FEASIBILITY OF UTILIZATING WOOD DEBRIS FOR BIOFUELS IN NORTHWESTERN ONTARIO

by

Eric J. Reist

FACULTY OF NATURAL RESOURCES MANAGEMENT
LAKEHEAD UNIVERSITY
THUNDER BAY, ONTARIO

April 25, 2017

FEASIBILITY OF UTILIZATING WOOD DEBRIS FOR BIOFUELS IN NORTHWESTERN ONTARIO

by

Eric J. Reist

Supervisor: Dr. M. Leitch

Second Reader: Dr. R. Pulkki

Faculty of Natural Resources Management
Lakehead University

April 25, 2017

LIBRARY RIGHTS STATEMENT

In presenting this thesis in partial fulfillment of the requirements for the H.B.Sc.F. degree at Lakehead University in Thunder Bay, I agree that the University will make it freely available for inspection.

This thesis is made available by my authority solely for the purpose of private study and research and may not be copied or reproduced in whole or in part (except as permitted by the Copyright Laws) without my written authority.

Signature: ________________________________
Date: ____________________________________

A CAUTION TO THE READER

This H.B.Sc.F 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 are those of the student and do not necessarily reflect the opinions of either the thesis supervisor, the faculty or Lakehead University.

ACKNOWLEDGEMENTS

First and foremost, I would like to thank my supervisor and second reader Dr. Mathew Leitch and Dr. Reino Pullki for their assistance and guidance during this process. Secondly, I would like to thank my family for their unwavering faith in me and this project. Finally, I would like to thank the Faculty of Natural Resources Management for selecting me to go on an international field school to Sweden that inspired me to do this topic.

CONTENTS

ABSTRACT

Reist, E.J. 2017. Potential Utilization of Biomass for Biofuels in Northwestern Ontario. 60 pp.

Keywords: Advanced Biofuels, Cellulosic Ethanol, Forest Residues, Thermochemical Conversion

In recent years' production of transportation biofuels generated from forest residues have grown rapidly on a global scale. Converting to advanced biofuels is enticing because they can help reduce dependence on oil; mitigate global warming; free up agricultural land and utilize waste wood. To encourage advanced biofuel production, Canada can look to Countries like Sweden that provide subsidies for advanced biofuels. In this undergraduate thesis thermochemical conversion had the lowest average cost of production for all the studies that had techno-economic in the production of cellulosic ethanol at US$0.33/L.

TABLES

FIGURES

INTRODUCTION AND OBJECTIVE

In recent years' biofuels have been considered as a potential substitute for fossil fuels in transportation fuels, heat and power generation, because of its potential to reduce our carbon footprint as well as offering an interesting solution to waste disposal (Baratieri et al. 2009). Biofuels are fuels that are derived from biomass or bio-waste (BiofuelUK 2010). There are two main types of biofuels; first generation biofuels that use food crops as a feedstock, and second generation biofuels (advanced biofuels) where non-agricultural crops are used as feedstocks (BiofuelUK 2010). The term third generation biofuels have been used to describe biofuels that are derived from algae (BiofuelUK 2010). Biofuels from woody biomass have become increasingly enticing as a transportation fuel because they are a renewable resource that offers a solution to energy security, in turn reducing over reliance on fossil fuels. Additionally, development in this sector could promote a large number of jobs in Northwestern Ontario, promote product diversification for the forestry sector, and add an additional revenue stream. Biomass is unique because it is the only renewable source of liquid transportation fuel.

Biomass including chipper debris and slash are not currently being used for energy because of the lack of demand in the region. The end result is biomass becoming a cost rather than a potential product. Approximately 3.8 million cubic metres of chipper debris has been produced in Northwestern Ontario over the past 5 years (Buda et al. 2014). Chipper debris and delimber slash piles occupy around 3 and 5 percent of harvest block areas, respectively (Buda et al. 2014). Forests account for our largest source of cellulose comprising around 80% of our global source (Badger 2002). Biofuels based from food crops like corn take up productive agricultural land that can be used for growing food. Whereas, biofuels based off woody debris in lots of places is a waste product that is currently not being utilized. Other benefits of using second generation biofuels include decreased dependence on fossil fuel reducing GHG emissions (50-60%) and increased food security (Smith 2014).

However, the use of woody biomass as a feedstock for biofuel production does have trade-offs including: comparatively less efficient than fossil fuels, energy intensive production and expensive transportation costs of wood waste. Other problems associated with utilizing wood debris include nutrient cycling and soil productivity, maintenance of biodiversity, water quality, and wildlife habitat (Parker et al. 2010).

This undergraduate thesis will focus primarily on two types of biofuels, namely ethanol and biodiesel. Ethanol is a two carbon alcohol that is often used as a substitute for gasoline (Dale and Kim 2005). Ethanol is used as liquid fuel in two ways: E10 (a mixture of 10% ethanol and 90% gasoline by volume) and E85 (a mixture of 85% ethanol and 15% gasoline by volume) (Dale and Kim 2005). Biodiesel is a monoalkyl esters of long chain fatty acids that comes from renewable feed stock like vegetable oils and animal fats (Meher et al.2006).

OBJECTIVE

The objective of this thesis is to investigate the conversion of forest waste into biofuels in Northwestern Ontario (NWO). Although, research indicates there is a lot of potential for biofuels, it still faces many challenges. This study will aim to determine the feasibility of the conversion of woody biomass into transportation biofuels and to resolve if this growing sector can become more widespread across NWO. If so, what is the optimal feedstock(s), biofuel(s), and pathway(s) to accomplish this goal? If not, what must be achieved to produce biofuels from woody biomass in NWO?

LITERATURE REVIEW

Current Status of Lignocellulosic Biofuels in Canada

This section will be a comprehensive analysis of biofuels in Canada, including government subsidies and policies. Additionally, problems associated with the use of corn and other crops as a feedstock will be discussed. In 2007 former Prime Minister Stephen Harper began the ecoEnergy for Biofuels Program (NRCAN 2014). The program invested $1.5 billion dollars over a 9-year span to grow Canada's biofuel industry (NRCAN 2014). The program used a four step approach to accomplish this goal:

1. reduce the greenhouse gas (GHG) emissions resulting from fuel use,
2. encourage greater production of biofuels,
3. accelerate the commercialization of new biofuel technologies, and
4. provide new market opportunities for agricultural producers and rural communities.

Source: NRCAN 2014

Projects have incentives available to them for up to seven consecutive years (NRCAN 2014). The program is intended to provide stable and predictable funding to the most promising projects to grow the biofuels industry in Canada (NRCAN 2014). This is because the program makes an investment feasible by partially offsetting the risk associated with fluctuating feedstock and fuel prices (NRCAN 2014).

Currently, Canada has several incentives in place to encourage the production of advanced lignocellulosic biofuels. It is led by the Renewable Fuel Strategy (RFS 2006), which guarantees a 5% proportion of bioethanol for all ground transportation fuels and 2% proportion of biodiesel for ground transportation fuels and home heating fuels (Longstaff et al. 2015).

In Canada there are many funding opportunities for companies who would like to produce next generation biofuels in Canada (SDTC 2017). One of these funding opportunities is called the Next Generation Biofuels Fund, where Sustainable Development Technology Canada supports large scale market entry in the production of next generation biofuels (SDTC 2017). The fund will support up to 40% of the eligible project costs and it is repayable up to 10 years after the completion of the project (SDTC 2017). To be eligible for funding the project must fulfill the following criteria:

1. be a first-of-a-kind facility that primarily produces a next-generation biofuel at large demonstration-scale,
2. be located in Canada,
3. use a feedstock that are or could be representative of Canadian biomass, and
4. have demonstrated their technology at the pre-commercial pilot scale level.

Source: SDTC 2017

Other funding opportunities for biofuel projects from the Canadian

Government subsidies are an important tool in assisting the development and implementation of biofuels in Canada. However, they come at a very high cost, Canada spends roughly 300 million dollars every year on biofuel subsidies (Laan and Litman

2009). Globally, an estimated 100 billion dollars has been spent on biofuel subsidies since 2005 (Longstaff et al. 2015). Ethanol from corn based feedstock, the most common biofuel product in Canada, requires subsidies of between C$ 0.50 and C$ 0.70 per litre to replace an equivalent litre of fossil energy (Laan and Litman 2009). Moreover, the estimated cost of cellulosic ethanol would be approximately C$ 0.24–C$ 0.33, although this is still very costly it is important to note that it is less expensive than ethanol from a corn based feedstock (Laan and Litman 2009). To replace a litre of petroleum diesel with a litre of biodiesel was found to cost C$ 0.40–C$ 0.80 in subsidies (Laan and Litman 2009). Listed in Table 1. are the available subsidies for biofuel production in Canada.

Table 1. Subsidies available to support biofuel production in Canada.

