University of Alberta

Techno-economic Assessment of Charcoal Production for Carbon Sequestration

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Abstract

Greenhouse gas (GHG) emission is one of the important environmental issues that world is facing today. Biomass usage, specifically capturing energy from biomass that would otherwise decay, is one the of many options available to mitigate the impact of the buildup of GHG emissions from fossil fuel utilization. This research investigates the pathway of utilization of agricultural biomass (e.g. straw) for charcoal production and its landfilling for sequestration of carbon. This pathway can help in increasing the rate of carbon sequestration. Charcoal is a solid fuel, which can be produced from agricultural biomass such as wheat and barley straw. It is an organic solid and can be produced by slow pyrolysis of straw. This research involves a conceptual techno-economic study to estimate the cost of production of charcoal from straw in a centralized plant and its storage in a landfill to sequester carbon. This study draws on actual data to determine the cost of charcoal production. The cost of production of charcoal from straw in a centralized system with nutrient replacement cost and its landfilling cost is $332.2/tonne of charcoal. The life cycle GHG emission for this pathway is 0.372 tonne of CO_2/tonne of charcoal produced. Based on the cost of production and landfilling of charcoal and the GHG emissions in this pathway, the cost of carbon sequestration is about $129.88/tonne of CO_2. This is higher than the biomass based electricity generation pathway but lower than some estimates of carbon capture and storage technologies for carbon sequestration.

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List of Abbreviations

BC	British Colombia
BiG	Black Is Green
CAD	Canadian Dollar
CSS	Carbon Capture And Storage
CO_2	Carbon Dioxide
CHP	Combined Heat And Power
dtpd	Dry Tonne Per Day
ft.	Feet
gal	Gallon
Gj	Gigajoule
GWP	Global Warming Potential
GHGs	Green House Gas Emissions
ha	Hectare
HHV	Higher Heating Value
hr.	Hour
H/C	Hydrogen To Carbon Ratio
ICPS	Improved Charcoal Production System
kpa	Kilo Gram Per Hour
km	Kilometer
kW	Kilowatt
kWh	Kilowatt-Hour
kWh	Kilowatt-Hour
LCA	Life Cycle Assessment
lcy	Loose Cubic Yards
LHV	Lower Heating Value
Mj	Mega Joule
m/s	Meter Per Second
CH_4	Methane
mm	Millimeter
NREL	National Renewable Energy Limited
NER	Net Energy Ratio
NO_x	Nitrogen Oxides
N_2O	Nitrous Oxide
oDt	Oven Dry Tonnes
PV	Present Value
SO_2	Sulfur Dioxide
tmph	Ton Mile Per Hour
t	Tonne
TEPC	Total Annual Production Cost
UP	Unit Processes

Chapter 1 Introduction

1.1 Background

Today primary source of energy for mankind is fossil fuels and the demand for this energy is increasing significantly. The use of fossil fuels is associated with emission of greenhouse gases (GHGs). This is a major concern for the world as GHGs are one of the primary contributors to global warming. Total GHG emissions in Canada in 2008 were 734 mega tonnes of carbon dioxide equivalent (Natural Resource Canada, 2012). Each GHG has a different potential to contribute to warming. Each GHG has been assigned a global warming potential (GWP), based on the gases' ability to contribute to global warming. Carbon dioxide is set as the baseline. (e.g., the GWP for methane (CH_4) is 21). The long-term trend indicates that emissions in 2008 were about 24% above the 1990 total for Canada. CO_2 emissions are a large part of the total GHG emissions. CO_2, which is emitted mainly due to the consumption of the fossil fuels, accounts for more than 75% of Canadian GHG emissions. Methane is produced mainly from agricultural activities, but also from waste sites and from the production and transportation of fossil fuels. Methane's share of GHG emissions is higher in provinces where agriculture and fossil fuel production are important economic activities.

There is a need to reduce the emissions of GHGs and this can be done in three different ways. These include: increase in efficiency for energy consumption and production in various energy demand and supply sectors; substitution of fossil fuel sources by renewable energy sources (e.g. wind, biomass, geothermal, hydro, solar); and, capture of emitted GHGs and its sequestration in the environmental sinks.

The interest in development of renewable energy technologies has grown in the recent years. Canada is considered to be a leader in terms of renewable sources around the world. About 16% of Canada's total primary energy supply comes from renewable sources (Natural Resource Canada, 2012). Renewable energy sources mainly include hydropower, wind energy, solar energy, geothermal energy, ocean energy and energy from biomass.

Biomass usage, specifically capturing energy from biomass that would otherwise decay, is one of many options available to mitigate the impact of the buildup of GHG emissions from fossil fuel utilization. Biomass is a key renewable energy source. There are various pathways to convert biomass in different forms of energy. Biomass can be directly converted to heat or electricity or other forms, such as liquid biofuel or combustible biogas or solid fuel like charcoal. One of the pathways of biomass processing is its thermo-chemical conversion. These are processes in which heat is the dominant agent to convert biomass into another chemical form. The basic alternatives are separated principally by the extent to which the chemical reactions involved are allowed to proceed. Various pathways are categorized on the basis of temperature of the operation as shown in Table 1-1. These conversion technologies are at different stages of development, deployment and commercialization.

Gasification is the conversion of biomass into gaseous fuel or chemical feedstock. In this process biomass is heated to high temperature using steam in the presence of a limited supply of air or oxygen. The end product i.e. syngas, can be burned to release energy or used for production of value-added chemicals. The gasification process increases hydrogen and strips carbon away from the feedstock to produce gases with a higher hydrogen-to-carbon (H/C) ratio (Basu, 2010; Dem, 2001; Sarkar & Kumar, 2010). Gasification consists of a series of process including heating and drying, pyrolysis, solid-gas reactions that consume char, and gas-phase reactions that adjust the final chemical composition of the producer gas (Basu, 2010; Brown, 2008; Mitchell et al., 1995). It requires a gasifying medium like steam, air, or oxygen to rearrange the molecular structure of the feedstock in order to convert the solid feedstock into gases or liquids.

Pyrolysis is a form of thermal process, which decomposes organic materials by heat in the absence of oxygen to vapors, which can further be condensed to liquid. Pyrolysis typically occurs under pressure and at operating temperatures about 400 to 500 °C (Bridgwater, 1999 & 2012; Bridgwater et al., 1999; Bridgwater & Peacocke, 2000; Sánchez et al., 2009; Yaman, 2004). The residue resulting from low- temperature pyrolysis is a form of charcoal called biochar, which is a fuel in itself.

Solid fuels such as biochar or charcoal can be produced from thermo-chemical treatment of biomass. Charcoal is interestingly different from other biomass-based solid fuels. The major difference is that charcoal, the product of the process, can be deposited back in the soil by land filling. Land filling has many environmental benefits (Lehmann, 2007a & 2007b; Lehmann et al., 2006). About 50% of the organic carbon found in crops can be returned back to ground where it originally belongs. One of the important characteristics of charcoal is its very long half-life in comparison with biomass or organic matter not undergone pyrolysis (Baldock, 2002). Re-growing biomass used for production of charcoal and landfilling of charcoal results in a net withdrawal of carbon dioxide from the atmosphere. There is a high theoretical potential to reduce global greenhouse gas emissions through the use of charcoal sequestration (Lehmann, 2007a & 2007b).

Table 1-1: Biomass pathways

Process	Process Description	Resultant Products	Product Characteristics
Torrefaction (200-300°)(Uslu et al., 2008)	Torrefaction is a thermal pre-treatment technology performed at atmospheric pressure in the absence of oxygen (Uslu et al., 2008)	A solid uniform product with very low moisture content and a high calorific value compared to fresh biomass	Torrefied biomass typically contains 70% of its initial weight and 90% of the original energy content(Prins et al., 2006)
Pyrolysis (400-800°C)(Bridgwater, 1999 & 2012)	Pyrolysis can be described as the direct thermal decomposition of biomass in the absence of oxygen (Yaman, 2004)	The products[1] are gas, liquid and solid char, generally, the yields are 40–65 wt.% organic condensates, 10–20% char, 10–30% gases and 5–15% water based on dry feed. (Bridgwater, 1999 & 2012)	The energy content of the pyrolysis oil is around 15–18 MJ/kg with moisture content around 25%. The LHV of gas is around 15 MJ/Nm^3 and the char is around 32 MJ/kg
Gasification (Above 800°C)	Gasification is the process of heating biomass to a high temperature using steam in presence of a limited supply of air or oxygen (Basu, 2010)	Syngas is a mixture of carbon monoxide and hydrogen (Basu, 2010)	
Combustion	Direct combustion of biomass in a chamber in presence of excess air	Direct heat, which can be converted into power.	

[1]*The product mixture varies with the heating rate, type of biomass used and temperature. It can be optimized for production of bio-oil (higher temperature and faster heating rate) or bio-char (lower temperature and slower heating rate).*

1.2 Biomass Feedstocks

Canada harvests millions of tonnes of biomass each year in various forms as trees and crops. It is estimated that the residues from forestry, agriculture and related manufacturing industries are equivalent to approximately 18–27 percent of the energy Canada derives from fossil fuel (BioProducts Canada, 2004). Biomass can be intentionally grown, such as switchgrass for ethanol production, or as a byproduct of some other industry or agricultural process (popularly known as opportunity-biomass) (Agriculture and Agri-Food Canada, 2012). Opportunity biomass can be straw, corn stover, wood resulting from insect attack such as the mountain pine infested wood (Kumar et al., 2008) in BC, forest fires, wood processing operations and timber related operations (Agriculture and Agri-Food Canada, 2012).

1.2.1 Whole Forest and Residues

Major sources of forest residues as described by (Röser et al., 2008) are as follows:

- Results of forest management, such as biomass from forest thinning, harvesting residues, non-commercial species.
- Industrial processes have several by-products, such as bark, sawdust and black liquor
- By-products of demolition, construction and packaging processes

Canadian sawmills are responsible for the majority of forest mill residues produced in 2004, lumber production in Canada was 35,510 Mfbm (million board feet) (BW McCloy & Associates Inc., 2005). According to a study performed by BW McCloy and Associates in 2005 there was surplus of 2,472,992 million bone-dry tonnes (BDt) of biomass, which is approximately equivalent to over 49,460 TJ of energy. Another study performed (Bradley, 2006) reports that Canada had 2.3 million oven dry tonnes (ODt) in 2007. According to the study, in Saskatchewan and in the eastern provinces incineration is not permitted and mills pile excess residue at the site. These are economically unusable as they get degraded due to natural causes. In 2005 total surplus heritage bark piles was 15,407,000 ODt. (Bradley , 2006 & 2007). Studies suggest that forest biomass though abundant cannot satisfy more than a small fraction of current energy demands (David et al., 2011)

1.2.2 Agriculture Residue

Crops are grown on 36 million hectares of land (Statistics Canada, 2010), representing 53% of total farmland (Li et al., 2012). This generates millions of tonnes of crop residues annually. In Western Canada, large amounts of forest and agricultural residues (e.g. wheat and barley straw) are left in the forest/field, which could be harvested for energy production. On an average 3.19 million dry tonnes/year of agricultural residue available in Alberta can be put to use (Kumar et al., 2006; Statistics Canada, 2010; Sultana et al., 2010). An earlier study has estimated the amount of agricultural residue available in Western Canada (Kumar et al., 2006). Studies have also shown that large-scale power production is also economically competitive with fossil fuel (Kumar et al., 2003). It can compete only if supported by carbon credits (Kumar et al., 2003) Section 2.3 of this study explains in depth analysis of availability of agricultural residue for production of biochar.

1.3 Statement of the Problem

Various studies have been performed on the use of biomass as a substitute to fossil fuels. Biomass energy has a potential to greatly reduce greenhouse gas emissions. Use of biomass approximately releases same amount of emissions as the use of fossil fuels. However fossil fuel captured carbon millions of years ago, hence emissions in today's world affect the balance. On the contrary emissions by use of biomass are largely balanced by the carbon dioxide captured in its own growth (depending how much energy was used to grow, harvest, and process the fuel). Hence they are considered to be carbon-neutral (Gupta, 2009; Roberts et al., 2010; Sebastián & Royo, 2007). This is one of the methods of reducing emissions but the efficiency rates seem not be low for energy conversion, as suggested by Manomet Center for Conservation Sciences 2010, green wood to electrical power is only 25%, into combined heat and power (CHP) is about 75%, and the efficiency of producing heat from wood pellets is 80% (David et al., 2011; Walker et al., 2010) Other means for reduction in emissions are – (1) Energy efficiency improvement (2) Use of renewable energy and (3) Increased use of Nuclear energy for power generation. These methods along with biomass-to-power reduce emissions that are yet to be generated (Gupta, 2008).

The focus of the problem is to reduce existing emissions or in other words capture carbon from atmosphere. There are various methods to achieve this currently the most popular and mature method is carbon capture and storage (CSS)(Gupta, 2009) Some of the issues with CSS as described, are high costs and issues with post operation liability. Studies suggest the cost of simply sequestering carbon is in the order of \$115-\$150 per tonne of CO_2 (Gupta, 2009; Harrison, 2009; Metz et al., 2005).

The alternative approach to address the issues is charcoal production, converting biomass to charcoal and sequestering it into the earth. As described above the process is energy self-sufficient as syngas produced during pyrolysis acts as a source of energy for carrying out pyrolysis of remaining biomass. This produces charcoal and hence it is considered to be a carbon negative process. This biomass can be re-grown and it absorbs new carbon from atmosphere, which results to further withdrawal. Some studies (Gupta, 2010; Lehmann et al., 2011) highlight the advantages of biochar sequestration.

- Charcoal is stable and can be stored for thousands of years (Laird, 2008)
- An easy monitoring and measurement of sequestered carbon

- The sequestered carbon can be used for production of energy when GHG emissions issue dies down
- Biochar for soil enhancement (Lehmann et al., 2011; Sánchez et al., 2009)

One issue where there is limited research has been conducted is to determine the cost of sequestration. This study focuses on determination of cost for carbon sequestration or in other words $ per tonne of CO_2 mitigated.

1.4 Objective of the Study

The overall aim of this research was to perform a techno-economic assessment of production of charcoal from agricultural biomass and land filling of this charcoal for sequestration for carbon. This work involves a conceptual estimation of the cost of production of biochar from straw in a centralized plant and its storage in a landfill to sequester carbon. This study draws on actual data to determine the cost of charcoal production. The specific objectives of the work include:

- Identify and analyze various technologies for production of charcoal;
- Estimation of the overall delivered cost of straw to the charcoal production plant;
- Estimation of the cost of transportation of charcoal to the landfill site;
- Estimation of the cost of land filling;
- Estimation of GHG emissions over the life cycle of this pathway of charcoal production and land filling;

- Estimation of the overall cost of carbon sequestration through charcoal land filling ($/tonne of charcoal);
- Estimate the cost of mitigation of CO_2 ($/tonne of CO_2).

1.5 Limitations of study

- This study is based on utilization of straw from wheat, oat and barely available in Alberta.
- This study focuses on currently available pyrolysis equipment and selects most suitable option for the selected biomass type.
- Various cost used have been adjusted for location and size of the plant considered.
- The study considers two cases for evaluation of costs, firstly a centralized plant where biomass is transported to a central location and secondly portable plant where the equipment travels to the biomass location.
- Charcoal produced is transported to field and landfill sites. The overall system comprises of following processes – straw harvesting, bailing transport, pyrolysis (conversation to charcoal), charcoal transport and land filling.
- A portable pyrolysis plant for production of charcoal in the farm has also been considered.

1.6 Organization of Thesis

This thesis has four chapters apart from table of contents, list of figures, list of tables and appendices.

Chapter One – This chapter introduces the field of research and briefly explains the need for the study.

Chapter Two – This chapter describes the development of techno-economic model and gives the detailed review of the various technologies considered for pyrolysis of biomass. Both mobile and de-centralized plants are are described.

Chapter Three – This chapter deals with assessment of carbon sequestration and describes the estimation of the cost of land filling charcoal, and determines the abatement cost ($/tonne of CO_2) mitigated by land filling. This chapter also determines the net carbon sequestered in process of biochar production.

Chapter Four – It summarizes the findings and explains the conclusion of the thesis. It also hints upon some future work that could be performed on the thesis.

1.7 References

Agriculture and Agri-Food Canada. (2012). Biomass. Retrieved 1 October, 2010. Retrieved from: http://www4.agr.gc.ca/AAFC-AAC/display-afficher.do?id=1226356636533&lang=eng

Baldock, J. (2002). Chemical composition and bioavailability of thermally altered *Pinus resinosa* (Red pine) wood. *Organic Geochemistry, 33*(9), 1093-1109.

Basu, P. (2010). Chapter 5 - Gasification Theory and Modeling of Gasifiers (pp. 117-165). Boston: Academic Press.

BioProducts Canada. (2004). Innovation roadmap on bio-based feedstocks, Fuels and Industrial Products. (54124E/F). Retrieved from: http://www.ic.gc.ca/eic/site/trm-crt.nsf/vwapj/biobased-biomasse_eng.pdf/$FILE/biobased-biomasse_eng.pdf

Bradley, D. (2006). Canada Biomass-Bioenergy Report (pp. 1-20). Ontario. Canada Climate Change Solutions. Retrived from: http://www.canbio.ca/upload/documents/canada-report-on-bioenergy-2010-sept-15-2010.pdf

Bradley, D. (2007). Canada- Sustainable Forest Biomass Supply Chains (pp. 1-31). Ontario, Canada Climate Change Solutions. Retrived from: http://www.canbio.ca/upload/documents/sustainableforestsupplychainsoct192007.pdf

Bridgwater A. V. (1999). Principles and practice of biomass fast pyrolysis processes for liquids. *Journal of Analytical and Applied Pyrolysis, 51*(1-2), 3-22.

Bridgwater A. V. (2012). Review of fast pyrolysis of biomass and product upgrading. *Biomass and Bioenergy, 38*, 68-94.

Bridgwater A. V., Meier D., & Radlein D. (1999). An overview of fast pyrolysis of biomass. *Organic Geochemistry, 30*(12), 1479-1493.

Bridgwater A. V., & Peacocke G. V. C. (2000). Fast pyrolysis processes for biomass. *Renewable and Sustainable Energy Reviews,* 4(1) 1- 73.

Brown, R. C. (2008). Biomass Conversion: Gasification and Pyrolysis *October*. Mankato, Minnesota: Iowa State University.

BW McCloy & Associates Inc. (2005). Estimated Production, Consumption and Surplus Mill Wood Residues in Canada - 2004. *Forest Products Association of Canada*(November). Retrived from: http://publications.gc.ca/collections/Collection/Fo4-7-2004E.pdf

David P., Pierre B., Evelyne T., & Titus B D. (2011). The potential of forest biomass as an energy supply for Canada. *Forestry*, 71-76.

Dem, R. A. (2001). Biomass to charcoal, liquid, and gaseous products via varbonization process. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects,* 23(6), 579-587.

Gupta S. (2008). *Carbon harvesting for saving the planet*. Paper presented at the Canadian International Petroleum Conference, Calgary, Alberta Canada. Jun 17 - 19, 2008

Gupta S. (2009, 4–7 October 2009). *Are there Less Costly Ways to Sequester Carbon than CCS ?* Paper presented at the SPE Annual Technical Conference and Exhibition, New Orleans, Louisiana, USA. 4-7 October 2009.

Gupta S. (2010). A practical way out of the GHG emissions problem. *Journal of Canadian Petroleum Technology, 49*(8), 33-42.

Kumar, A., Cameron, J. B., & Flynn, P. C. (2003). Biomass power cost and optimum plant size in western Canada. *Biomass and Bioenergy, 24*(6), 445-464.

Kumar, A., Flynn, P., & Sokhansanj, S. (2008). Biopower generation from mountain pine infested wood in Canada: An economical opportunity for greenhouse gas mitigation. *Renewable Energy, 33*(6), 1354-1363.

Kumar, A., Sokhansanj, S., & Flynn, P. C. (2006). Development of a multicriteria assessment model for ranking biomass feedstock collection and transportation systems. *Applied biochemistry and biotechnology, 129-132*, 71-87.

Laird, D. A. (2008). The Charcoal Vision: A Win-Win-Win Scenario for Simultaneously Producing Bioenergy, Permanently Sequestering Carbon, while Improving Soil and Water Quality. *Agronomy Journal. 100: 178–181*

Lehmann, J. (2007a). Biochar for mitigating climate change: carbon sequestration in the black. *Forum Geookol, 18*(2). 15-17

Lehmann, J. (2007b). A handful of carbon. *Nature, 447*(7141), 143-144.

Lehmann, J., Gaunt, J., & Rondon, M. (2006). Bio-char sequestration in terrestrial ecosystems – A review. *Mitigation and Adaptation Strategies for Global Change, 11*(2), 395-419.

Lehmann, J., Rillig, M. C., Thies, J., Masiello, C. a., Hockaday, W. C., & Crowley, D. (2011). Biochar effects on soil biota – A review. *Soil Biology and Biochemistry, 43*(9), 1812-1836.

Li, X., Mupondwa, E., Panigrahi, S., Tabil, L., Sokhansanj, S., & Stumborg, M. (2012). A review of agricultural crop residue supply in Canada for cellulosic ethanol production. *Renewable and Sustainable Energy Reviews, 16*(5), 2954-2965.

Metz, B., Davidson, O., Coninck, H. D., Loos, M., & Meyer, L. (2005, 2005). Summary for policymakers of the intergovernmental panel on climate change (IPCC), Montreal, Canada.

Mitchell, C. P., Bridgwater, A. V., & Stevens, D. J. (1995). Technoeconomic assessment of biomass to energy. *Biomass and, 9*(95), 205-226.

Natural Resource Canada. (2012). The Atlas of Canada, Retrived on 17th October 2011, Retrieved from: http://atlas.nrcan.gc.ca/auth/english/maps/climatechange/atmospherestress/trendsgreenhousegasemission

Prins, M. J., Ptasinski, K. J., & Janssen, F. J. J. G. (2006). Torrefaction of wood. *Journal of Analytical and Applied Pyrolysis, 77*(1), 35-40.

Roberts, K. G., Gloy, B. A., Joseph, S., Scott, N. R., & Lehmann, J. (2010). Life cycle assessment of biochar systems: estimating the energetic, economic, and climate change potential. *Environmental science & technology, 44*(2), 827-833.

