University of Alberta

Bio-oil Transportation by Pipeline

by

Thanyakarn Pootakham

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

Master of Science

Department of Mechanical Engineering

Fall 2009
Edmonton, Alberta

Examining Committee

Amit Kumar, Mechanical Engineering

Marc Secanell, Mechanical Engineering

Rajender Gupta, Chemical and Materials Engineering

Abstract

Bio-oil which is produced by fast pyrolysis of biomass has high energy density compared to 'as received' biomass. Two cases are studied for pipeline transport of bio-oil, a coal-based and hydro power based electricity supplies. These cases of pipeline transport are compared to two cases of truck transport (trailer and super B-train truck). The life cycle GHG emissions from the pipeline transport of bio-oil for the two sources of electricity are 345 and 17 g of CO_2 m^{-3} km^{-1}. The emissions for transport by trailer and super B-train truck are 89 and 60 g of CO_2 m^{-3} km^{-1}. Energy input for bio-oil transport is 3.95 MJ m^{-3} km^{-1} by pipeline, 2.59 MJ m^{-3} km^{-1} by trailer, and 1.66 MJ m^{-3} km^{-1} by super B-train truck. The results show that GHG emissions in pipeline transport are largely dependent on the source of electricity; substituting 250 m^3 day^{-1} of pipeline-transported bio-oil for coal can mitigate about 5.1 million tonnes of CO_2 per year in the production of electricity. The fixed and variable components of cost are 0.0423 \$/m^3 and 0.1201 \$/m^3/km at a pipeline capacity of 560 m^3/day and for a distance of 100. It costs less to transport bio-oil by pipeline than by trailer and super B-train tank trucks at pipeline capacities of 1,000 and 1,700 m^3/day, and for a transportation distance of 100 km. Power from pipeline-transported bio-oil is expensive than power that is produced by direct combustion of wood chips and transmitted through electric lines.

Acknowledgments

I would like to express my gratitude to Dr. Amit Kumar for his supervision, advice and guidance during my research. I am also grateful to him for the training that he provided throughout the research work.

I would also like to thank members of *Sustainable Energy Research Laboratory* including Susanjib, Hossein, Jason, Veena, Arifa and Shikhar for sharing, advising and supporting me both in my academics and research work.

Table of Contents

List of Tables

List of Figures

List of Abbreviations

Symbol	Definition
hp	Horse power
DFC	Distance Variable Cost
DVC	Distance Fix Cost
Tpd	Tonne per day
km	Kilometer
kW	Kilowatt
kWh	Kilowatt-hour
PE	Polyethylene
HDPE	High-density Polyethylene
GHG	Green house gas
psi	Pound per square inch
kPa	Kilo Pascal
cSt	Centistoke
LHV	Lower Heating Value
HHV	Higher Heating Value
ha	Hectare

Chapter One: Introduction

1.1 Background and overview

Energy consumption around the world is increasing. This consumption is predominantly based on fossil fuel. The total energy consumption in the world consists of 37% of oil, 27% of coal, 23% of natural gas and 13% of other sources (EIA, 2009). In Canada, about 32% of total energy comes from oil, 24% comes from natural gas, and 10% comes from coal (Statistic Canada, 2007). Clearly, fossil fuel is the main energy source.

The issues of climate change and global warming are getting a lot of attention. One of the key causes of global warming is the indiscriminate release of greenhouse gases (GHGs). Fossil fuel use is associated with emission of GHGs. This has resulted in increased effort in research, development and commercialization of renewable energy sources which have much lower carbon footprint. They are clean and a have fast reproduction cycle as compared to fossil fuel. There are many renewable energy technologies (e.g., wind energy, solar energy, geothermal energy, biomass energy) which are at various stages of research, development and commercialization.

Among these renewable energy technologies, biomass based technology is one of the key options. This is considered nearly carbon neutral i.e. the amount of CO_2 released during combustion is nearly the same as taken up by a plant during its growth. Biomass can be used for the production of solid fuels (i.e., charcoal, pellets), liquid fuels (i.e., bioethanol, biodiesel, biooil), and gaseous fuels (such as biohydrogen, syngas). Different forms of biomass based fuels can be used to produce heat and power. Many biomass conversion pathways to fuels and energy are already mature. Examples are conversion of biomass (a) to heat and power (b) to pellets or charcoal (c) conversion of corn to ethanol. This research work is an effort to address one of the key barriers of using biomass based energy technologies.

1.2 Statement of Problem

Currently, most of the biomass based energy facilities are on smaller scale as compared to fossil fuel (coal) based plants. For example, biomass based power plants are in the range of 1-80 MW (EERE, 2006). There is only one biomass power plant which is 240 MW in capacity and is located in Pietarsaari, Finland (Flynn, 2005). Biomass utilization for production of bioethanol and biodiesel is also on small scale. Current high cost of production makes it uneconomic.

Biomass consists of a range of feedstocks. These can be forest or agriculture based biomass. Forest based biomass include whole forest chips, the forest residues produced during logging operations and mill residues. Main agriculture biomass includes wheat and barley based straw, corn stover (residue left after removal of corn), and animal manure. These feedstocks are called lignocellulosic biomass.

There are two key characteristics of lignocellulosic biomass feedstocks. First, biomass feedstock has a low energy density (MJ/m^3). 'As-received' biomass has an energy density one-eighths of coal (e.g. sub-bituminous). As a result of this, the cost of transportation of biomass per unit energy is high as compared to fossil fuel. This has been reported extensively in earlier studies (Kumar, 2003; Searcy, 2007). Another key characteristic is low biomass yield i.e. the amount of biomass obtained per unit area (dry tonnes per hectare) (Kumar, 2003). The biomass requirement is more than the fossil fuels for the same amount of energy. Due to low yield, the biomass needs to be collected from a larger area which increases the transportation distance. As a result of this transportation cost higher and is a major component of total biomass processing cost. One of the ways of reducing biomass delivered cost is by converting it into a form which has higher energy density and which can be transported on a large scale.

Biomass can be converted to a liquid fuel called bio-oil (Bridgewater, 1999; Dynamotive Energy System Corp., 1999; Yaman, 2004; Badger, 2006). Bio-oil is a dark viscous liquid and is similar to fuel oil grade 2. Bio-oil is produced by fast pyrolysis of biomass. Fast pyrolysis is the process of heating biomass in absence of air at a temperature of around 450^{o}C (Bridgewater, 1999; Dynamotive Energy System Corp., 1999; Yaman, 2004; Badger, 2004). Bio-oil has a higher energy density as compared to 'as received' biomass. Conversion of biomass to bio-oil and then its transportation to longer distance for end-use can improve the economic attractiveness of biomass based energy. The details on the bio-oil production technology and characteristics are given in subsequent chapters.

Currently, bio-oil is transported to end users by truck trailer (capacity of about 30 m^3) and B-train truck (capacity of about 60 m^3) (Logistics solution builders Inc, 2005). Truck transportation cost does not depend on the scale of transport i.e. the cost of truck transportation of bio-oil ($/liter) do not change if the amount of transport is 1000 liters or 100,000 liters. Pipeline transport of bio-oil can help in reducing the cost of bio-oil transport. Pipeline transport cost is affected by the economy of scale. This cost decreases with the increase in throughput of the pipeline. There is a scarcity of data on pipeline transport of bio-oil. This research work is aimed at investigating the feasibility of pipeline transport of bio-oil.

1.3 Objective of Study

The overall purpose of this research is to study the feasibility and viability of transportation of bio-oil. This research will not only compare the pipeline transport of bio-oil with truck on economic aspects but also on environmental footprint. The specific objectives of this research are divided in three broad categories.

Category 1 - Feasibility of bio-oil pipelines

- Assess the feasibility of pipeline transport of bio-oil.
- Investigate the barriers to pipeline transport of bio-oil and propose solutions to it.

Category 2 - Emission and energy analysis of bio-oil pipelines

- Estimate the life-cycle GHG emission (tonne of CO_2 emitted per liter of bio-oil per km) for the pipeline transport of bio-oil.
- Compare the life-cycle GHG emission from pipeline transport of bio-oil to truck transport of bio-oil.
- Carry out an energy balance for pipeline transport of bio-oil and compare this with truck transport of bio-oil.

Category 3 - Economics of pipeline transport of bio-oil

- Estimate the life-cycle cost of pipeline transport of bio-oil ($/liter).
- Compare the cost of pipeline transport of bio-oil with truck transport of bio-oil.
- Determine the range of sizes of bio-oil pipeline at which the cost of pipeline transport of bio-oil is lower and higher than the truck transport of bio-oil.

- Compare the cost of electricity production from pipeline transported bio-oil with the cost of electricity production from truck transported wood chips.

1.4 Scope and Limitation of Study

The study is limited to two bio-oil transportation modes. These modes include:

- Pipeline systems
- Truck systems

The life cycle assessment for emissions is limited to only greenhouse gases including carbon dioxide, nitrous oxide and methane during the manufacture and transport of bio-oil pipelines and trucks.

The bio-oil production technology is based on fast pyrolysis of biomass. This is based on the current technology being demonstrated by various companies (Dynamotive Energy System Corp., 1999; Badger, 2006) for bio-oil production.

The study has considered whole forest biomass from boreal forest as the feedstock source. The whole forest biomass includes whole tree including the branches and tops. The whole tree is chipped before it is used for bio-oil production.

1.5 Organization of Thesis

The thesis consists of five chapters. The current chapter gives the introduction to and the objective of this study. This thesis is a consolidation of papers, each chapter of which is intended to be read independently. As a result, some concepts and data are repeated.

The second chapter gives the life cycle assessment (LCA) of pipeline and truck transport of bio-oil along with the methodology of the LCA. The LCA includes estimation of both GHG emissions and energy balance for different unit processes.

The third chapter presents the economics of bio-oil transportation by pipeline and truck. This paper also presents an analysis on the range of size of pipeline for cost of pipeline transport of bio-oil is lower and higher than truck.

The fourth chapter presents the estimation of electricity production cost from pipeline transported bio-oil. It also shows the comparison in this case with the electricity production cost from truck transported wood chips.

Finally, the fifth chapter presents the conclusions and recommendation for future work.

1.6 List of Contributions

Following refereed publications and conference presentations are contributions based on the research described in this thesis.

<u>Refereed journal publications</u>

1. Pootakham, T. and Kumar, A. 2010. A comparison of pipeline versus truck transport of bio-oil. *Bioresource Technology*, Vol. 101(1), 414-421.

2. Pootakham, T. And Kumar, A. Bio-oil transport by pipeline: A techno-economic assessment, 2009 (in preparation).

3. Pootakham, T. And Kumar, A. Comparison of bioenergy transportation forms: electricity versus bio-oil, 2009, (in preparation).

<u>Conference presentations</u>

1. Pootakham, T. and Kumar, A. Bio-oil as a carrier for bioenergy, accepted for presentation at *the Bioenergy Engineering Conference 2009*, October 11-14, Bellevue, Washington, USA.

2. Pootakham, T. and Kumar, A. A large scale of bio-oil transportation, presented at *the American Society of Agricultural and Biological Engineerins (ASABE) 2008*, June 29 - July 2, Providence, RI, USA.

3. Pootakham, T. and Kumar, A. A comparison of pipeline versus truck transport of bio-oil, *the American Society of Agricultural and Biological Engineerins (ASABE) 2007*, June 17-20, Minneapolis, MN, USA.

4. Pootakham, T. and Kumar, A. Life cycle assessment of bio-oil transportation: pipeline VS truck, *BIOCAP Conference* 2006, October 31 - November 1, Ottawa, ON, Canada.

5. Pootakham, T. and Kumar, A. Bio-oil; the liquid biomass energy. InnoWest 2006, November 28-29, Edmonton, AB, Canada.

1.7 References

Alberta energy. Electricity statistics. Available at http://www.energy.gov.ab.ca/Electricity/682.asp. Accessed on October 2007.

Badger, P.C., P. Fransham. 2006. Use of mobile fast pyrolysis plants to densify biomass and reduce biomass handing costs - A preliminary assessment. Biomass and Bioenergy volume 30(4): 321-325.

Bridgewater, A.V., 1999. Principle and practice of biomass pyrolysis process for liquid. Journal of Analytical and Applied Pyrolysis. 51, 3-22.

Cameron, J.B., A. Kumer, and P.C. Flynn. 2007. The impact of feedstock cost on technology selection and optimum size. Biomass and bioenergy volume 31: 137-144.

Dynamotive Energy System Corp. 1999. BioTherm A system for continuous quality, Fast pyrolysis Bio-oil. Forth biomass conference of the America, Oakland, California. September 1999.

EERE. 2006. Electrical power generation. Available at http://www1.eere.energy.gov/biomass/electrical_power.html, Accessed on September 2007.

EIA, 2009. World energy and economics outlook 2009. Available at http://www.eia.doe.gov/oiaf/ieo/world.html. Accessed on May 2009.

Flynn, P.C. and Kumar, A. 2005. Site Visit to Alholmens 240 MW Power Plant Pietarsaari, Finland. Available at: http://www.biocap.ca/reports. Accessed on: May 2008.

Kumar, A. 2006. A conceptual comparison of using bioenergy options for BC's mountain pine beetle infested wood. BIOCAP Canada.

Kumar, A., J.B. Cameron and P.C. Flynn. 2003. Biomass power cost and optimum plant size in western Canada. Biomass and Bioenergy volume 24 : 445-464.

Logistics solution builders Inc. 2005. Operating cost of truck in Canada 2005. Transportation Canada File Number T8080-05-0242.

Statistics Canada. The daily; Energy supply and demand. 2003. Available at http://www.statcan.ca/Daily/English/031002/d031002a.htm, Accessed on September 2007.

Statistics Canada. Energy statistics handbook; January to March 2007. Catalogue No. 57-601-XIE. Available at http://www.statcan.ca/english/freepub/57-601-XIE/57-601-XIE2007001.pdf.

Searcy, E., Flynn, P., Ghafoori, E., Kumar, A., 2007. The relative cost of biomass energy transport. Applied biochemistry and biotechnology. 137-140; 1-12.

Yaman, S., 2004. Pyrolysis of biomass to produce fuels and chemical feedstocks. Energy conversion and management. 45; 651-671.

Chapter Two: A Comparison of Pipeline Versus Truck Transport of Bio-oil[1]

2.1 Introduction

The threat of climate change and global warming is behind the increased interest in developing renewable energy technologies. Among the various renewable energy sources, biomass has a particularly high potential. It can be used to produce a range of fuels and chemicals such as bioethanol (Aden et al., 2002), biogas (Katinas et al., 2007), biohydrogen (Sarkar and Kumar, 2009) and biopower (electrical power generated using biomass as fuel) (Kumar et al., 2004). These products can be produced from both forest-based biomass (e.g., whole tree, forest residues, limbs and tops of trees) and agriculture-based biomass (e.g., straw, corn stover). Technologies for the production of fuel and chemicals using these biomass resources are at various stages of development, demonstration and commercialization.

There are two main characteristics of biomass which are critical to its utilization for fuels and chemicals. First, biomass yield is low per unit area (i.e. dry tonnes of biomass per hectare). This increases the transportation distance of biomass and, hence the cost of transportation. Various studies have reported that the transportation cost is between 25 to 50% of the delivered cost of agricultural biomass used in ethanol production (Aden et al., 2002; Perlack and Turhollow,

---

[1] A version of this chapter has been accepted for publication in *Bioresource Technology* *Pootakham, T. and Kumar, A. 2009. Bioresource Technology.* Vol.101(1), 414-421..

2002; Kumar at al., 2005; Glassner et al., 1998; Atchison and Hettenhaus, 2003). Forestry biomass (e.g., whole tree biomass) has better yield per unit area compared to agricultural biomass residues. The second critical characteristic of biomass is its low energy density (MJ m^{-3}) compared to fossil fuels. Its energy density is about 1/8th of coal's. Low yield per unit area and low energy density compared to fossil fuels contribute substantially to the high cost of biomass energy.

Bio-oil, one of the fuels which can be produced from biomass, is a thick dark brown liquid produced from forestry and agricultural biomass. It has a high viscosity and low pH compared to crude oil at room temperature. Its pH is low because of the presence of various acidic components (Yaman, 2004). One of the most important characteristics of bio-oil, one pertinent to its utilization as an energy carrier and fuel, is its high energy density (MJ m^{-3}), which is 6 to 8 times that of "as received" biomass (Badger, 2003). The high energy density of bio-oil is one of the key reasons for the interest in converting biomass to this form.

Bio-oil is produced by fast pyrolysis of biomass in a reactor. Fast pyrolysis is the process of heating biomass in the absence of oxygen to a temperature of 400-600^{o}C. Biomass breaks down into volatile gases, char and water. The volatile gases are condensed to bio-oil, the non-condensible gases are used as a heat source for the pyrolysis process, and char is obtained as a by-product

(Bridgewater, 1999; Yaman, 2004; NREL, 2004; Shaw, 2006; IEA, 2007). Bio-oil can be used to produce electricity (Bridgewater, 1999; Yaman, 2004; Brammer, 2006; Steware, 2004; Badger, 2003) or various specialty chemicals (Yaman, 2004). Several companies produce bio-oil; for example, Dynamotive Energy Systems Inc. has a plant in Canada which uses 100 dry tonnes per day of biomass. Efforts are being made to use the produced bio-oil from this plant for electricity generation (Dynamotive, 2001). Other prominent companies that produce bio-oils are ENSYN Systems and Renewable Oil International (ROI) (IEA, 2007; Bridgewater, 2003; Steware, 2004).

Currently, bio-oil is produced in plants utilizing 100 dry tonnes or less of biomass per day. Bio-oil is transported by tanker trucks, although this form of transport does not have the potential benefit of economy of scale even if large scale transport (e.g., bio-oil from plants utilizing more than 100 dry tonnes of biomass per day) is required (Dynamotive Energy Systems Inc., 2008). Pipeline transport helps in large scale transport of bio-oil. Today, most of the crude oil is transported by pipeline, the transport costs benefit from economy of scale in capital cost. Pipelines are also beneficial for large scale transport over longer distances. This study focuses on the comparison of truck transport and pipeline transport of bio-oil based on life cycle emissions and energy consumption. The objectives of this study are to: assess the transport of bio-oil by pipeline, study the life cycle GHG emissions for truck and pipeline transport of bio-oil, and evaluate the energy requirements of bio-oil transport by truck and pipeline.

2.2 Bio-oil production and the transportation process

In western Canada, both agricultural and forestry-based ligno-cellulosic biomass is available for utilization in the production of fuels and chemicals. Agricultural biomass includes straw from wheat and barley. Forest biomass includes whole tree biomass from boreal forests and forest harvest residues generated during logging operations. In western Canada, most logging companies delimb trees on the roadsides in the forest. The stem is taken for utilization as pulp and lumber, leaving the remainder on the roadside. These residues are termed forest harvest residues (Kumar et al., 2003). In this study, we focus on the production of bio-oil using whole tree biomass from the boreal forest in western Canada. The whole tree is felled in the stand and skidded to the roadside, where it is chipped with a whole tree chipper; finally these chips are transported to a centralized plant by truck for the production of bio-oil. Bio-oil produced in the plant is transported to an electricity generation plant by truck or pipeline.

2.3 Pipeline transport of bio-oil

Bio-oil can be transported by pipeline. This is similar to the transport of crude oil by pipeline over long distances. Bio-oil is more viscous than crude oil at room temperature but, in a temperature range of 35 to 40^{o}C, its viscosity is very similar to that of crude oil (Thamburaj, 2000; Bridgewater, 1999; Menon, 2005). If bio-oil is transported by pipeline, the temperature throughout the pipeline should be maintained in the range of 35 to 40^{o}C to keep the viscosity similar to that of crude oil. In the bio-oil production process, volatile vapours formed by fast pyrolysis of biomass start to condense below 95^oC, producing bio-oil. This is cooled further to room temperature by quenching it with previously produced bio-oil which is at room temperature. In this study, we assume that bio-oil is transported by pipeline for 100 km and its inlet temperature in the pipeline is in the range of 85 to 95^oC, so its viscosity is similar to or even lower than that of crude oil. The temperature in the pipeline is maintained at 35 to 40^oC throughout. The pipeline is insulated with 3.8 cm (or 1.5 inch) thick polyethylene (PE) foam insulation, to maintain the temperature (ARNCO Corporation, 2005). For transport over longer distances, booster stations are required.

Another characteristic of importance for pipeline transport of bio-oil is its pH. Bio-oil has a pH of 2.2 to 2.5 (Yaman, 2004; Badger 2003). This characteristic plays an important role when choosing the pipe material. Carbon steel has corrosion problems at such a low pH. According to experts in pipe manufacturing, high density polyethylene (HDPE) can be used for this application as HDPE is corrosion resistant at this pH (Menon, 2005). In this study, we have assumed HDPE is the pipe material.

2.4 Life cycle assessment of bio-oil transportation

2.4.1 Scope definition

Life cycle assessment (LCA) was carried out for two modes of bio-oil transportation. Mode 1 involved transportation by liquid tank truck of bio-oil from the production plant to an end-user such as a power plant. Mode 2 involved transportation of bio-oil by a pipeline to an end-user.

The unit processes considered in the truck transportation of bio-oil are shown in Figure 2.1. These unit processes include: construction of infrastructure (mainly consists of highway construction); manufacturing of trucks; and, operation of trucks. For each of the unit processes, energy consumption and emissions were estimated. The study investigated two types of trucks: a liquid tank trailer having a capacity of 30 m^3, and, a liquid tank super B-train trailer (or double trailer) having a capacity of 60 m^3. These tanks were made of stainless steel because bio-oil is corrosive.