Stage of Production	**Subsidy Type**
Research, development and demonstration	Grants and low-interest loans
Business planning	Grants for feasibility studies and market development
Plant construction	Grants and low-interest loans, accelerated depreciation
Production	Fuel tax exemptions, producer payments
Price support	Mandated biofuel blending requirements and tariffs
Distribution	Grants for storage and distribution infrastructure
Consumption	Tax-breaks for the purchase of biofuel-consuming vehicles, government procurement and dissemination of information to consumers

Source: Laan and Litman 2009

In North America two main types of feedstock are used in cellulosic ethanol production, the first being sourced from starch-based grains such as corn or sugar from sugarcane, and the second being based from cellulose or lignocellulose from woody parts of plants, trees, or manufacturing plant residues (Perez-Verdin. 2009). One of the main benefits of producing bioethanol is that it has a high octane level of 113. Therefore, it is one of the cleanest and least expensive octane enhancers available on the market today (Thomas and Kwong 2001). Biofuels based from food crops like corn take up productive agricultural land that can be used for growing food. This valuable farmland should be used instead for food production rather than biofuels. Concerns over food security and over land-use are considered some of the main advantages of lignocellusic based biofuels over first generation biofuels (Smith 2014).

Production of Biodiesel

Biodiesel can be formed through several pathways but is predominately produced by two methods, transesterification and esterification (Ng et al. 2008). These methods primarily use oils and fats as a feedstock rather than biomass (Ng et al. 2008). These oils are generally derived from animals and plants including soybeans, canola oil, animal fat, palm oil, corn oil, and even waste cooking oil (Christi 2007).

Biodiesel can also be made from woody residues using alcoholysis (Ng et al. 2008). Alcoholysis utilises oils extracted from wood during the pulping process and combines them with methanol and lipase to create biodiesel (Ng et al. 2008). Biodiesel can also be produced from biomass through gasification and creation of syngas (reference). Once the syngas is formed it can undergo the Fischer-Tropsch method to produce biodiesel (reference). A study conducted in the Netherlands tested 7 different production chains using biomass and converting it into biodiesel using the Fischer-Tropsch method (Faaiji et al. 2009). They estimated that on average biodiesel production would break even when oil prices rose above $75/barrel (Faaiji et al. 2009). They also concluded that the conversion of biomass to biofuels could reduce emission to 32-63g of CO_2/km (Faaiji et al. 2009). Furthermore, it can even be considered negative if carbon sequestration is taken into consideration (Faaiji et al. 2009). Carbon sequestration is the capture of CO_2 that would have otherwise been released into the atmosphere (Herzog and Golomb 2004).

Cellulosic Ethanol Conversion from Biomass through Cellulysis

Currently, there are multiple methods to produce cellulosic ethanol, but they can be classified into two types, the first being though cellulysis and the second through thermo-chemical conversion. There are two main forms of cellulysis: enzymatic hydrolysis and acid hydrolysis (Badger 2002). Cellulysis converts lignocellulose crystalline structures into sugars through the use of enzymes or acids (EBTP 2016). The second main method to transform woody biomass into ethanol is through thermo-chemical conversion. Thermo-chemical conversion gasifies the feedstock and then converts it into ethanol through chemical catalysts or fermentation (Dwivedi et al. 2009)

Enzymatic Hydrolysis

Enzymatic hydrolysis uses enzymes which are biological catalyst to convert the woody biomass into a fermentable sugar (Perez-Verdin 2009). The chemical formula for fermenting C6 sugars is as follows: C6H12O6 ↔ 2 C2H5OH + 2 CO2 (EBTP 2016). The yeast used in the process is very similar to that used in wine, bread and beer (EBTP 2016). The sugar solution is then separated from other extractives including lignin so that it can be fermented (Dwivedi et al. 2009). Once the solution is converted to ethanol it undergoes distillation and dehydration to concentrate the ethanol. Below is a figure displaying the process.

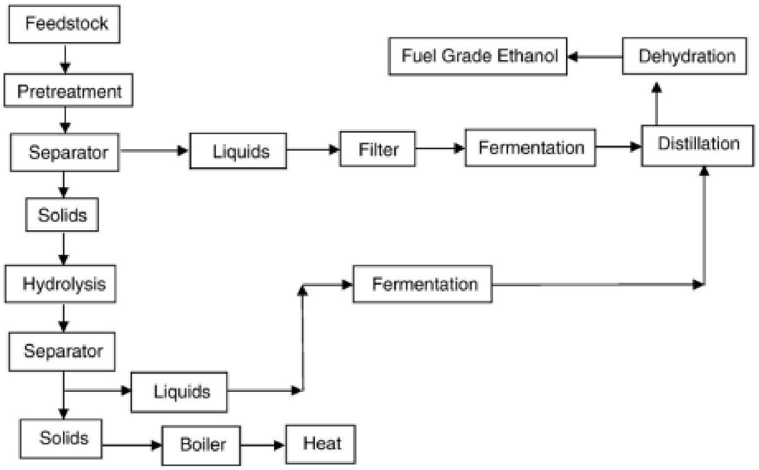


Figure1. A diagram depicting the process of producing ethanol through cellulysis.

Source: Dwivedi et al. 2009

In North America two main types of feedstocks are used in cellulosic ethanol production, the first being based from starch-based grains such as corn or sugar from sugarcane, and the second being based from cellulose or lignocellulose from woody parts of plants, trees, or manufacturing plant residues into sugars (Perez-Verdin. 2009). Outline in figure 2 are the six main steps of hydrolysis.

Pretreatment → Cellulysis → Separation of Extractives → Fermentation → Distillation → Dehydration

Figure 2. The six main steps of the enzymatic cellulysis process.

Source: Dwivedi et al. 2009

Acid Hydrolysis

There are two overarching types of acid hydrolysis: dilute acid and concentrated acid, both with multiple forms with variations (Badger 2002). The main differences are that the dilute acid process uses much higher pressures and temperatures with acid concentrations around 10 times less than concentrated acid hydrolysis (Badger 2002).

Sulphuric acid is the most common acid used in acid hydrolysis because it's relative abundance and affordability (Badger 2002). A major concern with acid hydrolysis is the degradation of equipment over time from the acids and without the use of an acid recovery unit a large quantity of lime must be used to neutralize the reaction (Badger 2002). The largest advantage of the dilute acid method over the concentrated acid is its fast rate of reaction, which allows for continuous processing. Whereas, the largest advantage of the concentrated acid approach is higher sugar yields with over 90% conversion, while the dilute acid approach only has yields around 50% (Badger 2002).

Cellulosic Ethanol Conversion from Biomass through Thermo-Chemical Conversion

Gasification is an enticing pathway to produce biofuels because of its flexibility (Dwivedi et al. 2009). Virtually any lignocellulosic material can be used as a feedstock (Dwivedi et al. 2009). The term lignocellulosic covers a range of plant molecules/biomass containing cellulose, with varying amounts of lignin, chain length, and degrees of polymerization. This includes wood from forestry, short rotation coppice (SRC) such as white birch or poplar, and lignocellulosic energy crops, for example grasses (Dwivedi et al. 2009). Below is a figure outlining the process of thermo-chemical conversion.

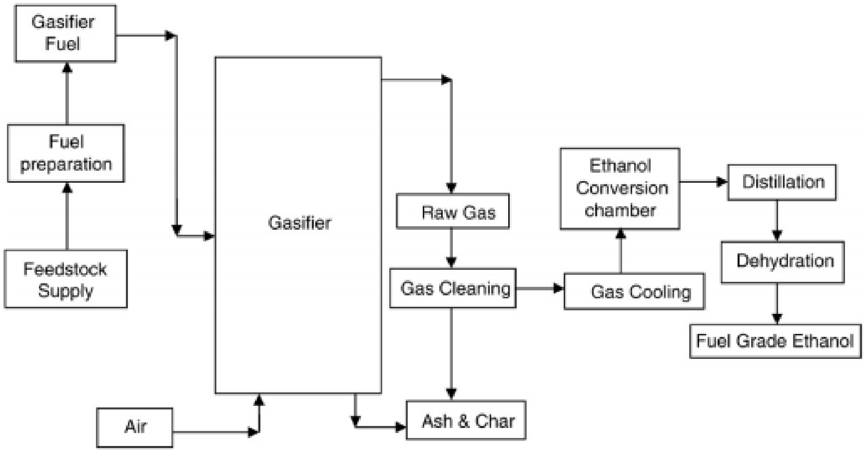


Figure 3. A diagram of cellulosic ethanol production through gasification.

Source: Dwivedi et al. 2009

Thermo-Chemical Conversion is another method to convert biomass into ethanol. It utilises the gasification process to convert the feedstock into syngas (Drift and Boerrigter 2006). Raw syngas is produced with the fluidized gasification process, which creates a mixture of mainly CO/H although it may contain other components including CO2, H2O, CH4 and other volatiles (Drift and Boerrigter 2006). Gasification heats feedstocks at 900-1300°C in an oxygen limited environment to prevent combustion and creates syngas (Drift and Boerrigter 2006). Following the conversion of the biomass into syngas, the syngas is either fermented or catalytically converted to obtain ethanol (Dwivedi et al. 2009).

Other Biofuels and Future Technologies

It is important to note that ethanol and biodiesel are not the only liquid biofuels, however aside from this section they will remain the primary focus of this study. Methanol, gasoline and jet fuel are also examples of biofuel products that can also be derived from biomass. Forest residues can be converted into hydrocarbons through the gasification process and then the Fischer-Tropsch method (EBTP 2016). The Fischer-Tropsch Method can convert feedstock like biomass, coal, and natural gas into liquid hydrocarbons (EBTP 2016). It utilizes a series of reactions that converts CO and H_2 into a link of hydrocarbons (EBTP 2016). Below is a figure outlining biomass-to-liquid and the potential biofuels that can be produced.