Röser, D., Asikainen, A., Stupak, I., & Pasanen, K. (2008). Sustainable use of forest biomass for energy. A synthesis with focus on the Baltic and Nordic Region. Springer, Dordrecht, The Netherlands.

Sánchez, M. E., Lindao, E., Margaleff, D., Martínez, O., & Morán, a. (2009). Pyrolysis of agricultural residues from rape and sunflowers: Production and characterization of bio-fuels and biochar soil management. *Journal of Analytical and Applied Pyrolysis, 85*(1-2), 142-144.

Sarkar, S., & Kumar, A. (2010). Biohydrogen production from forest and agricultural residues for upgrading of bitumen from oil sands. *Energy, 35*(2), 582-591.

Sebastián, F., Royo, J., & Serra, L. (2007). Life Cycle Assessment of Greenhouse Gas Emissions from Biomass Electricity Generation: Co-firing and Biomass Monocombustion. Paper presented at the 4th Dubrovnik Conference on Sustainable Development of Energy, Water and Environment Systems, Dubrovnik, Croatia.

Statistics Canada. (2010). Total farm area, land tenure and land in crops, by province (Census of agriculture, 1986 to 2006) Retrieved 10 June, 2010, from http://www.statcan.gc.ca/tables-tableaux/sum-som/l01/cst01/agrc25a-eng.htm

Sultana, A., Kumar, A., & Harfield, D. (2010). Development of agri-pellet production cost and optimum size. *Bioresource technology, 101*(14), 5609-5621.

Uslu, A., Faaij, A. P. C., & Bergman, P. C. A. (2008). Pre-treatment technologies, and their effect on international bioenergy supply chain logistics. Techno-economic evaluation of torrefaction, fast pyrolysis and pelletisation. *Energy, 33*(8), 1206-1223.

Walker, T., Cardellichio, P., Colnes, A., Gunn, J., Kittler, B., Perschel, R., & Aah, D. (2010). Massachu- setts biomass sustainability and carbon policy study: report to the commonwealth of Massachusetts department of energy resources. *Manomet Center for Conservation Sciences.*(June). Retrived from: http://www.mass.gov/eea/docs/doer/renewables/biomass/manomet-biomass-report-full-hirez.pdf

Yaman, S. (2004). Pyrolysis of biomass to produce fuels and chemical feedstocks. *Energy Conversion and Management, 45*(5), 651-671.

Chapter 2 Techno-economic Assessment of Charcoal Production

2.1 Introduction

Biomass is considered nearly carbon neutral, as the amount of CO_2 released during its combustion is nearly the same as taken up by the plants during its growth. Biomass can be used for production of solid, liquid and gaseous fuels as discussed in Chapter 1. The focus of this research is on techno-economic assessment of the pathway of conversion of biomass to charcoal and its landfilling for sequestration of carbon. Charcoal can be produced from biomass through slow heating process in absence of oxygen. This process is called as pyrolysis (Laird, et al. 2009). The charcoal produced from biomass can be either used as catalyst (Lehmann, 2009) or fertilizer (Deal et al., 2012; Gaunt & Lehmann, 2008; Lehmann et al., 2011) or fuels (Roberts et al., 2010; Society, 2012).

2.2 Scope of Research and Methodology

The overall aim of this research is to develop techno-economic models for the assessment of cost of production of charcoal from Alberta's agricultural-based biomass sources and storage of charcoal in the landfill for carbon sequestration.

In this study, two scenarios of production of charcoal have been estimated. First scenario as shown in Figure 2-1, system includes production of charcoal in a centralized plant where the required biomass is transported to the plant using trucks and is converted to charcoal through pyrolysis. The charcoal produced through this process is then transported back to the field for sequestration.

Second scenario includes production of charcoal in a mobile plant, which moves around and produces charcoal. This charcoal is then spread in the field. For both the scenarios, the whole chain is divided into a number of unit operations. Figure 2-2 shows various unit operations involved in production of charcoal from agricultural biomass.

Data were collected related to the characteristics and costs of each unit operation. These are detailed in subsequent sections. Data collection was based on detailed literature review, in consultation with the various manufacturing companies and in consultation with the experts in field. Wherever data was not available, it was developed based on certain assumptions. Once all the data were estimated, data intensive techno-economic models were developed to estimate the cost of production of charcoal in Alberta from the agricultural biomass and the cost of landfilling it.

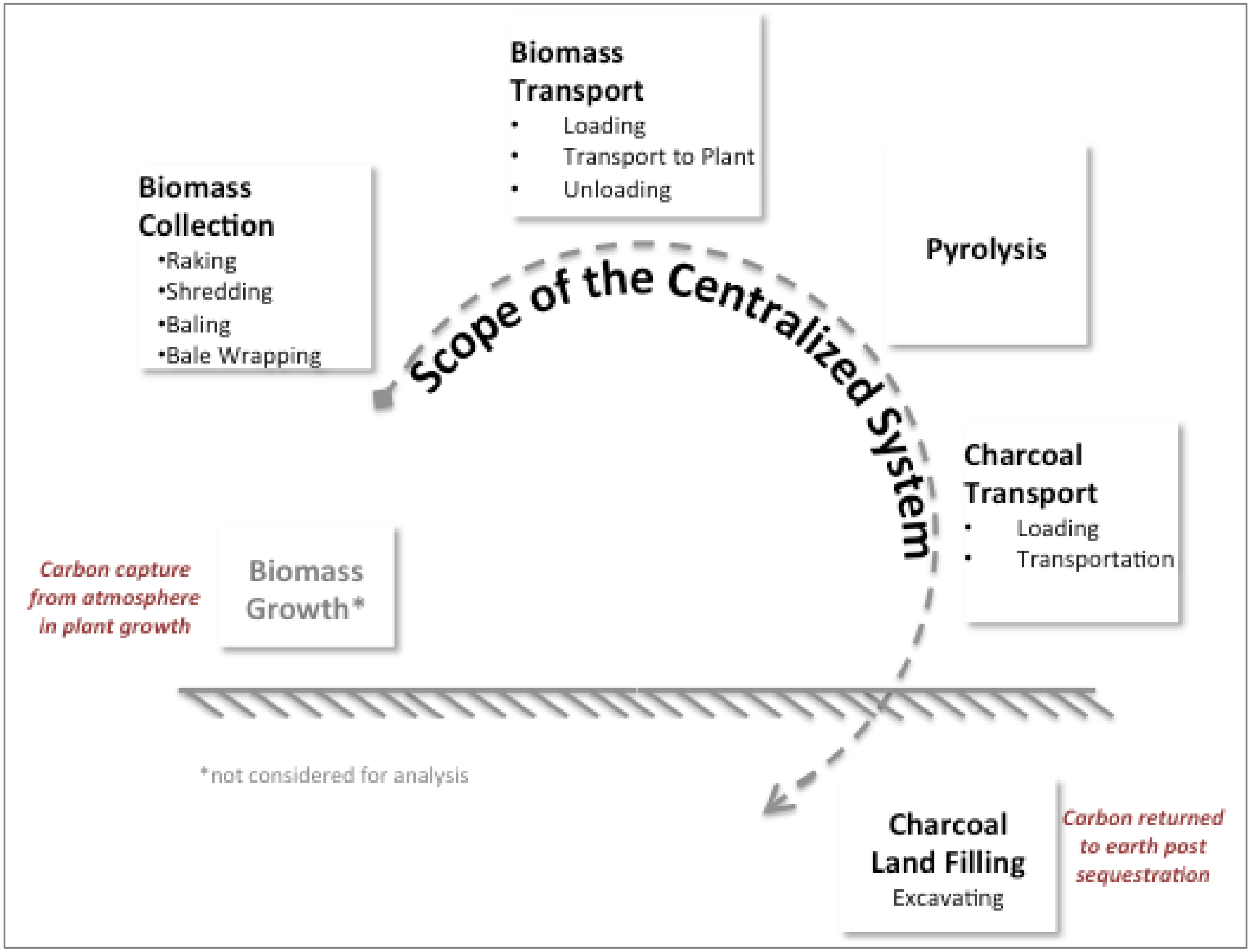

Figure 2-1: Scope of centralized production of charcoal for carbon sequestration

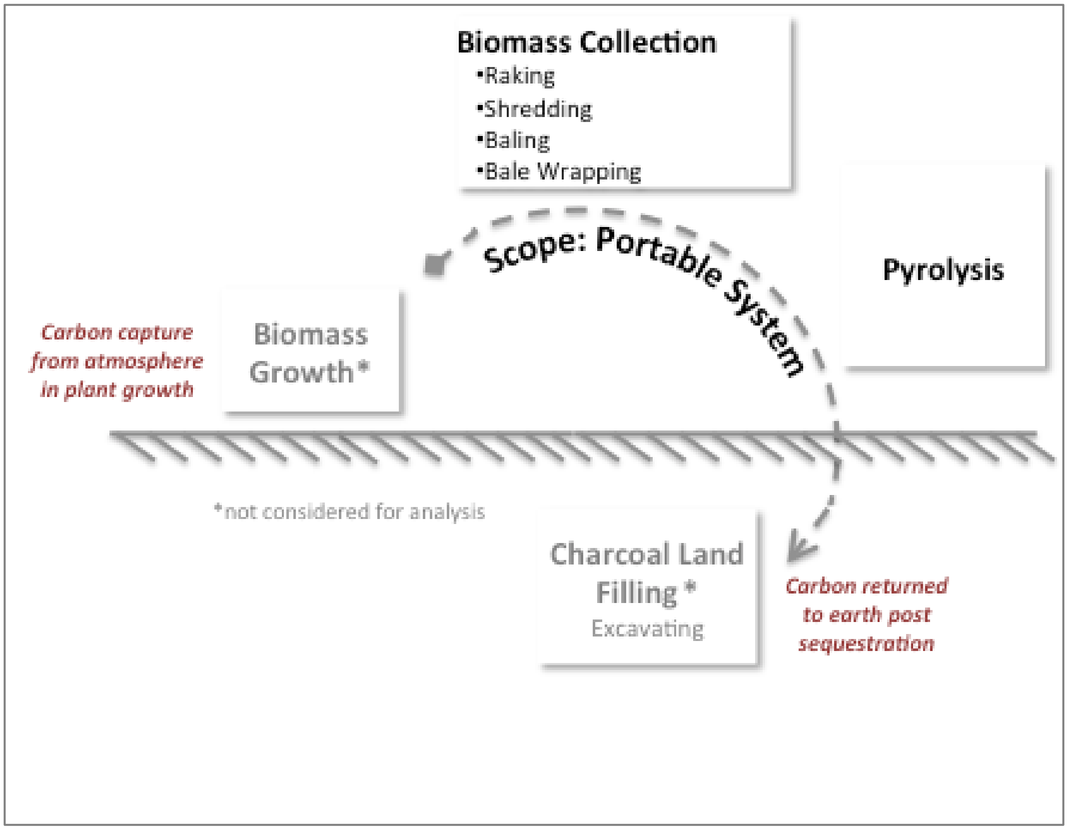

Figure 2-2: Scope of charcoal production in a portable system and its spreading in the field

These techno-economic models are based on discounted cash flow analysis and use the standard procedure used in the industry today. A detailed sensitivity analysis was also performed to assess the impact of variation in parameters. Assumptions for the techno-economic models were specific to the scenarios and are discussed in the subsequent sections.

2.3 Biomass Feed stocks and its Availability

Agriculture sector is an important contributor to Albert's economy. This sector produces large amount of grains, which are predominantly used for food. In the current practice, once the grains are harvested from the field, the associated straw is left in the field to rot. This straw decomposes emitting GHG to the atmosphere (Kumar et al., 2003). There is a large potential for production of fuels and chemicals from straw. Utilization of left over straw for production of charcoal is the focus of this study. Based on the estimates of grain production in Alberta and various agronomic factors overall availability of straw in Alberta can be estimated. Various parameters such as climate, type of crop, and the collection and harvesting operations have an impact on the straw yield. The net straw availability also depends on factors such as amount of straw, which needs to be left in the field; amount of straw currently used for animal feeding and associated transportation losses. For this study we consider year-to-year production of three major crops in Canada; wheat, oat and barley. Grain yields for last 11 years from 1997-2008 have been used for estimation of straw yield. Average yields of wheat, barley and oats in Alberta are 2.69, 3.15 and 2.58 green tonnes/ha, respectively (Agriculture Statistics Yearbook, 2010) The province has harvested area of about 2.77 Mha of land for wheat production, 1.51 Mha for barley production and 0.2 Mha for oat production in the year 2008. The yield data were collected from (Agricultural Statistical Yearbook – 2008). The detailed methodology used in the following section for determining the net availability of straw was adapted from (Sultana et al., 2010). A detailed assessment of the feedstock availability has been discussed in Sultana et al. (2010).

To estimate the net straw yield from the harvested area, one of the key parameters that was used is straw-to-grain conversation ratio. The straw-to-grain ratio factors for wheat, barley and oats are 1.1, 0.8 and 1.1, respectively (Sultana et al., 2010). Details on various straw-to-grain ratios and estimation of gross straw yields are given in Table 2-1.

Table 2-1: Average straw yield

Crop	Average Grain Yield[1] (green tonne/ha)	Assumed Straw-to-grain ratio[2]	Gross Straw Yield (green tonne/ha)
Wheat	2.69	1.1	2.96
Barley	3.15	0.8	2.52
Oat	2.58	1.1	2.83

According to earlier studies, some portion of straw has to be retained in soil for fertility and soil health. Table 2-2 indicates various estimates for the amount of straw that is required for soil retention and health. For this study we assume 0.75 tonne/ha of straw is left in the field.

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[1] *Source: (Alberta Agriculture and Rural Development, 2008)*

[2] *Source: (Sultana et al., 2010)*

Table 2-2: Amount of straw to be left in the field for soil conservation

No.	Source	Values
1	Sultana et al., 2010	0.75 tonne/ha
2	Liu, 2008; Stephen, 2008	0.75 tonne/ha
3	Sokhansanj & Fenton, 2006; Sokhansanj et al., 2009	1 tonne/ha of straw
4	Campbell & Coxworth, 1999; Campbell, 2007	1.3 tonne/ha of straw residue
5	Kline, 2000; Stumborg, et al., 1996	30 to 50% of straw residue
6	Stumborg et al., 1996	0.75 tonne/ha and 1.5 Mt/ha[1]
7	Elsayed & Mortirner, 2001	50 to 75% of straw residue

The next parameter affecting the net straw yield are the residues that are used for livestock feeding, bedding and mulching. There is very limited information available on assessment of this factor. Based on a study by Sokhansanj et al. (2006), Alberta's annual straw requirement for livestock is estimated to be 3.2 Mt for 4.85 ha of land. According to Sultana et al. (2010) the amount for livestock feeding and bedding was 0.66 tonne/ha. In this study we have used the same the assumption as reported by Sultana et al. (2010). The assumptions are shown in Table 2-3.

Another key factor that reduces the net straw yield is the efficiency of the harvesting machine. Several studies have indicated losses in the harvesting process. Table 2-4 gives various values of harvesting efficiency. In this study, a 30% loss of straw is considered during harvesting.

[1]*Straw retention for no tillage and conventional tillage of cropland, respectively.*

Table 2-3: Loss of straw in its collection and harvesting

No.	Source	Harvesting Efficiency / Loss
1	Sultana et al., 2010	30% loss.
2	Sokhansanj & Fenton, 2006; Sokhansanj et al., 2009	25% loss.
3	USDA, 2009	40%[1] loss.
4	Montross et al., 2003	Efficiency of 64-75% for corn stover.
5	Lang & Specialist, 2002	Efficiency of 80%.
6	Sheehan et al., 2003	Efficiency of 70% of residue collection in no-tillage condition and 40% with continuous tillage.
7	Liu, 2008	37% loss.

Due to bulky nature of straw, there are challenges in its transportation and storage. This adds to the cost of these unit operations. This is one of the key reasons for the restricted use of biomass for energy processes. The following Table 2-4 shows the losses during storage and transportation of straw based on literature.

Table 2-4: Storage and transportation losses

No.	Source	Storage and Transportation Losses
1	Sultana et al., 2010	30% loss.
2	Liu, 2008	18% (3% loss in field, 5% for transport and 2 to 10% for storage).
3	Campbell, 2007	10% loss due to handling and decomposition.
4	Perlack et al., 2005	Storage and handling losses of 10%.
5	Perlack et al., 2005	Storage piled at the roadside is 3.5% and a loss in intermediate storage and bunker is 2%. The typical dry matter losses for solid biomass transport are about 15%.

[1]*According to USDA (2005), it is possible under some conditions to remove as much as 60% to 70% with currently available equipment.*

Table 2-5: Net straw for bio-energy facilities

Crop	Gross yield[1]	Level of straw retained for soil conservation[2]	Fraction of straw harvest machine can remove[3]	Fraction removed For animal feeding and bedding[4]	Fraction of straw loss from harvest area to pellet plant[5]
Wheat	2.96	2.21	1.55	0.89	0.754
Barley	2.52	1.77	1.24	0.58	0.493
Oat	2.83	2.08	1.46	0.80	0.678

[1] *Based on the values detailed in Table 2-1: Average straw*

[2] *Based on the values detailed in Table 2-2: Amount of straw to be left in the field for soil conservation.*

[3] *Based on the values detailed in Table 2-3: Loss of straw in its collection and harvesting.*

[4] *Factors used from (Sultana et al., 2010)*

[5] *Based on the values detailed in Table 2-4: Storage and transportation losses.*

2.4 Current Technologies for Charcoal Production

Charcoal production from biomass is at a stage of development and demonstration. There are a number of technologies, which are in different stages of the development. Various companies around the world have developed technologies including different types of kilns, machines and retorts to convert biomass to charcoal. These companies use variety of biomass including wood, animal waste, straw and other sources of biomass for production of charcoal. There is a lot of focus on production of bio-oil (a thick dark liquid) through fast pyrolysis and production of charcoal as a secondary product. A detailed literature review of the technology was done as part of this study. The following section gives detail on some of the key technologies reviewed in this study.

2.4.1 Bio Energy LCC (Russia)

Bio Energy LCC has developed a family of Kilns called the EKOLON. The design has vertical movable retorts, which hold the biomass (in this case firewood). These retorts are placed in the kiln. The retorts have a special device at the bottom to extract steam and gas mixture to the furnace. To avoid emissions, the produced syngas and liquid products (tar) from wood decomposition are completely burned in the furnace. The heat flows through the sections for providing energy for pyrolysis and drying. There is no other power consumption except the lighting, mechanical wood-chopper and hoisting equipment - a crane with 3-5 tonne lifting capacity (Bio Energy LCC, 2010). The equipment developed by this company uses wood as a source of biomass. It can also accommodate any bulky biomass (e.g. straw in the form of briquettes). The source of energy to initiate pyrolysis and continuous operation is extra biomass in addition to requirement for production of charcoal. The upper limit of moisture content in the biomass is 40%. The capacity of the retorts ranges from 1 – 5.2 tonnes of charcoal per day. About eight people are required for the operation of these retorts and is highly dependent on the degree mechanization of the process.

2.4.2 Alterna Energy Inc. (Canada)

Alterna Energy Inc. is working on building and demonstrating a multi-module biochar production facility that will convert 110,000 tonnes of green wood residues (bark, forest waste including pine-beetle killed wood, hog fuel and sawmill residues) annually into 25,000 tonnes of biochar. They currently have a small industrial facility in South Africa and a demonstration plant in McBride, BC (Kutney, 2010). The equipment can handle any kind of biomass. Three persons are required per shift for the plant. The total capital costs for a 25,000 tonnes per year biochar facility is about $10 million.

2.4.3 Best Pyrolysis Inc. (Australia)

BEST Energies has a fully operational demonstration plant that has a capacity to take 300 kg/hr. of biomass. This design has been scaled up into 48 and 96 tonnes/day (dry feed basis) commercial modular units. These modular units can be designed with an engine component for electricity production or to interface with thermal energy processes such as steam boilers, dryers and absorption chillers (Best Pyrolysis Inc, 2010). The equipment operates on a continuous kiln mechanism. The biomass is put into small containers and are passed through the kiln and hence converted to char. The basic steps are shredding of the biomass into smaller size, drying to minimize moisture content, carbonization, cooling to avoid ignition, screening, grinding, bagging and shipping. It requires a process area of 70’ x 100’ and two operators to run the facility. The capital cost of the facility reported in 2009 is $3,500,000 and it takes about 18 months for installation. The capacity of the unit for production of biochar is 6,600 tonnes per year (Best Pyrolysis Inc, 2010).

2.4.4 Lambiotte Kiln (Belgium).

The automatic continuous Lambiotte SIFIC/CISR carbonization retort includes the system for preparation of wood, the retort itself, and the charcoal storage and handling equipment. In the Lambiotte process, the pyroligneous vapors are burnt for energy, which results in a yield 2 to 5 times higher than with the traditional processes. Water from the gas cooling circuit is recycled and the surplus pyroligneous vapors are burnt in a flare-stack to ensure the protection of environment. These vapors can also be reclaimed to feed a boiler. The charcoal produced has an excellent purity and consistency, with a very high carbon content (Herla, 2010; Lambiotte & Cie, 2008).

Table 2-6: Lambiotte technical specifications (Herla, 2010; Lambiotte & Cie, 2008)

1	Annual charcoal production	6,000 tonnes
2	Characteristics of the charcoal produced by the LAMBIOTTE process	Fixed carbon: 82 -90 % Moisture: 3 to 4 %
3	Reclaimable pyroligneous vapors	~3,000,000 kcal/H
4	Annual wood requirement	24,000 to 27,000 tonnes
5	Installed power	250 to 300 kW
6	Power consumption	100 to 120 kW
7	Man-power	14 to 17 people
8	Average life time	15 years
9	Approximate weight / volume	100-120 tonnes / 1200 m^3

2.4.5 Genesis Equipment (USA)

Genesis Industries (eGen) is another provider of pyrolysis machines. The existing commercial machine has been operationally tested for production of clean burning syngas and biochar. The machine has been designed for easy use and has a continuous feed system, and runs on a wide variety of waste biomass ranging from wood chips to poultry litter (E Genesis Industries, 2010). The equipment has clean, simple and continuous operation. It is a rugged design, which can handle various biomass variety of feedstock material from cereal straw to feedlot waste and timber-based wastes. Low-grade waste exhaust gases are utilized to pre-dry feedstock material to increase overall efficiency and reduce CO_2 emissions. Pyrolysis gases (syngas) maintain temperatures and high flow rates through the unit. Depending on biomass moisture content/energy values, excess syngas can be produced. Excess pyrolysis gases can be used to power a micro-turbine or furnace/boiler. The system requires outside energy source for start-up including natural gas or propane. The footprint of the site required for this kind of system is 40 ft. x 20ft x 15 ft. high with electrical service of 100 amp, water line and gas supply (propane or natural gas at a maximum rate of 280MJ @ 40kpa) (Gelwicks, 2010). Feedstock capacity of this unit assuming moisture content of 20-25% is 1000 kg/hr. and produces 250 kg/hr. of biochar (E Genesis Industries, 2010).