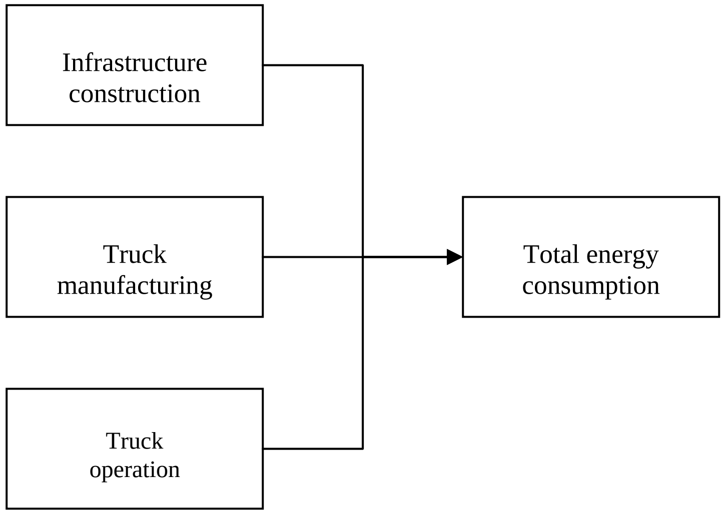

Figure 2.1: System boundaries for bio-oil transportation by truck

The unit processes considered in the transportation of bio-oil by pipeline are shown in Figure 2.2 These unit processes include: manufacturing and delivery of the pipe and pump system, manufacturing and delivery of polyethylene foam insulation, construction of the pipeline, and operation of the pipeline using electricity. For each of the unit processes energy consumption and emissions were estimated. Two cases of electricity generation were investigated for pipeline operation: electricity based on coal and electricity based on a renewable resource such as hydro power.

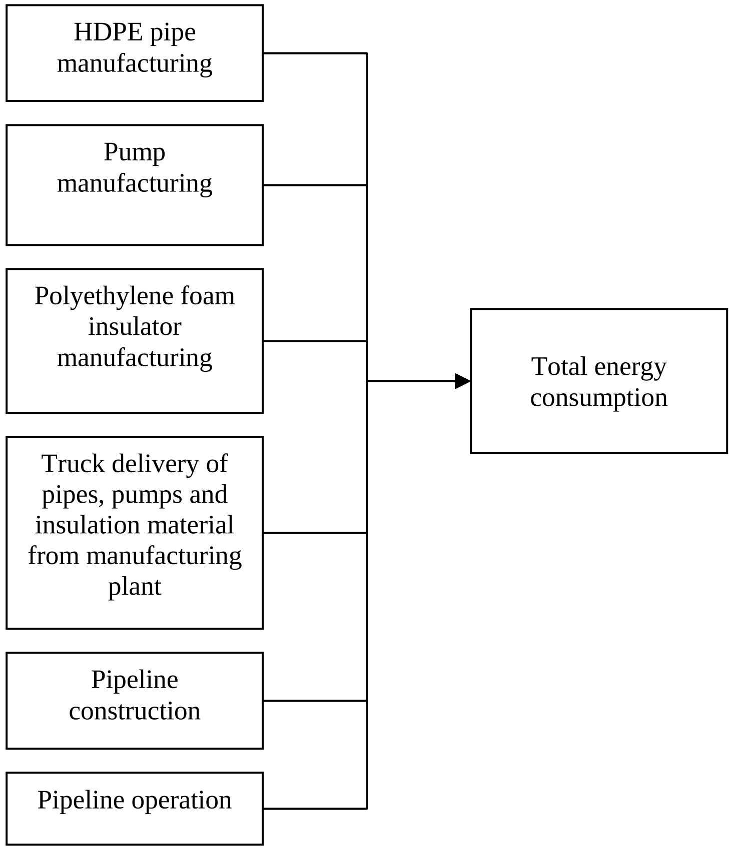

Figure 2.2: System boundaries for bio-oil transportation by pipeline

2.4.2 Data inventory and assumptions

2.4.2.1 Capacity and characteristics of bio-oil plants

In this study, we have assumed transport of bio-oil from a plant having a capacity of 400 dry tonnes per day. This size is based on previous design and feasibility studies and lab scale, and pilot scale testing (see, for example, Dynamotive Energy Systems Corporation, 2000; Freel and Graham, 2000; Biomass Technology Group, 2004; Grassi and Bridgwater, 1993; Juste and Monfort, 2000; Graham et al., 1994; Luo et al., 2004; Mullaney et al., 2002; Kumar, 2009).

Dynamotive Energy Systems Inc (Suite 140, 13091 Vanier Place, Richmond BC, V6V 2J1) is currently developing two plants in Ontario, Canada, one in Guelph and one in West Lorne. The Guelph plant started operating in January, 2008, and is in the very early stages of operation. Data from successful operation of these plants will be helpful in building a large scale plant (Dynamotive Energy Systems, 2008).

The yield of bio-oil depends on the type of feedstock used in its production. Various studies have suggested that the yield from biomass is in the range of 65 to 75% (Yaman, 2004; Dynamotive, 2000). We have selected a yield of 75% based on the values reported by Bridgewater (2003) and the demonstration scale testing of Dynamotive Energy Systems Inc (2008). Other input data on bio-oil plant capacity and characteristics, with assumptions, are given in Table 2.1. These data were used to determine the life cycle emissions and energy consumption given below.

Table 2.1: Input data and assumptions for bio-oil plant and truck transport

Items	Values	Comments/Remarks
Production capacity of bio-oil plant	400 dry tonnes day^{-1} of biomass	The largest bio-oil production plant available commercially is 100 dry tonnes day^{-1} of

Items	Values	Comments/Remarks
		biomass (IEA, 2007). A large scale plant would improve the economics (BTG, 2003).
Bio-oil yield	75% bio-oil, about 12% char, 13% gas	(Bridgwater, 2003). The process of bio-oil production is still changing and some studies report a lower yield (Wagenaar, 2003).
Density of bio-oil	1200 kg m^{-3}	(Dynamotive, 2000; Yaman, 2004).
Life of plant	20 years	Assumed.
Capacity factor of plant	90%	Percentage of time plant is running in a year.
Capacity of trucks 1. B-Train tank trailer 2. Liquid tank trailer	 60 m^3 30 m^3	The hauling capacity of the trailer and super B-Train liquid tank truck are average values. Some trailers and super B-trains might have a slightly different hauling capacity (TMIP, 2006). The power of engines for 60 m^3 and 30 m^3 are 354 kW (or 475 hp) and 283 kW (or 380 hp) (Transport

Items	Values	Comments/Remarks
		Canada, 2005).
Fuel used in operation of trucks	Diesel	

2.4.2.2 Capacity and characteristics of bio-oil pipelines

Based on the yield of bio-oil per unit of biomass (as discussed above), bio-oil pipeline capacity was calculated to be 250 m^3 day^{-1} from a 400 dry tonnes day^{-1} plant. For a suggested velocity of about 1.5 m s^{-1} (Kennedy, 1984; Menon, 2005; Escoe, 2006), the calculated pipe size was approximately 5 cm (or 2 inch). Bio-oil has a viscosity similar to that of crude oil in the temperature range of 35 to 40^{o}C (Thamburaj, 2000; Bridgewater, 1999; Menon, 2005). Based on the assumption that the temperature of bio-oil in the pipeline is in the same range, the pressure drop in the pipeline during its transport is the same as that of crude oil. The pipeline should be buried underground to maintain the desired temperature. The pressure drop in a bio-oil pipeline can be estimated based on different methodologies suggested for crude oil by various studies (Bell, 1963; Menon, 2005). In this study, we have estimated the pressure drop based on the Shell-MIT equation suggested by (Menon, 2005) in calculating the friction factor. The pressure drop was also used to calculate the pump power. In this study, we have arbitrarily considered the length of the pipeline to be 100 km. The number of booster stations required has been calculated based on the total pressure drop and maximum pressure generated by one pump (4100 kPa or 600 psi). The details on the pipeline characteristics and relevant parameters are given in Table 2.2.

Table 2.2: Input data and assumptions for pipeline transport

Items	**Values**	**Comments/Remarks**
Capacity of bio-oil pipeline	250 m^3 of bio-oil day^{-1}	Calculated using a yield of 75% for bio-oil per unit mass of biomass and a density of bio-oil of 1,200 kg m^{-3} (Yaman, 2004) for a bio-oil production plant having a capacity of 400 dry tonnes of biomass day^{-1}.
Velocity of bio-oil in pipeline	1.5 m s^{-1}	Based on earlier studies (Kennedy, 1984; Menon, 2005; Escoe 2006).
Diameter of pipeline	5 cm (or 2 inch)	Calculated using a velocity of 1.5 m s^{-1} of bio-oil in the pipeline and flow rate of 250 m^3 of bio-oil/day through the pipeline.
Material of pipe	High density polyethylene (HDPE)	Bio-oil is corrosive and HDPE can prevent corrosion (Miesner et al.,

Items	**Values**	**Comments/Remarks**
		2006; Menon, 2005).
Operating factor of pipeline	90%	Percentage of time pipeline runs in a year.
Pipeline length	100 km	This is the arbitrary distance of transport used for comparing the two modes of bio-oil transport.
Pump efficiency	80%	Assumed.
Pump power	14.9 kW (or 20 hp)	Calculated using the friction factor estimated based on the methodology suggested by Menon (2005) for transport of crude oil in the pipeline.
Pump discharge pressure	4100 kPa (or 600 psi)	The maximum pressure that a HDPE pipe can withstand is 11,030 kPa (or 1600 psi) (ARNCO, 2006). In this study, a safety factor of about 2.6 is used to calculate the maximum allowable pressure in the pipeline.

Items	Values	Comments/Remarks
Number of booster stations	25	Calculated based on the total pressure drop in a 100 km pipeline and maximum discharge pressure of a pump. Each booster station is powered by a 14.9 kW (or 20 hp) pump.
Pipe insulation	3.8 cm (or 1.5 inch) PE foam insulator	The insulation material and thickness of insulation are based on commercial pipe specifications. In this study, a particular thickness and material are chosen based on acceptable temperature drop of bio-oil through the pipeline. A model was developed for estimating the temperature drop in the bio-oil pipeline.

2.4.2.3 Energy and emissions in bio-oil transport

All information about input material, energy consumption and emissions are related to each unit process (as shown in Figures 2.1 and 2.2); these were developed separately for truck and pipeline transport. The functional unit in this study was "per cubic meter of bio-oil per kilometre of transport". The energy consumption and emissions for each of the unit process are expressed as MJ m^{-3} km^{-1} and g of CO_2 m^{-3} km^{-1}, respectively. The unit process energy consumption and emissions are combined to obtain the life cycle values.

Truck transport

In this study, the emissions and energy consumption from various unit processes of truck transport, as shown in Fig. 2.1, were derived from previous studies (Borjesson, 1996; Mahmudi and Flynn, 2005). In this study, we have modified the reported values and have estimated the total life cycle emissions and energy consumption in truck transport of bio-oil for two types of trucks. The energy consumption in various unit processes for trailer truck and super B-Train truck are shown in Table 2.3. The GHG emissions from trailer truck and super B-Train truck were 89 and 60 g of CO_2 m^{-3} km^{-1}, respectively (Mahmudi and Flynn, 2005).

Table 2.3: Energy consumption for each unit process for the truck transport of bio-oil

Unit Process	Energy Factor (MJ $tonne^{-1}$ km^{-1})	
	B-train truck (60 m^3 capacity)	Trailer Truck (30 m^3 capacity)
Truck manufacturing	0.04[1]	0.04[1]
Infrastructure construction	0.04[1]	0.04[1]
Truck operation	1.30[1]	2.08[2]
Total	1.66	2.12

[1]Taken from the values reported by Borjesson (1996).

[2]Calculated based on the capacity and engine power for two trucks (as given in Table 2.1).

<u>Pipeline transport</u>

The energy consumption and GHG emissions from pipeline transport of bio-oil were estimated based on the various unit processes shown in Fig. 2.2. The amount of material required for each of the unit processes was estimated for a 5 cm (or 2 inch) diameter and 100 km long pipeline. This was also the basis for calculating total energy consumption and emissions. The form, material required for the pipeline system and the amount of energy required per unit for each unit process are given in Table 2.4. The unit energy consumption (MJ kg^{-1}) of natural gas, diesel and electricity were used to calculate the total energy required for each unit process. Emissions from each of the unit processes were used to estimate the total emissions resulting from the pipeline transport of bio-oil. The emission factors for energy use based on different fuel sources are listed in Table 2.5.

Table 2.4: The embodied energy input data for bio-oil HDPE pipeline system

Unit process	Raw material	Energy source	Energy input per unit	Amount of material used	Remarks
HDPE pipe manufacturing	HDPE pallet	Natural gas & Electricity	90.0 MJ kg^{-1}	108.82 tonnes[a]	Ardente et al., 2005
Pump manufacturing	Cast iron	Natural gas & Electricity	37 MJ kg^{-1}	2.38 tonnes[b]	Energy consumption values are average of the values reported in Jaques (1992) and Krogh (2001).
	Aluminum	Natural gas & Electricity	44 MJ kg^{-1}	0.48 tonnes[b]	Energy values were taken from the published literature (ORTECH, 1994).
	Copper	Natural gas & Electricity	70.6 MJ kg^{-1}	0.32 tonnes[b]	Energy values were taken from the published literature (Robert, 2002).
Polyethylene (PE) foam Insulator manufacturing	Polyethylene	Electricity & Natural Gas	103 MJ kg^{-1}	23.40 tonnes[c]	The PE foam insulator is wrapped around the HDPE pipe (Embodies Energy Coefficient, 2007; Ambrose et al., 2002).
Truck delivery		Diesel fuel	1.4 MJ Mg^{-1} km^{-1}	135.40 tonnes	The energy consumption for truck

Unit process	Raw material	Energy source	Energy input per unit	Amount of material used	Remarks
of pipes, pumps and insulation material from manufacturing plant				of pipes, pumps and insulation delivery[d]	transportation includes the direct use of diesel fuel, embody energy of truck and infrastructure (Borjesson and Gustavsson, 1996). The distance assumed for transportation of pipe and pumps was assumed to be 300 km.
Pipeline construction		Diesel fuel	130,050[e] MJ km^{-1}	361,250 liters[f]	The estimated diesel fuel consumption for tractors is 3612 liter per km of pipeline construction.
Pipeline operation		Electricity	0.350[g] kW-h m^{-3} km^{-1}	57,788 MWh[h]	The energy consumption per functional unit is for 100 km of 5 cm (or 2 inch) bio-oil pipeline.

[a]- The amount of material was calculated for a 5 cm (or 2 inch) diameter, 100 km long pipeline, with a thickness of 0.64 cm (or 0.25 inch) and a density of 955 kg/m^3 (ARNCO, 2005).

[b] - The amount of material for pumps was estimated using a catalogue for pump manufacturing. To transport bio-oil 100 km through a 5 cm (or 2 inch) pipeline, twenty-five 14.9 kW (or 20 hp) pumps are required. The amount of material shows the total material required in manufacturing 25 pumps. The amount of material per pump was 127 kg according to the pump manufacturer's catalogue (Bell & Gossett, 2003). It was assumed that the pump consist of 75% cast iron, 15% aluminum and 10% copper.

[c] - The amount of material was estimated based on an insulator thickness of 3.8 (or 1.5 inch), on 100 km of pipeline, and on a 22 kg/m^3 density of Polyethylene foam insulator (ARNCO, 2005).

[d] - This reflects the total amount of material by adding the weights of pipes, pumps and insulation in the various unit processes

[e] - This is based on 3,612 liters of diesel consumption for construction of 1 km of pipeline (DMI, 2006 personal communication) and on a calorific value of diesel of 36 MJ/liter (DOE, 2006).

[f] - This is the total liters of diesel consumption for a 100 km pipeline.

[g] - This is estimated based on twenty-five 14.9 kW (or 20 hp) pumps required to pump 250 m^3/day of bio-oil (for capacity of plant, see Table 2) 100 km with an operating factor of 90% and a life of 20 years.

[h] - This reflects the total energy requirement in pumping bio-oil through a 5 cm (or 2 inch) diameter pipeline for 100 km over a life of 20 years with an operating factor of 90%.

Table 2.5: The GHG emissions input data for bio-oil HDPE pipeline system

Unit process	GHG emission	Remarks
HDPE pipe manufacturing	2.14 tonnes of CO_2 per tonne of material	Ardente et al., 2005
Pump manufacturing	0.27 tonnes of CO_2 per tonne of material	This is the emissions level for manufacturing cast iron. The emissions value is the average of the reported values in Jaques (1992) and Krogh (2001).
	1.53 tonnes of CO_2 per tonne of material	This is the emissions level for manufacturing aluminium. Emission values are taken from the published literature (ORTECH, 1994).
	1.39 tonnes of CO_2 per tonne of material	This is the emissions level for manufacturing copper. Energy and emissions values are taken from the published literature (Robert, 2002).
Polyethylene (PE) foam insulator manufacturing	35 tonnes of CO_2 per tonne of material	(Ambrose et al., 2002).
Truck delivery of pipes,	70.3 g of CO_2 per tonne	(Mahmudi and Flynn,

Unit process	GHG emission	Remarks
pumps and insulation material from manufacturing plant	of material delivered per km	2005)
Pipeline construction	8.97 tonnes of CO_2 per km of construction	(Dumouchel, 2006)
Pipeline operation	• Hydro power - 15 kg of CO_2 per MWh	This is the life cycle GHG emissions value for hydro power. This includes both direct and indirect emissions. Direct emissions represent the emissions during the construction of the dam and power plant. Indirect emissions represent GHG emissions during the decaying of biomass from flooded land (Gagnon and van de Vate, 1997).
	Coal power - 947 kg of CO_2 per MWh	This is the life cycle emissions GHG value for coal power in Alberta. This includes emissions during mining and transportation of coal,

Unit process	GHG emission	Remarks
		power plant construction and decommissioning, and the operation of the plant. The details are given in Odeh and Cockerill (2007).

2.5 Result and discussions

The overall unit process energy consumption and emissions level for the pipeline transport of bio-oil are shown in Tables 2.6 and 2.7, respectively. The energy consumption for each unit process in pipeline transport was the same for both sources of electrical power (i.e. coal and hydro). These were calculated based on the energy consumption involved in manufacturing each unit mass of materials, as shown in Table 2.4, for a pipeline with a 5 cm (or 2 inch) diameter and 100 km length. Table 2.6 also shows the energy consumption involved in the truck transport of bio-oil (MJ m^{-3} km^{-1}). As shown in Table 2.7, the emissions level for each unit process was calculated based on the data on emissions in manufacturing each unit mass of materials (as shown in Table 2.5) and the total amount of material required for a pipeline with a 5 cm (or 2 inch) diameter and 100 km length over 20 years of life. The total emissions were different for coal and hydro-based electricity. Table 2.7 also shows the life cycle emissions for truck transport of bio-oil.

Table 2.6: Energy consumption for each unit process for the pipeline transport of bio-oil

Unit Process	Energy Factor (MJ m^{-3} km^{-1}) Electricity from Coal or Hydro
Pipeline Transport	
HDPE Pipe manufacturing	0.06
Pump manufacturing	0.001
Polyethylene (PE) foam Insulator manufacturing	0.015
Truck delivery of pipes, pumps and insulation material from the manufacturing plant	0[1]
Pipe construction	0.08
Pipe operation	3.79
Total energy consumption for pipeline transport	3.946

Truck Transport

Unit Process	Energy Factor (MJ m^{-3} km^{-1})	
	B-train truck (60 m^3 capacity)	Truck trailer (30 m^3 capacity)

Truck manufacturing	0.05	0.05
Infrastructure construction	0.05	0.05
Truck operation	1.56	2.50
Total	1.66	2.59

[1] - The energy consumption in truck delivery of pipes, pumps and insulation material from the manufacturing plant is about 0.3 kJ km^{-1} m^{-3}. This is negligible compared to emissions from other unit processes.

Table 2.7: Emissions for pipeline and truck transport of bio-oil

Unit Process	**GHG Emissions**	
Pipeline transport		
	Coal based (g of CO_2 m^{-3} km^{-1})	Hydro based (g of CO_2 m^{-3} km^{-1})
HDPE pipe manufacturing	1.42	1.42
Pump manufacturing	0.01	0.01
Polyethylene (PE) foam insulator manufacturing	4.99	4.99
Truck delivery of pipes, pumps and insulation material from the manufacturing plant	0.02	0.02

Pipe construction	5.46	5.46
Pipe operation	333.00	5.27
Total emissions for pipeline transport	344.89	17.17
Truck transport		
	GHG Emission (g of CO_2 m^{-3} km^{-1})	
B-train truck (60 m^3 capacity)	60	
Truck trailer (30 m^3 capacity)	89	

2.5.1 Life cycle emissions

Life cycle emission levels from truck trailers were higher than those from super B-train truck (as shown in Table 2.7). This is because the bio-oil carrying capacity of the super B-train truck (60 m^3) is double that of the truck trailer (30 m^3). There is a similar advantage when comparing energy consumption: the super B-train consumes about 30% less energy compared to the truck trailer (as shown in Table 2.6). Note that the operational activities of truck transportation, such as truck maintenance, infrastructure maintenance, tire wear, and brake wear were assumed to be the same per unit transported for both the truck trailer and super B-train truck.

The life cycle emissions from pipeline transport of bio-oil depends chiefly on the fuel from which the electricity used is generated. The operation of pumps accounts for about 95% of the total energy consumption. If pumps for pipeline operation are supplied with electricity from coal power plants, the life cycle GHG emissions are about 18 times those produced when electricity is from a renewable-resource-based power plant (as shown in Table 2.7). In this study, we have considered a hydro-based power plant as the source of renewable electricity. Total energy consumption in both cases is the same (see Table 2.6).

Based on the life cycle emissions, truck transport is better than pipeline transport when the electricity for pumping bio-oil is generated from coal.

If the source of electricity is from a renewable resource like hydro, pipeline transport produces a much lower emissions level than does truck transport. Thus, the source of electricity for pumps is a critical factor. In the province of Alberta, about 60% of all electricity comes from coal; hence, pipeline transport for bio-oil might not be a good option based on emissions. In the neighbouring province of British Columbia, however, more than 80% of the electricity comes from hydro so pipeline transport of bio-oil could be a better option (assuming that the additional hydropower is available).