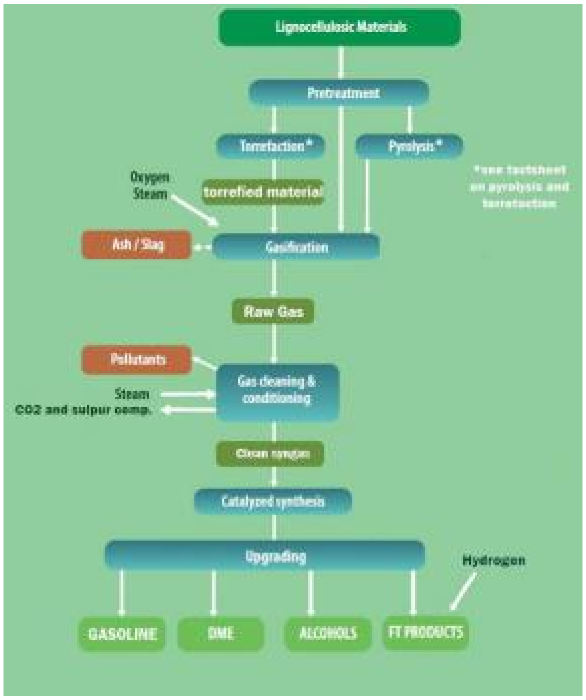


Figure 4. Various biomass-to-liquid pathways and value chain.

Source: EBTP 2016

Various biofuels such as ethanol, synthetics, methane and others can be created through a variety of pathways. Moreover, it is possible to produce biofuel intermediates such as bio-syngas (BioSNG), methanol, tall oil, dy-methyl ether, and biomass to liquids

(BtL) (EBTP 2016). Other products can be recovered from hydrolysis processing. An example of these co-products include animal feed, food ingredients, fibers, and solid fuels (EBTP 2016).

Biomass in Ontario

The forestry industry directly employs 50,900 people in Ontario and directly/indirectly employs approximately 152,700 people across 260 communities (Ontario 2014). Ontario’s forest sector was valued at 12.9 billion dollars in 2013 (Ontario 2014). Over 100 communities in Ontario are dependent on the forestry sector (Ontario 2014). The integration of biofuel production into Ontario’s forestry sector could prove to be a valuable decision.

Woody biomass is available in Ontario as forest harvest residues (FHR), and underutilized wood (UW) (Alam 2012). FHR are in the form of tree tops, branches and broken pieces left in the forest after harvesting operations (Alam 2012). UW are the tree species and non-merchantable wood, which are not considered commercially desirable (Alam 2012). Post-harvest inventories show that on average the theoretical availability of FHR in FMUs of NWO is approximately 60 $m^3 \cdot ha^{-1}$(Alam 2012). Although, leaving some biomass on site does have some benefits like adding nutrients to the soil and providing habitat to wildlife.

A case study in Sweden analyzed some of the environmental impacts of removing forest residues including tops branches and stumps. It classified the impacts in five categories including climate change, acidification, eutrophication, biodiversity and forest productivity (IEA Bioenergy 2014). Additional soil disturbance such as compaction and rutting is more likely to occur if additional machinery is required to collect forest residues

(IEA Bioenergy 2014). This could contribute to the alteration of the carbon pool in the soil or even the release of methane and nitrous oxides (IEA Bioenergy 2014). Soil acidification and decreased forest productivity is also a possible impact of removing nutrient rich forest residues (IEA Bioenergy 2014). Mercury methylation is also a possible risk from increased soil disturbance due to stump removal and machinery (IEA Bioenergy 201). The study also stated that loss of harvest residue contributes on some level to biodiversity loss due to its functions as substrate and habitat (IEA Bioenergy 2014). Finally, they suggested that ash (a by-product from many of the conversion processes of forest residues to biofuels) could be used to supplement some of the nutrient loss if returned to the site. This may lead to increased risk of nitrogen leaching (IEA Bioenergy 2014). A study done by a Lakehead masters student in 2013 found that there is little net nutrient loss when woody biomass is removed from a site as long as needles and leaves were left on site (Symonds 2013). All of these factors and more must be taken into account when determining how much forest residue can be removed.

It is important that the ecological integrity is not undermined. This is why using a 0.67 harvesting factor converts the actual availability of each type of woody biomass to an average 40.2 $m^3 \cdot ha^{-1}$ (Alam 2012). However, this is not necessarily a consistent source and contains a high degree of variation including different species and types of FHR and UW. For example, this could include material like delimbed branches, tops and chipper debris. Because of the variation in debris, for example hardwoods versus softwood, feedstock will have different properties and components when tested as shown in Table 2.

Table 2. The range of different wood components between hardwoods and softwoods.

Wood components	Hardwood (%)	Softwood (%)
cellulose	40-50	40-50
hemicellulose	25-35	25-30
lignin	20-25	25-35
pectin	1–2	1–2
starch	trace	trace

Source: Dwivedi et al.2009

Moreover, even within the same species there will be a great degree of variation depending on what portion of the tree the feedstock came from. Forest residues actually have a very similar composition to other feed stocks (Wyman 1994). As seen in the figure 5. below the largest differences between woody biomass and other feed stocks is the higher lignin content and the higher cellulose content (Wyman 1994).

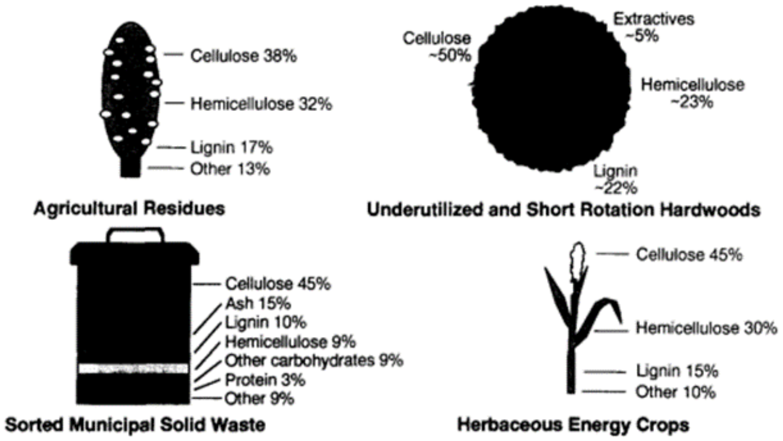


Figure 5. A comparison of the % contents within feedstocks for biofuel production.

Source: Wyman 1994

Possible Solutions to High Transportation Costs

Currently, the most cost effective use and available source of forest residues come as by-products from mills (CCFM 2016). For example, wood pellets source 88% of their feedstock from mill operations (CCFM 2016). These sources are much less expensive because they have already been transported and are readily available to be converted into another product. One of the main limiting factors preventing the production of transportation biofuels from wood residues is high transportation costs (reference). To transport forest residues that have low densities and high moisture contents over long hauling distances remains a challenge (CCFM 2016). This is why supply chain optimization will be key if biomass use is to be successful (Huang et al. 2010).

Some solutions have been proposed to help reduce some of the high transportation costs. Comminution can be defined as reducing the size of wood residues into finer particle sizes by means of chipping or pulverization (CCFM 2016). Simple things like chipping, grinding, or compacting can reduce the marginal costs by a significant proportion because it increases the density and therefore increases the efficiency (CCFM 2016). Another possible solution is the utilisation of a portable biorefinery to convert forest residues into an energy dense liquor (CCFM 2016). This process known as carbonization can be accomplished in the field with the use of portable truck-mounted units (CCFM 2016). The feedstocks undergo pyrolysis and are converted into energy dense liquids that can undergo further processing (CCFM 2016). Pyrolysis is the heating of biomass in an oxygen starved environment so that it decomposes (CCFM 2016). This process could drastically reduce transportation costs because instead of transporting large quantities of forest residues with low energy densities a company could potentially transport lower quantities of the energy dense liquor. One challenge is to produce a field unit that is durable enough to be in a forest environment and able to be moved in and around the forest. As seen in figure through the pyrolysis pathway, further processing of the resulting bio-oil could be converted into transportation biofuels such as biodiesel, cellulosic ethanol or even jet fuel (CCFM 2016). Pyrolysis could increase energy density about 6–7 times higher than the energy density of green whole tree chips at 45% and 56% moisture content (Czernik and Bridgwater 2004). Pyrolysis oil can be gasified and syngas can be utilized for ethanol production. This process could make secondary processing into biofuels like cellulosic ethanol much more economically feasible (CCFM 2016).

Projects in Sweden

Sweden is widely considered a world leader in sustainability and have taken initiatives to encourage transportation biofuel production and development. Sweden has set targets to become net GHG emissions free by 2050 (EBTP 2017). A large part of this initiative is cutting GHG emissions from the transportation sector. As of 2014 the market share of renewable energy used in the transportation sector was 12.5% (11.7 TWh, figure 6), an increase of 1.8% from 2013 (EBTP 2017). Sweden has had various tax exemptions/incentives to encourage biofuel production since the 1990's and now have a goal to have all vehicles fossil fuel free by 2030 (EBTP 2017).

