University of Alberta

Assessment of Densified Biomass for Fuels and Chemicals

by

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Dedicated to my parents

Shawkat Ali Siddique and Tahmina Shawkat

Abstract

Utilization of renewable bioenergy is a sustainable approach to reducing greenhouse gas (GHG) emissions. However, efficient use of this resource is hindered by the current knowledge-gaps concerning collecting and processing dispersed biomass from large areas. This study focuses on developing methodologies for assessing biomass-based facilities; availability of agri-biomass; their densification, energy and emissions compared to other fuels; transport logistics; and biofacility siting with optimum capacities analyzed in the GIS (geographical information system) environment. Densification of agricultural residue into pellets for fuels and chemicals was considered in the analyses. Agricultural pellets were ranked in order of preference using multi-criteria decision analysis which integrates economic, environmental and technical factors. The results show that straw pellets possess significant potential; they rank immediately after wood and switchgrass pellets for all scenarios. A data-intensive techno-economic model was developed to determine the optimum size of plants and the minimum cost of pellet production and the optimum capacity for pellet plants was 150,000 tonnes per year. To establish the supply logistics of large-scale biofacilities, a methodology was developed to assess the optimum delivery cost of multiple forms of lignocellulosic feedstocks. It was found that the optimal delivery mode can be achieved by combining 30% agricultural bales with 70% forest biomass in the form of wood chips. Agri-pellets' potential to offsetting GHG emissions is 50% – 350% higher than that of other fuel sources such as wood pellets, coal and natural gas. A procedural model was developed within the

GIS environment to determine an optimal system of biofacilities, considering environmental and economic factors. This methodology was applied to Alberta, and a land-suitability model was derived. The optimal capacity and cost change considerably in suitable locations. Methodologies developed under this study would be useful for optimal planning and siting of biofacilities in suitable geographical locations.

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List of Abbreviations

AARD	Alberta Agriculture and Rural Development
AESO	Alberta Electric System Operator
AHP	Analytic Hierarchy Process
ARI	Alternate Resource Inc.
CANBIO	Canadian Bioenergy Association
CD	Census Division
CFI	Canadian Fuel Institute
CR	Consistancy ratio
CSA	Canadian Standard Association
d	diameter
EPA	Environmental Protection Agency
ERS	Econ Research Services
ESRI	Environmental System Research Institute
EUBIONET	European Bioenergy Network
GEC	Grass Energy Collaborative
GEN	Generic
GHG	Greenhouse gas
GIS	Geographic Information System
GJ	Gigajoule
GVW	Gross Vehicle Weight
ha	Hectare
hr	Hour
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
km	Kilometer
kW	Kilowatt
kWh	Kilowatt-hour
LCA	Life Cycle Assessment
LHV	Lower heating value
MJ	Mega Joule

mm	Millimeter
MPCA	Minnesota Pollution Control
Mt	Million tonne
NG	Natural gas
NRC	Natural Resource Canada
NREL	National Renewable Energy Laboratory
OD	Origin-destination
odt	Oven dry tonne (0% moisture content)
PAMI	Prairie Agricultural Machinery Institute
PFE	Pellet for Europe
PFI	Pellet Fuel Institute
PFRA	Prairie Farm Rehabilitation Administration
PMP	P-median Problem
PROMETHEE	Preference Ranking Organization Method for Enrichment and Evaluation
REAP	Resource Efficient Agricultural Production
SI	Suitability Index
SOC	Soil Organic Carbon
USDA	United States Department of Agriculture
UTC	Unit Transportation Cost
WPAC	Wood Pellet Association of Canada
wt%	Weight %

Chapter 1. Introduction

1.1. Background

Increase in emissions of atmospheric carbon dioxide and other greenhouse gases (GHG) has raised widespread concern for the global climate. Enhanced GHG emissions results from utilization of fossil fuels (IEA, 2009). In 2008, the total worldwide consumption of energy was 474 exajoules, 81% of which came from fossil fuel sources (EIA, 2010). Energy usage was decreased for the first time in 30 years in 2009 by 1.1% as a result of that year's financial and economic crisis; it bounced back, however, in the following year. Energy consumption in the G20, the twenty most industrialized countries in the world, rose by more than 5% in 2010 after the slight decrease of 2009 (Enerdata, 2010). Canada produces about 6% of global energy supplies. It also consumes a large amount of energy - 7650 petajoules in 2009 - derived mainly from three fossil fuel sources: natural gas, refined petroleum and coal (Statistics Canada, 2009). The consumption of fossil fuels is escalating globally due to greater-than-ever energy demand. Due to this high dependency on fossil fuels, currently they play a very sensitive role in the global economy.

There are three broad options for addressing the increased emissions of GHGs caused by the use of fossil fuels. As a first approach, energy management has become a crucial pathway to reducing GHG emissions. The second option is sequestratio of emitted GHGs in carbon sinks; this obviously needs significant investment and further development of technology if it is to be implemented sustainably. The third option is to reduce dependence on fossil fuels by using low-carbon energy sources, thereby lowering GHG emissions. Using renewable energy sources (e.g., biomass, solar, hydro power) to produce different forms of energy (e.g., transportation fuels, heat and electricity) is a sustainable way of reducing GHG emissions.

In 2008, 33.5% of the world's energy supply came from oil, followed by coal (26.8%), natural gas (20.8%), renewable sources such as biofuel, hydro, solar, wind, and geothermal power (12.9%), nuclear power (5.8%) and other sources (4%) (IEA, 2010). Recently, IPCC (2011) has reported that by 2050 renewables could meet nearly 80 percent of global energy demand using existing technology if supported by the right government policies. Renewable energy capacity grew by over 30 percent for wind, 3 percent for hydropower, 50 percent for grid-connected photovoltaics, 4 percent for geothermal, 15.17 percent for ethanol, and 11.67 percent for biodiesel in 2009 compared to 2008 (IEA, 2011). In some cases renewable energy technologies are not economically competitive partly because, the cost of energy production is currently higher than it is for fossil fuel sources in most jurisdictions. If, however, the environmental benefits such as lower GHG emissions were included in the energy price, renewable energy technologies could become more attractive (IPCC, 2011).

Biomass is a renewable energy sources with high potential. Interest in this area has increased greatly in recent years due to environmental concerns as well as rising of fossil fuel prices. Biomass-based energy technologies are in different stages of development, deployment and commercialization. Emerging policies related to carbon caps, carbon trade and carbon taxes enhance the appeal of this option. The use of biomass is being considered as one of the key approaches to GHG mitigation (IPCC, 2007). It is the only renewable energy resource which can directly produce liquid fuels. However, significant research and policy formulation are required to ensure sustainability of biomass production and conversion (Layzell *et al.,* 2006).

Biomass feedstock can be based on forest or agricultural sources. Forest-based biomass includes whole tree biomass which can be converted into various transportable forms. Forest residue generated from logging operations is another major source. Currently in Alberta, 90 percent of logging operations include cutting (or felling) trees in the stand, skidding trees to the roadside and delimbing the trees on the roadside, that is, removing the branches and tops. The trunk is taken to a mill for pulp and lumber use. The limbs, tops and branches are subsequently forwarded, piled and burnt to prevent forest fires. This residue is a large source of forest biomass (Kumar *et al*., 2003; Sarkar and Kumar, 2009). In the current agricultural practice, grains are removed from wheat and barley crops and most of the straws are left in the field to rot (Kumar *et al.,* 2003; Searcy, 2008). Although Alberta has a large reserve of fossil fuel, it also has large biomass resource potential which could be used to produce energy. In addition to its 22.5 million hectares of harvestable wood forest, Alberta is the second largest producer of wheat and the largest producer of barley in Canada. As well, there is significant animal manure which could be used to produce energy (Sarapatka, 1993; Ghafoori *et al*., 2007). Some energy crops can also be grown to produce energy and heat (Gigler *et al.,* 1999; REAP, 2008).

Compared to fossil fuel, biomass is clean, renewable and nearly carbon neutral (CANBIO, 2009). It can be used to produce a range of fuels and chemicals as well as heat and power (Kumar *et al*., 2003; Brock *et al*., 1996; Cameron *et al*., 2007); these include bioethanol (Kim *et al*., 2004; Sassner *et al.,* 2008), biodiesel (Monyem and Gerpen, 2001; Chongkhong *et al,* 2007), biohydrogen (Levin *et al*., 2004; Sarkar and Kumar, 2009), and biochar (Lin and Hwang, 2009; Sohi *et al*., 2009). One of the main barriers to the utilization of biomass for producing fuels and chemicals in large scale is the cost of delivering biomass to its processing facility. Forest- and agriculture-based biomass (e.g., straw) have low energy density, but the cost of delivering them to a bioconversion facility is high, once costs of collection, transportation and handling are included. Unlike fossil fuels, biomass does not have a common fuel distribution infrastructure. Straw can be transported using existing public roads (Kumar *et al*., 2003) and can be produced each year even though straw yield is far less per hectare than does wood. There is a developed forest industry which uses the whole tree biomass. Forest harvest residue which constitutes about 20-25% of the whole tree biomass has low yield and is dispersed. These different biomass feedstocks have different characteristics which affect the production of fuels and chemicals. The current study focuses on biomass produced from agricultural crop residue, mainly straw from wheat, barley and oats.

The important characteristics of raw biomass are its low bulk density and high moisture content, which cause problems related to handling, transport and storage. Densified biomass in the form of pellets is a convenient form of fuel (CANBIO, 2008; PFI, 2009). In North America and Europe, the wood pellet is already an established form of bioproduct. Canada currently produces approximately three million tonnes of pellets each year, most of which are exported to European countries such as Sweden, Denmark, and the Netherlands (CANBIO, 2008). Wood pellets are, however, limited by factors like the availability of sawdust, other uses for woods, and limits on the availability of wood residue. In this context, the densified agricultural crop residue, e.g., straw pellets, is a potential candidate for biofuel where the raw material is abundant, especially in the case of Alberta.

Canada currently obtains only 16 percent of its primary energy supply from renewable energy sources including hydropower (NRC, 2008). In Canada, apart from hydropower, biomass is the largest source of electricity from renewable energy, accounting for about 6 percent of total primary energy. Biomass-based electricity relies mainly on sawmill and usemill residue for its feedstock. The rapid expansion of the energy industry and its accelerated economic growth has resulted in a growing demand for power which contributes to increasing GHG emissions. Currently, about 50% of Canada's GHG emissions is contributed by Alberta (Environment Canada, 2008), which is now considering the use of carbon capture and storage although it is expensive in its current form (Alberta Carbon Capture and Storage Development Council, 2009). One of the strategies Alberta could take up in the future to curb GHG emissions is replacement of fossil fuel with carbon neutral fuels. All these show the importance of assessing the potential for using biomass fuel in Alberta instead of existing (business-as-usual) fossil fuel uses. Replacing fossil fuels would require that appropriate forms of biomass be developed. This could reduce delivery cost by increasing energy density, thereby optimizing the cost of transportation.

1.2. Research Rationale

Although a large number of researches have been carried out on biomass resources in recent decades, systematic studies on densified biomass in the form of agricultural pellets are scarce. An extensive literature review for this study revealed that several issues need to be assessed in detail if we are to establish an efficient facility capable of producing densified biomass using agricultural straw. The current research is based on the issues outlined below. The approach this study adopted refers to the straw available in Western Canada; however, the methodology developed under this study can be applied to different biomass feedstocks available elsewhere.

1.2.1. Integration of economic, environmental and technical factors for ranking of pellets

Solid biofuel can be produced from different biomass feedstocks. Physical and chemical properties are not the same for the same biofuel made from different feedstocks e.g., wood, straw, switchgrass, alfalfa or poultry litter. The variations in physical properties are important for the final performance of the combustion system and the choice of the process and equipment. Chemical properties are a crucial factor in assessing environmental pollution and ash-related operational problems. Thus we need to compare and rank feedstock-based pellets in terms of the suitability for use. So far, comparative analyses of pellets have focused on a single characteristic rather than taking a multi-dimensional approach. Previous studies compared pellets solely on the basis of either economic factors (lowest cost i.e. $/tonne) or emissions (kg of CO_2/tonne) associated with their production and utilization (Pastre, 2002; Sokhansanj *et al*., 2006; Jannasch *et al*., 2000; Samson *et al*., 2000; Jannasch *et al*., 2001). The literature also reports studies on the physical characteristics (Tabil *et al.,* 1997; Obernberger and Thek, 2004; Mani *et al*., 2006), chemical composition and combustion behavior (Tabil *et al*., 1997; Obernberger and Thek, 2004; Mani *et al*., 2006), and economics of production (Mani *et al*., 2006; Thek and Obernberger, 2004; Sokhansanj and Fenton, 2006; PFE, 2002) with regard to different types of pellets. No research following a multi-dimensional approach, i.e., integrating economic, environmental and technical characteristics is available; in particular, no research has been done on selecting pellets as an energy source. Comparisons are needed that integrate relevant factors including both qualitative and quantitative criteria. This study seeks to address this gap, which is discussed in Chapter 2.

1.2.2. Agri-pellet production cost and the optimum size of a plant

Many decisions regarding biomass energy are derived from economic information (i.e. cost), that is insufficient and based mainly on small, uneconomical plants (Searcy, 2008). Currently most of the pellet-producing facilities in the world are small scale and make wood pellets (Karwandy, 2007). Small-scale facilities are not economically optimum and do not have the advantage of economy of scale in their capital and processing costs. Detailed studies are required on the techno-economic aspects of large-scale biomass facilities. Previous studies dealt with the optimization of bioenergy facilities e.g., the optimal sizes of a power plant from biomass (Kumar *et al*., 2003), bioethanol plant (Nguyen and Prince, 1996), biogas plant (Walla, 2008). Several researchers worked on the economics of producing wood pellets. Mani (2006), and Thek and Obernberger (2004) estimated the cost of producing pellets from sawdust (residue generated by sawmills). Other authors also estimated wood pellet production cost e.g., William (1995), Urbonowski (2005), Hoque *et al.* (2006). Samson (2000) estimated the cost of producing switchgrass pellets for commercial purposes. Pastre (2002) analyzed straw and wood pellet economics from a European perspective and overviewed some technical problems related to the production and utilization of pellet made from agricultural residue. Campbell (2007) estimated the per-tonne value of straw pellets at different plant capacities. However, none of these studies estimated the optimal capacity for the straw pellet plant. There is a need to investigate the optimum size for agri-pellet plants and the factors which make it optimum. This is further discussed in Chapter 3.

1.2.3. Energy and emission parameters for densified form of lignocellulosic biomass

Life cycle assessment (LCA) is a known methodology for evaluating a product's whole or partial life cycle environmental performance, process or pathway, typically considering all steps of its life. In previous studies, LCAs were done on the product, process or pathway analysis of biofuel (e.g., Searcy, 2008; Forsberg, 2000; Macedo *et al.,* 2004; Kim and Dale, 2005; Gabrielle and Gagnaire, 2008; Hedegaard *et al.,* 2008; Kim and Dale, 2008; Magelli *et al.,* 2009; Spatari *et al.,* 2010). Most LCAs were performed on transportation biofuels, such as, bioethanol, biodiesel and hydrogen. Few LCA have been done on solid biofuel, such as, pellets. Magelli *et al.* (2009) analyzed the fuel consumption and air emissions associated with wood pellet production using an LCA that started with tree harvesting for wood residue and ended with shipping of the pellets to Europe. LCAs on wood pellets were also performed in a few other studies, e.g., Magelli (2009), Craven (2008), Pa *et al.,(*2009), and Maclean *et al.* (2008).

Some previous LCA studies (Macedo *et al*., 2004; Shapouri *et al*., 2002; Wang, 2005; Malca and Freire, 2006; Beer and Grant, 2007) addressed same pathway using a different framework and scope. Greenhouse gas (GHG) emissions and energy balance are the most prevalent ways of conducting LCA on biofuels. The energy and GHG balances of bioenergy systems differ depending on the type of feedstock, technology, system boundary, end-use technology and reference energy system with which a given bioenergy system is compared. Agricultural practices, including resource usage and emissions, vary widely by location and crop (O'Donnell, 2009). Application rates for fertilizers (nitrogen and phosphorus) and insecticides are region-dependent and vary according to soil type and available nutrients (Fernandez-Cornejo and Jans, 1999). GHG emissions from crop production depend on agricultural practices, that is, use of machinery, seeds, fertilizers, and pesticides. It is essential to carry out LCA on agri-pellet production and utilization incorporating all the above factors. This is further detailed in Chapter 4.