Bio-oil can be used to produce electricity (Dynamotive, 2000; Brammer, 2006) through an integrated gasification combined cycle. A bio-oil plant using 400 dry tonnes of wood can produce 250 m^3 day^{-1} of bio-oil, as shown in Table 2.2. Based on the calorific value of 18 MJ kg^{-1} for bio-oil (Bridgewater, 2003; Dynamotive, 2000; Yaman, 2004) and the lower heating value efficiency of integrated gasification combined cycle plants of 45%, a bio-oil plant producing 250 m^3 day^{-1} can support a power plant with a 28 MW capacity. This bio-oil-based electricity can be used as a substitute for fossil fuel-based electricity. The GHG mitigation obtained by substituting electricity produced from pipeline-transported bio-oil compared to fossil-fuel based electricity is given in Table 2.8. The data are for transporting bio-oil 100 km.

Table 2.8: GHG mitigation by replacement of fossil-fuel-based electricity with pipeline and truck-delivered bio-oil-based electricity

Type of fuel	Life cycle GHG emissions (kg of CO_2 MWh^{-1})	GHG mitigation for 28 MW fossil fuel power plant by bio-oil-based power plant (million tonnes of CO_2 $year^{-1}$)
Pipeline-delivered bio-oil-based electricity	0.4[1]	-
Coal-based electricity	957.4[2]	5.1
Natural-gas-based electricity	405.3[3]	2.2
Oil-based electricity	661.9[4]	3.5

[1] - This emissions level is for transport of bio-oil 100 km by pipeline. If the mode of transport is changed to B-train truck, the GHG emissions amounts to 0.1 kg of CO_2 MWh^{-1}, the mitigation of GHG remains almost the same. The emission factors of pipeline and truck-transported bio-oil do not include emissions during conversion of biomass to bio-oil as this is considered carbon neutral i.e. the amount of CO_2 released during conversion is about the same as that taken up by trees during their growth.

[2] - This is the emissions factor for a coal power plant and includes only the emissions during energy conversion (Odeh, 2007).

[3] - This is the emissions factor for a natural gas power plant and includes only the emissions during energy conversion (Odeh, 2007).

[4] - This is the emissions factor for a natural gas power plant and includes only the emissions during energy conversion (Odeh, 2007).

2.5.2 Energy consumption

The energy consumption of truck trailers is greater than that of super B-train trucks (as shown in Table 2.6). The super B-train consumes about 30% less energy than does the truck trailer. One of the key reasons for this is the carrying capacity of the super B-train truck (60 m^3), which is double that of the truck trailer (30 m^3).

Energy consumption in the transport of bio-oil is different using the two modes of transport. If we consider pipeline transport of bio-oil, the total energy input is 3.95 MJ m^{-3} km^{-1}. This level of energy consumption is higher than that of truck transport. One of the key factors influencing the decision on which modes of transport to use is the impact of energy consumption on the economics of transport.

2.5.3 Impact of increased throughput of pipeline on emissions and energy consumption

The throughput (carrying capacity) of the pipeline (liters of bio-oil transport per year) plays a significant role in determining the energy consumption and emissions level per functional unit (m^{-3} km^{-1}). The energy consumption and emissions of pipeline transportation can be decreased by increasing the throughput of the bio-oil pipeline. The life cycle GHG emissions and energy consumption in pipeline transport of bio-oil from a plant using 1600 dry tonnes of biomass per day and producing 1000 m^3 of bio-oil per day are 159 g of CO_2 m^{-3} km^{-1} and 1.85 MJ m^{-3} km^{-1} (for electricity coming from a coal-based power plant). The values are 7 g of CO_2 m^{-3} km^{-1} and 1.85 MJ m^{-3} km^{-1} when the electricity for pump operation comes from a hydro power plant. The pipeline size for transporting bio-oil from a 1000 m^3 plant is 10 cm (or 4 inch). Energy consumption and emissions are clearly lower compared to those of a bio-oil production plant using 400 dry tonnes of biomass per day. This is due to an increase in efficiency regarding energy consumption and an increase of pipeline carrying capacity.

2.6 Conclusions

Bio-oil can be transported by truck or pipeline. We have compared these two modes of transportation based on energy input and life cycle emissions. Pipeline transport of bio-oil produces fewer emissions than does truck transport, if the source of electricity for pumping is a renewable-resource-based power plant (such as hydro). If the power for pumps comes from a coal-based plant, truck transport of bio-oil provides less emission. The life cycle GHG emissions from pipeline transport of bio-oil are much higher using electricity from a coal power plant compared to that from a hydro power plant: 345 and 17 g of CO_2 m^{-3} km^{-1}, respectively. Life cycle GHG emissions from bio-oil transport by truck trailer and super B-train truck are 89 and 60 g of CO_2 m^{-3} km^{-1}, respectively. If the bio-oil at the end of 100 km of transport is used for producing electricity and this electricity replaces electricity from fossil fuels, there is a significant mitigation of GHG emissions. A bio-oil plant producing 250 m^3 day^{-1} can replace a 28 MW coal power plant, resulting in mitigation of 5.1 million tonnes of GHG in a year.

Energy consumption is also significantly different if tanker truck transport is compared with pipeline transport. Energy consumption for pipeline transport of bio-oil is 3.95 MJ m^{-3} km^{-1}. It can be decreased by increasing the throughput of the pipeline per year. Energy consumption for bio-oil transport by truck trailer and super B-train truck are 2.59 and 1.66 MJ m^{-3} km^{-1}, respectively.

References

Aden, A., Ruth, M., Ibsen, K., Jechura, J., Neeves, K., Sheehan, J., Wallace, B., Montague, L., Slayton, A., Lukas, J., 2002. Lignocellulosic biomass to ethanol process design and economics utilizing co-current dilute acid prehydrolysis and enzymatic hydrolysis for corn stover. Report no. NREL/TP-510-32438. URL: http://www.nrel.gov/docs/fy02osti/32438.pdf. Accessed on August 12, 2007.

Ambrose M.D., Salomonsson G.D. and Burn S., 2002, Piping Systems Embodied Energy Analysis. Report No.; CMIT Doc. 02/302. Prepared by CSIRO.

Ardente, F., Beccali, G., Cellura, M., Brano, V.L., 2005. Life cycle assessment of a solar thermal collector. Renewable Energy. 30, 1031-1054.

ARNCO Corporation, 2006. Products specification. Available at: www.arncocorp.com. Accessed on April 20, 2006.

Atchison, J.E., Hettenhaus, J.R., 2003. Innovative methods for corn stover collecting, handling, storing and transporting. Prepared for National Renewable Energy Laboratory, Colorado, Report No. ACO-1-31042-01. URL: http://www.afdc.doe.gov/pdfs/7241.pdf Accessed on August 12, 2007.

Badger, P.C., 2003. Biooils: the world's growing energy resource. Renewable oil international. LLC Florence Alabama.

Badger, P.C., Fransham, P. 2006. Use of mobile fast pyrolysis plants to densify biomass and reduce biomass handing costs - A preliminary assessment. Biomass and Bioenergy. 30, 321-325.

Bell, H.S., 1963. Petroleum Transportation Handbook. McGraw-Hill Book Company, New York.

Bell & Gossett, 2003. Product specification. Available at http://www.bellgossett.com

Biomass Technology Group (BTG), 2004. Flash pyrolysis. Available at: http://www.btgworld.com/technologies/pyrolysis.html

Borjesson, P., Gustavsson, L., 1996. Regional production and utilization of biomass in Sweden. Energy. 21, 747-764.

Brammer, J.G., Lauer, M., Bridgwater, A.V., 2006. Opportunities for biomass-derived "bio-oil" in European heat and power markets. Energy Policy. 34, 2871-2880.

Bridgewater, A.V., 1999. Principle and practice of biomass pyrolysis process for liquid. Journal of Analytical and Applied Pyrolysis. 51, 3-22.

Bridgewater, A.V., Meier,D., Radlein, D., 1999. An overview of fast pyrolysis of biomass. Organic Geochemistry. 30,1479-1493.

Bridgewarter, A.V., 2003. Renewable fuels and chemicals by thermal processing of biomass. Chemical Engineering Journal. 91, 87-102.

Caterpillar, 2006. Products specifications. Available at: www.cat.com/products. Accessed on April 12, 2007.

Czernik, S. 2004. Review of Fast Pyrolysis of Biomass. *In Proc.* Mississippi Bioenergy Thermochemical Conversion Technologies Roundtable, National Renewable Energy Laboratory, US.

Dalquist, S., Gutowski, T., 2004. Life cycle analysis of conventional manufacturing techniques: Die casting. http://web.mit.edu/ebm/Die%20Casting%20Dalquist%20Gutowski.pdf. Accessed on 25 May 2006.

DOE, 2006. Alternative fuels data center (AFDC) Fuel Properties table. Available on: http://www.eere.energy.gov/afdc/pdfs/fueltable.pdf.

Dumouchel, A., 2006. Woodland Supervisor. Daishowa-Marubeni International Ltd. Peace River, Alberta, Canada.

Dynamotive Energy Systems Corporation, 2000. Fast pyrolysis of biomass for green power generation. Presented at the First World Conference and Exhibition on biomass for energy and industry. Available at: http://www.dynamotive.com/biooil

Dynamotive Energy System Corporation, 2001. Fast pyrolysis of bagasse to produce biooil for power generation. 2001 Sugar Conference.

DynaMotive Energy Systems Corporation, 2008. Comparison of Dynamotive's biofuels and fossil fuels. Available at: http://www.dynamotive.com/en/technology/products.html (accessed on Feb. 19, 2008)

Embodied energy coefficient, Available on; www.victoria.ac.nz/cbpr/documents/pdfs/ee-coefficients.pdf. Accessed on; March 2007.

Escoe, A.K., 2006. Piping and pipelines assessment. Gulf Professional Publishing, Burlington.

Freel, B., Graham, R., 2000. Commercial bio-oil production via rapid thermal processing, December 11. Available at: http://www.ensyn.com/info/11122000.htm.

Gagnon, L. and van de Vate, J.F. 1997. Greenhouse gas emissions from hydropower: The state of research in 1996. Energy policy 25(1), 7-13.

Glassner, D., Hettenhaus, J., Schechinger, T., 1998. Corn stover collection project. In Bioenergy'98 – Expanding bioenergy partnerships: Proceedings, Volume 2, Madison, WI, pp. 1100-1110. URL: http://www.ceassist.com/bio98paper.pdf. Accessed on August 12, 2007.

Graham, R.G., Freel, B.A., Huffman, D.R., Bergougnou, M.A., 1994. Commercial-scale rapid thermal processing of biomass. Biomass and Bioenergy 7(6), 251-258.

Grassi, G., Bridgwater, A.V., 1993. The opportunities for electricity production from biomass by advanced thermal conversion technologies. Biomass and Bioenergy 4(5), 339-345.

IEA Bioengineering. 2007. Biomass Pyrolysis. Available at: http://www.ieabioengineering.com. Accessed on April, 23 2007.

Jaques, A., 1992. Canada's greenhouse gas emissions: estimates for 1990. Environmental protection, conservation and protection. Environment Canada. EPS 5/AP/4.

Juste, G.L., Monfort, J.J.S., 2000. Preliminary test on combustion of wood derived fast pyrolysis oils in a gas turbine combustor. Biomass and Bioenergy. 19(2), 119-128.

Katinas, V., Markevicius, A., Kavaliauskas, A., 2007. Current status and perspects of biomass resources for energy production in Lithuania. Renewable Energy. 32, 884-894.

Kennedy, J.L., 1984. Oil and gas pipeline fundamentals. PennWell Publishing Company. Tulsa, Oklahoma.

Krogh, H., Myhre, L., Hakkinen, T., Tattari, K., Jonsson, A., Bjorklund, T., 2001. Environmental data for production of reinforcement bars prom scrap iron and for production of steel products from iron ore in the Nordic countries. Building and Environment. 36, 109-119.

Kumar A. A conceptual comparison of bioenergy options for using mountain pine beetle infested wood in Western Canada. Bioresource Technology. 100(1), 387-399.

Kumar A., Cameron, J.B., Flynn, P.C. 2005. Pipeline transport and simultaneous saccharification of corn stover. Bioresource Technology. 96, 819-829.

Kumar A., Cameron, J.B., Flynn, P.C. 2005. Biomass power cost and optimum plant size in western Canada. Biomass and Bioenergy. 24, 445-464.

Kumar A., Cameron J.B., Flynn P.C. 2004. Pipeline transport of biomass. Applied Biochemistry and Biotechnology. 113(3), 27-40.

Kumar A., Cameron, J.B., Flynn, P.C. 2005. Large-scale ethanol fermentation through pipeline delivery of biomass. Applied Biochemistry and Biotechnology. 121, 47- 58.

Kumar A. 2009. A conceptual comparison of bioenergy options for using mountain pine beetle infested wood in Western Canada. Bioresource Technology, 100(1), 387-399.

Luo, Z., Wang, S., Liao, Y., Zhou, J., Gu, Y., Cen, K. 2004. Research on biomass fast pyrolysis for liquid fuel. Biomass and Bioenergy 26(5), 455-462.

Mahmudi, H., Flynn, P.C., Checkel, M.D. 2005. Life cycle analysis of biomass transportation: Trains vs. trucks. SAE Conference. Paper No. 2005-01-1551.

Mahmudi, H., Flynn, P.C. 2006. Rail vs. truck transportation of biomass. Applied Biochemistry and Biotechnology. 129-132, 88-103.

Menon, S.E. 2005. Gas pipeline hydraulics. Taylor and Francis group. Boca Raton, FL.

Miesner, T.O., Leffler, W.L. 2006. Oil and gas pipelines in nontechnical language. PennWell Corporation. Tulsa, Oklahoma.

Mullaney, H., Farag, I.H., LaClaire, C.E., Battett, C.J. 2002. Technical, environmental and economic feasibility of bio-oil in New Hampshire's north country. (Final report). Project no. 14B316 UDKEIF or ABAN-URI-BO43. Project partially funded by the New Hampshire Industrial Research Center (NHIRC), August.

Odeh, N.A., and Cockerill ,T. 2007. Life cycle analysis of UK coal fired power plants. Energy Conversion and Management. 42(2), 212-220

ORTECH. 1994. Inventory methods manual for estimating Canadian emissions of greenhouse gases. Report to Environment Canada. www.ec.gc.ca/pdb/ghg/inventory_report/1990_01_report/Annex7_e.cfm. Accessed on 23 May 2006.

Perlack, R.D., Turhollow, A.F. 2002. Assessment of options for the collection, handling, and transport of corn stover. Report no. ORNL/TM-2002/44. URL: http://bioenergy.ornl.gov/pdfs/ornltm-200244.pdf. Accessed on August 12, 2007.

Robert, U. A. 2002. The life cycle of copper, its Co-production and by-product., Mining, materials and sustainable development. http://www.osti.gov/bridge/purl.cover.jsp?purl=/909957-1Dc8ok/. Accessed on 25 May 2006.

Sarkar, S., Kumar, A. 2009. Techno-economic assessment of biohydrogen production from forest biomass in Western Canada. Transactions of the ASABE. 52(2), 519-530.

Shaw., M. 2006. Pyrolyis lignocellulosic biomass to maximize bio-oil yield: An overview. CSBE/SCGAB Paper No. 06-105. Edmonton, Alberta: CSBE/SCGAB.

Steware, G.W. 2004. Bio-oil Commercialization Plan. Cole Hill Associates. Sugar Hill. New Hampshire.

Thamburaj, R. 2000. Dynamotive engineering. Fast pyrolysis of biomass for green power generation. http://www.dynamotive.com. Accessed on June 20, 2006.

TMIP. 2006. Accounting for commercial vehicle in urban transportation models. Available at: http://tmip.fhwa.dot.gov. Accessed on April 23, 2007.

Transport Canada. 2005. Operation costs of trucks in Canada 2005. Transport Canada file number: T8080-05-0242

Wagenaar, B.M., Florjin, J.H., Gansekoele, E., Venderbosch. 2003. Bio-oil as natural gas substitute in a 350 MW power station. Available at http://wwwbtgworld.com

Yaman, S. 2004. Pyrolysis of biomass to produce fuels and chemical feedstocks. Energy Conversion and Management. 45, 651-67.

Chapter Three: Bio-oil Transport by Pipeline: A Techno-economic Assessment

3.1 Introduction

Release of greenhouse gases (GHG) due to extensive utilization of fossil fuels has resulted in global warming. This has led to increased effort in development of renewable energy technologies for heat and power. Biomass based energy is considered to be carbon neutral. This can help in mitigation of GHGs and has increased interest in development of a biorefinery where fuels and chemicals can be produced using a lignocellulosic biomass source (e.g. straw, forest residues, corn stover, switchgrass). Biomass utilization for energy has two key characteristics which are barriers to it large scale utilization. These were discussed in chapter 2 earlier.

Bio-oil is a viscous dark liquid produced by fast pyrolysis of biomass. Fast pyrolysis is the conversion of solid biomass to liquid biomass by rapidly heating solid biomass in absence of air. This process is called as fast pyrolysis.(Bridgewater, 1999; Dynamotive Energy Systems Inc., 2000; Bridgewater, 2003; Yaman, 2004, Badger, 2006; IEA, 2007; Brown, 2008; Kumar, 2009). The vapor produced during the process is quenched to liquid called bio-oil. Two other products of fast pyrolysis process are solid char and fuel gas. Solid char is the pure solid carbon which can be used as fuel or as a catalyst for other chemical processes. Another product, the fuel gas which is produced during the process can be reused for heating the pyrolysis chamber or reactor (Bridgewater, 1999; Yaman, 2004, IEA, 2007). Bio-oil yield from pyrolysis process is about 75% (by weight) of biomass input and other products from pyrolysis process which are solid char and incondensable fuel gas account for remaining 25% (weight basis). Currently, a significant amount of research is going on bio-oil and various research groups are working on production processes (Bridgewater, 1999; Bridgewater, 2003; Yaman, 2004; IEA, 2007; Brown, 2008). Various companies have also developed technologies for production of bio-oil and these are at various stages of development, demonstration and commercialization (Dynamotive Energy Systems Inc., 1999; Dynamotive Energy Systems Inc., 2000; Dynamotive Energy Systems Inc., 2001; Yaman, 2004).

Current scale of bio-oil production is small i.e. plant have capacity of utilizing 200 dry tonnes of biomass for production of bio-oil (Brown, 2008). The produced bio-oil is transported by trucks. Increasing the scale of the bio-oil production plant and transportation of bio-oil by pipeline can help in reducing the overall delivered cost of bio-oil due to significant benefits from economy of scale in capital cost. This study is focused on techno-economic assessment of bio-oil transportation on large scale and to longer distances by pipeline. The key objectives of the study are: estimation of cost of bio-oil transportation by pipeline

($/liter of bio-oil); assessment of impact of size of pipeline on the cost of bio-oil transportation; assessment of impact of distance of transport on cost of bio-oil transportation by pipeline; and comparison of cost of pipeline transport of bio-oil with truck transport of bio-oil. This study also estimates the size of the pipeline and distance of transport at which cost of pipeline transport of bio-oil is economical as compared to truck. Figure 3.1 shows the scope of bio-oil transportation evaluated in this study.

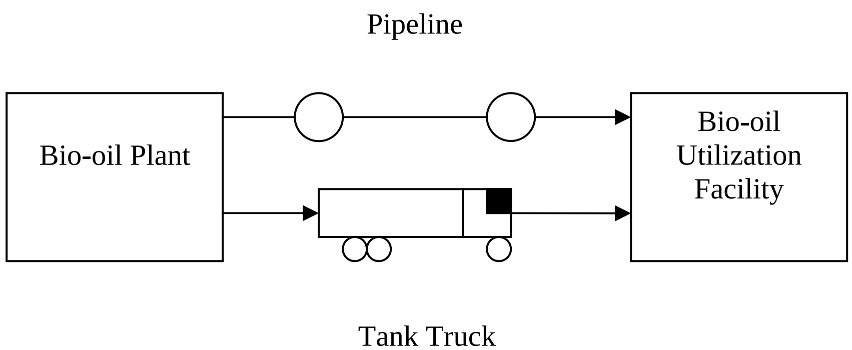

Figure 3.1 Modes of bio-oil transport

3.2 Truck Transportation of Bio-oil

Bio-oil can be transported by trucks over longer distances. It has properties similar to fuel oil # 2. Bio-oil transportation by trucks is similar to the transportation of conventional liquid petroleum product hauling by trucks. Two types of liquid tank trucks can be used to carry bio-oil from the production plant to the utilization facilities. These are truck trailer and super B-train tank trucks. The hauling capacity depends on the type of truck trailers. Typical liquid tank truck trailers for petroleum product has a capacity of 30 m^3 and super B train tank trucks has a capacity of 60 m^3 (Transport Canada, 2006). The energy consumption of the bio-oil truck transportation (liters/km/m^3) is a function of transportation efficiency, the volume and travel distance (Pootakham and Kumar, 2009). The liquid tank truck trailer and super B-train tank trucks are equipped with 385 to 450 hp diesel engine tractors (Transport Canada, 2006).

Bio-oil has a pH of 2.8 (Bridgewater, 1999; Dynamotive Energy Systems Inc., 1999 and 2001; Yaman, 2004). The acidic nature of bio-oil makes it corrosive for conventional truck tank's material (i.e. carbon steel). The material of the truck's tank carrying bio-oil should be corrosion resistant such as stainless steel, HDPE, PVC or powder coated material (Badger, 2006; Menon, 2005). In this study, the truck tanks are made of stainless steel (Badger, 2006).

Bio-oil truck transportation cost ($/$m^3$) is independent of scale i.e. it does not change with capacity. Bio-oil truck transportation cost has two components. These include fixed cost and variable cost. Fixed cost ($/$m^3$) of truck transportation is independent of distance of transport. The variable component of the truck transport cost changes with the distance of transport i.e. its value is different for 100 km and 500 km (Kumar et al., 2003, Kumar et al., 2004). The truck transportation cost ($\$/m^3$) can be represented by following formula.

$$C = FC + D \times VC \qquad (1)$$

Where,

C - total transportation cost of bio-oil ($\$/m^3$);

FC - fixed transportation cost of bio-oil ($\$/m^3$);

VC – unit variable transportation cost of bio-oil ($\$/m^3/km$);

D - one-way distance of transport.

