Biomass Energy Potential of Forest Harvest Residue in Northwestern Ontario

by

Maxime J Normand

Faculty of Natural Resources Management
Lakehead University
Thunder Bay, Ontario

April 17th 2020

Biomass Energy Potential of Forest Harvest Residue in Northwestern Ontario

by

Maxime J Normand

An Undergraduate Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of Honours Bachelor of Science in Forestry

Faculty of Natural Resources Management

Lakehead University

April 17th 2020

-- ------------------------------------

Dr. Mathew Leitch Dr. Reino Pulkki

Major Advisor Second Reader

LIBRARY RIGHTS STATEMENT

Date: __April 17, 2020___________

A CAUTION TO THE READER

This HBScF thesis has been through a semi-formal process of review and comment by at least two faculty members. It is made available for loan by the Faculty of Natural Resources Management for the purpose of advancing the practice of professional and scientific forestry.

The reader should be aware that opinions and conclusions expressed in this document ae those of the student and do not necessarily reflect the opinions of the thesis supervisor, the faculty or of Lakehead University.

ABSTRACT

Normand M, J. 2020. Biomass Energy Potential of Forest Harvest Residue in Northwestern Ontario 54pp.

Key Words: Biomass energy, Energy production, Availability, Thermal Potential, Economic Feasibility

Woody biomass contributes less than 6% of total energy production in Canada. Based on previous data relating to the supply, quality and economic potential, this compilation of relevant data provides an estimation on the available sustainable supply of woody biomass in Northwestern Ontario. This thesis explores the availability and thermal potential of biomass in the form of forest harvest residue and underutilized tree species in Northwestern Ontario and the potential for increased energy production at various existing facilities in the region. This study summarizes previously published data on availability, quality and economic feasibility of biomass acquisition in the region. It was estimated that there is 40.2m3/ha of available woody biomass feedstock throughout the study area, with an average thermal potential of 20.65 Mj/kg to 21.28 Mj/kg. These results indicate a sufficient supply with adequate thermal potential is readily available in the region. The total cost of procurement of biomass in the region averages 44-46$/gt, which indicates an economically feasible scale based on the technically available biomass. Summaries provided in this study quantify objective data on these objectives to determine the feasibility of increased biomass energy production in the region.

Contents

Table of Figures

List of Tables

ACKNOWLEDGEMENTS

I would like to thank my thesis supervisor Dr Mathew Leitch for his guidance and assistance he provided to make this thesis a reality. Thank you to my wonderful parents Anne and Jacques Normand for their unwavering support over the last 4 years to help me pursue my studies and dreams of becoming a professional lumberjack. I would also like to thank my girlfriend Mikaela and my roommates at 461 Darwin, I would have never dreamed of the support and the fun we've had during the course of my studies.

1.0 Introduction

Woody biomass is a relatively low greenhouse gas (GHG) emitting fuel source, which has the potential to replace or supplement fossil fuels in energy production. Seeing as woody biomass is a renewable resource, there is a unique opportunity to restructure energy production with a lower-emitting, renewable fuel source. Based on the current trends of increasing costs of fossil fuels and their environmental impact from a GHG emission standpoint, biomass energy could be a solution in the sense of economic and ecological impacts to mitigate these issues. Not only does it offset GHG emissions, but it also has the potential to provide local employment and economic growth. This thesis looks to examine the biomass potential of underutilized species and logging residues in the Thunder Bay district Region and Atikokan Region, and the feasibility of increased biomass energy production. Thermal properties, moisture content, road infrastructure, hauling configurations, inventory data and economic analysis from previous studies will be compiled to investigate the efficiency, availability, and feasibility of increased growth in the biomass energy sector in these regions.

2.0 Literature review

2.1 Tree species and Northern Region

Northern Ontario is home to the boreal forest, this region has warm, short, and relatively wet summers, and freezing, long and dry winters (MNRF 2019). A north-south gradient of increasing temperature is superimposed on a west-east gradient of increasing moisture (MNRF 2019). The landscape is primarily formed from various glacial geomorphology resulting in varied site conditions across the region (MNRF 2019). Merchantable species in this region are mostly White spruce, black spruce, jack pine, red pine, and a few other coniferous tree species, associated with deciduous taxa, dominate (MNRF 2019). Black spruce, the most common species, grows in a wide variety of ecological conditions but is particularly typical of wet lowlands. Sandplains and rocky ridges are typically occupied by jack pine, often with a mixture of black spruce. Mesic sites, on loam or fine sand, support mixed stands of trembling aspen (*Populus tremuloides*), white birch (*Betula papyrifera*), balsam fir (*Abies balsamea*) and black and white spruce (*Picea mariana* and *glauca,*). The Northwest Region contains portions of two forest regions: The Boreal Forest and the Great Lakes-St. Lawrence Forest (MNRF, 2019; NRC, 2016). The Boreal Forest, accounting for the majority of area in the Northwest Region, is characterized by extensive black spruce, jack pine, and balsam fir stands as well as mixed stands of conifer, poplar and white birch. The Great Lakes-St. Lawrence Forest, although smaller in size in the region, extends in a strip along the Ontario-Minnesota border west of Thunder Bay and contains a vast diversity of conifer and hardwood species, including white and red pine, red maple, yellow birch, and ash (MNRF 2019). The three significant species groupings that are used in the Northwest Region to portray commercial harvest volume information: spruce-pine-fir (SPF), poplar and white birch (Po Bw), and white and red pine (Pw Pr). Most of the forest industry in the region make products that fall into these groupings. Some of the products manufactured include SPF lumber, SPF pulp and paper (Northern Bleached Softwood Kraft), poplar lumber, poplar-oriented strand board, poplar laminated strand lumber, poplar pulp, and white or red pine lumber (MNRF 2019). Table 1 below displays the common tree species found in Northwestern Ontario.

Figure 1. Common tree species found in North Western Ontario (MNRO 1990)

Common Name	Scientific Name	Abbreviated Name
Balsam Fir	*Abies balsamea*	Bf
White Spruce	*Picea glauca*	Sw
Black Spruce	*Picea mariana*	Sb
Tamarack / Larch	*Larix laricina*	L
Jack Pine	*Pinus banksiana*	Pj
Red Pine	*Pinus resinosa*	Pr
White Pine	*Pinus strobus*	Pw
Eastern White Cedar	*Thuja occidentalis*	Ce
Balsam Poplar	*Populus balsamifera*	Pb
Trembling Aspen	*Populus tremuloides*	Pt
White Birch/Paper Birch	*Betula papyrifera*	Bw
Black Ash	*Fraxinus nigra*	Ab

2.2 Availability of biomass

A study conducted by the Ontario Ministry of Energy (OME 2007) found that within a 500km radius of the Atikokan generating station, approximately 2.7 million ODt of biomass feedstock is available annually from logging residues, underutilized wood and mill waste (Forest BioProducts Inc. 2006; OME 2007). This study relied on estimates utilizing survey plots and extrapolating in approximation across the region. Woody biomass currently contributes about 6% of total energy production in Canada (OME 2007). Canada has 402 million hectares (ha) of forest, covering 44% of the country, comprising 30% of the world's boreal forest (IEA 2011). This vast resource has the potential to supply much more energy to increase the biomass energy capacity to meet current demand. Biomass energy has the potential to meet 60% of domestic energy demand (Bradley 2006; Alam et al. 2008). Woody biomass has been globally recognized as a promising alternative energy source since it is renewable and nearly CO_2 neutral (Rauch and Gronalt 2010). However, renewable energy production from woody biomass faces many challenges due to uncertainty of its continuous availability and supply (Gan and Smith 2006; Wang 2007; Thornley et al. 2008; Kim et al. 2011b). Canada's exclusive dependence on fossil fuels has evolved recently and woody biomass energy production has become an important part of its sustainable energy production, supplying 6% of primary energy demand, the second largest source of renewable energy after hydroelectricity (IEA 2011). Woody biomass is typically available in 2 forms, either as forest harvest residue (FHR), which includes tops, branches, and un-merchantable wood waste left after harvest, or as underutilized wood (UW), which includes un-harvested tree species that are not commercially utilized in the region for timber as well as trees damaged by wildfire, windthrow and insects outbreaks that are not currently salvaged for other uses (IEA 2017; Alam et al. 2008, 2012). There are numerous options for transporting woody biomass, and several trucking and loading options having varying costs. Optimizing biomass procurement is, therefore, a complex problem with numerous supply and demand constraints. In 2012 a PHD study out of Lakehead University's Faculty of Natural Resources Management published a spatial assessment study investigating biomass energy in now (Alam et al. 2012). The study found that in the 19,315 depletion cells within the model (the forest areas where some level of timber harvest took place during 2002-2009) there was about 2.1 million green tonnes (gt) of forest harvest residue and 7.6 million gt of underutilized wood technically available. These figures suggest there is enough biomass to supply the annual biomass demand (2.21 million gt) of the four power plants in the region using only renewable energy sources (Alam et al. 2012). Other post-harvest inventories have shown that on average the theoretical availability of FHR in FMUs in NWO is approximately 60 m3·ha (Alam et al. 2012). Within the industrial sector, bioenergy use is common in industries which produce significant amounts of biomass residues on site, such as the pulp and paper industry, as well as the food processing industry, where it provides low- and medium-temperature heat for manufacturing processes. Modern bioenergy is also widely used for space and water heating, either directly in buildings or in district heating schemes. Around 500 TWh of electricity was generated from biomass in 2016, accounting for nearly 2% of world electricity generation (IEA 2017). World shortages of energy (oil and natural gas) are likely to occur between now and 2025. New sources of alternative fuels from renewable resources such as forest biofibre can be provided to help meet Ontario's needs (Ontario 2018).