2.4.6 Adam-Retort (Germany)

The Adam-Retort or the Improved Charcoal Production System (ICES) was developed in Burundi/East Africa and India. It is semi-portable equipment, with efficiency of about 30%. The retort uses a low cost construction model with material easily available in any part of the world. It can be considered as an improvised version of an earth kiln. The ICPS is basically a brick wall construction with two chimneys and a few metal plates. A single person can operate it. The pyrolysis is achieved in a two-phase process. In phase one of operation, the retort chamber with biomass in it, is open from two ends. Heat from an external firebox is used for drying and preheating the biomass. The firebox contains biomass, which is the initial source of energy to start the process. In phase two of operation, one of the open chambers is sealed. Smoke and gasses from heated biomass are forced in firebox. The smoke and volatiles (including methane) burns in hot firebox and gives it an additional advantage in the carbonization process. The heat transfer takes place through the metal sheets in the retort. This design prevents the harmful gases to leave the chamber and are less harmful to the environment (Adam, 2009 & 2010). The size of the retort depends upon the size of the metal sheet available. For this study, a dimension of 2.46 m (length), 1.26 m (width) and 1 m (height), therefore a total volume of 3.1 m3 was considered based on discussion with the technology developer (Adam, 2009 &2010). The Adam retort efficiency is about 30-40% depending upon the moisture content in biomass. It uses wood as a biomass resource, and extra biomass for initiation of pyrolysis process. Life of one retort is about 3 years. It operates in batch process and can have maximum (ideal) of 5 batches per week (Adam, 2009 & 2010).

2.4.7 Black is Green Pty. Ltd (BiG)

Black is Green Pty. Ltd (BiG) is a private Australian Company which has developed various pyrolysis equipment. BiG char units are offered in mobile or fixed configurations. BiG's patented fast rotary hearth technology was developed to satisfy a need for cost effective conversion of waste biomass to charcoal products. It has a self-fuelled direct pyrolysis by a patented fast rotary hearth process. The hearth is double walled, insulated vessel with stainless steel lining and decks. A range of feedstocks including chipped green waste, manures, crop waste, grass, and weeds etc. can be used for production of char through this technology. It needs one person for operation. It has nominal feed input of 5,500 kg/hr. and typical conversion efficiency of biomass to char is about 30-35 %. The equipment needs low maintenance.

2.5 Input Data and Assumptions

This study aims at developing data intensive techno-economic models for the production of charcoal from biomass and landfilling of this charcoal for carbon sequestration. In order to develop the techno-economic models, two cases are considered which vary in terms of scale of operation. Large-scale operation is based on the technology proposed by the North American Company BigChar This equipment is an automated machine, developed for a variety of feedstocks. In this study, the large-scale production of charcoal is done in a centralized facility. The other equipment (kiln) the Adam-retort is on small scale and is an easy to build kiln design and this technology has been considered as a representative case for portable option. This study develops detailed unit operations for Alberta and develops the costs and characteristics of the each unit operation including the detailed biomass supply and logistics. Table 2-7 shows properties of all the three straw types considered for the production of biomass based char.

Table 2-7: Straw properties

Characteristic	Wheat Straw	Barley Straw	Oat Straw
Moisture content (%)[a]	15.9	13.6	17.2
Lower heating value (GJ/ODt)[b]	18.45	19.2	18.1
Bulk density (kg/m^3)[3]	79	82	-

Characteristic	**Wheat Straw**	**Barley Straw**	**Oat Straw**
Nutrient content (%)[d]			
Nitrogen	0.66	0.64	0.64
Phosphorus	0.09	0.05	0.1
Potassium	1.6	2.5	2.4
Sulfur	0.17	0.19	0.16
Ash[d]	8	8	7

[a] Derived from (Várhegyi, Chen, & Godoy, 2009)

[b, d] Derived from (Bailey-Stamler S., Samson R., & Lem, 2007)

[c, d] Derived from Kumar et al., 2003.

The scope of the study includes several unit operations starting from harvesting of straw and to the production of charcoal. The total cost of production of charcoal consists of three broad categories of costs. These include:

1. Biomass delivery cost;
2. Capital cost;
3. Operational cost.

2.5.1 Biomass Cost

The delivered cost of biomass depends on the location of production and the producers. Straw needs to be harvested, collected, baled and tarped before it can be stored and transported. All these unit operations incur a cost. The straw removed from soil carries nutrients (as stated in Table 2-7). Once straw is removed for production of charcoal, these nutrients need to be replaced. In this study we have estimated the nutrient replacement cost. In addition to the cost of delivering straw to the charcoal production facility and nutrient replacement cost, in this study, we have also considered a payment to the farmers for selling their straw to the bioenergy facility. This cost is to ensure a continuous supply of biomass. Detailed delivered cost of biomass collection are given in Tables A3, A4 and A5 in the appendix.

2.5.1.1 Straw Harvesting and Collecting Cost

In this study, it is assumed that the plant owner contracts out the straw harvesting process; hence there is no capital cost of harvesting equipment involved. These contractors could be farmers or a third party supplier.

The cost of harvesting depends upon various factors but largely upon the equipment used in harvesting but a typical cost is about $10.50/bale ($21.00/green tonne for 500 kg bales) and $3.25/bale ($6.5/dry tonne for road siding) (Campbell, 2007). Earlier studies have suggested the cost of shredding, raking and baling to be $3.67, $2.31 and $3.65 per tonne, respectively (Brechbill & Tyner, 2008; Sultana et al., 2010). (Kumar et al., 2003; Sarkar & Kumar, 2010) Other studies have suggested the harvesting cost of straw as $8.86 per green tonne (Kumar et al., 2003) and $10.58 per dry tonne (Sarkar & Kumar, 2010), respectively. The cost of various harvesting operations for this study is given in Table 2-8.

Table 2-8: Straw processing equipment selection[1]

Equipment	Working Rate	Unit	Operational Cost ($/tonne)	Notes/ Source
Shredding	25	dry tonnes/hr.	35.55	Shahab Sokhansanj, Turhollow, & Wilkerson, 2008
Raking	30	dry tonnes/hr.	6.64	
Baler	20	dry tonnes/hr.	71.06	
Stinger – Wrapper	60	bales/hr.	27.24	
Weight per bale	0.512	tonnes		

2.5.1.2 Bale Wrapping Cost

Straw transport is usually in form of bales. Currently there are three types of baling options available. Depending upon the storage time required the baling could be either twine, plastic or net wrap. Plastic wrap is the most protective and is used for long-term storage options. Table 2-9 summarizes the percentage loss in dry matter for various types of storage (Brechbill & Tyner, 2008; Kumar et al., 2003; Sarkar & Kumar, 2010).

Table 2-9: Percentage dry matter losses in straw storage

Type of wrap	Values	Sources
Net wrap	18.8%	(Brechbill & Tyner, 2008; Kumar et al., 2003; Sarkar & Kumar, 2010).
Twine wrap	8.4%	
Plastic wrap	6.15%	

Table 2.10 lists the cost of bale wrapping for all three types of baling and also the bale collection cost.

[1]*Cost of equipment [(Quantity of biomass to be processed / capacity of equipment in dt/hr.)* $ cost per hour)]*

Table 2-10: Bale wrapping cost[1]

Cost Factor	Cost ($/tonne)	Source/Comments
Twine Wrap	0.49	(Brechbill & Tyner, 2008; Sultana et al., 2010)
Net Wrap	1.77	
Plastic Wrap	2.48	
Twine Wrap	0.89[1]	(Sokhansanj, Turhollow & Wilkerson, 2008)

[1]Cost in $/bale.

2.5.1.3 Straw Storage Cost

Biomass storage is another cost involved in the overall biomass delivery cost. The way biomass is stored also affects the quality of biomass. The loss in the storage depends largely upon the method of storage. In the plant considered in this study, storage requirement is for three months, as transportation from fields is difficult during early spring in Alberta. The bales are stored on ground to minimize the cost. On-field storage method is the cheapest option but the dry matter loss is 25% (Sokhansanj et al., 2008) to 30% (Campbell, 2007). Table 2-11 gives the straw storage cost.

Table 2-11: Straw Storage Cost

Equipment	Working rate (unit)	Cost amortized	Notes/Source
Storage	3.62 (kg/cubic feet)	0.16	(Sokhansanj et al., 2008)
Height of storage facility	10 (feet)		Assumption
On field storage cost		1.80	(Campbell, 2007)

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*[1]Bailing wrapping cost is calculated [(total biomass to be baled / weight per bale) * cost per bale]*

Equipment	Working rate (unit)	Cost amortized	Notes/Source
Storage Premium		0.10	(Brechbill & Tyner, 2008)

2.5.1.4 Nutrient Replacement Cost

Table 2.7 indicates various nutrients in straw. When straw is removed from field for bioenergy use, it causes loss of these nutrients, which could have returned to the soil if the straw was left to decay in the field. In order to account for these nutrients, a cost has been developed in this study that includes the cost of the nutrients. It is assumed that the there would not a significant incremental cost for spreading these nutrients as these could be spread in the field with the fertilizers. Table 2-12 gives the nutrient replacement cost.

Table 2-12: Nutrient replacement cost

Cost Factor	Cost ($/tonne)	Source/Comments
Nutrient replacement cost	22.62	This is based on the cost of nitrogen, phosphorus and potassium costs (Jensen T, 2008; Sultana et al., 2010)
Nitrogen cost	12.60	Four years (2005-2008) average data has been taken. The nutrient replacement is determined by multiplying by the amount of nutrient per unit of fertilizer. K_2O is 83% potassium. P_2O_5 is 44% phosphorous (Sultana et al., 2010; Kumar et al., 2003).
P_2O_5 cost	12.40	
K_2O cost	4.40	
Sulfur cost	5.20	

Based on the efficiency of the harvesting machines, some portion of straw and the roots are left in the field. Earlier studies indicate that the carbon levels remain high and need not be replaced artificially (Kumar et al., 2003)

Alberta has abundance of calcium and minerals in its soil, hence replacement of these nutrients are not considered in this study (Alberta Agricultural and Rural Development, 2010; Kumar et al., 2003). In this study, only the fertilizer cost equivalent to the straw nutrients is evaluated. It is assumed that the spreading is done along with existing operations in farming.

2.5.1.5 Premium to Farmer

To ensure an uninterrupted supply of biomass, in addition to harvesting, collection and nutrient cost, a premium is also is paid to the farmer for making the straw available for charcoal production. Table 2-13

Table 2-13: Premium cost

Cost Factor	Cost ($/tonne)	Source/Comments
Farmer premium cost	5.5	Cost of replacing the lost nutrients in the process of straw removal. (Kumar et al., 2003)

2.5.2 Biomass Transportation Costs

Various studies have indicated that the biomass transportation cost is a critical component of the overall delivered cost. The transportation cost of biomass in this study has been estimated based on following assumptions.

- The area from which the plant draws straw is circular.
- The straw transport is done on existing roads via trucks.
- The straw distribution in this circular region is assumed to be uniform; and the fraction of the harvest area used to grow wheat, barley and oats

to the total area is 30% in Alberta (Alberta Official Statistics, 2008; Sultana et al., 2010).

- Practically the distance of transport of biomass depends on the geographical locations as the roads are not always in a straight line. Hence a tortuosity factor or winding factor of 1.27 is considered in this study (Overend R. P., 2004; Perlack R.D. & Turhollow, 2002; Sarkar S., 2009; Sultana et al., 2010).
- The area required for a particular plant depends on the plant capacity and straw yield.

The transportation cost consists of fixed cost and variable cost. Fixed cost of transportation includes loading and unloading costs ($/dry tonne of biomass). Variable cost includes driver cost, fuel cost and other costs that are dependent on the distance ($/dry tonne/km).

The bales need to be loaded and stacked until the transport trucks come to pick them up. This is an additional operation for handling bales. Various studies have reported costs for this operation. Liu (2008) suggests $0.67/ green tonne for bale picker and $3.58/green tonne for tractor. (Kumar et al. (2003) and Sultana et al. (2010) have suggested $4.80/green tonne and $4.0/dry tone as loading and unloading values for straw, respectively. Mahmudi & Flynn (2006) suggests a value of $4.16/green tonne of fixed loading-unloading cost and 0.1309 $/green tonne/km of variable cost. The typical loading and unloading cost for truck transportation of biomass is \$5.45/green tonne (Campbell, 2007; Kumar et al., 2003; Searcy, Flynn, Ghafoori, & Kumar, 2007). The variable transportation cost for straw is assumed to be is \$0.22/dry tonne/km (Campbell, 2007; Liu, 2008). As the transportation cost changes with the distance travelled it forms, a sensitivity case has been evaluated to assess its impacts on the total charcoal production cost. In this study we assume a loader with a capacity of two bales per load and a 40' flat bed truck with a capacity of 26 bales per trip for transporting biomass to the plant.

Table 2-14: Biomass loading and unloading cost[1]

Equipment	Working Rate	Unit	Cost Amortized (\$/hr.)	Notes/ Source
Truck loader	2	Bales per load	130.98	(Sokhansanj et al., 2008)
Load time	0.5	Minutes per load		
Unload time	0.2	Minutes per unload		
Telescopic stacker	2	Bales per load	82.22	
Load time	0.25	Minutes per load		
Unload time	0.2	Minutes per unload		
Speed	30	Kmph		
Truck transport 40' Bale BC 4075	26	Bales per load	25.31	
Average travel speed	24	Mph		

[1]*Number of bales (0.512 * tonnes of biomass required per year); Hours required = Number of bales / bales per load * time for loading; Total trips per year = Number of bales per year / bales per trip); Hours of trucking required = number of trips * biomass transport distance / average speed).*

Equipment	Working Rate	Unit	Cost Amortized ($/hr.)	Notes/ Source
Time for load unload	2.6	Minute per bale x number of bales		
Time for inspection	1.3			

Using the calculations and equipment as mentioned in the table above, we get a loading-unloading cost of $1.056 ($/dry tonne) and $0.1584 ($/green tonne /km). The detailed calculation is shown in Table A3. This cost is low as per the literature found, thus we use $5.6 $per green tonne as loading and unloading cost.

2.5.3 Charcoal Production Cost

The production cost for charcoal has been evaluated for two cases. These have been described earlier in the section 2.3.7. Some of the common assumptions are listed in the Table 2-15. The detailed equipment/kiln specific costs are indicated in separate sections below.

Table 2-15: Economic assumptions

Factor	Value		Source/Comments
Inflation	2%		This is the average inflation over 12 years (Kumar et al., 2003; Sarkar & Kumar, 2009; Sultana et al., 2010)
Internal rate of return	10%		Assumed.
Inflation rates	**CAD**	**USD**	
2003-2009	1.110	1.170	(Bank of Canada, 2010)
2004-2009	1.090	1.140	
2007-2009	1.020	1.030	
2008-2009	1.010	1.000	

Factor	Value		Source/Comments
1 USD to $ CDN		1.065	(USA Inflation Calculator, 2010)

2.5.3.1 Labor Costs

There are two kinds of employees, temporary (hourly paid) and permanent (paid on monthly or annually salary). The requirement of number of labor depends upon the level of automation in the plant. Table 2.16 below summarizes the employee wages assumed for both the plants in the study.

Table 2-16: Labor costs

Type of Employee	Wage/Rate	Source/Comments
Labor ($/per annum)	$40,000	(PayScale, 2009)
Office Clark ($/per annum)	$60,000	
Manager (1) ($/per annum)	$100,000	

2.5.4 Production Cost for BiG Char Equipment

BiG Char is based on pyrolysis technology. The typical life of the plant is assumed to be 10 years based on discussion with the manufacture of the equipment (Joyce, 2011). Table 2.17 below lists various technical and economic assumptions related to BiG Char technology. In this case charcoal is produced in centralized facility and transported to the landfill for carbon sequestration.

Table 2-17: Assumption for Big Char equipment case

Parameter	**Value**	**Comments/remarks**
Plant life	10	Plant life is based upon life of equipment, which is 15 years.
Site reclamation	10%	(Kumar et al., 2003; Sarkar & Kumar, 2009).
Capacity profile Year 1 Year 2 Year 3 and onwards	 80% 85% 90%	There values are assumed based on operating factors reported in earlier studies on biomass handling facilities (Kumar et al., 2003; Sarkar & Kumar, 2009).
Biomass capacity (kg/hr.)	5,500	(Bigchar, 2009).
Charcoal production (kg/hr.)	1,925	The charcoal production efficiency ranges from 20 – 35%. The conversion efficiency depends on the type of biomass. The actual efficiency needs to be determined by practical experiments with the kind of biomass intended to be used. Hence, in this study an average efficiency of 30% for biochar conversion is assumed.
Capital cost ($/kiln) (Base year 2009)	1,884,000	(Bigchar, 2009)
Maintenance cost (% of capital cost)	5%	(Bigchar, 2009)
Biomass req.	48,180	This is at 100% capacity,
Charcoal production (tonne/annum)	14,454	

2.5.4.1 Capital Cost

The capital cost involved in this plant comprises of two major costs. The capital cost of the equipment and the plant set-up cost. The BiG Char has two models of pyrolysis equipment. These vary in size and in capacity for production of charcoal. Model BiGChar 3500 and Model BiGChar 4800 have biomass utilization capacity of 3,000 and 5,500Kg/hr., respectively. The BiG Char Model 4800, which is the largest available model for production of charcoal, is used in this study. It costs approximately US$ 1,844,000. This model is an automatic and continuous flow pyrolysis machine. The total capital cost components are shown in Table 2.18 based on assumption from earlier studies (Dassanayake & Kumar, 2012; Kabir & Kumar, 2011; Spath et al., 2005). Details on the calculation of each component are given in Appendix Table. A1.

Table 2-18: Capital cost break-up

	Cost component	**Cost ($ values on base year 2009)**
1	Equipment cost	1,884,000
2	Construction cost	640,560
3	Legal	433,320
4	Project contingency	697,080
5	Building cost	546,360
	Total capital cost	**4,201,320**

2.5.4.2 Labor Requirements and Cost

Labor cost is another key cost component of the overall charcoal production cost. The automation of the equipment decides the labor requirements. In the centralized production of charcoal assumed in this study, there is a need of total four people for biomass and charcoal handling. Another operator is required who is responsible for operating the kiln, this also acts as a back up for the biomass/charcoal handlers. For other responsibilities pertaining to the plant, it is assumed that one administrative staff, one accountant and one plant manager will be required.

2.5.4.3 Power Cost

The charcoal production plant requires electrical energy for its own operation. The electrical energy consumption is 4% of the total energy required to heat the biomass at the operational temperatures. Hence the total electrical energy is calculated using heat capacity (C_p) of straw as 2446 J/kg/K. The biomass is preheated to 500 ^oC from 30^oC. Based on calculations, as shown in Table A2, the energy required is 3.8 KWh. The cost of kWh is obtained from historic costs given by Alberta Utilities Commission. The costs of electricity from different sources are shown in Table 2-19.

Table 2-19: Cost of electricity in Alberta (cents/kWh)

ATCO Electric Ltd.	CAD	6.481	(Alberta Utilities Commision, 2009)
ENMAX	CAD	6.455	
Fortis Alberta Inc.	CAD	6.226	
Assumed	CAD	6.085	

2.6 Results for Centralized Production of Charcoal

A data intensive techno-economic model was developed for centralized production of charcoal. It is important to note that the cost model hasn't considered taxes, insurance payments and any government subsides. The charcoal price for an average yearly production capacity of 12,792 tonnes per year is $308.4[1] assuming a 10% IRR. The detailed cash flow forecasts are detailed in Table: A6. Figures 2-3 and 2-4 show the breakdown of the different cost components. Biomass related costs form a key component of charcoal production. (about 60%). Biomass transportation costs contribute to more than 50% of biomass costs, this forms the key reason to evaluate

[1] *Average yearly production capacity is based on the capacity profile of Year 1: 80%, Year 2: 85% and Year 3 Onwards 90% (previously mentioned in Table 2-17.*

portable production of charcoal. Following cost analysis is for 90% of production capacity.

