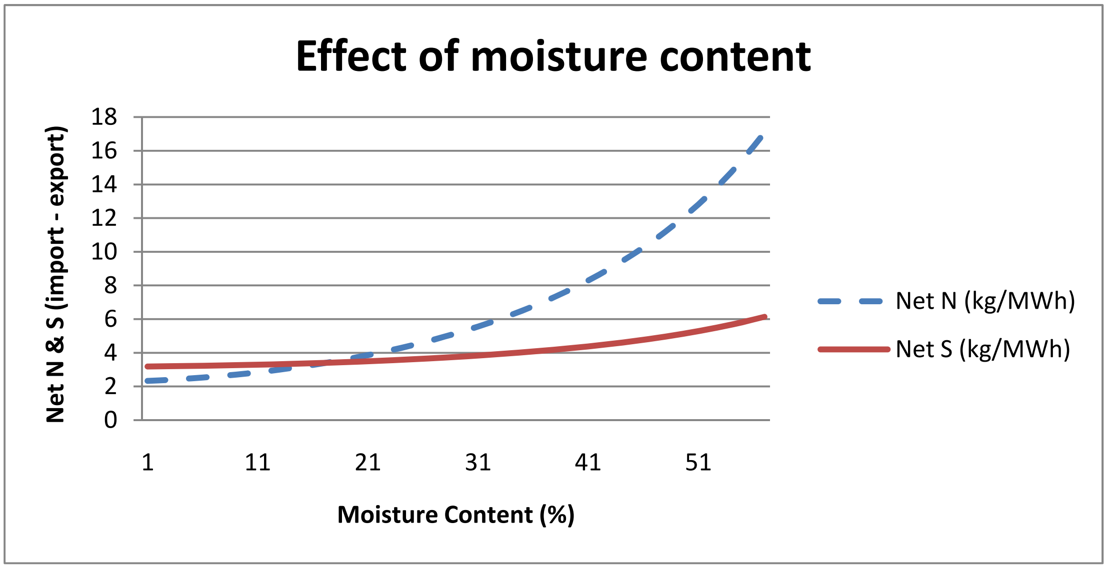

Figure 2-5: Effect of moisture content on net N and S (import-export)

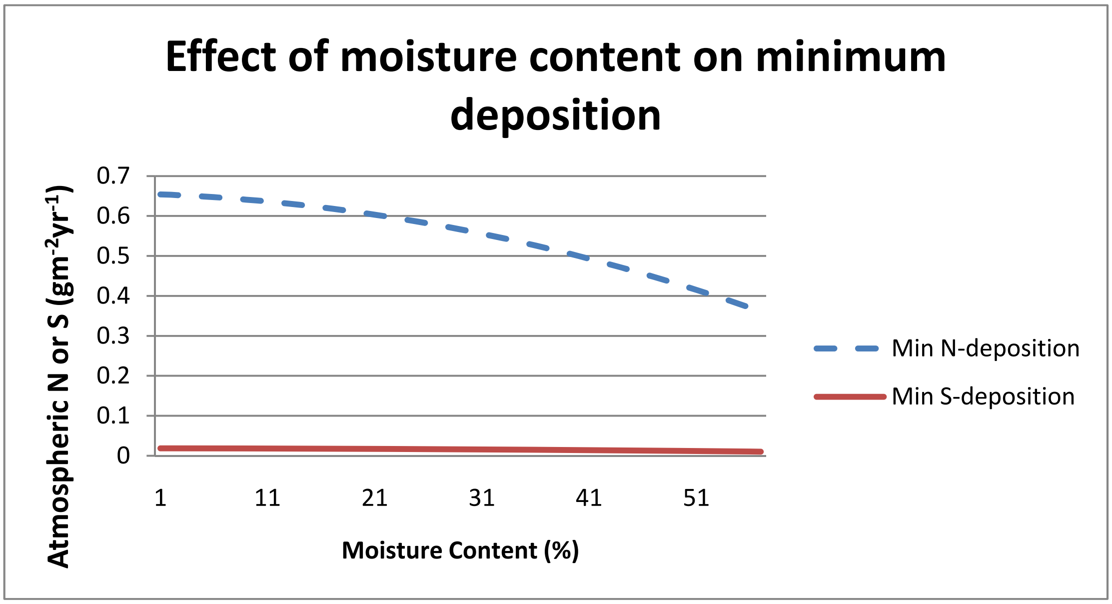

Figure 2-6: Effect of moisture content on minimum deposition

Figure 2-6 shows minimum atmospheric N and S deposition required for zero fertilization cost at different moisture contents. Another factor that affects the import of N and S is atmospheric deposition. For given moisture content and plant size, harvested area is fixed. Hence for this fixed area, there is a need for minimum atmospheric N and S deposition for zero fertilization cost. For example at 47% moisture content and a plant size of 300 MW, minimum requirement of N deposition is about 0.47 g/m^2/yr. From this figure it can be concluded that removing biomass at low moisture content from the area where atmospheric deposition of N is very low may require nitrogen fertilization cost. However minimum deposition of sulfur remained almost constant for different moisture contents

2.6 Conclusions

Nutrient import during biomass harvesting highly depends upon type of tree harvested and its nutrient content. Majority of nutrients reside in bark, tops, limbs, and leave of a tree. For coniferous, most of the nutrients are present in the needle part of tree. Ash recycling can be used as one of the effective methods to address the problem of nutrient export. While all other elements remain in the ash produced from the combustion of forest residues, nitrogen and sulfur are lost during combustion. Atmospheric deposition and external fertilization are the means by which nutrients can be imported to forest while leaching and biomass harvesting causes nutrients export from the forest. Wood ash recycling can also be used as the effective way to counteract the acidic nature of soil. Wood ash needs to be processed before it can be used as a fertilizer for two reasons. First, processed wood ash is convenient for handling. Second, it slows down the nutrients' transfer rate into the soil. Wood ash is stabilized through agglomeration or granulation process. The cost of wood ash granulation is $68/tonne of ash which includes all the costs except external fertilizer addition. Distance variable cost for ash granule transportation is 7.80 cents/tonne-km, while distance fixed cost is $5/tonne. The cost of ground based spreading is $20.10/tonne. However on peat lands, ground based spreading is difficult and helicopter will be required for this purpose. The overall cost of ash recycling is estimated to be $1.50 -$1.63 /MWh for plant having sizes in the range of 50 to 500 MW. If helicopter is used than this cost will go further up and would be in the range of $1.48 to $2.8 /MWh. Atmospheric depositions of nitrogen and sulfur play important roles in determination of fertilization cost. Moisture content of biomass also has significant effect on the fertilization cost. Higher moisture content increases the difference between import and export quantity for each of N and S. This increment occurs because higher moisture content in biomass requires larger area to be harvested for fuel supply.

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3 Biomass Power Generation Cost and Optimum Plant Size

3.1 Introduction

In this chapter, different cost factors associated with harvesting forest residues for electricity production are investigated. For biomass based facilities, as the size of the facility increases, the capital cost per unit output decreases due to the benefits of the economy of scale. On the other hand, the increase in the size of the plant increases the transport cost of biomass as size of collection area of forest residues increases, thereby increasing the biomass transportation distance. Hence, there is a size of biomass facility at which the total cost of power generation is minimum and this is called as the economic optimum size of the plant. This chapter estimates the economic optimum size of the power plant at which total cost of power generation is minimum. Two cases of fuel supply chain have been considered including in-wood chipping and chipping at plant. In case of in-wood chipping, harvest residues are collected and chipped along the roadside. Standard B-train chip vans are utilized to transport chip to power plant. In case of chipping at the plant, logging residues are converted into compressed log residues (CRLs) or bundles to densify the fuel during transportation. These CRLs are then chipped at plant before firing it into a boiler. This chapter also investigates the sensitivity of results towards various factors like capital cost, pre tax return, moisture content of fuel etc.

The overall objective of this chapter is to carry out a detailed techno-economic assessment of utilization of forest harvest residues for production of power through development of data intensive techno-economic model. The specific objectives of this chapter are described below.

- Determination of delivered cost of forest harvest residues to the power plant through two different pathways of fuel supply chain. These include:
    - Chipping of forest harvest residues and transportation of these through chip vans.
    - Conversion of compressed log residues (CRLs) from forest harvest residues and transportation of these CRLs to the plant.

- Development of cost and characteristics of each of the unit operations involved in production of power from forest harvest residues.
- Development of techno-economic model to estimate the cost of power generation from forest harvest residues ($/MWh) for the two fuel supply chain.
- Determination of the optimum size of the power plant from forest harvest residues for the two fuel supply chain.

All the costs mentioned in this chapter are in 2009 Canadian dollars, unless mentioned otherwise. Costs taken from various literatures were adjusted for inflation and 2009 Canadian dollar exchange rate. All moisture contents are on wet basis, unless mentioned otherwise.

3.2 Biomass Combustion Technologies

When biomass harvest residues after processing are directly fired into a boiler it is known as direct combustion. Two types of combustion technologies which are used on a large scale are available in the market: fixed bed combustion and fluidised bed combustion. Table 3-1 depicts different combustion technologies and their characteristics as reported in literature (NYSERDA, 2008; Broek et al., 1996; Nussbaumer, 2003; Faaij, 2006; Kumar et al., 2003)

Table3-1: Biomass combustion technologies and their characteristics

Type	Properties
Fixed bed combustion	
Underfeed stokers	• Suitable for small size plant • Relatively expensive • Relatively easier to control • Limited to fuel with low ash content • Can burn fuel with moisture content 5-50%
Grate firings	• Can handle fuel with different

Type	Properties
Available as fixed grate, moving grate, rotating grate and travelling grate	sizes • Can burn fuel with high ash content (up to 50%) • Suitable for small and medium size (5MW) plant
Fluidized bed combustion	• Can handle various fuel size • Can handle fuel with high moisture content (5 – 60%)
Bubbling fluidized bed (BFB)	• Can handle fuel with high ash content (up to 50%) • Suitable for medium to large size plant (5- 15 MW) • Can handle fuel with different types
Circulating fluidized bed (CFB)	All the properties of this combustion technology is same as BFB except • It can support large plant size (15 - 100MW) • It requires very high capital investment

3.3 Biomass Fuel Properties

Evaluation of fuel quality and its availability are important before it is used for energy purpose. Critical fuel properties which need evaluation are moisture content, heating value, ash content and availability of biomass. Moisture content of biomass affects both delivered cost ($ per oven dry tonne) and heating value. A study done by Forest Research Institute of Canada (FERIC) now a part of FP Innovations for northern Alberta shows that the average forest harvest residue moisture content is 47%, with lowest value being 30% and highest 65% (MacDonald, 2009). Several factors, such as time of harvesting, piling conditions, climatic conditions, storage methods etc., affect the moisture content of fuel. Low moisture content increases the heating value but decreases the bulk density of biomass transported to plant. This puts volume limitation and causes underweight utilization of truck which increases the total delivered biomass fuel cost (Johansson et al., 2006). High moisture content decreases the heating value but increases the biomass bulk density. In this case more water is transported rather than fuel and hence results in increase in delivered cost of biomass fuel. To calculate the heating value of fuel with given moisture content, following formula was used (Maker, 2004).

$$\begin{aligned} LHV(MJ/kg) &= HHV(MJ/kg) \times \left(1 - \frac{MC(\%)}{100}\right) - 2.44(MJ/kg) \\ &\quad \times \frac{MC(\%)}{100} - m_{H_2}[100 - MC(\%)] \times \frac{21.96(MJ/kg)}{10000} \end{aligned} \tag{3.1}$$

Where,

HHV = Higher heating value (MJ/kg)

m_{H2} = Hydrogen content of fuel (%)

MC = Moisture content of fuel (%)

2.44= Multiplication factor for water evaporation from MC

21.96= Multiplication factor for water evaporation from H_2O formation

Heating value of the biomass depends on the hydrogen content. Hydrogen content depends upon the biomass species and changes with time of harvesting (Nurmi, 1999; Demirbas, 2004). This study considers hydrogen content of 6% (wet basis) in the forest harvest residues. The higher heating value of softwood is 20-22 MJ / dry kg and hardwood is 19-21 MJ / dry kg (Baker et al., 1989). Higher heating value considered for this study is 20.30 MJ/ dry kg (REAP, 1994).

Biomass yield is another critical factor which affects the cost of delivery of biomass. Higher yield lowers the fuel transportation cost because of the lower transportation distance. Logging residues comprises about 10% of the harvest volumes in Alberta (Bradley, 2007). However not all of these are recoverable. Approximately 15.6 % of logging residues generated are lost during felling and skidding process round wood harvesting (Stokes et al., 1991). Experiment done by FERIC for northern Alberta for six different regions reported biomass yields in the range of 14.3 to 34.1 ODt/ha with an average yield of 23.6 ODt/ha (MacDonald, 2009). Biomass yield reported by Kumar et al. (2003) was 24.7 ODt/ha. This study considers an yield of 0.247 ODt/ha for 100 years rotation of forest growth biomass.

3.4 Harvesting, Processing and Transportation

Biomass need to be harvested before it is processed and transported to plant for firing in a boiler. More than 95% of harvesting operations in Alberta is cut-to-length system where trees are cut and dragged to roadside for delimbing (Bradley, 2007). With current practice of harvesting, logging residues are left dispersed or partially piled along the roadside. These residues must be piled using forwarders for efficient utilization of machines for further processing. Once logging residues are available in piles, the residue can be transported in two different forms: chips and bundles.

To reduce the size of residues, chippers are required. After chipping, standard B-train chip van is used for transportation of chips to plant. One of the limitations of this method is small to medium size of chipping machine because of the limited availability of biomass at a given logging site. Chips have low bulk density which causes increase in transportation cost due to under-utilization of chip-van. For a given tonnage, volume occupied by biomass fuel is large when compared with coal and other fossil fuel (Allen et al. 1998). Train and truck combination can also be utilized for chip transportation. A study done by Mahmudi et al. (2006) for transshipment option shows that for plant size larger than 130 MW it is economical to use rail and truck combination. Another study was done by Kumar et al. (2005) for truck and pipeline combination of wood chip transportation. This paper concluded that this option could be economical for large capacity with two way transportation distances greater than 470 km.

In another method, logging residues are compressed and bundles are formed. Increasing the load size and decreasing the terminal time can help to reduce the biomass transportation cost (Ranta et al., 2006). Compressed residue logs (CRLs) reduce transportation cost due to increased bulk density of biomass and are also benefited by the utilization of high capacity log haul truck (Johansson et al., 2006; Patterson et al., 2008; Schmidt, 2009). At plant, high capacity chipping machine can be used to chip these bundles thereby further reducing the processing cost of fuel (Schmidt, 2009; Aulakh, 2008; Gustavsson et al., 2010). Bundling process also enhance the site recovery of biomass (Gustavsson et al., 2010). This study considers both the forms of fuel transportation and estimates the optimum power plant size and corresponding minimum power generation cost.