2.3 Thermal value

A fuel quality assessment investigates the properties that affect the energy yield, which is also closely related to transportation costs. Common qualities assessed include moisture content, heat value, and ash content (Petterson and Nordfjell 2007). Thermal properties and the energy potential in biomass are typically measured in Gross Calorific Value (GCV) and Net Caloric Value (net CV). Calorific value (CV) is a measure of heating power and represents the amount of energy released when a fuel is completely combusted under specific laboratory conditions (Trossero 2001). This value is important to determine the energy production capacity of each species. “It is estimated that the energy content of one oven dry tonne (ODt) of woody biomass is about 19.6 GJ, which indicates that it can be used as an energy source for different purposes” (Alam et al. 2012). Biomass energy is typically used in a combustion reaction to release photosynthetic energy stored within (Hakkila 1989). A high carbon and hydrogen content translate directly to higher thermal values (Hakkila 1989). The variation of thermal values is due to the difference in the chemical composition of the biomass. Lignin, resin, and terpenes have much higher thermal values than cellulose and hemicellulose (Hakkila 1989; Guatum 2010). Thermal values of softwoods tend to be higher than that of hardwoods; on average, softwood thermal value is 21.18 MJ/Kg while hardwood is 19.35 MJ/Kg (Kryla 1984; Guatum 2010). This higher thermal value of softwoods can be attributed to a much higher content of lignin, resins, and terpenes (Hakkila 1989). Table 2 below displays measured thermal values from different components of 10 boreal tree species.

Oven dry thermal values (MJ·kg^{-1}) of 10 boreal species from Manitoba.

	Species	Stump	Stem	Treetop	Bark	Foliage	Branches	Mean
Softwoods	White spruce	19.8	19.0	21.6	19.8	20.6	21.1	20.3
	Black spruce	19.2	18.8	21.6	19.5	20.9	20.7	20.1
	Jack pine	20.0	19.4	21.2	21.3	21.4	21.3	20.8
	Eastern white cedar	19.4	20.0	19.5	18.7	21.4	18.7	19.6
	Tamarack	19.9	18.8	21.3	19.5	20.1	21.4	20.2
	Balsam fir	19.7	18.7	21.4	18.5	21.5	20.6	20.1
Hardwoods	Aspen	18.7	18.7	20.2	19.5	18.8	19.9	19.3
	Balsam poplar	18.5	17.7	20.5	19.5	17.7	19.1	18.8
	White birch	18.9	18.5	19.8	20.2	21.1	19.7	19.7

Table 1. Thermal values of 10 boreal species (Singh and Kostecky 1989)

2.4 Moisture content

Logging residue quality is subject to seasonal variation, storage methods, and the duration of storage also affects the quality (Rogers 1981; Gautam et al. 2010). The procurement of biomass can often be uneconomical due to high moisture content increasing transport costs as well as low thermal value when in a green state (Gautam 2009). Logging residues are hygroscopic, meaning the equilibrium moisture content (MC) fluctuates with temperature and relative humidity (Siau 1995; Gautam 2009). The hydroxyl groups in the cell wall capture and release water when there are changes in temperature and humidity (Esteban et al. 2005). As the fluctuation continues, some of the hydroxyl groups form new hydrogen bonds among themselves in the absence of water, leading to fewer bonding sites for water when remoistened. This process of loss of hygroscopic response is termed hygroscopic aging (Esteban et al. 2005). Biomass is generally low in energy content and bulk density, and high in moisture content after harvest compared to equivalent volumes of fossil fuels. This requires a much larger quantity of biomass to generate an equivalent amount of energy obtained from fossil fuels (Gautam et al. 2010). Studies have shown the effectiveness of various storage methods in decreasing moisture content. A study in 2010 in northern Ontario suggests the average MC of logging residues drops significantly from year 1 to year two and stabilizes to result in little change thereafter (Gautam et al. 2010). This proves the effectiveness of drying biomass in piles and windrows, although results from each method vary for different species. The results from the study in 2010 suggest softwood species are best suited for large beehive piling, due to the increased airflow, and hardwood species are better suited to smaller piles, likely due to the increased branching volume resulting in more voids within the smaller piles (Gautam et al. 2009). The moisture content of wood is defined as the weight of the moisture within the wood expressed as a percentage of its oven-dry weight (Leitch 2019). Naturally, the water content of wood is relatively high, considering that it typically comprises over half the weight of a living tree. The weight of the water within a green tree is oftentimes larger than the dry weight of the wood itself (Leitch 2019). Once cut, the weight, shrinkage, strength, and various other properties are highly dependent on the moisture content of the wood. Moisture content is such an important measurement due to the fact that wood is a hygroscopic material (gaining or losing moisture based on surrounding air) (Ekleman 2004). Depending on relative humidity and temperature, the moisture content of the wood can naturally fluctuate, resulting in dimensional swelling and shrinking in width across the grain (Simpson et al. 1999). Wood is fairly dimensionally stable when the moisture content is greater than the fiber saturation point, which is defined as “the moisture content at which only the cell walls are completely saturated (all bound water), but no water exists in cell lumens” (FSP 1999). The fiber saturation point is loosely considered to be at a 30% MC average for most species, although this is variable within species and individual pieces of wood, seeing as there is always natural variation present.

The concept of fiber saturation point demonstrates the difference between bound water and free water within the material, which are the two ways water is held within the wood. Bound water is water found within the cell wall and is tightly bound by adsorption forces, mainly hydrogen bonds (Panshin and De Zeeuw 1980). Water is absorbed into the cellulose, hemicellulose, and lignin components of the cell wall with hydrogen-bonded attraction. Density strongly correlates to pore size, resulting in the bound water in more dense species being much more difficult to remove than that of a lower density species where the pores tend to be larger. Free water is the liquid found in the cell lumina (cell cavity) and is more easily removed due to the lack of strong hydrogen bonds (Panshin and De Zeeuw 1980). Generally, the mechanical properties of wood increase as the wood dries. This is very prominent when the wood dries below the FSP as most strength and elastic properties increase significantly (Panshin and De Zeeuw 1980). “This is a result of water leaving the cell wall allowing long-chain molecules to move closer together and therefore become more tightly bonded” (Bowyer et al. 2003). There are a few advantages to drying wood for bioenergy production. Drying wood prevents fungal activity by reducing potential due to the fact that fungal activity tends to require a moisture content higher than the FSP. Dry logging residue is significantly lighter, thus reducing transportation costs. Net thermal values increase when dry due to being highly dependent on the MC of the biomass (Peterson and Nordfjell 2007; Gautam 2010).

2.5 Ash Content

Commercial combustion energy produces ash as a residue. The ash found in biomass is primarily made up of calcium, magnesium, potassium, and silica (Petterson and Nordfjell 2007). Foliage and bark have a significantly higher ash content than that of the stem and branches, and hardwoods tend to have a higher ash content than softwoods. The ash content is also affected by the proportion of juvenile wood and mature wood, seeing as juvenile wood has a higher ash content than mature wood. By seasoning biomass, the MC will be reduced as well as needles will be shed, thus reducing ash content, weight and increasing thermal properties (Petterson and Nordfjell 2007). Ash content is the total weight of non-combustibles or inorganics in material being burnt. Ash content is an important fuel characteristic due to its relationship with the gross calorific value of biomass, with the more non-combustibles in biomass the lower the gross calorific value (Hakkila 1989; Rhen 2004). It has been shown that gross calorific value is negatively related to ash content; for every 1% increase in ash content the heating value decreases by 0.2 MJ/kg (Cassida et al. 2005). Ash content can also have detrimental effects to the boiler system and reduce its efficiency. The higher proportion of inorganics in biomass allows greater amounts of residue on burning equipment (Monti et al. 2008). Ash must also be removed from the boiler to avoid congestion inside the burning chamber. Extraction systems are designed only to handle certain amounts of ash and exceeding that will cause accumulation of ash (FERIC 2008). Ash is not solely an unwanted by-product and there is currently research being done to use biomass ash in a productive manner. When policies allow it, wood ash can be used as a fertilizer to replenish nutrients at the site (Demeyer et al. 2001).

2.6 Transport

Transportation of available biomass from harvest operations to biomass facilities remains the single biggest inhibitor of cost-effective biomass energy production. Currently, the most cost-effective and most widely available source of biomass is in the form of by-products from mills (CCFM 2016). Wood pellet manufacturers source up to 88% of their feedstock from mill operations (CCFM 2016). This is primarily due to these sources being much less expensive because they have already been transported to a central location and are in a form that is more easily converted into another product. To transport forest residues that have low densities and high moisture contents over long hauling distances remains an economic challenge (CCFM 2016). Logging residues are produced year-round, but immediate transport is inefficient due to high moisture content limiting potential volumes being transported (Pettersson and Nordfjell 2007). Supply chain optimization will be key if biomass use is to be successfully increased in the coming years (Huang et al. 2010). Studies in biomass procurement, therefore, have recently focused on reducing overall transportation costs (Rauch et al. 2010; Guatam et al. 2010). Existing roads may be impassible for some biomass trucks due to gradeability, cornering, and ground clearance requirements that differ from other conventional log trucks (FERIC 2008). Some solutions exist to help reduce some of the transportation costs. Comminution is a method of reducing the size of wood residues into finer particle sizes by means of chipping or pulverization (CCFM 2016). Methods such as chipping, grinding, or compacting can reduce transportation costs by a significant proportion due to increases in the density of the payload and therefore increases in the efficiency of the volume being transported (CCFM 2016). The cost of hauling is dependent on the trucking configuration, road class, distance to the end-use location, and the form in which the biomass is delivered in. These factors result in a highly variable hauling economic feasibility. Based on previous studies, the average hauling cost in Northwestern Ontario has been determined to be between 17$ and 23$/gt, but the hauling cost is highly dependent on moisture content, distance, and road classification. Routes running on primary roads and highways ultimately cost significantly less than those requiring extensive travel on secondary and tertiary roads.