This formula has been discussed in earlier studies on transportation of biomass and other materials (e.g. Kumar et al., 2003; Kumar et al., 2005a; Ghafoori and Flynn, 2007; Searcy et al., 2007). Fixed cost in case of bio-oil transportation by truck includes the loading and unloading cost of bio-oil between trucks and storage tank. Variable cost of transportation of bio-oil by truck includes fuel consumed by engine, labour charges, maintenance charges etc. These are discussed in detail below.

3.2.1 Fixed cost for bio-oil transportation

The fixed cost (FC) is the cost of loading and unloading bio-oil at the biomass facility. In this study it is considered that the driver has responsibility to load and unload bio-oil in the tank truck by using the loading equipment. This is similar to the practice currently used in petrochemical industry (Jones, 2006). In an oil refinery, the loading system includes fuel loading pump which is operated at 170 - 240 kPa (or 25-35 psi), the fuel meter and the strainer to indicate amount of fuel loaded. For the petroleum product such as gasoline and diesel fuels, the loading equipment operates between 0.9 - 1.3 m^3 per minute (250 to 450 gallons per minute). As bio-oil has high viscosity as compared to crude oil; the loading equipment is assumed to be operated at a volume flow rate of 0.6 m^3 per minute (or 150 gallons per minute) and an operating pressure of 205 kPa (or 30 psi) for safety (Jones, 2006). The loading and unloading time of bio-oil trailer truck and B-train trucks is estimated based on the capacities of the trucks and flow rate. Additional 20 minutes is added to the total time to allow for the initial time required for the driver to setup the loading and unloading equipment to trucks. Table 3.1 gives the total loading and unloading time for the truck trailer and super B-train trucks.

3.2.2 Variable cost for bio-oil transportation

The variable costs of truck trailer and super B-train trucks are the operational costs of truck driven for a particular distance (km). In this study, the variable costs are the average variable cost for Canada and derived from detailed study done earlier (Transport Canada, 2006). The same study gives the variable and fixed costs for US also and these costs are similar to Canadian values.

Table 3.1 gives the fixed and variable cost of bio-oil transportation by liquid truck trailers and super B train trucks. All the costs are given in US$ and in base year 2008.

Table 3.1: Fixed and variable for truck transportation of bio-oil.

Items	Truck trailer	Super B-train truck
Capacity (m^3)	30	60
Loading and unloading rate (m^3 per minute)	0.6[1]	0.6[1]
Loading time (minutes)	50	100
Unloading time (minutes)	50	100
Additional time for set-up during loading and unloading (minutes)	20	20
Total time for loading and unloading	120	220

Items	Truck trailer	Super B-train truck
(minutes)		
Truck/Trailer charge out rate ($/hour)	85.04[2]	93.54[2]
Total fixed cost (FC) of transportation of bio-oil ($/m^3)	5.67	5.71
Total variable cost (VC) of transportation of bio-oil ($/m^3/km)	0.07[2]	0.05[2]

[1]- This is equivalent to 150 gallons per minute.

[2] - These are costs for trailer and B-train tank truck per hour (Ghafoori, 2007).

3.3 Pipeline Transportation of Bio-oil

Pipeline transportation of liquid fuels has been used over several decades. Crude oil is transported to longer distances by pipeline. Recently, several studies have been carried out on the pipeline transport of raw biomass in the form of a slurry (Kumar et al., 2003; Kumar et al, 2005a; Kumar et al., 2006; Searcy, 2007). Bio-oil which is produced by fast pyrolysis of biomass can be transported by pipeline in larger capacities and over longer distances.

Current practice is to transport bio-oil by trucks from the production plant. The plant has loading and unloading terminals. When pipeline is used for transport of bio-oil, the same loading and unloading terminal can be used with minor modifications. This study considers various aspects of pipeline transportation of bio-oil (discussed in subsequent sections) and estimates the cost of pipeline transport of bio-oil ($\$/m^3$).

3.3.1 Characteristics of bio-oil

Bio-oil has high viscosity at room temperature. The viscosity of the bio-oil is dependent on the temperature. With the increase in temperature of bio-oil, the viscosity decreases. At about 45 ^oC, the viscosity of bio-oil for pipeline transportation is 15 cSt which is similar to crude oil (Menon, 2005; Pootakham and Kumar, 2009). As discussed earlier, bio-oil is produced by the fast pyrolysis of biomass. The volatile vapors produced during fast pyrolysis are at 300 ^oC. These vapors are condensed by quenching with already produced bio-oil and cools down to 90-120^oC in a storage tank. In this study, it is assumed that bio-oil enters the pipeline transportation system at this temperature. To maintain the bio-oil in the pipeline over 45^oC so that the viscosity is similar to crude oil during the transport, the pipeline is insulated. In this study, the polyethylene (PE) foam is considered as pipeline insulating material (ARNCO, 2006; Pootakham and Kumar, 2009).

Bio-oil has a low pH of 2.8 as discussed earlier. Hence, it is corrosive to carbon steel. Carbon steel is the most common material which is used as pipeline material for crude oil. In this study, a detailed research was carried out for finding a suitable material for bio-oil pipeline and it was concluded that high density polyethylene (HDPE) which is used for pipeline manufacturing is a suitable material for bio-oil pipeline. In this study bio-oil pipeline is made of HDPE material (Badger, 2006; Menon, 2005; Dynamotive Energy Systems Inc., 1999).

3.3.2 Cost components of pipeline transport

Pipeline transportation cost has two main components. Similar to truck transportation cost, pipeline transportation cost has both fixed cost (FC) and variable cost (VC). The total cost of pipeline transportation at a particular capacity can be calculated using equation (1). Several earlier studies show this concept (Kumar et al., 2003; Kumar et al., 2005a; Kumar et al., 2005b; Searcy et al., 2007; Ghafoori et al., 2007).

Fixed cost of pipeline transport of bio-oil includes capital cost of inlet and outlet stations. Inlet station refers to the terminal where bio-oil moves from the storage tank to the pipeline through pumps. Outlet station refers to the terminal where bio-oil moves from the pipeline to the storage tank. In this study the inlet station costs include: capital cost of storage tank; building and foundation cost; fittings and valves cost; inlet pump cost; and access road cost. Similarly, the outlet station costs include: storage tank cost; fittings, valve and small distribution pump cost; and building and foundation cost. Road access is not considered for the outlet station as this station is in the plant. Table 3.2 gives the inlet and outlet station costs for a bio-oil pipeline at a transportation capacity of 560 m^3 per day which is equivalent to a bio-oil plant using 900 dry tonnes of biomass per day. Yield of bio-oil is assumed to be 75% based on earlier studies (Dynamotive Energy Systems Inc., 1999; Bridgewater, 2003; Yaman, 2004).

Table 3.2: Inlet and outlet station costs for a bio-oil pipeline at a transportation capacity of 560 m^3 of bio-oil per day

Cost Components	Cost ($/yr)
Inlet station	
Storage tank cost[1]	76,960
Building and foundation cost[2]	1,175
Fittings and valve cost[3]	465
Inlet pump cost[4]	3,260
Road access cost[5]	470
Total inlet station cost	82,330

Cost Components	Cost ($/yr)
Outlet station	
Storage tank cost[1]	76,960
Building and foundation cost[2]	1175
Fittings, valve and pump cost[3]	560[6]
Total outlet station cost	78,695

[1] - The storage tank cost is based on a 3 days storage capacity of bio-oil. The cost of a stainless steel tank of capacity 9,400 m^3 is $2 million (Badger, 2006). Using a scale factor of 0.65, the cost of storage tank for a 560 m^3 per day is calculated.

[2] - Building and foundation cost is estimated based on figures given an earlier study by Liu et al. (1995) and was adjusted for inflation.

[3] - Fittings and valve cost is estimated based on the formula, Cost ($) = $12900 \cdot D^{1.05}$, where D is the diameter of the pipe in ft (Liu et al,, 1995). For a 560 m^3 per day bio-oil plant, at a velocity of bio-oil in the pipeline of 1.5 m/s, the diameter of pipe is 9.9 cm (or 3.90 inche).

[4] - Pump cost is based on the capacity of the pump. This is estimated using the formula, Cost ($) = $1290 \cdot (\text{Power})^{0.8056}$, where power of pump is in hp. This formula is derived from an earlier study by Liu et al. (1995). Pump power was 45 hp and was based on determination of friction factor using the methodology suggested by Menon (2005) for transport of crude oil in the pipeline. It was also assumed that the one pump is capable of delivering a pressure of 4100 kPa (or 600 psi) and has an efficiency of 80% (Kumar et al., 2003; Kumar et al., 2005a; Kumar et al., 2005b). The HDPE pipeline in this study can handle the hydraulic pressure up to 11,030 kPa (or 1,600 psi)

(ARNCO Corporation, 2006). Details on estimation of the pump power are given in an earlier study by Pootakham and Kumar (2009).

[5] - Assumed.

[6]- The pump size assumed at the outlet station is 5 horsepower. This size is smaller than the inlet pump as this pump is just used for distribution for shorter distances within the plant.

Variable cost of pipeline transport includes capital cost of pipeline, installation and construction cost, operating cost of pipeline, booster station cost, maintenance cost of pipeline and pumps, communication line cost, and road access cost. In this study variable cost also includes the pipeline insulation cost. Operating cost of the pipeline includes labor required for running the system and electricity required for pumps. For transport of bio-oil over longer distances, booster stations are required to overcome the frictional losses during the transport. In this study booster station cost includes: capital cost of building and foundation; cost of access road; cost of power line; cost of pump and its installation. Table 3.3 gives the variable cost including the booster station cost for a pipeline having transportation capacity of 560 m^3 of bio-oil per day. The length of the pipeline is assumed to be 100 km for simplicity. Table 3.4 gives the characteristics and general assumptions for the pipeline transport of bio-oil from a plant using 900 dry tonnes of biomass per day and producing 560 m^3 of bio-oil per day.

Table 3.3: Variable cost for a bio-oil pipeline at a transportation capacity of 560 m^3 per day and length 100 km

	Cost ($/yr)
Pipeline system cost	
Pipe and insulation cost[1]	276,220
Construction cost[2]	796,960
Road access cost[3]	17,625
Pump maintenance cost[4]	1,425
Pipeline maintenance cost[5]	8,290
Communication line cost[6]	4,700
Total pipeline system cost	1,105,220
Pipeline operating cost	
Labor cost[7]	592,800
Electricity cost[8]	231,900
Total operating cost	824,700
Booster station cost	
Building and foundation cost[9]	1,175
Road access cost[3]	470

	Cost ($/yr)
Power line cost[10]	19,805
Booster pump cost[11]	3,260
Booster pump installation cost[11]	6,730
Total booster station cost	31,440

[1]- Pipe and insulator cost is estimated based on the formula, Cost ($/km) = $1000*[(0.02805*D^2)+(0.64515*D)+20.5656]$, where D is the diameter of the pipe in inches (Liu et al., 1995).

[2] - Construction cost is based on a rate of $17,391.30 per km per inch diameter (Escoe, 2006).

[3] - Assumed.

[4] - Pump maintenance cost is assumed to be 3% of the capital cost (Bell, 1963, Kennedy, 1984; Menon, 2006).

[5] - Pipeline maintenance cost is assumed to be 3% of the capital cost (Bell, 1963, Kennedy, 1984; Menon, 2006).

[6] - Based on earlier studies by Kumar et al. (2004 & 2005) on biomass pipeline.

[7] - Labor cost is for two operators working 10,400 hours per year at an hourly rate of $28.50/hr. This is based on earlier studies (Kumar et al., 2003).

[8] - Electricity cost is calculated base on a power price of $60/MWh, pump power consumption of 45 hp.

[9] - Estimated based on the methodology explained earlier.

[10] - Power line cost is estimated based on the formula, Cost ($) = 1.29*((8400*N)+8400), where N is the number of booster stations for transporting bio-oil for 100 kms (Liu et al., 1995).

[11] - Based on the methodology discussed earlier for estimating pump cost. Installation cost is assumed to be 10% of the capital cost (Menon, 2006).

Table 3.4: General assumptions and characteristics of bio-oil pipeline system

Items	Values	Comments/Remarks
Operation factor of pipeline	90%	Kumar et al., 2003; Kumar et al., 2005a; Kumar et al., 2005b.
Density of bio-oil	1.2 kg/liter	(Dynamotive Energy Systems Corporation, 2000; Bridgewater, 2003; Yaman, 2004)
Discount rate	10%	Assumed.
Contingency	20% of total cost	Assumed.
Engineering cost	10% of capital cost	Assumed.
Life of pipeline	20 years	The life time of the project is set for 20 years. The HDPE pipe can last more than 20 years (ARNCO Corporation, 2006; Menon, 2005).

Items	Values	Comments/Remarks
Thickness of pipeline insulation	3.8 cm (or 1.5 inch)	The thickness of the PE foam insulator is based on the available thickness of the product in the market.

Using the data given in Tables 3.1, 3.2, 3.3 and 3.4, a detailed techno-economic model was developed based on discounted cash flow analysis. This techno-economic model was used to calculate the cost of pipeline transport ($\$/m^3$) of bio-oil. Figure 3.2 shows the cost of pipeline transport of bio-oil for different capacities of pipeline of bio-oil (m^3/day) at various length of pipeline.

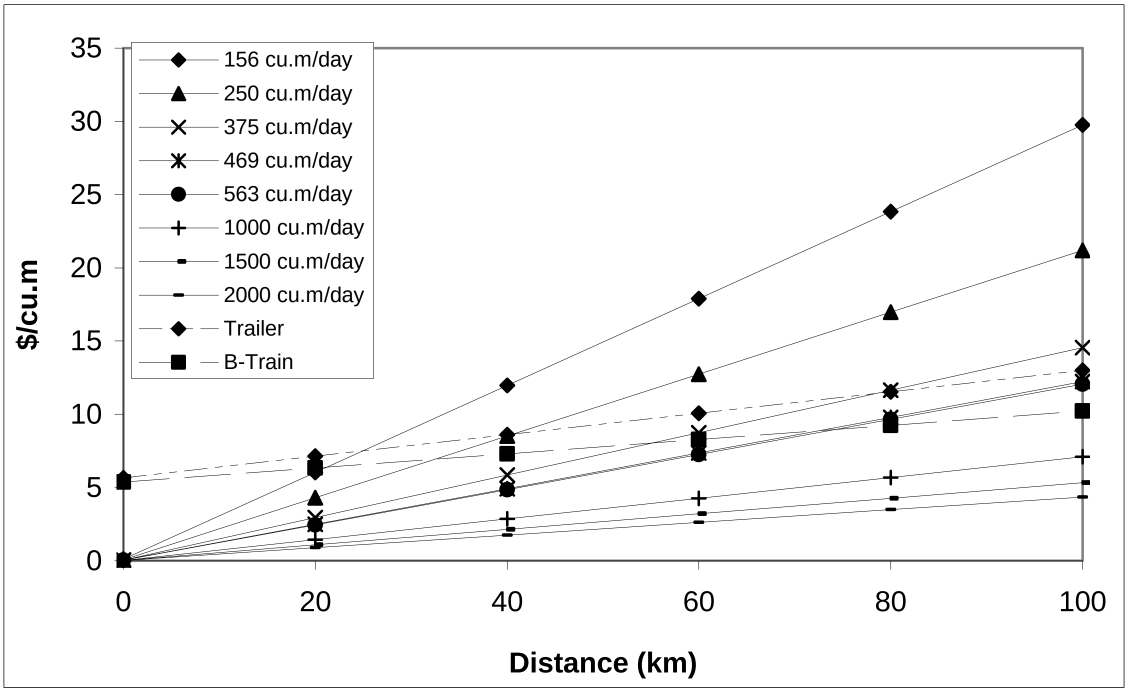

Figure 3.2: Pipeline transport cost of bio-oil versus distance at various capacities.

In Figure 3.2, solid lines represent the pipeline transportation cost of bio-oil at various capacities. The two dotted lines are for truck transportation of bio-oil. The pipeline transportation cost decreases with the increase in capacity of pipeline and is directly proportional to the distance of transport. Although the pump power increases with the increase in the capacity, the total cost of pipeline transport of bio-oil ($/m^3.) decreases with the capacity, predominantly due to the benefits from the economy of scale in the capital cost of pipeline. Another important observation from the Figure 3.2 is that, the different points show the booster station required for the pumping bio-oil at various capacities.

The intercept of the lines in Figure 3.2 represent the fixed cost which are not variable with distance of transport. In case of truck transport, the intercept of the lines represent the loading and unloading costs which are independent of distance traveled. The slope of the line shows the variable cost which includes the fuel cost, labour cost, maintenance cost etc. for the truck transport case. In case of pipeline transport of bio-oil, the intercept consists of inlet and outlet station costs of the pipeline. These costs are given in Table 3.1. The slope of the line represents the cost which varies with distance. The slopes of the lines mainly consist of pipeline capital cost, booster station cost, pipeline operating and maintenance cost. Table 3.5 shows the formulae for calculating pipeline transportation cost at various capacities of the pipeline. It also gives the capacity of the sizes of the pipeline which is required for various capacities of bio-oil production plant. The distance between the booster stations changes with the capacity of the bio-oil transportation. Table 3.5 also gives the distance between booster stations for different capacities of the pipeline.

Table 3.5: Formulae for pipeline transport cost of bio-oil

Capacity of bio-oil plant (dry tonnes per day)	Capacity of pipeline transporting bio-oil (m^3 per day)	Diameter of pipeline	Formulae for pipeline transportation cost	Distance between booster station (km)
250	156	5.1 cm (or 2 in.)	0.2966X+0.1022	9.1
350	219	5.1 cm (or 2 in.)	0.2293X+0.0785	5.1
400	250	5.1 cm (or 2 in.)	0.2112X+0.0710	4.1
600	375	7.6 cm (or 3 in.)	0.145X+0.0522	12.1
750	469	7.6 cm (or 3 in.)	0.1218X+0.0467	9.4
900	562	9.9 cm (or 3.9 in)	0.1201X+0.0423	6.9
1600	1000	9.9 cm (or 3.9 in)	0.0706X+0.0291	8.1
2400	1500	12.2 cm (or 4.8 in.)	0.0531X+0.0249	11.7
3200	2000	14.0 cm (or 5.5 in)	0.0433X+0.0205	11.9

3.4 Economics of pipeline transport versus truck transport of bio-oil

Pipeline transport cost of bio-oil would be economical than the truck transport cost if the slope of the line representing the pipeline transport cost (i.e., the variable transportation cost of pipeline) is lower than the slope of the line representing truck transport cost (i.e. the variable transportation cost of truck). Figure 3.3 shows the plot of variable transportation cost of pipeline with the capacity of the pipeline for a pipeline of length 100 km. Figure 3.3 also shows two dotted lines which represent the variable cost of truck transport of bio-oil.

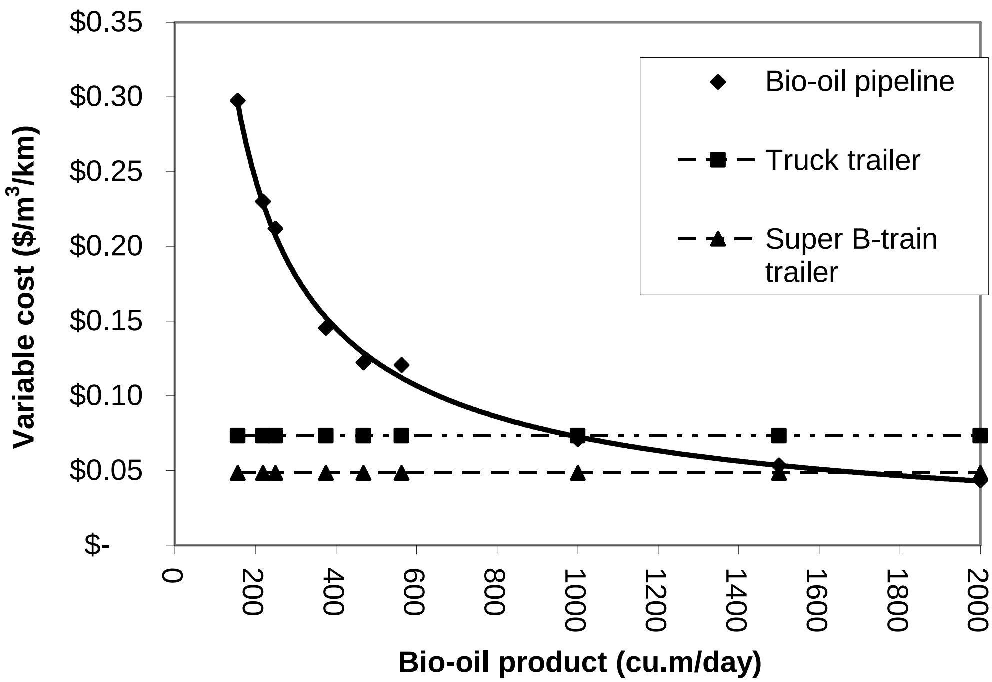

Figure 3.3: Capacity versus variable cost of pipeline transportation of bio-oil

The variable cost of pipeline transportation of bio-oil ($/m^3/km) decreases with the increase in the capacity of the pipeline. The decrease in the variable cost of pipeline is due to the benefits of the economy of scale in the capital cost of pipeline and also the operating cost. The capital cost per unit output of pipeline ($/m^3) decreases with the increase in the capacity (m^3/day). The scale factor for the pipeline transportation cost is 0.75 and is obtained by the determining the capital cost of pipeline at various capacities using the formula given above (Liu et al., 1995; Kumar et al., 2004).