3.5 Optimal Plant Size and Generation Cost

3.5.1 Power Plant Capital Cost

Biomass power plant requires high capital investment compared to equal size coal power plant (Blades, 2007). One of the key factors which contribute to high capital investment in biomass power plant is the high mass flow rate of biomass compared to coal plant (Blades, 2007). However like other power plant, capital cost of a biomass power plant has an economy of scale. IEA reported that for small sized power plant (size in the range of 5-25 MW), the capital investment ranges from \$3000 to \$5000 (IEA, 2007). Searcy et al. (2009) compiled capital investment (million of C\$) data from different sources and found the following relationship (R=0.98) between capital cost capacity (MW).

$$CapitalCost(Y) = 7.24 \times (capacity)^{0.76} \tag{3.2}$$

In the base case of this study, Equation 2 was used for estimation of the capital cost of biomass power plant at different sizes.

Scale factor is another important parameter that impacts the capital cost of biomass power plant. Based on extensive literature review and discussions with the firms, Kumar et al.(2003) found scale factor for biomass power plants to be in the range of 0.6 - 0.9 for a single unit size up to 450 MW. Jenkins identified that for small scale plant (<10MW) scale factor ranges from 0.6 to 0.8 while for large size it approaches 1 (Jenkins, 1997). For large scale power production, CFB boilers are most commonly used for the power generation (NYSERDA, 2008). Until 2009, the available CFB subcritical boilers range from 25 to 350 MW_e with largest 460 MW_e atmospheric supercritical CFB boiler in operation (Goidich et al., 2006). This study assumes that maximum unit size of CFB boiler that can be used for power production will be 450 MW_e. For the plant size larger than 450 MW, it was assumed that two identical units will be built and the cost of an additional identical unit will be 95% of the first unit cost (same as considered by Kumar et al., 2003).

3.5.2 Operating and Maintenance Cost

Plant operation requires operating labor and administrative staff. For this analysis, the assumptions and the number of operating labor and staff required for single boiler unit was taken from Kumar et al. (2003). According to them 26 administrative staff will be required for single unit boiler with 8 operators working per shift (each shift 8 hours). For each additional unit four more operators were added with same administrative staff.

3.5.3 Bundling Cost

Loose harvesting residues are spread over a larger area and has a very low yield per unit area (dry tonnes per ha). These biomass residues can be forwarded and piled and can be compacted into Compressed Residue Logs (CRLs). This method helps in increasing the bulk density of biomass during handling, processing and transportation. Several bundlers are available in the market but Timber Jack’s 1490D is most popular in Europe and North America (Patterson et al., 2008; Schmidt, 2009; Kärhä et al., 2006). This study also considers the same bundler for estimating the cost of bundling forest residues. Table 3-2 gives input parameters used for estimating the cost of bundling ($ per bundle).

Table 3-2: Cost parameters and their values for bundling operation

Cost parameters	Values	Reference/remarks
Capital cost ($)	500,000	Patterson et al., 2008.
Expected life (years)	7	Assumed.
Schedule machine hours	2,000	Patterson et al., 2008.
Fuel consumption (L/hour)	11	Patterson et al., 2008.
Fuel price ($/L)	1.01	Average 2009 diesel fuel price in Canada (Natural Resource Canada, 2009).
Annual repair and maintenance (% of capital cost)	26%	Calculated based on Patterson et al. (2008).
Wages ($/hour)	23.8	Average wage rate in 2009 (Alberta wage & salary survey, 2009).
Interest rate	10%	Assumed.
Availability	90%	Assumed.
Productivity (bundles/hour)	40	Schmidt, 2009.

The input parameters given in Table 3-2 were used to develop a detailed techno-economic model to estimate the cost of bundling. The estimated cost is $5.61 per bundle. The cost of bundling very much depends upon productivity of bundler which in turn depends upon the way residues are available and operator's skill. The productivity can be as high as 50 bundles per hour if residues are available in piles and bundled with skilled operator (Schmidt, 2009). Experiment conducted on bundler's operation in Nordic conditions also shows the dependency of productivity over operator's skill (Kärhä et al., 2006). This study uses a bundler productivity of 40 bundles per hr.

3.5.4 Chipping Cost

Forest harvest residues need to be chipped for efficient firing into the boiler. In this study two cases are considered including chipping at landing and chipping at plant. In the former case, chips are transported to the plant using large chip van; and in the latter case logging residues bundles are transported and chipped at the plant. In either case biomass must be collected and piled for efficient processing. A forwarder is used for initial collection and piling operations. Piling and other initial pre-processing work required before chipping is C$25.68/ODt of total delivered cost of biomass in northern Alberta (MacDonald, 2009). Another study reported the same cost at C$10.64/ODt (Bradley, 2007). This cost is much lower than what MacDonald (2009) reported in his trial. The reasons for lower cost were integration of fuel collection with harvesting system by making some change in existing forestry equipment and the use of Scandinavian system and technologies.

There are several chipper and grinder types available in the market for logging residue processing. Logging residue type, availability, and the distance from plant are the limiting factors for choosing particular chippers. Chippers with low or medium productivity (engine power <300 kW) are best suited for chipping at landing. Horizontal grinders are best suited for communition of “short log” form of bundles and this increases the grinder’s efficiency by 10% to 30% by keeping the in-feed full (Schmidt, 2009; Kärhä et al., 2006). In case of chipping at roadside, chipper and truck mutually are dependent on each other but in-plant chipping removes this dependency hence reducing cost due to high capacity utilization (Laitila, 2005). There is variety of chipping machines available in the market. For this analysis Beast 3680 chipper were used and the cost estimated was not significantly different than if other chippers of same capacity was used. In case of chipping bundle at plant, largest capacity chipper available (beast 4680) were used for analysis. Table 3-3 lists the parameters used to estimate chipping cost for both the options.

Table 3-3: Cost parameters and their values for chipping operation

Parameters	Beast 3680	Beast 4680	Reference/Assumptions
Purchase price (P)	350,000	800,000	Bandit Industries, 2009
Salvage value (% of P)	20%	20%	Brinker et al. 2002; Westbrook et al., 2007
Expected life (years)	5	5	(Morey et al., 2009; Brinker et al. 2002; Westbrook et al., 2007)
Scheduled machine hours	2,000	2,000	FERIC (McDonald, 2009)
Interest rate	10%	10%	Assumed
Insurance rate	1.5%	1.5%	Assumed
Fuel consumption (L/hr)	85	125	Based on McDonald (2009) for 3680 and estimated for 4680 using method outlined in an earlier study (Klvac et al., 2009)
Annual repair & maintenance (% of depreciation)[11]	100%	100%	Brinker et al. 2002; Westbrook et al., 2007.
Wages ($/hr) (Including contingencies)	27.5	27.5	(Employment Alberta, 2009)
Availability	90%	90%	Assumed
Productivity (ODt/hr)	30	70	Assumed that machine will work at their rated maximum capacity

Using the above parametric value and calculation methodology provided in appendix A, the chipping cost for base case at roadside is estimated at $9.10/ODt and for in-plant chipping is $7.30/ODt. It is assumed that a separate loader is accompanied with chipper in both the cases. The estimated loading cost is $2.58/ODt. Chipping

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[11] This includes track and tire replacement cost

cost is highly affected by productivity of chipper which in turn affected by biomass availability and type. Impact of high maintenance requirements, interactions with trucking fleet, and cut blocks' properties further reduce the chipper utilization (Spinelli et al., 2009). The productivity considered for base case cost estimation assumes that machine will be utilized at their rated production capacity with readily available resources to minimize delays.

3.5.5 Transportation Cost

Total transportation cost is divided into two parts: fixed and variable transportation cost. Fixed cost includes loading and unloading of biomass and it is independent of transportation distance. Variable cost depends upon transportation distance and directly proportional to distance travelled. Table 3-4 gives parameters for estimation of variable haul cost for chip and bundles. Based on the input parameters as given in Table 3-4, the variable transportation cost for chip and bundle are $1.62/km and $1.97/km respectively. Moisture content plays an important role when estimating cost of transportation of biomass. Overloading and volume are the limiting factors for fuel transportation at high and low moisture contents, respectively. A study done by Johansson et al. (2006) showed that up to a moisture content level of 40.9% for chips and 44.7% for bundles, the dry tonnes of chip and bundle transported are 19 and 21.5, respectively.

Table 3-4: Cost parameters for transportation

Parameters	Chip transportation	Bundle transportation	Reference/assumptions
Type	B-train	Log haul	
Purchase price ($)	201,185	316,724	The price includes trailer cost.
Salvage value (% of P)	21%	21%	Transport Canada, 2005.
Useful life (year)	5	5	Typical life of moderately used truck (Transport Canada, 2005).
Annual Utilization (km)	160,000	160,000	Moderately used truck (Transport Canada, 2005).
Interest rate (%)	10%	10%	Includes profit & risk and interest paid towards any loan amount.
Insurance rate	1.5%	1.5%	Transport Canada, 2005.
Fuel Consumption (liter/tonne)	0.59	0.62	Transport Canada, 2005.
Fuel Price ($/L)	1.01	1.01	Natural Resource Canada, 2009.
Annual repair and maintenance ($/km)	0.14	0.14	Victoria Transport Policy Institute, 2007.

Above these moisture content levels, the amount of dry tonnes transported fall linearly. The following equations are used to estimate cost dollar per oven dry tonne per kilometer for one way transport of fuel based on Johansson et al. (2006). These equations were obtained by taking end point data to get equation of straight line for the graph provided in Johansson et al. (2006).

$$Variable\ haul\ cost\ (chip) = \begin{cases} \dfrac{C(\$/km)}{19} & MC \leq 40.9\% \\ \dfrac{C(\$/km)}{32.37 - 0.33 \times MC(\%)} & MC > 40.9\% \end{cases} \tag{3.3}$$

Similarly, for bundle transportation following equation can be used.

$$Variable\ haul\ cost(bundle) = \begin{cases} \dfrac{C(\$/km)}{21.5} & MC \leq 44.7\% \\ \dfrac{C(\$/km)}{38.37 - 0.38 \times MC(\%)} & MC > 44.7\% \end{cases} \tag{3.4}$$

Equations 3.3 and 3.4 are used to calculate to estimate variable cost of transportation (dollar per green tonne per kilometer). Fixed cost of transportation (loading and unloading) is taken from Flynn et al. (2007) and it was assumed to be the same for both options of fuel supply.

3.5.6 Nutrient Replacement Cost

As described in Chapter 2, there is nutrient export from forest where logging residues will be used as fuel. To prevent the nutrient’s loss and to maintain its balance in the forest ecosystem, ash recycling is done. Chapter 2 describes various issues of nutrients’ recycling and the methods of recycling by which ash can be used to prevent nutrients’ loss. It also estimates cost associated with each stage of ash recycling. The estimated cost of ash recycling is $90 per tonne of ash generated for ash transportation distance of 63 km. It was assumed that all the ash generated is returned back to forest after processing.

3.5.7 Ash Disposal Cost

This analysis assumes that all the ash generated is recycled for nutrient replacement. Hence disposal of ash is not required.

3.5.8 Other Assumptions

This techno-economic analysis includes the following additional assumptions

- There are no delays due to resource requirement at any stage of fuel supply. This means equipments are available at: their maximum possible availability.
- Roadside logging residues are available at no cost to the power plant owner.
- Power plant owner has access to fuel as and when required in any amount without any constraint.
- Power plant is constructed at the centre of the fuel access area. Hence no locality constraints.
- There is no cost associated with roads and other infrastructure required for fuel supply, plant operation and power transmission.
- No cost is paid to forest owners for the use of infrastructure made for forestry operations.

3.6 Results and Discussions

3.6.1 Optimal size and Cost of Power Production

Calculation was done to find power generation cost for plant size ranges from 1 MW to 1000 MW. Power generation cost starts decreasing with increasing the plant size and a minimum point occurs after which generation cost starts increasing. For the two options of fuel supply, table 3-5 shows the economic optimum size and corresponding power generation cost. It also shows economic optimum size with and without restriction on power plant size.

Table 3-5: Economic optimum size and power generation cost

Type of fuel supply	Optimum size (MW) (size unrestricted)	Optimum size (MW) (unit size 300 MW)	Power price ($/MWh) (size unrestricted)	Power price ($/MWh) (unit size 300 MW)
In-wood chipping	524	300	74.21	75.5
Chipping at plant	520	300	87.29	88.54

When the unit size of the boiler is unconstrained, in case of in-wood chipping (chipping at the roadside) optimum size of power plant is 524 MW and power generation cost is $74.21 /MWh. Whereas in case of bundle transportation, optimum size of the power plant is 520 MW with power generation cost of $87.29 /MWh. Table 3-6 gives the breakdown of the cost of power generation at the optimum size for these cases. Table 3-7 gives area over which forest residues is collected and also the distance of transport at the optimum size of the power plant. Based on Table 3-6 and Figures 3-1 and 3-2, some points are worth noting here. There is no significant difference in the theoretical optimum size of power plant for cases of in-wood chipping and chipping at the plant. However, power generation cost is about 18% more in case of bundle transportation and chipping at plant compared to in-wood chipping. The analysis shows that the cost savings from transportation and chipping of bundles compared to in-wood chipping case does not overcome the cost of bundling ($14.31 /MWh) of the logging residues. Capital and transportation costs are the major contributors to the power production cost (Table 3-6). The overall profile of power production cost versus plant size in Figure 3-1 is flat after 350 MW. For power plant sizes higher than 800 MW the curves show significant increase in power cost because of higher transportation cost compared to the benefits of economy of scale in capital cost. In Figure 3-1, the zoomed section of the curve shows that there exists a theoretical optimum size in both the supply options. Within 1% of the power cost at the optimum size, a range of power plant sizes exist (approximately, 300 - 800 MW).

Table 3-6: Cost component and their share in power cost at optimum sizes

Cost component	In-wood chipping		Chipping at plant	
	Size unconstrained $/MWh (% of total)	Unit size 300 MW $/MWh (% of total)	Size unconstrained $/MWh (% of total)	Unit size 300 MW $/MWh (% of total)
Capital cost	30.37(40.92)	34.91 (46.20)	30.42 (34.85)	34.91 (34.06)
Transportation cost	25.24(34.02)	20.03(26.51)	25.29(28.98)	20.13 (19.64)
Maintenance cost	9.08(12.24)	10.44(13.81)	9.10(10.42)	10.44 (10.18)
Chipping cost	6.83 (9.20)	6.83(9.04)	5.48(6.27)	6.43 (6.27)
Nutrient replacement	1.73 (2.33)	1.68(2.23)	1.73(1.98)	1.51 (1.48)
Bundling	-	-	14.31 (16.40)	14.31 (13.96)
Operation	0.95(1.29)	1.67(2.21)	0.96(1.10)	1.63 (1.59)
Total cost	**74.21**	**75.5**	**87.29**	**88.54**

Table 3-7: Area harvested and transportation distance at optimum sizes

Type of fuel supply	Biomass Yield (ODt/hectare)	Area harvested (km^2)	Transportation distance (km)
In-wood chipping			
Size unrestricted	0.247	92,171	145
Unit size 300 MW	0.247	52,469	109
Chipping at plant			
Size unrestricted	0.247	91,822	145
Unit size 300 MW	0.247	52,469	109

If a unit size of the plant is considered, the unit size becomes the limiting factor and the optimum size is the same as the unit size for in-wood chipping and bundle chipping case at plant. The assumption of the unit size of the power plant gives rise to the saw tooth nature of the curve. For example, if unit size is assumed to be 300 MW then at 301 MW two equal unit sizes of 150.5 MW is built which in turn increases the capital cost per unit output of the plant (i.e. $/kW) compared to 300 MW plant.