2.7 Costing and logging methods

In order for biomass energy to become a feasible large-scale energy option, the system is fully dependent on the biomass quality, availability, and cost incurred during procurement to the energy plant (Guatam 2009). Accurate costing of the processes required to deliver quality biomass is essential in operating a profitable biomass energy facility. Harvesting method is one of the main costs in terms of availability and profitability; a harvesting method refers to the form in which wood is delivered to a logging access road (Pulkki 2003). Complimentary to the harvesting method, a harvesting system is the equipment and machines used within the harvesting method. The harvesting system can be costed through various analyses to determine the cost per unit of biomass, cost per day, and various other units. In Ontario, full tree (48%) and cut to length (40%) are the most common harvesting methods used (FERIC 2008). In a full tree harvest method operation, trees are felled and brought to roadside with a skidder, then are subsequently processed at roadside to specifications defined by the mill or end-use customer (Pulkki 1997). In full tree logging, the harvest residue is typically concentrated along the roadside in the form of tops and limbs (Pulkki 1997; Pulkki 2003). This results in a lesser volume of logging residue in the cut block, and the available residues are much more accessible. Currently, roadside logging residue is typically piled and burned in the fall or winter to recover land and minimize wildfire hazards (Gautam 2009). Cut-to-length harvesting method (CTL) involves trees being felled, delimbed and bucked to size at the fell location with a single grip harvester, then the bucked logs are transported to roadside by a forwarder (Pulkki 1997; FERIC 2008). This method is seen to be lower in terms of environmental impact, due to the logging residue being left scattered across the cut block. For biomass energy, it seems to favor the full tree system (FT) due to the accessibility of the fuels, thus reducing cost. Figure 1 below illustrates the components of a tree during a commercial harvest.

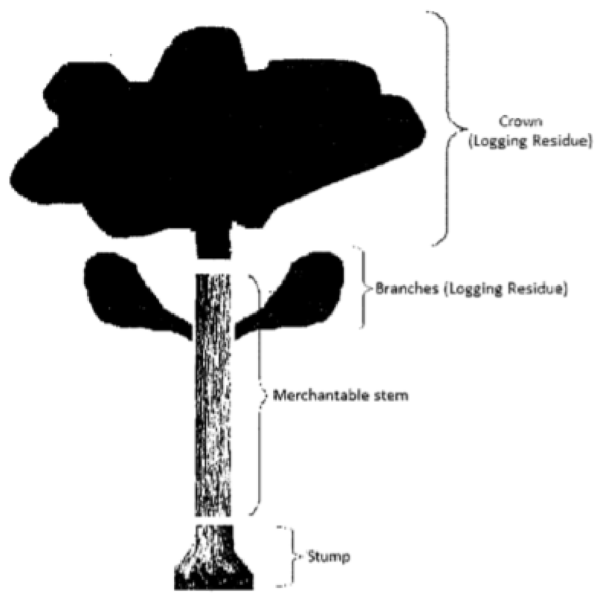

Figure 2. Components of a Tree During Commercial Harvest (Gautam 2010)

The quantity of harvest residue is highly dependent on the intended use of the logs being harvested. In Northern Ontario, the primary products produced include OSB with minimum diameter requirements of 10 cm, veneer with a minimum diameter requirement of 22 cm, sawlogs with a minimal top diameter of 9 cm, and pulpwood is generally 5 cm acceptable top diameter (Gautam 2009). Biomass energy producers face a challenge competing for logs within these requirements, seeing as traditional forest products have garnered a higher price.

2.8 Existing biomass plants in the region

There are currently four biomass based combined heat and power generating stations operating in North Western Ontario. These plants include Resolute Thunder Bay, Resolute Fort Frances, and Domtar Dryden CHP plants, as well as the Atikokan generating station (Alam et al. 2012). The recently decommissioned Thunder Bay Generating Station (TBGS) was closed in 2018, due to the lack of demand and cost of required repairs to the boiler systems. The biomass (wood pellets) generating station located in Atikokan has been retrofitted from an existing coal-based generating station. Based on the consumption of the four plants in the region, the estimated total annual biomass feedstock requirement is around 2.2 million green tonnes (Alam et al. 2012). Figure 2 below displays the biomass generating stations currently in place across Northwestern Ontario.

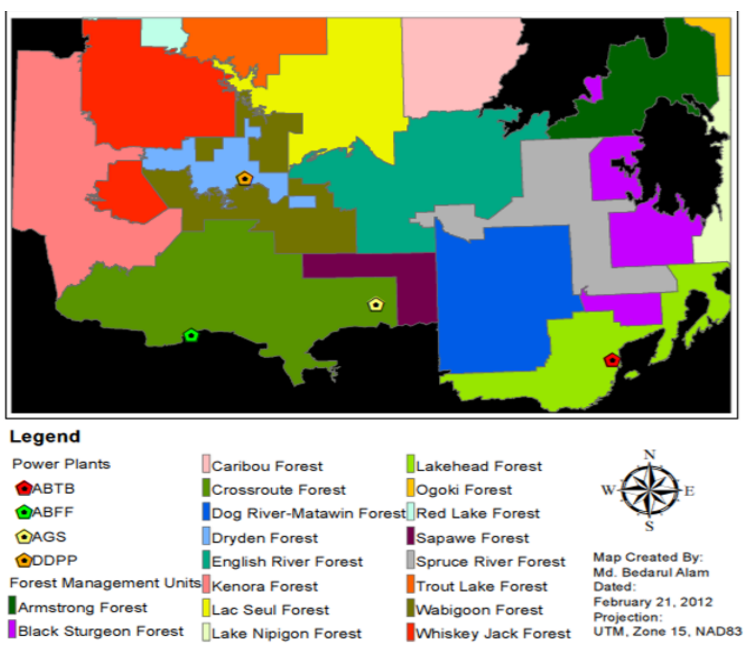

Figure 3. Biomass generating stations across NWO and corresponding forest units (Alam et al. 2012)

2.9 Co-generation potential

Global wood pellet consumption for both industrial and heating purposes increased by 60% during 2010-16 (IEA 2017). Wood pellet production in 2016 reached 28.5 million tonnes with the United States, the European Union, and Canada as key producers. The main markets for industrial and heating wood pellets are found in the European Union, this is supplemented by pellet demand in Japan and Korea, and heating demand in North America (IEA 2017). Mill closures across the country have resulted in negative impacts in many forestry dependent communities. One of the main factors in the Canadian forest industry's loss of competitiveness is attributed to higher electricity costs, resulting in higher production costs and lower market prices (Frederic 2005). In 2005 the Minister's Council on Forest Sector Competitiveness published a report estimating that Ontario's forest industry faces the highest electricity costs in North America (MCOF 2005). Co-Generation has the potential to supplement energy requirements by producing affordable energy onsite at the mill from waste materials such as sawdust, chips, and bark. This also has the potential to be profitable by selling electricity back to the grid to meet peak demand. For example, the Resolute pulp mill in Thunder Bay sells excess electricity back to the grid earning approximately $2 million per year.

2.10 Policy

The Ontario Biofiber act aims to create and support new opportunities to develop and use new technologies and products, which will help to diversify the Ontario economy. It will also encourage the use of forest biofibre and bioenergy to reduce Ontario's dependence on fossil fuels and reduce energy costs through the development of bioenergy and biofuels projects (Gautam 2010; MNRF 2017). In 2009 Ontario launched a program seeking expressions of interest to use Crown biofibre commercially (OMNDMF 2009). The government of Ontario then enacted a

Green Energy Act, designed to stimulate growth in renewable energies such as biomass (OMEI 2010). One of the major components and milestones of the Green Energy Act is a feed-in-tariff system, which allows companies or individuals to sell the renewable energy they produced, such as wood bioenergy onto the provincial grid at set rates to meet peak demand. New regulations under the Act also guarantee a streamlined approvals system and a service guarantee in order to offer developers greater certainty and incentive (OMEI 2010). Within the last decade, Canada's forest industries have been faced with a number of challenges, including fluctuations and market uncertainty in the American housing market, threats of recession, and an increasing cost for transportation, energy, and fuels. These pressures have been compounded by increasing competition in forest product manufacturing from international producers and a decline in demand for a fundamental traditional forest product, namely pulp and newsprint (Stone and Coughlin 2009; Gautam 2010; IEA 2017). The loss of traditional markets for wood fiber threatens the profitable survival of the forest industry. The industry must adapt and pursue new markets for the existing wood fiber that are economically and environmentally sustainable (Chase 2009). By providing demand for wood fiber, wood-based bioenergy can address the issues of energy sustainability, revitalization of forest industries, and rural economic development as well as new business opportunities for the forest industry (Speers 2009).