The two dotted lines in Figure 3.3 represent the variable transportation cost of liquid tank truck and B-train truck trailer. The variable transportation cost of truck transportation of bio-oil is constant. This means that either transportation capacity is 100m^3/day or 10,000 m^3/day, the variable transportation cost of truck do not change. This is shown by straight lines and it indicates that there is no economy of scale benefits in the transportation of bio-oil by trucks. The variable transportation costs of liquid tank truck and B-train truck trailer are $0.07 and $0.05 per m^3 per km, respectively. The variable transportation cost of B-train truck trailer is lower than the liquid tank truck because of its larger capacity.

When variable transportation cost of bio-oil pipeline is compared with variable transportation cost by liquid tank truck, there are two regions of capacities. For a capacity of pipeline below 1,000 m^3/day (which is equivalent to a bio-oil plant using about 1,600 dry tonnes of biomass/day), transport of bio-oil by liquid tank trucks and and super B-train trailer is economic as compared to pipeline transport of bio-oil because the variable transportation cost of pipeline is higher than the trucks. At a capacity of 1,000 m^3/day, the variable cost of transportation of bio-oil by pipeline is same and as that of liquid tank truck. This capacity is the cross over point or economic capacity of pipeline transport of bio-oil as compared to liquid tank truck. Similarly, when variable transportation cost of bio-oil by pipeline is compared with variable transportation cost of bio-oil by B-train truck trailer, again there are two regions of capacities. For a capacity of pipeline below 1,700 m^3/day (which is equivalent to a bio-oil plant using about 2,720 dry tonnes of biomass/day), transport of bio-oil by B-train truck trailer is economic as compared to pipeline transport of bio-oil as the variable transportation cost of pipeline is higher than the B-train truck trailer. For a capacity of pipeline greater than 1,700 m^3/day, the variable transportation cost of bio-oil pipeline is lower than the B-train truck trailer. At a capacity of 1,700 m^3/day, the variables cost of transportation of bio-oil by pipeline is same and as that of B-train truck trailer. This economic capacity of pipeline transport of bio-oil as compared to B-train truck trailer is 1,700 m^3/day.

3.5 Discussion

Pipeline transport of bio-oil helps in transporting it in larger capacities from a large scale bio-oil production plant. There have been several studies which suggest that biomass based facilities need to be at large scale to be competitive with fossil fuel based energy facilities. These sizes are in the range of utilization of 5,000-6,000 dry tonnes of lignocellulosic biomass per day (Kumar et al., 2003; Kumar et al., 2005a; Searcy et al., 2007). A bio-oil production plant processing 6,000 dry tonnes of biomass would produce about 4,500 m^3/day of bio-oil. If truck transport is used for transporting bio-oil from this large scale production plant to the consumer, there could be road congestion issues. For example, a plant producing 4500 m^3/day, with a liquid tank truck having capacity of 30 m^3/load, about 6 to 7 trucks will be loaded every hour, this might lead to congestion. Pipeline transport of bio-oil helps in reducing this congestion and also lowering cost at these scales.

In this study, the distance of transport of bio-oil by pipeline is arbitrarily assumed to be 100 km. Pipeline can be used to transport bio-oil to longer distances much more than the 100 km. One of the keys in transportation of bio-oil by pipeline is that the temperature of bio-oil should be maintained above 45 ^{o}C so that the viscosity of bio-oil is similar to the crude oil (Menon, 2005). In this study, it is assumed that HDPE pipeline is insulated with 3.8 cm (or 1.5 inch) PE foam

(ARNCO Corporation, 2006). The modeling of the temperature profile shows that the pipeline with PE insulation can maintain the bio-oil's the temperature above 45^{o}C upto 100 km (Logstor, 2006). If bio-oil has to be transported for a distance greater than 100 km, heating of bio-oil at different booster stations will be required. Figure 3.4 shows the cost of pipeline transport of bio-oil at various capacities with cost of heating included. The dots in the Figure 3.4 show the booster station. After each booster station there is an increase in the pipeline cost due to the cost of heating at the booster stations.

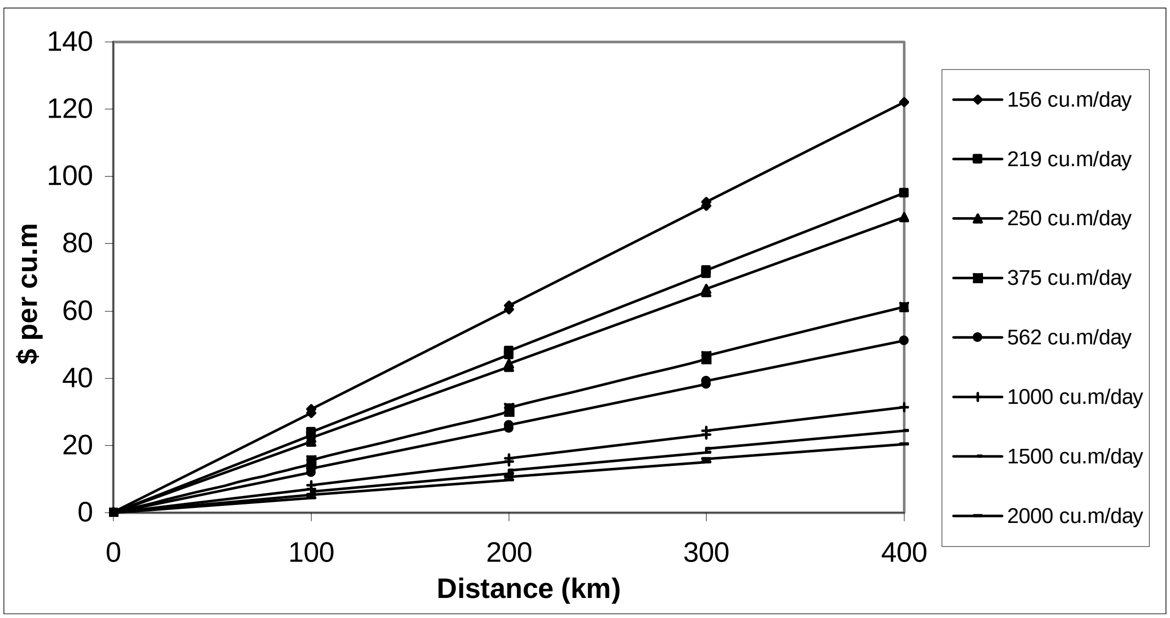

Figure 3.4 Cost of pipeline transport of bio-oil at various capacities with cost of heating included

Figure 3.5 shows the variable cost of pipeline transport of bio-oil for distances longer than 100 km as compared variable cost of trucks. The variable cost of pipeline included the cost of heating the bio-oil at various booster stations. If the length of pipeline is 400 km, the comparison of the variable costs shows two regions of capacities. For a capacity of pipeline below 1,150 m^3/day (which is equivalent to a bio-oil plant using about 1,840 dry tonnes of biomass/day) and its transportation to 400 km, transport of bio-oil by liquid tank trucks and super B-train trailer is economic as compared to pipeline transport of bio-oil because the variable transportation cost of heated pipeline is higher than the trucks.

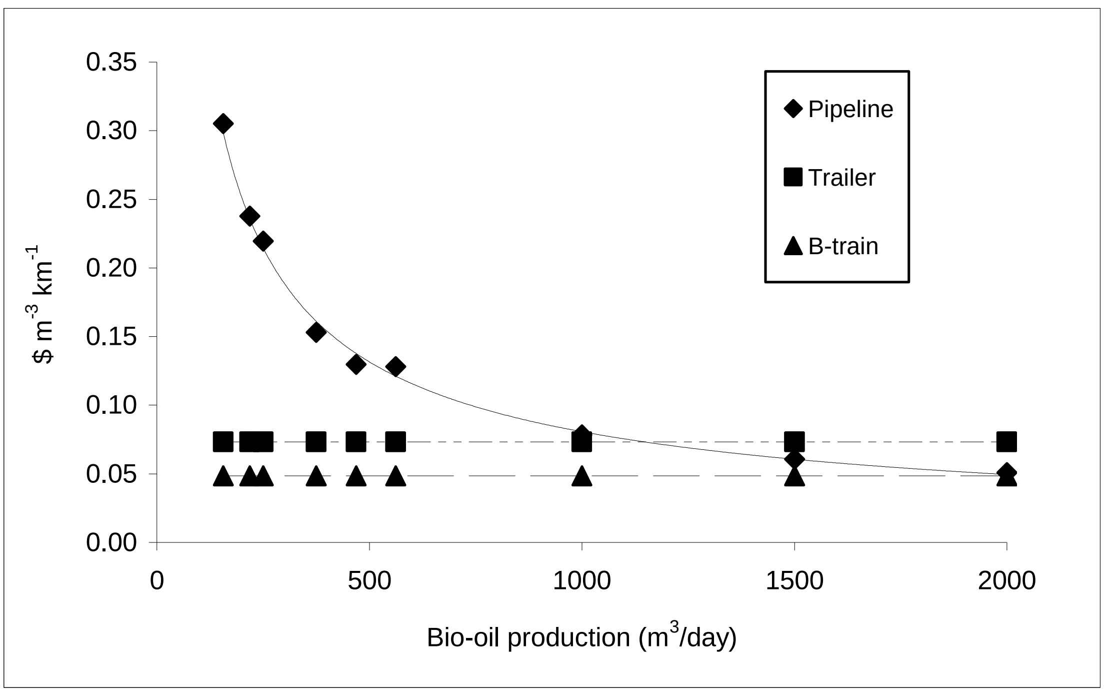

Figure 3.5: Variable cost of pipeline transportation of bio-oil with heating cost for 400 km

.At a capacity of 1,150 m^3/day, the variable cost of transportation of bio-oil by heating pipeline is same as that of liquid tank truck. This capacity is the cross over point or economic capacity of heating pipeline transport of bio-oil as compared to liquid tank truck for a distance of transport of 400 km. Similarly, when variable transportation cost of bio-oil by pipeline is compared with variable transportation cost of bio-oil by super B-train truck trailer, again there are two regions of capacities. For a capacity of pipeline below 2,000 m^3/day (which is equivalent to a bio-oil plant using about 3,200 dry tonnes of biomass/day), transport of bio-oil by super B-train truck trailer is economic as compared to pipeline transport of bio-oil as the variable transportation cost of pipeline is higher than the B-train truck trailer. For a capacity of pipeline greater than 2,000 m^3/day, the variable transportation cost of bio-oil pipeline is lower than the B-train truck trailer. At a capacity of 2,000 m^3/day, the variables cost of transportation of bio-oil by pipeline is same and as that of super B-train truck trailer. This economic capacity of heated pipeline transport of bio-oil as compared to B-train truck trailer is 2,000 m^3/day for a distance of transport of 400 km.

The comparison of pipeline transport of bio-oil with truck transport depends a lot on the distance variable cost of the truck and pipeline transport of bio-oil. In this study we have assumed the trucks which are used for crude oil transport is used for pipeline transport. The variable and fixed cost of transport of crude oil trucks are assumed as for bio-oil truck. An accurate determination of the variable cost of transport of bio-oil will help in accurate determining of the size of the pipeline at which pipeline transport is economical as compared to truck transport.

In this study, it is assumed that friction factor for bio-oil transport in the pipeline would be the same as for crude oil. The friction factor plays an important role in determining the pump power required for pumping at certain velocity and through a particular pipe. Sensitivity analysis was performed on the friction factor. Figure 3.6 shows the percentage change in total transportation cost of pipeline transport of bio-oil from a 900 dry tonnes per day plant, transporting 560 m^3/day versus changes in friction factor. The total cost of transportation would decrease with the decrease in the friction factor (due to decreased pumping cost). But in this case, percentage change in the total transportation cost of bio-oil is also affected by the heating cost. At 200 km, there is additional cost of heating to keep the temperature of bio-oil in a range so that it has the properties similar to crude oil. As a result of additional heating compared to transportation to 100 km, the percentage contribution of the pumping cost (depends on the friction factor) in the total cost of transportation decreases and hence, the percentage change in the total cost is lower compared to change in transportation cost at 100 km. As the distance of transportation increases, the percentage contribution of the pumping cost in the total transportation cost decreases due to the increase in the contribution of heating cost component. At 800 km, the percentage change in the total transportation cost reflects the contribution of the significantly increased heating cost.

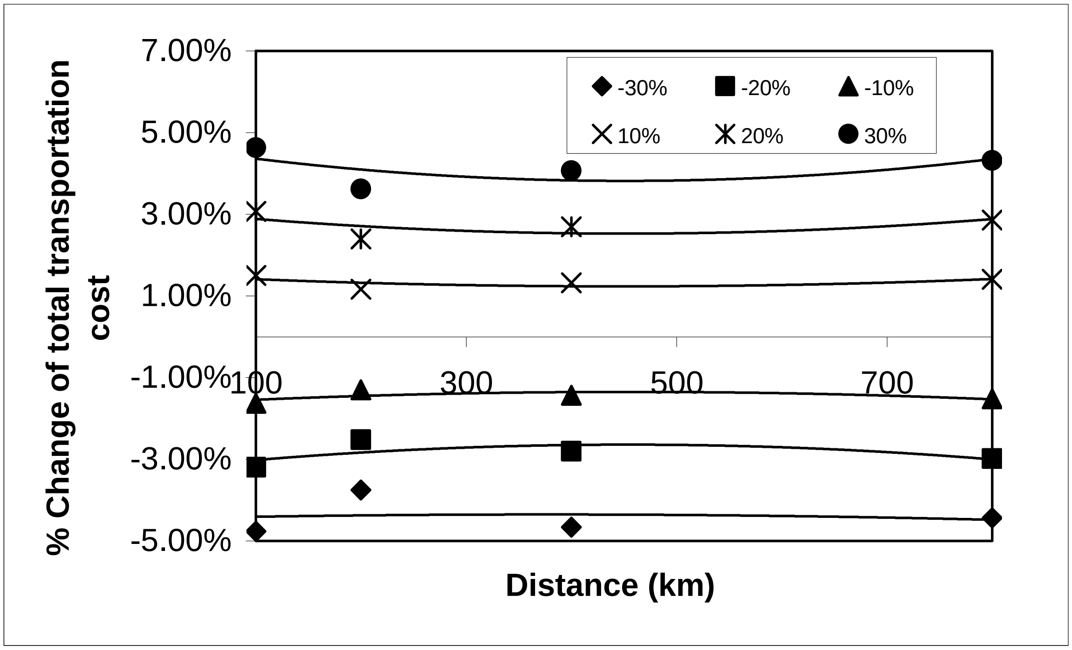

Figure 3.6: Impact of change in friction factor on total transportation cost with distance of transportation of bio-oil in pipeline.

Capital cost of pipeline plays an important role in determining the distance variable cost of pipeline transport of bio-oil. In this study the HDPE pipeline is considered as the pipeline material and the cost details are obtained from the manufacturers. A sensitivity analysis was performed to study the impact of change of capital cost on the distance variable cost and ultimately on the economic pipeline size. Figure 3.7 shows the impact of capital cost on variable transport cost of pipeline. The percentage change in the total cost of transportation is influenced by the change in the capital cost of the pipeline as well as increase in the heating cost with distance of transport.

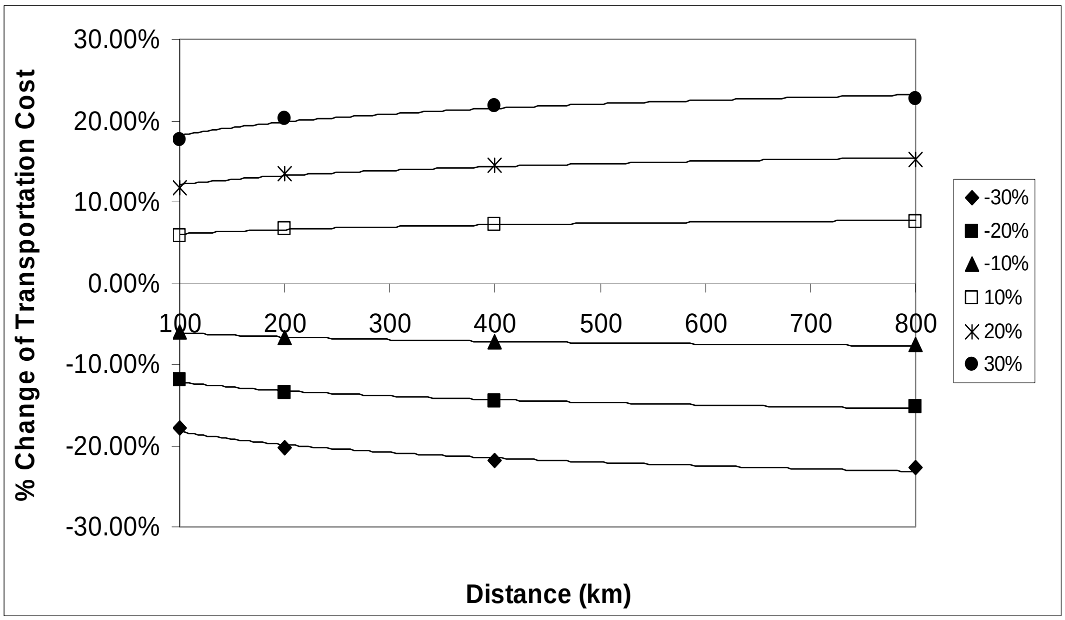

Figure 3.7: Impact of change in capital cost of pipeline on total cost with distance of pipeline transport of bio-oil.

3.6. Conclusions

Bio-oil is transported by truck from the bio-oil production plant. Pipeline transport of bio-oil can help in decreasing the cost of transportation and also help in transporting larger capacities of bio-oil. Pipeline transport cost of bio-oil decreases with the increase in the capacity of the pipeline. The fixed and variable components of pipeline transport of bio-oil at a pipeline capacity of 560 m^3/day and to a distance of 100 km are 0.0423 \$/m^3 and 0.1201 \$/m^3/km. Pipeline transportation cost of bio-oil is cheaper than the cost of transportation by liquid tank truck (load capacity 30 m^3) and super B train trailer (load capacity 60 m^3) at pipeline capacities of 1,000 and 1,700 m^3/day, respectively and for a transportation distance of 100 km. For transportation of bio-oil through pipeline for distance longer than 100 km, heating of bio-oil is required at the booster stations. The transportation of bio-oil by pipeline to a distance of 400 km, the pipeline capacities need to be 1,150 m^3/day and 2,000 m^3/day for it to economical than liquid tank truck and super B train tank trailers. Heating increases the cost of pipeline transport of bio-oil by 3.33%.

References

ARNCO Corporation, 2006. Perma-Guard Gathering HDPE 3408 Tubing and Pipe for oil and gas application. Available at; www.arncorp.com. Accessed on; April 2006.

Badger, C.P., Fransham, P., 2006. Use of mobile pyrolysis plant to densify biomass and reduce biomass handling cost- A preliminary assessment. Biomass and Bioenergy. 30, 321-325.

Bell, H.S. 1963. Petroleum Transportation Handbook. New York, NY: McGraw-Hill Book Company.

Borjesson, P., Gustavsson, L., 1996. Regional production and utilization of biomass in Sweden. Energy. 21, 747-764.

Brammer, J.G., Lauer, A., Bridgewater, A.V., 2005. Opportunities for biomass-derived Bio-oil in European heat and power market. Energy Policy, 34, 2871-2880.

Bridgewarter, A.V., 1999. Principle and practice of biomass pyrolysis process for liquid. Journal of Analytical and Applied Pyrolysis. 51, 3-22.

Bridgewarter, A.V., 2003. Renewable fuels and chemicals by thermal processing of biomass. Chemical Engineering Journal. 91, 87-102.

Brown, R.C., 2008 Fast Pyrolysis and bio-oil upgrading. USDA, ARS Available at:

www.ars.usda.gov/sp2UserFiles/Program/307/**bio**masstoDiesel/Robert**Brown**&Je nniferHolmgrenpresentationslides.pdf. Accessed on April 2009.

Dynamotive Energy Systems Inc. Energy System Corp. 1999. BioTherm A system for continuous quality, Fast pyrolysis Bio-oil. Forth biomass conference of the America, Oakland, California. September 1999.

Dynamotive Energy Systems Inc. Energy System Corp, Thamburaj,R., 2000. Fast pyrolysis of biomass for green power generation. First world conference and exhibition on biomass for energy and industry.

Dynamotive Energy Systems Inc. Energy System Corp. 2001. Fast pyrolysis of bagasse to produce biooil for power generation. Sugar Conference 2001.

Escoe, A.K., 2006. Piping and Pipelines Assessment Guide. Burlington, MA: Gulf Professional Publishing.

Ghafoori, E., Flynn, P.C., Feddes, F.J. 2007. Pipeline vs. truck transport of beef cattle manure. Biomass and Bioenergy, 31(2-3), 168-175.

Ghafoori, E. 2007. The economics of energy from animal manure for greenhouse gas mitigation. University of Alberta, Spring 2007.

IEA Bioengineering. 2007. Biomass Pyrolysis. Available at: www.ieabioengineering.com. Accessed on April 2007.

Jones, David S J and Pujadó, Peter P. 2006, Handbook of Petroleum Processing. Page 545. Chapter. 13. Springer. First edition

Kennedy, J.L., 1984. Oil and gas pipeline fundamentals. Tulsa, Oklahoma. PennWell Publishing Company.

Kumar A. 2009. A conceptual comparison of bioenergy options for using mountain pine beetle infested wood in Western Canada. Bioresource Technology. 100(1), 387-399.

Kumar A., Cameron, J.B., Flynn, P.C. 2005a. Pipeline transport and simultaneous saccharification of corn stover. Bioresource Technology. 96, 819-829.

Kumar A., Cameron, J.B., Flynn, P.C. 2004. Pipeline transport of biomass. Applied Biochemistry and Biotechnology. 113, 27-40.

Kumar A., Cameron, J.B., Flynn, P.C. 2005b. Large-scale ethanol fermentation through pipeline delivery of biomass. Applied Biochemistry and Biotechnology. 121, 47- 58.