1.2.4. Multiple feedstock delivery to a large-scale biofacility

Low conversion efficiency, availability and logistical constraints are the major challenges to the large-scale development of biomass-based facilities for the production of fuels and chemicals (Caputo *et al*., 2005). Supply and logistics are influenced by biomass's complex texture, limited period of availability and scattered distribution. The transportation cost of biomass is a significant factor in the total cost of production. The main factor associated with transporting biomass for producing biofuel or other value-added products is its low bulk density. This and biomass's complex texture also create delivery issues related to its transportation to a biofacility. Biomass can be transported in different forms depending on the type of biomass to be transported. Various forms of woody biomass are sawdust, chips, bundles and pellets. Agricultural biomass feedstocks can be transported as ground, chopped, baled or made into pellets. Studies were carried out on the technology used to transport different forms of biomass and the related cost. Badger (2003) discussed the technology used to transport biomass considering whole tree, bales, pellets and pipeline transportation. Sokhansanj *et al*. (2006) proposed a fuel-handling system in which the biomass received were in the form of ground, baled or pellets. A detailed cost analysis was performed that start with collecting biomass in the field and ends with delivering heat and power to the ethanol plant. Studies were also conducted on the implications of the long distance haulage of biomass using different modes of transportation (e.g., Kumar *et al*., 2005; Sokhansanj *et al*., 2006; Mahmudi and Flynn, 2006; Rogers and Brammer, 2009; Searcy *et al*., 2007). These studies estimated the relative cost of transportation by truck, rail, ship, and pipeline for three biomass feedstocks. Several studies focused on analyzing the cost of transporting woody biomass (Suurs, 2002; Yoshioka *et al*., 2006; Ashton *et al*., 2007) and herbaceous biomass (Turhollow *et al*., 1996; Perlack and Turhollow, 2002; IEA, 2007; Sokhansanj *et al*., 2006). Economic analyses were conducted on different forms of biomass (Johansson *et al*., 2006; Ranta and Rinne, 2006) and their related pre-treatment operations such as transpirational drying (Stokes *et al*., 1987; Stokes *et al*., 1993). Angus-Hankins *et al*. (1995) determined the minimum bulk density required to achieve full payload within the maximum allowable load dimension restrictions. However, none of these studies explicitly analyzed and compared the effects of bulk density and forms on the total cost of delivering biomass feedstock to an end-use biofacility. Information on the delivery cost of multiple biomass feedstocks and different forms of woody and agricultural biomass to a biofacility is very limited. This study investigates the total delivery cost of different forms of multiple feedstocks (i.e., woody and agricultural biomass mainly wheat straw and corn stover) to a biofacility. Baled, chopped and pelletized forms were considered for the agricultural biomass. This study aims to assess optimum delivery cost of multiple forms of lignocellulosic feedstock to biofacility and to analyze the effect of bulk density on total delivery cost of selected agricultural and woody biomass. The issue of traffic congestion is also investigated. All this is further discussed in Chapter 5.

1.2.5. Optimal siting and size of bioenergy facilities using the Geographic Information System

The problem of locating bioenergy facilities is a very particular case of the general facility location problem, and finding the optimum location for a bioenergy facility is a challenging task (Rentizelas and Tatsiopoulos, 2009). It has significant impact on the investment cost and especially on the logistic cost. Dispersed biomass is the major factor affecting the potential location of the facility. Biomass availability eventually affects the cost of transportation. Geographic Information System (GIS) has been used in a number of studies to determine optimal locations for various developments (Basagaolu *et al.,* 1997; Mielenz, 1997; Voivontas *et al*., 2001; Papadopoulos and Katsigiannis, 2002; Ma *et al*., 2005). A GIS-based decision support tool was developed and applied to the siting of a solar power plant (Vandenbergh et al., 1999) and various wind farms (Baban and Perry, 2001). Dagnall *et al.* (2000) used GIS for resource mapping and analysis in order to identify sources of collectable farmyard manure. They determined potential sites for anaerobic digestion plants. Several studies have employed GIS-based analyses to find suitable locations of biomass plants; their research included economic aspects of exploiting resources [e.g., Noon and Daly, 1996; Graham *et al*., 1997; Perpina *et al*., 2009). Hadad and Anderson (2008) developed a spatial location model, using GIS to identify potential biomass collection sites along an existing railroad. It appears that GIS-based analysis is a useful procedure for solving facility location problems involving dispersed natural resources. However there is scarcity of studies on integration of suitable biofacility locations using GIS and its integration with optimal capacities of large-scale plants. In this study, a methodology is developed for siting a bio-energy system, with particular reference to the agri-biomass resources of Alberta. This model integrates various constraints in order to identify the most suitable location for a biofacility, considering the distribution of agri-biomass.

1.3. Objectives of the Research

The overall aim of this research is to develop methodologies assessing the optimum biofacility system and performance of densified biomass for producing fuels and chemicals from agri-biomass residues. The specific objectives include:

- Ranking of pellets on the basis of economical, environmental and technical factors using multi-criteria analysis.
- Development of a data intensive techno-economic model for determining the optimum size for a pellet production plant designed to process agriculture residues (i.e., straw from wheat, barley and oats).
- Development of a life cycle energy and environmental assessment model for agricultural pellets.
- Determination of the optimum delivery cost for multiple forms of lignocellulosic feedstock to a large-scale biofacility; also analyzing the effect bulk density has on the total delivery cost of selected agricultural and woody biomass. In this regard the issue of traffic congestion is investigated.
- Development of a Geographic Information System (GIS)-based model for determining the optimal site and size of biomass-based facilities considering dispersed feedstock sources and local road network.

The information from the Western Canada (Alberta Province) is used as a case study to implement some of the developed methodologies.

1.4. Scopes and Limitations of the Research

This study is limited to pellet production using biomass residues. The residues are:

- agricultural, including straw from wheat, barley and oats;

- forest residues, including limbs, tops and branches from logging operations in the forest and residues from mills.

The cost of pellet production has been estimated for Western Canadian setting. The result could be used elsewhere with suitable modification of local cost factors.

The life cycle assessment for emissions is limited to greenhouse gases such as carbon dioxide, nitrous oxide and methane which are released during the collection and harvesting of biomass, its transport by trucks, and its conversion at processing facilities.

This study is based on current technology for biomass harvesting, collection, transportation and processing.

1.5. Organization of the Thesis

This thesis consists of seven chapters. It is a consolidation of papers, each chapter of which is intended to be read independently. As a result, some concepts and data are repeated.

The current chapter introduces this study and outlines its objectives.

The second chapter discusses developing of the multi-criteria analysis model for ranking pellets from different feedstocks by combining economic, environmental and technical factors.

The third chapter goes into details on developing the techno-economic model for estimating the cost of producing agricultural pellets and the optimum size for pellet production plants.

The fourth chapter explains the energy flows and GHG emissions from the agricultural pellets over its entire life cycle; it also compares pellets with other existing fuels used for domestic heating in Alberta.

The fifth chapter determines the optimum cost of delivering multiple types and forms of feedstock to a large-scale biofacility; it also analyzes the effect bulk density has on the total delivery cost of selected forms of agricultural and woody biomass. The issue of traffic congestion is investigated.

In the sixth chapter, a model is presented that uses GIS environment to locate suitable sites for a bio-energy facility (pellet plant) integrating various constraints. This model is implemented to determine suitable locations and optimal sizes for bioenergy facilities in Western Canada (Alberta) considering distributed biomass and local road network.

Finally, Chapter Seven presents the conclusions and provides recommendations for future research.

Appendices are provided at the end of the thesis, which contains the related information.

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Chapter 2. Ranking of Biomass Pellets by Integration of Economic, Environmental and Technical Factors

2.1. Introduction

Climate change concerns coupled with the unstable fossil fuel market and government incentives in many countries are the driving forces to increased use of renewable fuels. Policies related to carbon caps, carbon trade, and carbon taxes enhance the appeal of this option. Biomass-based energy technologies are at various stages of demonstration, implementation and commercialization and these are one of the most viable renewable energy options. The pellet is a solid biofuel derived from biomass which can be used for energy and chemicals. Pellets can be produced from a variety of residue feedstocks; these include agricultural and forest biomass such as straw, sawdust, and animal waste (Kaliyan, 2008; Timmenga & Associates Inc, 2003). Biomass feedstocks are characterized by low energy density (MJ m^{-3}) and mass density (kg m^{-3}). Biomass-based pellets are an attractive option due to their, high energy density and increased mass density. These characteristics make them easier to transport and store (Hamelink *et al.*, 2005; Mckeough *et al.*, 2005). The established quality standard (European Pellet Centre, 2008; PFI, 2008) makes pellets a convenient fuel to use. Canada currently produces approximately two million tonnes of wood pellets each year, most of which are exported to European countries such as Sweden, Denmark, and the Netherlands (EUBIONET, 2008).

Comparative analyses of pellets have focused on a single characteristic rather than taking a multi-dimensional approach. Previous studies compared pellets solely on the basis of economic factors (production cost in \$ $tonne^{-1}$) or

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emissions (kg of CO2 $tonne^{-1}$) involved in the production of pellets and their utilization (Samson and Duxbury, 2000; Pastre, 2002; Sokhansanj and Fenton, 2006). The literature reports studies on the physical characteristics (Tabil and Sokhansanj, 1997; Obernberger and Thek, 2004; Mani *et al*., 2006), chemical composition and combustion behavior (Obernberger and Thek, 2004), and economics of production (Thek and Obernberger, 2004; Mani *et al*., 2006; Sokhansanj and Fenton, 2006) with regard to different types of pellets. However, research following a multi-dimensional approach, i.e., integrating economic, environmental and technical characteristics is absent. A multi-dimensional approach is needed to combine different qualitative and quantitative criteria in an optimal way to give a credible solution. A comprehensive literature review does not yield any research that has taken a multi-dimensional approach integrating both qualitative and quantitative criteria, especially for selecting pellets as an energy source.

The objective of this paper is to present a multi-criteria assessment model and to use it to rank different biomass feedstock-based pellets as an energy source for combined heat and power generation plants (CHP). This study integrates environmental, economic and technical criteria, both quantitative and qualitative. Five feedstock alternatives and eleven criteria are defined and compared using Decision Lab 2000-Executive Edition software (Visual Decision Inc., 2008). The alternatives include those from wood, straw, switchgrass, alfalfa and poultry litter. The criteria were selected based on consumer perspective. The consumer could be power plant or utility. The quantitative criteria selected for this study are: production cost ($ per tonne of pellets), bulk density (kg per m^3), NOx emissions (kg per GJ), SOx emissions (kg per GJ), CH_4 emission (kg per GJ), deposit (ash) formation (%), lower heating value (MJ per kg of pellets), durability (%), and storage time before degradation (years). The qualitative criteria include acceptability to the user and the maturity of the technology. The criteria were selected based on customers' perspective. It reflects what criteria are deemed important to the CHP plant when considering pellet as fuel.

2.2. Methodology

The Preference Ranking Organization Method for Enrichment and Evaluation (PROMETHEE) is used in this study. It is one of the best known and the most widely applied outranking method (Hyde *et al.,* 2003). It has a transparent computational procedure which can incorporate qualitative data and scenario comparisons can be performed without difficulty. Overall, the procedure and results are easy-to comprehend for decision makers (Hyde *et al.*, 2003; Buchholz *et al*., 2009). This method has been widely applied in different disciplines including energy planning (Georgopoulou *et al.*, 1998; Haralambopouloas and Potatidis, 2003). PROMETHEE integrates quantitative and qualitative criteria for different alternatives by comparing the alternatives in pairs in order to make the assessment more realistic. In this study PROMETHEE I and PROMETHEE II methods have been used. PROMETHEE I ranking uses only the dominant characteristics of one alternative over other. PROMETHEE II ranking uses both dominant and outranked characteristics of one alternative over other. This gives a complete ranking (Brans and Mareschal, 2005). Both methods are explained in further detail in Appendix B.

2.2.1. The PROMETHEE method

The multi-criteria comparison of pellets was performed using the PROMETHEE. A detailed description of PROMETHEE can be found in Brans and Vincke (1985), Brans *et al.* (1986), Kumar *et al.* (2006) and Mohammadabadi *et al.* (2009). Decision Lab 2000- Executive Edition software uses the PROMETHEE method for ranking different alternatives based on multi-criteria (Visual Decision Inc., 2008).

The PROMETHEE method is based on a comparison of paired alternatives dependent on several selected criteria. Let N be a set of alternatives for ranking and k be the total number of criteria. For each alternative, $a \in N$, $f_j(a)$ is the value for the criterion, j, for alternative a. If a problem has two alternative solutions, a and b, the values for the alternative solutions for a certain criterion, j, are represented by $f_j(a)$ and $f_j(b)$, respectively. A preference function, P_j, is associated with each criterion. A preference function, P_j, helps to bring the values of different criteria to a single uniform scale. Six different preference functions are defined in Decision Lab 2000 and have been listed in Table B1 (Appendix B). These are discussed elsewhere (Brans and Vincke, 1985; Brans *et al.,* 1986; Kumar *et al.,* 2006; Mohammadabadi *et al.,* 2009). This P_j translates the difference between the values for two alternatives, $d_j(a,b)$, over a criterion in terms of degree of preference. The degree of preference is expressed

$$P_j(a,b) = P_j\left[d_j(a,b)\right] \qquad (2\text{-}1)$$

where, $0 \leq P_j(a.b) \leq 1$, and the difference between the values for two alternatives is defined by

$$d_j(a,b) = f_j(a) - f_j(b) \qquad (2\text{-}2)$$

The degree of preference is higher if the value for $d_j(a.b)$ is higher so it is indicating a higher preference for a over b. Thus the degree of preference function is

$$P_j(a,b) = \begin{cases} 0 & if \quad f_j(a) \leq f_j(b) \\ P_j\left[d_j(a,b)\right] & if \ f_j(a) > f_j(b) \end{cases} \qquad (2\text{-}3)$$

The values of these degrees of preference lie between 0 and 1. These degrees of preference are used to estimate the multi-criteria preference index of one alternative over another, based on the weights assigned to different criteria in the analysis. The multi-criteria preference index represents the extent of preference of the decision maker of one alternative over alternative considering all criteria simultaneously.

Each criterion $f_j(j = ,2.....k)$, has a specific preference function, P_j, and weight, w_j. The weight, w_j, represents the relative importance of the criteria, f_j. Therefore, the multi-criteria preference index, π of alternative a over b is represented as the weighted average of the degree preference P_j (a, b).

$$\pi(a,b) = \frac{\sum_{j}^{k} w_j\, P_j(a,b)}{\sum_{j}^{k} w_j} \tag{2-4}$$

Where $\pi(a, b)$ is the extent to which a is preferred to b over all the criteria and $\pi(b ,a)$ shows how b is preferred to a. $\pi(a, b)$ and $\pi(b, a)$ are computed for each pair of alternatives of N, to obtain a complete outranking. The leaving flow or positive outranking flow $\varphi^+(a)$ indicates the dominance of alternate a over other alternatives and is a measure of outranking character. Higher the value of $\varphi^+(a)$, better the alternative. On the other hand, entering flow or negative flow $\varphi^-(a)$, is the measure of outranked character i.e., how an alternative a is outranked by all the others. Lower the value of $\varphi^-(a)$, better the alternative. The net flow is the difference between these two flows. The leaving flow, $\varphi^+(a)$, the entering flow, $\varphi^-(a)$ and the resultant net flow, $\varphi(a)$, for each alternative can be calculated using the following multi-criteria preference index. Each alternative a is compared with $(n-1)$ other alternatives in N,

$$\varphi^+(a) = \frac{1}{n-1}\sum_{x\in N}\pi(a,x) \tag{2-5}$$

$$\varphi^-(a) = \frac{1}{n-1}\sum_{x\in N}\pi(x,a) \tag{2-6}$$

$$\varphi(a) = \varphi^+(a) - \varphi^-(a) \tag{2-7}$$

PROMETHEE I and PROMETHEE II methods are further explained in Appendix B.

2.2.2. Pellets as an energy source

Five types of pellets selected for this study are produced from different biomass feedstocks. The physical and chemical properties are not same for these pellets. The variations in physical properties are important for the final performance of the combustion system and in the choice of process and equipment. Chemical properties are the significant factor for assessing environmental pollution and ash-related operational problems.

Wood pellets are a clean and convenient fuel. They are mostly produced from sawdust, wood chips and wood shavings. The cost of transporting wood pellets is low compared to wood biomass, due to their uniform size and compressed form (Thek and Obernberger, 2004; Hamelink *et al*., 2005; Mani *et al*., 2006). Generally, field straws have a low moisture content compared to woody biomass. Combustion of straw pellets releases smaller amounts of particulates, sulfur, carbon monoxide, arsenic, carbon dioxide and other greenhouse gases than that if straw is used as fuel which is also true for wood pellet and wood combustion. However, high ash, nitrogen and chlorine content cause noxious and corrosive emissions for straw as well as straw pellet (Pastre 2002; Obernberger and Thek, 2004). Switchgrass (Panicum virgatum) has a high net energy yield per hectare and low pollutant gas emissions. Switchgrass is an ideal biomass energy source because of its moderate to high productivity, longevity, low water demand, nutrient efficiency, high quality of product and adaptability to most agricultural regions in North America (Jannasch *et al*., 2001). Alfalfa (Medicago sativa) is a high-yielding, nitrogen-fixing perennial crop. At least three harvests are possible during the Canadian growing season. The physical quality of alfalfa pellets may vary depending on the manufacturing process and the quality of the hay (Tabil, 1996). Poultry litter pellets are basically a mixture of bedding materials (sawdust, wheat hulls, straw hulls etc.) and manure generated by broiler and turkey production houses. Chemical emissions of particular concern include nitrogen and sulfur derivatives (Environment Canada, 1996; Livington, 2006). Due to the detrimental environmental impact of applying surplus poultry litter to cropland as fertilizer, poultry litter in the form of pellets have good potential as a fuel source (Timmenga & Associates Inc., 2003).