3.0 Methods and Materials

Data used for this thesis was compiled from previous studies within the Faculty of Natural Resources Management at Lakehead University. These studies include; Modeling Forest Biomass Availability in Northwestern Ontario Alam et al. (2012), Economic and energy efficiency of salvaging biomass from wildfire burnt areas of bioenergy production in northwestern Ontario Gautam et al. (2010), Fuel characteristics of northwestern Ontario tree species and their components Hosegood (2010), and Reynolds (2009) Feasibility of forest feedstock for bioenergy in northwestern Ontario. These studies provide the data needed for the basis of the thesis. Fuel availability, costing models, and consumption data were obtained from Md. Bedarul Alam's 2012 Ph.D. thesis, as well as Reynolds (2009) and Gautam et al (2010). Fuel quality assessments for the forest units were obtained from Hosegood (2010), providing the thermal and ash data as well as geographical data for multiple different FU's in NWO. The compiled data was then organized to examine the efficiency of fuels within the geographic scope, the availability of the fuel source/feedstock within the geographic scope, and the economic feasibility and maximum operability based on acquisition cost and energy production capacity. The compiled data was then used to draw conclusions with a larger, more diverse dataset, which provided insight into the objectives outlined in this thesis.

4.0 Results

4.1 Availability of Biomass

4.1.1 Pre-Harvest Inventories

The study areas within the Boreal forest is dominated by upland and lowland coniferous and mixed-wood forests (OMNR 2011). The most common tree species available in these northwestern Ontario FMUs are balsam fir (*Abies balsamea*), balsam poplar (*Populus balsamifera*), black spruce (*Picea mariana*), jack pine (*Pinus banksiana*), red pine (*Pinus resinosa*), tamarack (*Larix laricina*), trembling aspen (*Populus tremuloides*), white birch (*Betula papyrifera*), white pine (*Pinus strobus*), and white spruce (*Picea glauca*). Harvestable biomass availability can be accurately estimated by using pre- and post-harvest forest inventory surveys to determine the volume of FHR left in the cut block. By doing cut block sampling and measuring slash piles, the amount of biomass left in the forest after harvesting can be determined. These techniques of post-harvest forest sampling are discussed in Sorenson (2007), Bilyk (2009), Kurikka (2008), Reynolds et al. (2008), Gautam (2010) and Alam et al. (2012). The pre-harvest forest inventory studies conducted in 2008 and 2009 in the Crossroute Forest published in Alam et al. (2012) and Reynolds (2009) are compiled in tables 3 and 4, respectively. These inventories found the net total merchantable volume to be 109 m^3/ha in the Crossroute forest unit and 108.5 m^3/ha in the Black Sturgeon forest unit, reinforcing the parity within the boreal FMUs in NWO. The average gross and merchantable volume were found to be 190 m^3/ha and 116 m^3/ha, respectively, for both forest units. Reynolds et al. (2008) published similar results in their study done in the Black Sturgeon Forest, with gross merchantable volume and merchantable volume of wood at 189 m^3/ha, 116 m^3/ha, respectively. This data suggests there is little difference between the western FMU sampled (Crossroute forest) and the eastern FMU (Black sturgeon).

Table 2 Sampled Volumes from the Crossroute Forest (Alam et al. 2012)

Crossroute Forest

Block Number	Species Composition	Age	Volume Gross	Volume Merchantable	Volume Net	Volume UW
71430	Pt45 Mr16 Pj16 Bf7 Bw6 CE4 Sb3 Sw3	61	186	116	112	126
72219	Pt67 Pb23 Bw4 Ab3 Sw3	59	175	53	52	171
72801	Pj53 Sb38 Bw9	69	192	111	103	9
72805	Pj51 Sb45 Sw3 La1	80	212	158	147	2
71093	Pj55 Sb38 Bf7	68	228	66	62	0
71579	Sb31 Bf18 Bw16 Mr15 Pw10 Pt7 Pj3	69	146	192	178	82
Average		68	190	116	109	65

Table 3 Sampled Volumes from the Black Sturgeon Forest (Reynolds 2009)

Black Sturgeon Forest

Block Number	Species Composition	Age	Net Merchantable Volume
5334	Sb43 Po27 Bw26 Pj3 Sw1	Po44	121.93
5336	Sb30 Po26 Pj22 Bw20 Bf2	Po74 Sb79	103.35
5354	Sb49 Pj30 Po18 Bw3	Sb114 Pj64 Po54	134.10
5384	Sb60 Po23 Bw15 Pj2	Sb69 Po74	89.50
5875	Sb41 Bw32 Po23 Bf4	Sb69 Bw79 Po69	94.10
Average			108.60

4.1.2 Post Harvest Inventories

The average FHR in the Crossroute Forest was sampled at 61.55 m^3/ha (Alam et al 2012) and is displayed in table 4. Based on the similarity of pre-harvest inventories conducted by Reynolds et al. (2008) and Alam et al. (2012) within the Black Sturgeon Forest, the assumption of about 60 m^3/ha of post-harvest FHR available in NWO can be applied. This estimation was determined in

Alam et al. (2012) due to the variation of sample size and volume variation between the 2 FMUs sampled. Although the volume of FHR was determined during the sampling, due to various technical and environmental limitations, it is not technically feasible to harvest all available woody biomass from the forest (Viana et al. 2010; Alam et al. 2012; Gautam 2010). A 0.67 harvesting factor was used in Alam et al. (2012) based on previously published data. This harvesting factor was derived based on Borjesson (2000), and Gan and Smith (2006) who used a 70% FHR recovery rate; Kerstetter and Lyons (2001) who estimated an FHR recovery rate between 70% and 97%; Ranta (2004) who estimated an economic FHR recovery rate of 65%; Nurmi (2007) who determined an FHR recovery between 66.8% and 78.7%; and FPInnovations FERIC (2008) in which the report determines 67% woody biomass is recoverable in NWO. Based on this availability factor, the technical availability of woody biomass was determined to be 40.2 m^3/ha. This volume is consistent with the assumption that there can be an average one truck-load of biomass per hectare harvested, seeing as a truckload of wood in Ontario is typically about 40 m^3. This harvesting factor ensures that there is still a sufficient volume of coarse woody debris and “logging slash” left on-site to ensure nutrient retention on-site and avoid site degradation by removing biomass, which will decompose and provide vital nutrients to the future forest. This factor also meets the Ontario Forest Management Guide for Natural Disturbance Pattern Emulation requirements, as long as this practice is avoided in areas with shallow soils, which are susceptible to nutrient loss (OMNR 2002).

Table 4 Post Harvest FHR Survey Compilation (Alam et al. 2012)

Crossroute FHR Post Harvest Survey

Block Number	Species Type	Total volume of FHR (m3/ha)
6950	Conifer	66.09
6991	Hardwood	76.69
6992	Hardwood	37.79
7021	Conifer	58.86
7262	Mixed	35.95
7263	Mixed	69.01
7264	Mixed	76.45
7271	Conifer	44.40
7276	Hardwood	74.08
72782	Conifer	76.44
72802	Conifer	35.02
72803	Conifer	45.62
72809	Conifer	53.91
72842	Hardwood	100.76
72954	Hardwood	72.23
	Average m3/ha	61.55

4.2 Efficiency/ Quality of Biomass

A fuel quality assessment investigates the properties which affect the energy yield. Common qualities assessed include moisture content, heat value, and ash content (Petterson and Nordfjell 2007). Thermal properties and the energy potential in biomass are typically measured in Gross Calorific Value (GCV) and Net Caloric Value (net CV). Calorific value (CV) is a measure of heating power and represents the amount of energy released when a fuel is completely combusted under specific laboratory conditions (Trossero 2001). This value is important to determine the energy production capacity of each species. Biomass energy is typically used in a combustion reaction to release photosynthetic energy stored within (Hakkila 1989). A high carbon and hydrogen content translate directly to higher thermal values (Hakkila 1989). The variation of thermal values is due to the difference in the chemical composition of the biomass. Lignin, resin, and terpenes have much higher thermal values than cellulose and hemicellulose (Hakkila 1989; Guatum 2010). Thermal values of softwoods tend to be higher than that of hardwoods; on average, softwood thermal value is 21.18 MJ/Kg while hardwoods are 19.35 MJ/Kg (Kryla 1984; Guatum 2010). This higher thermal value of softwoods can be attributed to a much higher content of lignin, resins, and terpenes (Hakkila 1989). In a study by Guatam (2010), the thermal qualities of FHR were sampled in the Crossroute forest west of Atikokan, Ontario. This fuel quality assessment, along with a similar study by Hosegood (2010), which quantifies fuel characteristics of northern Ontario tree species and their components, provide a comprehensive representation of fuel quality in NWO. The study area for both publications is within the boreal forest, which, as presented by Alam (2012), Gautam (2010), and OMNR (2011), contain the same species. In Hosegood (2010), seven species were sampled at two different sites, one site was located 30 km west of Atikokan in the Crossroute forest, and the other site was located 50 km northeast of Thunder Bay in the Black Sturgeon forest. These sites were chosen to determine the level of geographic variation in thermal values and due to the proximity to biomass plants and correlate well to the other data obtained for this thesis. The seven species and their abbreviations in the study by Hosegood (2010) include Sb (black spruce), Bf (balsam fir), Pj (jack pine), Ta (tamarack), Bw (white birch), Po (trembling aspen) and Ab (black ash). These species comprise of primary merchantable species as well as under-utilized species such as Tamarack, Trembling aspen, Black ash, and White birch. This study does not include White Pine nor Red Pine, likely due to the commercial importance, high value making it unsuitable for biomass, and due to availability within the sampled blocks. Four samples were taken of each of the six tree components for all seven tree species at the two sites. The chosen components in this study were chosen for their likelihood of being harvested for biomass: foliage, branches, bole and bark at 10 cm diameter, and bole and bark at breast height. Average calorific values of both lower and upper bole wood for softwoods were found to be 19.76 MJ/kg and hardwoods 19.62 MJ/kg. The difference is relatively minute considering the difference in cellulose, hemicellulose, and lignin composition between softwoods and hardwoods (Panshin and DeZeeuw 1980). Based on the sampling from the two sites, it was determined in Hosegood (2010) that there is little difference between the values obtained in the eastern portion of the study areas versus that obtained in the western portion. The ANOVA performed in Hosegood (2010) determines that there is no significant statistical difference between the sites. This analysis allows the species and components to be analyzed as if they were from one site. Based on this statement, the average component values from both sites were compiled in table 5, 6 and 7, where the average thermal value of all components combined for this dataset was determined to be 20.65 MJ/Kg.