Kumar, A., J.B. Cameron and P.C. Flynn. 2003. Biomass power cost and optimum plant size in western Canada. Biomass & bioenergy 24: 445-464.

Liu, H., Noble, J., Zuniga, R., Wu, J., 1995. Economics analysis of coal and log pipeline transportation of coal. Capsule pipeline research Center (CPRC). Report No. 95-1, University of Missouri, Columbia, USA.

Logstor Pipe Company's software for insulation and heat lost calculation, 2006. Provided by Logstor Company.

Menon, S.E., 2005. Gas pipeline hydraulics, Boca, FL: Taylor and Francis Group.

Pootakham, T., Kumar A. 2009. A comparison of pipeline versus truck transport of bio-oil. Bioresource Technology (Accepted, *in-press*).

Searcy, E., Flynn P, Ghafoori E, Kumar A. 2007. The relative cost of biomass energy transport. Applied Biochemistry and Biotechnology. 137-140(1-12):639-52.

Transport Canada. 2006. Operating cost of truck in Canada 2005. Transportation Canada File Number T8080-05-0242.

Yaman, S., 2004. Pyrolysis of biomass to produce fuels and chemical feedstocks. Energy Conversion and Management. 45, 651-671.

Chapter Four: Comparison of Bioenergy Transportation Forms: Electricity versus Bio-oil

4.1 Introduction

Today, most energy comes from fossil fuel. In 2008, 88% of the energy consumed by the world came from fossil fuel (BP, 2009). Using fossil fuel to produce energy results in a significant release of greenhouse gases (GHGs), some portion of which could be filled by renewable energy sources, for which various technologies are at different stages of development, demonstration and implementation. Biomass, one of the renewable sources, has high potential and has attracted a lot of interest. Biomass-based energy is considered nearly carbon neutral because the amount of CO_2 released during the combustion of biomass is the same as the amount taken up by the plant during its growth. Biomass can be used to produce a variety of fuels such as bioethanol (Aden et al., 2002), biodiesel (Holbein, 2004), bio-oil (Pootakham and Kumar, 2009a; Bridgewater, 2003), biohydrogen (Sarkar and Kumar, 2009) and biopower (Kumar et al., 2003). Biomass conversion technologies are at different stages of development. Biomass has two key characteristics which stand in the way of its large scale implementation as discussed in chapter 2.

Increasing the energy density (MJ/m^3) of biomass feedstocks could reduce the overall bioenergy transportation cost; converting biomass to a dark viscous liquid known as bio-oil increases the energy density significantly. Bio-oil has 7 times the energy density of 'as received' biomass (Pootakham and Kumar, 2009a and 2009b). Bio-oil is produced from the fast pyrolysis of biomass (i.e. rapid heating of biomass in the absence of air) (Bridgewater, 2003; Dynamotive Energy Systems 1999 & 2000; Yaman, 2004; Kumar, 2009). Its characteristics are similar to those of fuel oil grade #2; it has high viscosity at room temperature, and it has low pH (Bridgewater, 2003; Dynamotive Energy Systems Corporation, 1999 and 2000; Yaman, 2004). Several research groups and companies are working to develop appropriate processes for producing bio-oil; among these: Dynamotive Energy Systems Inc. (Dynamotive Energy Systems Corporation, 1999 and 2000), Renewable Oil International (ROI) (Badger, 2006) and Biomass Technology Group (BTG) (BTG, 2002). Bio-oil can be used for producing heat, power, and specialty chemicals.

Biomass is used extensively to produce heat and power. It can be directly combusted in a boiler to produce heat which can then be used to produce power (Dynamotive Energy Systems Corporation, 2000; BTG, 2002; Yaman, 2004; Badger, 2006). It can be gasified to produce syngas which can then be used in a gas turbine to produce power (Dynamotive Energy Systems Corporation, 2000; BTG, 2002; Yaman, 2004; Badger, 2006). Production of power from raw biomass is a well developed technology. The largest direct-combustion-based biomass power plant, which is currently operating in Pietarsaari, Finland, produces 240 MW of power (Kumar et al., 2008). In a study of biomass-based power generation in Western Canada, Kumar et al. (2003) developed cost estimates for power generation from three biomass sources: whole trees, forest residue (i.e. branches and tops of trees left by logging) and straw (from wheat and barley). There have been other studies on field-sourced biomass-based power generation in Western Canada and all have concluded that biomass-based power is more expensive than fossil-fuel-based power (Kumar et al., 2003; Cameron et al., 2007; Kumar et al., 2003; Stennes and McBeath, 2005). One of the key reasons is the high cost of transporting biomass.

Bio-oil can be used for power production (Dynamotive Energy Systems Corporation, 2000; BTG, 2002; Yaman, 2004; Badger, 2006). The compatible combustion technologies are diesel engine, gas turbine and steam-based rankine cycle. \as well, integrated combined cycle has been proposed for production of power from bio-oil (Brammer, 2005; Dynamotive Energy Systems, 2000). The thermal efficiency of bio-oil for combined heat and power plant systems increases as the size of the generation unit increases. The larger scale of bio-oil power gives it higher thermal efficiency (Brammer, 2005). Studies on bio-oil utilization for power generation show that the potential for electricity generation is high (Dynamotive Energy Systems Corporation, 2000; BTG, 2002, Yaman, 2004).

Pipelines, widely used for transporting liquid, compressed gas, and slurry, provide economical transportation for liquid and slurry over greater distances and at larger capacities (Kumar at al., 2004; Kumar et al., 2005a and 2005b; Ghafoori et al., 2007; Searcy et al., 2007). Bio-oil is a liquid fuel that can be transported considerable distances by pipeline (Pootakham and Kumar, 2009). The merit of large scale pipelines is that there is an economy-of-scale benefit for the capital cost; that is, the capital cost of the pipeline per unit of output decreases with increases in throughput. Thus, the transportation of bio-oil by pipeline results in an overall decrease of the transportation cost of biomass energy (Pootakham and Kumar, 2009b). Bio-oil has a viscosity similar to that of crude oil in the temperature range of 30 to 45^{o}C (Dynamotive Energy Systems Corporation, 2000; Yaman, 2004). Studies have detailed the technical and economic feasibility of the pipeline transport of bio-oil (Pootakham and Kumar, 2009a and 2009b) comparing it with truck transport of bio-oil. Pipeline transportation costs less than truck transportation over longer distances and larger capacities (Pootakham and Kumar, 2009b).

There is a scarcity of data on the cost of generating power from pipeline-transported bio-oil. The objective of this research is to develop a techno-economic model to calculate the cost of producing electricity ($/MWh) from pipeline-transported bio-oil, comparing it with the cost of producing electricity ($/MWh) from the direct combustion of biomass. The overall aim is to compare the cost of transporting bioenergy in the form of bio-oil and electricity.

4.2 Scope of the Study

In this study, whole tree biomass from forests in Western Canada is the biomass feedstock. In the base case, whole trees are harvested in the forest stand and dragged to the road side, where they are put through a chipper. The tree chips are transported by B-train chip van to a bio-oil production plant in the forest. The bio-oil produced in the forest is transported to a power plant by pipeline. In this study, the power plant is assumed to be 100 km from the bio-oil production plant and is near an existing consumer grid. This study estimates the cost of all the upstream and downstream processes, developing a techno-economic model that takes into account all the upstream and downstream cost components along with production plant characteristics as it estimates the cost of power based on bio-oil ($/MWh).

In an alternative case, biomass chips produced in the forest from the whole tree are transported by B-train chip van to an electricity production plant which burns biomass, and uses the steam produced to drive a steam turbine that produces electricity. The electricity produced is transmitted to consumers through transmission lines. In this study the length of the transmission line is assumed to be the same length as the bio-oil transportation pipeline that is 100 km. Finally, the cost of power ($/MWh) from pipeline-transported bio-oil is compared to the cost of delivered power ($/MWh) generated by direct combustion of biomass in the forest and transmitted through a transmission line to an existing consumer grid. All costs are given in 2008US$ unless otherwise stated.

4.3 Biomass Delivery Cost

In the base case, the wood chips are transported to a bio-oil production plant; in the alternative case, they are transported to an electricity production plant that burns biomass. Biomass harvesting and transportation to a bioenergy processing facility is estimated for both cases. In Western Canada, 80% of logging operations include felling the trees in the stand, skidding the trees to the roadside, chipping the trees on the roadside and transporting the chips to a plant (Kumar et al., 2003). In this study, the biomass delivery cost includes the cost of felling, skidding, chipping and B-train chip van to a bioenergy facility.

The cost of biomass harvesting and processing has been studied extensively. In Canada, the Forest Engineering Research Institute of Canada (FERIC) and the Canadian Forest Service (CFS) have done extensive work (Gingras, 1996; Favreau, 1992) on estimating forest harvesting and processing costs. In addition, there have been many studies on biomass harvesting and transportation costs (Puttock, 1995; Hudson and Mitchell, 1992; Hankin et al., 1995; Hudson, 1995; Perlack et al., 1996; Zundel and Lebel, 1992; Hall et al., 2001; LeDoux and Huyler, 2001; McKendry, 2002; Zundel et al., 1996; Silversides and Moodie, 1985; Zundel, 1986; Mellgren, 1990; Routhier, 1982; Desrochers, 2002;

Kowallic, 2002; Wiksten and Prins, 1980; Folkema 1989; Favreau, 1992; Spinelli and Hartsough, 2001; Asikainen and Pulkkinen, 1998; Folkema, 1982). Earlier studies on biomass-based power generation in Western Canada estimated these costs in detail (Kumar et al., 2003; Cameron et al., 2007). Also with these studies, there was estimation of forest biomass delivery costs including various components. In this study, the costs of the biomass harvesting and transportation used in this study are derived from these studies.

The biomass delivery cost includes the cost of road construction because bioenergy facility developers would have to build roads for the transportation of biomass. It also includes silviculture cost, which is the cost of preparing the land for replanting. Table 4.1 shows all the cost components of biomass delivery to bioenergy facility.

Table 4.1: Biomass delivery cost

Cost components	Values ($/dry tonne)
Felling cost	$5.36[1]
Skidding cost	$4.27[2]
Chipping cost	$4.38[3]
Road construction cost	$7.31[4]
Silviculture cost	$7.10[5]

Cost components	Values ($/dry tonne)
Transportation cost	$7.40[6], $6.31[7]
Overhead cost	$8.00
Total cost of delivery	
• To a bio-oil production plant	$43.82
• To a biomass based power production plant	$42.74

[1] - This value is calculated based on the formula derived from Kumar et al. (2003) at a merchantable volume per stem of 0.26 m^3/stem for Alberta.

[2]- This value is calculated based on the formula derived from Kumar et al. (2003) at a merchantable volume per stem of 0.26 m^3/stem for Alberta and a skidding distance of 150 m.

[3]- The chipping cost is taken from Kumar et al., (2003) and is adjusted to US$2008.

[4] - This value is calculated based on the formula derived from Kumar et al. (2003) at a stem volume of 185.4 m^3 per ha for Alberta.

[5] - This value is calculated based on the formula derived from Kumar et al. (2003) at silviculture cost of $151.69 per ha and a biomass yield of 84 dry tonnes per ha.

[6] - $7.40/dry tonne is the cost of transportation of chips from forest to a bio-oil production plant having a capacity of utilizing 2,200 dry tonnes of biomass/day. The transportation cost is calculated based on the formula derived from Kumar et al. (2003).

[7] - $6.31/dry tonne is the cost of transportation of chips from forest to a biomass based power production plant having a capacity of utilizing 4,905 dry tonnes of biomass/day. The transportation cost is calculated based on the formula derived from Kumar et al. (2003).

4.4 Base Case – Delivered Electricity Cost from Bio-oil

This section gives the cost parameters associated with bio-oil production, its transportation by pipeline to a power plant, and the cost of generating electricity from the bio-oil.

4.4.1 Bio-oil production cost

Bio-oil can be produced from a variety of biomass feedstocks. In this study it is produced from chips transported from the forest. The key components of the cost of producing this bio-oil are the cost of harvesting and transporting biomass from forest to production plant, processing the biomass, building the production plant and operating/maintaining it. Other studies have estimated the cost of producing bio-oil from biomass for different locations and different feedstocks (Kumar, 2003; Gingras, 1996; Borjessen, 1996). The data for this techno-economic model has been derived from various studies. Table 4.2 gives the input data and assumptions on the basis of which the cost of bio-oil production has been estimated. Additional data is to be the same as in an earlier study by Kumar (2009) on bio-oil cost.

Table 4.2: Input data and assumptions for bio-oil production plant

Details	Values	Comment and reference
Bio-oil plant capacity	2,200 dry tonnes per day	This size of biomass plant is assumed based on earlier studies of biomass based energy facilities (Aden et al., 2002; Kumar et al., 2003).
Bio-oil production	1,375 m^3/day	This is estimated based on a plant using 2,200 dry tonnes per day of biomass at an yield of 75% of bio-oil and a density of bio-oil of 1200 kg/m^3 (Dynamotive Energy Systems Corporation, 2000; Yaman, 2004).
Plant life	20 years	The life time of power plant facility is 20 to 50 years. (Kumar, 2009).
Bio-oil production plant capital cost	$115 million	The capital cost is estimated using a scale factor of 0.75 from an earlier study on estimation of bio-oil cost by Kumar (2009). The plant is constructed in 3 years and an investment profile of 20% in first year, 35% in second year, 45% in third year is

Details	Values	Comment and reference
		assumed based on (Kumar, 2009).
Products of fast pyrolysis of forest biomass • Bio-oil • Char • Water	 66% 21% 13%	(Dynamotive Energy Systems Corporation, 2000; Yaman, 2004).
Operation factor of power generation facility • First year • Second year • Third year	 70% 80% 90%	This is based on other solid handling facilities. These numbers are derived from earlier studies (Kumar, 2009; Kumar et al., 2003).
Operating cost and administration cost	$3.64 million per year	Total of 7 people working in bio-oil production plant. The total working hour per year per person is 10,400 hrs/year (Kumar et al., 2003). The labour cost is assumed to be $50/hr.
Maintenance cost	3%	It is assumed to fixed percentage of the capital cost.
Biomass delivery cost	$43.83/dry tonne	This includes the cost of

Details	Values	Comment and reference
		felling, skidding, chipping and transporting biomass from forest to the bioenergy facility. The different cost components are given in Table 4.1.
Discount factor (%)	10%	Assumed.
Decommissioning and reclamation cost	20%	Assumed based on earlier studies on bioenergy facilities (Kumar et al., 2003; Kumar 2009).

4.4.2 Pipeline transportation cost of bio-oil

In earlier studies by the authors, the pipeline transport of bio-oil was evaluated (Pootakham and Kumar, 2009a and 2009b). Bio-oil can be transported by high density polyethylene (HDPE) pipe at a temperature of about 40^{o}C. At this temperature its viscosity is similar to that of crude oil (Dynamotive Energy Systems Corporation, 2000; Yaman, 2004). In these earlier studies, frictional losses due to the transportation of bio-oil were assumed to be the same as for crude oil. In the current study, bio-oil is produced from forest biomass by fast pyrolysis and the vapours produced are quenched to about 90^{o}C, this is then pumped 100 km through an HDPE pipeline (Pootakham and Kumar, 2009a and 2009b). The temperature of the bio-oil is higher than 40^{o}C for a transport of 100 km, so no additional heating of it is required. The details are given in Pootakham and Kumar (2009a and 2009b). Table 4.3 gives the input data and assumptions.

The cost of transporting bio-oil by pipeline varies linearly with the distance of transport for a particular throughput (Pootakham and Kumar, 2009b; Kumar et al., 2004, 2005a and 2005b). The cost of pipeline transportation at a particular capacity can be represented in the form of equation 1, given below.

$$C = A + B*X$$

where,

C - pipeline transport cost of bio-oil ($\$/m^3$)

A - distance fixed cost of pipeline transport cost of bio-oil ($\$/m^3$)

B - distance variable cost of pipeline transport cost of bio-oil ($\$/m^3/km$)

X - distance of transport (km)

The data from Table 4.3 on pipeline transport of bio-oil was used to determine the total cost of pipeline transportation ($/litre). Values for distance fixed and variable costs are given in Table 4.3. The details on the methodology for estimating these values are given in Pootakham and Kumar (2009a and 2009b).

Table 4.3: Input data and assumptions for pipeline transport of bio-oil

Details	Values	Comment and reference
Capacity of the bio-oil pipeline	542 (m^3/yr)	This is based on a production of 1,375 m^3/day of bio-oil from the production plant and an annual operating factor of a 0.9 for a fully operating plant.
Length of pipeline, 'X'	100 km	Assumed.
Diameter of pipeline (m)	12.2 cm (or 4.80 inch)	This based on a velocity of 1.5 m/sec of bio-oil in the pipeline.
Life of pipeline	20 years	Assumed.
Distance variable cost of pipeline transport of bio-oil, 'B'	0.0575X	These values have been derived from earlier studies by authors (Pootakham and Kumar, 2009b).
Distance fixed cost of pipeline transport of bio-oil, 'A'	0.0259	These values have been derived from earlier studies by authors (Pootakham and Kumar, 2009b).
No. of booster stations required to transport bio-oil to 100 km	9	Based on pump power of 86 kW and 600 psi of pressure developed by one pump. This was based on the pressure-

Details	Values	Comment and reference
		drop model for pipeline transport of bio-oil detailed in an earlier study (Pootakham and Kumar, 2009b).

4.4.3 Electricity production cost from bio-oil

Bio-oil can be combusted in a boiler and the steam generated can be used to produce of power through a steam turbine. There is a scarcity of detailed data on power generation from bio-oil, very few studies having been done in this area (Dynamotive Energy Systems Corporation, 2000; Badger, 2006). In this study, the power generation from bio-oil is assumed to be from the biomass woodchip power plant. Data were collected on the capital and operating costs a power plant based on pipeline-delivered bio-oil and on the operating characteristics of that power plant. These data were used to develop the techno-economic model estimating the cost of power ($/MWh). Table 4.4 gives details on the characteristics of the power plant.

Table 4.4: Input data and assumptions for bio-oil power plant

Details	Values	Comment and reference
Bio-oil power plant capacity	150 MW	This capacity was based on a large scale power plants

Details	Values	Comment and reference
		which are operating based on biomass feedstocks around the world and proposed in earlier studies (Kumar et al, 2005; Kumar et al., 2008; Kumar et al., 2003).
Bio-oil utilization by the power plant (litres/yr)	423 millions	This is based on a lower heating value efficiency of the bio-oil of 18.8 MJ/kg (Bridgewater, 1999) and efficiency of the power plant of 45% (BTG, 2002).
Plant life	30 years	The life time of power plant facility is 25 to 50 years. (Kumar, 2003).
Plant capital cost	$256.3. million	This cost is derived based on a unit cost of $2056/kW for an oil fired power plant (Boyce, 2002) and taking into account the recent increase in steel price. The plant is constructed in 3 years and an investment profile of 20% in first year, 35% in second year, 45% in third year is assumed based on (Kumar, 2003).

Details	Values	Comment and reference
Scale factor	0.75	Kumar, 2003
Cost of pipeline delivered bio-oil ($/litre)	$0.144/L	This is calculated based on the fixed and variable cost of pipelining of 0.0259 $\$/m^3$ and 0.0575 $\$/m^3/km$, respectively for a distance of 100 km.
Operating factor of power generation facility • First year • Second year • Third year	 70% 80% 90%	This is based on other solid handling facilities. These numbers are derived from earlier studies (Kumar, 2009; Kumar et al., 2003).
Operating cost and administration cost	$2.2 million per year	Total of 9 people working in bio-oil production plant. The total working hour per year per person is 10,400 hrs/year (Kumar et al., 2003). The labour cost is assumed to be $50/hr.
Maintenance cost	3%	It is assumed to fixed percentage of the capital cost.
Discount factor (%)	10%	Assumed.
Decommissioning and	20%	Assumed based on earlier studies on bioenergy facilities

Details	Values	Comment and reference
reclamation cost		(Kumar et al., 2003; Kumar 2009).

4.5 Alternative Case – Delivered Electricity Cost from Direct Combustion of Biomass

4.5.1 Electricity production cost from direct combustion of biomass

Generating electricity by direct combustion of biomass is a mature technology. Several studies have discussed different aspects of it (Kumar, 2003; Badger, 2006). Kumar et al. (2003) studied the generation of power from forest and agricultural biomass for Western Canada. Other authors also have studied utilizing biomass for power generation in Western Canada (Ghafoori, 2006; Searcy, 2006). Biomass in the form of chips is fed into a boiler and steam is produced, which is then used to run a turbine to generate power. In this study, a fluidized bed boiler is assumed. The electricity is produced in the forest and then transmitted to a grid near consumers. As stated above, data were collected for the various cost components and characteristics of biomass-based power plants and then used to develop a techno-economic model estimating the cost of power generation ($/MWh). Table 4.5 gives the input data and assumptions alluded to.

Table 4.5: Input data and assumptions for biomass based power generation plant

Details	Values	Comment and reference
Biomass power plant capacity (MW)	150 MW	This capacity was based on a large scale power plants which are operating based on biomass feedstocks around the world and proposed in earlier studies (Kumar et al, 2005; Kumar et al., 2008; Kumar et al., 2003).
Biomass utilization by the power plant (dry tonnes/yr)	814,000 dry tonnes/yr.	This is based on a moisture content of 50% (Kumar, 2003) of biomass and a lower heating value of 8.8 MJ/kg (Searcy, 2007).
Plant life	30 years	The life time of power plant facility is 25 to 50 years (Kumar, 2003).
Plant capital cost	$376 million	This cost is derived based on a unit cost of $3097/kW for an oil fired power plant (Boyce, 2002) and taking into account the recent increase in steel price. The plant is constructed in 3 years and an investment profile of 20% in

Details	Values	Comment and reference
		first year, 35% in second year, 45% in third year is assumed based on (Kumar, 2003).
Scale factor	0.75	Kumar et al., 2003
Cost of delivered biomass ($/cu.m)	$42.74/dry tonne	This includes the cost of felling, skidding, chipping and transporting biomass from forest to the bioenergy facility. The different cost components are given in Table 4.1.
Operation factor of power generation facility • First year • Second year • Third year	 70% 80% 90%	This is based on other solid handling facilities. These numbers are derived from earlier studies (Kumar, 2009; Kumar et al., 2003).
Operating cost and administration cost	$3.64 million per year	Total of 9 people working in bio-oil production plant includes extra 30% overhead cost. The total working hour per year per person is 10,400 hrs/year (Kumar et al., 2003). The labour cost is assumed to

Details	Values	Comment and reference
		be $50/hr.
Maintenance cost	3%	It is assumed to fixed percentage of the capital cost.
Ash disposal cost ($/tonne)	$0.14/MWh	This is estimated based on ash spreading cost of $17.01/tonne (Kumar et al., 2003) and ash transportation to 50 km of $6.10/tonne (Kumar et al., 2003).
Discount factor (%)	10%	Assumed.
Decommissioning and reclamation cost	20%	Assumed based on earlier studies on bioenergy facilities (Kumar et al., 2003; Kumar 2009).