2.2.3. Input data and assumptions

Eleven different criteria are considered when comparing and ranking five different types of pellets. The criteria are selected based on the pellet users' perspective. Tables 2-1 and 2-2 show the input data and assumptions for each criterion and type of pellet selected for this study. Data on various parameters are adopted and estimated mainly from previous studies. Some information have been collected by personal communication and discussion with experts in this field, and from pellet manufacturers and users. An extensive literature review has been carried out to identify reliable sources of information. Finally, the criteria are categorized as being economic factors, environmental factors and technical factors. The production cost constitutes the economic factor in the analysis. Deposit formation, maturity of the production technology, bulk density, lower heating value, durability, storage time before degradation and acceptability to the user are all technical factors. Emissions of NOx, SOx, and CH_4 (methane) of pellets are the environmental factors for the analysis. A sensitivity analysis was performed by changing various parameters and input data to examine their impact on ranking.

Table 2-1: Input data for pellet selection

Alternatives	Production cost ($ $tonne^{-1}$)	Bulk density (kg m^{-3})	Lower heating value (MJ Kg^{-1})	Durability (%)	Storage time before degradation (year)	Acceptability to user	NOx emission (kg GJ^{-1})	SOx emission (kg GJ^{-1})	CH_4 emission (kg GJ^{-1})	Deposit formation (kg GJ^{-1})	Maturity of technology
Wood pellet	140.00[a]	650[f]	19.0 [i,] [f]	98[j]	5[m]	high	0.065[q]	0.040[i]	0.147[u]	0.03 [i][f]	high
Straw pellet	132.00[b]	600[f]	17.4 [i][f]	95[j]	5[m]	medium	0.090[i]	0.130[i]	0.149[v]	3.43 [i][f]	low
Switchgrass pellet	146.00[c]	635[d]	18.5[d]	96[c]	3[n]	low	0.145[r]	0.102[r]	0.008[w]	1.8 [y]	low
Alfalfa pellet	156.00[d]	560[g]	18.0[g]	95[k]	0.75[o]	low	0.000[s]	0.266[s]	0.77[v]	2.92 [k]	average
Poultry pellet	120.00[e]	780[h]	14.8[e]	45[l]	5[p]	low	2.500[t]	0.500[t]	0.007[x]	8.78[z]	low

[a] Porter *et al.,* 2008; [b] Sultana *et al*., 2010; [c] REAP-Canada, 2008; [d] Jannasch *et al*., 2001a; [e] Environment Canada, 1996; [g] Tabil and Sokhansanj, 1997; [h] McMullen *et al*., 2005 [i] Pastre, 2002; [j] Temmerman *et al*., 2006; [k] Tabil, 1996; [l] McMullen *et al*., 2004; [m] Wright, 2008; [n] Samson, 2008; [o] Khashtaghaza, 1997; [p] Fasina, 2008; [q] Johansson *et al.,* 2004; [r] MPCA, 2007; [s] Gary *et al*., 1996; [t] Mukhtar *et al.,* 2002; [u] Olsson, 2006; [v] Allen and Davis, 2000; [w] Qin *et al*., 2006; [x] ARI, 2001; [y] Jannasch, 2001; [z] Livington, 2006.

Criteria

Economic factor

Cost of production ($ per tonne) – It is obvious that the price of pellet will depend directly on the cost of producing pellets. The cost of production of straw pellet $132 per tonne was considered based on a pellet production capacity of 50,000 tonnes per annum (Sultana *et al.*, 2010). The plant operates 24 hours a day and 6 days a week i.e., for 300 days annually. Note that all the costs are in 2008 US$. At the same capacity, the cost of wood pellets was $140 per tonne (Porter *et al.*, 2008), assuming the raw material was wet sawdust with a moisture content of 40%. The cost of switchgrass pellets was $146 tonne^{-1} for a plant with a capacity of 53,000 tonnes per year (REAP-Canada, 2008). The cost saving of switchgrass pellets over alfalfa pellets was between $8 per tonne and $12 per tonne at the same plant capacity (Jannasch *et al.*, 2001). In this study the cost of alfalfa pellet production was considered $156 per tonne. The cost of poultry pellets was $120 per tonne from a plant having an annual production capacity of 46,000 tonnes (Environment Canada, 1996).

Technical factors

Deposit formation (kg per GJ of pellet burnt) – The detrimental effects of deposit formation are high furnace wear, reduction of heat transfer efficiency, drop in pressure and increased boiler corrosion.. These are eventually concerns for the utilization of pellets in the combustion systems. Most biomass materials have significant inorganic matter contents, which dominate nature of the biomass ash components and the other inorganic constituents. Ash is related to various issues such as slag formation, corrosion under deposit, erosion and ash abrasion of boiler wall. Straw contains potassium and sodium compounds which combine with silica during combustion and result in slagging and fouling. The ash content of wood pellets is much lower than that of straw and switchgrass pellets (Pastre, 2002; Jannasch *et al.*, 2001). The combustion of poultry litter is challenging because of the problem of high ash content and ash fusion (Timmenga & Associates Inc., 2003; Livington, 2006). There is a scarcity of data on the ash content of alfalfa pellets and hence, it is the ash content of alfalfa stem that was considered in this study (Tabil, 1996). Table 2-1 gives the ash content of different pellets used in this study.

Maturity of technology – The production technology for wood pellets is more mature than that for straw pellets (Pastre, 2002). This is evident from the number of plants making pellets today from sawdust. There are 80 wood-pellets plant in the USA and 33 plants in Canada (WPAC, 2011). As of now, there are some plants those produce straw pellet. For example, one plant in Denmark produces straw pellets with capacity 140,000 tons year^{-1} in addition to wood pellets (Koge, 2003)) and a straw-pellet plant in Missouri produces 100,000 tons year^{-1} (Campbell, 2007). Pellet production technology from energy crops are still in the research and development phase. Currently, some research is in progress on advancing the technology for producing switchgrass-based pellets (Samson and Duxbury, 2000; Jannasch *et al*., 2001a; Jannasch *et al*., 2001).Canada is the world's largest producer of alfalfa; however, this is used as animal feed not as fuel (Government of Saskatchewan, 2004). The alfalfa dehydration industry in Canada has conducted research on improving the physical characteristics of alfalfa pellets (Government of Saskatchewan, 2004). Power plants fueled by poultry litter are commercially generating electricity in the UK and Minnesota (Morrison, 2008); however, no power plant using poultry-litter pellets is yet available on a commercial scale.

Bulk density (kg per m^3) – Low bulk density has a negative effect on transportation cost and storage capacity. Studies (Tabil and Sokhansanj, 1997; Jannasch *et al.,* 2001; Obernberger and Thek, 2004; McMullen *et al*., 2005) have reported the bulk density of pellets (Table 2-1).

Lower heating value (MJ per kg) – This is the useful energy contained (dry basis) in a kilogram of fuel. The heating value is important for fuel utilization and plant design. A number of studies estimated the lower heating value of wood, straw, switchgrass, alfalfa and poultry pellets (Tabil and Sokhansanj, 1997; Jannasch *et al*., 2001; Obernberger and Thek, 2004; McMullen *et al*., 2005). The Lower heating values used in this study are shown in Table 2-1.

Durability (%) – Durability is one of the main parameters for handling pellets. The 'tumbling-can' method adopted by the American Society of Agricultural Biological Engineers (ASABE, 2003; standard S269.4) is used in this study for all data extracted from literatures (in Table 2-1). Low pellet durability results in problems like disturbances within pellet feeding systems, handling and transport difficulties, and inhomogeneous combustion of pellets (Temmerman *et al*., 2006). Comparing the durability of different pellets is difficult because it depends on many factors such as feedstock moisture content, feedstock particle size, use of steam conditioning, use of binders, equipment variations for making pellet and post production conditions (e.g., cooling, storage condition) (McMullen *et al*., 2004; Kaliyan and Morey, 2009).

Storage time before degradation (in years) – The time for which pellets can be stored before degradation is an important parameter for their selection. Deterioration depends on factors such as feedstock type, moisture content, chemical structure, and type of storage (e.g., covering, size of pile) (Lehtikangas, 2000). Wood and straw pellets can last more than 5 years without significant degradation if relative humidity, temperature and ventilation are controlled (Wright, 2008). Lehtikangas (2000) reported that storage of wood pellets for 5 months had a negative effect on durability if storage condition has not been controlled. Under good storage conditions, switchgrass pellets can last 1 to 3 years without any loss of quality (Samson, 2008), while alfalfa pellets degrade after 0.75 year (Khashtaghaza, 1997) and poultry pellets after 4-5 years (Fasina, 2008).

Acceptability to the user – Product acceptability depends on attributes such as usability, reliability and efficiency of use. Wood pellets are considered highly user-acceptable because people have used wood as a fuel for a long time. On the other hand, the acceptability of switchgrass is low because people are not very familiar with this energy crop (Jannasch *et al*., 2001a). Alfalfa is more often used as an animal feed than fuel (Tremblay, 2008), and poultry pellets are not very acceptable because of their dust and odor (Tabler, 2008).

It is difficult to assign a quantitative value to criteria such as acceptability to the user and maturity of technology; therefore, a qualitative scale was used for comparison. The values for these three qualitative criteria were selected based on the judgment of the authors and in discussion with experts in the industry. A three-point semantic scaling technique was used for analyzing those criteria (1 = low, 2 = average/medium, 3 = high).

Environmental factors

NOx emission (kg per GJ of pellet burnt) –There are more nitrogen (N), sulphur (S) and chlorine (Cl) present in straw than in wood (Pastre, 2002). During the combustion process, these elements are released as gases and may produce atmospheric pollutants such as nitrogen oxides (NO, NO_2), sulphur dioxide (SO_2), hydrogen chloride (HCl) and chlorinated hydrocarbons (Pastre, 2002). Incomplete combustion may form methane, particulates and tar. NOx formation is a complex process. It depends on fuel's nitrogen content and specific combustion conditions. NOx emissions increase as the N content of the fuel increases. Due to the scarcity of data on emissions from straw, switchgrass, alfalfa and poultry pellets, the emissions data during combustion of their feedstock are considered in this paper (Gary *et al*., 1996; Mukhtar *et al*., 2002; Pastre 2002; Johansson *et al*., 2004; MPCA, 2007). Table 2-1 lists the emissions data used in this study.

SOx emission (kg per GJ of pellet burnt) – The burning of wood, straw, alfalfa, switchgrass or poultry litter emits sulfur into the atmosphere in the form of SO_2 and SO_3. After the burning of pellets, 99% of a feedstock's sulfur is released in the form of SO_2 and remaining is present in the form of SO_3 (Pastre, 2002). Wood pellets emit less SO_2 compared to other pellets (Gary *et al*., 1996; Mukhtar *et al*., 2002; Pastre 2002; MPCA, 2007). SO_2 emission data are given in Table 2-1.

CH_4 emission (kg per GJ of pellet burnt) - Methane is another important organic compound which is emitted during biomass burning because of its carbon content. Methane emission largely depends on the burning method; it decreases with increasing combustion efficiency. The methane emissions for pellets are reported in different studies (Allen and Davis, 2000; ARI, 2001; Olsson, 2006; Qin et a., 2006). The data used in this study are shown in Table 2-1.

Weights

Assigning weights to criteria is an important step in multi-criteria assessment. Weight expresses the relative importance of one criterion over another. It reflects not only what is deemed important to the decision maker, but also the decision maker's judgment on the relative importance of that criterion. In this study, the base case scenario was developed by assigning equal weights to each criterion. The sensitivity analysis is discussed later in this chapter by varying weights of the criteria. In the following two scenarios, different weights were assigned to the criteria so as to maintain identical alternatives, criteria, preference functions, and threshold levels. In the economic and environmental scenarios, more weight were assigned to economic criteria and environmental criteria respectively. Table 2-2 shows weights for various criteria in both scenarios.

Preference functions and threshold values

A preference function was associated with each criterion. Six preference functions are available in the literature: usual, U-shaped, V-shaped, level, linear and Gaussian (Brans and Vincke, 1985, Brans *et al.,* 1986, Kumar *et al,.* 2006 and Mohammadabadi *et al.*, 2009). The selection of preference functions for this study was based on the authors' judgment as well as insight gained from other studies (Brans and Vincke, 1985; Brans *et al,.* 1986; Georgopoulou *et al.*, 1998; Hyde *et al.*, 2003; Haralambopouloas and Potatidis, 2003; Kumar *et al.* 2006; Buchholz *et al*., 2009; and Mohammadabadi *et al.* 2009).

The V-shape and Linear preference functions are best suited for quantitative criteria because of the nature of the functions. The main difference between V-shape and Linear preference function is that an indifference threshold is introduced in the Linear preference function. So we can say that V-shape preference function is a special case of Linear preference function. The Gaussian preference function is less often used because it is difficult to parameterize. Usual and Level preference functions are best suited for qualitative criteria. If there is only one level (yes/no) in the criteria scale the Usual preference function should be the best choice. The Level function works well if small numbers of different levels (3-point or 5-point) on the criteria scale are considered. The U-shape preference function is another special case of Level preference function. Different preference functions are shown in Table B1 in Appendix.

Table 2-2 gives selected preference functions and indifference and preference thresholds. The indifference threshold (q) represents the largest value below which there is no preference for one alternative over another. The preference threshold (p) represents the smallest value above which there is a strict preference for one alternative over another. In this study 5% and 10% of the average input data values for the criteria are taken as q and p values, respectively. These values are selected based on our own judgment which is consistent with previous studies (Kumar *et al.,* 2006 and Mohammadabadi *et al.*, 2009). A sensitivity analysis for q and p values is discussed in subsequent sections.

Objective functions

In multi-objective decision problems, there is usually more than one objective function. In this study for each of the criteria there is an objective function. It is assumed that lower production costs, emissions and deposit formations are desirable. Therefore, it is preferable to minimize these criteria. On the other hand, higher bulk density, heating value, acceptability to user, storage time before degradation and maturity of technology are desirable. These criteria are sought to be maximized.

Table 2-2: Assumptions for pellet selection (Base case, Economic and Environmental scenario)

Criteria	Production cost	Bulk density	Lower calorific value	Durability	Storage time before degradation	Acceptability to user	NOx emission	SOx emission	CH_4 emission	Deposit formation	Maturity of technology
Unit	$ $tonne^{-1}$	Kg m^{-3}	MJ kg^{-1}	%	Years		Kg GJ^{-1}	Kg GJ^{-1}	Kg GJ^{-1}	Kg GJ^{-1}	
Max/Min	Min	Max	Max	Max	Max	Max	Min	Min	Min	Min	Max
Type	Quantitative	Quantitative	Quantitative	Quantitative	Quantitative	Qualitative	Quantitative	Quantitative	Quantitative	Quantitative	Qualitative
Weight											
Base case	1	1	1	1	1	1	1	1	1	1	1
Economic	2	1	1	1	1	1	1	1	1	1	1
Environmental	1	1	1	1	1	1	2	2	2	1	1
Function	Linear	Linear	Linear	Linear	Linear	Level	Linear	Linear	Linear	Linear	Level
Preference Threshold	14.00	64	1.7	8.6	1.9	2.5	0.06	0.02	0.02	0.38	2.5
Indifference Threshold	7.00	32	0.84	4.3	0.95	0.5	0.03	0.01	0.01	0.19	0.5

2.3. Results and Discussion

Table 2-3 shows the results of PROMETHEE I (partial ranking) and PROMETHEE II (complete ranking) rankings for the base case scenario. In this scenario, using PROMETHEE II, wood pellets ranked first, followed by pellets produced from switchgrass, straw, alfalfa and poultry. This ranking is obvious from the computed net flow values given in Table 2-3. Similar results were also obtained using PROMETHEE I for the base case scenario. Except for production cost, all other factors favor wood pellets, especially environmental and technical factors such as SOx, NOx and CH_4 emissions, deposit formation, higher maturity of technology, acceptability to user, lower heating value and durability., NOx, SOx and CH_4 emissions and deposit formation are determining factors for the higher ranking of switchgrass pellets; whereas production cost, acceptability to the user and maturity of technology pulled back switchgrass pellets. Low bulk density, comparatively lower heating value and high deposit formation are major factors in determining straw pellets' rank. Production cost and bulk density are the criteria which favor poultry pellets. High production cost, low bulk density, low storage time before degradation, less acceptability to user and high SOx and CH_4 emissions and deposit formation put alfalfa pellets in fifth place.

Using PROMETHEE II in the economic scenario, wood pellets showed a better result than other pellets. However, unlike the base case, straw pellets come up to the second position as more weightage has been given to the economic factor i.e., production cost. These are followed by switchgrass pellets as third and then poultry and alfalfa pellets in order. Using PROMETHEE I, wood pellets ranked first followed by straw pellets. Switchgrass and poultry pellets were incomparable with each other on the grounds that the leaving and entering flows contradicted the rule based on Eq. (B-3) in the Appendix. Looking at the original data (Table 2-1) Switchgrass pellets score well environmentally and technically but are rather expensive.