Table 5 Thermals Values in the Thunder Bay Region (Hosegood 2010)

Thermal Values Thunder Bay Region MJ/Kg

	Tree Components					
Species	Lower Bole	Lower Bark	Upper Bole	Upper Bark	Branch	Foiliage
Ab	19.21	18.35	19.41	18.85	19.64	19.36
Bf	19.88	21.13	19.97	21.74	20.47	22.57
Bw	19.78	24.54	19.77	24.64	20.69	21.1
Pj	19.56	21.58	19.73	21.01	20.27	22.45
Po	19.68	22.25	19.59	21.57	21.03	21.68
Sb	19.18	20.58	19.26	20.24	21.41	21.35
Ta	19.98	21.1	19.97	21.41	20.15	21.47

Table 6 Thermal Values for the Atikokan Region (Hosegood 2010)

Thermal Values
Atikokan Region
MJ/Kg

	Tree Components					
Species	Lower Bole	Lower Bark	Upper Bole	Upper Bark	Branch	Foliage
Ab	18.99	18.07	19.17	18.27	19.12	19.13
Bf	19.9	21.52	20.24	20.83	21.04	23.06
Bw	19.67	26.8	20.12	24.37	21.28	20.97
Pj	20.25	21.78	20.03	20.3	20.57	22.19
Po	19.44	22.63	19.9	22.52	21.2	21.4
Sb	19.56	19.88	19.51	19.59	20.55	20.74
Ta	19.44	20.94	19.71	20.73	20.12	21.13

Table 7 Average Thermal Values for Both Sites MJ/Kg (Normand 2020)

	Tree Components						
Species	Lower Bole	Lower Bark	Upper Bole	Upper Bark	Branch	Foliage	Combined
Ab	19.10	18.21	19.29	18.56	19.38	19.25	18.96
Bf	19.89	21.33	20.11	21.29	20.76	22.82	21.03
Bw	19.73	25.67	19.95	24.51	20.99	21.04	21.98
Pj	19.91	21.68	19.88	20.66	20.42	22.32	20.81
Po	19.56	22.44	19.75	22.05	21.12	21.54	21.07
Sb	19.37	20.23	19.39	19.92	20.98	21.05	20.15
Ta	19.71	21.02	19.84	21.07	20.14	21.30	20.51
			Average				20.65

The study by Gautam (2010) focused on the effects of drying patterns and weathering years on various fuel characteristics of the species present within the Crossroute forest. Thermal quality data in the form of thermal values were tested based on two different harvesting methods; Cut-to-length and Full-tree to the roadside. This study determined that there is no statistical difference between drying years and thermal values in full-tree harvesting, which is the primary method of harvest, and most conducive to biomass harvesting. The thermal values for both harvesting methods are displayed in tables 8 and 9 below. The average thermal values were found to be 21.1 MJ/Kg and 21.28 MJ/Kg for CTL and FT harvesting, respectively.

Table 8 Average Thermal Value of CTL Blocks (Gautam 2010)

Average Thermal Value MJ/Kg in CTL Blocks Sampled

Storage Years	Species Group		Diameter Class	
			Large	Small
1	Hardwood		20.1	21.3
	Softwood		20.4	21.4
2	Hardwood		21.6	22.0
	Softwood		20.2	20.8
3	Hardwood		19.5	22.8
	Softwood		20.7	22.1
Average MJ/Kg	Combined		Large	Small
		21.1	20.4	21.7

Table 9 Average Thermal Value of FHR (Gautam 2010)

Average Thermal Value MJ/Kg in FHR Sample

Storage Years	Location	Species Group	Diameter Class	
			Small	Large
1	Inside Pile	Softwood	21.2	22.4
		Hardwood	20.3	21.7
	Surface	Softwood	21.2	22.3
		Hardwood	20.4	20.9
2	Inside Pile	Softwood	20.8	23.1
		Hardwood	20	21.4
	Surface	Softwood	19.9	21.7
		Hardwood	20.7	22.5
	Average MJ/Kg	Combined	Large	Small
		21.28	20.56	22.00

Based on the thermal data compiled, an average thermal value of 20.65 MJ/Kg seems to accurately represent the data conservatively. The average from Hosegood (2010) is based on a larger dataset. Due to variation in harvesting method, the figures found in Gautam (2010) serve to support the credibility of the average thermal value in NWO, rather than combining it, especially since the diameter class was unspecified in Hosegood (2010). Seeing as the values in both studies were found to be relatively similar, it can be assumed that the average thermal value of biomass harvested within the boreal forest is within the measured range.

4.3 Feasibility/Costing

4.3.1 Specific Gravity and Weight

Considering the average thermal value is 20.65 MJ/kg, and the average technically available volume of FHR within the study area is 40.2 m^3/ha, by determining the weight of 1 m^3 of wood based on the specific gravities of the present species, the average thermal potential per m^3 can then be determined. Based on the seven species specified in the previous data, the average specific gravity was calculated to be 0.411 using specific gravity figures at green MC from Simpson (1999). These figures are displayed below in table 10. The specific gravity figures obtained in Hosegood (2010) are displayed in table 11, where average specific gravity for all species was calculated to be 0.607. This higher value could be due to various factors, from slow growth to the ecosite or limited sample size, but due to the study area of Hosegood (2010), the figures published in that study are likely more reflective of the true values in the study area.

Table 10 Specific Gravity for 7 Boreal Tree Species (Simpson 1999)

Published Specific Gravity	
Black Spruce	0.38
Tamarack	0.49
Black Ash	0.45
Trembling aspen	0.35
White Birch	0.48
Balsam Fir	0.33
Jack Pine	0.40
Combined Average	0.41
Weight of 1 m3 combined	411.43

Table 11 Specific Gravity Values Within the Study Area (Hosegood 2010)

Thunder Bay	Specific Gravity Averages					
Species	Lower Bowl	Lower Bark	Upper Bole	Upper Bark	Branches	Average
Ab	0.617	0.565	0.615	0.625	0.688	0.622
Bf	0.373	0.697	0.396	0.695	0.563	0.545
Bw	0.576	0.610	0.600	0.594	0.654	0.607
Pj	0.476	0.622	0.464	0.720	0.536	0.564
Po	0.427	0.742	0.460	0.821	0.528	0.596
Sb	0.516	0.730	0.578	0.696	0.664	0.637
Ta	0.596	0.664	0.574	0.619	0.584	0.607
Atikokan						
Ab	0.651	0.568	0.645	0.671	0.702	0.647
Bf	0.396	0.705	0.442	0.710	0.633	0.577
Bw	0.675	0.676	0.652	0.613	0.652	0.654
Pj	0.471	0.640	0.468	0.721	0.568	0.574
Po	0.513	0.689	0.501	0.882	0.563	0.630
Sb	0.495	0.685	0.488	0.739	0.683	0.618
Ta	0.617	0.675	0.547	0.676	0.563	0.616
Combined Average		0.607				

Based on this specific gravity species average, the average thermal potential of the FHR within the sample area was calculated to be 12,532 MJ/m^3 (607 kg/m^3 x 20.65 MJ/kg). In Alam et al. (2012), a conversion factor of 0.878 was used to convert cubic meters (m^3) to green tonnes (gt), resulting in an average volume of 35.40 gt/ha technically available. Based on this conversion, the average thermal potential per green tonne was calculated to be 11,003.18 MJ/gt. In comparison to other fuel sources, mainly natural gas and coal, the thermal potential of biomass is significantly lower than that of the two other common fuel sources. Table 12 displays the thermal values for common fuel sources in Canada. Although biomass is less dense than other traditional fuels, it remains a viable option seeing as it has high potential as an auxiliary output of traditional logging, therefore allowing for optimized supply chains to increase the cost-efficiency.

Table 12. Thermal Potential of 3 Common Fuel Sources in Canada, (World Nuclear Association 2018)

Thermal Potential of 3 Common Fuel Sources in Canada

Fuel Source	Specific gravity	Thermal Value MJ/Kg	Installed Capacity Mw	Thermal Potential per m3
Sub bitimous coal	1.32	18	0	23,760.00
natural gas	0.65	46.5	10,000	30,225.00
Biomass	0.607	20.65	295	12,534.55

4.3.2 Trucking

An average truckload of biomass in loose form is 16 tons and in chipped form is 20 tons (McNeel et al. 2010). The conversion from imperial ton to metric tonne is 0.907185, resulting in a load weight capacity of 14.51 and 18.14 for Loose and Chipped loads, respectively. Table 13 displays the payload capacity of different trucking configurations used in Ontario.