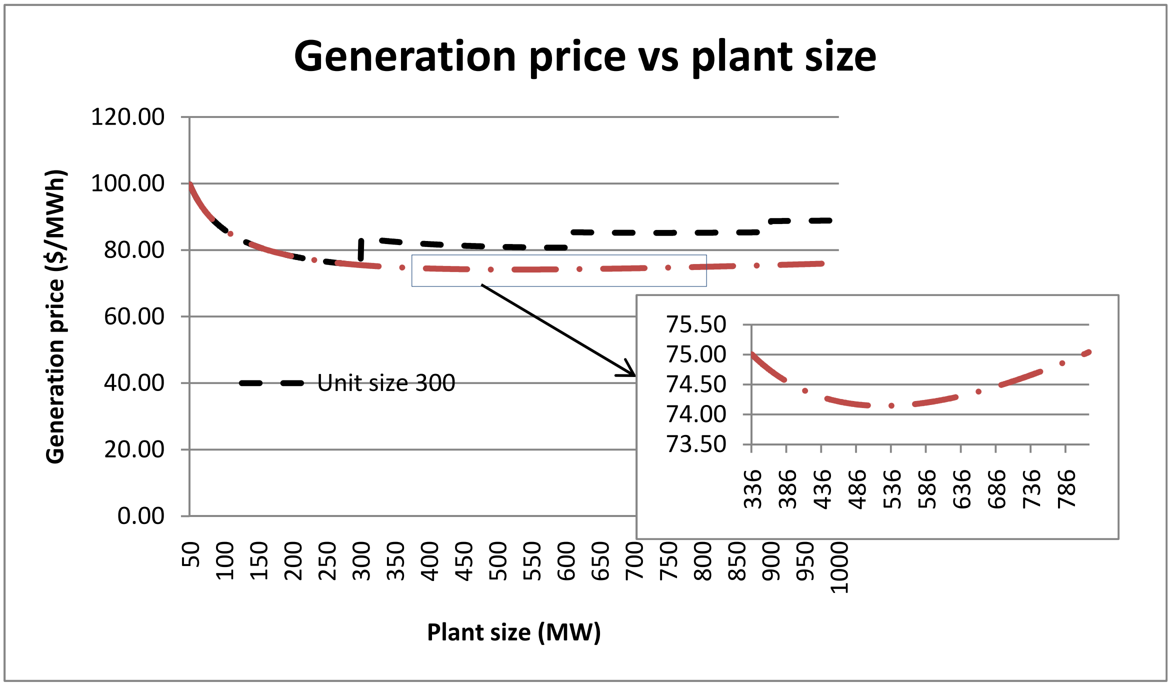

Figure 3-1: Profile of generation cost as a function of plant size for in-wood chipping

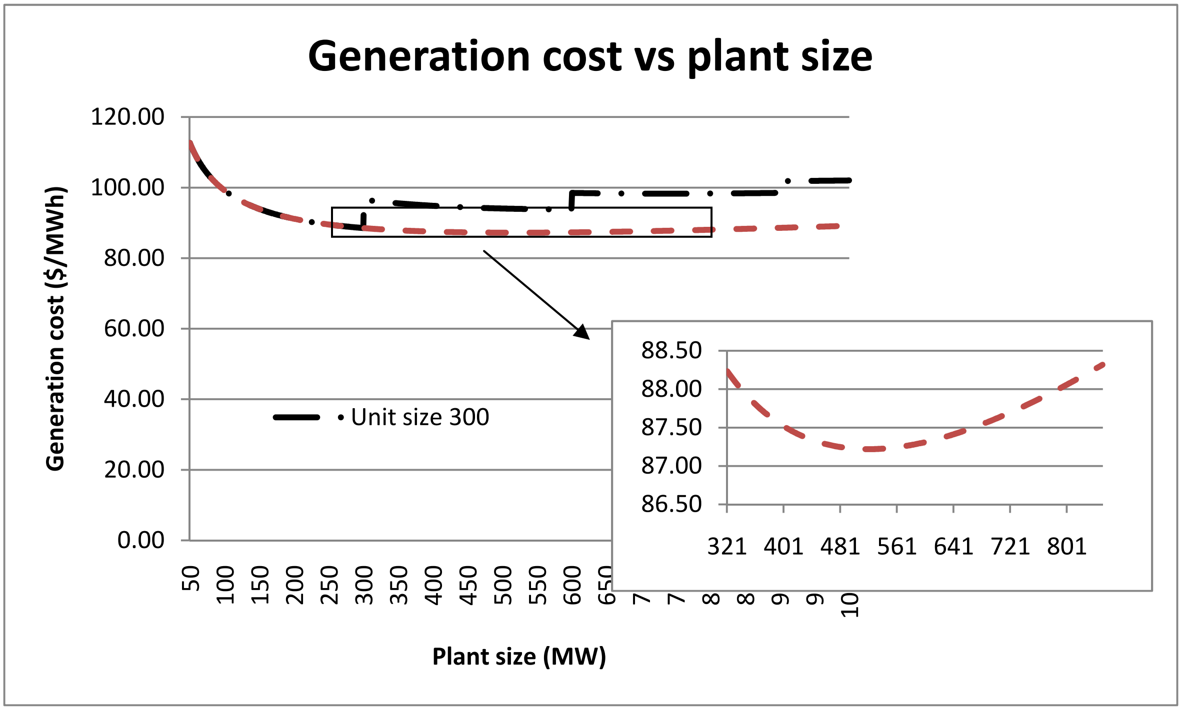

Figure 3-2: Profile of generation cost as a function of plant size for chipping at plant

3.7 Sensitivity Analysis

3.7.1 Effect of moisture content

In this study it is analyzed that there is significant impact of moisture content on optimum size and power production cost. The moisture content of biomass is a function of temperature and relative humidity of environment. Also the moisture content in woody biomass changes with time. Moisture content measurement of Norway spruce showed that it increased by 10% in the following winter when harvested in September. However, moisture content decreased by approximately 50% a year later in next September (Nurmi, 1999). This same report also mentioned that variation of moisture content over the time horizon is very much dependent upon the climatic conditions and the type of storage. The loss of moisture content in open air takes place through transpirational drying. The rate at which the woody biomass loses its moisture depend upon many factors like ambient temperature, relative humidity, wind speed, season, rainfall pattern, tree species, and tree size (Jackson et al., 2010). Excessive precipitation and low temperature conditions may hinder the efficiency of transpirational drying particularly if biomass is left open in the winter season (Lehtikangas et al., 1993a). According to McMinn (1986), drying hardwood in summer for 40 days may reduce moisture content to between 45 and 60% on the oven dry basis. After four months of field drying, it was found that minimum moisture content of woody biomass was 29% in Virginia, USA (Stokes et al., 1993). In Stokes et al. (1987) a method was proposed to predict the transpirational drying of group of species using above mentioned parameters for southern US. It was found that stabilization of weights started after 50 days for pine, after 40 days for hardwood and after 30 days for softwood. Another method adopted in Sirois et al. (1991) for enhanced transpirational drying is by crushing round, smaller diameter stems. The study concludes that longer period of drying has no guaranteed benefit from crushing trees to enhance moisture loss. In this study an impact of change in moisture content from 15 to 50% has been analyzed. Table 3-8 shows the impact of moisture content on optimum size and cost.

Table 3-8: Effect of moisture content on optimum size and power price

Moisture content (%)	In wood chipping		Chipping at plant	
	Size unconstrained	**Unit size 300 MW**	**Size unconstrained**	**Unit size 300 MW**
15	721 MW (67.84 $/MWh)	300 MW (70.78 $/MWh)	886 MW (76.45 $/MWh)	300 MW (80.60 $/MWh)
20	708 MW (68.22 $/MWh)	300 MW (71.06 $/MWh)	838 MW (77.49 $/MWh)	300 MW (81.29 $/MWh)
25	694 MW (68.66 $/MWh)	300 MW (71.39 $/MWh)	788 MW (78.65 $/MWh)	300 MW (82.10 $/MWh)
30	677 MW (69.17 $/MWh)	300 (71.77 $/MWh)	737 MW (79.97 $/MWh)	300 MW (83.03 $/MWh)
35	659 MW (69.77 $/MWh)	300 MW (72.22 $/MWh)	684 MW (81.47 $/MWh)	300 MW (84.12 $/MWh)
40	637 MW (70.50 $/MWh)	300 MW (72.77 $/MWh)	630 MW (83.22 $/MWh)	300 MW (85.44 $/MWh)
45	559 MW (72.91 $/MWh)	300 MW (74.55 $/MWh)	566 MW (85.51 $/MWh)	300 MW (87.20 $/MWh)
50	473 MW (76.17 $/MWh)	300 MW (77.11 $/MWh)	455 MW (90.06 $/MWh)	300 MW (90.85 $/MWh)

Table 3-8 shows that a decrease in moisture content increases the theoretical optimal size and decreases the total cost of power production. However, if unit size of the plant is 300 MW, then power cost decreases with decrease in moisture content but optimal size remains the same. At lower moisture content transportation cost decreases because small area is required to harvest the biomass due to increased heating value.

3.7.2 Cost Factors

The impact of change of various parameters on power cost is shown in Table 3-9. Pre tax return, capital cost and transportation cost are most significant factors affecting the total power production cost. Variation in other cost factors such as operating, harvesting, labor and nutrient recycling costs have minimal impact on the total power production cost.

Table 3-9: Sensitivity of power cost toward various cost factors

Cost factor	In-wood chipping				Chipping at plant			
	Size unconstrained		At 300 MW		Size unconstrained		At 300 MW	
	Cost ($/MWh)	Impact (%)	Cost ($/MWh)	Impact (%)	Cost ($/MWh)	Impact (%)	Cost ($/MWh)	Impact (%)
Capital cost								
✓ +10%	78.08	+5.21	80.03	+6.00	91.17	+4.44	93.07	+5.12
✓ -10%	70.02	-5.40	70.96	-6.01	83.27	-4.61	84.00	-5.13
Operating cost								
✓ +10%	74.24	+0.04	75.66	+0.21	87.31	+0.02	88.70	+0.18
✓ -10%	74.05	-0.22	75.33	-0.23	87.12	-0.19	87.03	-0.1.71
Transportation cost								
✓ +10%	76.67	+3.31	77.33	+2.42	89.75	+2.82	90.55	+2.27
✓ -10%	71.62	-3.49	73.33	-2.87	84.69	-2.98	88.37	-0.19
Biomass yield								
✓ +10%	73.14	-1.44	74.74	-1.01	86.21	-1.24	87.77	-0.87
✓ -10%	75.31	+1.48	76.38	+1.17	88.39	+1.26	89.43	+1.01
Harvesting cost								
✓ +10%	74.83	+0.84	76.18	+0.90	87.77	+0.55	89.08	+0.61
✓ -10%	73.46	-1.01	74.81	-0.91	86.67	-0.71	87.99	-0.62
Labor cost								
✓ +10%	74.24	+0.04	75.66	+0.21	87.31	+0.02	88.70	+0.18
✓ -10%	74.05	-0.22	75.33	-0.23	87.13	-0.18	88.37	-0.19
Nutrients recycling cost								
✓ +10%	74.32	+0.15	75.66	+0.21	87.39	+0.11	88.7	+0.18
✓ -10%	73.97	-0.32	75.33	-0.23	87.05	-0.27	88.37	-0.19
Pre tax return 2% higher	67.66	-8.83	69.76	-9.1	78.60	-9.96	80.55	-9.02

3.8 Conclusions

A data intensive techno-economic model was developed to estimate the optimum size and corresponding power generation cost from forest harvest residues. At optimum size of 524 MW, the power generation cost is $74.21/MWh if there is no constraint on unit size in case of in-wood chipping. Unit size of the power plant is a limiting factor for determining the optimum size of the power plant. For in-wood chipping, power generation cost at an unit size of 300 MW is $75.5 /MWh. Similarly, in case of bundle chipping at plant, the theoretical optimum size is 520 MW with power generation cost of $87.29 /MWh. At an unit size of 300 MW, the power generation cost is 88.54 $ /MWh. For bundle chipping at plant, cost incurred due to bundling ($14.31 /MWh) is more than cost saving from transportation and chipping operation compared to in-wood chipping. The contribution of capital cost to total power cost is highest (40.92%) followed by transportation cost (34.02%), maintenance cost (12.24%), chipping cost (9.20%), nutrient replacement cost (2.33%) and operational cost (1.29%) in case of in-wood chipping and size unconstrained. Power generations cost is more sensitive to changes in capital cost, transportation cost and pre-tax return. Moisture content of biomass is found to be an important factor in determining optimum size and generation cost. At moisture content of 15%, power generation cost can be $67.84 /MWh (optimum size - 721 MW) and $70.78 /MWh (unit size 300 MW) for in-wood chipping.

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4 Life Cycle Energy and Emission Analysis of Power Generation from Biomass

4.1 Introduction

Biomass feedstocks are considered nearly carbon neutral. The amount of CO_2 released during combustion of biomass is nearly the same as taken up by tree during its growth. Hence, it is considered carbon neutral. The energy produced using forest harvest residues can be considered nearly GHG neutral. This is because GHG emissions will take place during transportation and processing of these forest harvesting residues but it is still substantially lower than the total GHG emissions in production of energy using fossil fuels. Forest harvest residue collection, pilling, processing, and transportation are the key unit processes where energy input is required before fuel reaches to the boiler.

Logging residues or wood chips have low bulk density and energy content which causes less energy transportation per trip. To increase the bulk density and utilize maximum allowable load during transportation, logging residues are bundled and transported to plant for chipping. At plant, chipper of higher productivity can be used for processing. This study evaluates energy input for two pathway of fuel supply for electricity production for Western Canada. The first pathway (Option 1) involves residue collection, piling, chipping at roadside (landing), and transportation of chip to power plant. The second pathway involves residue collection, piling, bundling of slash, transportation of bundle to the plant and chipping at plant. Optimal plant sizes as calculated in chapter 3 were considered to estimate the net energy input over the 30 years life of plant for both the options. This study also estimates life cycle GHG emissions from the power plant for both the pathways of fuel supply. Life cycle energy input-output ratio as well as CO_2 emissions in gCO_2/kWh is estimated. The study also analyzes the impact of power plant size and fuel moisture content on the above mentioned parameters.

4.2 Life Cycle Assessment of Biomass based Power Generation

4.2.1 Scope

In this study, life cycle assessment (LCA) of power generation using forest harvesting residues has been carried out. The study presents the results for two pathways of fuel supply for Western Canada. The unit processes involved in each option of fuel supply and system boundary considered for power generation are shown in Figure 4-1.