Poultry pellets, on the other hand, are not so good environmentally and technically but are the cheapest option. By applying more weightage to the economic factor, the alfalfa pellet, which was the costliest one among other pellets in the base case, become the most unfavorable one in the economic scenario. Though production cost was weighted more than other criteria in the economic scenario, it is the combined effect of criteria weights that control the ranking.

In the environmental scenario, based on PROMETHEE I, wood pellets ranked highest (Table 2-3), followed by switchgrass, straw, alfalfa and poultry pellets. In PROMETHEE II the result is same as PROMETHEE I. In both PROMETHEE I and II, wood pellets ranked first, mainly because of their relatively low emissions and deposit formation. Low emissions (NOx, SOx and CH_4) also enabled switchgrass pellets to rank as the second most desirable pellets. Similarly, straw pellets have low emissions of NOx and little higher (%) emission of SOx and CH_4 than switchgrass pellets and were ranked third. Alfalfa ranked fourth because it has relatively high SOx emissions and high deposit formation. Poultry pellets were the least desirable option in this scenario due to their poor performance on all environmental criteria.

2.3.1. Sensitivity Analyses

Sensitivity analyses of important input parameters were performed to determine their impact on the ranking of the pellets.

The sensitivity analysis on weight

To test the sensitivity of weights in the three scenarios, the stability intervals of the weights were calculated for each scenario. The stability interval is the range of weights for each criterion for which there is no change in the ranking of alternatives. The method of determining stability intervals in the Decision

Lab software is based on the procedure explained by Mareschal (1988). Table 2-4 shows assigned weights and upper and lower stability interval limits for each criterion for base case, economic and environmental scenarios.

Table 2-3: Results in different scenarios

Options	Leaving flow $\Phi^+(a)$	Entering flow $\Phi^-(a)$	Net flow Φ (a)	Ranking *PROMETHEE I*	Ranking *PROMETHEE II*
Base Case Scenario					
Wood pellet	0.54	0.07	0.46	1	1
Straw pellet	0.31	0.32	-0.007	3	3
Switchgrass pellet	0.32	0.29	0.023	2	2
Alfalfa pellet	0.24	0.49	-0.25	5	5
Poultry pellet	0.26	0.50	-0.23	4	4
Economic Scenario					
Wood pellet	0.51	0.09	0.42	1	1
Straw pellet	0.33	0.31	0.02	2	2
Switchgrass pellet	0.29	0.31	-0.01	3	3
Alfalfa pellet	0.22	0.51	-0.29	5	5
Poultry pellet	0.32	0.46	-0.14	4	4
Environmental Scenario					
Wood pellet	0.54	0.09	0.39	1	1
Straw pellet	0.35	0.36	-0.01	3	3
Switchgrass pellet	0.35	0.30	0.05	2	2
Alfalfa pellet	0.28	0.49	-0.21	4	4
Poultry pellet	0.24	0.54	-0.29	5	5

In the base case scenario, bulk density, durability, SOx emissions, and deposit formation had large stability intervals. This means that changes in weights (within the interval) assigned to these criteria will not change the ranking of the alternatives. Other criteria had narrow range of stability intervals implying that the ranking is sensitive to the weights given to these criteria. In the economic scenario, bulk density, durability, SOx emissions and deposit formation showed large stability intervals similar to those in the base case scenario. Storage time before degradation, acceptability to users, and the maturity of technology are the criteria closer to the upper limit of the interval. Lower heating value, and CH_4 emission are the criteria closer to the lower limit of their interval. The small stability intervals of these criteria indicate that ranking are more sensitive to these criteria in the economic scenario.

In the environmental scenario, bulk density, durability, SOx emissions, and deposit formation have wide stability intervals but the other remaining criteria have narrow intervals. In this scenario, ranking is sensitive to, lower heating value, storage time before degradation, acceptability to user, CH_4 emission, and maturity of technology.

From all three scenarios, it appears that the ranking is more sensitive to the weights given to lower heating value, storage time before degradation, acceptability to user, CH_4 emission, and the maturity of technology.

The sensitivity analysis on preference function

This sensitivity analysis was done by replacing the Linear preference function with the V-shape preference function for all quantitative criteria keeping preference threshold same. The preference functions of qualitative criteria were not changed because the Level preference function describe the qualitative criteria best if multiple levels on the criteria scale is used. The results show no change in the ranking in base case, economic and environmental scenarios. The wood pellet is still the best performer followed by switchgrass, straw, alfalfa and poultry litter pellets.

Table 2-4: Stability interval of weights for different scenarios

Criteria	Weight (%)	Min (%)	Max (%)	Weight (%)	Min (%)	Max (%)	Weight (%)	Min (%)	Max (%)
	Base Case Scenario			***Economic Scenario***			***Environmental Scenario***		
Production cost	9.09	8.35	12.59	16.67	12.59	23.79	7.14	0.00	11.57
Bulk density	9.09	0.00	68.61	8.33	29.12	79.07	7.14	0.00	100.00
Lower heating Value	9.09	1.48	21.77	8.33	6.18	25.15	7.14	0.00	17.30
Durability	9.09	0.00	100.00	8.33	6.18	100.00	7.14	0.00	100.00
Storage time before degradation	9.09	0.00	14.67	8.33	0.00	7.93	7.14	0.00	14.90
Acceptability to the user	9.09	0.00	20.66	8.33	0.00	11.97	7.14	0.00	22.09
NOx emission	9.09	18.45	30.35	8.33	8.21	33.38	14.29	25.4	100.00
SOx emission	9.09	0.00	100.00	8.33	4.70	100.00	14.29	0.00	100.00
CH_4 emissions	9.09	0.00	16.95	8.33	6.49	17.19	14.29	0.00	20.80
Deposit formation	9.09	0.00	100.00	8.33	5.48	100.00	7.14	0.00	100.00
Maturity of technology	9.09	0.00	21.14	8.33	0.00	9.46	7.14	0.00	26.81

The sensitivity analysis on thresholds

The ranking is not only a function of weights assigned to criteria and preference function, but also to preference and indifference thresholds. In order to study the effects of the values selected for preference and indifference thresholds, a sensitivity analysis was performed. For the base case scenario, the values for each threshold were changed by ±10% and ± 20% from the original value for both p and q. Table 2-5 shows ranking of pellets at various threshold values in the base case scenario using PROMETHEE I and II. In the base case scenario, changing the thresholds by ±10% and ±20% neither changed the order of the complete ranking nor the partial ranking. The base case scenario was not sensitive to changes in threshold values if p and q values were either decreased or increased simultaneously. On the other hand, by increasing p and decreasing q both by 10% at a time result in the change of the ranking. The wood pellet becomes the first, followed by pellets from straw, switchgrass, alfalfa and poultry in order.

The sensitivity analysis on production cost

The production cost was considered in the sensitivity analysis because it is a key parameter. Most of the input criteria are the physical or chemical properties of pellets which would not vary at large extend at different locations. However, production costs of pellets are location specific. The cost of production of each type of pellets was changed ±25% at a time from the original values of the base case scenario and rankings were analyzed. Table 2-5 shows the impact of changing production cost of pellets individually on their ranking. The Pro. cost wood (+25%) and Pro. cost wood (-25%) (similarly for other feedstocks) are the new scenarios in which the pellet production costs are increased and decreased by 25% at a time, respectively. When production costs of pellets are increased or decreased by 25% for wood, alfalfa and poultry litter pellets, the ranking is nearly the same as in the base case scenario except the scenario Pro. cost switchgrass (+25%) and Pro. cost straw (-25%). In the later scenarios straw pellets are ranked second. A further checking is

Table 2-5: Results of sensitivity analysis

Options	Threshold (+10%)		Threshold (-10%)		Threshold (+20%)		Threshold (-20%)		*p* (+10%) *q* (-10%)		
	P-I	P-II	P-I	P-II	P-I	P-II	P-I	P-II	P-I	P-II	P-II
Wood pellet	1	1	1	1	1	1	1	1	1	1	1
Straw pellet	3	3	3	3	3	3	3	3	2	2	2
Switchgrass Pellet	2	2	2	2	2	2	2	2	3	3	3
Alfalfa pellet	5	5	5	5	4	4	5	5	4	4	4
Poultry pellet	4	4	4	4	5	5	4	4	5	5	5

Options	Pro. cost_wood (+25%)		Pro. cost straw (+25%)		Pro. cost switchgrass (+25%)		Pro. cost alfalfa (+25%)		Pro. cost poultry (+25%)	
	P-I	P-II	P-I	P-II	P-I	P-II	P-I	P-II	P-I	P-II
Wood pellet	1	1	1	1	1	1	1	1	1	1
Straw pellet	3	3	3	3	2	2	3	3	3	3
Switchgrass pellet	2	2	2	2	3	3	2	2	2	2
Alfalfa pellet	4	4	4	4	4	4	5	5	4	4
Poultry pellet	5	5	5	5	5	5	4	4	5	5

Options	Pro. Cost wood (-25%)		Pro. cost straw (-25%)		Pro. cost switchgrass (-25%)		Pro. cost alfalfa (-25%)		Pro. cost poultry (-25%)	
	P-I	P-II	P-I	P-II	P-I	P-II	P-I	P-II	P-I	P-II
Wood pellet	1	1	1	1	1	1	1	1	1	1
Straw pellet	3	3	2	2	3	3	3	3	3	3
Switchgrass pellet	2	2	3	3	2	2	2	2	2	2
Alfalfa pellet	4	4	4	4	4	4	4	4	5	5
Poultry pellet	5	5	5	5	5	5	5	5	4	4

*P-I refers to *PROMETHEE I* ranking.
*P-II refers to *PROMETHEE II* ranking.
*Pro. Cost refers to Production cost.

performed by increasing switchgrass pellet production costs or decreasing straw pellet production costs at different percentages. It is found that the change between the second and third positions of ranking of switchgrass and straw pellets occurs at about 10% production cost change from the base case. That means by increasing the switchgrass pellet production cost or by decreasing the straw pellet production cost by more than 10% would change the ranking. It is evident that production cost is a sensitive criterion for ranking straw and switchgrass pellets.

The model without qualitative criteria

The model was run without qualitative criteria to test their effect on the model and how they influence the ranking of pellets. The results are shown in Table 2-6. Compared to the base case, the ranking did not change when qualitative criteria were excluded from the analysis. Only difference is observed in economic scenario where switchgrass pellets ranked second position instead of straw pellets and alfalfa pellets came ahead of poultry litter pellets when qualitative criteria are excluded from the model. This implies that the selected qualitative criteria did not dominate over quantitative criteria in pellet ranking.

Table 2-6: Results of scenarios without considering qualitative factors

Options	Net flow Φ (a)	Ranking *PROMETHEE II*	Net flow Φ (a)	Ranking *PROMETHEE II*	Net flow Φ (a)	Ranking *PROMETHEE II*
	Base Case(w/o qualitative)		***Economic Scenario (w/o qualitative)***		***Environmental Scenario (w/o qualitative)***	
Wood pellet	0.46	1	0.41	1	0.45	1
Straw pellet	-0.01	3	0.03	3	0.11	3
Switchgrass pellet	0.08	2	0.04	2	-0.01	2
Alfalfa pellet	-0.30	5	-0.36	5	-0.25	4
Poultry pellet	-0.23	4	-0.11	4	-0.30	5

*w/o refer to without.

The wood pellet's superiority to other pellets can be explained by its high bulk density, low friability, lower emissions, and low deposit formation compared to other pellets. Wood pellets have low alkalis and halides as compared to straw pellets and hence lower deposit formation. Switchgrass pellets ranked second (except in economic scenario) in the multicriteria analysis because of their low ash content, low emissions, and long life. However, switchgrass is especially suitable for warm weather and has high production cost. Further research is required to improve the cost of producing switchgrass pellets. Straw pellets are a good option, as it is produced from a residue and majority of this is not utilized for energy purpose in North America today. When used for large scale production of pellets, straw need to be collected over a large area as the yield of straw (dry tonnes per hectare) is low. This results in higher cost of delivery of straw. Although straw pellets require less energy for production, they have some drawbacks related to combustion such as fouling, slagging and corrosion due to presence of alkalis and halides. Other criteria such as low bulk density, and lower heating value held straw pellets back in third position. The combustion performance of straw could be improved if the alkalis and halides are reduced in the straw. The production cost and storage time before degradation favors selection of poultry pellets. All other factors, especially, higher emissions, more deposit formation drag poultry pellets to fourth place in ranking as a fuel option. Alfalfa pellets are popular as an animal feed but not as a fuel option. These are still not attractive as a fuel for economic reasons. Finally, unfavorable qualities like low bulk density, low storage time before degradation, high SOx emissions and high deposit formation place alfalfa pellets in the last position. In case of environmental scenario the alfalfa pellet improves its rank from fifth to fourth position because of their favorable environmental criteria especially SOx and NOx emissions.

There are some limitations which exist in the application of PROMETHEE method. The main limitation is associated with the assignment of weight and preference function to the criteria. The selection of the preference function and their associated thresholds for each criterion depend on the decision maker. This could be different for the different stakeholders. Therefore, these forms of limitations are assessed via sensitivity analyses which were performed in this study.

2.4. Conclusions

A multi-criteria assessment model was developed for ranking various pellets. The model was based on the integration of quantitative and qualitative criteria. In this study, five types of pellets were ranked with regard to eleven criteria: production cost, bulk density, lower heating value, durability, storage time before degradation, acceptability to the user, NOx emissions, SOx emissions, CH_4 emission, and deposit formation. Besides the base case scenario where weights given to all criteria were kept equal, two separate scenarios were developed by varying weights to emphasize the economic and environmental parameters in the economic scenario and the environmental scenario, respectively.

Results from the base case scenario show that wood pellets were the best among the five alternatives, followed by switchgrass, straw, poultry and alfalfa pellets. In the economic scenario, the production cost was of greater importance than other criteria. The ranking was changed such that wood pellets and switchgrass pellets interchanged their positions while other pellets were in the same order as the base case. In the environmental scenario, NOx, SOx, and CH_4 emissions were assigned higher importance than other criteria. The ranking order of pellets in this scenario was same as in the base case scenario except that the poultry and alfafa pellets swapped their positions. Either increasing or decreasing the preference and indifference threshold values simultaneously by 10% and 20% the order of the ranking did not change compared to the base case scenario. On the other hand, by increasing p and decreasing q both by 10% at a time result in the change of the preference rank. The ranking of pellets did not changed from the base case if the production cost was varied ±25% for one type of pellets at a time. The exception to this insensitivity was observed if the production cost of switchgrass pellets was increased or that for straw pellet was decreased by more than 10% from the base case. Then straw pellets ranked over the switchgrass pellets. Sensitivity analyses on weights, threshold values and production cost indicate the ranking was reasonably stable. Same results were obtained excluding the qualitative criteria which indicate the stronger influence of quantitative counterparts.

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Chapter 3. Development of Agri-Pellet Production Cost and Optimum Size

3.1. Introduction

Energy security, global warming and utilization of local resources are the driving factors for using biomass as an alternative energy source. Biomass is nearly carbon neutral, hence its utilization for fuel helps mitigate greenhouse gas emissions. Studies have estimated the amount of agricultural residue (e.g. wheat and barley straw) available in Western Canada (Sokhansanj *et al.*, 2006). Currently large amounts of these agricultural residues are left in the field to rot, ultimately releasing carbon dioxide to the atmosphere. This biomass could be used to produce pellets which is a form of fuel. Biomass, including agricultural residue, is not competitive with fossil fuel (e.g. coal) for large scale power production in Western Canada (Kumar *et al.,* 2003). It can compete only if supported by carbon credits (Kumar *et al.,* 2003). The value of carbon credits required to make biomass competitive as fuel production depends on the type of biomass and the technology for its conversion to fuel (Kumar *et al.,* 2003).

Biomass has low energy density (MJ m^{-3}) and low yield per unit area (dry tonnes ha^{-1}) (Kumar *et al.,* 2003). These two key factors result in a high cost of biomass delivery, which increases the total biomass processing cost. Densified biomass, especially pellets has drawn attention due to its superiority over raw biomass in terms of its physical and combustion characteristics (Oberberger and Thek, 2004). Like other biomass feedstocks, pellets are carbon neutral, i.e., the carbon emitted

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during their combustion is taken up in the re-growth of the biomass used to produce them. Moreover, pellets have other value-added advantages over raw biomass. Pelletization reduces moisture content, increases energy content (MJ kg^{-1}), enhances combustion efficiency, and produces greater homogeneity of composition as compared to raw biomass (Obernberger and Thek, 2004). The bulk density of biomass pellet is 4-10 times that of 'as received biomass' (Karwandy, 2007). This makes for easier handling and transport. All these factors make pellets one of the more attractive forms of biomass-based energy.