Table 13 Biomass Trucking Configurations (FERIC 2009)

Table 1. Example empty weights and dimensions for example biomass truck configurations

	Steer	Driver group			Lead trailer group			Rear trailer group			Capacity		
	Weight (kg)	Axles	Weight on axle group (kg)	Wheel base (m)	Axles	Weight on axle group (kg)	Wheel base (m)	Axles	Weight on axle group (kg)	Wheel base (m)	Total axle weight (kg)	Box volume (m^3)	Payload (ODt)
53' Semi-trailer chip van[1]	4700	2	7300	6.7	3	6400	12.4	-	-	-	18 400	113	17.7
Highway drop-belly B-train	4700	2	7000	5.8	3	5500	9.1	2	3500	7.8	20 700	162	26.0
Highway high-clearance B-train[2]	4700	2	7000	6.2	2	6000	8	2	5000	8.0	22 700	147	23.5
Straight-body (tridem), triaxle bin trailer	6000	3	12 200	6.6	1	3200	3.7	2	5100	6.5	26 500	101	15.8
Pole trailer/container	5500	2	6500	6.5	2	7000	7	-	-	-	19 000	67	10.5
Pole trailer - empty log truck tandem/tridem	5000	2	11 000	6.5	-	-	-	-	-	-	16 000	-	-
Large grinder (45 000 kg) on 50 t lowbed w/ jeep (loaded)	6500	3	28 000	6.7	1	6000	6	3	27 000	12.0	67 500	-	-

1 "Chip van" is used generically to mean a vehicle that can haul chips or hog fuel.
2 Most B-trains currently used for transporting chips or hog fuel on resource roads are lightweight designs intended for highway usage. Off-highway usage may result in excessive wear.

The average total energy per truckload was calculated to be 199,638.36 MJ, while in Hosegood (2010), a weighted average based on the composition of tree components, species, and the respective specific gravity values was calculated for a management scenario and determined to be 590,921.7 MJ. This average takes into account a block with 42% Pj, 42% Po and 17% Bf while also accounting for the percentage of tree components, which includes over 55% of the components to be branches that have the highest thermal values. This value may also take into account different trucking configurations and volumes than the one used in this thesis. The average total energy per truckload calculated from average combined specific gravity was also significantly lower than the management scenario in Hosegood (2010) based on previously published data, which again accounted for the percentage of species and tree components. Table 14 displays the management scenarios used in Hosegood (2010).

Table 14 Two Management Scenarios (Hosegood 2010)

Scenario 1, Data From This Study			
		Species	
Tree Component	Jack Pine	Balsam Fir	Trembling Aspen
Lower Bole	5.0%	5.0%	30.0%
Lower Bark	2.5%	2.5%	15.0%
Upper Bole	25.0%	25.0%	20.0%
Upper Bark	12.5%	12.5%	10.0%
Branches	55.0%	55.0%	25.0%
% of all Residues	42.0%	17.0%	41.0%
Calorific Value (MJ/kg)	20.86	20.79	20.54
Ash Content	0.802	1.982	1.602
Specific Gravity	0.566	0.593	0.566
Total Energy Per Truck (MJ)		590921.7	
Total Ash Content Per Truck (kg)		379.5	
Scenario 2, Previously Published Data			
		Species	
Tree Component	Jack Pine	Balsam Fir	Trembling Aspen
Lower Bole	5.0%	5.0%	30.0%
Lower Bark	2.5%	2.5%	15.0%
Upper Bole	25.0%	25.0%	20.0%
Upper Bark	12.5%	12.5%	10.0%
Branches	55.0%	55.0%	25.0%
% of all Residues	42.0%	17.0%	41.0%
Calorific Value (MJ/kg)	20.61	19.69	19.19
Ash Content (%)	1.372	1.705	1.373
Specific Gravity	0.400	0.350	0.380
Total Energy Per Truck (MJ)		380793.8	
Total Ash Content Per Truck (kg)		273.8	

4.3.3 Cost of Acquisition

In Alam et al. (2012), harvesting costs per green tonne, as well as average hauling cost per green tonne, are specified based on the BASE scenario of the model created in the study. The average hauling costs, based on depletion cells and their proximity to logical generating stations, as well as the average harvesting costs, were compiled in table 15, providing the costing basis for this average feasibility analysis.

Table 15 Harvest and Hauling Data Compilation

Descriptions	Unit	Estimates	Source
Harvesting and processing costs of FHR	$/gt	26.00	OME 2006
Harvesting and processing costs of UW	$/gt	31.00	OME 2006
Average transport cost of woody biomass from productive forest Resolute TB	$/gt	21.90	Alam et al. 2012
Average transport cost of woody biomass from depleted forest Resolute TB	$/gt	20.20	Alam et al. 2012
Average transport cost of woody biomass from productive forest AGS	$/gt	20.18	Alam et al. 2012
Average transport cost of woody biomass from depleted forest AGS	$/gt	18.11	Alam et al. 2012

Based on the averages compiled above, the average acquisition cost (harvest + haul) for the Resolute Thunder Bay CHP, and the Atikokan Generating Station were determined to be $46.20 /gt and $44.11 /gt, respectively. Harvesting data remains constant based on values provided in OME (2006), and hauling cost can vary greatly based on moisture content and hauling distance. Based on the average acquisition cost per green tonne, the average thermal potential per green tonne and the average consumption of biomass in green tonnes for both generating facilities (based on 2012 figures from Alam et al. 2012), the average acquisition cost for the Resolute TB CHP and the Atikokan Generating Station was calculated to be $33,726,000 and $8,822,000 per year, respectively.

5.0 Discussion

5.1 Availability

5.1.1 Pre-Harvest Inventory

The analyses of pre-harvest inventory in Alam et al. (2012) within the Crossroute Forest demonstrated that stand volume might vary in blocks within the same FMU due to the influence of environmental and physical factors such as species composition, age, and ecosite. The net merchantable volume sampled varied from 52 m^3/ha to 178 m^3/ha, with an average across the dataset being 109 m^3/ha. The results of Reynolds et al. (2008) found a similar trend, with a net merchantable volume sampled ranging from 94 m^3/ha to 134 m^3/ha with an average across the dataset being 108.5 m^3/ha. In Alam et al. (2012), the variation of net merchantable volume between the two studies is attributed to a larger sampled area in the Crossroute forest, resulting in a larger variation within the species, as well as a larger overall sample size. Regardless of the variation present within the two sampled FMUs the pre-harvest inventories published in both Alam et al. (2012) and Reynolds et al. (2008) established that there is little statistical difference in stand volume between the western FMU sampled (Crossroute forest) and the eastern FMU (Black sturgeon). In Alam et al. (2012), the proportion of UW measured within the FMU was found to be 38% of the volume, theoretically resulting in approximately 60 m^3/ha of UW. In Reynolds et al. (2008), the proportion of UW was determined to be 43% of the pre-harvest volume, further reinforcing the parity between the two FMUs sampled.

5.1.2 Post-Harvest Inventory

Based on the assumption that there is little variation between the FMUs latitudinally, the post-harvest data obtained in Alam et al. (2012), as well as in Bilyk (2009), can reasonably be extrapolated between the two FMUs (Crossroute and Black Sturgeon). This post-harvest available volume was measured as 61.55 m^3/ha in Alam et al. (2012). Due to various technical and environmental limitations, a harvesting factor of 0.67 was used in Alam et al. (2012) to represent the total harvestable FHR based on previously published data. This harvesting factor was derived based on studies by; Borjesson (2000), and Gan and Smith (2006) who estimated a 70% FHR recovery rate; Kerstetter and Lyons (2001) who estimated an FHR recovery rate between 70% and 97%; Ranta (2004) who estimated an economic FHR recovery rate of 65%; Nurmi (2007) who determined an FHR recovery between 66.8% and 78.7%; and FPInnovations FERIC (2008) in which the report determines 67% woody biomass is recoverable in NWO. Based on this factor, the technical availability of woody biomass is 40.2 m^3/ha. This volume is consistent with the assumption that there can be an average one truck-load of biomass per hectare harvested, seeing as a truckload of wood in Ontario is typically about 40 m^3. This harvesting factor ensures that there is still a sufficient volume of coarse woody debris and "logging slash" left on-site to ensure nutrient retention on-site and avoid site degradation by removing biomass, which will decompose and provide vital nutrients to the future forest. This factor also meets the Ontario Forest Management Guide for Natural Disturbance Pattern Emulation requirements, as long as this practice is avoided in areas with shallow soil, which are susceptible to nutrient loss (OMNR 2002).

5.1.3 Implications

This research published in Alam et al. (2012) and Reynolds et al. (2008), as well as supplemental data in Bilyk (2009) and Gautam (2010), suggest there is sufficient FHR available in NWO to support the biomass power generating plants (TB CHP and AGS). The data also suggests there is potential for increased use of UW, due to the sufficient quantity of volume, providing another form of feedstock to the plants. Currently, both plants within reasonable proximity of the 2 FMUs analyzed are running as peaking or supplemental generating stations, where the Resolute CHP burns a combination of mill residue and FHR to power the operations in Thunder Bay, while partially contributing to the grid. While the Atikokan Generating Station annually runs under capacity on residential size wood pellets. Based on availability, the data suggests there are sufficient quantities of feedstock to increase biomass energy production. The data also suggests there may be a basis to reinvestigate the closure of the Thunder Bay Generating Station, which was officially closed in 2018. The plant requires $5 million dollars in boiler repairs but was also converted to burn a specialized pellet sourced from Europe. Based on the economic feasibility models as well as the availability and economic potential, there may be a basis for adding additional capacity to the provincial bio-energy sector by reopening the plant. Future research needs to be done using updated FRI data as well as in procurement efficiency to determine if it is economically feasible to establish more biomass energy generating stations in NWO, but this data suggests there could be the feedstock required to support increased power generation from forest biomass.