Biomass production, collection and piling operations are common to each option. The other unit processes involved in option 1 are biomass processing (chipping at landing), chip transportation, construction of power plant and recycling of all the material used. Similarly, other unit processes involved in option 2 are bundling, bundle transportation, chipping at plant, power plant construction and recycling of material. The number inside the bracket for each unit process is arbitrarily assigned to each unit process. For unit process 1 (biomass collection) energy consumption and GHG emissions are taken from the detailed literature review. For all the other unit operations, energy consumption and GHG emissions are estimated.

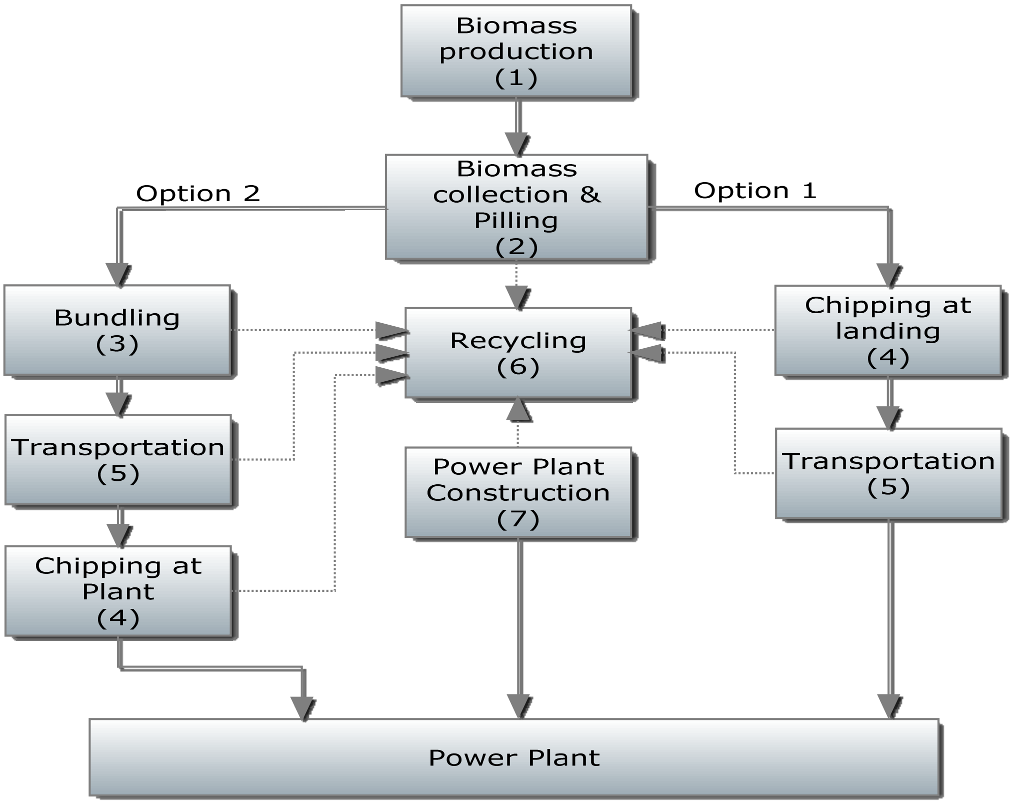

Figure 4-1: Unit processes of power production from forest harvest residues

4.3 Inventory and Assumptions of Study

4.3.1 Biomass collection and piling

Logging slash is dispersed at the landing site of tree length harvesting. These slash need to be collected and piled before chipping or bundling operation. Normally, a forwarder is used for collection and piling. For this analysis Caterpillar's CAT 322L excavator is considered assuming that choice of other excavator with similar capacity will not significantly affect the overall results. Table 4-1 shows the input parameters used in this study.

Table 4-1: Characteristics of forwarder

Parameters	Value	Unit	Reference
Gross equipment weight	25	tonnes	Caterpillar spec sheet
Productivity	20	tonne/hour	MacDonald, 2009
Fuel consumption	30	liter/hour	MacDonald, 2009
Machine life	5	years	Typical machine life (Brinker et al. 2002)
Utilization	90	%	Assumed
Schedule machine hour	2000	hour	

Timberjack (a John Deere company) has conducted life cycle assessment for several forestry machines. A report presented by this company states that for harvesters and forwarders 92.4% and 91.8% of material can be recycled, respectively (John Deere, 2010). The same report mentions that steel, cast iron and tires are the major materials used in manufacturing and their contributions to the total weight of the machine are 65.5%, 11.2% and 12.8%, respectively. In this study only these three materials and its percentage contribution in the total equipment weight is considered to estimate life time energy and emission from these unit processes. Minor changes in percentage contribution are possible but these would not change the overall result.

4.3.2 Bundling of harvesting residues

Wood fuel has lower heating value compared with fossil fuels. Apart from lower heating value, biomass has low bulk density, ranging from 120 to 150 kg/m^3. To achieve maximum allowable load for transportation biomass must have minimum bulk density in the range of 250 to 280 kg/m^3 (Angus-Hankin et al., 1995). Hence to achieve maximum bulk density, bundling is one option which can be used. Composite residues logs (CRL) or bundles are formed to increase the bulk density of fuel wood. Log haul trucks and other conventional logging equipments can be used in the process of fuel supply using this method (Mitchell, 2009; Rummer et al., 2004). Operational results and performance data is available for John Deere 1490D bundler (Rummer et al., 2004; Mitchell, 2009; Patterson et al., 2008). This study considers this same bundler for analysis assuming that other bundler with same capacity will not significantly affect the overall result. A forwarder is used to load forest residues on bundler. Table 4-2 gives the characteristics of a bundle considered in this study.

Table 4-2: Characteristics of a bundler

Parameters	Value	Unit	Reference/comment
Equipment weight	24,489	tonne	Rummer et al., 2004
Fuel consumption	11	liter/ODt	Mitchell, 2009
Machine life	5	years	Typical life of forestry machine (Brinker et al. 2002)
Annual operating hours (SMH)	2,100	hours	Mitchell, 2009
Productivity	40	bundles/PMH	Schmidt, 2009
Average bundle weight	0.5	tonne/bundle	(Mitchell, 2009; John Deere, 2010)

Bundler's productivity is important parameter in determining energy and emission in this unit process. Harvested tree species, moisture content, forest residue density, forest residue arrangement, size and operator's skill are critical parameters which decide the productivity of a bundler (Rummer et al., 2004).

To estimate energy and emission for this unit process, the material requirement and its percentage share in total equipment weight was assumed to be same as in section 4.3.1 for forwarder and piler.

4.3.3 Chipping of harvesting residues

Woody biomass need to be ground or chipped before it can be fired into a boiler to produce energy. When forest residues are transported to the power plant in form of CRL, chipping is done at plant. In other case the forest residues are chipped at the roadside and chips are transported to plant using chip vans. A large scale chipper can be used to reduce the cost of chipping. This can be easily done at power plant by using stationary chipper (John Deere, 2010). Largest size chipper available from Bandit Beast (4680) is used in this analysis (Bandit Industries, 2007). Maximum rated production capacity was taken from beast recycler (Beast Recycler, 2007) and fuel consumption was estimated by using methodology provided in an earlier study (Klvac et al., 2009). On the other hand, chipper with lower capacity is used for chipping of forest residue on the roadside. Bandit Beast 3680 chipper is used in this analysis (MacDonald, 2009). Chipper is also accompanied by a forwarder to load CRL or forest residues. It is also assumed that chipper will be operated at their maximum rated production capacity in both the cases. Table 4-3 shows the characteristics of the chippers used for chipping CRLs in the plant and forest harvest residues at the roadside.

Table 4-3: Characteristics of chipper

Parameters	Chipping at roadside (option1)	Chipping at plant (option 2)
Machine	Bandit Beast (3680 HG)	Bandit Beast (4680 HG)
Gross weight of machine (tonnes)	26 (Beast recycler, 2007)	37.8 (Beast recycler, 2007)
Productivity (tonnes/hr)	100 (Beast recycler, 2007)	170 (Beast recycler, 2007)
Fuel Consumption (liter/PMH)	85 (MacDonald, 2009)	125 (estimated as per Klvac et al., 2009)
Machine Life (years)[12]	5	5
Utilization	70%	70%
Schedule machine hour	2000	2000

To estimate energy and emissions associated with equipment manufacturing for this unit process, the material requirement and its percentage share in total equipment weight is assumed to be same as in section 4.3.1.

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[12] (Morey et al., 2009; Brinker et al. 2002; Westbrook et al., 2007)

4.3.4 Biomass transportation

Super B-train chip van is considered for transportation of chips from roadside to power plant. For this analysis Super B-train trailer with combined double trailer capacity of 177 m^3 with maximum payload of 45.4 tonnes for Canada is used (Angus-Hankin et al., 1995). Payload of chip van is highly dependent upon bulk density of chips that is transported. It is assumed that the chip will be compacted into the van so that vehicle will reach its maximum pay load capacity. Chip will also be directly fed to chip van from chipper. Log haul trucks are used to transport bundles to the power plant (Johansson et al., 2006). Log haul trucks are accompanied by loader for both loading and unloading of CRLs. Data required to estimate total fuel consumption are derived from Harrill et al.(2009). Table 4-4 provides characteristics of chip van and log haul truck.

Table 4-4: Characteristics of chip van and log haul truck

Parameters	Chip Van	Log Haul Truck	Comment/assumptions
On Road - Highway Transportation distance (km)	129	129	Derived from Heller et al.(2004)
Gross vehicle weight (tonnes)	60	60	(Transport Canada, 2005)
Maximum payload capacity (tonnes)	30 (MacDonald, 2009)	39 (Johansson et al., 2006)	
Fuel Consumption (L/hour)	40	40	(UNB, 2010)
Max on highway speed (km/h)	90	90	(UNB, 2010)
Vehicle life (years)	10	10	Assumed
Annual availability	90%	90%	(UNB, 2010)

Three key materials used to manufacture trucks are cast iron, steel and rubber (Gaines et al., 1998). Table 4-5 gives the amount and percentage composition of different materials used for truck and trailer manufacturing.

Table 4-5: Material for manufacturing of truck and trailer (derived from Gaines et al., 1998)

Material	**Truck (% of total weight)**	**Trailer (% of total weight)**
Steel	57.38	41.30
Iron	16.98	6.42
Cast Aluminium	3.47	0.00
Wrought Aluminium	3.43	26.47
Plastic	4.85	0.00
Rubber	8.04	10.59

Table 4-5 gives material composition for chip van truck. For log haul trailer, the percentage of iron taken for analysis is 33% with composition of steel and rubber same as mentioned in table 4-5. It was assumed that zero or insignificant amount of aluminium parts will be in trailer section of truck.

4.3.5 Power generation unit

Biomass power plant size depends upon availability of biomass in the region. All the energy consumption and GHG emissions are evaluated for their optimum. The impact of change of size is also discussed in subsequent sections. The plant life is assumed to be 30 years with capacity factor of 85% (Kumar et al., 2003). Boiler efficiency of 95% and lower heating value of biomass 18.5 GJ/tonne are used to estimate the annual fuel requirement. Power plant construction material requirement is assumed to be same as a coal fired power plant and is given in Table 4-6.

Table 4-6: Material requirement for construction of power plant (derived from Spath et al., 1999)

Material	Quantity	Unit
Concrete	158,758	kg/MW
Steel	50,721	kg/MW
Aluminium	419	kg/MW
Iron	619	kg/MW

4.3.6 Recycling of Material

It is assumed that recyclable material used in the above mentioned unit processes will be recovered and recycled for further use. The energy requirement and emission are highly dependent upon collection efficiency and the type of material used. The collection efficiency is assumed to be 90% of total material used.

4.4 Results and Discussions

4.4.1 Life Cycle Energy Consumption

Table 4-7 shows the life cycle energy consumption of each of the unit processes for optimal plant sizes (the estimation of the optimum size of the forest residues based plants have been discussed in Chapter 3). The energy consumption shown in the Table 4-7 is represented as a percentage of total energy supplied in the form of biomass to power plant. For chipping at landing option, unit process transportation consumes more energy (2.03% and 1.53% respectively) at both the optimal size followed by chipping and fuel collection. For chipping at plant option, unit process transportation consumes more energy (1.83% and 1.46% respectively) at both optimal sizes followed by chipping and fuel collection. Overall energy consumption in option 2 (2.59%) was more than in option 1 (2.44%) at 300 MW. However, it is almost same at their theoretical maximum size.

Table 4-7: Energy consumption in each unit process (%)[13]

Unit Process	Fuel Supply option 1 (Chipping at landing)		Fuel Supply option 2 (Chipping at plant)	
	At 524 MW	**At 300 MW**	**At 520 MW**	**At 300 MW**
Power plant construction	0.05	0.05	0.05	0.05
Fuel collection and piling	0.31	0.31	0.31	0.31
Bundling	0	0	0.28	0.29
Transportation	2.03	1.53	1.83	1.46
Chipping	0.48	0.48	0.43	0.43
Recycling	0.06	0.05	0.07	0.06
Total	**2.95**	**2.44**	**2.97**	**2.59**

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[13] This % is calculated as fraction of total thermal energy available at boiler.

Figure 4-2 and Figure 4-3 shows energy consumption of each of the unit processes as a function of power plant size for both the options. Percentage energy consumption for transportation unit process increases as the size of power plant increases while for other unit processes it remains constant. As the size of biomass power plant increases biomass transportation distance increases. This is the reason for increase in energy consumption with increase in power plant size.

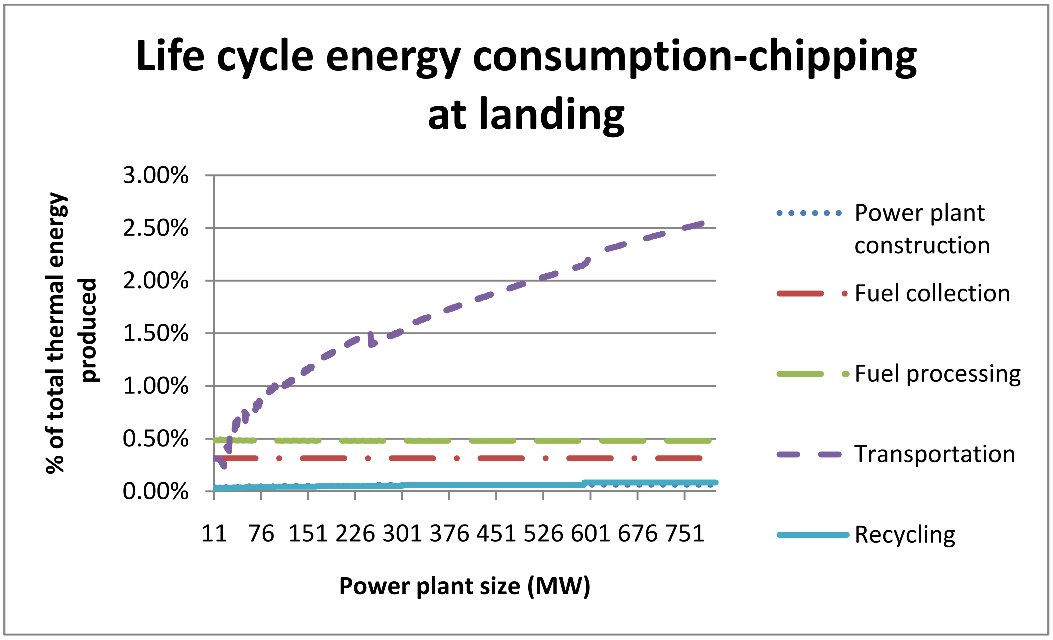

Figure 4-2: Impact of plant size on energy consumption for option 1

Bundle transportation method of fuel supply followed the same energy consumption pattern as shown in Figure 4-3. Transportation again was the highest energy consumer for any given power plant size. Few points are worth noting at this stage. Graph for transportation shows stepwise decrease in life cycle energy consumption. This stepwise decrease is due to the increase in plant efficiency with increasing the plant size as shown in Table 4-8. When number of equipment operated per year for a given unit process is estimated, the next nearest integer is considered because this number can never be fractional. Hence, for a range of power plants same number of equipment is possible. This results in the wavy nature of the curve as shown in Figure 4-2 and Figure 4-3

Figure 4-4 provides a comparison of energy consumption between the two options of fuel supply considered. For smaller plant size (< 600 MW) chipping at landing method of fuel supply consumes overall less energy than chipping at plant method. For plant size greater than about 600 MW chipping at plant consumes less energy.