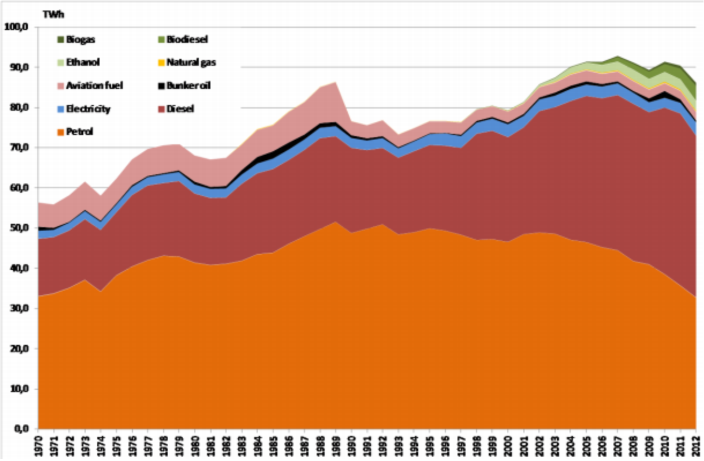


Figure 6. The use of fuels for transportation in Sweden from 1970-2012 measured in TWh.

Source: Waldheim Consulting 2015

The goal of decarbonisation of the transportation sector is going to be achieved through a variety of initiatives including an overall increase in investment by the Swedish government in the combination of electric vehicles and biofuels as seen in figure 7 below.

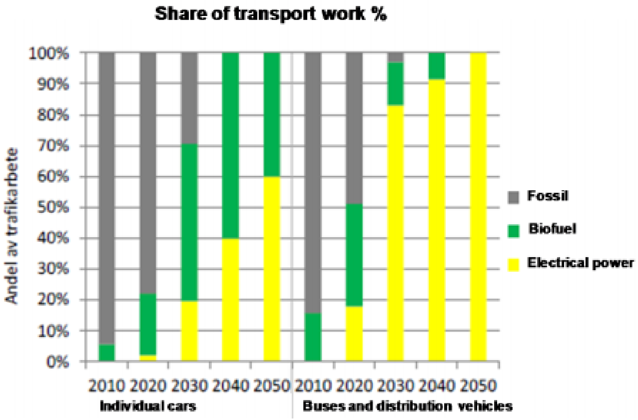


Figure 7. A display of the projected development of vehicle types in Sweden.

Source: Waldheim Consulting 2015

Sweden is planning on a major shift from fossil fuels to biofuels along with improvements in efficiency for the transportation sector overall (Waldheim Consulting 2015). Some of the changes include improvements in drivetrain efficiency for both electric and combustion engines in combination with infrastructure improvements (Waldheim Consulting 2015). The figure below shows the proportion of transportation biofuels in Sweden and their increase from 1995-2012 in the country.

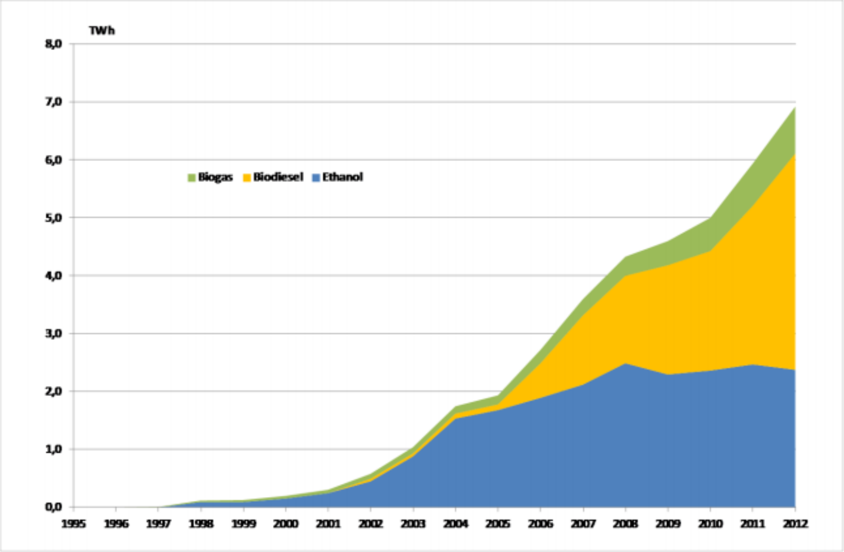


Figure 8. Proportion of market share for transportation biofuels in Sweden from 1995-2012.

Source: Waldheim Consulting 2015

The vast majority of transportation biofuels in Sweden are made up of biodiesel and ethanol with a small proportion of biogas (Waldheim Consulting 2015). Sweden set targets to increase 10 % renewable energy in the transport sector with the ultimate goal being that Sweden will be independent of fossil transport fuels in 2030 (Waldheim

Consulting 2015). The figure below is a map showing all planned, commercial and research and development projects surrounding gasification.

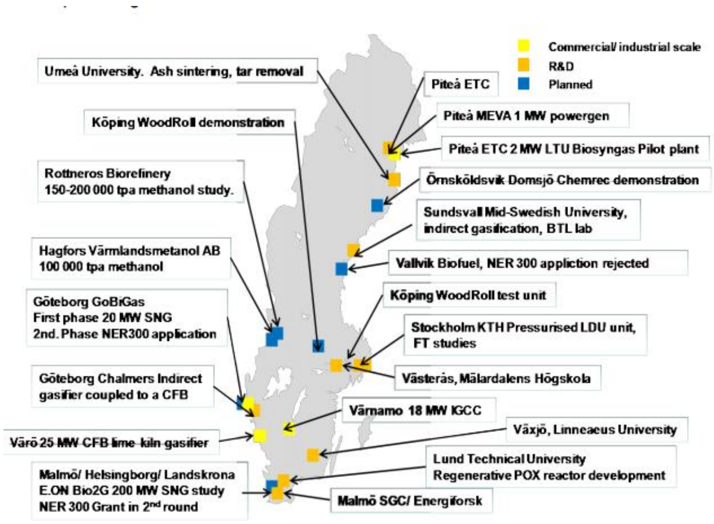


Figure 9. A map showing ongoing gasification projects in Sweden as of 2015.
Source: Waldheim Consulting 2015

Tax exemptions in Sweden for Biofuel

Similar to Canada, in Sweden certain biofuels are eligible for assistance from the Swedish government. This is meant to encourage the production of biofuels and increase their overall competitiveness with traditional fossil fuels. In Sweden fossil fuels are subject to a carbon tax and an energy tax (RES Legal Europe 2017). This includes the production, supply, and imports of all fossil fuels (RES Legal Europe 2017). All deductions biofuels are eligible for are summarized in table 3 below.

Table 3. A list summarising the available carbon and energy tax exemptions for transportation biofuels in Sweden.

Tax type	**Fuel Type** Ethanol from biomass used in low percentage blend	Ethanol blend in E85 and produced from biomass	Acid methyl esters (FAME) produced from biomass used in low-percentage blend in diesel	Biodiesel fatty acid methyl esters (FAME) produced from biomass used in high-percentage blend in motor fuel or sold or used as pure fuel	Biogas sold or used as a motor fuel
Energy Tax	88%	92%	36%	63%	100%
Carbon Tax	100%	100%	100%	100%	100%

Source: RES Legal Europe 2017

This system contrasts with many other countries that use a quota strategy to promote biofuels and create a competitive market instead of tax exemptions. Sweden currently does not have a quota system in place because according to state-aid rules a compulsory quota cannot be combined with tax exemptions (Waldheim Consulting 2015).

Global Production Trends

Transportation biofuels are growing rapidly on a global scale. As seen in the (figure 10) below biodiesel is approaching 20 billion litres with the EU producing the majority followed by the US and Brazil (Smith 2014).

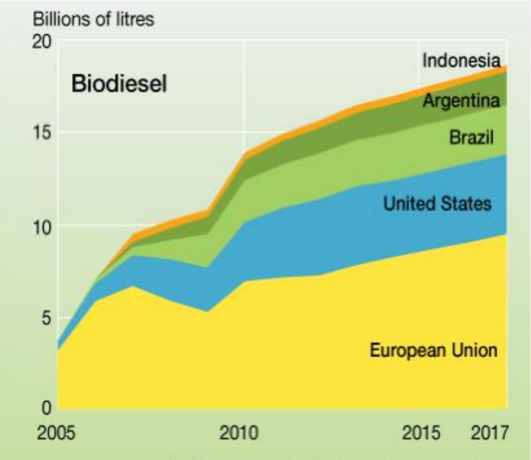


Figure 10. Global production trends of biodiesel (billions of litres).

Source: Smith 2014

Whereas, ethanol production is approaching 120 billion litres with the global leader is the US followed by brazil and then the EU as seen in (Figure. 11) below.