5.2 Efficiency / Quality of Biomass

A fuel quality assessment investigates the properties which affect the energy yield. Common qualities assessed include moisture content, heat value, and ash content (Petterson and Nordfjell 2007). Thermal properties and the energy potential in biomass are typically measured in Gross Calorific Value (GCV) and Net Caloric Value (net CV). Calorific value (CV) is a measure of heating power and represents the amount of energy released when a fuel is completely combusted under specific laboratory conditions (Trossero 2001). This value is important to determine the energy production capacity of each species. Based on the fuel quality data obtained from Hosegood (2010) and Gautam (2010), the average fuel characteristics from North Western Ontario were compiled to evaluate the effects of geography on fuel quality. Based on these two studies, which took place in the eastern and western portions of the study area, it was determined that there is little geographic variation in fuel quality in NWO. This assumption allows for the data to be analyzed as one dataset. The average thermal potential of the sampled biomass provides insight into the thermal potential of available biomass per hectare, which provides the basis for a cost analysis. Based on the thermal values within the dataset, there is sufficient thermal potential of biomass for energy production, with the average thermal value being within a range of 20.65 Mj/kg to 21.28 Mj/kg. This dataset has demonstrated that the fuel characteristics in northwestern Ontario are conducive to supporting a profitable bioenergy sector. Calorific value, specific gravity, and ash content of northwestern trees were all shown to meet or exceed previously published data while providing an accurate depiction of biomass energy potential in the region.

5.2.1 Implications

Increasing efficiency is key in the continued growth and diversification of the forestry sector. In the present market situation, optimal utilization provides auxiliary sources of income in order to minimize waste and maximize profits from a limited land base. Currently, there is decreasing room for errors while managing a forest due to increased public and private interests. Growing the established bioenergy sector in Ontario must be as efficient as possible with the implementation of extensive planning and modeling to ensure the profitability and efficiency of all new ventures within this sector. The fuel characteristics within this dataset can be instrumental in the implementation of proper planning and estimations of forest harvesting residues and their respective thermal potentials. By modeling the thermal potential of each block, harvesting operations can be efficiently planned and executed in the most cost-effective manner and can be used to forecast supply to meet growing demands. Future research should be focused on sampling other FMUs using similar compartmentalized analysis as was done in Hosegood (2010) to determine the thermal potential of individual tree components, which can then be used to more accurately forecast actual thermal yield from individual blocks rather than averages. Through the use of waste and residue scaling to determine FHR volume species composition and distribution of FHR components from the respective species present, models will be able to accurately forecast the weighted thermal potential for individual blocks and harvest operations.

5.3 Economic Feasibility

In order to successfully grow the bioenergy sector, FHR acquisition must be economically feasible, while thermal potential must be high enough to remain profitable. Based on the objectives of availability and quality of biomass, relevant literature has been combined to determine both objectives have been adequately met. Economic feasibility is highly dependent on the amount of integration and optimization of acquisition and transportation from the forest to the powerplant. Based on the costing data compiled, there is sufficient thermal potential to offset the costs of hauling within a reasonable distance. This cost-effective hauling radius is highly geographically dependent, and with integrated road maintenance could be reduced by optimizing road networks. The overall cost of acquisition for the Resolute CHP and the Atikokan Generating Station if they were to run exclusively of FHR and UW procured in the region would be $33,726,000 and $8,822,000 per year, respectively. If sufficient power distribution contracts can be procured for both facilities or any new facilities in the future, the acquisition cost would likely be offset by the power distribution revenue. In order to operate profitably, an economy of scale must be reached to ensure the optimal allocation and use of all resources procured for the plant to avoid sunk costs due to inefficient transportation. Based on the amount of technically available FHR and UW determined in Alam et al. (2012) and the monthly consumption of an average Canadian household of 1000Kwh (OEB 2020), Biomass energy in the region has the potential to power approximately 5700 households in the region annually exclusively from forest-based biomass energy. Once optimized, with the use of forestry 4.0 or other technological integrations, there is sufficient data to suggest the feasibility of a cost-effective, renewable forest-based energy sector.

5.3.1 Implications

Due to the lack of complete data on energy production costs, operating costs, and other inherent costs, a complete economic feasibility analysis remains incomplete. More research on supply chain optimization coupled with increasingly accurate species composition and post-harvest surveys could provide an accurate depiction of the costs and profitability of biomass energy production in the future. With the continued development of forestry 4.0, a fully integrated, connected supply chain optimization, biomass energy has a high potential for growth in both production capacity and profitability. By continuing to acquire relevant data and increasing sampling, a more accurate forecasting model can be created which will be able to use weighted averages, operational costs, and supply chain efficiency to predict and model biomass energy production in the future.

Conclusion

The research findings show that there are sufficient FHR and UW biomass feedstocks available in NWO to run the four major power generating plants sustainably. There is enough FHR to produce bioenergy in NWO sustainably based on the inventories compiled. The species composition across the FMUs in the research area is almost similar (OMNR 2011). As the forest inventory conducted by Reynolds et al. (2008) in the Black Sturgeon Forest (in the eastern part of research area) and the forest inventory in the Crossroute Forest (in the western part of research area) found similar residue volumes, we assume for the purpose of this study that there is no major difference in woody biomass availability per hectare harvested between eastern and western parts of the study area. In the future, as additional similar pre- and post-harvest studies are conducted, better precision in the data can be developed. Woody biomass feedstock from some areas (which are farther from power plants) in the research area will not be economically available due to cost resulting from excessive transport distances. This study has found that it is economically feasible to increase biomass energy production in the region, although increased integration and data acquisition is needed to accurately model the supply chain. Based on these results bioenergy has the potential to meet the increasing demand for renewable energy in Ontario with sufficient quantities available, adequate quality of fuels and economically feasible acquisition.

Work Cited

Alam M.B., Pulkki, R. and Shahi, C. 2008. Forest biomass availability in northwestern Ontario. In: Council on Forest Engineering: Addressing Forest Engineering Challenges for the Future. June 22-25, 2008, South Carolina, USA.

Bowyer, J.L.; Shmulsky, R.; Haygreen, J.G. 2007. Forest products and wood science: An introduction. New York, NY: John Wiley & Sons. 576 p.

Bradley, D. 2006a. Canada Biomass- Bioenergy Report. Climate Change Solutions – IEA Bioenergy Task 40-Biotrade; Canada Country Report. http://bioenergytrade.org/t40reportspapers/0000009a190b6270c/0000009b0808e c301.html. Sept. 10, 2010.

Cassens D. and Maeglin R. R. 1987. Live-sawing low-grade red oak logs. Forest Products Journal Vol. 37(10): 49-53

CCFM. 2016. Bioenergy From Canadian Forests. Retrieved From: http://www.sfmcanada.org/images/Publications/EN/Bioenergy_EN.pdf. Retrieved: November 3rd 2019

Eckelman, C. A. 1996. Wood Moisture Calculations. FNR 156. 18pp

Esteban L, Gril J, Palacios De Palacios P, Casasus A. 2005. Reduction of wood hygroscopicity and associated dimensional response by repeated humidity cycles. Ann for Sci. 62:275 - 284.

FPInnovations FERIC. 2008. Forest feedstocks (biomass) tutorial. FPInnovations FERIC, 580 boul, Saint-Jean, Pointe-Claire, QC H9R 3J9, Canada

Forest BioProducts Inc. 2006. An Assessment of the Viability of Exploiting Bio-Energy Resources Accessible to the Atikokan Generating Station in Northwestern Ontario. Ontario Ministry of Energy: Final Report. Forest BioProducts Inc., 645 Queen Street East, 2nd Floor, Sault Ste. Marie, Ontario, Canada. Web source from: https://collections.ola.org/mon/14000/261875.pdf

Forest Products Laboratory. 2010. Wood handbook—Wood as an engineering material. General Technical Report FPL-GTR-190. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 508 p.

Gan, J. and Smith, C.T. 2006. Availability of logging residues and potential for electricity production and carbon displacement in the USA. Biomass and Bioenergy, 30: 1011-1020.

Gautam S, Pulkki R, Shahi C, Leitch M. 2010. Economic and energy efficiency of salvaging biomass from wildfire burnt areas of bioenergy production in northwestern Ontario: a case study. Biomass Bioenergy 34(11):1562 - 572

Gautam, S.H. 2009. Assessment of fuel quality changes during storage of biofibre and its effect on cost. Lakehead Knowledge Commons 2010 Retrieved from https://knowledgecommons.lakeheadu.ca/handle/2453/88?show=full

Goss, W.P. and R.G. Miller. 1989. Literature review of measurement and prediction of reflective building insulation system performance: 1900- 1989. ASHRAE Transactions 95(2).

Government of Ontario, Provincial Wood Supply Strategy 2019 Retrieved from https://www.ontario.ca/page/provincial-wood-supply-strategy Retrieved: Nov 3rd 2019

H. E. Desch J. M. Dinwoodie 1996. Timber Structure, Properties, Conversion and Use 7th edition, Macmillan Publishers Limited, New York, 306.

Hakkila, P. 1989. Utilization of Residual Forest Biomass. Berlin. Heidelberg, New York: Spring. 569 pp.

Huang, Y., Chen, C. W., and Fan, Y. 2010. Multistage optimization of the supply chains of biofuels. Transportation Research Part E: Logistics and Transportation Review, 46(6), 820-830.