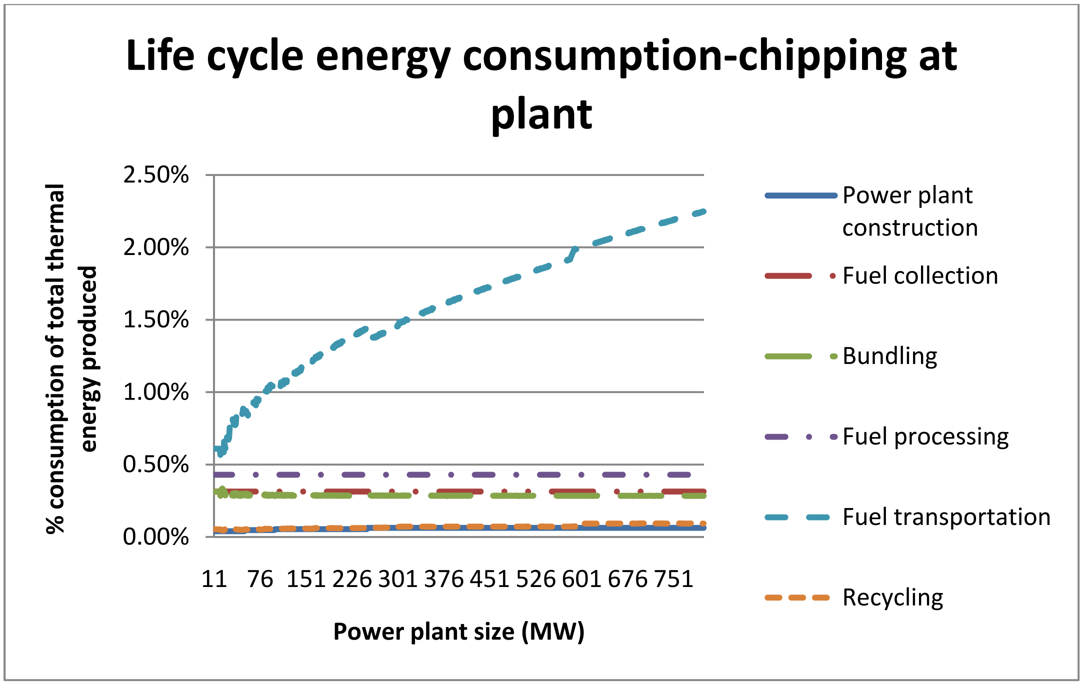

Figure 4-3: Impact of plant size on energy consumption for option 2

Some of the unit processes like power plant construction, fuel collection and piling and recycling are same for both the options. Hence energy consumption remained same for given power plant size. The difference of the energy consumption in chipping process between the two options (≈0.01%) remained same for all sizes of power plant. Bundling is an additional process for chipping at plant method when compared with chipping at landing method. This unit process consumes an

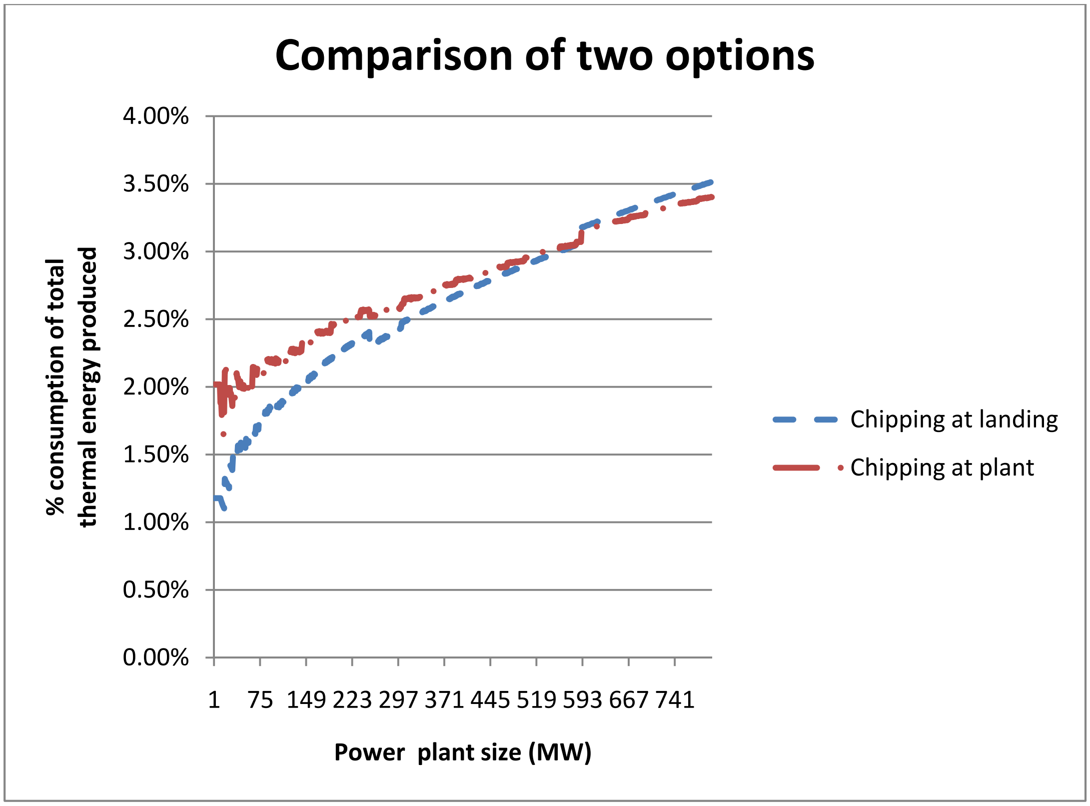

Figure 4-4: Energy consumption as a function of power plant capacity for two options

additional amount of energy (≈0.29%). The difference of energy consumption of transportation process between the two options decreases as the plant size increases. However for plant size less than 600 MW this gap is less than 0.30%[14]. When the gap is 0.30% then crossover point occurs and this is at 600 MW. This is the reason for crossover point and less energy consumption in chipping at plant method for larger plant sizes.

Table 4-8: Plant size versus efficiency

Plant Size (MW)	Efficiency
Less than 50	25%
Greater than 50 but less than 100	30%
Greater than 100 but less than 250	35%
Greater than 250	40%

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[14] 0.01 % from chipping plus 0.29 % from bundling

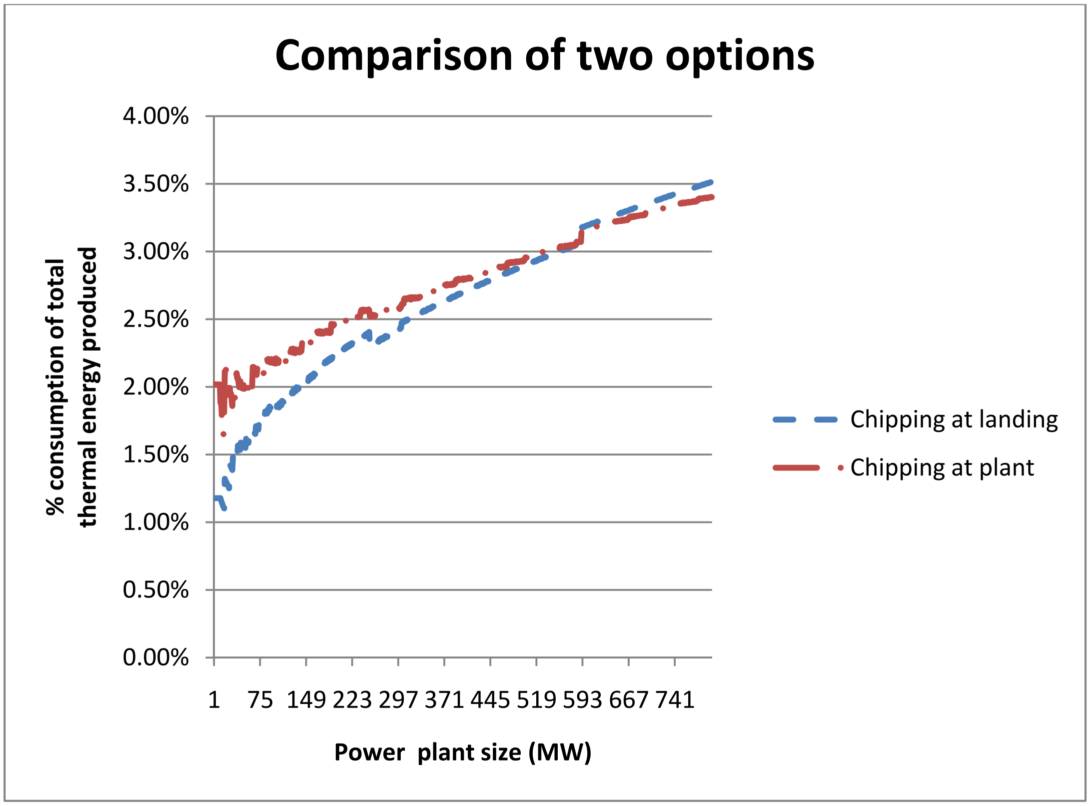

Figure 4-5: Energy consumption as a function of power plant capacity for two options

4.4.2 Life Cycle Emissions

Table 4-9 shows the life cycle emissions (g/kWh) of each of the unit processes for optimal plant size. For chipping at landing option, unit process of transportation emits more CO_2 (17.56 and 13.20 g/kWh, at power sizes of 524 and 300 MW, respectively) followed by chipping and fuel collection. Similarly for chipping at plant option, unit process of transportation emits more CO_2 (15.80 and 12.89 g/kWh at power plant sizes of 520 and 300 MW, respectively) followed by chipping and fuel collection. Overall emissions in option 2 (22.70 g/kWh) was more than in option 1 (21.32 g/kWh) for a power plant of size 300 MW. However, at their theoretical optimal size life cycle emissions are almost the same.

Table 4-9: Emissions from each unit process at optimal sizes (gCO2/kWh)

Unit Process	Fuel Supply option 1 (Chipping at landing)		Fuel Supply option 2 (Chipping at plant)	
	At 524 MW	**At 300 MW**	**At 520 MW**	**At 300 MW**
Power plant construction	0.52	0.52	0.52	0.52
Fuel collection and piling	2.72	2.72	2.72	2.72
Bundling	0	0	2.52	2.52
Transportation	17.56	13.20	15.80	12.59
Chipping	4.14	4.14	3.48	3.48
Recycling	0.85	0.73	0.95	0.85
Total	**25.79**	**21.32**	**25.97**	**22.70**

Figure 4-5 and Figure 4-6 shows CO_2 emissions (gCO_2/kWh) of each of the unit processes as a function of power plant size. Most of the energy is consumed during operation of equipments as diesel fuel input. Hence, more energy consumption means more emissions. This can be seen after comparing the two Figures 4-5 and 4-6 where all the unit processes follows same trends. The impact is evaluated over the range of 10 to 800 MW plant size. The overall plant efficiency at different sizes of the power plant is shown in Table 4-8. For each option, the emissions (gCO_2/kWh) during transportation increases with increase in plant size. Figure 4-7 shows overall emission per kWh for both options of fuel supply. It can be concluded from Figure 4-7 that the gap between the two options of fuel supply is higher for smaller size plants (<100 MW) and it reduces with increasing plant size.

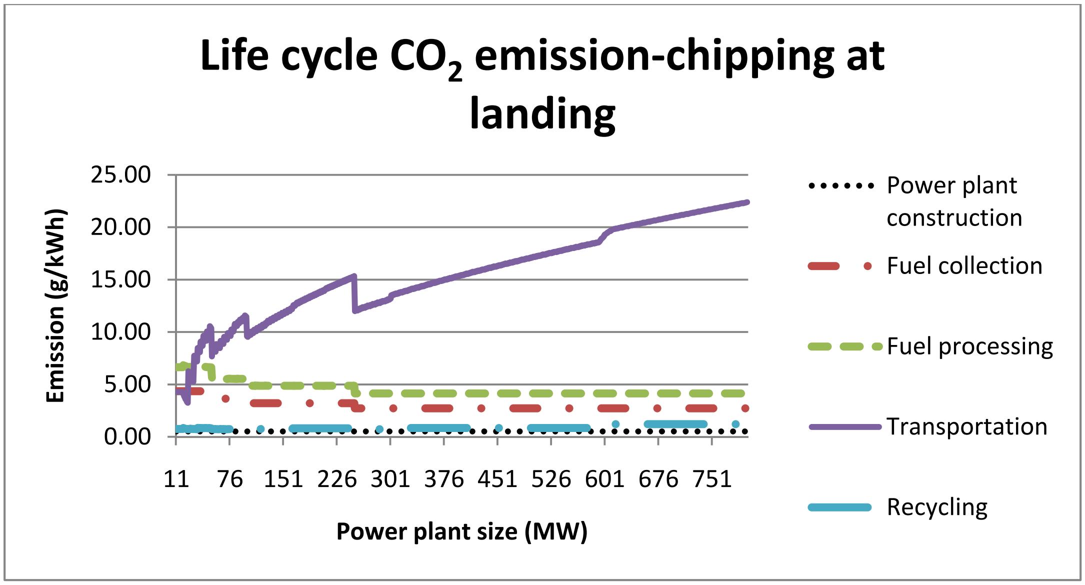

Figure 4-6: Impact of plant size on emissions (gCO2/kWh) for option 1

Few points are worth noting at this stage. For plant size less than 250 MW Figure 4-5 and Figure 4-6 show stepwise decrease in life cycle emissions for fuel collection and fuel processing. This stepwise decrease is due to the increase in plant efficiency with increasing the plant size as shown in Table 4-8. The reason is same as explained earlier in case of variation of energy consumption with size of the plant. When number of equipment operated per year for a given unit process is estimated, the next nearest integer is considered because this numbers can never be fractional. Hence, for a range of power plants same number of equipment is possible. This results in the saw-tooth nature of the curve as shown in Figure 4-5 and Figure 4-6.