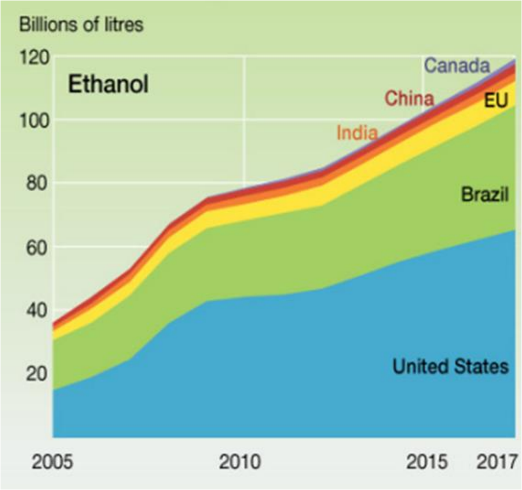


Figure 11. Global production trends of ethanol (billions of litres).

Source: Smith 2014

Many countries have mandated amounts for biofuels to be mixed into transportation fuels. As mentioned earlier Canada has a 5% mandate for bioethanol and a 2 % mandate for biodiesel (Smith 2014). However, in comparison to many other countries Canada has fairly conservative mandates as seen in the table below.

Table 4. Global mandates of required proportion of transportation biofuels measured in %.

Country	Proportion of renewable fuels mandated	Advanced biofuels mandated
Canada	Ethanol: 5% Biodiesel: 2%	
US	66 B L (9.7%) 144 B L by 2022	10.8 B L (1.6%)
EU	5.75% 10% by 2020	6% cap for first generation biofuels
China	10 provinces require 10% ethanol 15% by 2020	
Brazil	Ethanol: 18-20% Biodiesel: 5%	
India	Ethanol: 5% 20% by 2017	

Source: Smith 2014

This undergraduate thesis will aim to analyze some of the challenges in the production in advanced biofuels in Northern Ontario and determine what is the most cost effective method in the production of ethanol. This will be done by comparing various techno-economic analyses done from other authors. Additionally, trade-offs between the various pathways for bioethanol production will be determined.

METHODS

Data for this thesis was collected from a variety of sources and will be assembled to determine the feasibility of the utilization of chipper and slash debris as a potential feed stock for biofuels. Any other relevant information to help determine if biofuels are a viable product for wood waste was also gathered. This was accomplished primarily through reviewing literature surrounding biofuels such as biodiesel and cellulosic ethanol. Policies and methodology surrounding biofuels and their forest sector was also examined. Finally, through this meta-analyses all the required data will be synthesised to determine the most appropriate feedstock and pathway for the conversion of wood waste into biofuels for the forestry sector in NWO.

Cost Analysis was also conducted comparing cellulosic ethanol conversion technologies. Cost in US $/L was used to compare thermochemical conversion, enzymatic hydrolysis, acid hydrolysis with first generation biofuels such as corn starch and soybeans, this was then compared to the cost of producing petrol. These numbers were adjusted for inflation from the year the results were collected so that the results could be analyzed. Percent yield was also used to measure the conversion efficiency of the respective lignocellulosic conversion methods. The studies used for this process are the following: Foust, T. D., Aden, A., Dutta, A., and Phillips, S. 2009. An economic and environmental comparison of a biochemical and a thermochemical lignocellulosic ethanol conversion processes; Phillips SD. 2007. Technoeconomic analysis of a lignocellulosic biomass indirect gasification process to make ethanol via mixed alcohols synthesis; Gnansounou, E., Dauriat, A., and Wyman, C. E. 2005. Refining sweet sorghum to ethanol and sugar; Zhu, Y., & Jones, S. B. 2009. Techno-economic analysis for the thermochemical conversion of lignocellulosic biomass to ethanol via acetic acid synthesis; Frederick Jr WJ, Lien SJ, Courchene CE, DeMartini NA, Ragauskas AJ, and Lisa K. 2008. Production of ethanol from carbohydrates from loblolly pine: a technical and economic assessment; McAloon, A., Taylor, F., Yee, W., Ibsen, K., and Wooley, R. 2000. Determining the cost of producing ethanol from corn starch and lignocellulosic feedstocks; Thomas, C. E., James, B. D., Lomax, F. D., and Kuhn, I. F. 2000. Fuel options for the fuel cell vehicle: hydrogen, methanol or gasoline and Dien, B. S., Bothast, R. J., Nichols, N. N., and Cotta, M. A. 2002. The US corn ethanol industry: an overview of current technology and future prospects.

Global trends surrounding the biofuel industry were discussed along with Canada’s subsidy strategy in comparison to that of strategies implemented by other countries. Current challenges that the advanced biofuels industry will face along with some of the limitations that have hindered the growth of the advanced biofuels in the region. Finally, recommendations are made based on the findings of this undergraduate thesis.

RESULTS

Table 5. below summarizes the costing analysis done in this undergraduate thesis. It synthesizes data from multiple studies to compare production costs to produce ethanol by the means of multiple pathways and feedstocks, with one study focusing on the production of petrol as a benchmark.

Table 5. A table summarizing the studies and the conversion technologies and the associated costs of production measured in US $/L.

	Thermochemical conversiolon wood chips	**Enzymatic cellulysis corn stover**	**Thermochemical conversion hybrid poplar woodchips**	**Acid hydrolysis of poplar**	**Thermochemical conversion of wood chips**	**Dilute acid hydrolysis of lobolly pine**	**Enzymatic hydrolysis of corn stover**	**Corn starch to ethanol using dry mill process**	**Petrol Production**	**Corn starch to ethanol using dry mill process**
US $/L	0.32	0.35	0.28	0.76	0.63	0.34	0.4	0.23	0.2	0.25
Inflation adjusted US $/L 2017	0.36	0.39	0.33	0.85	0.72	0.38	0.58	0.34	0.28	0.34

Sources: Foust et al. 2010; Phillips 2007; Gnansounou and Dauriat 2010; Zhu and Jones 2009; Frederick et al 2008; USDA and US DE 1999; Thomas et al 2000; USDA 2002

Figure 12. below is a graphical representation of Table 5. averaging the studies into 5 categories of production: enzymatic cellulysis, acid hydrolysis, thermochemical conversion, corn ethanol, and petrol. The dry milling process for conversion of corn starch had the lowest average cost for producing ethanol among all studies examined with and average cost of US$0.34/L (USDA 1999; USDA 2002).

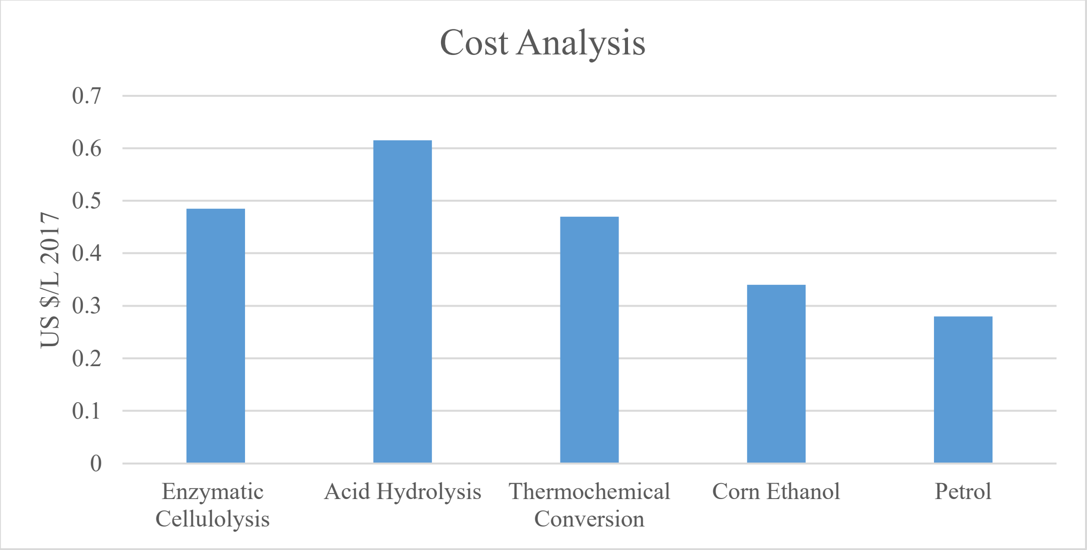


Figure 12. A figure displaying the average cost (US $/L 2017) for fuel production.

Sources: Sources: Foust et al. 2010; Phillips 2007; Gnansounou and Dauriat 2010; Zhu and Jones 2009; Frederick et al 2008; USDA and US DE 1999; Thomas et al 2000; USDA 2002

Table 6. is another representation of table 5. measuring cost of production measured for first and second generation biofuels. First generation biofuels were calculated to be US$0.18/L less expensive (Foust et al. 2010; Phillips 2007; Gnansounou and Dauriat 2010; Zhu and Jones 2009; Frederick et al 2008; USDA and US DE 1999; Thomas et al 2000; USDA 2002)

Table 6. Comparison of average costs associated with first and second generation biofuels.

	Second Generation Biofuel	First Generation Biofuel
Inflation adjusted US $/L 2017	0.52	0.34

Sources: Foust et al. 2010; Phillips 2007; Gnansounou and Dauriat 2010; Zhu and Jones 2009; Frederick et al 2008; USDA and US DE 1999; Thomas et al 2000; USDA 2002

Figure 13. below is a graphical representation of Table 5. averaging the studies into categories based on 3 feedstock sources: wood feedstock, corn feedstocks, and lignocellulosic feedstocks.