IEA Bioenergy Task 40 Country Report Canada 2011 Retrieved from: http://task40.ieabioenergy.com/wp-content/uploads/2013/09/iea-task-40-country-report-2011-canada.pdf Retrieved Nov 1st 2019

International Energy Agency 2017 Technology Roadmap Delivering Sustainable Bioenergy Retrieved from: https://www.ieabioenergy.com/wp-content/uploads/2017/11/Technology_Roadmap_Delivering_Sustainable_Bioenergy.pdf

Kim, J., Realff, M.J., Lee, J.H., Whittaker, C. and Furtner, L. 2011b. Design of biomass processing network for biofuel production using an MILP model. Biomass and Bioenergy, 35: 853-871.

Kryla J. 1984. Determination of Available Heat of Combustion Data for Canadian Woody Species. ENFOR Project P-256

Leitch, Mathew 2019. Lecture 5a, 5b, 5c, 5d NRMT 3178

Marschner Stephen R. Westin Stephen H. Arbree Adam Moon Jonathan T. 2005. Measuring and Modeling the Appearance of Finished Wood. ACM Transactions on Graphics (SIGGRAPH 2005 Proceedings), 727–734 Cornell University

Meier, Eric 2019. Wood database web resource https://www.wood-database.com/wood-articles/dimensional-shrinkage/

Miguel A. Trossero, Luiz Horta Nogueira, Tina Etherington, Robert Flood. 2001. UNIFIED WOOD ENERGY TERMINOLOGY UWET, Food and Agriculture Organization of the United Nations, Retrieved from: http://www.fao.org/3/j4504e/j4504e00.pdf

Miles Patrick D. Smith Brad. 2009. Specific Gravity and Other Properties of Wood and Bark for 156 Tree Species Found in North America. United States Department of Agriculture Forest Service Northern Research Station. Research Note NRS-38.

Nurmi, J. 1999. The storage of logging residue for fuel. Biomass and Bioenergy, 17: 4147.

Nurmi, J. 2007. Recovery of logging residues for energy from spruce (Pices abies) dominated stands. Biomass and Bioenergy, 31(6): 375-380.

Ontario Ministry of Energy (OME). 2007. Ontario Ministry of Energy website. http://www.energy.gov.on.ca. Sept. 16, 2007.

Panshin AJ, Carl De Zeeuw 1980. Textbook of Wood Technology: Structure, Identification, Properties, and Uses of the Commercial Woods of the United States and Canada. 2nd ed. New York, NY, USA, McGraw-Hill. 643pp.

Pettersson, M and T Nordfjell 2007. Fuel Quality changes during seasonal storage of compacted logging residues and young trees. Biomass and Bioenergy. 31: 782-792

Pulkki R. Minimizing negative environmental impacts of forest harvesting operations. In: Adamowicz W, Burton P, editors. Towards sustainable management of the boreal forest. Ottawa: National Research Council of Canada, NRC Research Press; 2003. p. 581 - 628.

Pulkki, R. 1997. Cut-to-length, tree-length or full tree harvesting? Central Woodlands 1(3): 22-37.

R.A. Sims, H.M. Kershaw and G.M. Wickware 1990. The Autecology of Major Tree Species in the North Central Region of Ontario Minister of Natural Resources Ontario. 1990, Catalog ID: 22213.

Rauch, P. and Gronalt, M. 2010. The Terminal Location Problem in the Forest Fuels Supply Network. International Journal of Forest Engineering, 21(2), 32-40.

Rogers K. 1981. Preharvest drying of logging residues. For Prod J. 31(12):32 - 36.

Siau J. Wood: influence of moisture on physical properties. Blacksburg, VA: Dept. Of Wood Sci.. and Forest Products, Viriginia Polytechnic Institute and State University, ISBN 0- 9622181-0-3; 1995.

Simpson W.T. 1984. Drying wood - a review. Drying Technology 235-264; 353-366. USDA Forest Service Forest Products Laboratory Box 5130 Madison, WI 53705 FPL-GTR-190.

Simpson, W.T. 1993. Specific gravity, moisture content, and density relationship for wood. Gen. Tech. Rep. FPL-76. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 13 p.

Thornley, P., Upham, P., Huang, Y., Rezvani, S., Brammer, J. and Rogers, J. 2008. Integrated assessment of bioelectricity technology options. Energy Policy, 37(3): 890-903.

Tsoumis George Thomas. Wood, plant tissue, thermal properties Encyclopedia Britannica 2019 Web resource https://www.britannica.com/science/wood-plant-tissue

V3-USA. 2017. Comparing quarter sawn, rift sawn and plain sawn flooring. Web resource http://www.v3-usa.com/learn/comparing-plain-sawn-quarter-sawn-rift-sawn-flooring/

Wang, J. 2007. Woody Biomass Resources, Utilization, and Opportunities in West Virginia, USA. Proceedings of the 3rd Forest Engineering Conference, MontTreblant, Quebec, Canada, October 1-4, 2007.

Appendix I

Data Compilation

Descriptions	Unit	Estimates	Source
Harvesting and processing costs of FHR	$/gt	26.00	OME 2006
Harvesting and processing costs of UW	$/gt	31.00	OME 2006
Average transport cost of woody biomass from productive forest Resolute TB	$/gt	21.90	Alam et al 2012
Average transport cost of woody biomass from depleted forest Resolute TB	$/gt	20.20	Alam et al 2012
Average transport cost of woody biomass from productive forest AGS	$/gt	20.18	Alam et al 2012
Average transport cost of woody biomass from depleted forest AGS	$/gt	18.11	Alam et al 2012
Biomass demand for Resolute TB CHP	gt/yr	730000.00	OPG
Biomass demand for AGS	gt/yr	200000.00	OPG
Total procument cost per year FHR TB*	$/gt	33726000.00	Alam et al 2012
Total procurment cost per year UW TB*	$/gt	38617000.00	Alam et al 2012
Total procument cost per year FHR AGS*	$/gt	8822000.00	Alam et al 2012
Total procurment cost per year UW AGS*	$/gt	10236000.00	Alam et al 2012
Average FHR Volume per ha	m3	41.24	Alam et al 2012
Average Thermal Value	MJ/kg	20.65	Hosegood 2010
FHR Green Metric Tonnes per ha	gt/ha	35.40	
Weight of 1 m3 (Simpson 1999)	kg	411.00	Simpson 1999
Weight of 1 m3 (Hosegood 2010)	kg	607.00	Hosegood 2010
Weight of 1 gt	kg	2000.00	Timber Measure
Average Thermal Potential per m3	MJ/m3	8485.49	Normand 2020
Average Thermal Potential per m3	MJ/m3	12532.09	Hosegood 2010
Average Thermal Potential per ha	MJ/ha	349928.73	Normand 2020
Average Thermal Potential per gt	MJ/gt	7450.26	Normand 2020
Average Thermal Potential per gt	MJ/gt	11003.18	Hosegood 2010
Conversion gt to m3	Ratio	0.88	Normand 2020
Conversion m3 to gt	Ratio	1.12	Normand 2020
Conversion green tonne to oven dry tonne	Ratio	0.50	Normand 2020

Average Thermal Potential per gt	MJ/gt	9520.72	Normand 2020
Average Green Tonne per ha	gt/ha	35.40	Normand 2020
Kwh per ha	Kwh/ha	73242.33	Normand 2020
Mj to Kwh	Kwh	0.28	Unit Conversion.org
Kwh per gt	Kwh/gt	2068.94	Normand 2020
Acquisition Cost per kwh TB	$/Kwh	0.02	Normand 2020
Average Acquisition cost Kwh AGS	$/Kwh	0.02	Normand 2020
FHR technically available	gt	15004140.00	Alam et al 2012
UW technically available	gt	53014019.00	Alam et al 2012
Biomass Total	gt	68018159.00	Normand 2020
Average FHR acquisition cost TB	$/gt	46.20	Normand 2020
Average FHR acquisition cost AGS	$/gt	44.11	Normand 2020
Energy production for TB	Kwh	1510323566.38	Normand 2020
Energy production for AGS	Kwh	413787278.46	Normand 2020
Cost of energy production for TB	$/Kwh	33726000.00	Normand 2020
Cost of energy production for AGS	$/Kwh	8822000.00	Normand 2020
1 m3 to gt	gt	0.88	Normand 2020
Average Volume per ha in m3	m3	40.32	Normand 2020
Average Thermal Potential	Mj	20.65	Normand 2020
gt per ha	gt/ha	35.40	Normand 2020
Truck load of biomass averge in gt	gt	35.12	Normand 2020
Average acquisition cost TB per ha	$/ha	1635.52	Normand 2020
Average acquisition cost AGS per ha	$/ha	1561.54	Normand 2020
Cost per Kwh/ha	$/Kwh/ha	44.78	Normand 2020
Average Thermal Value per truck load	MJ	135175.23	Normand 2020
Imperial tons to metric tonnes		0.91	Unit Conversion.org
Loose biomass truck load in tons	gt	16.00	Normand 2020
Chipped biomass truck load in tons	gt	20.00	Normand 2020
Loose biomass truck load in tonnes	gt	14.51	Normand 2020
Chipped biomass truck load in tonnes	gt	18.14	Normand 2020

Summary of Transport Cost

	Power Plant	Transport cost of woody biomass from productive forest ($/gt)			Transport cost of woody biomass from depleted forest ($/gt)		
		Mean	Median	Maximum	Mean	Medium	Maximum
Resolute Thunder Bay	RTB	21.9	22.03	49.09	20.2	19.64	39.76
Resolute Fort Frances	RFF	22.31	22.16	53.67	20.58	20.32	53.19
Atikokan Generation Station	AGS	20.18	19.69	48.05	18.11	17.41	47.56
Domtar Dryden Power Plant	DDPP	18.82	17.76	50.98	17.39	16.44	50.49

Alam et al 2012