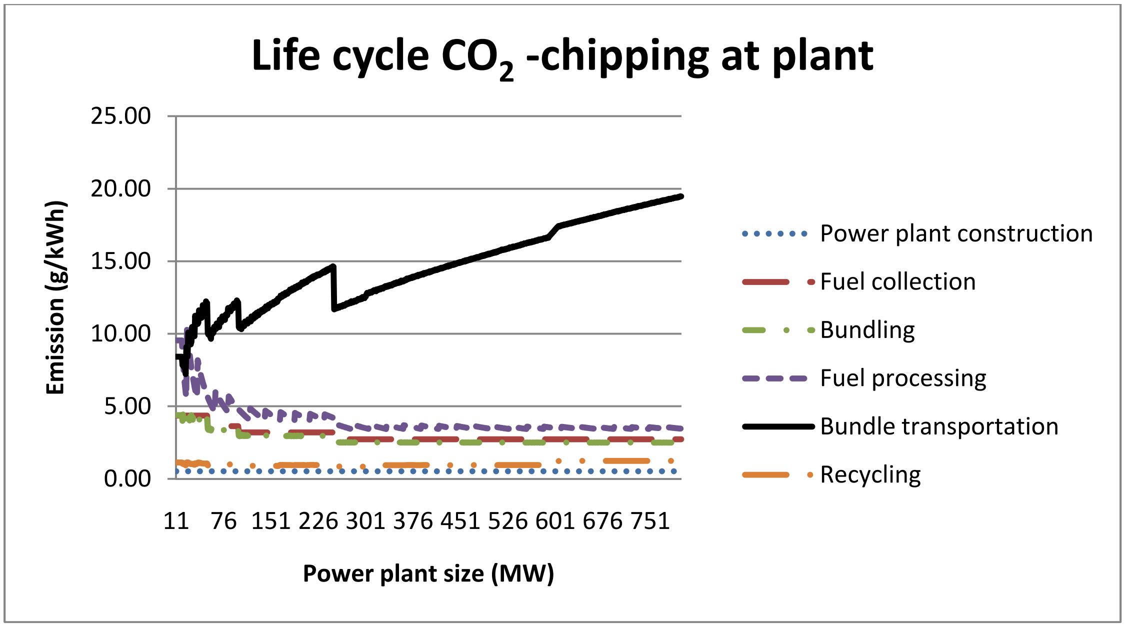

Figure 4-7: Impact of plant size on per unit emission for option 2

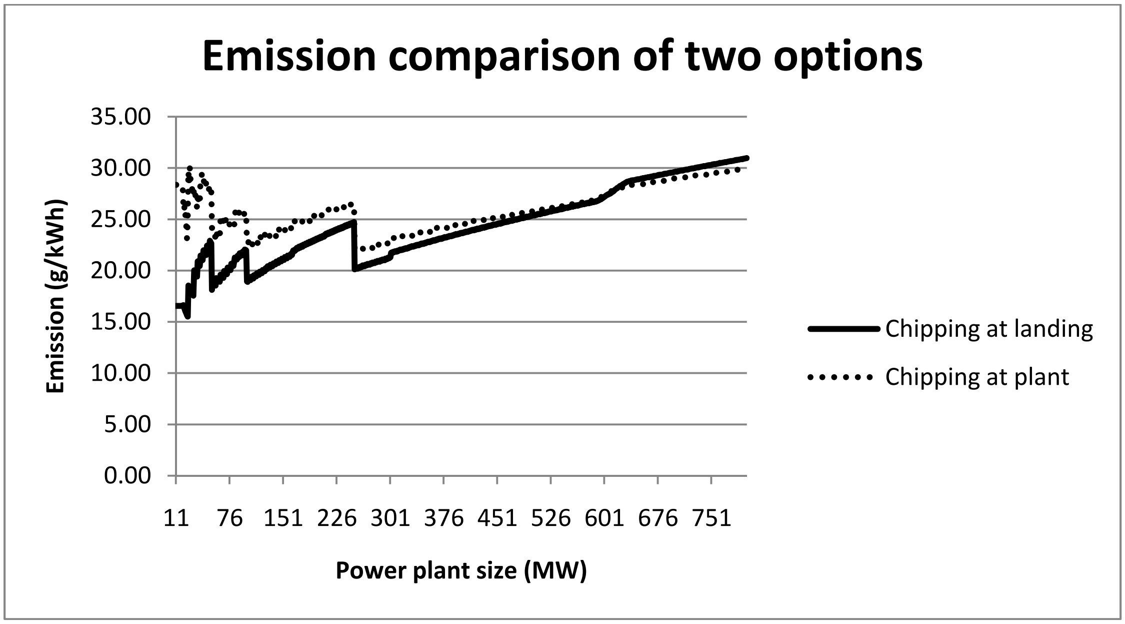

Figure 4-8: Overall LCA emissions (gCO2 per kWh)

If only transportation is compared for both the options of fuel transport than for smaller size plant, option 1 (chipping at landing) emits less CO_2 per unit power generated compared to option 2 (chipping at plant). For this unit process, estimated emissions of CO_2 per unit power output are approximately same at 150 MW for the options. Plant size greater than 150 MW emits less in option 2 than option 1 for transportation. This is the only reason for gap reduction in emissions of CO_2 per unit for higher size plant. For other unit processes like fuel collection, processing etc. the emissions (gCO_2/kWh) are higher for smaller size plant (<100 MW) and remains constant for larger size plant.

4.4.3 Effect of moisture content

Moisture content impacts the life cycle energy consumption and emissions for the two options. The above result presented was based on harvesting residue moisture content of 47% (wet basis). This is the average moisture content of roadside logging residues in Alberta (MacDonald, 2009). Some of the findings of impact of moisture content are worth noting here. For given moisture content, increase in power plant size show increase in overall emissions (gCO_2/kWh). For a given plant size, higher moisture content results in higher emissions per unit of electricity generation. The same results were also found for energy consumption. Figure 8 shows how emissions (gCO_2/kWh) changes with changing moisture content of logging residues from 15% to 50% at theoretical optimum as well as at 300 MW for both option of fuel supply. For plant size of 300 MW, graphs of option 1 lies below option 2. This is because as mentioned above for small size power plant, option 2 emits more than option 1. The difference in emission level is found to be 10.5% at moisture content of 15% and decreases to 5.7% at moisture content 50%. However, at theoretical maximum size the graphs almost coincide for both the options. The difference in emissions level found to be less than 0.5% with graph of option 2 slightly below option 1. This happens because for higher size of power plant option 2 emits less than option 1 due to increase in the efficiency of the processing equipment.

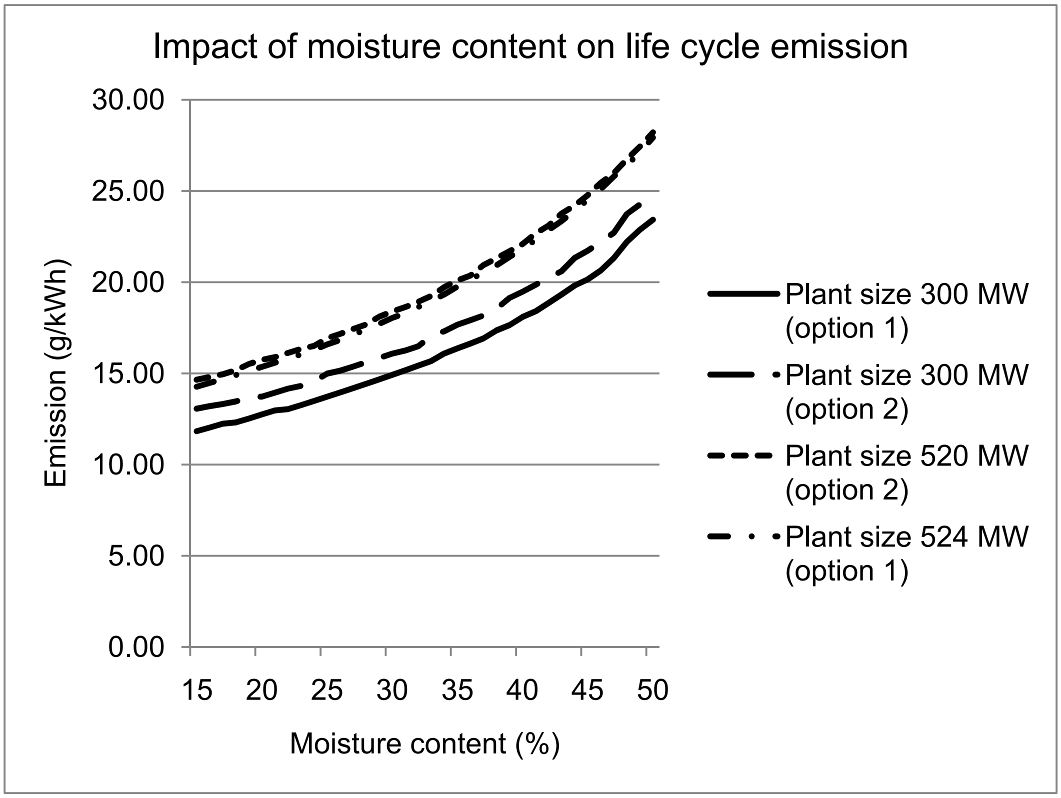

Figure 4-9: Moisture content effect on life cycle emissions

4.4.4 Abatement Cost

As mentioned in Chapter 3, power production using harvesting residues is not cost competitive with coal based power generation. Power based on forest harvest residue could become competitive with the help of carbon credits. Abatement cost is defined as

	$Carbonabatementcost(\$/tCO_2) = \frac{C_{biomass} - C_{coal}}{LCE_{coal} - LCE_{biomass}}$	(4.1)

where,

$C_{biomass}$ = cost of producing electricity using biomass ($/MWh)

C_{coal} = cost of producing electricity using coal ($/MWh)

$LCE_{biomass}$ = life cycle emissions for producing electricity from biomass (tCO_2/MWh)

LCE_{coal} = life cycle emissions for producing electricity from coal (tCO_2/MWh)

A life cycle emission for producing electricity using biomass was discussed in detail in previous sections of this chapter. $LCE_{biomass}$ highly depends upon the size of power plant as shown in Figure 4-4. The results presented exclude the emissions during logging residues production. To estimate these emissions, information provided by Berg et al. (2003) was used. It was estimated to be 1.86 gCO_2 per oven dry tonne of logging residues produced and with 20% of this is allocated to forest residues based on the assumption that forest residues constitute only 20% of the whole tree biomass. This is equivalent to 0.93 gCO_2/kWh for plant size greater than 250 MW. These emissions could be higher for smaller size plant due to efficiency. Average LCE_{coal} is given in Table 4-10 for different unit processes of electricity generation (Spath et al., June 1999).

Table 4-10: Life cycle emissions from coal based power generation

CO_2 from power generation subsystem (g/kWh)	**CO_2 from transportation (g/kWh)**	**CO_2 from surface mining (g/kWh)**	**Total CO_2 emissions (g/kWh)**
996	17	9	1022

Power price is highly volatile and depends upon several factors including peak or off peak demand. The average pool price of electricity in 2009 was \$48 /MWh with price as high as \$1000 /MWh and as low as \$0.1 /MWh (Alberta Electric System Operator). Figure 4-9 shows abatement cost required for various C_{coal} in case of in-wood chipping option of power generation using forest residues.

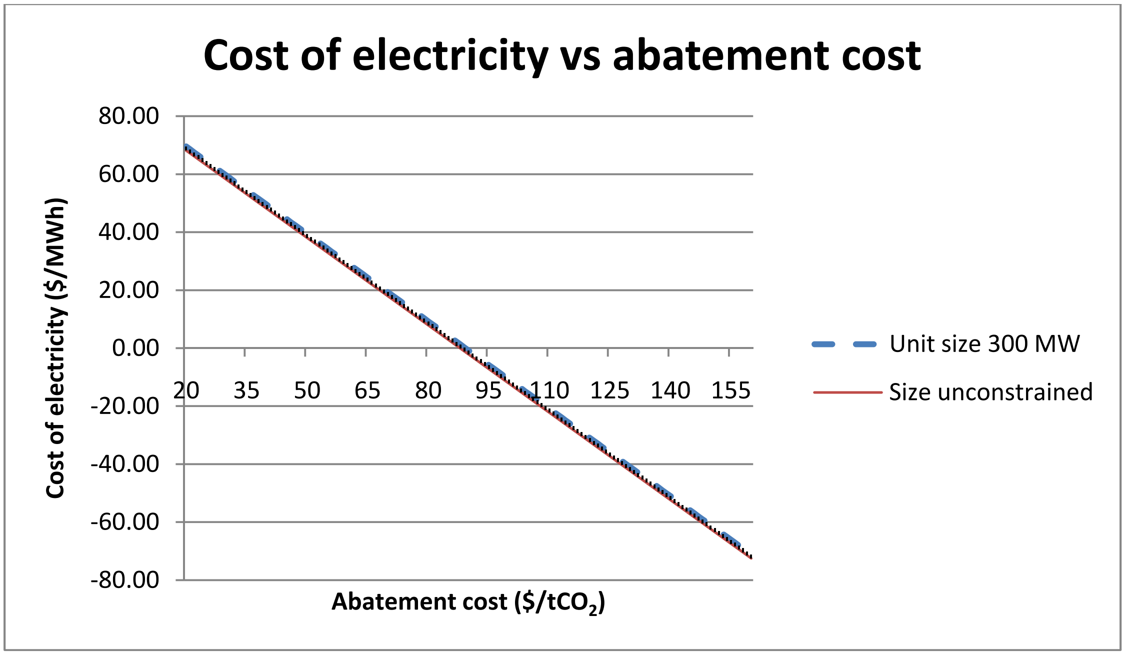

Figure 4-10: Carbon abatement cost as a function of average electricity price for in wood chipping

Figure 4-10 shows abatement cost required for various C_{coal} in case of chipping at plant power generation method. At average price of $60 /MWh, abatement cost found to be $28.17 /t$CO_2$ and $29.56 /t$CO_2$ for unconstrained size and unit size 300 MW in case of in wood chipping respectively. The same cost was $41.53 /t$CO_2$ and $42.90 /t$CO_2$ for chipping at plant respectively.