4.5.2 Electricity transmission cost from forest to consumer

The power plant based on woodchips is in a remote location and supplies electricity to customers by transmission lines. For a woodchip power plant with a capacity of 150 MW, a 230 kV transmission line can transmit the electricity produced to a grid near a consumer base. The major cost components of the transmission line are its capital cost and its operation and maintenance costs. The capital cost of a transmission line includes the cost of transmission poles, wires and their installation. The operating cost includes annual labour and maintenance for the transmission line; it is independent of the cost of the electricity transmitted. It is assumed that the transmission line consists of 90% self-poles and 10% guyed poles. The self-poles cost \$95,068 km^{-1} and guyed poles cost \$142,076 km^{-1}. Guyed pole can support the transmission line on corners. The cost per km of the transmission line is \$13,479 km^{-1} in 2008 US dollars value.

Table 4.6: Input data and assumptions for power transmission line from power generation plant to consumer grid

Details	Values	Comment and reference
Transmission capacity of the power line	150 MW, 230kV	
Life of transmission line	30 years	Assumed.
Capital cost of transmission line (million $/km)		(Searcy et al., 2007).
• Self pole cost	$99,156/km	
• Guyed pole cost	$148,184/km	
Scale factor for the capital cost of the transmission line	0.492	Kumar et al., 2003
Operation factor of	90%	Based on the power plant

Details	Values	Comment and reference
transmission lines		utilization factor.
Maintenance cost	3%	It is assumed to fixed percentage of the capital cost.
Discount factor (%)	10%	Assumed.
Power loss in the transmission lines	3%	(Searcy, 2007).

4.6 Results and discussion

<u>Cost of bio-oil production in the forest</u>

Table 4.7 gives a detailed cost breakdown of bio-oil production using whole forest biomass in the Province of Alberta. This cost is for a bio-oil plant utilizing 2,200 dry tonnes/day. The cost of producing bio-oil from whole-tree-chipped biomass is \$0.144/liter of bio-oil. This is lower than the cost reported earlier by Kumar (2009). The difference is mainly because, in this study, the yield per ha of biomass is higher, and the plant is 10 times larger. The total cost of bio-oil production includes \$43.82 per dry tonne or \$0.047/liter for delivering biomass to the production plant. This biomass delivery cost is at 33%, a major component of the total cost of bio-oil. This consists of the costs of felling (\$5.36/dry tonne), skidding (\$4.27/dry tonne), chipping (\$4.38/dry tonne), road construction (\$7.31/dry tonne), silviculture (\$7.10/dry tonne), biomass transportation

($7.40/dry tonne) and overhead ($8.00/dry tonne). Capital cost contributes about 27% of the total cost of bio-oil whereas operating cost (including operating labour, chemicals, water and utilities) contributes about 33% and maintenance cost contributes about 7%.

Table 4.7: Bio-oil production cost in third year of operation (US$2008)

Cost components	Value ($/litre)
Capital cost	0.039
Operating cost	0.009
Maintenance cost	0.010
Biomass delivery cost	0.041
Transportation cost	0.006
Miscellaneous chemicals and water cost	0.018
Natural gas cost	0.007
Electricity cost	0.013
Non production utilities and labour	0.001
Total cost	0.144

Cost of power generation from pipeline transported bio-oil

Table 4.8 gives the cost of power generation using pipeline-transported bio-oil as a feedstock for the power plant. A bio-oil production plant using 2,200 dry tonnes of biomass/day can support a 150 MW biomass-based power plant. The total cost of power production in this case is $86.83 per MWh in the third year of operation. Biomass feedstock contributes to about 58% of the total cost of power production. The feedstock delivered cost includes the cost of transporting the bio-oil by pipeline; this transportation cost constitutes 4% of the total bio-oil delivered cost. A distance of 100 km between production plant and power plant contributes about 3% of the total power production cost. The capital cost of the plant contributes about 31% of the total cost. The operating and maintenance costs are 2% and 10% of the total cost, respectively.

Table 4.8: Cost of power production from pipeline delivered bio-oil in the third year of operation (US$2008)

Cost components	Value ($/MWh)
Capital cost	26.66
Operating cost	1.81
Maintenance cost	8.27
Bio-oil delivered cost	50.09
Total delivered cost of power	86.83

Delivered cost of power generated from direct combustion of biomass

Table 4.9 shows the cost of generating power from direct combustion of wood chips in a boiler. The cost of power generated by 150 MW biomass-based power plant is from its third year of operation. This plant would use about 814,000 dry tonnes of biomass per year at full capacity. The cost of producing power from the direct combustion of whole-tree-chipped biomass is $77.98/MWh of electricity produced. The total cost of biopower production includes the cost of delivering the biomass to the power production plant, which is $42.74 per dry tonne or $22.81/MWh. Biomass delivery constitutes a major component of the total cost of producing power, contributing about 29% of the total cost of the power produced. It consists of the costs of felling ($5.36/dry tonne), skidding ($4.27/dry tonne), chipping ($4.38/dry tonne), road construction ($7.31/dry tonne), silviculture ($7.10/dry tonne), biomass transportation ($6.31/dry tonne) and overhead ($8.00/dry tonne). Capital cost contributes about 51% of the total cost. Operating cost (including administration) and maintenance cost contribute about 4% and 15% of the total cost of power, respectively.

Table 4.9: Cost of produced power by direct combustion of wood chips (US$2008)

Cost components	Value ($/MWh)
Capital cost	39.45
Operating cost	3.10
Maintenance cost	11.88
Biomass cost	22.81
Transmission cost	0.59
Ash disposing cost	0.14
Total delivered cost of power	77.98

Comparison delivered power cost from bio-oil and direct combustion of woodchips

Power generated from direct combustion of wood and transmitted 100 km as electricity is cheaper than bio-oil produced 100 km from a power plant and transported to it by pipeline. The former is about 10% cheaper than the latter. There are several reasons for this. In the bio-oil case, the cost of production of bio-oil remotely and then its transportation to the power production plant contribute significantly to the cost of power production. This could be one of the reasons for this difference.

In this study, a power plant of 150 MW is assumed. If the size of the power plant were increased, there would be two key benefits to the bio-oil case. The cost of producing bio-oil would go down due to economy of scale in the capital cost of the bio-oil production plant. This would require a larger pipeline to transport the additional bio-oil. The cost of transporting bio-oil through a larger pipeline would be lower due to the benefit of economy of scale. Larger pipeline throughput results in a lower cost of transportation per unit (Kumar et al., 2004; 2005a; 2005b; Thanyakarn and Kumar, 2009). The two cases considered in this study need to be investigated at larger scales where the benefit of pipeline transport of bio-oil can be explored.

The main difference between the two cases is in the cost of transporting energy 100 km. In a bio-oil-based power plant, bioenergy is transported in the form of bio-oil. In a direct-combustion-of-wood-chips-based power plant, bioenergy is transmitted in the form of electricity. This study has determined that the latter is less expensive. A detailed analysis of the fixed and variable costs of the two modes of transportation would illustrate the impact distance has on the transport of bioenergy.

4.7 Conclusion

Biomass can be used to generate power through different thermo-chemical conversion pathways. In the form of chips, it can be directly combusted in a boiler to produce power through a steam turbine. Through fast pyrolysis, it can be converted to bio-oil, which can be combusted to produce power. In this study, techno-economic models were developed to calculate the cost of producing electricity ($/MWh) from pipeline-transported bio-oil and the cost of delivered electricity ($/MWh) produced from direct combustion of biomass. The former was $86.83/MWh in a 150 MW power plant. The major cost in this was the cost of the bio-oil, which was about 58% of the total cost of the power. The cost of transporting bio-oil by pipeline was only 3% of the total. By contrast, the cost of producing electricity through direct combustion of biomass in the form of wood chips was $77.98/MWh, with the biomass contributing about 29% of the total cost. Clearly this is the cheaper option at this scale. This suggests that further investigation into scale of power plant considerations would be advisable.

References

Aden, A., Ruth, M., Ibsen, K., Jechura, J., Neeves, K., Sheehan, J., Wallace, B., Montague, L., Slayton, A., Lukas, J., 2002. Lignocellulosic biomass to ethanol process design and economics utilizing co-current dilute acid prehydrolysis and enzymatic hydrolysis for corn stover. Report no. NREL/TP-510-32438. URL: http://www.nrel.gov/docs/fy02osti/32438.pdf. Accessed on August 12, 2007.

ARNCO Corp., 2006. Perma-Guard Gathering HDPE 3408 Tubing and Pipe for oil and gas application. Available at; www.arncorp.com. Accessed on; April 2006.

Badger, C.P., Fransham, P., 2006. Use of mobile pyrolysis plant to densify biomass and reduce biomass handling cost- A preliminary assessment. Biomass and Bioenergy. 30, 321-325.

Borjesson, P., Gustavsson, L., 1996. Regional production and utilization of biomass in Sweden. Energy. 21, 747-764.

Boyce, M.P. 2002. Handbook of cogeneration and combine cycle power plant. American Society of Mechanical engineer.

Brammer, J.G., Lauer, A., Bridgewater, A.V., 2005. Opportunities for biomass-derived Bio-oil in European heat and power market. Energy Policy, 34, 2871-2880.

Bridgewarter, A.V., 1999. Principle and practice of biomass pyrolysis process for liquid. Journal of Analytical and Applied Pyrolysis. 51, 3-22.

Bridgewarter, A.V., 2003. Renewable fuels and chemicals by thermal processing of biomass. Chemical Engineering Journal. 91, 87-102.

Biomass Technology Group (BTG), 2004. Flash pyrolysis. Available at: http://www.btgworld.com/technologies/pyrolysis.html

Bowater Newfoundland Ltd. 1983. Harvesting forest biomass as an alternative fuel. Project Report P-191,ENFOR.

Cameron, J.B., A. Kumer, and P.C. Flynn. 2007. The impact of feedstock cost on technology selection and optimum size. Biomass and bioenergy volume 31: 137-144.

Dynamotive Energy System Corp. 1999. BioTherm A system for continuous quality, Fast pyrolysis Bio-oil. Forth biomass conference of the America, Oakland, California. September 1999.

Dynamotive Energy system Corp, Thamburaj,R., 2000. Fast pyrolysis of biomass for green power generation. First world conference and exhibition on biomass for energy and industry.

Dynamotive Energy System Corp. 2001. Fast pyrolysis of bagasse to produce biooil for power generation. Sugar Conference 2001.

Favreau, 1992 Favreau, J.F.E., 1992. In-woods chipping: a comparative cost analysis. Forest Engineering Research Institute of Canada (FERIC), Technical Report No TR-105.

Folkema,MP. 1986. Handbook for small to medium size fuelwood chipping operations. Technical Report No. HB-07,FERIC.

Gingras, J. 1996. Cost of product sorting during sorting. Report submitted to FERIC.

Ghafoori, E., Flynn, P.C., Feddes, F.J. 2007. Pipeline vs. truck transport of beef cattle manure. Biomass and Bioenergy, 31(2-3), 168-175.

Hall P,Gigler JK,Sims REH. 2001. Delivery systems of forest arising for energy production in New Zealand. Biomass and Bioenergy Vol. 21(6):391–9.

Hankin, A.C., Stokes, B. and Twaddle, A. 1995 The transportation of fuel wood from forest to facility, *Biomass Bioenergy* 10 (2–3), pp. 141–151.

Holbein, B.E., Stephen, J.D. and Layzell, D.B., 2004. Canadian Biodiesel Initiative: Aligning Research Needs and Priorities With the Emerging Industry. Final Report by Biocap Canada Foundation, Ontario.

Hudson JB,Mitchell CP. 1992. Integrated harvesting system. Biomass and Bioenergy Vol. 2(1–6):121–30.

Hudson JB. 1995. Integrated harvesting system. Biomass and Bioenergy Vol. 9(1–5):141–51.

IEA Bioengineering. 2007. Biomass Pyrolysis. Available at: www.ieabioengineering.com. Accessed on April 2007.

Kumar, A., et al. 2005. Pipeline transport and simultaneous saccarification of corn stover. Bioresource Technology. 96, 819-829.

Kumar, A., et al. 2004. Pipeline transport of biomass. Applied Biochemistry and Biotechnology. 113, 27-40.

Kumar, A., J.B. Cameron and P.C. Flynn. 2003. Biomass power cost and optimum plant size in western Canada. Biomass & bioenergy 24: 445-464.

LeDoux CB,Huyler NK. 2001. Comparison of two cut-to-length harvesting systems operating in eastern hardwoods. Journal of Forest Engineering Vol. 12(1):53–9.

Logistics solution builders Inc. 2005. Operating cost of truck in Canada 2005. Transportation Canada File Number T8080-05-0242.

Liu, H., Noble, J., Zuniga, R., Wu, J., 1995. Economics analysis of coal and log pipeline transportation of coal. Capsule pipeline research Center (CPRC). Report No. 95-1, University of Missouri, Columbia, USA.

McKendry P. 2002 Energy production from biomass (part 1):overview of biomass. Bioresource technology Vol. 83(1):37–46.

Mellgren PG. 1990. Predicting the performance of harvesting systems in different operating conditions. Special Report No. SR-67, FERIC.

Menon, S.E., 2005. Gas pipeline hydraulics, Boca, FL: Taylor and Francis Group.

Perlack RD,Walsh ME,Wright LL,Ostlie LD. 1995. The economic potential of whole-tree feedstock production. Bioresource Technology Vol. 55(3):223–9.

Pootakham T., Kumar A. A comparison of pipeline versus truck transport of bio-oil, *Bioresource Technology,* 2009a, 101(1), 414-421.

Pootakham T., Kumar A. Bio-oil transport by pipeline: techno-economic assessment, submitted to *Bioresource Technology*, 2009b (in review).

Puttock GD. 1995. Estimating cost for integrated harvesting and related forest management activities. Biomass and Bioenergy Vol. 8(2):73–9.

Sarkar, S., Kumar, A. 2009. Techno-economic assessment of biohydrogen production from forest biomass in Western Canada. Transactions of the ASABE. 52(2), 519-530.

Searcy, E., Flynn P, Ghafoori E, Kumar A. 2007. The relative cost of biomass energy transport. Applied Biochemistry and Biotechnology. 137-140(1-12):639-52.

Silversides CR,Moodie RL. 1985. Transport of full trees over public roads in eastern Canada—A state of the art report. Forest. Engineering Research Institute of Canada (FERIC), Special Report No. SR-35,Energy from forest (ENFOR), Project P-312.

Spinelli R,Hartsough B. 2001. A survey of Italian chipping operations. Biomass and Bioenergy Vol. 21(6):433–44.

Sternnes, B and McBeath, A. 2005. Bioenergy options for woody feedstock: are tree killed by mountain pine beetle in British Columbia a viable energy source? Natural Resource Canada. Report No. BC-X-405.

Yaman, S., 2004. Pyrolysis of biomass to produce fuels and chemical feedstocks. Energy Conversion and Management. 45, 651-671.

Zundel P. 1986. The economics of integrated full-tree harvesting and central processing in jack pine. Special Report No. SR-37, ENFOR Project P-322, FERIC.

Zundel P,Lebel L. 1995. Comparative analysis of harvesting and silviculture costs following integrated harvesting. Journal of Forest Engineering Vol. 4(1):31–7.

Zundel, P.E., Hovingh, A.J., Wuest, L., MacElveney, D., Needham, T.D., 1996. Silviculture systems for the production of energy biomass in conventional operations in Atlantic Canada, University of New Brunswick, Canada. <http://www.unb.ca.login.ezproxy.library.ualberta.ca/forestry/centers/biomass.htm>.

Chapter Five: Conclusions and Recommendation for Future Work

5.1 Conclusions

Biomass-based energy and fuels are receiving attention because they are considered carbon neutral; i.e. the amount of CO_2 released during combustion of this biomass is nearly the same as that taken up by the plants during their growth. Bio-oil, a dark viscous liquid consisting of hydrocarbons is produced by fast pyrolysis of biomass. 'As-is' biomass material has a low energy density ($MJ.m^{-3}$), hence, the cost of transporting this energy is high. Bio-oil has a high energy density compared to 'as-is' biomass material, consequently it helps in reducing the cost of energy transport. This study investigates the conversion of biomass to bio-oil as an option for increasing the energy density of biomass, which can then be transported by a large scale and for longer distances.

5.1.1 A life cycle energy and emission analysis of pipeline and truck transport of bio-oil

This study compares the life cycle assessments transporting bio-oil by pipeline and transporting it by truck. This involves the transportation of bio-oil by truck or pipeline from a centralized plant (supplied with forest biomass) to an end-user. Two cases are studied for the pipeline transport of bio-oil: the first considers a coal-based electricity supply for pumping bio-oil through a pipeline; the second considers a renewable electricity supply resource such as hydro-based electricity. The two cases of pipeline transport are compared with two cases of truck transport (truck trailer and super B-train truck). The life cycle greenhouse gas (GHG) emissions from the pipeline transport of bio-oil are 345 and 17 g of CO_2 $m^{-3}.km^{-1}$ for the two electricity supplies, respectively. Similar values for transport by trailer (capacity 30 m^3) and super B-train truck (capacity 60m^3) are 89 and 60 g of CO_2 m^{-3} km^{-1}, respectively.

Pipeline transport of bio-oil produces fewer emissions than does truck transport, if the source of electricity for pumping is a renewable-resource-based power plant (i.e. hydro power). If the power for pumps comes from a coal-based plant, truck transport of bio-oil produce fewer emissions. Energy consumption is also significantly different if tanker truck transport is compared with pipeline transport: the energy input is 3.95 MJ m^{-3} km^{-1} by pipeline, 2.59 MJ.m^{-3} km^{-1} by truck and 1.66 MJ m^{-3} km^{-1} by super B-train truck. The energy consumption of transporting bio-oil can be decreased by increasing the yearly throughput of the pipeline. The results also show that GHG emissions in pipeline transport are largely dependent on the source of electricity (higher for coal-based electricity). So substituting 250 m^3 day^{-1} of pipeline-transported bio-oil for supplying 28 MW coal-based power plant can mitigate about 5.1 million tonnes of CO_2 per year. Overall, this study gives a comprehensive life cycle assessment of bio-oil transport comparing pipeline and truck transport.

5.1.2 A techno-economic assessment of bio-oil transport by pipeline

The transportation of biomass is a key issue in utilizing of biomass for fuels and chemicals. Bio-oil is a product of the thermo-chemical transformation of biomass in order to increase the energy density. Transporting this bioenergy in the form of bio-oil can help reduce the cost. The key objectives of this study include estimating the cost of transporting bio-oil by pipeline ($/liter of bio-oil) and comparing that cost with the cost of transporting by truck. This study also estimates the size of pipeline and distance of transport at which cost of pipeline transporting bio-oil is more economical by pipeline then by truck.

Pipeline transport of bio-oil can decrease the cost of transportation while increasing capacity. Its cost components vary with the distance of transport. The fixed and variable cost components of pipeline transport of bio-oil at a pipeline capacity of 560 m^3/day and for a distance of 100 km are 0.0423 $/$m^3$ and 0.1201 $/$m^3$/km. Pipeline transportation of bio-oil costs less than transportation by liquid tank truck (load capacity 30 m^3) and super B train trailer (load capacity 60 m^3) for a distance of 100 km at pipeline capacities of 1,000 and 1,700 m^3/day, respectively. For distances greater than 100 km, bio-oil requires heating at the booster stations to maintain proper viscosity. The transportation of bio-oil by pipeline to a distance of 400 km require pipeline capacities of 1,150 m^3/day and 2,000 m^3/day if it is to be more economical than transportation by liquid tank trucks and super B train tank trailers. Heating increases the cost of pipeline transport by 3.33%. At a pipeline length of 400 km, the variable costs have two categories of capacity. For a capacity below 1,150 m^3/day (equivalent to the output of a bio-oil plant using about 1,840 dry tonnes of biomass/day) liquid tank trucks and super B-train trailers are more economical, because of the variable transportation cost of the heated pipeline. At a capacity of 1,150 m^3/day, the variable cost of transporting bio-oil by heated pipeline is the same as that of transporting it by liquid tank truck. This capacity is the cross over point or in economics of heated pipeline transport and liquid tank truck transport for a distance of the 400 km. Similarly, when the variable transportation cost of bio-oil by pipeline is compared with variable transportation cost of bio-oil by super B-train truck trailer, again there are two categories of capacity. Below 2,000 m^3/day (which is the output of a bio-oil plant using about 3,200 dry tonnes of biomass/day), transport by super B-train truck trailer is more economical than pipeline transport, because the variable transportation cost is higher for the pipeline than for the B-train truck trailer. For a pipeline capacity greater than 2,000 m^3/day, the variable transportation cost for the pipeline is lower than that for the B-train truck trailer. At a capacity of 2,000 m^3/day, the variables cost of transporting bio-oil 400 km by pipeline is the same as that of transporting it 400 km by super B-train truck trailer.