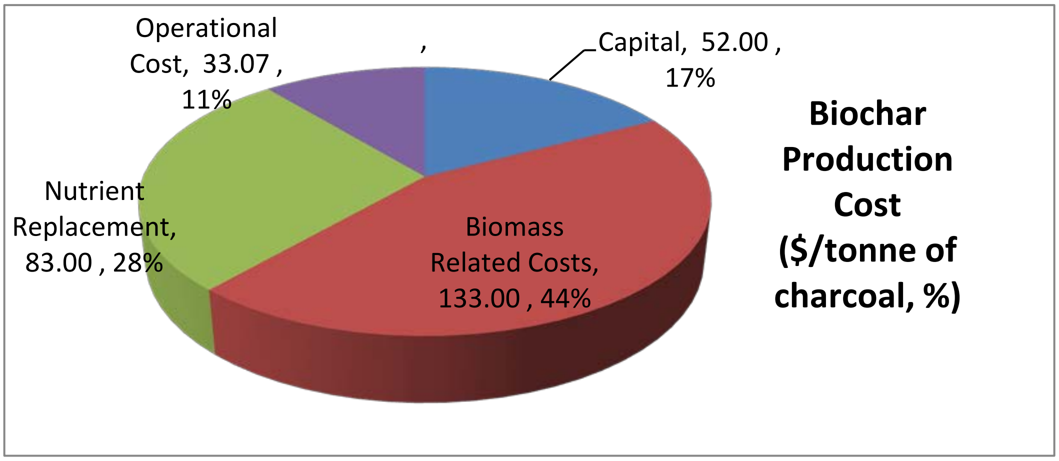

Figure 2-3: Biochar production cost break-down

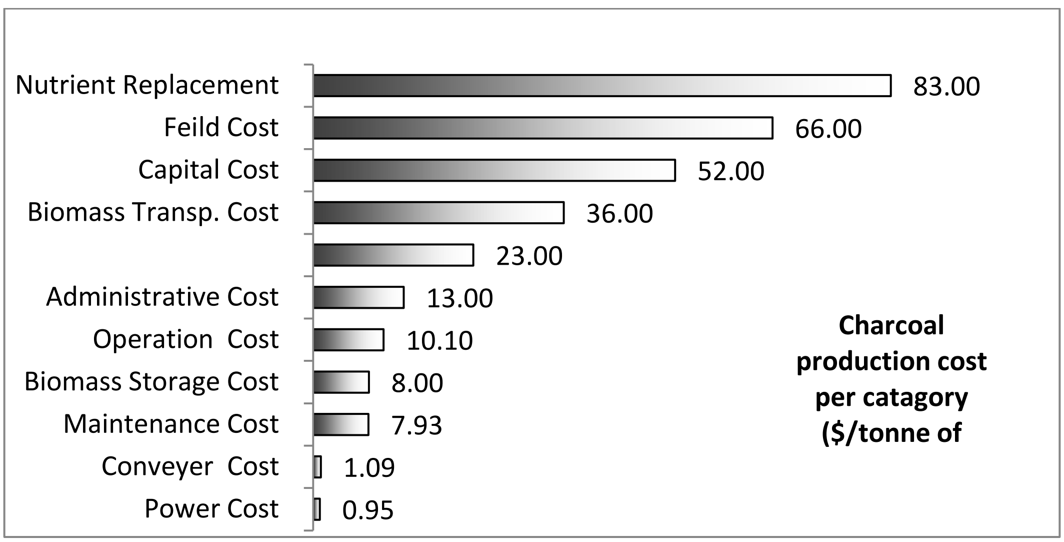

Figure 2-4: Breakdown of charcoal production cost ($/tonne of charcoal)

2.7 Sensitivity Cases

2.7.1 Capital Cost Curve

Capital cost for charcoal production plants depend on the level of sophistication or stage of development of the technology of the plant. Figure 2-5 shows the variation in cost of production of charcoal with capital cost.

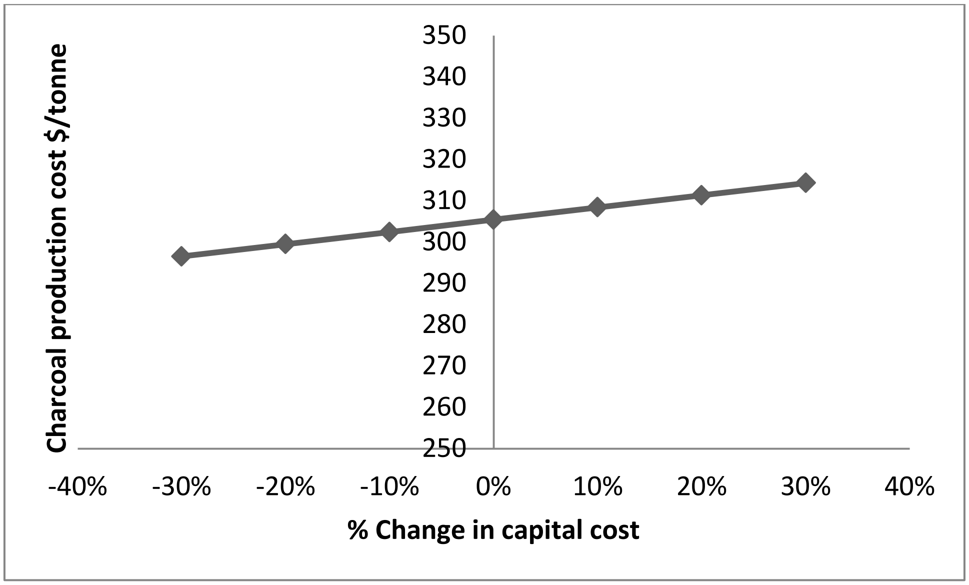

Figure 2-5: Effect of capital cost

2.7.2 Effect of Charcoal Yield

The charcoal yield can be enhanced if the machine feeding mechanism and process are modified further to suit straw as a biomass. Charcoal production cost as a function of yield is shown in Figure 2-6. The yield values have been varied from 15% to 35% as shown in Figure 2-6.

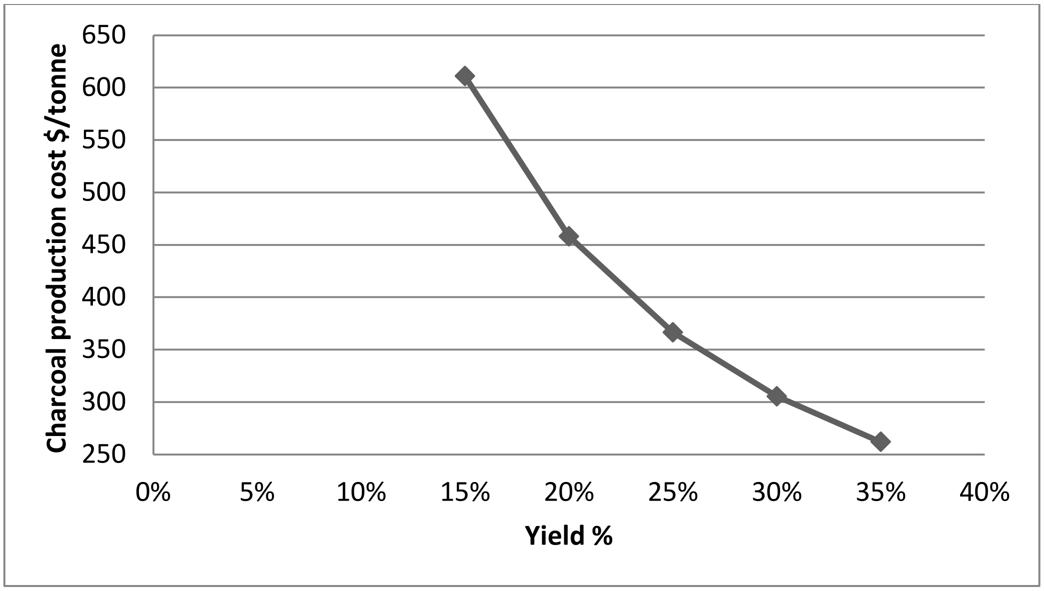

Figure 2-6: Effect of variation in charcoal yield on the charcoal production cost

2.7.3 Auxiliary Costs

Farmers' premium costs and nutrient replacement costs are two costs considered in the analysis to protect the farmer's future requirement and consistent supply of biomass for the plant. These costs can be skipped, if charcoal production is as a secondary operation to farming. The farmer benefits from the charcoal and uses it along with its fertilizer, hence preventing the soil erosion and carbon content. All this happens through landfilling of charcoal.

Table 2-20: Impact of auxiliary costs

Case	Nutrient Replacement Cost ($/tonne of charcoal)	Premium Cost to biomass owner ($/tonne of charcoal)	Resulting Charcoal Production cost ($/tonne of charcoal) (%)
Base Case	22.62	6.44	306.3 (100)
Case 1	22.62	0	222.8 (-28)
Case 2	0	6.44	282.5 (-08)
Case 3	0	0	199 (-36)

2.7.4 Biomass Transport Distance

The study assumes circular field and draws biomass along the radius. The radius forms the transportation distance. The biomass transportation cost contributes to 31% of the biomass procurement production cost in the base case. The biomass transportation distance depends on the yield of biomass. Figure 2-7 shows the variation in transportation distance with the yield of biomass.

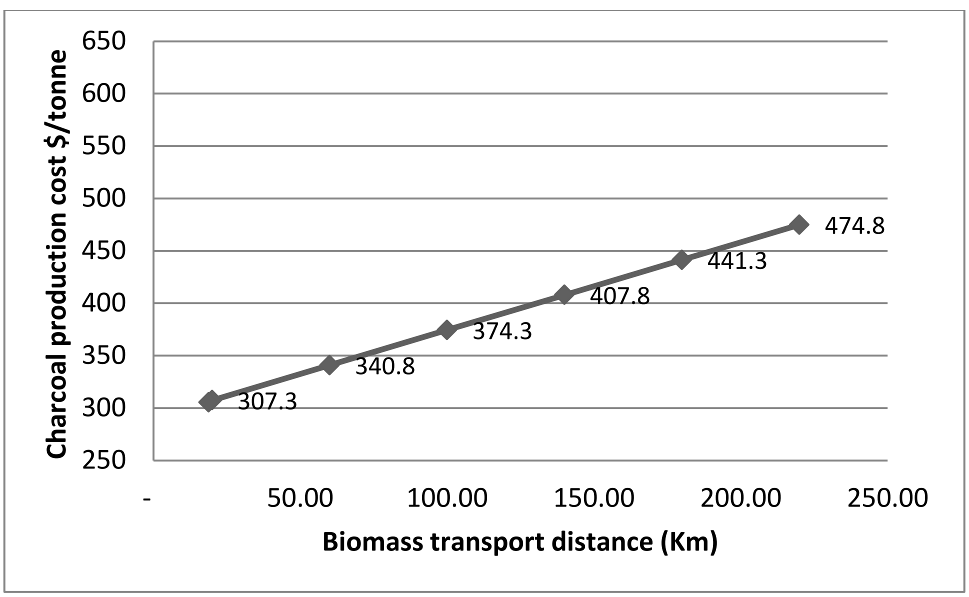

Figure 2-7: Impact of biomass transportation distance

2.7.5 Operational Cost

The operational cost consists of conveyer cost, power cost, maintenance cost of the plant and administrative cost. It contributes to 10.6 % of the total production cost of charcoal. Impact of operational cost from 70% to 130% has been showed in the Figure 2-8 below.

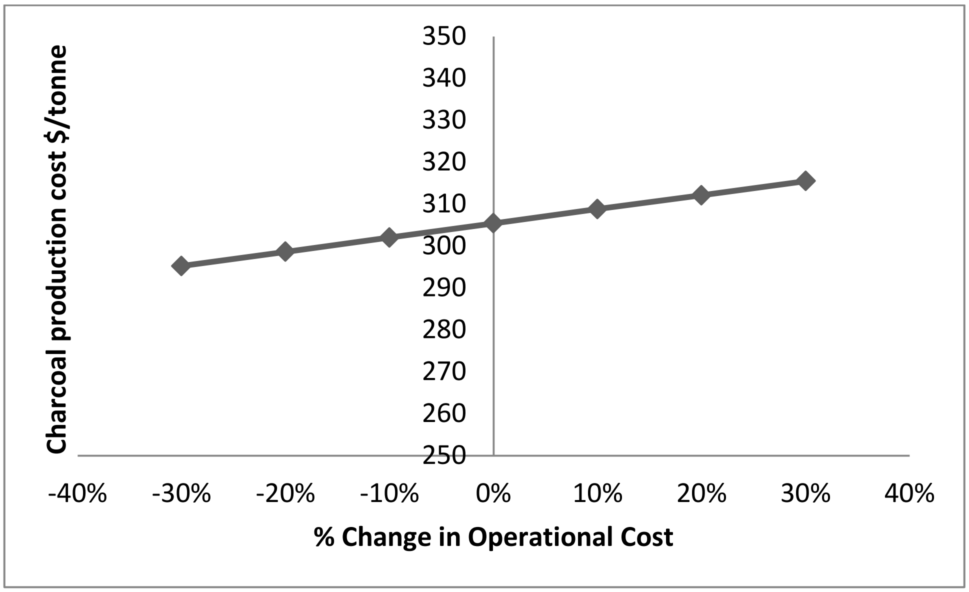

Figure 2-8: Operational cost analysis

2.7.6 Summary of Cost Analysis

The cost analysis performed is summarized in the Table 2-21. The value of charcoal yield has the maximum impact on the cost of charcoal production. Charcoal yield depends on various factors from biomass quality to equipment efficiency.

Table 2-21: Sensitivity case summaries

Parameter	**% Variation from base value**		**Min Value Cost ($/tonne)**	**Max Value Cost ($/tonne)**	**% Change**	
Capital cost	-30%	30%	296.5	314.3	3.13%	0.00%
Charcoal yield	-50%	17%	610.8	261.8	0-84 %	21.2%
Biomass Transport Distance	0%	325%	306	474.8	8.01%	- 7.81%

2.8 Charcoal Production in a Portable Plant

The second set-up for production of charcoal assesses the production of charcoal in a portable plant. The study identifies various portable technologies for charcoal production and estimates the cost of production of charcoal. The system consists of portable plant, which is transported to the source of biomass i.e. to the field. The plant converts biomass to charcoal and is spread in the field. The farmer along with spreading of other fertilizers will spread the charcoal back to the farm.

This system eliminates the need to transport biomass over long distances, hence reducing the transportation costs and some losses of biomass associated with long distance transport of biomass. The plant size is restricted due to the need for portability. This reduces the annual charcoal production capacity and is also a barrier to getting economy of scale benefits. This section covers various assumptions, technologies currently available and costs involved in the production of charcoal through portable plant. The trade-off between portability and volume is studied.

2.8.1 Various Portable Technologies for Charcoal Production

2.8.1.1 BiG Char

Black is Green Pty. Ltd (BiG) is a private Australian Company which developed various pyrolysis equipment. BiG Char units are available in mobile configuration. BIG's has developed a fast rotary hearth technology to convert biomass to charcoal products. They have two models for portable biochar equipment. These include version 2200-G, optimized for processing of chipped green waste, manures and sawdust and version 2200-C which is optimized for processing fibrous, lighter grasses and crop wastes (e.g. cotton and cane trash, straw, hay, stubble, grass and weeds) (Bigchar, 2009).

These technologies include self-fuelled direct pyrolysis by fast rotary hearth process. These are double walled, insulated vessel with stainless steel lining and decks. These can take a variety of feedstocks including chipped green waste, manures, crop waste, grass, weeds etc. These are movable by trailer or light truck. One person could operate these. These can be operated on a vehicle, off a vehicle, or in containers. These systems have removable jacking legs for easy loading/unloading without need of a forklift or crane and this makes it easily portable equipment. It requires minimal maintenance and has controlled emissions.

Table 2-22: Characteristics of BIG Char technology

Items	**Values/Features**
Biomass feedstock	Chipped green waste, manures, crop waste, grass, weeds etc.
Feed input rate	1000-1200 kg/hr.
Charcoal output rate	200-360 kg/hr.
Charcoal Yield	20-30%
Operating temperature	400-600 ^{0}C
Equipment size	2000 mm in diameter and 1200 mm in height
Power requirement	900 watts, 24 volt DC
Number of operators per equipment	1
Weight of the equipment	2 tonnes

2.8.1.2 Biochar Engineering Corporation (BEC)

BEC is developing light industrial equipment that produces charcoal. This unit processes up to 500 lbs. of woody biomass per hour. These mobile units can be deployed at the source of the biomass. Over 500 lbs./hr. (225 kg/hr.) screened woody biomass or agricultural biomass could be used. The biomass should have 10% or less moisture on a dry weight basis. It can use biomass with maximum moisture content of 20%. The electric power requirement is about 10 kW and 12 kW at startup. The electrical connection requirement should be about 208 V, 3-phase, or 240 V single-phase. It needs about 0.25 lb./hr. of propane at the start-up. Charcoal production capacity for this equipment is 50-100 lbs./hr. (22-45 kg/hr.). Charcoal produced by this equipment has about 90-98% fixed carbon. The heat requirement for these systems is about 1.5 million Btu/hr. or 440 kW/hr. The thermal energy for these systems could come from producer gas. The footprints of these systems is about 5' x 18' x 10' (1.5m x 5.5m x 3m) and has a capacity of 2.5 tonnes (2.2 metric tonnes) when empty (Biochar Engineering, 2010).

Table 2-23: Characteristics of plant by Biochar Engineering Corporation

Items	Values/Features
Biomass feedstock	Woody biomass
Feed input rate	225 kg/hr.
Biomass moisture content	10% to 20%
Electrical connection requirements	12 kW at startup, 208 V, 3-phase, or 240 V single-phase
Propane for startup	about 0.25 lb./hr.
Carbon content	about 90-98% fixed carbon
Charcoal output rate	50-100 lbs./hr. (22-45 kg/hr.
Equipment size	5' x 18' x 10' (1.5m x 5.5m x 3m)
Number of operators per equipment	1
Weight of the equipment	2.5 tonnes

2.8.2 Input Data and Assumptions

The scope of the study involves estimation of cost of production of charcoal using portable pyrolysis equipment. Various costs involved are estimated using detailed literature review and in consultation with the experts. Wherever the costs were not available, these were developed. The biomass costs including straw harvesting and collection, bale wrapping, straw storage, nutrient replacement, premium to farmer and storage premium cost have already been derived in the section 2.4 and these are used for portable equipment as well. As discussed above, the primary intention of using portable equipment is to minimize the biomass transportation cost as the equipment travels to the source of biomass. Hence, there is no biomass transportation cost involved. The only transportation of biomass occurs is from the field to the roadside or wherever the equipment is located in the field. This cost component will be negligible and has been neglected. The transportation of the equipment from farm to farm is used in the analysis. The model used for the purpose of study for portable charcoal production is BiGChar 2200-C which was described earlier in the section 2.8.1.1. The key parameters and assumptions are listed in Table 2-24.

The calculation is done for various levels of productivity ranging from 21 hours per day to 24 hours per day. The methodology adopted is that equipment is assumed to produce for entire year and various costs are adjusted accordingly.

Table 2-24: Key assumptions for portable charcoal production

Parameter	**Value**	**Source/Comments**
Kiln Life	10	The kiln life is based on the equipment life suggested by the manufacturer.
Charcoal production yield	20%	Lower value of the yield is assumed. (Bigchar, 2009)
Biomass capacity (kg/hr.)	1,000	(Bigchar, 2009)
Charcoal production (kg/hr.)	250	(Bigchar, 2009)
Cost ($/Kiln)	$250,000	Base year 2009, (Bigchar, 2009)
Related cost ($/kiln/year)	$125,000	The over all equipment cost has been

Parameter	Value	Source/Comments
		amortized to one year, base year 2009
Biomass requirement (tonne/annum)	8736	Assuming productivity of 90%, 21.6 hours per day. (Bigchar, 2009)
Charcoal production (tonne/annum)	2184	
Maintenance cost	5%	(Bigchar, 2009)
Labor requirements (# of persons)	1	(Bigchar, 2009)

2.8.3 Cost Estimation

2.8.3.1 Capital Cost

The equipment used for the portable set up is the BiGChar 2200 G. The cost of the equipment is shown in the Table 2-25 below. Assuming the life of the equipment to be 10 years and the internal rate of return of 10% the cost of equipment amortized over its life comes to $61,029.

Table 2-25: Capital cost of portable equipment

Items	Costs
Ex-factory	$250,000
Other cost (Includes installation cost, truck mounting cost and secondary equipment cost for straw)	$125,000
Total cost	$375,000
Life of the equipment	10 Years
Amortized cost	**$61,029**

2.8.3.2 Cost of Equipment Transportation

The portable equipment has to be transported to the field where charcoal could be produced. It is assumed that once the equipment has used the entire quantity of straw around it, then it moves on to the next closest field using a truck. Normally it takes about three hours for loading, transporting and unloading the equipment from one farm to another. The average field size of a farm in Canada is 1055 Acres (426.9 ha) (Statiscs Canada, 2010). The biomass requirement for the production of one year is 8736 green tonnes based on the full capacity of the assumed equipment. To supply this much of biomass, the required area is 40,669 ha. Hence, on an average about 22 fields need to be visited to complete the one-year's production of charcoal from biomass. Table 2-26 shows the calculations for the cost estimation of transportation of equipment.

Table 2-26: Equipment transportation cost

Items	Values	Source/comments
Average farm size in Alberta	1055.0 (ha)	Alberta Official Statistics, 2008.
Biomass area requirement	40,669 (ha)	Calculation details explained as per earlier section 2.5.2.
Average number of farms required	22 units	
Average time to transport equipment	3 hours	Assumption
Rental cost	$225/hr.	
Total cost for a year	$9696.70	

2.8.4 Results and Discussion

The analysis was done for various productivity levels of the equipment. The range of calculations is from 10 hrs. per day (low productivity case) to the maximum of 20 hours a day (high productivity case). To ensure that the volume of production does not impact the cost we have developed this methodology. The total production in a given period (a year in our case) of time is determined; it is then divided by the total cost incurred in running the equipment for the given year. The cost of production of tonne of charcoal ranges from $330 to $365/tonne of charcoal depending upon the capacity. Table 2-23 gives the charcoal production cost from portable equipment.

Table 2-27: Cost assessment charcoal production from portable plant

Items	Values (Low productivity case)	Values (high productivity case)
Productivity (hrs. /day)	12	21
Productivity %	50.00%	87.50%
Biomass Quantity (tonne/year)	4,600	8,050
Biomass Area (he)	20,336	35,587
Charcoal Quantity (tonne/year)	874	2,293
Capital Cost ($/year)	61,030	61,030
Field Cost ($/year)	82,883	145,045
Biomass Transp. Cost ($/year)	3,511	6,144
Nutrient Replacement ($/year)	104,050	182,088
Premium to fuel owner ($/year)	25,070	43,872
Biomass Storage Cost ($/year)	10,141	17,747
Conveyer Cost ($/year)	1,364	2,386
Operation Cost ($/year)	20,800	36,400
Maintenance Cost ($/year)	1,526	2,670

Items	Values (Low productivity case)	Values (high productivity case)
Truck Transport Cost ($/year)	8,674	15,179
Total Costs ($/year)	**319,048**	**$512,561**
Cost of charcoal ($/tonne)	**$365.2**	**$335.3**

Figure 2.9 shows various portable equipment costs with the capacity of the equipment. In the figure X-axis is the capacity of equipment per year and Y-axis is the $/tonne cost of production of charcoal.