Wood-based pellets are produced commercially around the world (e.g. USDA, 2009) but there is limited production of agricultural biomass-based pellets. Few studies have reported results on the economics of pellet production. Mani *et al.* (2006a) estimated the cost of producing pellets from sawdust, reporting that these pellets could be economically produced at a cost of \$51 $tonne^{-1}$ for a plant with a capacity of 45,000 tonne $year^{-1}$. The production cost could be further reduced by using larger plants to gain benefits of economy of scale. Thek and Obernberger (2004) did a detailed study of sawdust pellet production in a European setting. Urbonowski (2005) derived the capital cost estimate from this study and used in designing a Canadian pellet plant. Hoque *et al.* (2006) estimated the economics of wood pellet production for export market. Other studies such as NEOS (1995) and William and Lynch (1995) have worked on the cost of wood pellet production. Samson and Duxbury (2000) estimated the cost of switchgrass pellets for commercial purposes. Pastre (2002) analyzed the economics of straw and wood pellets from a European perspective and overviewed some technical problems related to the production and utilization of pellets made from agricultural residue. Campbell (2007) estimated the cost of straw pellets at different capacities. Fasina *et al.* (2006) estimated the cost of pelleting switchgrass, peanut hull and poultry litter for heating greenhouses. There is little data, however, on the details of producing agricultural biomass-based pellets and how the cost of these varies according to the scale of the production plants.

The economics of biomass processing facilities is different from that of fossil-fuel-based energy facilities. For the latter, larger plants are more cost effective, whereas, in the case of biomass-processing facilities, there is a trade-off between the cost of transporting biomass to the facility and the capital cost of the facility. The cost of transportation of biomass increases as the size of the processing facility increases, because the area for collecting field-sourced biomass increases. The capital cost per unit of output decreases as the size of the facility increases, because there economies of scale benefits. As a result of the trade-off between the two costs, there is a size of facility at which the cost of processing biomass is minimal. This is the economically optimum size of the biomass utilization facility. The development of pellet production plants of this size reduces the total cost of producing of pellets. This concept has been applied to the production of fuels and electricity from biomass (Larson and Harrison, 1997; Dornburg and Faaij, 2001; Mcllveen-Wright *et al.,* 2001). Kumar *et al.* (2003) estimated the optimal size for power plants using three biomass sources: straw, whole forest and forest residue. Jenkin (1997) estimated the optimal size for biomass utilization facilities under constant and variable costs. Nguyen and Prince (1996) determined the optimal size for bio-ethanol plants processing sugarcane and sweet sorghum. Walla and Schneeberger (2008) estimated the optimal size of a biogas plant. Other studies have assessed biomass economics from a general perspective (Overend, 1982; Larson and Harrison, 1997; Dornburg and Faaij, 2001; Mcllveen-Wright *et al.,* 2001). However, none of these studies estimated the optimal size for an agricultural biomass-based pellet production plant. There is very little information available on the economically optimum size for facilities producing agricultural biomass-based pellets.

The key objective of this research is to develop a data intensive techno-economic model for assessing the economic viability of using agricultural residue for pellet production. Specific objectives include:

- Estimation of pellet production cost ($ per tonne of pellets) from agricultural biomass (e.g. wheat, barley and oat straw) in Western Canada;
- Determination of the optimum size of the pellet production plant based on agricultural biomass; and,
- Development of cost curves to study the variation in pellet production cost as the size of the pellet production plant varies.

The scope of this research is to conduct a techno-economic assessment for developing a straw pellet plant operating for 30 years using wheat, barley and oat straw. This includes estimating the cost of all operations including harvesting and collection, handling, storage, transportation, and pellet production.

3.2. Current Technology for Pellet Production

Pellet production is a combination of sequential steps including preprocessing, drying, grinding, pelleting, cooling, screening, and bagging. These processes play an important role in the techno-economic analysis. A detailed review is provided elsewhere in the literature (e.g., NEOS, 1995; William and Lynch, 1995; Samson and Duxbury, 2000; Pastre, 2002; Thek and Obernberger, 2004; Hoque *et al.*, 2006; Mani *et al,* 2006a; Wolf *et al,* 2006; Campbell, 2007; Karwandy, 2007).

Usually straw for processing into pellets comes in the form of round or rectangular bales. Chopping of straw to reduce its length is the first step. The length of the straw is reduced to 2.5 to 10 cm (Jannasch *et al.,* 2001) using a tub grinder or shredder. If straw has high moisture content, drying is used to reduce the feedstock moisture to a level suitable for pelleting. The average received moisture content of straw before the drying process is 15%; after drying it is 8-10% (Campbell, 2007). Dryer size should be appropriate; over-sizing can increase capital and operating costs significantly. If straw is delivered to the pellet plant with moisture content lower than 12% drying may be bypassed (Campbell, 2007). The rotary drum dryer is the one most commonly used in pellet production plants (Campbell, 2007; Karwandy, 2007). There is an additional cost for the associated hopper, bin, and handling system if the biomass fuel requires drying.

The output of the dryer and tub grinder or shredder is then ground in a hammer mill to a small uniform size of 3.2 mm or less (Mani *et al.,* 2006b). In other words, particle size reduction for pelletization is a two-step process: chopping by tub grinder or shredder and then grinding by a hammermill. The particle size is controlled through the hammer mill's changeable screen. Small particles increase the density and hardness of the pellets but very finely ground feedstock loses its fibrous characteristic (NEOS, 1995). Grinding straw requires more energy than grinding woody biomass, and therefore costs more.

The lignin content of wood is high and generally sufficient to bind wood pellets properly, but straw requires conditioning to achieve enough strength to provide durable pellets and minimize fines (Karwandy, 2007). Conditioning, which can be done with steam or hot water to soften the fibrous material in straw, and may require the inclusion of binder material. Usually the conditioning system is an integral part of pellet mill. The requirement of steam for conditioning purpose is approximately 4% of total amount of biomass feedstock used (Thek and Obernberger, 2004). At times binders such as starch, molasses, paraffin, or lignin sulphate are added to increase the pellet durability. Conditioned feedstock is fed into a pellet mill where rollers extrude it, forcing it to pass through die holes which effectively compress it into pellets. Adjustable knives attached to the pellet mill cut the pellets into desired length. A pellet mill has different feed rates over its die life. For example, a new pellet mill may run at a rate of 4.5 tonnes per hour, but, when half worn, it may need to run at 3.5 tonnes per hour, to maintain the required pellet quality (Wright, 2008). Straw has a higher mineral content and is therefore more abrasive than wood. The pellet mill configuration including the effective die length, feed rate and rotating speed is set up differently for straw than for wood pellets. Operating parameter including die temperature, pressure, and die/roller configuration determine pelleting efficiency (Campbell, 2007). Pellets leaving the pellet mill at a high temperature and with excess moisture are then cooled and dried using forced air over a screen to gently cool the hot fragile pellets from 95-100^{0}C to 25^{0}C. This results in increased hardness and durability of the pellets, and removes fines. The final moisture content is typically in the range of 5 to 8%.

Screening is required to separate residual fines from the finished pellets before bagging. Fines and fragments collected from screening are returned to the dryer or pelletizer. If fines exceed 3% of the product issuing from the screening process there is a problem with feedstock or the pelleting process which needs to be corrected (Campbell, 2007). The last step of the pelleting process is to fill the appropriate (typically 18 kg) amount of pellets into bags and seal them. The bagging system may be manual, semi-automatic or fully automatic depending on the size of the plant.

3.3. Methodology of Techno-Economic Analysis and Optimization

Detailed data collection was carried out for the development of a data intensive techno-economic model of agricultural biomass pellet production. Various parameters were developed for the pellet production plants and also taken from the existing literature. The determination of cost was based on data taken from the literature, on personal communication with pellet plant manufacturers, equipment suppliers, and experts, and author developed data.

The techno-economic model was developed for a straw pellet plant operating for 30 years. All life cycle costs of the pellets were considered, including the cost of obtaining the straw, transporting to pellet plant, and producing pellets. Costs incurred by the plant for the production of pellets include capital cost, energy cost, employee cost, and consumable cost. To develop the model, yields of wheat, barley and oats were considered. The biomass procurement area was determined to estimate the transportation cost. The scale factors for all the equipment related to pellet production were determined based on the data of previous studies. All costs associated with pellet production were added to the field and transportation costs to obtain the total cost of pellet production. Iterations were carried out to obtain the minimum cost of producing pellets. The capacity corresponding to the minimum cost of pellet production is the optimal size of the processing plant. The optimum size of the plant was determined for average, maximum and minimum biomass yields. The following sections demonstrate the application of this methodology of techno-economic assessment and optimization to agricultural pellet production in Western Canada.

3.4. Assessment of Availability of Straw

Considering the variability of production and crop supply, the annual volume of straw that potentially could be procured in a particular region can be assessed. The actual amount depends on many factors which include biomass species, biomass yield, location, climate, time of harvest, and the technology used for the harvesting and collection of the biomass. The yield of residue is an important parameter for determining the capacity and location of a bioenergy facility. It eventually affects the production cost.

The year-to-year supply availability of net crop residue (straw) is an important consideration for the development and operation of any bioenergy facility. The lifespan of a typical bioenergy facility is 25 to 30 years which requires continuous and constant supply of feedstock. This is particularly true for facilities which depend on annual crop production.

In Western Canada (Alberta), the total average production of wheat, barley and oats over the last twelve years (1997- 2008) has been 6.8, 6.3 and 0.72 million tonnes yr^{-1}, respectively. Since straw yield is not measured by farmers, the available straw production volumes are typically determined by measuring and applying straw to grain mass ratios. The average yields of wheat, barley and oats are 2.66, 3.03 and 2.49 green tonnes ha^{-1}, respectively. Different levels of straw to grain mass ratios were recommended in different studies (Stumborg *et al*., 1996; Klass, 1998; Levelton *et a*l., 2000; PAMI, 2001; PFRA, 2003; Sokahnsanj *et al.,* 2006; Sokhansanj and Fenton, 2006; Liu, 2008). After an extensive analysis of all the values, the ratios adopted in this study for estimating crop residue for wheat, barley and oats are 1.1, 0.8 and 1.1, respectively. To determine the net yield of straw, additional factors have been taken into consideration. Some residue is retained for soil conservations, some is left on the field in accordance with the removal efficiency of the harvesting machine, and some is needed for livestock feeding, bedding and mulching. There is a small amount of straw lost through handling, transport and storage. The quantity of straw is further reduced in accordance with its moisture content. A portion of available straw must remain on the field to prevent soil erosion and maintain soil health and fertility. Previous studies estimated different amounts of straw for soil conservation (Lindstorm *et al,* 1979; Stumborg *et al.,* 1996; Campbell and Coxworth, 1999; Kline, 2000; Sokahnsanj *et al.,* 2006; Liu, 2008). Considering all the estimated values from the literature, an amount of 0.75 tonne ha^{-1} was allocated to soil conservation in this study. Some of the residues are used for livestock feeding, bedding and mulching. Based on Sokhansanj *et al.* (2006), Alberta's annual straw requirement for livestock is considered to be 3.2 Mt for 4.85 ha of land. In this study, the amount for livestock feeding and bedding was 0.66 tonne ha^{-1}. The total yield was further reduced by a number of factors, such as the portion of straw that a harvesting machine is capable of removing. Several earlier studies have reported the harvest losses (e.g., Sheheen *et al.,* 2003; Perlack *et al.,* 2005; Sokhansanj and Fenton, 2006; Liu, 2008). Based on all the available data a conservative estimate of 30% was used for harvest loss in this study. Based on previous studies (Perlack and Turhollow, 2002; Hamelinck *et al.,* 2005; Liu, 2007), the storage and transportation loss was assumed to be 15%. Of this, field loss was 3%, handling loss was 5% (Liu, 2007) and storage loss was 7% (3.5% for each storage) (Hamelinck *et al.*, 2005). All these losses are shown in Table 3-1.

In this study, the assumed moisture content of the straw was 14%, wet basis. After considering all the factors mentioned above, the average net yields of wheat, barley and oat straw over twelve years (1997-2008), are shown in Figure 3-1. Gross yields refer to the total yield of residue without any reduction in yield due to the various factors mentioned. The net yields take into account all the factors which affects the yields. A wide variability was observed in the net yields of straw over the years. To develop our techno-economic model, we have considered three cases: the average yield, the maximum yield, and minimum yield. Fuel and residue properties of the three kinds of straws are shown in Table 3-2.

Table 3-1: Calculation of net yield for wheat, barley and oat straw

Crop	Average Yield grain (green tonne ha^{-1})	Straw to grain ratio	Gross yield (green tonne ha^{-1})	Level of straw retained for soil conservation (green tonne ha^{-1})	Fraction of straw harvest machine can remove (%)	Fraction removed For animal feeding and bedding (green tonne ha^{-1})	Fraction of straw loss from harvest area to pellet plant (%)	Net yield (green tonne ha^{-1})	Moisture in straw (%)	Net yield (dry tonne ha^{-1})
Wheat straw	2.66	1.1	2.93	0.75	70	0.66	15	0.73	14	0.63
Barley straw	3.03	0.8	2.42	0.75	70	0.66	15	0.48	14	0.38
Oat straw	2.49	1.1	2.74	0.75	70	0.66	15	0.78	14	0.54

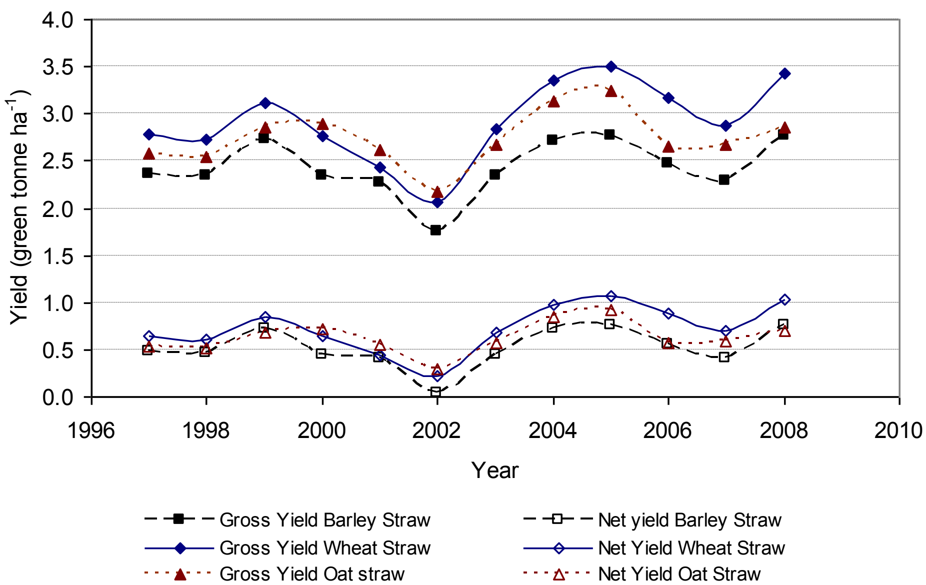

Figure 3-1: Gross and net yield of wheat, barley and oat straw

Table 3-2: Properties of residues

Characteristic	Wheat Straw	Barley Straw	Oat Straw	Source
Moisture content (%)	15.9	13.6	17.2	Verhegyi *et al.,* 2009
Heating value (GJ/odt)	17.8	19.20	18.10	Bailey-Stamler *et al.,* 2007; Chico *et al.,* 2009
Bulk density (kg/m^3)	79.0	82.0	85.0	Bailey-Stamler *et al.,* 2007
Nutrient content (%)				
Nitrogen	0.66	0.64	0.64	Kumar *et al.,* 2004;
Phosphorus	0.09	0.05	0.10	Bailey-Stamler *et al.,* 2007
Potassium	1.60	2.5	2.4	
Sulfur	0.17	0.19	0.16	
Ash	8	8	7	Bailey-Stamler *et al.,* 2007

3.5. Input Data and Assumptions for Development of Cost Estimates

The production of pellets from agricultural residue involves harvesting and collection, handling, storage, transportation and pellet production. Cost factors are developed for each element and are discussed in detail in subsequent sections. Total cost incurred from straw harvesting to pellet production can be divided into three main components:

(1) Field cost, all costs incurred in the field;
(2) Cost of transportation from field to pellet plant;
(3) Pellet production cost.

All cost figures are given in $US, base year 2008. The inflation rate is assumed to be 2.0%.

3.5.1. Field cost

The estimated price of biomass can vary from producer to producer and from plant to plant (Brechbill and Tyner, 2008). The field cost of agricultural residue consists of the cost of: harvesting and collection, on-farm storage, nutrient replacement, and farmer's premium. It is assumed that fuel consumption in collecting straw involves single pass, i.e. grain harvesting and stalk collection are done at the same time. All costs were estimated based on the application of existing technologies and practice, therefore the cost of harvesting biomass was based on current farming practice. Rround bales were considered because they are more prevalent. Bale weights vary in the range of 360 to 500 kg (Liu, 2008). It was assumed that all farmers are willing to sell their straw to a bioenergy facility.

Harvesting and collection cost of straw

The capital costs for harvesting equipment are not estimated in this paper. It was determined that the pellet plant operators contract out the straw harvesting. It was therefore assumed that farmers harvest the straw and deliver it to the roadside in the form of large bales which they cover with tarp to limit the ingress of moisture. The pellet plant operator is responsible for arrangement of bales pick-up. Another option could be assigning all activity to an intermediary party (a custom harvester) who harvests, collects and delivers the straw to the biofacility as needed. This type of intermediary party is called a third party logistic (3PL) provider. This type of concept is now becoming popular. After farmers finish their harvest, custom harvesters harvest and bale the straw, putting the bales near the edge of the field for collection and delivery to the pellet plant. The hauling of the bales from the farmer's field to the pellet plant can be done by the custom harvester or a commercial trucking company. Custom harvesters' rates are based on the equipment they use in harvesting but a typical rate is about \$10.50 bale^{-1} (\$21.00 tonne^{-1} for 500 kg bales) and \$3.25 bale^{-1} (\$6.5 tonne^{-1} for road siding) (Campbell, 2007).