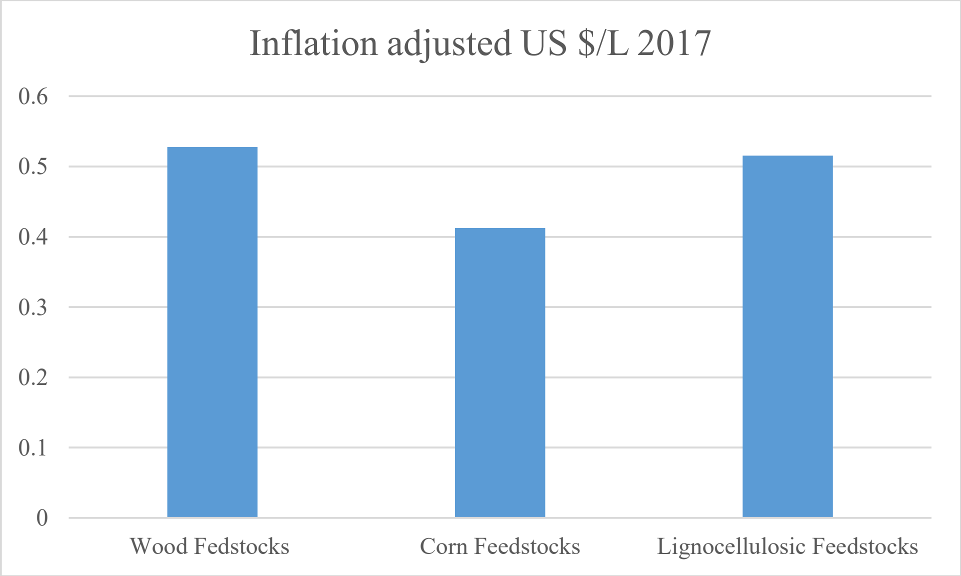


Figure 13. Cost comparison between wood feedstock, corn feedstock, and lignocellulosic feedstocks measure in US $/L.

Sources: Sources: Foust et al. 2010; Phillips 2007; Gnansounou and Dauriat 2010; Zhu and Jones 2009; Frederick et al 2008; USDA and US DE 1999; Thomas et al 2000; USDA 2002

Table 7. breaks down the percent glucose yield for the 3 types of hydrolysis: dilute acid, concentrated acid, and enzymatic. The concentrated acid had the highest yields followed by enzymatic hydrolysis and dilute acid hydrolysis (Hamelinck et al 2004).

Table 7. A comparison of % yield of glucose for the three methods of hydrolysis.

	Dilute Acid	**Concentrated Acid**	**Enzymatic**
% Glucose Yield	50-70	90	75

Source: Hamelinck et al 2004

Table 8. is a comparison of energy efficiency for 4 different types of lignocellulosic feedstocks: wood chips, corn stover, waste paper, and wheat straw using thermochemical conversion and enzymatic hydrolysis as methods to break down the feedstock into fermentable sugars. Wood chips had the greatest energy efficiency as a feedstock for both thermochemical conversion and enzymatic hydrolysis (Source: Mu et al. 2010)

Table 8. A comparison of energy efficiency (% ethanol) for multiple lignocellulosic feedtocks using both thermochemical conversion and enzymatic hydrolysis

	Wood Chips		**Corn Stover**		**Waste Paper**		**Wheat Straw**	
	Thermo	**Enzymatic**	**Thermo**	**Enzymatic**	**Thermo**	**Enzymatic**	**Thermo**	**Enzymatic**
Energy Effiency (as ethanol) %	41	38	36	35	36	31	36	30

Source: Mu et al. 2010

DISSCUSSION

This study is meant to give a general cost for the production of bioethanol and their respective conversion efficiencies. This study does not take into account the local conditions and differences in within these pathways. It is meant to give a general background into lignocellulosis ethanol and its conversion technologies in the context of Northern Ontario.

The main motivations behind the utilization of biofuels are global warming, energy security, food security. Rising temperatures and greenhouse gas accumulation should be a major concern for the Canadian Government. Ethanol-from-cellulose (EFC) holds great potential due to the widespread availability, abundance, and relatively low cost of cellulosic materials (Badger 2002). Tembo et al. (2003) noted that the breakeven cost for the ethanol produced using thermochemical-fermentation technology is around US$0.76/ gal or US$0.20/L. As technology continues to advance second generation biofuels will become more cost competitive with first generation biofuels and fossil fuels.

As seen in the results section in figure 12 petrol had the lowest cost at US$0.28/L when compared to other conversion technologies including thermochemical conversion, enzymatic hydrolysis, acid hydrolysis, and the dry milling process for conversion of corn starch (Thomas et al 2000). However, the price of petrol is heavily reliant on the price of oil therefore if the price of oil rises biofuel may become much more cost competitive. Biofuels become competitive with fossil fuel when oil prices rose above $75/barrel (Faaiji et al. 2009).

The dry milling process for conversion of corn starch had the lowest average cost for producing ethanol among all studies examined with and average cost of US$0.34/L (USDA 1999; USDA 2002). This is most likely due to the fact that it has been in commercial production for much longer than lignocellulosic ethanol. Furthermore, I believe it is in the best interest of the public to produce ethanol from lignocellulosic materials because unlike first generation biofuels it does not take up agricultural land.

Acid hydrolysis had the highest average production cost of US$ 0.62/L compared to enzymatic hydrolysis which only had a cost of US$ 0.48/L and thermochemical conversion that had a cost of US$/L (Foust et al. 2010; Phillips 2007; Gnansounou and Dauriat 2010; Zhu and Jones 2009; Frederick et al 2008). There was great disparity between the two studies that did costing analysis on acid hydrolysis. Gnansounou and Dauriat (2010) published a cost of US$ 0.76/L in 2010 looking into dilute acid hydrolysis using poplar chips as a feedstock whereas Frederick et al. (2008) published a cost of US$ 0.34/L using dilute sulphuric acid and loblolly pine as a feedstock. Table 7. compares % glucose yields between dilute acid hydrolysis, strong acid hydrolysis, and enzymatic hydrolysis. Strong acid hydrolysis had the highest glucose conversion rate at

90%, however this comes with tradeoffs because it takes much more time than the dilute acid process (Hamelick et al. 2004). The enzymatic hydrolysis had the second highest conversion rate at 75%, but similar to the concentrated acid process it remains very time consuming (Hamelick et al. 2004).

A study analyzing the cost of producing ethanol from wood chips through thermochemical conversion had the lowest cost of production for all the studies analyzed in the production of ethanol at US$0.33/L (Philips 2007). This was 1 cent/ L lower than both studies that produced ethanol from corn starch. Table 6. Was used for a cost comparison between first generation and second generation biofuels. First generation biofuels had an average lower cost at US$ 0.34/L whereas, second generation biofuels had an average cost of US$ 0.52/L (Foust et al. 2010; Phillips 2007; Gnansounou and Dauriat 2010; Zhu and Jones 2009; Frederick et al 2008; USDA and US DE 1999; Thomas et al 2000; USDA 2002).

Table 8. compares energy efficiency measured in (% ethanol) of wood chips, corn stover, waste paper, and wheat straw using both thermochemical conversion and enzymatic hydrolysis. For all four feedstock's thermochemical conversion had the higher energy efficiency over enzymatic hydrolysis. Furthermore, wood chips had the highest energy efficiency among all the feedstocks yielding 41% for thermochemical conversion and 38% for enzymatic hydrolysis. Figure 13. compares the average cost of wood feedstocks, corn feedstocks and lignocellulosic feestocks. Corn feedstocks had the lowest cost at a production rate of US$ 0.41/L with wood feesdtocks and lignocellulosic feedstocks remaining at a comparable cost of US$ 0.53/L and US$ 0.52/L respectively

(Foust et al. 2010; Phillips 2007; Gnansounou and Dauriat 2010; Zhu and Jones 2009; Frederick et al 2008; USDA and US DE 1999; Thomas et al 2000; USDA 2002).

Moisture content and degree of variation found within wood debris debris (Panshin and de Zeeuw 1980) will remain a challenge when attempting to utilize wood debris as a consistent feedstock. When wood is being harvested it will be still green and have a relatively high moisture content. Moisture content can drop in slash piles from 21.3% to 17.8% in the second drying season (Guatam et al. 2012). To remove the water from the feedstock will require a significant amount of energy. Therefore, money/energy could be saved if the wood waste was collected at a later date so it has had some time to decrease its MC. However, it must be collected before the wood begins to rot.

Challenges

For advanced biofuels and the utilization of woody biomass in the production to be successful in Northern Ontario, certain challenges must be overcome prior to market entry. One of the main challenges in the reduction of transportation costs because low value products with low energy densities are being moved long distances. Another concer is feedstock consistency. Feedstocks that utilize woody biomass tend to be variable by nature making it challenging to yield a consistent product. Moreover, if transportation biofuels are going to be produced on a commercial scale feedstock must be readily available for production. Another major challenge in transportation biofuels is the affordability and access to enzymes. This will need to be addressed if conversion pathways like enzymatic hydrolysis and catalytic conversion technologies are to be used in Northern Ontario. Finally based on the studies analyzed in this undergraduate thesis advanced biofuels appear to have an average higher cost than first generation biofuels.