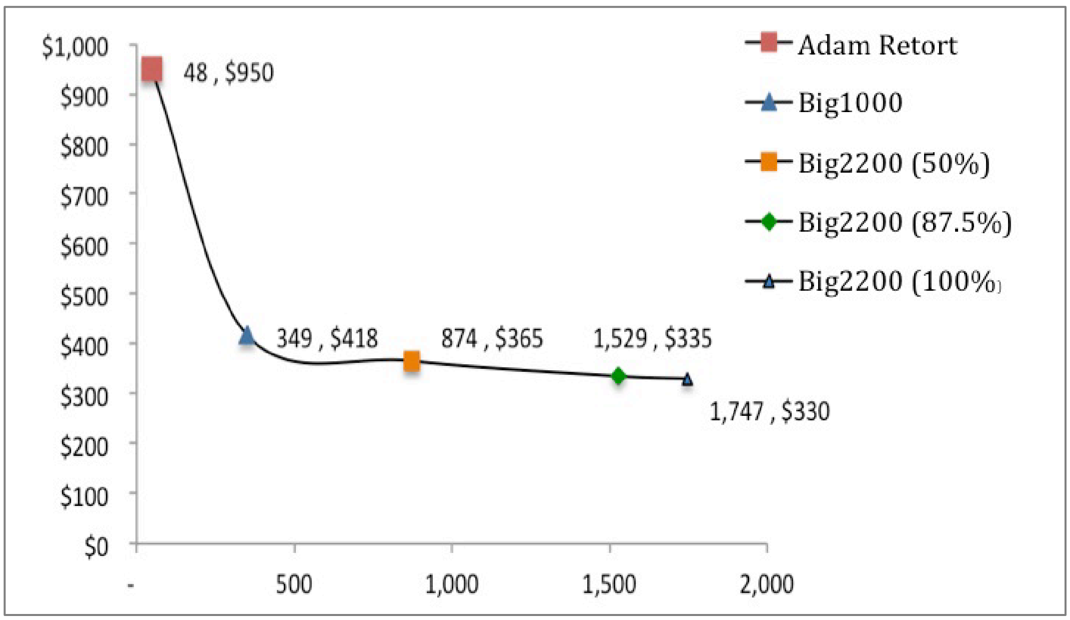

Figure 2-9: Various portable Biochar Equipment costs[1]

[1] *Detailed NPV calculation for other equipment shown in the graph is detailed in Appendix: Table A6.*

2.9 Cost of Landfilling of Charcoal

The cost of carbon sequestration through landfilling of charcoal involves three major costs: cost of production of charcoal; cost of transportation of charcoal; and cost of landfilling it. The landfilling cost is estimated as one option and another option include the spreading of charcoal in the field along with fertilizer to obtain other benefits of charcoal for plant growth. Landfilling of charcoal is considered for the case when it is produced in a centralized plant and in larger amount. The spreading of charcoal in the field is considered for the case when it is produced in portable plants and in smaller amount.

Charcoal storage at the plant for a longer time can be a significant fire hazard. To mitigate this risk we consider disposing of charcoal approximately every two-three months when its production is in a centralized plant. This leads to a landfill site to be created every two-three months of production.

The quantity of charcoal produced in one year by the centralized plant is 12,792 tonnes per year (at a 90% plant capacity factor) and is used as a basis for calculations in this study. The density of charcoal is assumed to be 300 kg/m^3 (ECN, 2010). Thus average volume of charcoal per year is 43,362 m^3.

2.9.1 Productivity Calculations

To execute the landfill digging in one pass, the dimensions of landfill should be based upon the arm length of the excavator. A detailed literature review and consultation with the industry was conducted to decide on the selection of the equipment. The medium range CAT excavators are the best suited. Caterpillar® (CAT) has a series of excavator options; they are categorized into mini, small, medium, large and ultra high demolition excavators (CAT®, 2010). The easily available CAT excavator was found to be CAT 385C-L. This was considered in this as the digging equipment. Table 2-28 give the details on the input data and assumptions used for estimating the landfilling cost of the charcoal. Equations for calculation of the productivity and cycle time are given in the appendix.

Table 2-28: Input data and assumptions for landfilling

No	Item	Value	Source/comments
1	Sand gravel density around land fill site	1317 kg/m^3	Assumption, as area for landfill is not a rocky land (SI Metric, 2010).
2	Bucket size	5 Cu. ft.	Equipment manual and based on the sand grave density (CAT®, 2000).
3	Depth of landfill	9 m	90% of arm length, suggested for optimum performance of the excavator.
4	Width of landfill	14 m	
5	Volume of the landfill	4516 m^3	Estimated based on the length, width and depth of the landfill.
6	Volume of charcoal	43,362 m^3	Average yearly production.
7	Number of landfills	10	Rounded up.
8	Gravel dump distance	10 km	Assumption.
9	Excavator cycle time	0.283 min	(CAT, 2009).
10	Truck volumetric capacity	31.4 l cycle	

Using selected excavator-truck combination, the excavation rate can be estimated. The excavation rate and the volume of material that needs to be removed give the total time required for digging the landfill. With the efficiency of 83% (50 min in hour, recommended by equipment manufacturers) (CAT, 2009) the excavation equipment is required for 7 hours. Based on this, one excavator and 14 trucks are required for transporting charcoal to a distance of 10 km for landfilling.

This study assumes that the excavation process is contracted out. Hence, the rental cost for the equipment is considered. Table 2-29 indicates the total land filling cost for the considered landfill size. These costs include the labor, equipment and fuel cost associated with the equipment.

Table 2-29: Charcoal-landfilling cost

Equipment	Number[1]	Rental cost ($/hour)[2]	Total cost ($)
Excavator	1	$300	$2,100
Trucks	14	$225	$22,050
Total digging cost (per landfill)			$24,150

[1]*Based on the calculations explained in Appendix Table: A9*

[2] *Based on rental costs from local equipment rental companies*

2.9.2 Cost of charcoal transportation

The second component of cost of landfilling is the charcoal transportation cost. The process of charcoal transport involves two stages: the loading of charcoal on trucks; and transportation of charcoal to the landfill site. Similar to the excavation, the transportation is also done through contractors.

Equations 4-1 and 4-2 (included in the appendix) can also be applied to the loader and truck. It is assumed that the transportation of charcoal is done on a weekly basis. The number of trucks required for the transportation of charcoal per week is based on the net volume of charcoal production in a week and the truck's volumetric capacity.

The total truck time required is the sum of truck loading time, dump time, and haul time and empty return time. The truck loading time is the sum of the loader cycle time and total number of loader bucket loads required to fill the truck. The detailed calculations are shown in the Table A: 9 in the appendix.

Table 2-30: Charcoal transportation cost

Items	Values	Comments
Charcoal transportation cost	\$0.1832/tonne	Five axle semi – trailer with 2200 cubic feet capacity is used for transportation of charcoal. Cost is specific for Alberta conditions and needs to be adjusted for other jurisdictions.
Loader heaped capacity	5 cy	Maximum quantity of material the loader bucket can hold. Equipment

Items	Values	Comments
		Manual (CAT, 1999)
Loader cycle time	0.28 min	Equipment Manual (CAT, 1999)
Loader production rate	1015 cy/hr.	Calculated using equation 2-1.
Loader rental cost	$300/hr.	
Loader total cost	$16,768	Total rental cost of the loading equipment

2.9.3 Charcoal production cost with landfilling cost

The landfilling cost has a significant impact on the total charcoal production costs. The landfilling is estimated based on the digging cost as estimated in Table 2-29 and charcoal loading and transportation cost as estimated in Table 2-30. Based on these costs the landfilling cost is $26.80/tonne of charcoal. Hence, the total production cost of charcoal with landfilling 332.2 $/tonne. Table A11 in the appendix gives the detail on charcoal production and landfilling cost.

In the base case, the landfill site distance of 20 km is assumed. For distances of 10 km, 20 km, 30 km and 40 km, the total charcoal landfilling costs are $332, $340, $348.1 $356 $363.9 and $371.8 tonne of charcoal.

In portable production of charcoal, it is assumed that the charcoal is spread in the field along with fertilizers. Existing equipment is used hence this case does not incur extra cost.

2.10 Conclusion

Total production cost for centralized production of cost is $306.3 per tonne for an average annual capacity of 12,729 tonnes of charcoal. Biomass related costs are major components of charcoal production cost; about 50%. Using sensitivity case studies, Charcoal yield has the maximum impact on the cost of production, while the capital cost, operational cost and transport distance have a lower impact on the production cost.

Charcoal production in portable plant costs $335.3 tonne of charcoal, with an annual capacity of 1,529 tones of charcoal. The major component of portable costs is biomass related costs contributing over 60% of production cost. Thus portable system costs lower but has lower volumes.

Charcoal production with landfilling costs is $332.2 tonne of charcoal and landfilling cost is a major component for landfilling contributing to 80% of costs.

2.11 References

Adam, J. C. (2009). Improved and more environmentally friendly charcoal production system using a low-cost retort–kiln (Eco-charcoal). *Renewable Energy,* 34(8), 1923-1925.

Adam, J. C. (2010). [Personal Communication].June, 2010

Agricultural Statistics Yearbook 2008. (2008). Edmonton, Alberta Canada: Retrieved from: http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/sdd12885.

Agriculture Statistics Yearbook. (2010). (1927-4106). Edmonton Alberta. Retrived from: http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/agdex13714

Alberta Utilities Commision. (2009). Rate and tariffs, Retrieved from: http://www.auc.ab.ca/utility-sector/rates-and-tariffs/Pages/default.aspx

Bailey-Stamler S., Samson R., & Lem, C. H. (2007). Assessing the Agri-Fibre Biomass Residue Resources for Creating a BIOHEAT Industry in Alberta. Sainte Anne de Bellevue, Quebec: Resource Efficient Agricultural Production (REAP)-Canada. Retrived from: http://www.reap-canada.com/online_library/feedstock_biomass/Assessing%20the%20

Agri-Fibre%20Biomass%20Residue....%20(Bailey-Stamler%20et%20al.,%202007).pdf

Bank of Canada. (2010). Rates and Statistics. Retrieved 1 July 2011, from: http://www.bank-banque-canada.ca/en/rates/inflation_calc.html

Best Pyrolysis Inc. (2010). Sponsored listings. Retrieved 1 August, 2010, from: http://www.bestenergies.com/companies/bestpyrolysis.html

Bigchar, T. (2009). Black is Green Pty Ltd BiGchar 2200. Retrived from: http://www.ehp.qld.gov.au/ecobiz/network/previous-forums/pdf/mackay-2011/chris-gruhler.pdf

Bio Energy LCC. (2010). Bioenergy LCC ecologically clean charcoal technologies, Russia Retrieved 1 July, 2009, from: http://www.bioenergylists.org/stovesdoc/Yudkevitch/charcoal/business.html

Biochar Engineering. (2010). BEC Biochar Sales. In B. Engineering (Ed.), *Water Resources* (Vol. v.1.0 6/25/10, pp. 25).

Brechbill, S. C., & Tyner, W. E. (2008). The Economics of biomass collection, transportation and supply to Indiana celluosic. Working Papers 08-03, Purdue University, College of Agriculture, Department of Agricultural Economics.

Campbell, C. A., & Coxworth, E. (1999). Final report on feasibility of sequestering carbon through use of crop residue for industrial products. Report to options table of *Agriculture and Agri-food table on climate change: Analysis of greenhouse gas mitigation practices, 1999.*

Campbell, K. A. (2007). A feasibility study guide for an agricultural biomass pellet company. Agricultural Utilization Research Institute. Retrived from: http://www.auri.org/wp-content/assets/legacy/research/FINAL%20FEASIBILITY%20STUDY%20GUIDE%2011-26-07.pdf

CAT. (1999). Wheel loader. In CAT (Ed.), (Vol. 3). AEHQ5657-02 (5-07) USA

CAT. (2009). Articulated truck. In CAT (Ed.), (pp. 1-20). AEHQ6031-01 (04-2009). USA

CAT®. (2000). Comparative Bulletin 320C and 320B. In CAT (Ed.), (TEJB7010 ed.).

Dassanayake, G. D. M., & Kumar, A. (2012). Techno-economic assessment of triticale straw for power generation. *Applied Energy, 98*, 236-245.

David A. Laird, Robert C. Brown, James E. Amonette, & Johannes Lehmann. (2009). Review of the pyrolysis platform for coproducing bio-oil and biochar. *Biofuels Bioproducts & Biorefining*(3), 547-562.

Deal, C., Brewer, C. E., Brown, R. C., Okure, M. a. E., & Amoding, A. (2012). Comparison of kiln-derived and gasifier-derived biochars as soil amendments in the humid tropics. *Biomass and Bioenergy, 37*, 161-168.

Development, A. A. a. R. (2010, November 2, 2011). Agriculture Statistics Yearbook, Retrieved from: http://www.agric.gov.ab.ca/flippingbook/agdex/853-10/html/index.html

E Genesis Industries. (2010). E Genesis Industries Retrieved 1 November, 2010, from: http://www.egenindustries.com/

ECN. (2010). Phyllis database for biomass and waste, Retrieved from: http://www.ecn.nl/phyllis/DataTable.asp

Elsayed M. A., & Mortirner N.B. (2001). Carbon and Energy Modelling of Biomass Systems: Conversion Plant and Data Updates. *Journal of Environmental Quality, 8*(4), 533-537.

Gaunt, J. L., & Lehmann, J. (2008). Energy balance and emissions associated with biochar sequestration and pyrolysis bioenergy production. *Environmental Science & Technology, 42*(11), 4152-4158.

Gelwicks, J. (2010). [Personal Communication]. Co-founder, Genesis Industries, March 2010.

Herla, F. (2010). [Personal Communication]. Lamboitte Brusels, Feburary 2010.

Jensen T. (2008). Food Production and Economics of fertilizer Use — Tracking the Returns in a Grain Crop. *Better Crops,* 92(3), 26-27.

Joyce, S. A. (2011). [Personal Communication]. Director, Black is Green Pty Ltd., January 2011.

Kabir, M. R., & Kumar, A. (2011). Development of net energy ratio and emission factor for biohydrogen production pathways. *Bioresource Technology,* 102(19), 8972-8985.

Kline, R. (2000). Estimating Crop Residue Cover for Soil Erosion Control. *Soil FactSheet*(641), 1-4.

Kumar, A., Cameron, J. B., & Flynn, P. C. (2003). Biomass power cost and optimum plant size in western Canada. *Biomass and Bioenergy,* 24(6), 445-464.

Kutney, G. (2010). [Personal Communication]. Gerry Kutney Chief Operating Officer, Alterna Biocarbon. Feburary 2010.

Lambiotte & Cie. (2008). Lambiotte & Cie Retrieved 1 September, 2008, from: http://www.lambiotte.com/page.php?use=62

Lang, B., & Specialist, E. C. (2002). Estimating the Nutrient Value in Corn and Soybean Stover. *Office*, 5-6.

Lehmann, J. (2009). Biological carbon sequestration must and can be a win-win approach. *Climatic Change,* 97(3-4), 459-463.

Lehmann, J., Rillig, M. C., Thies, J., Masiello, C. a., Hockaday, W. C., & Crowley, D. (2011). Biochar effects on soil biota – A review. *Soil Biology and Biochemistry,* 43(9), 1812-1836.

Liu, E. (2008). Straw Procurement business case. Retrived from: https://www.gov.mb.ca/agriculture/ri/community/pdf/straw_procurement.pdf

Mahmudi, H., & Flynn, P. C. (2006). Rail vs truck transport of biomass. *Applied Biochemistry and Biotechnology, 129-132*, 88-103.

Montross M.D., Prewitt R., Shearer S.A., Stombaugh T.S., McNeil S.G., & Sokhansanj S. (2003). *Economics of Collection and Transportation of*

Corn Stover. Paper presented at the American Society of Agricultural Engineers Annual International Meeting, no. 036081. Berkeley, California

Overend Ralph P. (2004). Thermochemical conversation of biomass. Renewable Energy Sources Charged with Energy from the Sun and Originated from Earth-Moon Interaction. Oxford ,UK: UNESCO, Eolss Publishers, Encyclopedia of Life Support Systems (EOLSS)

PayScale. (2009). Compare your Salary. Retrieved Jan 2010, from: http://www.payscale.com/

Perlack, R. D., & Turhollow, A. F. (2002). Assessmment of optionf for the collection, handling and transport of corn stover. Retrived from: http://www.ornl.gov/~webworks/cppr/y2001/rpt/113127.pdf

Perlack, R. D., Wright, L. L., Turhollow, A. F., Graham, R. L., Stokes, B. J., Erbach, D. C., & Tn, O. R. N. L. (2005). Biomass as feedstock for a bioenergy and bioproducts industry: the technical feasibility of a billion-ton annual supply. US Department of Agriculture. Retrived from: http://www1.eere.energy.gov/biomass/pdfs/final_billionton_vision_report2.pdf

Roberts, K. G., Gloy, B. A., Joseph, S., Scott, N. R., & Lehmann, J. (2010). Life cycle assessment of biochar systems: estimating the energetic, economic, and climate change potential. *Environmental Science & Technology, 44*(2), 827-833.

Sarkar, S., & Kumar, A. (2009). Tehcno-economic assessment o biohydrogen production from forest biomass in western Canada. *Transactions of the ASABE, 52*(2), 519-530.

Sarkar, S., & Kumar, A. (2010). Biohydrogen production from forest and agricultural residues for upgrading of bitumen from oil sands. *Energy, 35*(2), 582-591.

Sarkar Susanjib. (2009). *Hydrogen production from biomass.* M Sc. Thesis, Department of Mechanical Engineering, University of Alberta, Edmonton, Alberta.

Searcy, E., Flynn, P., Ghafoori, E., & Kumar, A. (2007). The relative cost of biomass energy transport. *Applied Biochemistry and Biotechnology, 137-140*(1-12), 639-652.

Sheehan, J., Aden, A., Paustian, K., Killian, K., Brenner, J., Walsh, M., & Nelson, R. (2003). Energy and environmental aspects of using corn stover for fuel ethanol. *Journal of Industrial Ecology, 7*(3/4), 117-146.

SI Metric. (2010). SI Metric Retrieved 1 August, 2010, from: http://www.simetric.co.uk/si_materials.htm

Society, E. (2012). Bio-energy in the black. *America, 5*(7), 381-387.

Sokhansanj, S., & Fenton, J. (2006). Cost Benefit of Biomass Supply and Pre-processing. *BIOCAP Canada Foundation, Kingston, Ontario, Canada* Retrived from: http://www.biocap.ca/rif/report/Sokhansanj_S.pdf

Sokhansanj, S., Mani, S., Turhollow, A., Kumar, A., Bransby, D., Lynd, L., & Laser, M. (2009). Large-scale production, harvest and logistics of switchgrass (Panicum virgatum L.)-current technology and envisioning a mature technology. *Biofuels, Bioproducts and Biorefining, 3*(2), 124-141.

Sokhansanj, S., Turhollow, A., & Wilkerson, E. (2008). Development of the integrated biomass supply analysis and logistics model (IBSAL) *Biomass and Bioenergy,* 30 (10) 838 - 847

Spath, P., Aden, A., Eggeman, T., Ringer, M., Wallace, B., & Jechura, J. (2005). Biomass to hydrogen production detailed design and economics utilizing the battelle columbus heated gasifier biomass to hydrogen production detailed design and dconomics Utilizing the dattelle columbus.NREL. Retrived from http://www.nrel.gov/docs/fy05osti/37408.pdf

Statiscs Canada. (2010). Total farm area, land tenure and land in crops, by province (Census of Agriculture, 1996 to 2006). Retrieved 10 June, 2010, from: http://www.statcan.gc.ca/tables-tableaux/sum-som/l01/cst01/agrc25a-eng.htm

Stephen, J. D. (2008). Biorefinery feedstock availablity and price variablity: Case study of the Peace River region. Retrived from: https://circle.ubc.ca/handle/2429/1008

Stumborg, M., Townley-Smith, L., & Coxworth, E. (1996). Sustainability and economic issues for cereal crop residue export. *Canadian Journal of Plant Science/Revue Canadienne de Phytotechnie, 76*(4), 669-673.

Sultana, A., Kumar, A., & Harfield, D. (2010). Development of agri-pellet production cost and optimum size. *Bioresource Technology, 101*(14), 5609-5621.

USA Inflation Calculator. (2010). USA Inflation Calculator Retrieved 1 July, 2010, from: http://www.usinflationcalculator.com/

Usda. (2009). North America ' s Wood Pellet Sector. *United Stated department of Agriculture.* Retrived from: http://www.fpl.fs.fed.us/documnts/fplrp/fpl_rp656.pdf

Várhegyi, G. b., Chen, H., & Godoy, S. (2009). Thermal Decomposition of Wheat, Oat, Barley, and Brassica carinata Straws. A Kinetic Study. *Energy & Fuels, 23*(2), 646-652.

Chapter 3 Life Cycle Energy and Emission Analysis of Charcoal Production from Biomass and its Sequestration

3.1 Introduction

The charcoal produced from agricultural biomass is landfilled that can help in sequestering of carbon in the soil. Charcoal predominantly consists of carbon and it can stay there for a long time with minimal degradation. The stability of charcoal depends upon the feedstock properties and pyrolysis process (Gaunt & Lehmann, 2008). In this study the focus is on production of charcoal from straw. Currently, most of the straw produced in Canada is left in the field to rot and ultimately it emits carbon dioxide to the atmosphere (Kumar et al., 2003; Sultana et al., 2010).

The process of production of charcoal from straw and its landfilling involves a number of unit operations. All these unit operations need energy and material inputs. Hence, it is critical to assess the amount of GHG emissions in all these unit operations. This would help in finally assessing the net carbon sequestration through this pathway. In this chapter the focus is on assessment of energy inputs and associated GHG emissions over the life cycle of the charcoal production and it's landfilling.

There are some studies done on carbon sequestration through charcoal production. Earlier studies on charcoal production use theoretical values of yield of charcoal from biomass (Gaunt & Lehmann, 2008; Hammond et al., 2011; Ibarrolaet al., 2012). In reality, the key constraint for current charcoal production equipment is capacity of the plant. The capacities of plants discussed in earlier studies are higher than any current commercially available pyrolysis equipment optimized for charcoal production. The results of the life cycle assessment of all the cases are discussed in Chapter 4.