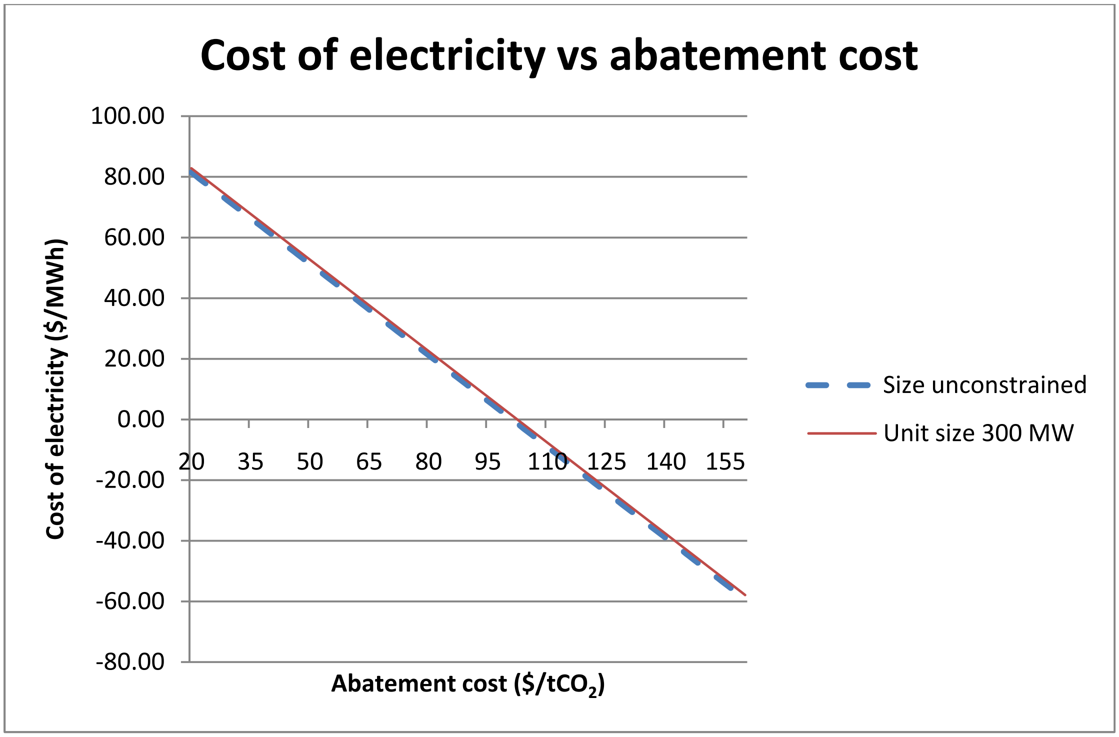

Figure 4-11: Carbon abatement cost as a function of average electricity price for chipping at plant

4.5 Conclusions

Fuel can be supplied to a power plant using two supply chains. The two supply chains mainly differ in form of fuel transportation to the power plant. In Option 1 the harvesting residues are collected, piled and chipped at roadside site and chips are transported to the power plant. In option 2 harvesting residues are collected, piled and bundled and these bundles are transported to the power plant where these are chipped before combustion. Option 1 requires less energy input and lower emissions when compared with option 2 of transporting bundle to plant site at 300 MW. At their theoretical optimal size (524 MW for option 1 and 520 MW for option 2) energy consumption and emissions are almost the same. Bundling of the logging residues provides higher density of fuel supply during transportation. Energy consumption and emissions in option 2 are lower compared to option 1 for plant size greater than 550 MW. The difference between overall energy consumption and emissions are much higher for smaller sized plant. This is mainly due to extra energy consumption and emissions of bundling process in option 2. The gap between the two options is reduced as the plant size increases. This is because there is less energy consumption and emissions during transportation of option 2 than option 1.

Option 1 consumes about 3% and 2.5% of energy at 524 MW and 300 MW plant size during life time operation of plant. The total life cycle CO_2 emissions for the same were 26 gCO_2/kWh and 21 gCO_2/kWh, respectively. Options 2 require about 3% and 2.6% of energy at 520 MW and 300 MW, respectively. Total life cycle CO_2 emissions for the same were 26 gCO_2/kWh and 23 gCO_2/kWh, respectively.

For power plant with smaller capacity, the gap between the total life cycle energy consumption and emissions remained significant between both the fuel supply options. The gap decreases as the size of power plant increases. Higher efficiency of power plant significantly reduces the overall life cycle per unit emissions and energy consumption. This reduction in gap is mainly due to saving more energy and less emission during transportation in option 2.

Abatement cost help biomass power production cost competitive with coal. This cost linearly depends upon cost of coal based electricity generation. At average price of \$60 /MWh, abatement cost found to be \$28.17 /tCO_2 and \$29.56 /tCO_2 for unconstrained size and unit size 300 MW in case of in wood chipping respectively. The same cost was \$41.53 /tCO_2 and \$42.90 /tCO_2 for chipping at plant respectively.

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5 Conclusions and Recommendations for Future Work

This research analyzes various aspects of power production by utilizing forest harvesting residues in Alberta. Removal of harvesting residues causes net nutrients export from forest, hence impacts the forest ecosystem. Most of the nutrients are found in branches, twigs and leaves of the tree. The issue of nutrient removal becomes especially important in case of reforestation. Nutrient balance approach (net export – net import) were used to estimate the amount to be returned to the forest when forest residues are removed from the forest for energy production. Recycling of ash from the power plant is one of the options which can be implemented to address this issue. A data intensive techno-economic assessment model of ash recycling was presented including pros and cons of ash utilization. Two methods of harvesting residue supply as fuel were discussed and analyzed. Option one followed collection, piling, chipping, and chip transportation to the power plant whereas option two followed collection, piling, bundling, bundle transportation, and chipping of bundles at the power plant. Techno-economic models were developed for both the options of fuel supply and optimum size of power plant utilizing these residues with corresponding power generation costs. Sensitivity of optimum size and power generation costs towards various factors and moisture content of fuel were also assessed. The power generation process requires various energy inputs at different unit processes. The energy inputs to equipment manufacturing and their operation at each of the unit process were estimated. Finally life cycle emissions and abatement costs of power generation from harvesting residues were estimated.

5.1 Optimal Size and Generation Cost for In-wood chipping

One of the options of fuel supply considered in this analysis is forest residues collection, piling, chipping along roadside, and chip transportation to a power plant. Standard B-train chip van is utilized for chip transportation. The cost of biomass fuel supply increases with increase in power plant size. However, due to economy of scale, capital investment per unit output decreases with increase in the power plant size. Hence, there exists a point where theoretical minimum power generation cost occurs. The theoretical optimum size estimated in this case is 524 MW with the corresponding power generation cost of $74.21 /MWh. However, a range of power plant sizes exists (336 MW – 810 MW) between first $75 /MWh to $150 /MWh cost.

Capital cost contributed about 41% of total power generation cost followed by transportation cost (~25%), maintenance cost (~9%) and chipping cost (~7%), respectively. Any unit size of boiler less than the above theoretical size becomes the limiting factor for optimal sizing. At 300 MW the estimated generation cost was $75.5 /MWh. Moisture content plays an important role during estimation of optimum size and generation cost. The theoretical optimum size increases to 721 MW with generation cost of $67.84 /MWh at a fuel moisture content level of 15%. The cost estimated cost was found to be more sensitive towards capital cost, transportation cost and pre-tax return parameters.

5.2 Optimal Size and Generation Cost – Chipping at Plant

The other fuel supply option considered in this study is the bundling of biomass in the forest. In this method roadside logging residues after collection and piling are bundled into Compressed Residue Logs (CRL). The purpose of this bundling is to have increased weight of biomass transportation per unit distance. CRL can be transported using standard log haul trucks and a stationary high capacity chipper can be utilized for biomass fuel processing at the plant. For this method, the estimated theoretical optimum size of the power plant was 720 MW with corresponding power generation cost of $87.29 /MWh. Similar to in-wood chipping a range of power plant existed (341 MW – 789 MW) between cost of power in the range of $88 /MWh to $176 /MWh. Capital cost contribution was highest (~35%) followed by transportation cost (~29%), bundling cost (~16.5%), maintenance cost (~10.4%), and chipping cost (~6.3%). Power generation cost at 300 MW was $88.54 /MWh. Moisture content played an important role in determining optimal size as well as power generation cost. Theoretical optimum size of the power can reach as high as 886 MW with generation cost $76.45 /MWh at fuel moisture content level of 15%. Pretax return had highest impact on generation cost followed by capital cost and fuel transportation cost, respectively.

5.3 Comparison of Two Power Generation Options

The two options of power generation differ in their mode of fuel supply to the power plant. In the case of in-wood chipping, chip has to be transported to plant using a chip van. The amount of energy transported per unit distance at given moisture content depends upon two important fuel properties: bulk density and heating value. Given the same moisture content and heating, higher bulk density means higher energy will be transported per unit distance. In case use of logging residues as fuel, the purpose of bundling is to increase the bulk density of fuel in comparison with chips. Another purpose of bundling is the utilization of higher capacity chippers at plant for reduction of chipping cost. However, bundling operation itself incurs some cost which is about $14 /MWh. Our analysis as presented in chapter 3 shows there is not much difference in optimal sizes in either options of fuel supply. The theoretical optimal size in case of bundle transportation found to be 520 MW whereas in case of chip transportation it was 524 MW for the case when there is no constraint on the unit size of the boiler. However, their power generation cost differed significantly. Power generation costs in case of bundle transportation were $87.29 and $88.54 /MWh at power plant sizes of 520 MW and 300 MW, respectively. Similarly, in the case of chip transportation the costs were $74.21 and $75.5 /MWh at power plant sizes of 524 MW and 300 MW, respectively. The generation cost differs by an amount of 17.6% at theoretical optimum size. Capital and transportation costs contribute to majority of the generation cost in both the fuel supply cases. However capital and transportation costs contributions in case of in-wood chipping were 6.86% and 14.38% more than the chipping at plant case, respectively. A range of power plant sizes around theoretical optimum existed within 1% change of generation cost in both fuel supply cases. Transportation distances at optimal plant sizes were same because it only depends upon the biomass availability and fuel moisture content. The moisture content of the fuel has significant impact on the generation cost as well as optimal size in both the cases of fuel supply. The power generation cost can go to as low as $67.84 /MWh with higher optimal size of 721 MW for in-wood chipping at 15% moisture content. This can be $76.45 /MWh with optimal size of 886 MW at moisture content of 15% in case of bundling. Amount of nutrients exported from forest and ash recycling cost was independent of mode of transportation of fuel supply. Energy consumption and emissions were higher for the bundling option for plant size less than 500 MW when compared with in-wood chipping option. In case of in-wood chipping, about 2.95% and 2.44% of energy is consumed at 524 MW and 300 MW plant size during life time operation of plant. The total life cycle CO_2 emissions for the same were 25.79 gCO_2/kWh and 21.32 gCO_2/kWh, respectively. In case of bundling, it requires about 2.97% and 2.59% of energy at power plant sizes of 520 MW and 300 MW, respectively. Total life cycle CO_2 emissions for the same were 25.97 and 22.70 gCO_2/kWh, respectively.

5.4 Carbon Credit Required

Abatement cost linearly depends upon the cost of coal-based electricity generation. Significant differences of abatement costs were found between the two options at a given cost of coal based electricity generation. At average price of $60 /MWh, abatement cost found to be $28.17 /$tCO_2$ and $29.56 /$tCO_2$ for unconstrained size and unit size 300 MW in case of in wood chipping respectively. The same cost was $41.53 /$tCO_2$ and $42.9 /$tCO_2$ for chipping at plant respectively.

5.5 Recommendations for Future Work

In this study, a techno-economic assessment of power generation from available logging residues was investigated for western Canada. Two modes of fuel supply option, bundle transportation and chip transportation were considered for estimating the power generation cost and optimal size. However, several scopes for future research to reduce the generation cost and identify optimal size still exists. Some opportunities for future research are given below:

- Capital cost contributes to the majority of generation cost. A research in the area of technological advancement of direct biomass combustion will have significant impact on generation cost. This will be particularly helpful if capital cost of biomass based power plant is reduced to the level of capital cost of coal based power plant.
- Transportation cost is a major contributor to the total power generation cost. It might be interesting to investigate other modes of low transportation cost like pipeline transportation, train transportation or train and truck transportation, and identify optimal plant size and corresponding generation cost.

- The total delivered biomass cost ($/GJ) is much higher if compared with any fossil fuel delivered fuel cost. It might be interesting to investigate the impact on optimal sizing and generation cost if biomass fuel supply chain is integrated with logging operation.

- Fuel moisture content had large impact on optimal sizing and generation. No experimental data is available for western Canada about change of moisture content of fuel as a function of time. Hence, experimental work to identify logging residues moisture content as function of time since harvested could be performed to determine most economical biomass harvesting time during the year.
- More thorough assessment of uncertainties and possible sources of error would be an important addition to this research work.

Appendix A: Summary of chipping and transportation cost calculation.

Chipping cost for in wood chipping and chipping at landing method is explained in table A-1. Costs are estimated from data cited from various literatures. The methodology used for calculation is taken from FERIC (Desrochers et al., 1993; ALPAC, 2006; MacDonald 2006). All the cost presented is Canadian dollars in 2009. Hence, the cost given in literatures for different point of time adjusted for inflation and currency conversion.

Table A-1: Chipping cost for in-wood and at plant chipping

Fixed Cost	**Beast 3680 (in-wood)**	**Beast 4680 (at plant)**	**Loader**
Ownership Cost			
Purchase price (P)	350,000	800,000	350,000
Salvage value (S)	70,000	160,000	73,500
Expected life (y)	5	5	7
Schedule machine hour per year (h)	2,000	2,000	2,000
Interest rate (i)	10%	10%	10%
Insurance rate (I)	1.50%	1.50%	1.50%
Average investment (AVI)	210,000	480,000	211,750
Hourly ownership cost ($/hr)			
Loss in resale value($/hr)	28	64	19.75
Interest	10.50	24.00	10.59
Insurance	1.58	3.60	1.59
Total hourly ownership cost	**40.08**	**91.6**	**31.93**
Operating and repair cost ($/hr)			
Fuel consumption (F)	85	125	22.71
Fuel cost (f)	1.01	1.01	1.01
Annual repair & maintenance (R)	16%	16%	26%
Track/tire replacement cost (T)	0	0	35,000

Fixed Cost	**Beast 3680 (in-wood)**	**Beast 4680 (at plant)**	**Loader**
Track/tire life	0	0	5,000
Wages	27.4	27.5	24
Other benefit	22%	22%	22%
Hourly Operating and Repair Cost($/hr)			
Fuel cost (FC)	85.85	126.25	22.94
Lube and oil cost	20%	20%	20%
Repair & maintenance cost	28	64	45.5
Track/tire cost			7.00
Labour cost (LC)	27.4	27.5	29.28
Total hourly operating & repair costs	141.25	217.75	104.72
Total costs	181.33	309.35	136.65
Total hourly ownership cost	40.08	91.60	31.93
Total hourly operating & repair costs	141.25	217.75	104.72
Net	170.83	285.35	126.06
Availability	90%	90%	90%
Total	**195.64**	**330.39**	**144.23**
Productivity (Odt/hr)	30	70	
Cost per Odt	**6.52**	**4.72**	

Table A-2: Chip and bundle transportation cost

Fixed Cost	Log Haul Truck	B-train chip van
Ownership Cost		
Purchase Price (P)	316724	137768
Salvage Value (S)	66512.04	28931.28
Expected Life (y)	5	5
Annual Utilization per year (km)	160000	160000
Interest Rate (i)	10%	10%
Insurance Rate (I)	1.50%	1.50%
Average Investment (AVI)	191618.02	83349.64
Hourly Ownership Cost ($/km)		
Loss in resale value($/km)	0.31276495	0.1360459
Interest	10%	10%
Insurance	1.5%	1.5%
Total hourly ownership cost	**0.45**	**0.20**
Operating and repair cost ($/hr)		
Fuel Consumption (F) (liter/km)	0.62	0.44
Fuel Cost (f)	1.01	1.01
Annual repair & Maintenance (R) %of P	17%	17%
Track/Tire replacement cost (T)	31672.4	13776.8
Track/Tire Life	600000	600000
Wages ($/km)	0.3	0.28
Other benefit	22%	22%
Hourly Operating and Repair Cost($/km)		
Fuel Cost (FC)	0.6262	0.4444
Lube and Oil Cost	20%	20%
Repair &Maintenace Cost	0.33651925	0.1463785
Track/Tire Cost	0.05	0.02
Labour Cost (LC)	0.366	0.3416
Total ($/km)	**2.03**	**1.28**

Appendix B: Nutrient balance table calculation methodology

Table B-1 below describes the methodology used to calculate nutrient balance. The table estimates N and S requirements at moisture content of 47%. The base case moisture content is considered because change of this variable will change the amount of biomass required (tonnes/yr) for 300 MW plant size. Increase in biomass requirement means larger area will be harvested. A larger area will increase natural deposition of N and S.