For advanced biofuels to become more competitive with fossil fuels and first generation biofuels, conversion technologies must come down in production costs.

Opportunities

Despite the challenges I do believe there are many opportunities manufactures could explore for the production of advanced biofuels in Northern Ontario out of woody biomass. The use of wood to produce advanced biofuels will reduce GHG emissions. Reduce dependence on fossil fuels. Furthermore, if lignocellulosic materials are used in biofuel production it will increase food security by freeing up farmland that are being used to grow energy crops instead of food. The production of advanced biofuels in Northern Ontario would help diversify the forestry sector and possibly generate new jobs. Additionally, it is beneficial that it allows for a waste product that is taking up productive land to be utilized and converted into a product.

Recommendations

1. That Canada increase is mandated proportion of biofuels that must be incorporated with petrol (5% ethanol) and diesel/heating oil (2% biodiesel) and explore the possibility mandating a certain proportion to use advanced biofuels.
2. If advanced biofuels are going to produced in Northern Ontario manufactures should look to reduce their bottom line through the production of by-products and co-products.
3. That manufactures study the possibility of incorporating advanced biofuels into the pulping process as a means to cut transportation costs.

4. Portable gasification/ pyrolysis units should be field tested to see if they can potentially be used to reduce transportation costs.

Further Research

I would like to see a research/pilot project for the testing of forest residues in Northwestern Ontario and their potential conversion into transportation biofuels. Furthermore, it would also be interesting to look into portable pyrolysis/ gasification units as a means to reduce transportation costs.

CONCLUSION

Canada and Ontario should continue to explore opportunities to invest in advance biofuels because they can help reduce dependence on oil; mitigate global warming; free up agricultural land; utilize waste wood that is currently seen as a cost rather than a potential product; potentially generate new jobs in the forestry sector and diversify the forestry sector through the production of new products. Furthermore, I would like to see Canada increase its mandates for biofuel and potentially introduce a mandate for advanced biofuels similar to that which the European Union and United States currently have in place. However, this should occur until the near future when commercial production of advanced biofuels actually begins in Canada.

Thermochemical conversion was on average had lowest ethanol production costs for advanced biofuels. In addition to it's relatively low production costs for advanced biofuels it is very versatile because many lignocellulosic materials can be gasified and once it is gasified it can then be converted into a multitude of products. Advanced Biofuels currently not quite competitive with fossil fuels and first generation biofuels based on the studies analyzed. However, some studies most notably Philips (2007) cited production costs for thermochemical conversion that was competitive with both first generation biofuels and costs for petrol production.

Further research and field tests will be required to determine what production costs of ethanol or other biofuels would actually be in Northwestern Ontario. If this would occur, it would give a better idea of what local production costs may actually be. There are many challenges that will have to be resolved if transportation biofuels are to be commercially produced from wood waste in Northern Ontario, but if research continues to advance and conversion technologies become more affordable, I do believe advanced biofuels can be commercially produced from wood waste in Northwestern Ontario in the near future.

LITERATURE CITED

Alam, M. B. 2012. Modeling the woody biomass supply chain for energy production in northwestern Ontario (Doctoral dissertation, Lakehead University).

Badger, P. C. 2002. Ethanol from cellulose: A general review. Trends in new crops and new uses, 1, 17-21.

Baratieri, M., P. Baggio, B. Bosio, M. Grigiante and G. A. Longo. 2009. The use of biomass syngas in IC engines and CCGT plants: a comparative analysis. Applied Thermal Engineering. 29(16), 3309-3318.

Biofuels Uk. 2010. What are Biofuels. Retrieved From: http://biofuel.org.uk/what-are-biofuels.html

Buda, N., J, Lane., N. Buda, J. Lane, J. Harrison, D. Morris, G. Nishio, P. Poschmann and D. Reid. 2014. The Northwestern Ontario Chipper Debris Working Group. A Summary of Activities and Findings.

CCFM. 2016. Bioenergy From Canadian Forests. Retrieved From: http://www.sfmcanada.org/images/Publications/EN/Bioenergy_EN.pdf. Retrieved: September 27, 2016.

Czernik, S., and Bridgwater, A. V. 2004. Overview of applications of biomass fast pyrolysis oil. Energy & fuels, 18(2), 590-598.

Chisti, Y. 2007. Biodiesel from microalgae. Biotechnology advances, 25(3), 294-306.

Dale, B., and Kim, S. 2005. Life cycle assessment of various cropping systems utilized for producing biofuels: Bioethanol and biodiesel. Biomass and Bioenergy, 29(6), 426-439.

Dien, B. S., Bothast, R. J., Nichols, N. N., and Cotta, M. A. 2002. The US corn ethanol industry: an overview of current technology and future prospects. International sugar journal, 103(1241), 204-8.

Dwivedi, P., Alavalapati, J. R., and Lal, P. 2009. Cellulosic ethanol production in the United States: Conversion technologies, current production status, economics, and emerging developments. Energy for Sustainable Development, 13(3), 174-182.

European Biofuels Technology Platform. 2017. Biofulels-to-Liquid. Retrieved From:http://www.biofuelstp.eu/factsheets/EIBI-1-biomass-to-liquids.pdf

European Biofuels Technology Platform. 2017. Biofuels in Sweden. Retrieve From: http://www.biofuelstp.eu/factsheets/CountryFactsheets/EBTP_Factsheet_Sweden.pdf. Retrieved: January 5, 2017

European Biofuels Technology Platform. 2017. Sugars-to-Alcohols. Retrieved From: http://www.biofuelstp.eu/factsheets/EIBI-5-sugar-to-alcohols.pdfRetrieved: January 5, 2017

European Biofuels Technology Platform. 2017. Sugars-to-Alcohols. Retrieved From: http://www.biofuelstp.eu/biodiesel.html . Retrieved: January 5, 2017

Faaij, A. P., Van Vliet, O. P., and Turkenburg, W. C. 2009. Fischer–Tropsch diesel production in a well-to-wheel perspective: a carbon, energy flow and cost analysis. Energy Conversion and Management, 50(4), 855-876.

Foust, T. D., Aden, A., Dutta, A., and Phillips, S. 2009. An economic and environmental comparison of a biochemical and a thermochemical lignocellulosic ethanol conversion processes. Cellulose, 16(4), 547-565.

Frederick Jr WJ, Lien SJ, Courchene CE, DeMartini NA, Ragauskas AJ, and Lisa K. 2008. Production of ethanol from carbohydrates from loblolly pine: a technical and economic assessment. Bioresour. Technol.99:5051–7

Gautam, S., Pulkki, R., Shahi, C., and Leitch, M. 2012. Fuel quality changes in full tree logging residue during storage in roadside slash piles in Northwestern Ontario. Biomass and Bioenergy, 42, 43-50.

Gnansounou, E., Dauriat, A., and Wyman, C. E. 2005. Refining sweet sorghum to ethanol and sugar: economic trade-offs in the context of North China. Bioresource technology, 96(9), 985-1002.

Hamelinck, C. N., Van Hooijdonk, G., and Faaij, A. P. 2005. Ethanol from lignocellulosic biomass: techno-economic performance in short-, middle-and long-term. Biomass and bioenergy, 28(4), 384-410.

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.

Herzog, H., and Golomb, D. 2004. Carbon capture and storage from fossil fuel use. Encyclopedia of energy, 1, 1-11.

IEA Bioenergy. 2014. Consequences of an Increased Extraction Forest Biofuel in Sweden. Retrieved From: http://www.ieabioenergytask43.org/wp-content/uploads/2013/09/IEA-BIOENERGY-TR2014-1.pdf. Retrieved: November 15, 2016.

Klein- Marcuschamer, D., Oleskowicz- Popiel, P., Simmons, B. A., & Blanch, H. W. 2012. The challenge of enzyme cost in the production of lignocellulosic biofuels. Biotechnology and bioengineering, 109(4), 1083-1087.

Laan, T., Steenblik, R., & Litman, T. A. 2009. Biofuels--at what Cost?: Government Support for Ethanol and Biodiesel in Canada. International Institute for Sustainable Development.

Longstaff, H., Secko, D. M., Capurro, G., Hanney, P., and McIntyre, T. 2015. Fostering citizen deliberations on the social acceptability of renewable fuels policy: The case of advanced lignocellulosic biofuels in Canada. Biomass and Bioenergy, 74, 103-112.

McAloon, A., Taylor, F., Yee, W., Ibsen, K., and Wooley, R. 2000. Determining the cost of producing ethanol from corn starch and lignocellulosic feedstocks. National Renewable Energy Laboratory Report.

Meher, L. C., Sagar, D. V., and Naik, S. N. 2006. Technical aspects of biodiesel production by transesterification—a review. Renewable and sustainable energy reviews, 10(3), 248-268.

Mu, D., Seager, T., Rao, P. S., and Zhao, F. 2010. Comparative life cycle assessment of lignocellulosic ethanol production: biochemical versus thermochemical conversion. Environmental management, 46(4), 565-578.

NRCAN. 2014. ecoEnergy Biofuels Program. Retrieved From:http://www.nrcan.gc.ca/energy/alternative-fuels/programs/12358. Retrieved: December 10, 2016.