3.2 Methodology, Scope and Limitations

In this study, the GHG emissions in various operations of charcoal production are assessed. Various studies have shown numbers for GHG emissions in agricultural activities, such as harvesting, bailing and transportation (Nagy, 1999; Sokhansanj et al., 2008). The estimation of CO_2 abatement is dependent on the quantity of carbon in landfilled charcoal (80% of charcoal). The carbon abatement cost is also calculated ($ per tonne of CO_2 mitigated) based on the production cost charcoal estimated in chapter 2.

Studies have shown that charcoal has a capacity to reduce N_2O emissions from soil (Beesley et al., 2011; Bruun et al, 2012; Bruun, et al. 2011; Loa, 2010; Rogovska et al., 2008). Currently we do not have enough data to identify the net sequestration; but this can enhance the potential of GHG mitigation through landfilling of charcoal. In addition, charcoal also enhances the plant growth and hence increases the rate of absorption of CO_2 by biomass. This additional sequestration potential of CO_2 has not been considered in this study (Bruun et al., 2011; Loa, 2010; Rogovska et al., 2008).

The net carbon mitigation in production of charcoal and its sequestration in landfill are estimated by taking into account the carbon emissions in various unit operations including harvesting and collection of straw, transportation of straw, pyrolysis of straw, transportation of charcoal and landfilling of charcoal. The carbon emissions are calculated based on the amount of fuel consumption in each of the unit operations. Table 3-1 summarizes various parameters used to calculate energy requirements and carbon emissions in various unit operations. Figure 3-1 shows the unit operations involved in life cycle assessment.

Table 3-1: Emission and energy factors

Items	Energy required (GJ/t)[1]	GHG emissions involved (Kg CO_2 eq./t)[2]	% To be land filled [3]	Source / Comments
Steel (usage 30%)	25.5	2500	25%	For material acquisition, manufacturing and transportation (ICF Consulting, 2005)
Recycled steel (usage 70%)	9.7	1820		
Aluminum	120.3	3470	100%	
Landfilling	0.08	7.45		Based on transportation of charcoal to a distance of 200 km for landfilling(ICF Consulting, 2005).
Concrete	0.87	120	100%	Includes procurement, processing, and transportation of concrete (Flower & Sanjayan, 2007; Horvath, 2004)
Diesel	51.5	4.1		Values for IL of diesel combustion ((S&T)2 Consultants Inc., 2009; Elsayed et al., 2003; ICF Consulting, 2005)

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[1]*Energy required in GJ per tonne of raw material consumption due to its manufacturing, transportation, acquisition and other related operations.*

[2]*GHG emissions involved in per tonne of raw material consumption (manufacturing, transportation, acquisition and other related operations).*

[3]*This column indicates the % of material that is assumed to be landfilled after the plant is decommissioned.*

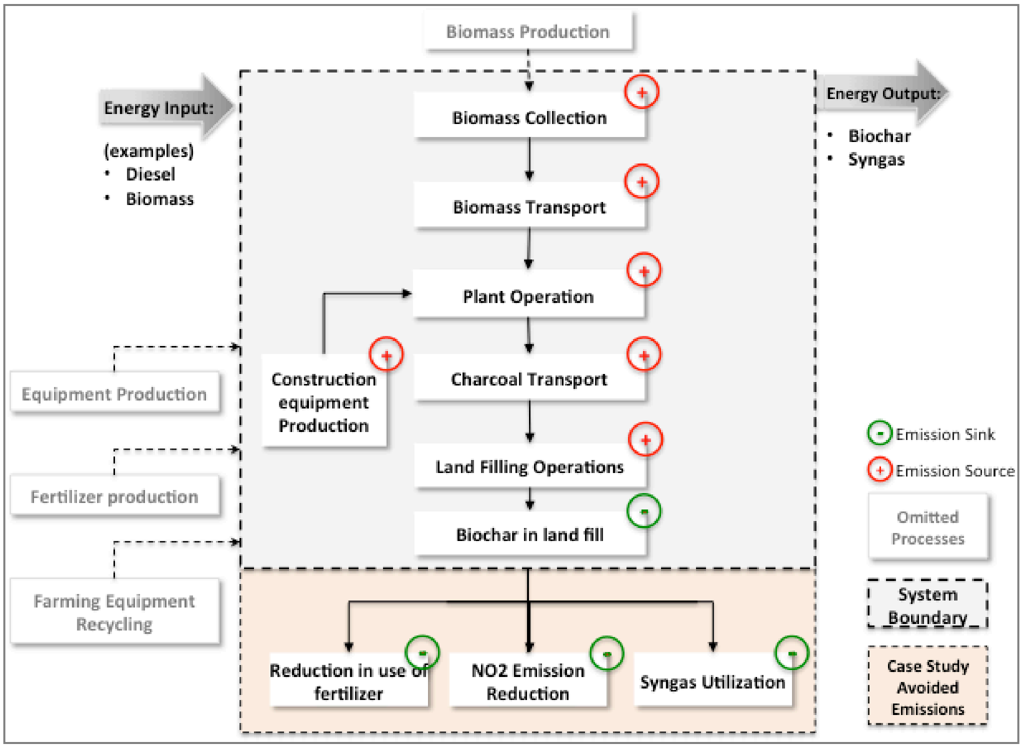

Figure 3-1: LCA and energy methodology

3.3 Life Cycle Assessment for Production of Charcoal

The life cycle assessment (LCA) of the pathway for production of charcoal and its landfilling would help in assessing the net impact of the process on the environment. This study is based on the LCA methodology documented in ISO 14040 and ISO 14044. The overall process of LCA follows three steps as defined by the standard and these include: goal and scope definition, inventory analysis and impact assessment.

3.3.1 Goal and Scope

The LCA is used in this study to determine the net carbon sequestered in the soil through conversion of agricultural biomass to charcoal and it landfilling. The GHG emitted in each of the unit operations involved in this pathway has also been considered in determining the net carbon sequestration. The results of this study would help in comparative assessment of this pathway of sequestration of carbon with other pathways of carbon sequestration based on other renewable energy processes.

3.3.1.1 Key Objectives

The overall objective of this study is to assess the total carbon sequestration in the conversion of agricultural biomass to charcoal and its sequestration in the landfill. The specific objectives are:

- Determination of life cycle energy consumption in production of 1 tonne of charcoal from agricultural biomass and its landfilling;
- Determination of net energy ratio (NER) for this pathway where the NER of the system is defined as the energy produced divided by the life cycle fossil fuel energy consumption. (Kabir et al. 2012; Keoleian & Volk, 2005)
- Quantification of GHG emissions in production of 1 tonne of charcoal from agricultural biomass and its landfilling;
- Determination of GHG emissions over the life cycle of charcoal from agricultural biomass considering all the unit operations involved in this pathway.

3.3.1.2 Functional Unit

The primary purpose of the functional unit is to provide a reference to compare the inputs and outputs of the different unit operations. In this study one tonne of C is the functional unit.

3.3.2 Unit Processes

The overall charcoal production and landfilling pathway is divided into five major unit operations over the life cycle. These include: straw processing (UP1), straw transport (UP2), plant operations & charcoal production (UP3), charcoal transport (UP4) and landfilling of charcoal (UP5). These major unit operations have several sub-unit operations. The GHG emissions have been assessed for all these unit operations. The system omits processes for production of biomass as it is assumed that existing straw is used. Figure 3.2 shows the detailed unit operations involved in production of charcoal from straw and it's landfilling.

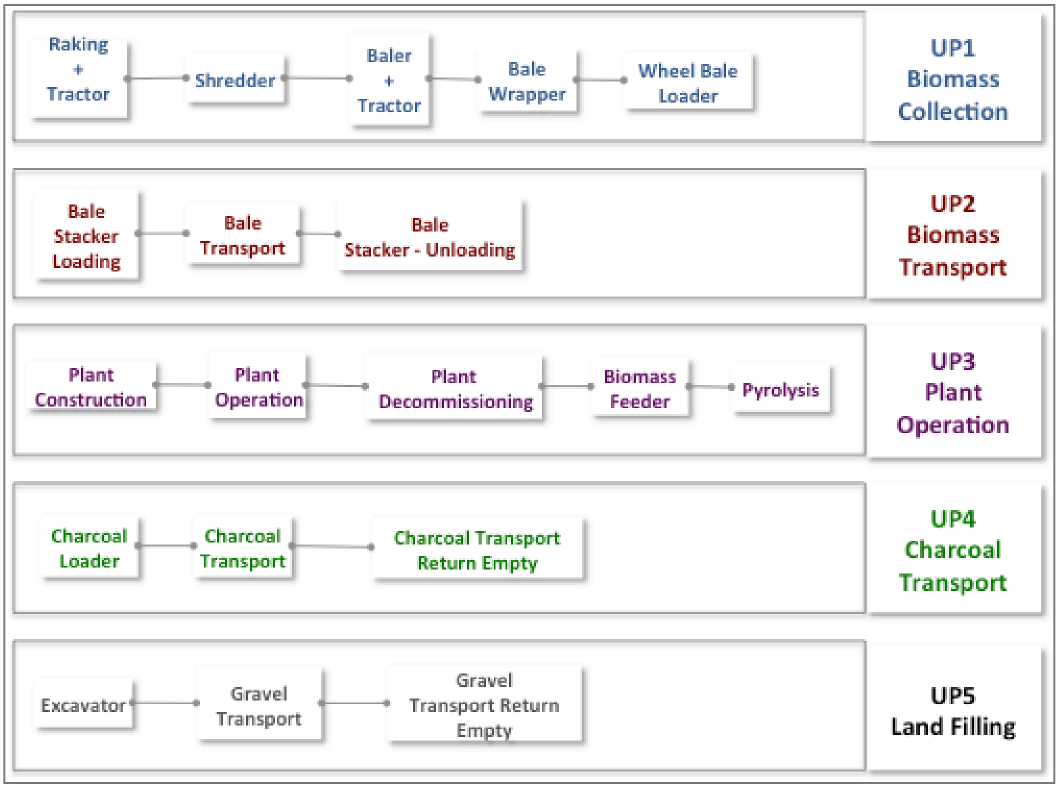

Figure 3-2: Unit operations involved in charcoal production from agricultural biomass.

3.4 Impact Assessment (Central Production System)

3.4.1 Straw Harvesting, Collection and Processing (UP1)

This study focuses on utilization of straw from wheat, barley and grains for production of charcoal. Under current practice in Western Canada, farmers remove the grains from the field and leave the straw in the field to rot. Some straw is used for bedding and other applications but the level of utilization is very small compared to the total volume of straw produced (Sultana et al., 2010). Harvesting of straw involves raking, baling, tarping/stringing and road siding. This study has assumed zero-till system since it is environment friendly and cost efficient (Tillage, 2012).

The total amount of straw harvested per year depends on the size of the charcoal production plant. In the LCA study, the size of the charcoal production is assumed to be the same as discussed in Chapter 2. The total production capacity of charcoal from straw is 13,009 tonnes per year based on earlier calculation for a centralized system. The average harvested area for production of 13,009 tonnes of charcoal is 196,774 ha.

The LCA analysis assumes conventional equipment, which is used for harvesting in Western Canada, and data has been collected from earlier studies. Wherever possible, the largest size of the machinery has been considered to get better processing efficiency. The assumption in this study is that the baler picks up the straw and produces rectangular bales (4′ x 4′ x 8′). After baling, the automatic bale collector collects the bales and puts them into the side of the field. In section 2.5.1 of this thesis, various equipment costs have been determined. These calculations were based on the hours required by equipment to complete the process for the selected size of the plant. Equipment fuel requirements were determined from earlier studies (Sokhansanj et al., 2008; Nagy, 1999). Table 3.2 gives the detail on energy requirement and GHG emissions for straw collection and processing.

Table 3-2: Energy and emission for UP1

	Operation	Total time required (hours)[1]	Fuel Economy (gallons/ hour) [2]	Energy required (GJ)[3]	Emissions (Kg of CO_2)
1.1	Shredding	21,885.7	9.86	42,068	3,349,140
1.2	Tractor for Shredder	21,885.7	5.26	22,442	1,786,661
1.3	Rake	20,843.5	3.72	15,116	1,203,400
1.4	Baler	33,670.2	15.33	100,626	8,010,972
1.5	Tractor for Bailer	33,670.2	5.26	34,526	2,748,709
UP1	Straw Collection and Processing	131,955		214,779	17,098,882

3.4.2 Straw Transport (UP2)

Transportation of biomass is a critical unit operation. In this study, it is assumed that straw is collected from a circular area. The transportation distance, as discussed in chapter 2, is the radius of a circular area with plant located at the center. The total amount of straw required by the charcoal plant depends on the size of the plant. Hence the area and radius of the field are proportional to the size of the plant. For GHG emission calculations, average yield of straw was considered. The average yield of straw is 0.75 tonnes/ha as given in chapter 2. Based on this yield, a total area of 196,774

[1]*Total amount of time required by each step is calculated previously in section 2.5.1.*

[2] *Fuel economy is obtained from (Sokhansanj et al., 2008).*

[3] *Energy and emission calculations are based on factors using Table 3-1: Emission and energy factors.*

ha and radius of 21.19 km is estimated. Table 3.3 gives the energy and GHG emissions for straw transport.

Table 3-3: Energy and GHG emissions for UP2

	Operation	Total time required (hours)[1]	Fuel Economy (gallons/ hour)[2]	Energy required (GJ)[3]	Emissions (Kg of CO_2)
2.1	Loader field	2550.8	14.81	7,365	586,306
2.2	Biomass loading	2550.8	3.5	1,740	138,560
2.3	Biomass truck transport	69660.5	24.09	327,147	26,044,734
2.4	Unloaded	2040.6	3.5	1,392	110,848
UP2	Straw transport (Sub-total)	76802.6		337,645	26,880,447

3.4.3 Plant Construction, Operation and Commissioning (UP3)

3.4.3.1 Plant Construction

Energy and GHG emissions in production of the materials used for the construction of the plant have been studied to determine the GHG emissions in overall plant construction. Primary energy inputs and GHG emissions during the plant construction is difficult to determine and can be considered negligible compared to the construction materials embodied impacts.

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[1]*Total amount of time required by each step is calculated previously in section 2.5.2.*

[2] *Fuel economy is obtained from (Sokhansanj et al., 2008)*

[3]*Energy and emission calculations are based on factors using Table 3-1: Emission and energy factors multiplied by fuel consumption*

Various earlier studies such as LCA of natural gas combined power generation system (Mann & Spath, 2000), hydrogen production via natural gas steam reforming (Mann & Spath, 2001), bio-hydrogen production (Kabir & Kumar, 2011) and power production from triticale (Dassanayake, 2011) were used to approximate the plant size and material required. GHG emissions and energy requirements for plant construction are detailed in Table 3-4: Energy and GHG emissions for plant operations (UP3)

3.4.3.2 Plant Operation

Energy input and GHG emissions involved during plant maintenance is found to be 2.5 to 5% of the plant construction energy and GHG emission (Elsayed et al., 2003). For this study, it is considered that the GHG emissions are 3% (assumption) of the plant construction.

Pyrolysis: It is assumed that CO_2 emissions during biomass conversion step are balanced by the CO_2 absorbed during the phases of its growth (Gupta, 2010; Roberts et al., 2010). Hence, GHG emissions during energy conversion stage of straw (pyrolysis) have been disregarded. No fossil fuel or electricity needed to operate a pyrolysis plant (Ringer et al., 2006).

Biomass feeding mechanism: A chain conveyer is used to transfer biomass to the pyrolysis equipment. The equipment is a chain conveyer with a capacity of 50 dt/hour and fuel consumption of 2.19 gallons/hour (Sokhansanj et al., 2006). The total hours required for this operation was calculated previously in section 2.5.3.

3.4.3.3 Plant Decommissioning

For all plants, the decommissioning impact is assumed to amount to 3% of the construction impact (Dassanayake & Kumar, 2012; Kabir et al., 2012). After decommissioning, materials are transported by truck for 50 km to a landfill. Inventory data for the truck are given above. All non-recyclables are landfilled at a distance of 50 km from the plant. Only 25% of the steel used is landfilled while all the other materials are 100% landfilled (ICF Consulting, 2005).

Table 3-4: Energy and GHG emissions for plant operations (UP3)

Material required in plant construction	Amount of material required (tonnes)	Energy required (GJ)[1]	GHG emissions (Kg of CO_2 eq.)
Plant Construction[2]			
Concrete	967.72	842	116,126
Steel	307.20	4,436	621,767
Aluminum	2.02	243	7,008
Total (plant construction)		**5,521**	**744,901**
Plant Operation			
3% of Construction		**166**	**22,347**
Plant Decommissioning			
Land filling concrete	100%	77	116,126
Land filling steel	25%	6	572
Land filling aluminum	100%	0.16	15
Decommissioning process 3% of construction		221	29,796

3.4.4 Transportation (UP4) and Landfilling of Charcoal (UP5)

The volume of charcoal produced in a year is 13,009 tonnes. The transportation of charcoal is described in section 2.9.2 of this thesis. The

[1]*Energy and emission calculations are based on parameters using Table 3-1: Emission and energy factors.*

[2]*Materials required for the construction of the size of the charcoal production plant considered in this study were estimated based on data from earlier studies and also adjusted using a scale factor of 0.76 (Anex et al., 2010; Gaunt & Lehmann, 2008; Kabir et al., 2012; Mann & Spath, 2001).*

landfilling operation requires two machines: an excavator and a truck to transport gravel, as described in section 2.9. GHG emissions are calculated based on the amount of fuel used by equipment. The amount of fuel is dependent on the duration that equipment takes to operate. In case of trucks, GHG emissions are calculated for hauling as well as for the waiting time while loading or unloading of gravel or charcoal. Table 3.5 gives details on transportation and landfilling.

Table 3-5: Energy and emission calculation for UP4 and Up5

	Operation	Total time required[1] (hours)	Fuel economy (L/hour)[2]	Energy required (GJ)[3]	GHG emissions (kg of CO_2)
4.1	Charcoal Loader	446.3	20	1,740	138,518
4.2	Truck Transport	25,72.5	16	8,024	638,811
UP4	Charcoal Transportation (Sub-total)	82,270		9,764	777,328
5.1	Excavator	673.7	25.15	3,303	262,986
5.2	Dump gravel (loading + travel + unloading)	6,851.1	16	21,370	1,701,287
UP5	Land-filling	7,524		24,673	1,964,273

[1] *Total amount of time required by each step is calculated previously in section 2.9.*

[2] *Fuel economy is obtained from CAT®(2000 & 2010) and Sokhansanj et al(2008).*

[3] *Energy and GHG emissions calculations are based on factors using Table 3-1: Emission and energy factors and are multiplied by fuel consumption.*

3.5 Energy and Emission Analysis

The above steps determine the net fuel consumption for each unit processes production of biomass-based charcoal. Figure 3-3[1] summarizes the results for the GHG emissions and energy consumptions for each unit process. Straw transport contributes to 56% of the GHG emissions followed by straw processing (36%). The total average fuel consumption per year is 2,452,358 liters of diesel, which amounts to the GHG emissions of 9951 tonnes of CO_2 per year. Biomass-based charcoal consists of 80% carbon (ECN, 2010; Lehmann, 2007; Roberts, Gloy, Joseph, Scott, & Lehmann, 2010), thus using molecular weight of carbon dioxide we can estimate the amount of carbon sequestered.

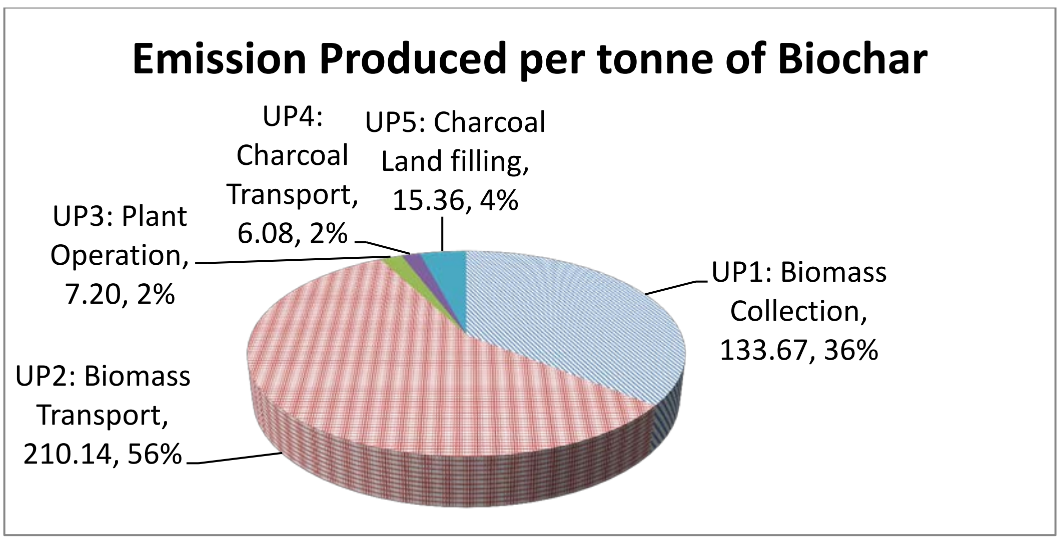

Figure 3-3: GHG emissions source break-up

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[1] *The values in pie charts for emission are in the format (UP, KgCO2eq per tonne of biochar, % share) for emission and are (UP, GJ/tonne of biochar, % Share) for energy consumed.*

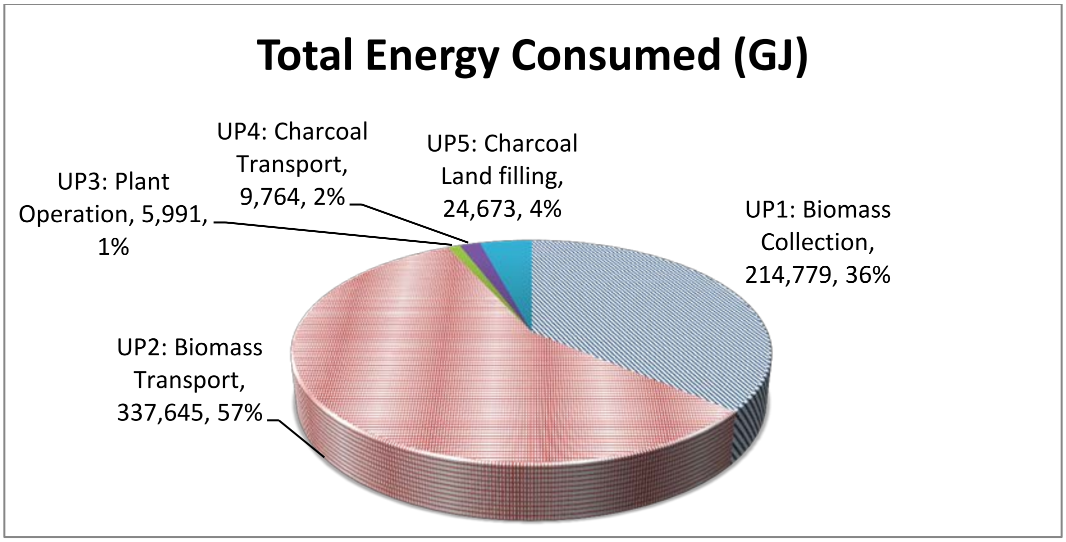

Figure 3-4: Energy consumption in Charcoal production

The net carbon sequestered is 7,691 tonne per year. Thus efficiency in mitigation is calculated as per Equation 3-1.