Where straw is stored depends on the type of procurement system used to collect it. There are three storage options available, including at the end-of-field, intermediate (central depot), and plant storage. In winter if the roads are impassible, end-of-field storage might not be useful. However, from an economic perspective end-of-field storage is a good option because it provides accessibility to both the farmer and the transporter. Intermediate (central depot) storage is feasible if the market matures for agricultural pellets and other biomass products, creating many buyer and suppliers (Campbell, 2007). In most situations, storage at the plant will be the most expensive option. Some companies needing high quality feedstock, may choose plant storage in order to have better control over the quality of their input feedstock and avoid spoilage and shrinkage (Liu, 2008).

Bale wrapping cost

The type of wrap for the bales depends on the length of time of its storage. The loss of dry matter during storage depends on how long bale are stored and what type of wrapping is used. Sometimes it also depends on the type of the baler. Three types of bale wrapping are available – twine, net wrap, and plastic wrap. If the bales are stored for a short time, twine is useful, though losses will be high. If bales have to be stored for a long time, extra protection is required in order to reduce dry matter loss. In this situation, plastic wrapping is useful because it is the most protective of the three options. Over six months storage time the dry matter loss for twine is 18.8%, for net wrap it is 8.4% and for plastic wrap it is 6.15% (Brechbilland Tyner, 2008). In this study, it is assumed that bales are wrapped with twine.

Storage cost

The quality of biomass and its cost depend on the type of storage. In an enclosed storage structure, quality remains good due to less dry matter loss, but this is the most expensive option. The costs for various storage facilities include: on-field storage at \$0.9 -\$1.8 tonnes^{-1}, outside on a crushed rock base at \$2.0 - \$2.7tonne^{-1}, open structure (under a roof) on a crushed rock base at \$5.4 - \$7.2 tonne^{-1}, and enclosed structure with a crushed rock base at \$9 - \$13.5 tonne^{-1}. The associated losses are 10-20%, 5% and 2%, respectively (Liu, 2008; Swoboda, 2008; Craig, 2009). In this study, bales are stored in the field in open condition.

Nutrient replacement cost

In Western Canada the soil's carbon level remains high in spite of repetitive straw recovery because plant roots and the residue retained in the field, decompose in the soil (Kumar *et al.,* 2003). Alberta soil has an abundance of calcium and some minerals (Kumar *et al.,* 2003; AARD; 2009). Nitrogen, phosphorous, potassium and sulfur are the only fertilizers that need to be applied to the soil (Kumar *et al.*, 2003). Fertilizers containing these nutrients are spread over the crop for replacement of the nutrients removed when straw is removed. The cost associated with these fertilizers is considered a nutrient replacement cost. Farmers usually apply fertilizer to their crops, so the nutrient payment is for incremental fertilizer only and does not include the cost of application. The cost of nutrient replacement is shown in Table 3-3.

Premium to the farmer

To ensure a constant supply of biomass throughout the year, a premium should be paid to the farmer to encourage participation in biomass collection and selling. This cost is also shown in Table 3-3.

Storage premium cost

This is the payment for the opportunity cost for the land on which the bales are stored. If the bales are kept on the edge of the field for a long time, the land is not available for planting a crop. Table 3-3 shows the storage premium cost.

Table 3-3: Field cost of biomass

Factor	Value ($\$ tonne^{-1}$)	Source/ Comments
Harvesting cost		
- Shredding	3.67	Brechbill, 2008
- Raking	2.31	Brechbill, 2008
- Baling	3.65	Brechbill, 2008
Bale Wrap		
- Twine	0.49	Brechbill, 2008
- Net wrap	1.77	Brechbill, 2008
- Plastic wrap	2.48	Brechbill, 2008
Bale collection		
- Bale picker	0.67	Liu, 2008
- Tractor	3.58	Liu, 2008
Bale on-field storage cost		
- On-field storage	1.80	Campbell, 2007
- Storage premium	0.10	Brechbill, 2008
Farmer Premium cost	5.50	Kumar *et al.,* 2003
Nutrient replacement cost	22.62	Kumar *et al.,* 2003; Pauly, 2008; Jensen, 2008. 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_2 is 44% phosphorous.
- Nitrogen cost	1,260*	
- P_2O_5 cost	1,240*	
- K_2O cost	440*	
- Sulfur cost	520*	

* These costs are used to calculate nutrient replacement cost.

3.5.2. Transportation cost

It is assumed in this analysis that the area from which feedstock is drawn is circular. The center of the circular area can be a pellet plant or an intermediate storage area from which biomass is transported to a pellet plant. It is assumed that biomass distribution is uniform within the circular area. Straw transport is done over existing publicly maintained roads. Pellet plants are located near existing consumers adjacent to the transmission lines and biomass is transported from field to pellet plant by trucks.

The average radius of a circular area is $r_{av} = \frac{2}{3}r$, where r is the length of the radius of the circular area. As all the transportation is not necessarily in straight line, a tortuosity factor of 1.27 is considered in this study (Overand, 1982; Sarkar and Kumar, 2009). Perlack and Turhollow (2002) considered a tortuosity factor of 1.3.

For the Province of Alberta, the fraction of the total harvest area used to grow wheat, barley and oats to total harvest area is 30% (Statistics Canada, 2008). This land is located mainly in southern Alberta which is a highly agriculturally intensive area. This study assumes that the storage of big round bales is at the roadside and the bales are covered with tarp, and also the pellet plant contracts the straw transportation to trucking firms. Trucks are contracted year round and have self-loading equipment. The straw bales are stored at field's edge and transported on public roads. The road allowances are large in North America (Mahmudi and Flynn, 2006). If roads are impassible due to weather conditions then storing is done in the plant. We assume at least three months storage at the plant for the season when the roads are impassible. Although, 'just in time' delivery reduces feedstock storage requirements, operational disruptions resulting from unreliable delivery may cost the pellet company more than was saved in the capital budget (Campbell, 2007).

Transportation cost has two components irrespective of its mode, i.e. truck, rail or pipeline. The fixed component of the cost of truck transportation is the cost of loading and unloading cost ($ $tonne^{-1}$). The variable component of the cost of truck transportation includes cost of wages for the driver, fuel, and maintenance

(\$ tonne^{-1} km^{-1}). These variable costs are proportional to the distance travelled and changes with transportation distance. The typical loading and unloading cost for truck transportation in North America is \$5.45 green tonne^{-1} (Kumar *et al.,* 2003; Campbell, 2007; Searcy *et al.*, 2007). The straw truck variable transportation cost is \$0.22 green tonne^{-1} km^{-1} (Campbell, 2007; Liu, 2008).

The size of the pellet plant determines the biomass draw area, thus the total cost of transportation increases as pellet plant capacity increases. Figure 3-2 shows the correlation between transportation cost and capacity. The transportation distance is proportional to the square root of the capacity of the plant; and this is reflected by the curve in Figure 3-2. Considering all the unit operation costs, straw delivery at the plant gate costs \$95.33 tonne^{-1} for a plant having capacity of 150,000 dry tonnes year^{-1}.

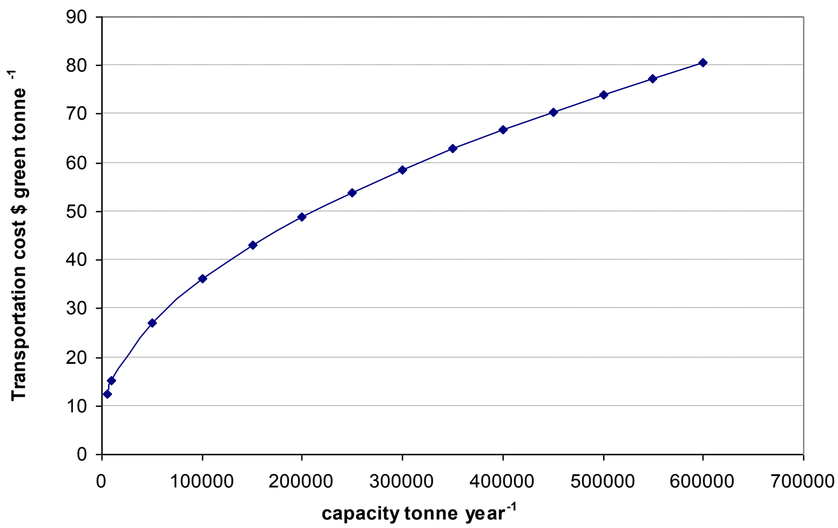

Figure 3-2: Delivery cost of straw as a function of pellet plant cost

3.5.3. Pellet production cost

A techno-economic assessment model was developed to assess the cost of production of pellets including various cost components. These cost components include:

- Capital cost
- Employee cost
- Energy cost
- Consumable cost

Employee, energy and consumable costs are considered as operating costs. The input data and assumptions for the techno-economic model are summarized in Table 3-4.

3.5.4. Capital cost

Capital cost includes the cost of process equipment and utility and its installation. It also includes capital cost of land, storage, buildings, and other infrastructure. The capital cost of different equipment has been collected from equipment suppliers, pellet manufacturer and the literature. The maintenance cost of the equipment in this study is 2.5% of the equipment capital cost except for the hammer mill and pellet mill (Thek and Obernberger, 2004). These mills cost more to maintain than the other equipments. In this study, the annual maintenance cost of the hammer mill and pellet mill are assumed to be 18% and 10% of the installed equipment capital cost, respectively (Thek and Obernberger, 2004). The mechanical and electrical installation of the equipment cost 32% and 20% of the equipment's capital cost, respectively. Freight and sales tax is 4% of the equipment's capital cost (Campbell, 2002). All equipment prices are adjusted to 2008 US dollar value by using inflation factor.

Table 3-4: Input data and assumptions for techno-economic model

Factors	Value
Plant life (years)	30[a]
Inflation	2.0%[b]
Internal rate of return	10%[c]
Material loss during pelleting process	5%[d]
Plant operating factor[e]	
Year 1	0.70
Year 2	0.80
Year 3 and onward	0.85
Spread of capital cost during construction[f]	
Year 1	20%
Year 2	35%
Year 3	45%
Cost of additional equal sized pellet plant unit relative to the first	0.95[g]
Other costs such as tax, insurance etc. are assumed to be a percentage of capital cost.	0.5%
Power requirement for different equipment for pellet production [h ,i]:	(KW)
Primary grinder	112
Dryer	120
Hammermill	75
Boiler	75
Pellet mill	300
Cooling	5
Bagging	40
Other	40
Lighting and heating	112

[a]- Plant life for the pellet plant is assumed based on the other biomass processing facilities. There is large number of studies which assumes similar number (Kumar *et al.*, 2003, Sarkar and Kumar, 2009).

[b]- This is the average inflation over 12 years (Kumar *et al.,* 2003, Sarkar and Kumar, 2009)

[c]- Assumed.

[d] - Derived from earlier studies on pellet production.

[e] - Solid handling plants have a start-up profile. These values are assumed based on operating factors reported in earlier studies on biomass handling facilities. (Kumar *et al.,* 2003, Sarkar and Kumar, 2009)

[f] - Taken from earlier studies and values reported on the investment profile. Kumar et al., 2003; Sarkar and Kumar, 2009)

[g] - (Kumar *et al*., 2003; Sarkar and Kumar, 2009).

[h]- (Campbell, 2007)

[i]- (Pastre, 2002)

3.5.5. Scale factor

The power function is an acceptable way of estimating capital cost at various capacities within a typical range of up to 10 times the calculated costs. It can increase more or less proportionately with plant capacity depending on the parameters (Gallagher *et al.,* 2005). This exponent for adjusting the cost of equipment from one capacity to another is given in equation (3-1).

$$Cost_2 = Cost_1 * \left(\frac{Capacity_2}{Capacity_1} \right)^{Scale\ factor} \qquad (3\text{-}1)$$

If the scale factor = 1, means capital cost increases proportionately with capacity. This indicates there is a constant rate to scale. A scale factor < 1, means the capital cost increases at a rate less than the capacity, so, there is an increasing return to scale. For biomass processing equipment, there is an economy of scale benefit as plant size increases. Capital cost per unit of output decreases as plant capacity increases. Mani *et. al*. (2006) and Hoque *et al*. (2006) both considered a scale factor of 0.6 for estimating cost of wood pellet processing equipment. A scale factor of 0.6 means that one percent increase in the plant size, increases capital cost by 0.6 percent. There is a range of scale factor for biomass processing facilities. For dry mill ethanol plants it was reported to be 0.836 (Larson and Harrison, 1997), which suggests that capital cost increases more rapidly with capacity for these plants than for processing plants having a scale factor of 0.6. Nguyen and Price (1996) considered a scale factor of 0.7 for capital, administrative, and operating costs. Boerrigter (2006) reported different scale factors (0.5 to 0.7) for different scale plants. Lower scale factors for small scale plants and higher scale factors for larger plants. Other studies gave different scale factors for different biomass processing equipment (Hamelinck and Faaij, 2002; Spath *et al.,* 2005). Remer *et. al* (1998) used three types of indices (scale factor, location index and inflation index) in the same calculation to adjust for size, geography and time (Remar *et al.,* 1998; Remar and Mattos, 2003).

In this study the scale factors for the main equipment in a pellet production plant were derived from the values of capital cost reported in the literature for different equipment, such as pellet mill, dryer, hammer mill, cooler, pellet shaker, boiler, grinder, bagging system, and feeder; as well as storage bins and the building. The scale factors for all these equipment and infrastructure were used to estimate the overall scale factor for an agricultural pellet production plant. The scale factors are discussed below. Figure 3-3(a) shows the capital cost of pellet mills at various capacities, as reported in the literature (NEOS, 1995; William and Lynch, 1995; Thek and Obernberger, 2004; GEC, 2006; Hoque *et al.,* 2006; Mani *et al.,* 2006; Campbell 2007; Polagye *et al.,* 2007). Based on these figures, the derived scale factor for pellet mills is 0.72.

Figure 3-3(b) shows the capital cost of dryers at different capacities reported in the literature (NEOS, 1995; William and Lynch, 1995; Thek and Obernberger, 2004; GEC, 2006; Hoque *et al.,* 2006; Mani *et al.,* 2006; Campbell 2007; Polagye *et al.,* 2007). The scale factor for dryer derived from Figure 3-3(b) is 0.38. This estimate is lower than that found in different literature. Hammelinck and Faaij (2002) considered it to be 0.8 and Spath *et. al* (2005) gave it a value of 0.75.

Figure 3-3(c) shows the capital cost of hammer mills at different capacities (NEOS, 1995; William and Lynch, 1995; Thek and Obernberger, 2004; GEC, 2006; Hoque *et al.,* 2006; Mani *et al*., 2006; Campbell 2007; Polagye *et al.,* 2007). Based on Figure 3-3(c), the estimated scale factor for hammer mills is 0.38. The scale factor reported in other studies is 0.6 (Hamelinck and Faaij, 2002; Spath *et al.,* 2005). The main reason for this large variation in values reported by different studies is that costs were estimated for different countries setting and at different times. The range of capital costs for coolers is shown in Figure 3-3(d) (NEOS, 1995; William and Lynch, 1995; Thek and Obernberger, 2004; GEC, 2006; Hoque *et al.,* 2006; Mani *et al.,* 2006; Campbell 2007; Polagye *et al.*, 2007). The scale factor derived from Figure 3-3(d) is 0.49. The scale factor derived for the primary grinders considered for this paper is 99%. Figure 3-3(e) shows the capital cost of grinders of different capacities (NEOS, 1995; Samson and Duxbury, 2000; Campbell, 2007). The scale factor derived for the bagging system is 0.87. This is based on the capital cost data for bagging system given in Figure 3-3(f) (NEOS, 1995; William and Lynch, 1995; Samson and Duxbary, 2000; Hoque *et al.,* 2006). Based on the capital cost data in Figure 3-3(g) the scale factor for feeding systems is 0.57(William and Lynch, 1995; Samson and Duxbary, 2000; Polagye *et al.,* 2007). This value is less than the value used in Hamelinck and Faaij (2002). The estimated scale factor for storage is 0.85. This is based on capital cost values at various capacities as shown in Figure 3-3(h) (Thek and Obernberger, 2004; Campbell, 2007). The scale factor for conveyors considered in this study is 0.80, based on a previous study (Hamelinck and Faaij, 2002). Some of the scale factors derived in this study are not same as those considered in previous studies because estimation of costs was done in different countries and at different times.