Ontario. 2014. Annual report on forest management 2012-2013. Retrieved From: https://www.ontario.ca/page/annual-report-forest-management-2012-2013. Retrieved; November 3, 2016.

Panshin, A. J., and Zeeuw, C. D. 1980. Textbook of wood technology. McGraw-Hill Book Co..

Perez-Verdin, G., D. L. Grebner, C. Sun, I. A. Munn, E. B. Schultz and T. G. Matney. 2009. Woody biomass availability for bioethanol conversion in Mississippi. Biomass and Bioenergy. 33(3), 492-503.

Phillips SD. 2007. Technoeconomic analysis of a lignocellulosic biomass indirect gasification process to make ethanol via mixed alcohols synthesis. Ind. Eng. Chem. Res. ;46:8887–97.

Parker, N., Tittmann, P., Hart, Q., Nelson, R., Skog, K., Schmidt, A., and Jenkins, B. 2010. Development of a biorefinery optimized biofuel supply curve for the Western United States. biomass and bioenergy, 34(11), 1597-1607.

Res Legal. 2017. Energy and CO2 Tax Exemptions in Sweden. Retrieved From:http://www.res-legal.eu/search-by-country/sweden/tools-list/c/sweden/s/res-t/t/promotion/sum/200/lpid/199/

Smith, D. 2014. Biofuels development in Canada and the US. Retrieved From: http://www.biofuelstp.eu/spm6/docs/don-smith.pdf. Date Retrieved: March 2, 2017. Retrieved: March 2, 2017.

Sustainable Development Technology Canada. 2017. NextGen Biofuels Fund. Retrieved From: https://www.sdtc.ca/en /funding/funds/nextgen Retrieved: October 2, 2016

Symonds, J., Morris, D. M., and Kwiaton, M. M. 2013. Effect of harvest intensity and soil moisture regime on the decomposition and release of nutrients from needle and twig litter in northwestern Ontario. Boreal Environment Research, 18(5), 401-414.

Tan, R. R., Foo, D. C. Y., Aviso, K. B., and Ng, D. K. S. 2009. The use of graphical pinch analysis for visualizing water footprint constraints in biofuel production. Applied Energy, 86(5), 605-609.

Thomas, C. E., James, B. D., Lomax, F. D., and Kuhn, I. F. 2000. Fuel options for the fuel cell vehicle: hydrogen, methanol or gasoline?. International Journal of Hydrogen Energy, 25(6), 551-567.

Thomas, V., and Kwong, A. 2001. Ethanol as a lead replacement: phasing out leaded gasoline in Africa. Energy policy, 29(13), 1133-1143.

Van der Drift, A. and H, Boerrigter. 2006. Synthesis gas from biomass for fuels and chemicals ECN Biomass, Coal and Environmental Research. Pp.13.

Wadheim, L. 2015. IEA Biomass Agreement Task 33 Country Report Sweden.

Wyman, C. E. 1994. Ethanol from lignocellulosic biomass: technology, economics, and opportunities. Bioresource Technology, 50(1), 3-15.

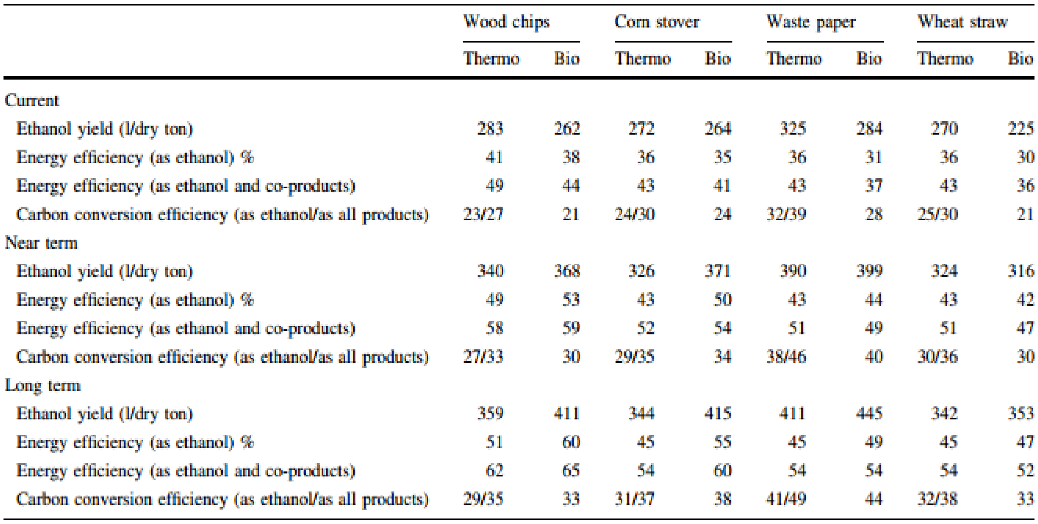
Yan, S., S. O. Salley, and K.S. Ng. 2009. Simultaneous transesterification and esterification of unrefined or waste oils over ZnO-La 2 O 3 catalysts. Applied Catalysis A: General. 353(2):203-212.

Zhu, Y., ans Jones, S. B. 2009. Techno-economic analysis for the thermochemical conversion of lignocellulosic biomass to ethanol via acetic acid synthesis. Retrieved: April, 1, 2017.

APPENDICES

Appendix I

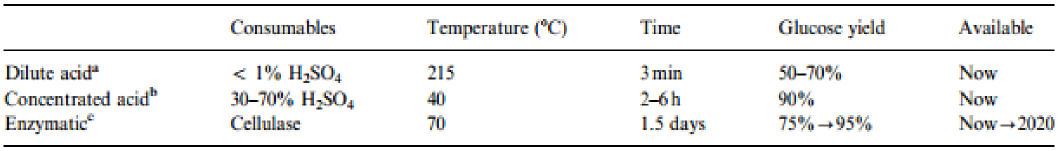
Table 9. A comparison of ethanol yields and efficiency between thermochemical conversion and enzymatic cellulysis using multiple lignocellulosic feedstocks.



	Wood chips		Corn stover		Waste paper		Wheat straw	
	Thermo	Bio	Thermo	Bio	Thermo	Bio	Thermo	Bio
Current								
Ethanol yield (l/dry ton)	283	262	272	264	325	284	270	225
Energy efficiency (as ethanol) %	41	38	36	35	36	31	36	30
Energy efficiency (as ethanol and co-products)	49	44	43	41	43	37	43	36
Carbon conversion efficiency (as ethanol/as all products)	23/27	21	24/30	24	32/39	28	25/30	21
Near term								
Ethanol yield (l/dry ton)	340	368	326	371	390	399	324	316
Energy efficiency (as ethanol) %	49	53	43	50	43	44	43	42
Energy efficiency (as ethanol and co-products)	58	59	52	54	51	49	51	47
Carbon conversion efficiency (as ethanol/as all products)	27/33	30	29/35	34	38/46	40	30/36	30
Long term								
Ethanol yield (l/dry ton)	359	411	344	415	411	445	342	353
Energy efficiency (as ethanol) %	51	60	45	55	45	49	45	47
Energy efficiency (as ethanol and co-products)	62	65	54	60	54	54	54	52
Carbon conversion efficiency (as ethanol/as all products)	29/35	33	31/37	38	41/49	44	32/38	33

Source: Mu et al. 2010

Table 10. Comparison of process conditions and performance of three cellulose hydrolysis process.



	Consumables	Temperature (°C)	Time	Glucose yield	Available
Dilute acid[a]	< 1% H_2SO_4	215	3 min	50–70%	Now
Concentrated acid[b]	30–70% H_2SO_4	40	2–6 h	90%	Now
Enzymatic[c]	Cellulase	70	1.5 days	75% → 95%	Now → 2020

Source: Hamelinck et al 2004

Appendix II

Table 11. Costing analysis for fuels measured in US$/L

	Foust et al 2010 thermochemical conversiolon wood chips	**Foust et al 2010 enzymatic cellulysis corn stover**	**Philips 2007 modeled cellulosic ethanol production through gasification technology and catalytic conversion of syngas to ethanol with hybrid poplar woodchips**	**Gnansounou and Dauriat 2010 with poplar as the feedstock using dilute acid hydrolysis**	**Zhu and Jones 2009 thermochemical conversion of wood chips acetic acid sythesis**	**Frederick et al 2008 conversion of hydrolysis using dilute sulphuric acid lobolly pine**	**Lignocellullosic corn stover conversion to ethanol through enzymatic hydrolysis 1999 by USDA and U.S Departement of Energy**	**Corn starch to ethanol using dry mill process flow 1999 by USDA and U.S Departement of Energy**	**Petrol C.E. Thomas et al 2000**	**Corn starch to ethanol using dry mill process flow 2002 by USDA 2002**
US $/L	0.32	0.35	0.28	0.76	0.63	0.34	0.4	0.23	0.2	0.25
Inflation adjusted US $/L 2017	0.36	0.39	0.33	0.85	0.72	0.38	0.58	0.34	0.28	0.34

Sources: Foust et al. 2010; Phillips 2007; Gnansounou and Dauriat 2010; Zhu and Jones 2009; Frederick et al 2008; USDA and US DE 1999; Thomas et al 2000; USDA 2002