Equation 3-1 Efficiency of Carbon Mitigation

$$\eta_{mitigation} = \ (C_p - C_f)/(C_p)$$

Where: $\eta_{mitigation}$ is plant efficiency of carbon mitigation, C_p is carbon content in biomass-based charcoal and C_f is carbon consumed due to use of fossil fuel. The carbon mitigation efficiency including the landfilling operation is about 87%.

3.5.1 Energy Ratio

The net energy of the system is defined as the energy produced in the form of charcoal divided by the life cycle fossil fuel energy consumption (Kabir & Kumar, 2011; Kabir et al., 2012; Keoleian & Volk, 2005). This value gives the utilization effectiveness of fossil fuel consumption. It can be used as a benchmark to compare other GHG mitigation pathways. Life cycle efficiency on the other hand is a measure of overall system efficiency. It is basically total output energy in form of charcoal to total fossil fuel input energy. The calorific value of charcoal is assumed to be 28 MJ/Kg (ECN, 2010), this is used to calculate net energy ratio. Total energy consumed during production is 592,852 GJ while the total energy produced in form of charcoal is 3,581,701 GJ. Hence, the net energy ratio is 5.041.

3.6 Emission and Energy Analysis of Portable System

3.6.1 Impact Assessment

3.6.1.1 Straw Harvesting Collection and Processing (UP1)

GHG emission and energy calculations are done as described in section 3.4. The in-depth calculations have been shown in Table A12.

3.6.1.2 Straw Transport (UP2)

Portable system eliminates a major unit operation compared to the centralized system. This is biomass transport to the conversion plant. As concluded in previous (section 3.5) biomass transport contributes to over 50% of energy consumption and emissions involved in charcoal production. Hence, UP2 is not considered for portable system.

3.6.1.3 Plant Construction, Operation and Decommissioning (UP3)

The GHG emissions in plant construction, operation and decommissioning have also been not considered in the portable production. As the portable equipment travels to the field for processing, emissions and energy consumption in plant set-up is also omitted.

3.6.1.4 Transportation (UP4) and Land Filling Biochar (UP5*)*

The quantities of charcoal produced in the portable equipment are much lower as compared to centralized production (5% to 20% of average yearly production). The charcoal is not landfilled but spread in the field along with fertilizers at no extra cost. It is assumed that this operation is performed with existing farming equipment hence there is no new energy consumption or emissions involved. As the equipment travels to the field and charcoal is spread in the field, any special transporting equipment is not required.

3.6.2 Energy and GHG emission Results for Portable System

Table 3-6 summarizes the results from energy and emission calculations. In comparison to base case the NER increases to 14.4 (5.01 for centralized) and mitigation efficiency increases to nearly 100% (87% for centralized production).

Table 3-6: Energy and GHG emissions for portable systems[1]

Equipment	Charcoal production (tonnes/year)	Net emission reduction (Kg of CO_2 eq.)	NER	Net carbon sequestered (tonne)
BIG 22 12 HRS	1,310	3,839,878	14.4	1,048
BIG 22 21 HRS	2,293	6,719,786	14.4	1,835
BIG22 24 HRS	2,621	7,679,755	14.4	2,097
ADAM	48	141,710	15.3	39
BIG 1000	524	1,535,952	14.7	419

3.7 Sensitivity Cases

The impact of variation in input parameters on net GHG emissions and NER during production of charcoal has been estimated. Table 3.7 shows the results of the sensitivity cases evaluated to understand the impact of variation of different parameters on energy and emissions.

Charcoal Yield: The charcoal yield is a critical characteristic of the charcoal producing equipment. It has a significant impact on the energy produced in form of charcoal. Under current specification of equipment and quality of biomass, it is assumed to be 30%. The values for analysis range from theoretical values of 15% to 35%.

Straw to grain ratio: The ratio impacts biomass yield, higher ratio results in higher yield of straw per unit area of biomass harvested. As a result, the

[1] *Detailed calculations are discussed in Appendix tables: 12, 13 and 14.*

transportation distance for straw is lower for higher yields. Lower distance results in lower GHG emissions compared to the base case. Various studies have suggested values for straw-to-grain ratio. The range of values is from 0.8 to 2.

Heating Value of Charcoal: Charcoal's heating value determines the energy output of the system. Charcoal properties are dependent upon the feedstock properties and the pyrolysis process parameters.

Charcoal Loss in Transportation: Charcoal is transported to landfill site using a loader and a truck, as explained in section 2.9. The base case assumed 0% losses in charcoal handling and transportation. For the sensitivity analysis, range of handling losses is assumed to be 5% to 25%.

Biomass Transportation Distance: As described before the study assumes a circular field and the plant draws biomass from the area around it. The radius of the circular area is the transportation distance for biomass. As discussed earlier in cost and energy analysis, UP2 biomass transport contributes to more than 50% of emissions in production of charcoal. Thus the impact of biomass transport is studied by varying the distance of transport from 20 to 220 km.

Charcoal Transportation Distance: The location of landfill site for charcoal can vary. The base case assumes a distance of 20 km. The impact of charcoal transport is studied by varying the distance of its transport from 20-220 km.

Table 3-7: Sensitivity study results[1]

Parameter	Range[2]	% Change in net carbon sequestration[3]	% Change in NER
Charcoal yield	15% to 35%	-57% to +19%	-58% to 19%
Straw to grain ratio	0.88 to 2	-3% to +3%	-19% to 32%
Heating value of charcoal	24 to 30 MJ/Kg	No change	-17% to 9%
Biochar loss in transportation	25% to 5%	-28% to 6%	-29% to -6%
Biomass transportation distance	220 km to 20 km	-78% to –16%	-101% to -63%
Biochar transport distance	220 km to 20 km	-1% to 0%	-10% to -2%

The net impact of all above parameters on carbon sequestration and NER are showed in Figure 3-5 and Figure 3-6. Variation in charcoal yield and biomass transportation distance has large impact on the net carbon sequestration, while charcoal transportation distance has a negligible impact. Variation charcoal yield and straw to grain ratio also have a substantial impact on NER for the system.

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[1] *The detailed calculations for each case have been attached in the appendix.*

[2] *Range indicates the extreme values for the selected parameter in consideration.*

[3] *Indicates the corresponding percentage change with respect to the base case values at the end values of the range.*

3.8 Conclusion

Energy and emission calculations have been done on basis of a functional unit of per tonne of charcoal, the overall processes are divided in five unit processes (UP) straw processing (UP1), straw transport (UP2), plant operations & charcoal production (UP3), charcoal transport (UP4) and landfilling of charcoal (UP5). Net CO_2 mitigated is 7691 tonne/year. UP2 contributed to 56% of total emissions and UP1 contributed on 36%. Efficiency of mitigation for centralized production of charcoal was 87%. Net energy ratio (NER) for centralized production was 5.04.

With portable production of charcoal the mitigation potential is directly proportional to volume of production, and average NER is 14.1.

Various sensitivity cases were analyzed; biomass transportation has a huge impact on carbon sequestration, as longer the travel distance lower the mitigation potential. Charcoal yield and biochar loss in transport have significant impact on carbon mitigation.

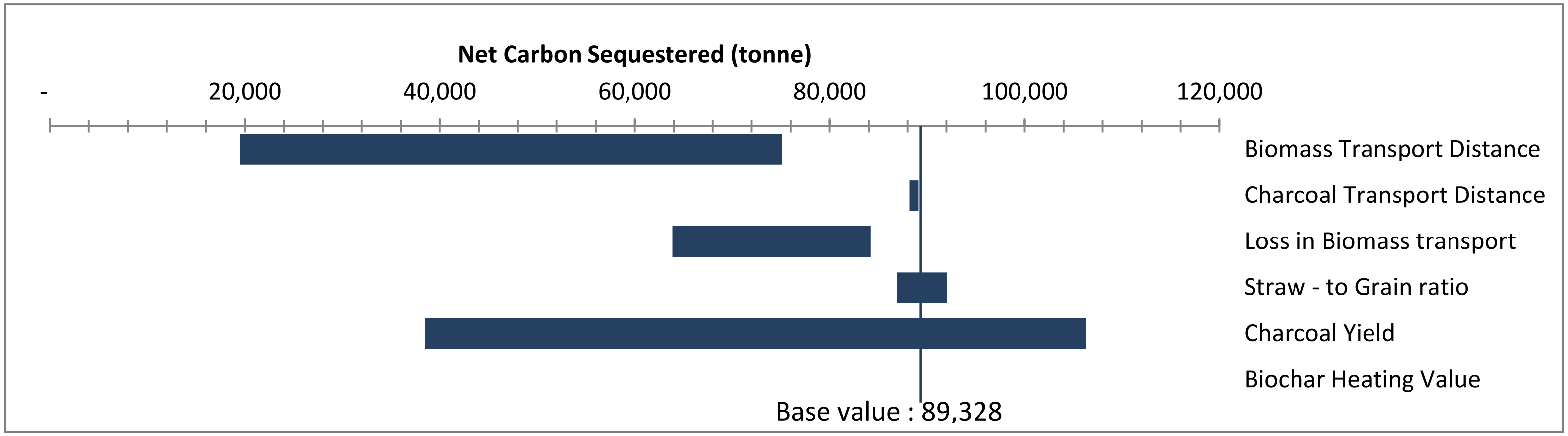

Figure 3-5: Impact on Net carbon sequestration

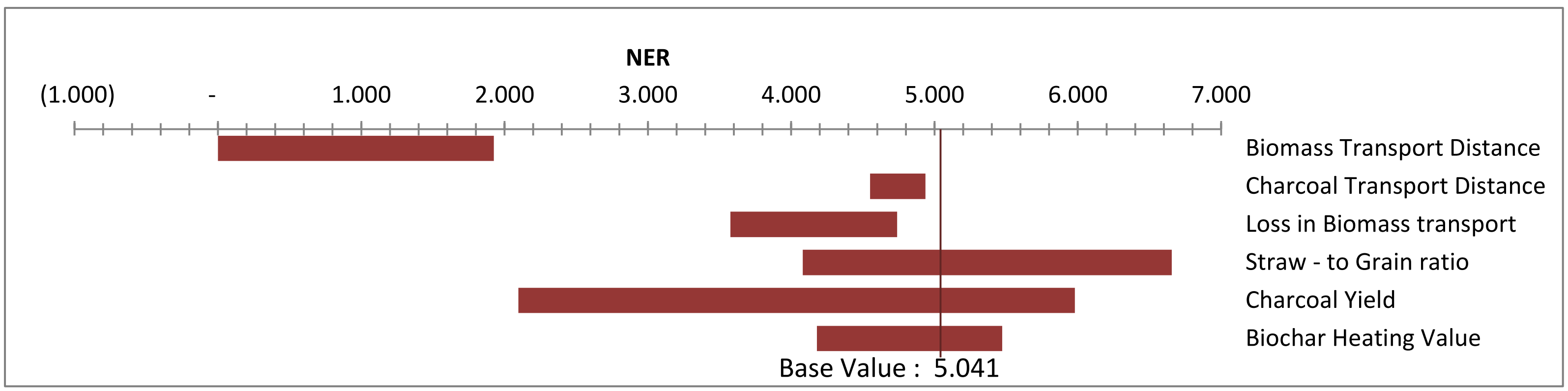

Figure 3-6: Impact on NER

3.9 References

Anex, R. P., Aden, A., Kazi, F. K., Fortman, J., Swanson, R. M., Wright, M. M., Dutta, A. (2010). Techno-economic comparison of biomass-to-transportation fuels via pyrolysis, gasification, and biochemical pathways. *Fuel, 89*, S29-S35.

Beesley, L., Moreno-Jiménez, E., Gomez-Eyles, J. L., Harris, E., Robinson, B., & Sizmur, T. (2011). A review of biochars' potential role in the remediation, revegetation and restoration of contaminated soils. *Environmental Pollution (Barking, Essex : 1987),* 159(12), 3269-3282.

Bruun, E. W., Ambus, P., Egsgaard, H., & Hauggaard-Nielsen, H. (2012). Effects of slow and fast pyrolysis biochar on soil C and N turnover dynamics. *Soil Biology and Biochemistry,* 46, 73-79.

Bruun, E. W., Müller-Stöver, D., Ambus, P., & Hauggaard-Nielsen, H. (2011). Application of biochar to soil and N2O emissions: potential effects of blending fast-pyrolysis biochar with anaerobically digested slurry. *European Journal of Soil Science, 62*(4), 581-589.

CAT®. (2000). Comparative Bulletin 320C and 320B. In CAT (Ed.), (TEJB7010 ed.)

CAT®. (2010). CAT - Hydrolic Excavators. In CAT (Ed.)

Dassanayake, G. D. M. (2011). *Utilization of Triticale Straw for Power Generation.* M.Sc. Thesis, Department of Mechanical Engineering, University of Alberta, Edmonton, Alberta.

Dassanayake, G. D. M., & Kumar, A. (2012). Techno-economic assessment of triticale straw for power generation. *Applied Energy,* 98, 236-245.

ECN. (2010). Phyllis database for biomass and waste., Retieved from: http://www.ecn.nl/phyllis/DataTable.asp

Elsayed, M. A., Matthews, R., & Mortimer, N. D. (2003). *Carbon and energy balances for a range of biofuels options*. Retrived from: http://webarchive.nationalarchives.gov.uk/+/http://www.berr.gov.uk/files/file14925.pdf

Flower, D. J. M., & Sanjayan, J. G. (2007). Green house gas emissions due to concrete manufacture. *International Journal of Life Cycle Assessment, 12*(5), 282-288.

Gaunt, J. L., & Lehmann, J. (2008). Energy balance and emissions associated with biochar sequestration and pyrolysis bioenergy production. *Environmental Science & Technology, 42*(11), 4152-4158.

Gupta S. (2010). A practical way out of the GHG emissions problem. *Journal of Canadian Petroleum Technology*. 33-42

Hammond, J., Shackley, S., Sohi, S., & Brownsort, P. (2011). Prospective life cycle carbon abatement for pyrolysis biochar systems in the UK. *Energy Policy, 39*(5), 2646-2655.

Horvath, A. (2004). Construction materials and the environment. *Annual Review of Environment and Resources, 29*, 181-204.

Ibarrola, R., Shackley, S., & Hammond, J. (2012). Pyrolysis biochar systems for recovering biodegradable materials: A life cycle carbon assessment. *Waste Management (New York, N.Y.), 32*(5), 859-868.

ICF Consulting. (2005). Determination of the impact of waste management activities on greenhouse gas emissions: 2005 Update.

Kabir, M. R., & Kumar, A. (2011). Development of net energy ratio and emission factor for biohydrogen production pathways. *Bioresource Ttechnology,* 102(19), 8972-8985.

Kabir, M. R., Rooke, B., Dassanayake, G. D. M., & Fleck, B. A. (2012). Comparative life cycle energy, emission, and economic analysis of 100 kW nameplate wind power generation. *Renewable Energy,* 37(1), 133-141.

Keoleian, G. A., & Volk, T. A. (2005). Renewable energy from willow biomass crops: life cycle Energy, Environmental and Economic Performance. *Critical Reviews in Plant Sciences,* 24(5-6), 385-406.

Kumar, A., Cameron, J. B., & Flynn, P. C. (2003). Biomass power cost and optimum plant size in western Canada. *Biomass and Bioenergy,* 24(6), 445-464.

Lehmann, J. (2007). Biochar for mitigating climate change: carbon sequestration in the black. *Forum Geookol,* 18(2). 15-17

Mann M.K., & Spath P.L. (2000). Life cycle assessment of a natural gas combined-cycle power generation sSystem. Report No. DE-AC36-99-

GO10337, National Renewable Energy Laboratory (NREL), Golden, Colorado, USA.

Mann M.K., & Spath P.L. (2001). Life Cycle Assessment of Hydrogen Production via Natural Gas Steam Reforming. Retrived from: http://www-pord.ucsd.edu/~sgille/mae124_s06/27637.pdf

Nagy, C. N. (1999). Energy Coefficients for Agriculture Inputs in Western Canada Canadian Agricultural Energy End-Use Data Analysis Centre. *Agriculture*

Ringer M., Putsche V., & J., S. (2006). Large-Scale Pyrolysis Oil Production: A Technology Assessment and Economic Analysis. *National Renewable Energy Laboratory.* (NREL), Golden, Colorado, USA.

Roberts, K. G., Gloy, B. A., Joseph, S., Scott, N. R., & Lehmann, J. (2010). Life cycle assessment of biochar systems: estimating the energetic, economic, and climate change potential. *Environmental Science & Technology,* 44(2), 827-833.

Rogovska, N., Fleming, P., & Laird, D. (2008). Greenhouse gas emissions from soils as affected by addition of biochar. Retrived from: http://www.biochar-international.org/images/Rogovska_et_al..pdf

Sokhansanj, S., Kumar, a., & Turhollow, a. (2006). Development and implementation of integrated biomass supply analysis and logistics model (IBSAL). *Biomass and Bioenergy,* 30(10), 838-847.

Sokhansanj, S., Turhollow, A., & Wilkerson, E. (2008). Development of the integrated biomass supply analysis and logistics model (IBSAL) *Biomass and Bioenergy,* 30 (10) 838 – 847.

Sultana, A., Kumar, A., & Harfield, D. (2010). Development of agri-pellet production cost and optimum size. *Bioresource Technology, 101*(14), 5609-5621.

Tillage, A. R. (2012). Alberta Reduced Tillage Linkages Retrieved 1 September, 2011, Retrieved from: http://www.reducedtillage.ca/article445.aspx

Chapter 4 Conclusion and Future Work

4.1 Conclusion

Biomass utilization for production of fuels and chemicals has lower carbon footprint compared to fossil fuels. Biomass could be forest-based as well as agricultural-based. In this study the focus is on agricultural biomass. Several GHG mitigation pathways based on utilization of biomass have been studied earlier. This study is focused on utilization of agricultural biomass i.e. straw for production of charcoal and landfilling of charcoal for sequestration of carbon.

This study was aimed at conducting techno-economic assessment of conversion of straw to charcoal and it's landfilling for sequestration of carbon. This research involved development of data intensive techno-economic models including various cost parameters and characteristics of the conversion system. A life cycle assessment of this pathway was also performed to estimate the net energy ratio and net GHG emission of this pathway. The techno-economic model was developed for two scenarios, a decentralized system and a centralized production system. The main objective was to estimate the cost of production of charcoal for both these systems. The cost was also estimated for landfilling of charcoal. The cost of production and landfilling of charcoal and the net GHG emission of this pathway were used to estimate the GHG abatement cost (\$/tonne of CO_2) for this pathway.

The methodology for estimation of cost of production of charcoal and its landfilling included development of capital cost, field cost, collection cost, transportation cost, operational cost and landfilling cost. Various equipment were assessed for both the centralized and decentralized scenarios. The key results from the techno-economic models are summarized in Table 4-1. In both scenarios biomass costs for the major cost component of charcoal production around 50%, followed by capital cost involved. The total cost of production for centralized production is $332.2 per tonne of charcoal produced including landfilling operation. The total production cost of portable system is $335.3 per tonne of charcoal produced. Although the costs of the centralized and portable systems are similar, the portable system does not include landfilling cost.

Various parameters were analyzed for performing sensitivity analysis; charcoal yield has a maximum impact on the cost followed by capital cost and biomass transport cost.

The net carbon mitigation in production of charcoal and its sequestration in landfill are estimated by taking into account the carbon emissions in various unit operations including harvesting and collection of straw, transportation of straw, pyrolysis of straw, transportation of charcoal and landfilling of charcoal. All measurable direct and indirect fossil fuel-based energy forms were included in the life cycle analysis. Table 4-2 summarizes the results for energy and emission calculations.

Table 4-1: Summary of results

Cost Parameter	Centralized System - BigChar 4800 12792 tonnes/Year		Decentralized System - BigChar 2200 2692 tonnes /year	
	$/tonne of Charcoal	% contribution	$/tonne of Charcoal	% contribution
Nutrient Replacement	83.45	25.3%	119.11	36.1%
Feild Cost	66.48	20.1%	94.87	28.7%
Capital Cost	52.56	15.9%	39.92	10.6%
Biomass Transp. Cost	36.53	11.1%	4.0	1.2%
Premium to fuel owner	23.76	7.2%	28.70	8.7%
Landfilling	20.33	6.2%	N/A	
Administrative Cost	13.47	4.1%	N/A	
Operation Cost	10.10	3.1%	23.81	7.2%
Biomass Storage Cost	8.13	2.5%	11.61	3.5%
Maintenance Cost	7.93	2.4%	1.75	0.5%
Charcoal Transportation	5.36	1.6%	N/A	
Conveyer Cost	1.09	0.3%	1.56	0.5%
Power Cost	0.95	0.3%	N/A	
Truck Transport Cost	N/A		9.9	3.0%
Total Cost	**332.00**		**335.3**	

Emissions are represented per tonne of charcoal produced. Straw processing UP1 and straw transport UP2 contribute to maximum emissions in production cycle. Thus the, portable system has higher net emissions reduction potential per tonne of charcoal. Table 4-2 indicates the energy consumption in each stage of charcoal production. Corresponding to emissions energy consumption is highest in straw related operations. The net energy ratio is 5.2 for centralized production and 14.1 for portable system.