Table B-1: Methodology for calculation of nutrient balance

Items	Nitrogen	Sulfur	Calculation method
N and S distribution (A)	2.85%	815 mg per dry kg of biomass	
Annual dry tonnes biomass required at 300 MW (B)	1,165,123		Assuming 85% capacity factor.
Nutrient export from forest (C)	33,206 tonnes per year	949.6 tonnes per year	A×B
Annual electricity generation (D)	2,233,800 MWh		
Nutrient export from forest (kg/MWh) -N_e	15.88	0.45	C÷D
N and S atmospheric deposition (E)	7.5 kg/ha/yr	1.1 kg/ha/yr	
Area harvested each year (F)	5,246,900 ha	5,246,900 ha	
Natural nutrient import – N_i	26.59 kg/MWh	3.9 kg/MWh	E×F÷D
Fertilization cost ($/MWh)	0	0	Since import is greater than export.

Appendix C: Summary of cash flows (in $'1000)

Table C-1: Summary of discounted cash flow of forest residue for chipping at landing method at optimum size

Year	-2	-1	0	1	2	3	4
Capital Cost	375,236	375,236	187,618	-	-	-	-
Operation Cost (includes admin)				3,062	3,124	3,186	3,250
Maintenance Cost				28,143	28,706	29,280	29,865
Administrative Cost				-	-	-	-
Chipping Cost				17,559	20,469	22,183	22,627
Transp. Cost				59,067	72,817	80,962	82,581
Roads & Infras.				-	-	-	-
Silvil. Cost				-	-	-	-
Nutrient Replacement				4,967	5,677	6,032	6,152
Miscellaneous Cost				0	0	0	0
Transmission charge					-	-	-
Site recovery and reclamation cost				-	-	-	-
Salvage Value				-	-	-	-
Ash Disposal							
Total Costs	375,236	375,236	187,618	112,799	130,792	141,642	144,475
pv of total costs at 10%	454,035	412,759	187,618	102,544	108,093	106,418	98,678
MWH produced				3,066,000	3,504,000	3,723,000	3,723,000
revenue required for 10% return				227,324	231,871	236,508	241,239
pv of revenue at 10%				206,659	191,629	177,692	164,769

Table C-1 (continued)

	5	6	7	8	9	10	11	12
Capital Cost	0	0	0	0	0	0	0	0
Operation Cost	3,315	3,381	3,449	3,518	3,588	3,660	3,733	3,808
Maintenance Cost	31,553	32,184	32,827	33,484	34,154	34,837	35,534	36,244
Chipping Cost	24,187	24,671	25,164	25,667	26,181	26,704	27,238	27,783
Transp. Cost	90,048	91,849	93,686	95,560	97,471	99,420	101,409	103,437
Roads &Infras.	0	0	0	0	0	0	0	0
Silvil. Cost	0	0	0	0	0	0	0	0
Nutrient Replacement	6,109	6,231	6,355	6,483	6,612	6,745	6,879	7,017
Miscellaneous Cost	0	0	0	0	0	0	0	0
Transmission charge	0	0	0	0	0	0	0	0
Site recovery and reclamation cost	0	0	0	0	0	0	0	0
Salvage Value	0	0	0	0	0	0	0	0
Ash Disposal	0	0	0	0	0	0	0	0
Total Costs	155,211	158,315	161,482	164,711	168,006	171,366	174,793	178,289
pv of total costs at 10%	96,374	89,365	82,866	76,839	71,251	66,069	61,264	56,808
MWH produced	3,901,704	3,901,704	3,901,704	3,901,704	3,901,704	3,901,704	3,901,704	3,901,704
revenue required for 10% return	257,874	263,032	268,292	273,658	279,131	284,714	290,408	296,217
pv of revenue at 10%	160,120	148,475	137,676	127,664	118,379	109,770	101,786	94,384

Table C-1 (continued)

	13	14	15	16	17	18	19	20
Capital Cost	0	0	0	0	0	0	0	0
Operation Cost	3,884	3,962	4,041	4,122	4,204	4,288	4,374	4,461
Maintenance Cost	36,969	37,708	38,463	39,232	40,017	40,817	41,633	42,466
Chipping Cost	28,339	28,905	29,484	30,073	30,675	31,288	31,914	32,552
Transp. Cost	105,506	107,616	109,768	111,963	114,203	116,487	118,817	121,193
Roads &Infras.	0	0	0	0	0	0	0	0
Silvil. Cost	0	0	0	0	0	0	0	0
Nutrient Replacement	7,157	7,300	7,446	7,595	7,747	7,902	8,060	8,222
Miscellaneous Cost	0	0	0	0	0	0	0	0
Transmission charge	0	0	0	0	0	0	0	0
Site recovery and reclamation cost	0	0	0	0	0	0	0	0
Salvage Value	0	0	0	0	0	0	0	0
Ash Disposal	0	0	0	0	0	0	0	0
Total Costs	181,855	185,492	189,202	192,986	196,845	200,782	204,798	208,894
pv of total costs at 10%	52,677	48,846	45,293	41,999	38,945	36,112	33,486	31,051
MWH produced	3,901,704	3,901,704	3,901,704	3,901,704	3,901,704	3,901,704	3,901,704	3,901,704
Price required for 10% return								
revenue required for 10% return	302,141	308,184	314,347	320,634	327,047	333,588	340,260	347,065
pv of revenue at 10%	87,519	81,154	75,252	69,779	64,705	59,999	55,635	51,589

Table C-1 (continued)

	21	22	23	24	25	26	27	28	29	30
Capital Cost	0	0	0	0	0	0	0	0	0	0
Operation Cost	4,551	4,642	4,734	4,829	4,926	5,024	5,125	5,227	5,332	5,438
Maintenance Cost	43,315	44,181	45,065	45,966	46,886	47,823	48,780	49,756	50,751	51,766
Chipping Cost	33,203	33,867	34,545	35,236	35,940	36,659	37,392	38,140	38,903	39,681
Transp. Cost	123,617	126,089	128,611	131,183	133,807	136,483	139,213	141,997	144,837	147,733
Roads &Infras.	0	0	0	0	0	0	0	0	0	0
Silvil. Cost	0	0	0	0	0	0	0	0	0	0
Nutrient Replacement	8,386	8,554	8,725	8,899	9,077	9,259	9,444	9,633	9,825	10,022
Miscellaneous Cost	0	0	0	0	0	0	0	0	0	0
Transmission charge	0	0	0	0	0	0	0	0	0	0
Site recovery and reclamation cost	0	0	0	0	0	0	0	0	0	0
Salvage Value	0	0	0	0	0	0	0	0	0	0
Ash Disposal	0	0	0	0	0	0	0	0	0	0
Total Costs	213,072	217,333	221,680	226,113	230,636	235,248	239,953	244,753	249,648	254,641
pv of total costs at 10%	28,793	26,699	24,757	22,956	21,287	19,739	18,303	16,972	15,738	14,593
MWH produced	3,901,704	3,901,704	3,901,704	3,901,704	3,901,704	3,901,704	3,901,704	3,901,704	3,901,704	3,901,704
revenue required for 10% return	354,006	361,086	368,308	375,674	383,188	390,851	398,668	406,642	414,775	423,070
pv of revenue at 10%	47,837	44,358	41,132	38,141	35,367	32,795	30,410	28,198	26,147	24,246

Table C-2: Summary of discounted cash flow of forest residue for chipping at plant method at optimum size

Year	-2	-1	0	1	2	3	4
Capital Cost	386,438	386,438	193,219	-	-	-	-
Operation Cost				3,047	3,108	3,171	3,234
Maintenance Cost (including admin)				28,983	29,562	30,154	30,757
Administrative Cost				-	-	-	-
Chipping Cost				14,645	17,072	18,502	18,872
Transp. Cost				62,765	77,394	86,059	87,781
Roads & Infras.				-	-	-	-
Silvil. Cost				-	-	-	-
Nutrient Replacement				5,177	5,916	6,286	6,412
Miscellaneous Cost				0	0	0	0
Bundling Cost				37,870	44,145	47,842	48,799
Site recovery and reclamation cost				-	-	-	-
Salvage Value				-	-	-	-
Ash Disposal							
Total Costs	386,438	386,438	193,219	152,487	177,199	192,014	195,854
pv of total costs at 10%	467,589	425,081	193,219	138,625	146,445	144,263	133,771
MWH produced				3,188,640	3,644,160	3,871,920	3,871,920
revenue required for 10% return				278,073	283,635	289,308	295,094
pv of revenue at 10%				252,794	234,409	217,361	201,553

(costs are in $'1000)

Table C-2 (continued)

Year	5	6	7	8	9	10	11	12	13
Capital Cost	-	-	-	-	-	-	-	-	-
Operation Cost	3,299	3,365	3,432	3,501	3,571	3,642	3,715	3,789	3,865
Maintenance Cost (including admin)	31,372	31,999	32,639	33,292	33,958	34,637	35,330	36,036	36,757
Administrative Cost	-	-	-	-	-	-	-	-	-
Chipping Cost	19,249	19,634	20,027	20,427	20,836	21,252	21,678	22,111	22,553
Transp. Cost	89,536	91,327	93,154	95,017	96,917	98,855	100,832	102,849	104,906
Roads & Infras.	-	-	-	-	-	-	-	-	-
Silvil. Cost	-	-	-	-	-	-	-	-	-
Nutrient Replacement	6,540	6,671	6,804	6,941	7,079	7,221	7,365	7,513	7,663
Miscellaneous Cost	0	0	0	0	0	0	0	0	0
Bundling Cost	49,775	50,771	51,786	52,822	53,878	54,956	56,055	57,176	58,319
Site recovery and reclamation cost	-	-	-	-	-	-	-	-	-
Salvage Value	-	-	-	-	-	-	-	-	-
Ash Disposal									
Total Costs	199,771	203,767	207,842	211,999	216,239	220,563	224,975	229,474	234,064
pv of total costs at 10%	124,042	115,021	106,656	98,899	91,706	85,037	78,852	73,118	67,800
MWH produced	3,871,920	3,871,920	3,871,920	3,871,920	3,871,920	3,871,920	3,871,920	3,871,920	3,871,920
revenue required for 10% return	300,996	307,015	313,156	319,419	325,807	332,323	338,970	345,749	352,664
pv of revenue at 10%	186,895	173,302	160,698	149,011	138,174	128,125	118,807	110,166	102,154

Table C-2 (continued)

Year	14	15	16	17	18	19	20
Capital Cost	-	-	-	-	-	-	-
Operation Cost	3,942	4,021	4,101	4,184	4,267	4,353	4,440
Maintenance Cost (including admin)	37,492	38,242	39,007	39,787	40,583	41,395	42,222
Administrative Cost	-	-	-	-	-	-	-
Chipping Cost	23,004	23,464	23,934	24,412	24,901	25,399	25,907
Transp. Cost	107,004	109,144	111,327	113,554	115,825	118,141	120,504
Roads & Infras.	-	-	-	-	-	-	-
Silvil. Cost	-	-	-	-	-	-	-
Nutrient Replacement	7,816	7,972	8,132	8,295	8,460	8,630	8,802
Miscellaneous Cost	0	0	0	0	0	0	0
Bundling Cost	59,486	60,675	61,889	63,127	64,389	65,677	66,991
Site recovery and reclamation cost	-	-	-	-	-	-	-
Salvage Value	-	-	-	-	-	-	-
Ash Disposal							
Total Costs	238,745	243,520	248,390	253,358	258,425	263,594	268,866
pv of total costs at 10%	62,869	58,297	54,057	50,126	46,480	43,100	39,965
MWH produced	3,871,920	3,871,920	3,871,920	3,871,920	3,871,920	3,871,920	3,871,920
revenue required for 10% return	359,718	366,912	374,250	381,735	389,370	397,157	405,100
pv of revenue at 10%	94,725	87,836	81,448	75,524	70,032	64,938	60,216

Table C-2 (continued)

Year	21	22	23	24	25	26	27	28	29	30
Capital Cost	-	-	-	-	-	-	-	-	-	-
Operation Cost	4,528	4,619	4,711	4,806	4,902	5,000	5,100	5,202	5,306	5,412
Maintenance Cost (including admin)	43,067	43,928	44,807	45,703	46,617	47,549	48,500	49,470	50,460	51,469
Administrative Cost	-	-	-	-	-	-	-	-	-	-
Chipping Cost	26,425	26,953	27,492	28,042	28,603	29,175	29,759	30,354	30,961	31,580
Transp. Cost	122,914	125,372	127,880	130,437	133,046	135,707	138,421	141,190	144,013	146,894
Roads & Infras.	-	-	-	-	-	-	-	-	-	-
Silvil. Cost	-	-	-	-	-	-	-	-	-	-
Nutrient Replacement	8,978	9,158	9,341	9,528	9,718	9,913	10,111	10,313	10,520	10,730
Miscellaneous Cost	0	0	0	0	0	0	0	0	0	0
Bundling Cost	68,330	69,697	71,091	72,513	73,963	75,442	76,951	78,490	80,060	81,661
Site recovery and reclamation cost	-	-	-	-	-	-	-	-	-	-
Salvage Value	-	-	-	-	-	-	-	-	-	-
Ash Disposal										
Total Costs	274,243	279,728	285,322	291,029	296,849	302,786	308,842	315,019	321,319	327,746
pv of total costs at 10%	37,059	34,363	31,864	29,547	27,398	25,405	23,558	21,844	20,256	18,783
MWH produced	3,871,920	3,871,920	3,871,920	3,871,920	3,871,920	3,871,920	3,871,920	3,871,920	3,871,920	3,871,920
revenue required for 10% return	413,202	421,466	429,896	438,494	447,264	456,209	465,333	474,640	484,132	493,815
pv of revenue at 10%	55,836	51,775	48,010	44,518	41,281	38,278	35,495	32,913	30,519	28,300

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