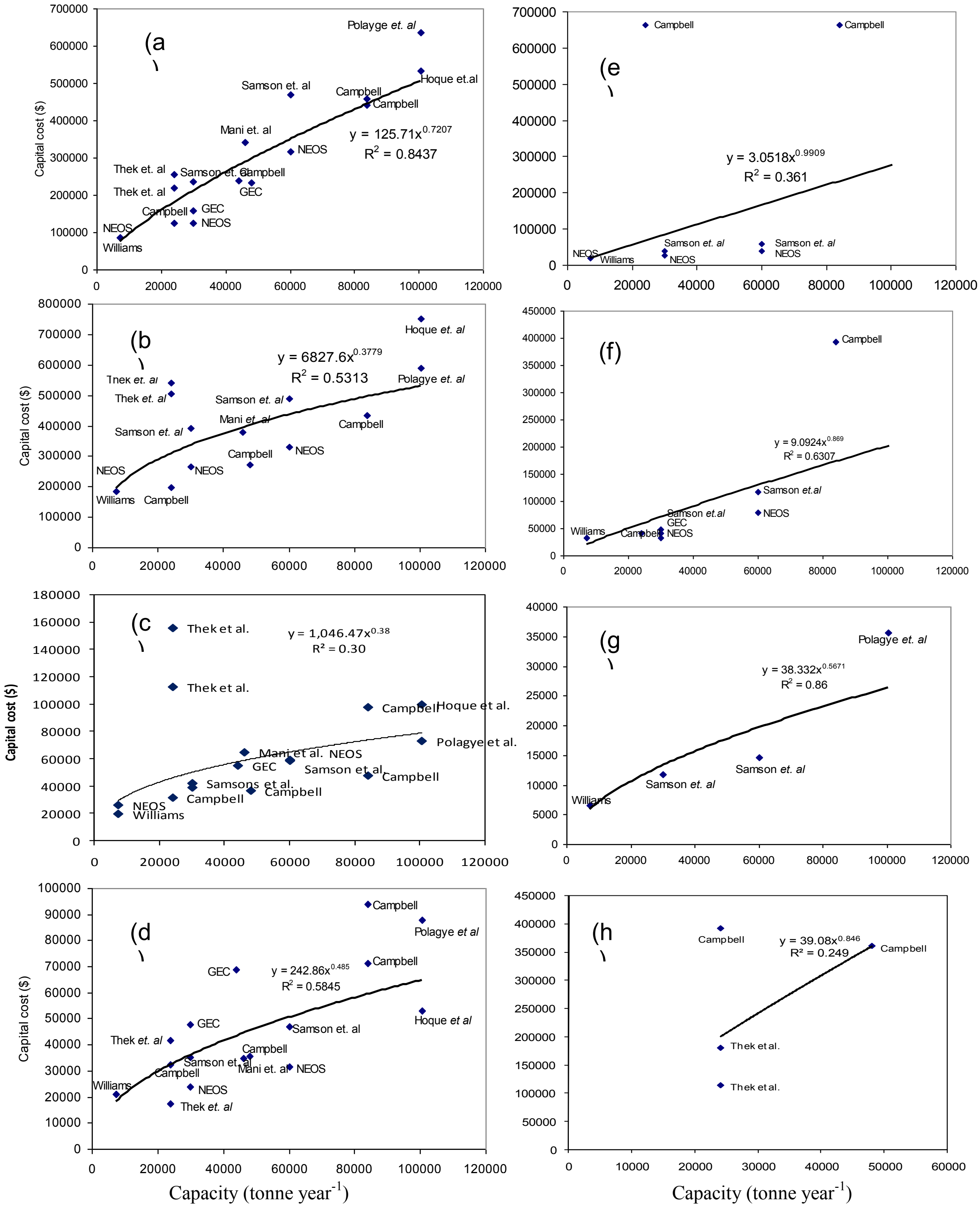

Figure 3-3: Scale factors (a) pellet mill; (b) dryer; (c) hammermill; (d) cooler; (e) primary grinder; (f) bagging system; (g) feeder; (h) storage

In the base case, the pellet plant has a production capacity of 6 tonnes $hour^{-1}$ with an annual production capacity of 44,000 tonnes. The plant operates for 7200 hours annually, which is about 24 hours day^{-1} and 300 days $year^{-1}$ (capacity factor of 85%). The selection of equipment size or capacity depends on the type of feedstock, particle size and moisture level. It takes less energy to create 8 mm pellets than it does to make 6 mm pellets. A 12 mm pellet requires even less horsepower. The smaller the particle size, the larger the capacity of the equipment and the horsepower required for processing (Wright, 2008). Softwood requires equipment with lower horsepower and capacity compared to hardwood (Wright, 2008). The capacity of coolers is based on the volume of air flow, ambient temperature, and design particulars (Wright, 2008). Table 3-5 lists the equipments, its capital cost and the maximum possible size available today.

In this study, the assumed maximum sizes for the equipment are given in Table 3-5. To provide any capacity over maximum size, two or more identical sized units can be purchased. The maximum capacity of the pellet mill is 50,000 tonnes per year. However, pellet manufacturers prefer smaller units in order to avoid unnecessary full shut down for maintenance. Large pellet mills are limited (Macarthur, 2008). The larger the diameter of die and roller, the greater the force that is exerted on a given area and so is the risk of causing metal fatigue. There is also a problem with peripheral speed. With larger diameters, the dies or rollers turn more slowly. For these reasons high capacity single unit pellet mills are not available on the market (Polman, 2008; Macarthur, 2008). There are some other costs associated with pellet production such as site preparation, plant and office building, feedstock storage, pellet storage, wheel loaders, forklifts and office materials. The capital costs of these items were taken from a previous study (Campbell, 2008).

Table 3-5: Capital cost of equipment and employee costs of pellet production plant (base case 6 tonnes hour^{-1})

Capital Cost Plant equipment	Scale Factor	Capital cost - base case ($)	Maximum size of equipment (tonne year^{-1})	Source
Primary grinder	0.99	650,000	105,000	Campbell, 2007; Polamn, 2008
Dryer	0.6	430,000	100,000	Hamelinck and Faaij, 2002; Campbell, 2007,
Hammermill	0.6	150,000	108,000	Wright, 2008; Polman, 2008
Feeder	0.57	44,700	50,000	Campbell, 2007; Polman, 2008
Boiler	0.7	51,000		Campbell, 2007; Kumar et.al., 2003
Pellet mill (with Conditioner)	0.72	350,000	50,000	Wright, 2008; Polman, 2008
Pellet cooler	0.58	170,000	216,000	Wright, 2008; Polman, 2008
Screener/Shaker	0.6	18, 300	100,800	Campbell, 2007; Polaman, 2008
Bagging system	0.63	450,000	100,800	Campbell, 2007; Polaman, 2008
Conveyor tanks etc	0.75	1,130,000	84,000	Campbell, 2007; Polaman, 2008

Cost of hourly-wage employee

Hourly wage employee	Hourly rate	Worker shift	Annual hours	Source
Supervisor	21.00	1	7200	Hoque *et al*., 2006
Maintenance worker	18.00	On-call	2080	Hoque *et al*., 2006
Machinery operator	16,00	2	7200	Campbell, 2007
Packaging	15.00	2	7200	Campbell, 2007
Forklift operator	15.00	1	7200	Hoque *et al.,* 2006

Cost of permanent employee

Salary labor	Salary ($ yr^{-1})	Payroll tax benefit	Source
General Manager	100,000	45%	Hoque *et al.,* 2006
Financial Manager	75,000	45%	Hoque *et al*., 2006
Supervisor	60,000	45%	Campbell, 2007
Secretary	40,000	45%	Campbell, 2007

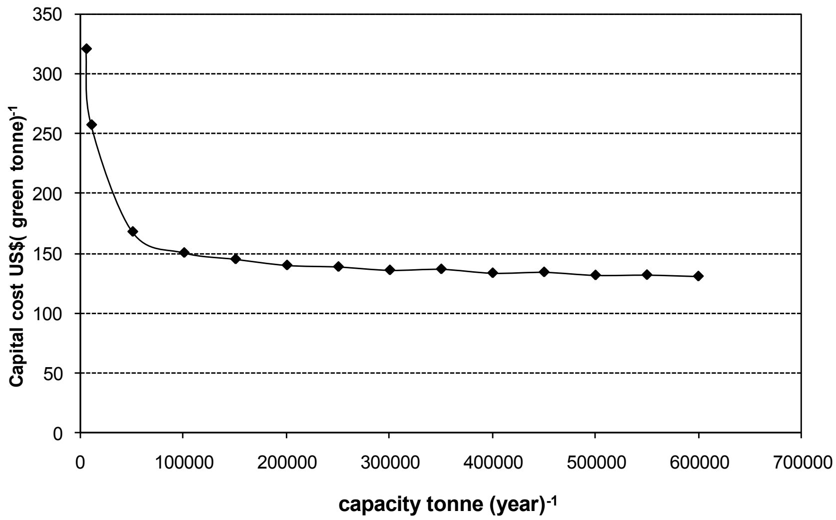

Figure 3-4: Change of unit capital cost of pellet production plant with capacity

Figure 3-4 shows how the of unit capital cost of the whole plant changes with capacity. Capital cost of the pellet production plant per unit of output decreases with increase in capacity, due to economy of scale. For plant capacities higher than 100,000 dry tonnes per year, the change in unit capital cost is not significant.

3.5.6. Employee cost

Another major cost component is the employee cost, which includes the cost of personnel in production, marketing and administration. Two types of employee are usually involved in a pellet production process i.e., permanent employees and hourly-wage employees. In the production process, seven hourly-wage employees and four permanent employees are required for an entire 44,000 tonne year^{-1} production plant. This is based on the literature and in discussions with the pellet plant operators (Campbell, 2007; Macarthur, 2008). The labor cost does not increase linearly with the capacity of plant; there is an economy of scale here too. For example, large pellet plants do not have higher labor costs per tonne of produced pellets; nearly the same number of worker is required, to operate a half capacity plant. There are break-points at some production level above which another worker is required (Campbell, 2007). Handling the feedstock and finished pellets is more labor-intensive than the production process. Three workers are required for bagging if it is done manually for the base case plant. The total number of workers required in any pellet plant is largely determined by the loading, unloading, handling and storing of feedstocks and pellets. The employee and administrative costs of a 44,000 tonne $year^{-1}$ plant are given in Table 3-5. Payroll taxes and fringe benefits are considered to be 25% of the hourly wages (Wright, 2008).

3.5.7. Energy Cost

Electricity cost

All pellet plant equipment needs electricity, which is a significant part of pellet production cost. Of all the equipment required for straw pellet production, the pellet mill consumes the most electricity, followed by the dryer (Pastre, 2002). In contrast, the dryer consumes the most electricity in wood pellet production (Pastre, 2002). If an equipment of the proper size is not installed, an overly large unit will waste electricity. The feedstock species, particle size, pellet size and moisture level all play an important part in determining how much horsepower is needed. Hardwood is more difficult to pelletize than softwood and requires additional horsepower. Pellets can be produced at a rate of 4 tonnes per hour for softwood and 2-3 tonnes per hour for hardwood using the same machine (Wright, 2008). Similarly, straw pelleting requires less power than pelleting of softwood, but requires extra power for chopping than does wood. It takes less power to create an 8 mm pellet than it does to make a 6 mm pellet (Wright, 2008). Table 3-

4 shows the power requirement for all the equipment used for pellet production. The data in Table 3-4 were derived from studies by Campbell (2007) and Pastre (2007).

In this study, the allowance for idle hours includes 5% for warming up a machine, shutting down, running without products etc (Campbell, 2007). Thus there are 6,840 annual full-time production hours. The energy charges considered for this study amount to \$0.122 kWh^{-1} $month^{-1}$. Table 3-4 shows that pellet mill is the highest (34%) power consuming unit followed by dryer (19%).

Natural gas cost

Natural gas is used to reduce the moisture content of feedstock in a dryer and, as a boiler fuel, to produce steam. It is assumed in this study that the moisture content of the feedstock was reduced from 14% to 10%. This use of natural gas costs \$1.00 $tonne^{-1}$. The steam required to condition feedstock before it enters the pellet mill is 4% of the total weight of the feedstock (Thek and Obernberger, 2004). The boiler efficiency considered for steam production is 80% (Dias *et al.*, 2004; Kristensen and Kristensen, 2004). Assuming a gas price of \$5.94 GJ^{-1} - based on the 2008 price of natural gas (Energy shop, 2009; Direct Energy, 2009), the gas for drying costs \$1.27 $tonne^{-1}$.

3.5.8. Consumables Cost

In pellet production dies and rollers are considered consumable items. Their useful life depends on the physical characteristics of the feedstock. Straw is more abrasive than wood so dies wear out more easily (Pastre, 2002). Similarly, if pellets are made out of bark, dies need to be changed 3-4 times, due to abrasion (Wright, 2008). The cost of rollers, blades and screens is \$2.75 $tonne^{-1}$ (Campbell, 2007). Pellet bags are another consumable item and costs \$0.15 bag^{-1}. Assuming the capacity of 50 bags to be one tonne, the cost of bags is \$7.50 tonne^{-1} (Campbell, 2007). A 110 horsepower wheel loader uses 18.65 litre of diesel per hour at full load (Campbell, 2007). If the diesel costs \$1.43 gallon^{-1} (NRC, 2009) the cost of fuel for the wheel loader is \$1.27 tonne^{-1}.

3.6. Results and Discussion

The techno-economic model developed in this study estimates the cost of producing agricultural biomass-based pellets and the economically optimum plant capacity using the cost and technical parameters provided in earlier sections. The costs and technical parameters were considered for each unit operation from feedstock harvesting to pellet storage. The model considered straw yield, field costs such as straw acquisition, nutrient replacement and farmer premium along with the cost of transportation and maintenance, and operating costs such as labor, energy and consumable items.

The cost of producing pellets from biomass is highly dependent on the size of the plant. The optimum size for a pellet plant is a trade-off between the cost of transporting biomass, which increases as plant capacity increases and capital cost per unit of output that, due to economy of scale, decreases as plant capacity increases. As a result of this trade-off, there is a particular capacity at which production cost is minimal; this is the optimum size for the production plant. Table 3-6 shows the optimum sizes in the average, maximum and minimum yield scenarios for agricultural biomass-based pellet production plant. It gives, as well, the area from which straw is drawn and the agri-pellet production cost.

The cost of biomass transportation increases in proportion to the square root of capacity, whereas per unit capital cost decreases with capacity. Figure 3-5 shows the variation in the production cost of agri-pellets with the capacity of the plant. The pattern of the curve is similar for the average and maximum yield scenarios. For the minimum yield scenario, the pattern of the curve is different after 70,000 tonnes year^{-1}. Figure 3-5 shows two regions. For the average and maximum yield scenarios and plants with capacities less than 70,000 dry tonnes year^{-1}, the production cost rapidly increases as the size of the agri-pellet production plant decreases.

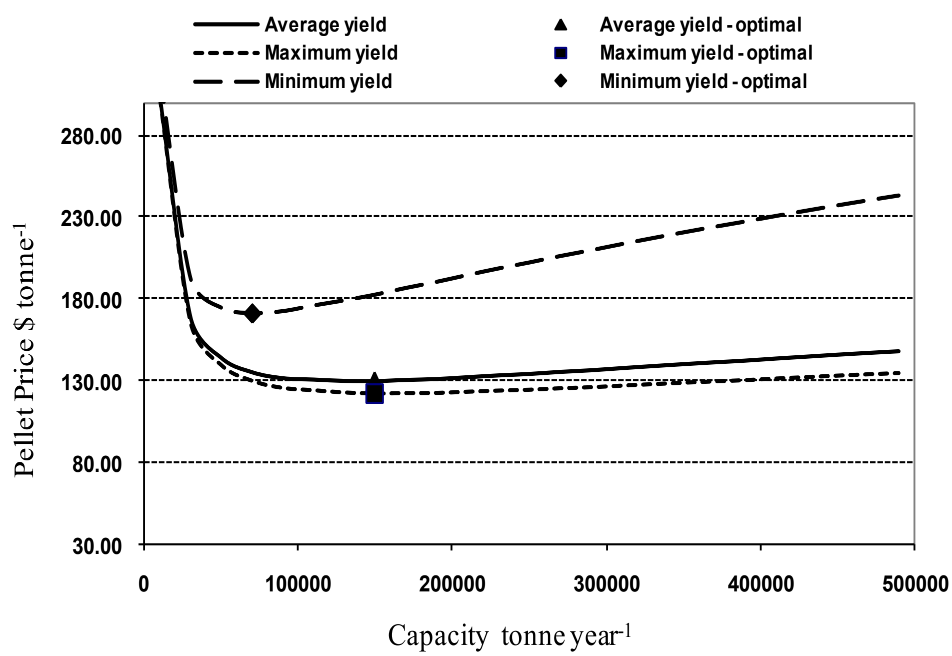

Figure 3-5: Pellet cost as a function of capacity for three cases of straw yield

Above 70,000 dry tonnes year^{-1}, the cost of production is almost flat. The reason is that the benefit in the plant's capital cost per unit output due to economy of scale is offset by the increased cost of transporting the agricultural biomass. Thus, in this region agricultural biomass-based pellet plants can be built over a wide range of capacities without significant cost penalties. For example, the economically optimum size of plant for the average yield case is 150,000 tonnes year^{-1}, but agri-pellet production cost remains within 10% of the optimum value from 70,000 tonnes year^{-1} to more than 500,000 tonnes year^{-1}. While the calculated optimum size is 150,000 tonnes year^{-1}, it is more likely that the plant would be built to handle 70,000 tonnes year^{-1} in order to minimize risk. For the minimum yield scenario, above 70,000 tonnes year^{-1}, any increase in capacity will increase the cost of production considerably. In this case, an increase in transportation cost outweights the reduction of capital cost per unit of output. Above 70,000 tonnes year^{-1}, reduction in capital cost is 5% for the minimum yield case, but the biomass must be collected from a very widespread area. The minimum yield scenario is based on yields obtained in the drought years which were observed two years out of the twelve years of data collection. The agri-pellet plant can be built at a capacity of 70,000 tonnes year^{-1} which will result in pellet production cost of \$130 tonne^{-1} to \$132 tonne^{-1}. It is evident that agri-pellets (at \$7.2 GJ^{-1}) are still not economical as a fuel today compared to fossil fuel (i.e., natural gas at \$6.5 GJ^{-1}).