High-energy ratio indicates higher efficiency for portable system.

Table 4-2: Results for energy and emission calculation

Unit Processes	**Emission produced per tonne of biochar**		**Total Energy consumed**	
	$KgCO_2eq$/tonne		**GJ**	
	Central	Portable	Central	Portable
UP1: Straw processing	133.67	141.8	214,779	4,669
UP2: Straw Transport	210.14	0	337,645	0[a]
UP3: Charcoal Production	7.20	2.7	5,991	87
UP4: Charcoal Transport	6.08	0	9,764	0[a]
UP5: Charcoal Land filling	15.36	0	24,673	0

[a] These would very small amount as the transportation is in the farm itself.

In conclusion, production and sequestration of charcoal produced from biomass helps in sequestration of carbon and can contribute significantly to efforts of reducing GHG emissions. Table 4-3 indicates the abatement cost of carbon. Thus $129.88 is the cost per tonne of CO_2 mitigation through the process of landfilling of charcoal using straw as a biomass.

Table 4-3: Carbon abatement cost

Cost Components	**Values**
Total production cost with landfilling cost with nutrient replacement cost *($/tonne of charcoal)*	332.2
GHG emissions in production and landfilling of biomass-based charcoal *(tonnes of C emitted/tonne of charcoal)*	0.102
Amount of carbon sequestered through landfilling of charcoal (tonne of C/tonne of charcoal)	0.800

Cost Components	**Values**
Net carbon sequestered through landfilling of charcoal (tonne of C/tonne of charcoal)	0.698
Abatement cost of carbon through landfilling of charcoal ($/tonne of CO_2 mitigated)	129.88

4.2 Recommendations for Future Research

i. A study biochar production from other sources of biomass, such as wood and animal waste would be helpful in comparing the different options.

ii. Specific equipment can be designed for a certain kind of biomass; this can enhance the charcoal production yield and would improve overall efficiency and economics of the plant.

iii. The portable production of biochar can be further analyzed to accommodate the travel of the equipment from one farm to another.

iv. Biochar has a further potential to absorb nitrogen from atmosphere, currently this has not been included in this scope of study. It might be useful to see the impact of emission reduction accommodating this property of biochar.

Appendix

A1: Capital cost factors

Cost Factors for Indirect Costs	
Indirect Costs	% Of TPEC
Engineering	32
Construction	34
Legal and contractors fees	23
Project contingency	37
Total Indirect Costs	126

A2: Electrical energy calculations

Calorific Value of Straw	2446	J/ kg/K	
Final Temperature	500	dC	Pyrolysis temperature
Initial Temperature	30	dC	Initial biomass temperature
Mass required	5500	Kg/hr.	Rate of biomass
Heat required	6322910000	J/hr.	
Heat required	1896873000	J/hr.	
Electrical Energy Required per hour	526.91	KWh	
Electrical Component	21.08	KWh	
Thermal to Electricity	30%	Assumption	

A3: Biomass process cost and calculations

	Tonne p. a.	Ha	Km	Shredder		Tractor		RAKER		Baler		
CASE	Biomass Requirement	Min Area Required p.a. WHEAT	Min Average Radius WHEAT	Hours	Cost ($)	Hours	Cost ($)	Hours	Cost ($)	Hours	Twine cost ($)	Cost ($)
Year 1	39,567	174,922	17.98	1,978	70,331	1,978	124,261	1,884	12,511	3,044	57,552	273,833
Year 2	42,040	185,854	18.53	2,102	74,727	2,102	132,027	2,002	13,293	3,234	61,149	290,948
Year 3	44,513	196,787	19.07	2,226	79,122	2,226	139,794	2,120	14,075	3,424	64,746	308,062
Year 4	44,513	196,787	19.07	2,226	79,122	2,226	139,794	2,120	14,075	3,424	64,746	308,062
Year 5	44,513	196,787	19.07	2,226	79,122	2,226	139,794	2,120	14,075	3,424	64,746	308,062
Year 6	44,513	196,787	19.07	2,226	79,122	2,226	139,794	2,120	14,075	3,424	64,746	308,062
Year 7	44,513	196,787	19.07	2,226	79,122	2,226	139,794	2,120	14,075	3,424	64,746	308,062
Year 8	44,513	196,787	19.07	2,226	79,122	2,226	139,794	2,120	14,075	3,424	64,746	308,062
Year 9	44,513	196,787	19.07	2,226	79,122	2,226	139,794	2,120	14,075	3,424	64,746	308,062
Year 10	44,513	196,787	19.07	2,226	79,122	2,226	139,794	2,120	14,075	3,424	64,746	308,062

A4: Biomass process cost calculations (cont.)

	Tonne p. a.	Tractor		Stinger - Bale Wrapper		Wheel Loader - Bale		Telescopic Bale Stacker – Loading		Baler		
CASE	Biomass Requirement	Hours	Cost	Hours	Cost	Hours	Cost	Hours	Cost	Hours	Twine cost	Cost
Year 1	39,567	3,044	191,171	1,499	40,826	231	30,201	231	18,958	3,044	57,552	273,833
Year 2	42,040	3,234	203,119	1,592	43,378	245	32,089	245	20,143	3,234	61,149	290,948
Year 3	44,513	3,424	215,067	1,686	45,930	259	33,976	259	21,328	3,424	64,746	308,062
Year 4	44,513	3,424	215,067	1,686	45,930	259	33,976	259	21,328	3,424	64,746	308,062
Year 5	44,513	3,424	215,067	1,686	45,930	259	33,976	259	21,328	3,424	64,746	308,062
Year 6	44,513	3,424	215,067	1,686	45,930	259	33,976	259	21,328	3,424	64,746	308,062
Year 7	44,513	3,424	215,067	1,686	45,930	259	33,976	259	21,328	3,424	64,746	308,062
Year 8	44,513	3,424	215,067	1,686	45,930	259	33,976	259	21,328	3,424	64,746	308,062
Year 9	44,513	3,424	215,067	1,686	45,930	259	33,976	259	21,328	3,424	64,746	308,062
Year 10	44,513	3,424	215,067	1,686	45,930	259	33,976	259	21,328	3,424	64,746	308,062

A5: Biomass process cost calculations (cont.)

	Tonne p. a.	Track transport				Telescopic Bale Stacker - Unloading		TOTAL Field Cost		Total Transport Cost		Storage cost
CASE	Biomass Requirement	Hours	Cost	Hours	Cost	Hours	Cost	Hours	Cost	Hours	Twine cost	Cost
Year 1	39,567	18	2,767	6,008	152,053	184	15,167	712,933	$18.018	216,379	$3.077	87,231
Year 2	42,040	19	2,940	6,564	166,135	196	16,114	757,492	$18.018	234,481	$3.138	92,683
Year 3	44,513	19	3,113	7,136	180,615	208	17,062	802,050	$18.018	252,981	$3.197	98,135
Year 4	44,513	19	3,113	7,136	180,615	208	17,062	802,050	$18.018	252,981	$3.197	98,135
Year 5	44,513	19	3,113	7,136	180,615	208	17,062	802,050	$18.018	252,981	$3.197	98,135
Year 6	44,513	19	3,113	7,136	180,615	208	17,062	802,050	$18.018	252,981	$3.197	98,135
Year 7	44,513	19	3,113	7,136	180,615	208	17,062	802,050	$18.018	252,981	$3.197	98,135
Year 8	44,513	19	3,113	7,136	180,615	208	17,062	802,050	$18.018	252,981	$3.197	98,135
Year 9	44,513	19	3,113	7,136	180,615	208	17,062	802,050	$18.018	252,981	$3.197	98,135
Year 10	44,513	19	3,113	7,136	180,615	208	17,062	802,050	$18.018	252,981	$3.197	98,135

A6: NPV calculations for centralized plant

Year	Capital Cost	Field Cost	Biomass Transp. Cost	Nutrient Replacement	Premium to fuel owner	Biomass Storage Cost	Conveyer Cost	Operation Cost	Power Cost	Maintenance Cost	Administrative Cost
Year 0	$4,433	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Year 1	$0	$713	$383	$895	$255	$87	$12	$120	$2	$94	$160
Year 2	$0	$773	$421	$970	$276	$95	$13	$122	$2	$96	$163
Year 3	$0	$834	$460	$1,048	$298	$102	$14	$125	$2	$98	$166
Year 4	$0	$851	$469	$1,069	$304	$104	$14	$127	$2	$100	$170
Year 5	$0	$868	$479	$1,090	$310	$106	$14	$130	$2	$102	$173
Year 6	$0	$886	$488	$1,112	$317	$108	$15	$132	$2	$104	$177
Year 7	$0	$903	$498	$1,134	$323	$111	$15	$135	$2	$106	$180
Year 8	$0	$921	$508	$1,157	$329	$113	$15	$138	$2	$108	$184
Year 9	$0	$940	$518	$1,180	$336	$115	$15	$141	$2	$110	$187
	$0	$959	$528	$1,203	$343	$117	$16	$143	$2	$113	$191

A7: NPV calculations for centralized plant

Year	Total Costs	Charcoal Price	Revenue from Charcoal	Net Income	PV of net income
Year 0	$4,201	$0.0000	$0	($4,201)	($4,201)
Year 1	$2,730	$0.3063	$3,542	$812	$738
Year 2	$2,940	$0.3063	$3,764	$824	$681
Year 3	$3,157	$0.3063	$3,985	$828	$622
Year 4	$3,220	$0.3063	$3,985	$765	$522
Year 5	$3,285	$0.3063	$3,985	$700	$435
Year 6	$3,350	$0.3063	$3,985	$635	$358
Year 7	$3,417	$0.3063	$3,985	$568	$291
Year 8	$3,486	$0.3063	$3,985	$499	$233
Year 9	$3,556	$0.3063	$3,985	$430	$182
	$3,626	$0.3063	$3,985	$359	$139

A8: NPV calculation for portable equipment

	Big 2200 (50%)	Big 2200 (87.5%)	Big 2200 (100%)	ADAM	Big1000
Productivity (HRS/DAY)	12	21	24		
Productivity %	50.00%	87.50%	100.00%		
Biomass Qty	4,600	8,050	9,200	170	1,840
Biomass Area	20,336	35,587	40,671	750	8,134
Charcoal Qty	1,310	2,293	2,621	48.36	524.16
Capital Cost	61,030	61,030	61,030	273	11,229
Field Cost	82,883	145,045	165,765	3,059	33,153
Biomass Transp. Cost	3,511	6,144	7,022	130	1,404
Nutrient Replacement	104,050	182,088	208,101	0	41,620
Premium to fuel owner	25,070	43,872	50,139	0	10,028
Biomass Storage Cost	10,141	17,747	20,282	374	4,056
Conveyer cost	1,364	2,386	2,727	0	545
Operation Cost	20,800	36,400	41,600	41,600	40,000
Maintenance Cost	1,526	2,670	3,051	200	561
Truck Transport Cost	8,674	15,179	17,348	320	3,470
Total Costs	**319,048**	**$512,561**	**$577,066**	**45,956**	**146,068**
Cost per ton	**$243.5**	**$223.5**	**$220.2**	**$950.3**	**$278.7**

Equation 4-1 Productivity Calculations

$$\Pr oduction = \frac{3{,}600\sec \times Q \times F \times (AS:D)}{t} \times \frac{E}{60-\min hr} \times \frac{1}{\begin{array}{c}Veolume\\ correction\end{array}}$$

Where-

Q = Heaped bucket capacity (lcy), maximum quantity of materiel the bucket can hold.

F = Bucket Fill Factor, this factor depends upon the kind of gravel, for coarse gravel factor is a low number, for fine gravel such as sand the number tends to 1.

AS: D = angle of swing and depth of cut correction

t = cycle time in seconds, time required to load , swing, unload and return.

E = Efficiency (min per hour)

Volume correction for loose volume to bank volume = 1/(1+ swell factor),

Equation 4-2 Truckload time

$$Truck\,Load\,Time =$$

$$Excavator\,Cycle\,Time \times \frac{Truck\,Volumetric\,Capicaty}{Heaped\,Bucket\,Capicaty \times Bucket\,Load\,Factor}$$

Where-

Excavator cycle time = Sum of bucket load time, swing time, unload time and swing empty time

Truck volumetric capacity = Amount of material it can hold

Heaped bucket capacity = Maximum volume of material the bucket can hold

Load factor = Depends upon the kind of gravel, higher load factor for fine material

A9: Land filing equipment selection and calculation

Line #	Description	Unit	Value
	Excavator		
10	Heaped Bucket Capacity	cy	5.00
15	Unit Bucket Weight	Kg	6582.8
20	Bucket Fill Factor		100%
30	Angle Of Swing: Depth		1

Line #	Description	Unit	Value
40	Excavator Cycle Time	Min	0.283
41	Load	Min	0.154
42	Swing	Min	0.047
43	Dump	Min	
44	Swing Empty	Min	0.047
50	Efficiency (Min Per Hour)	Min	50
60	Volume Correction Factor		1
70	Production	lcy/hr.	882
90	Average Height Of Excavation	ft.	15.68
100	Maximum Digging Height Of The Shovel	ft.	34.83
102	Maximum Reach	ft.	51.42
110	Optimum Digging Height = 50% Of Max	ft.	17.42
120	Swing Angle Assumed	deg	110
130	% Of Optimum Height	ft.	90%
	<u>Truck</u>		
200	Truck Capacity	lcy	31.4
210	Balanced Number Of Bucket Loads	#	6.28
210	Balanced Number Of Bucket Loads (Round)	#	6.00
220a	Load Time	Min	1.7
230a	Truck Load (Volumetric)	cy	30.00
240	Truck Load (Gravimetric)		197485
250	Haul Distance	Km	10
260	Haul Speed	Km/hr.	54.7
270	Haul Time	Min	11.0
280	Return Distance	Km	10
290	Return Speed	Km/hr.	54.7
300	Return Time	Min	11.0
310	Truck Dump Time	Min	0.32
320	Truck Cycle Time	Min	23.95
330	Balanced Number Of Trucks	#	14.09
340a	Production (N Rounded To Smaller)	cy/hr.	1051.99
350	Empty Tire Load	Ton	36
360	Loaded Tire Load	Ton	197521
365	Average Truck Load	Ton	98778
370	Trips Per Day	#	1
380	Hours Per Day	hrs.	8
390	Average Speed	Mph	2.5

Line #	Description	Unit	Value
400	Tmph		246946
	Ensure Tire TMPH That Is Used Is Higher Than Our 400 Value		
410	Over Efficiency In Min		50
420	Over Efficiency In %		83%
430	Swing Speed	RPM	6.5
440	Swing Speed	d/min	2340
450	Assumed To Dump Charcoal	Kg/ m3	1317
460	Volume Of Charcoal Per Land Fill	y3	5906
470	Number Of Truck Loads / Land Fill		188

A10: Cost of landfilling

Description	Value	Unit	
Maximum Depth	9.00	M	
Maximum Reach	14.00	M	
L X B	501.76	m^2	
Volume	4516	m^3	
Volume	5906.50	y^3	
Hours Required For Land Fill	6.74	hrs.	
Charcoal Per Anum	13,008,600		
Density Of Charcoal (Kg/M^3**)**	300		
Charcoal Volume M3	43,362		
Charcoal Volume Y3	56,715		
# Of Landfills	**9.60**		
Round Up	10.00		
Months Per Land Fill	1.2		
Cost per land fill			
Equipment	**Numbers**	**$/hour**	**$**
Excavator	1	$300	$2,100
Trucks	14	$225	$22,050
Total Dig Cost			$24,150
Total Cost Per Year			$241,500

A11: NPV calculation for biochar production with land filling

Year	Capital Cost	Field Cost	Biomass Transp. Cost	Nutrient Replace ment	Premium to fuel owner	Biomass Storage Cost	Conveyer Cost	Operatio n Cost	Power Cost	Maintena nce Cost	Administ rative Cost
Year 0	$4,433	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Year 1	$0	$713	$383	$895	$255	$87	$12	$120	$2	$94	$160
Year 2	$0	$773	$421	$970	$276	$95	$13	$122	$2	$96	$163
Year 3	$0	$834	$460	$1,048	$298	$102	$14	$125	$2	$98	$166
Year 4	$0	$851	$469	$1,069	$304	$104	$14	$127	$2	$100	$170
Year 5	$0	$868	$479	$1,090	$310	$106	$14	$130	$2	$102	$173
Year 6	$0	$886	$488	$1,112	$317	$108	$15	$132	$2	$104	$177
Year 7	$0	$903	$498	$1,134	$323	$111	$15	$135	$2	$106	$180
Year 8	$0	$921	$508	$1,157	$329	$113	$15	$138	$2	$108	$184
Year 9	$0	$940	$518	$1,180	$336	$115	$15	$141	$2	$110	$187
	$0	$959	$528	$1,203	$343	$117	$16	$143	$2	$113	$191

A12: Energy and emission calculations for portable production of biochar

Operation	BIG22 12 Hrs.	Fuel Economy (Gallons/hour)	Total fuel Required (L/yr.)	Energy (GJ)	$KgCO_{2e}$
Shredding	230	9.86	8,584.42	442.10	22.77
Tractor for Shredder	230.0	5.26	4,579.52	235.85	12.15
Raker	219.0	3.72	3,084.52	158.85	8.18
Baler	353.8	15.33	20,533.49	1,057.47	54.46
Tractor for Baler	353.8	5.26	7,045.41	362.84	18.69
Loader	26.8	14.81	1,502.80	77.39	3.99
Conveyer	102.2	2.19	847.41	43.64	2.25
Truck Transport of Kiln					
				2,378.15	**122.47**
Operation	**BIG22 21 Hrs.**	**Fuel Economy (Gallons/hour)**	**Total fuel Required (L/yr.)**	**Energy (GJ)**	**KgCo2e**
Shredding	402.5	**9.86**	15,022.74	773.67	39.84
Tractor for Shredder	402.5	5.26	8,014.16	412.73	21.26
Raker	383.3	3.72	5,397.91	277.99	14.32
Baler	619.2	15.33	35,933.62	1,850.58	95.30
Tractor for Baler	619.2	5.26	12,329.47	634.97	32.70
Loader	46.9	14.81	2,629.90	135.44	6.98
Conveyer	178.9	2.19	1,482.97	76.37	3.93
Truck Transport of Kiln					

				4,161.75	**214.33**
Operation	**BIG22 24 Hrs.**	**Fuel Economy (Gallons/hour)**	**Total fuel Required (L/yr.)**	**Energy (GJ)**	**KgCo2e**
Shredding	460.0	**9.86**	17,168.84	884.20	45.54
Tractor for Shredder	460.0	5.26	9,159.04	471.69	24.29
Raker	438.1	3.72	6,169.04	317.71	16.36
Baler	707.7	15.33	41,066.99	2,114.95	108.92
Tractor for Shredder	707.7	5.26	14,090.83	725.68	37.37
Loader	53.6	14.81	3,005.60	154.79	7.97
Conveyer	204.4	2.19	1,694.83	87.28	4.50
Truck Transport of Kiln					
				4,756.29	**244.95**
Operation	***Adam***	**Fuel Economy (Gallons/hour)**	**Total fuel Required (L/yr.)**	**Energy (GJ)**	**KgCo2e**
Shredding	8.5	**9.86**	316.81	16.32	0.84
Tractor for Shredder	8.5	5.26	169.01	8.70	0.45
Raker	8.1	3.72	113.83	5.86	0.30
Baler	13.1	15.33	757.78	39.03	2.01
Tractor for Shredder	13.1	5.26	260.01	13.39	0.69
Loader	0.0	14.81	0.00	0.00	0.00
Conveyer	0.0	2.19	0.00	0.00	0.00
Truck Transport of Kiln	0.0	0	0.00	0.00	0.00
				83.30	**4.29**

Operation	big 1000	Fuel Economy (Gallons/hour)	Total fuel Required (L/yr.)	Energy (GJ)	KgCo2e
Shredding	92.0	**9.86**	3,433.77	176.84	9.11
Tractor for Shredder	73.6	5.26	1,465.47	75.47	3.89
Raker	87.6	3.72	1,233.81	63.54	3.27
Baler	141.5	15.33	8,213.40	422.99	21.78
Tractor for Shredder	141.5	5.26	2,818.17	145.14	7.47
Loader	10.7	14.81	601.12	30.96	1.59
Conveyer	40.9	2.19	338.97	17.46	0.90
Truck Transport of Kiln				**932.39**	**48.02**

A13: Energy and emission results for portable system

Case	Total Biomass	Total Biochar	Total emissions produced (Kg CO_{2e})	Total CO2 mitigated (Kg CO_{2e})	Net GHG Reduced (Kg CO_{2e})	Net Emission produced per tonne of Biomass KgCo2e/tonne
BIG 22 12 HRS	4,600	1,310	122.474	3,840,000	3,839,878	834.77
BIG 22 21 HRS	8,050	2,293	214.330	6,720,000	6,719,786	834.77
BIG22 24 HRS	9,200	2,621	244.949	7,680,000	7,679,755	834.77
ADAM	170	48	4.290	141,714	141,710	834.77
BIG 1000	1,840	524	48.018	1,536,000	1,535,952	834.77

A14: Energy and emission results for portable system (cont.)

Case	Emission produced per tonne of Biochar	Emission reduction efficiency	Total Energy consumed	Total Energy Produced	NER	Total Carbon Emitted
	KgCo2e/tonne	%	**GJ**	**GJ**		**Tonne**
BIG 22 12 HRS	2,930.31	100.00%	2,378.15	36,691	14.4	0.03
BIG 22 21 HRS	2,930.31	100.00%	4,161.75	64,210	14.4	0.06
BIG22 24 HRS	2,930.31	100.00%	4,756.29	73,382	14.4	0.07
ADAM	2,930.31	100.00%	83.30	1,354	15.3	0.00
BIG 1000	2,930.31	100.00%	932.39	14,676	14.7	0.01