5.1.3 A comparison of bioenergy transportation forms: electricity versus bio-oil

Biomass can be used to generate power through different thermo-chemical conversion pathways. In the form of woodchips it can be directly combusted in a boiler to produce power through a steam turbine. Through fast pyrolysis it can be converted to bio-oil, which can then be combusted to produce power. In this study techno-economic models are developed to calculate the cost of producing electricity ($/MWh) from pipeline-transported bio-oil; this is then compared with the cost of delivered electricity ($/MWh) produced from the direct combustion of biomass in s forest plant and subsequently transmitted through transmission lines. The cost of producing electricity from pipeline-transported bio-oil is $86.83/MWh in a 150 MW power plant. A major cost component of production cost of electricity is bio-oil. It is about 58% of the total cost of power, whereas transporting of bio-oil by pipeline is only 3% of this cost. Producing of electricity through direct combustion of biomass in the form of wood chips costs $77.98/MWh, with biomass contributing about 29% of the total cost. The results indicate that the latter is less expensive than the former for this size of power plant.

5.2 Recommendations for future work

This study is basically a comparative assessment of bio-oil transportation by truck and pipeline from biomass resources in Western Canada. It estimates the energy required for and emissions released during the transport of bio-oil by pipeline and truck; it also compares the cost of bio-oil transport by pipeline and truck. Some opportunities for future research are given below.

- Bio-oil has chemical properties similar to liquid petroleum in the temperature range of 30-45 ^{o}C. In this study, it is assumed that the friction factor of crude oil during pipeline transportation is the same as for bio-oil. For the accurate pressure loss calculation and bio-oil pipeline system design, the friction factor and viscosity of bio-oil are the important parameters. It is recommended that the friction factor of bio-oil should be experimentally determined.

- Viscosity is an important parameter for estimating pipeline pressure drop of bio-oil flow. There are two basic methods of improving the viscosity of bio-oil. The first method is by increasing its temperature and the second is by mixing it with additives (e.g. alcohol) which reduce the viscosity of bio-oil at low temperature. This needs to be experimentally investigated.

- This study compares two cases of bioenergy transportation. In the first scenario biomass is transported to a bio-oil production plant in the forest, and the bio-oil produce is transported by pipeline to a power plant 100 km away where power is generated. In the second scenario, biomass is transported to a power plant in the forest, the power produced is transported by transmission line to the consumer. The power produced in the second scenario is less expensive than that produced in the first scenario. In both scenarios, the size of the power plant is 150 MW. Further techno-economic assessment of these scenarios is required at larger scale to make possible a more comprehensive comparison.

Appendix

TABLE A1: Summary of discount cash flow of the 150 MW woodchip based power plant

Cost items ($ '000)/year	**-2**	**-1**	**0**	**1**	**2**	**3**	**4**
Capital Cost	92913.0	162597.8	209054.3	0.0	0.0	0.0	0.0
Operation Cost and Administration Cost	0.0	0.0	0.0	3640.0	3712.8	3787.1	3862.8
Maintenance Cost	0.0	0.0	0.0	13937.0	14215.7	14500.0	14790.0
Felling	0.0	0.0	0.0	2877.3	3288.4	3493.9	3563.8
Skidding	0.0	0.0	0.0	2289.2	2616.2	2779.7	2835.3
Chipping	0.0	0.0	0.0	2349.8	2685.5	2853.3	2910.4
Road construction	0.0	0.0	0.0	3922.8	4483.2	4763.4	4858.7
Silviculture + Loading	0.0	0.0	0.0	8098.2	9255.1	9833.5	10030.2
Transportation	0.0	0.0	0.0	3385.9	3869.6	4111.5	4193.7
Transmission charge	0.0	0.0	0.0	592.9	677.6	719.9	719.9
Site recovery and reclamation cost	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Ash Disposal	0.0	0.0	0.0	161.8	165.1	168.4	171.7
Total cost	92913.0	162597.8	209054.3	41254.9	44969.2	47010.8	47936.6
PV 10% of total cost	112424.7	178857.5	209054.3	37504.5	37164.6	35319.9	32741.3
MWH sold	0.0	0.0	0.0	892206.0	1019664.0	1083393.0	1083393.0
Price	0.0	0.0	0.0	84.4	86.1	87.8	89.6
Price required for 10% return	0.0	0.0	0.0	75313.6	87794.1	95146.9	97049.8
PV 10% of revenue	0.0	0.0	0.0	68466.9	72557.1	71485.3	66286.3

TABLE A1 Cont'd

Cost items ($ '000)/year	**5**	**6**	**7**	**8**	**9**	**10**	**11**
Capital Cost	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Operation Cost and Administration Cost	3940.1	4018.9	4099.2	4181.2	4264.8	4350.1	4437.1
Maintenance Cost	15085.8	15387.5	15695.3	16009.2	16329.4	16655.9	16989.1
Felling	3635.1	3707.8	3781.9	3857.6	3934.7	4013.4	4093.7
Skidding	2892.0	2949.9	3008.9	3069.1	3130.4	3193.0	3256.9
Chipping	2968.6	3028.0	3088.6	3150.3	3213.3	3277.6	3343.2
Road construction	4955.8	5055.0	5156.1	5259.2	5364.4	5471.7	5581.1
Silviculture + Loading	10230.8	10435.4	10644.1	10857.0	11074.1	11295.6	11521.5
Transportation	4277.6	4363.1	4450.4	4539.4	4630.2	4722.8	4817.3
Transmission charge	719.9	719.9	719.9	719.9	719.9	719.9	719.9
Site recovery and reclamation cost	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Ash Disposal	175.2	178.7	182.3	185.9	189.6	193.4	197.3
Total cost	48880.9	49844.1	50826.6	51828.7	52850.9	53893.5	54957.0
PV 10% of total cost	30351.2	28135.7	26082.1	24178.5	22413.9	20778.3	19262.1
MWH sold	1083393.0	1083393.0	1083393.0	1083393.0	1083393.0	1083393.0	1083393.0
Price	91.4	93.2	95.1	97.0	98.9	100.9	102.9
Price required for 10% return	98990.8	100970.7	102990.1	105049.9	107150.9	109293.9	111479.8
PV 10% of revenue	61465.5	56995.3	52850.2	49006.5	45442.4	42137.5	39073.0

TABLE A1 Cont’d

Cost items ($ '000)/year	**12**	**13**	**14**	**15**	**16**	**17**	**18**
Capital Cost	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Operation Cost and Administration Cost	4525.9	4616.4	4708.7	4802.9	4899.0	4996.9	5096.9
Maintenance Cost	17328.8	17675.4	18028.9	18389.5	18757.3	19132.4	19515.1
Felling	4175.5	4259.0	4344.2	4431.1	4519.7	4610.1	4702.3
Skidding	3322.0	3388.5	3456.3	3525.4	3595.9	3667.8	3741.2
Chipping	3410.0	3478.2	3547.8	3618.7	3691.1	3764.9	3840.2
Road construction	5692.7	5806.6	5922.7	6041.1	6162.0	6285.2	6410.9
Silviculture + Loading	11752.0	11987.0	12226.7	12471.3	12720.7	12975.1	13234.6
Transportation	4913.6	5011.9	5112.1	5214.4	5318.6	5425.0	5533.5
Transmission charge	719.9	719.9	719.9	719.9	719.9	719.9	719.9
Site recovery and reclamation cost	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Ash Disposal	201.2	205.2	209.4	213.5	217.8	222.2	226.6
Total cost	56041.7	57148.2	58276.8	59427.9	60602.0	61799.7	63021.3
PV 10% of total cost	17856.6	16553.8	15346.1	14226.6	13188.8	12226.7	11334.9
MWH sold	1083393.0	1083393.0	1083393.0	1083393.0	1083393.0	1083393.0	1083393.0
Price	105.0	107.1	109.2	111.4	113.6	115.9	118.2
Price required for 10% return	113709.4	115983.5	118303.2	120669.3	123082.7	125544.3	128055.2
PV 10% of revenue	36231.3	33596.3	31152.9	28887.3	26786.4	24838.3	23031.9

TABLE A1 Cont'd

Cost items ($ '000)/year	19	20	21	22	23	24
Capital Cost	0.0	0.0	0.0	0.0	0.0	0.0
Operation Cost and Administration Cost	5198.8	5302.8	5408.8	5517.0	5627.4	5739.9
Maintenance Cost	19905.4	20303.5	20709.6	21123.8	21546.2	21977.2
Felling	4796.4	4892.3	4990.2	5090.0	5191.8	5295.6
Skidding	3816.0	3892.3	3970.1	4049.6	4130.5	4213.2
Chipping	3917.0	3995.4	4075.3	4156.8	4239.9	4324.7
Road construction	6539.1	6669.9	6803.3	6939.4	7078.2	7219.7
Silviculture + Loading	13499.3	13769.3	14044.7	14325.6	14612.1	14904.3
Transportation	5644.2	5757.1	5872.2	5989.7	6109.5	6231.6
Transmission charge	719.9	719.9	719.9	719.9	719.9	719.9
Site recovery and reclamation cost	0.0	0.0	0.0	0.0	0.0	0.0
Ash Disposal	231.1	235.8	240.5	245.3	250.2	255.2
Total cost	64267.3	65538.3	66834.6	68156.9	69505.7	70881.4
PV 10% of total cost	10508.2	9741.8	9031.4	8372.8	7762.3	7196.3
MWH sold	1083393.0	1083393.0	1083393.0	1083393.0	1083393.0	1083393.0
Price	120.6	123.0	125.4	127.9	130.5	133.1
Price required for 10% return	130616.3	133228.6	135893.2	138611.1	141383.3	144211.0
PV 10% of revenue	21356.8	19803.6	18363.3	17027.8	15789.4	14641.1

TABLE A1 Cont'd

Cost items ($ '000)/year	25	26	27	28	29	30
Capital Cost	0.0	0.0	0.0	0.0	0.0	0.0
Operation Cost and Administration Cost	5854.7	5971.8	6091.2	6213.1	6337.3	6464.1
Maintenance Cost	22416.7	22865.0	23322.3	23788.8	24264.6	24749.9
Felling	5401.5	5509.5	5619.7	5732.1	5846.8	5963.7
Skidding	4297.4	4383.4	4471.0	4560.5	4651.7	4744.7
Chipping	4411.2	4499.4	4589.4	4681.2	4774.8	4870.3
Road construction	7364.1	7511.4	7661.6	7814.9	7971.2	8130.6
Silviculture + Loading	15202.4	15506.5	15816.6	16132.9	16455.6	16784.7
Transportation	6356.3	6483.4	6613.1	6745.3	6880.2	7017.8
Transmission charge	719.9	719.9	719.9	719.9	719.9	719.9
Site recovery and reclamation cost	0.0	0.0	0.0	0.0	0.0	74330.4
Ash Disposal	260.3	265.5	270.8	276.2	281.8	287.4
Total cost	72284.6	73715.9	75175.8	76664.9	78183.8	154063.5
PV 10% of total cost	6671.6	6185.2	5734.2	5316.2	4928.7	8829.2
MWH sold	1083393.0	1083393.0	1083393.0	1083393.0	1083393.0	1083393.0
Price	135.8	138.5	141.3	144.1	147.0	149.9
Price required for 10% return	147095.2	150037.1	153037.8	156098.6	159220.6	162405.0
PV 10% of revenue	13576.3	12588.9	11673.4	10824.4	10037.2	9307.2

TABLE A2: Summary of discount cash flow of the 150 MW bio-oil based power plant

Cost items ($ '000)/year	-2	-1	0	1	2	3	4
Capital Cost	63354.5	110870.4	142547.7	0.0	0.0	0.0	0.0
Labour cost	0.0	0.0	0.0	2121.6	2164.0	2207.3	2251.5
Bio-oil cost	0.0	0.0	0.0	48372.3	56388.3	61110.8	62333.0
Maintenance cost	0.0	0.0	0.0	9693.2	9887.1	10084.9	10286.5
Total Costs	63354.5	110870.4	142547.7	60187.2	68439.4	73403.0	74871.0
PV of total costs at 10%	76659.0	121957.5	142547.7	54715.6	56561.5	55148.7	51137.9
MWH Sold	0.0	0.0	0.0	892.2	1019.7	1083.4	1083.4
Revenue required for 10% return	0.0	0.0	0.0	83847.4	97742.1	105928.1	108046.6
PV of revenue at 10%	0.0	0.0	0.0	76224.9	80778.6	79585.3	73797.3

Cost items ($ '000)/year	5	6	7	8	9	10	11
Capital Cost	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Labour cost	2296.5	2342.4	2389.3	2437.1	2485.8	2535.5	2586.2
Bio-oil cost	63579.7	64851.3	66148.3	67471.3	68820.7	70197.1	71601.1
Maintenance cost	10492.3	10702.1	10916.2	11134.5	11357.2	11584.3	11816.0
Total Costs	76368.5	77895.8	79453.7	81042.8	82663.7	84317.0	86003.3
PV of total costs at 10%	47418.8	43970.2	40772.3	37807.1	35057.5	32507.8	30143.6
MWH Sold	1083.4	1083.4	1083.4	1083.4	1083.4	1083.4	1083.4
Revenue required for 10% return	110207.5	112411.7	114659.9	116953.1	119292.2	121678.0	124111.6
PV of revenue at 10%	68430.2	63453.5	58838.7	54559.5	50591.5	46912.2	43500.4

TABLE A2 cont'd

Cost items ($ '000)/year	**12**	**13**	**14**	**15**	**16**	**17**	**18**
Capital Cost	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Labour cost	2637.9	2690.7	2744.5	2799.4	2855.4	2912.5	2970.8
Bio-oil cost	73033.1	74493.7	75983.6	77503.3	79053.4	80634.4	82247.1
Maintenance cost	12052.3	12293.4	12539.2	12790.0	13045.8	13306.7	13572.9
Total Costs	87723.4	89477.8	91267.4	93092.7	94954.6	96853.7	98790.7
PV of total costs at 10%	27951.4	25918.5	24033.6	22285.7	20664.9	19162.0	17768.4
MWH Sold	1083.4	1083.4	1083.4	1083.4	1083.4	1083.4	1083.4
Revenue required for 10% return	126593.8	129125.7	131708.2	134342.4	137029.2	139769.8	142565.2
PV of revenue at 10%	40336.7	37403.1	34682.9	32160.5	29821.6	27652.7	25641.6

Cost items ($ '000)/year	**19**	**20**	**21**	**22**	**23**	**24**	**25**
Capital Cost	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Labor cost	3030.2	3090.8	3152.6	3215.6	3280.0	3345.5	3412.5
Bio-oil cost	83892.1	85569.9	87281.3	89026.9	90807.5	92623.6	94476.1
Maintenance cost	13844.3	14121.2	14403.7	14691.7	14985.6	15285.3	15591.0
Total Costs	100766.6	102781.9	104837.5	106934.3	109073.0	111254.4	113479.5
PV of total costs at 10%	16476.1	15277.9	14166.8	13136.4	12181.1	11295.2	10473.7
MWH Sold	1083.4	1083.4	1083.4	1083.4	1083.4	1083.4	1083.4
Revenue required for 10% return	145416.5	148324.8	151291.3	154317.2	157403.5	160551.6	163762.6
PV of revenue at 10%	23776.8	22047.5	20444.1	18957.2	17578.5	16300.1	15114.6

TABLE A2 cont'd

Cost items ($ '000)/year	26	27	28	29	30
Capital Cost	0.0	0.0	0.0	0.0	0.0
Labour cost	3480.7	3550.3	3621.3	3693.8	3767.6
Bio-oil cost	96365.6	98292.9	100258.8	102263.9	104309.2
Maintenance cost	15902.8	16220.9	16545.3	16876.2	17213.7
Total Costs	115749.1	118064.1	120425.4	122833.9	125290.6
PV of total costs at 10%	9712.0	9005.7	8350.7	7743.4	7180.2
MWH Sold	1083.4	1083.4	1083.4	1083.4	1083.4
Revenue required for 10% return	167037.9	170378.6	173786.2	177261.9	180807.2
PVof revenue at 10%	14015.4	12996.1	12050.9	11174.5	10361.8

TABLE A3: Summary of discount cash flow of the 2,200 Dry Tonne/day capacity of the bio-oil production plant

Cost items ($ '000)/year	**-2**	**-1**	**0**	**1**	**2**	**3**	**4**	**5**
Capital Cost	28496.8	49869.4	64117.8	0.0	0.0	0.0	0.0	0.0
Operation and administration cost	0.0	0.0	0.0	3640.0	3712.8	3787.1	3862.8	3940.1
Maintenance Cost	0.0	0.0	0.0	4274.5	4360.0	4447.2	4536.2	4626.9
Harvesting Cost	0.0	0.0	0.0	7550.3	8182.7	8664.0	8837.3	9014.0
Transportation Cost	0.0	0.0	0.0	2379.5	2578.8	2785.1	2840.8	2897.6
Roads & Infrastructure	0.0	0.0	0.0	3130.6	3326.3	3522.0	3592.4	3664.2
Silviculture cost	0.0	0.0	0.0	3040.7	3230.7	3420.8	3489.2	3559.0
Site recovery and reclamation cost	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Miscellaneous chemicals plus water	0.0	0.0	0.0	7678.6	7832.2	7988.8	8148.6	8311.5
Chipping cost	0.0	0.0	0.0	1875.8	2032.9	2195.5	2239.5	2284.2
Natural gas requirement	0.0	0.0	0.0	2826.6	3003.2	3179.9	3243.5	3308.3
Electricity cost	0.0	0.0	0.0	5221.0	5547.3	5873.6	5991.1	6110.9
Non production utilities and labour	0.0	0.0	0.0	413.3	421.5	430.0	438.6	447.3
Total Costs	28496.8	49869.4	64117.8	42030.9	44228.4	46293.9	47219.7	48164.1
PV of total costs at 10%	34481.1	54856.3	64117.8	38209.9	36552.4	34781.3	32251.7	29906.1
Price required for 10% return	0.0	0.0	0.0	0.2	0.2	0.2	0.2	0.2
Revenue required for 10% return from bio-oil	0.0	0.0	0.0	54401.4	58957.5	63674.1	64947.6	66246.5
PV of revenue at 10%	0.0	0.0	0.0	49455.8	48725.2	47839.3	44360.1	41133.9

TABLE A3 cont'd

Cost items ($ '000)/year	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
Capital Cost	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Operation and administration cost	4018.9	4099.2	4181.2	4264.8	4350.1	4437.1	4525.9	4616.4
Maintenance Cost	4719.4	4813.8	4910.1	5008.3	5108.4	5210.6	5314.8	5421.1
Harvesting Cost	9194.3	9378.2	9565.8	9757.1	9952.2	10151.3	10354.3	10561.4
Transportation Cost	2955.6	3014.7	3075.0	3136.5	3199.2	3263.2	3328.4	3395.0
Roads & Infrastructure	3737.5	3812.3	3888.5	3966.3	4045.6	4126.5	4209.1	4293.2
Silviculture cost	3630.2	3702.8	3776.8	3852.4	3929.4	4008.0	4088.1	4169.9
Site recovery and reclamation cost	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Miscellaneous chemicals plus water	8477.8	8647.3	8820.3	8996.7	9176.6	9360.1	9547.3	9738.3
Chipping cost	2329.9	2376.5	2424.1	2472.5	2522.0	2572.4	2623.9	2676.4
Natural gas requirement	3374.5	3442.0	3510.8	3581.1	3652.7	3725.7	3800.3	3876.3
Electricity cost	6233.1	6357.8	6484.9	6614.6	6746.9	6881.8	7019.5	7159.9
Non production utilities and labour	456.3	465.4	474.7	484.2	493.9	503.8	513.8	524.1
Total Costs	49127.4	50110.0	51112.2	52134.4	53177.1	54240.6	55325.4	56432.0
PV of total costs at 10%	27731.1	25714.3	23844.2	22110.1	20502.1	19011.0	17628.4	16346.3
Price required for 10% return	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Revenue required for 10% return from bio-oil	67571.5	68922.9	70301.3	71707.4	73141.5	74604.4	76096.4	77618.4
PV of revenue at 10%	38142.3	35368.3	32796.1	30410.9	28199.2	26148.4	24246.7	22483.3

TABLE A3 cont'd

Cost items ($ '000)/year	14	15	16	17	18	19	20
Capital Cost	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Operation and administration cost	4708.7	4802.9	4899.0	4996.9	5096.9	5198.8	5302.8
Maintenance Cost	5529.5	5640.1	5752.9	5868.0	5985.4	6105.1	6227.2
Harvesting Cost	10772.6	10988.1	11207.8	11432.0	11660.6	11893.8	12131.7
Transportation Cost	3462.9	3532.2	3602.8	3674.9	3748.4	3823.3	3899.8
Roads & Infrastructure	4379.1	4466.7	4556.0	4647.1	4740.1	4834.9	4931.6
Silviculture cost	4253.3	4338.4	4425.1	4513.6	4603.9	4696.0	4789.9
Site recovery and reclamation cost	0.0	0.0	0.0	0.0	0.0	0.0	22797.4
Miscellaneous chemicals plus water	9933.1	10131.7	10334.4	10541.0	10751.9	10966.9	11186.2
Chipping cost	2729.9	2784.5	2840.2	2897.0	2954.9	3014.0	3074.3
Natural gas requirement	3953.8	4032.9	4113.5	4195.8	4279.7	4365.3	4452.6
Electricity cost	7303.1	7449.1	7598.1	7750.1	7905.1	8063.2	8224.4
Non production utilities and labour	534.6	545.3	556.2	567.3	578.7	590.2	602.0
Total Costs	57560.6	58711.8	59886.0	61083.8	62305.4	63551.5	87620.0
PV of total costs at 10%	15157.5	14055.1	13032.9	12085.1	11206.2	10391.2	13024.2
Price required for 10% return	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Revenue required for 10% return from bio-oil	79170.7	80754.2	82369.2	84016.6	85697.0	87410.9	89159.1
PV of revenue at 10%	20848.1	19331.9	17925.9	16622.2	15413.4	14292.4	13252.9