Table 3-6 shows the different cost components of producing straw-based pellets. From Table 3-6 it can be seen that transportation contributes the most to total cost, followed by field cost. Transportation alone contributes almost 40% of the total cost. The main reason for the cost of transportation being high is that the biomass feedstock is very dispersed due to low yield. Straw harvesting requires nutrient replacement, which is a significant field cost in all cases.

Plant capacity and the agri-pellet production cost associated with it depend on crop yield and the distance between where the biomass is collected and the plant is built. In Alberta, one of the western Canadian provinces, the net yield of straw is 0.50 tonne ha^{-1} whereas, in other prairie provinces, such as in Manitoba, the net yield is 0.65 tonne ha^{-1}. The economic optimum size is larger when the yield is higher.

Table 3-6: Economic optimum size of agricultural based pellet production plant

	Average Yield	Maximum Yield	Minimum Yield
Straw yield (dry tonnes ha^{-1})	0.50	0.78	0.08
Optimum size (tonnes $year^{-1}$)	150,000	150,000	70,000
Project area from which straw is drawn $(km)^2$	12,287	7,829	34,928
Agri-pellet cost (\$ $tonne^{-1}$)	129.42	122.17	170.89
- Capital recovery	7.61	8.76	5.22
- Maintenance cost	2.41	2.47	2.71
- Field cost	47.61	47.61	47.61
- Transportation cost	47.72	39.32	76.27
-Employee cost	8.23	8.23	17.63
-Energy cost	5.92	5.92	11.37
-Consumable item cost	9.86	9.86	10.10

Sensitivity analysis

The sensitivity of the cost factors and technical factors were studied for the average yield case. This sensitivity analysis was carried out by changing the values for different costs and technical factors from -50% to +50% in steps of 10% for each case. Cost factors such as field, transportation, capital, employee, energy, and consumable costs were included in the analysis. Technical factors, including moisture content, feedstock material loss, inflation, internal rate of return (IRR), and percentage of area used for wheat, barley and oat production were considered. Figure 3-6 shows the results of the sensitivity analysis done on cost factors, and technical factors.

It can be seen from Figure 3-6(a) that the cost of agri-pellet production is most sensitive to field cost, followed by transportation cost. A variation of about ±50% of field cost can change the pellet price from \$153.33 $tonne^{-1}$ to \$105.52 $tonne^{-1}$. The agri-pellet production cost changes from \$150.05 $tonne^{-1}$ to \$108.79 $tonne^{-1}$ given a change of ±50% in transportation cost. Table 3-7 shows that variation in field cost does not affect optimum plant size, however, variation in transportation cost changes the optimum size from 190,000 to 90,000 tonnes $year^{-1}$. As transportation cost increases, the optimal size of the agricultural pellet production plant decreases. The opposite result is observed when the cost increases. With a change from +50% to -50% in capital cost, the cost of production changes by \$13.36 $tonne^{-1}$. Other costs, such as employee cost, energy cost and consumable cost, do not change the total cost of production significantly.

It can be concluded from Figure 3-6(b) that changes in moisture content and IRR have nearly the same impact on the total production cost. An increase in the moisture content, IRR, inflation and loss of feedstock material in the plant contribute to increase in the pellet production cost. Higher inflation and increase of the production area for wheat, barley and oats reduces the cost of pellets. Pellet production cost is most sensitive to changes in moisture content.

With a -50% to +50% change in moisture content, the cost increases by \$21.92 $tonne^{-1}$. An increase of moisture content adversely affects the heating value of fuel. The percentage of area used for wheat, barley and oat production changes the total cost significantly. A slightly nonlinear pattern is observed for the impact of the amount of area used for wheat, barley and oat production. This is due to the fact that the cost of producing pellets depends on the radius of the circle from which agricultural residue is collected. The variation in optimum size (Table 3-7) has to do more with percentage of change in this area than with the moisture content. The impact that values for cost and technical factors have on optimal plant size are shown in Table 3-7.

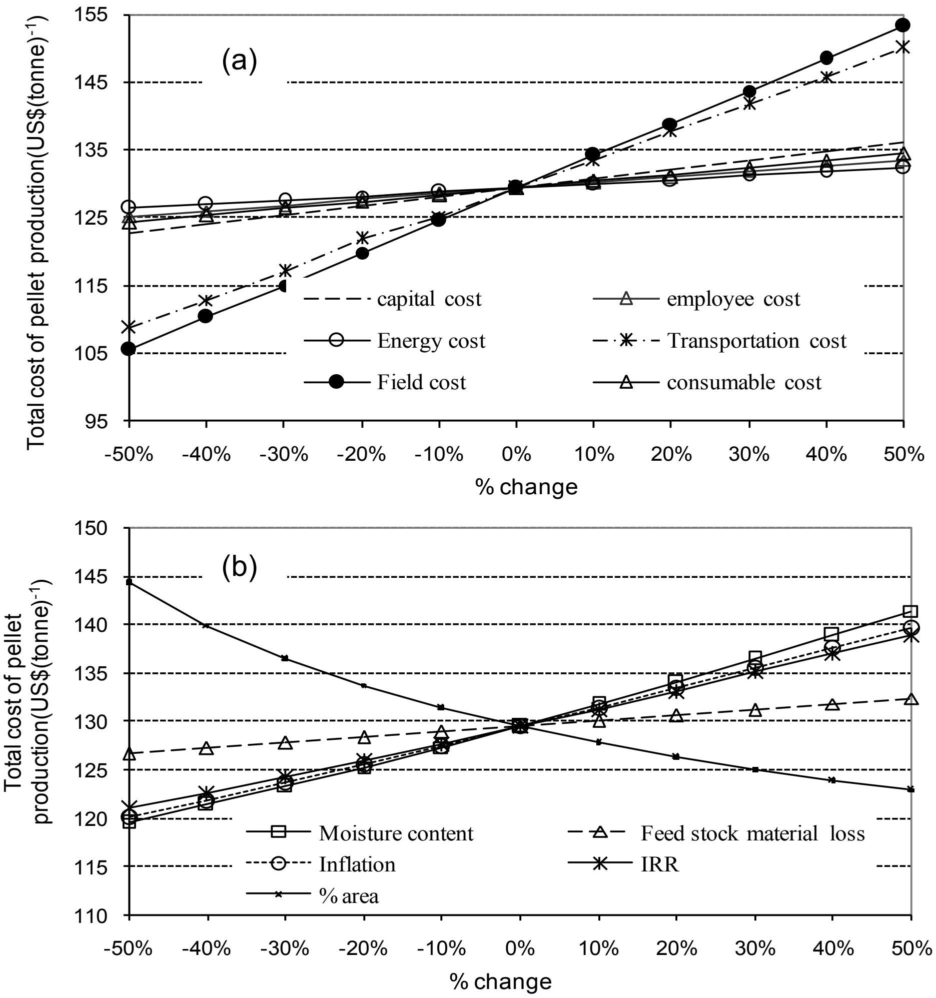

Figure 3-6: Sensitivity analysis of (a) cost factors and (b) technical factors

Table 3-7: Impact of cost factors and technical factors on optimal size (in tonne $year^{-1}$) for average yields (base case 150,000 tonnes $year^{-1}$)

% change	50% lower	40% lower	30% lower	20% lower	10% lower	10% higher	20% higher	30% higher	40% higher	50% higher
Cost Factors										
Field cost	No change	No change	No change	No change	No change	No change	No change	No change	No change	No change
Transportation Cost	Increase 40,000	Increase 40,000	Increase 40,000	No change	No change	Decrease 20,000	Decrease 20,000	Decrease 60,000	Decrease 60,000	Decrease 60,000
Capital cost	Decrease 20,000	Decrease 20,000	No change	No change	No change	No change	No change	No change	No change	No change
Employee cost	Decrease 60,000	Decrease 60,000	Decrease 20,000	Decrease 20,000	No change	No change	No change	No change	No change	No change
Energy cost	Decrease 20,000	Decrease 20,000	Decrease 20,000	Decrease 20,000	No change	No change	No change	No change	No change	No change
Consumable item cost	No change	No change	No change	No change	No change	No change	No change	No change	No change	No change
Technical Factors										
Moisture content	No change	No change	No change	No change	No change	No change	No change	Decrease 20,000	Decrease 20,000	Decrease 20,000
Material loss	No change	No change	No change	No change	No change	No change	No change	No change	No change	No change
Inflation	Decrease 20,000	Decrease 20,000	No change	No change	No change	No change	No change	No change	No change	No change
IRR	No change	No change	No change	No change	No change	No change	No change	No change	No change	No change
% area for biomass	Decrease 60,000	Decrease 20,000	Decrease 20,000	Decrease 20,000	No change	No change	No change	No change	No change	No change

3.7. Conclusions

A techno-economic model was developed for estimating the cost of producing pellets and the optimum size of pellet plants based on agricultural biomass. Agricultural residue, including wheat, barley and oat straw, were considered at average, maximum and minimum yield cases. The total cost was calculated from the harvest of straw to pellet production. The techno-economic model was applied to Western Canada. For average and maximum yield cases, cost curves are quite flat for a wide range of plant sizes over 70,000 tonnes $year^{-1}$. This implies that plants smaller than the economically optimum size can be built with only minor cost penalty. From the sensitivity analysis it can be concluded that total cost of production of pellet is most sensitive to field cost followed by transportation cost.

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Chapter 4. Development of Energy and Emission Parameters for Densified form of Lignocellulosic Biomass

4.1. Introduction

Environmental concern and unstable fossil fuel market are main drivers for use of biomass based pellet as an energy fuel. Governmental obligations on use of biomass fuel is another predominant basis for increasing use of pellet in European countries (8 million tonnes in 2008) (Sikkema *et al*., 2010), which is not common in North America. A significant amount of pellets produced today in North America are exported to European countries (Swan, 2008; Spelter and Toth, 2009). The conversion of biomass to pellet form upgrades it's physical and chemical properties especially in terms of calorific value. In addition to the environmental advantages, biomass based pellets have other value-added opportunities, such as, increased energy density, higher bulk density, and higher heating value.

A number of studies have been performed on the life cycle analysis (LCA) of biofuels especially on ethanol from straw which have shown positive energy balance and reduced greenhouse gases (Punter *et al*., 2004; Mortimer, 2004; Gabrielle and Gagnaire, 2008; Spatari *et al*., 2010). Most of the LCA analyses were done on transportation fuels, such as, bioethanol, biodiesel, hydrogen (Kim and Dale, 2004 & 2005; Manish and Banergee, 2008). Both the emission and the energy-use of wood pellet have been analyzed in previous studies (Mani *et al*., 2005; Raymer, 2006; Hangberg *et al*., 2009; Magelli, *et al*., 2009; Sikkema *et al*., 2010; Zhang *et al*.2010).

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Mani (2005) analyzed streamlined life cycle analysis approach to quantify emissions of wood pellet production. Raymer (2006) quantified the amount of GHG emissions for six forms of woody biofuels including wood pellet. Hagberg *et al*. (2009) calculated life cycle energy and emission analysis of wood pellet production in Swedish settings by considering different assumptions and methodological choices. Magelli (2009) mainly dealt with life cycle analysis of wood pellet production and transportation from Canada to Europe. Zhang *et al.* (2010) investigated a life cycle analysis of wood pellet with co-firing options and compared with coal and hypothetical natural gas combined cycle. The aforementioned studies focused on pellets from woody biomasses. The life cycle analysis of pellet made of agricultural biomass (i.e. straw) is non-existent. The aim of this paper is to analyze pellet production from agricultural residue, especially from wheat straw with regard to its energy input and emission throughout its life cycle. This study uses data on Western Canada (Prairie Provinces) for life cycle analysis of pellets. The selected geographic region is endowed by large agricultural land area and large energy demand.

Canada is the sixth largest producer of wheat in the world and most of which is produced in prairie provinces, e.g., Saskatchewan, Alberta and Manitoba. Agricultural residues are available in significant quantities in areas where growth of grain crops are concentrated (Sultana *et al.,* 2010; Searcy and Flynn, 2010). Agricultural activities of Western Canada produce 37 million of tonnes of biomass each year (Sokhansanj *et al*., 2006). The potential of recovering agricultural residues (i.e. straw from wheat, barley and oats) after accounting for current use is about 6.2 million tonnes per annum (Sultana *et al.*, 2010). Most of these biomass resources are wasted or underutilized. This biomass potential could be used as a feedstock for bioenergy development.

The objective of the current study was to develop a data intensive model to estimate of the energy use and GHG emission associated with production and use of agricultural biomass based pellets (or agri-pellets). The scope of the paper includes the life cycle analysis of agricultural pellet starting from wheat farming to the distribution of pellets to users taking into account all the input and output flows of energy and emission occurring along the pellet life cycle. This is a standard approach and has been applied to life cycle analysis of other biofuels from herbaceous residues. A number of scenarios have been examined to study the impacts of changing tillage system, taking organic farming option, omitting farming activities, modes of transport and drying options. The analysis also takes into account land use change aspect, i.e., effect of crop residue removal on soil organic carbon and N_2O emission.

4.2. Methodology

This study followed four steps to a life cycle analysis: goal definition and scoping; inventory assessment; impact assessment; and interpretation. In this chapter a detailed model was developed to determine energy consumption and emission over the life cycle of biomass pellet using agricultural residues. Direct and indirect energy consumptions and emissions at each stage of life cycle of pellet production were considered in the model. Key stages of energy consumption and emission estimation included (i) crop production and harvesting, (ii) transportation of crop residue from field to the pellet plant, (iii) pellet production, (iv) transportation to user.

The agricultural residue in the form of straw has been considered as feedstock in this research because of its large availability in Western Canada. Spring wheat is the prime wheat crop in the considered region among others such as durum, winter wheat. This represents about 85% of the provincial total wheat production for the last ten years. Wheat yields have averaged 2.69 tonne/ha over the past twelve years (AARD, 2008). Residue yields considered 1.1 times grain yield (Sultana *et al*., 2010).

For life cycle analysis of energy and GHG emissions of agri-pellets, following types of energy and emission sources were considered:

- Manufacturing, distribution and application of fertilizer, herbicides, insecticides and fuel used for growing the biomass feedstock;
- Harvesting and collection of biomass residues;
- Land use change resulting from production and removal of biomass residues;
- Transportation of biomass from farm to pellet plant;
- Conversion of biomass residues to pellet;
- Transporting pellets to the user.

Goal Definition

Information from existing literature was compiled for the determination of energy consumption and GHG emission from pellet utilizing the most currently available data for each unit process. For wheat farming, wheat transportation and pellet production, current technology and practices in Canada are considered. The goal of this study was to analyze agri-pellets in terms of energy and emission impact when it is used for heating purposes.

Scope

When comparing biofuel with fossil fuels, it is of utmost importance to consider the same relevant service from the various systems (Gnansounou *et al*, 2009). LCA requires the use of a functional unit for comparison, of different energy systems. The functional unit of current analysis is the 1 MJ heat produced from pellet.

Three major gaseous emissions make long term contribution to the global warming, which were included in this study, are CO_2, CH_4 and N_2O. Based on earlier studies (IPCC, 2001; Jugmeier and Spitzer, 2001), the 100-year time horizon was used to determine global warming potential. The CO_2 emission are described in terms of CO_2 eq, which is the weighted sum of CO_2, CH_4 and N_2O emission considering the global warming potential values for these gaseous as 1, 21 and 310, respectively (EPA, 2009).

Carbon emission from biomass combustion is considered zero as all carbon released from straw during its combustion is taken up by the plant during its growth (Raymer, 2006; Sikkema *et al*., 2010). Figure 4-1 illustrates the base-line system boundary used in this study which shows the unit processes considered in this analysis. The life cycle of natural gas includes gas extraction from well, upgrading, refining, transmission, storage, distribution and combustion. The emissions associated with each step were considered. The life cycle of coal pathways consist of coal mining, processing, coal transportation to plant and burning in coal-fired plant. The life cycle emissions of natural gas and coal have been taken from previous studies (Jungmeier and Spitzer, 2001; Magelli *et al*., 2009).

The base case is developed by considering the current and existing practices of pellet production in Western Canada. Wheat planting is included in the base case as one of the unit operations. In base case, the farming practice of wheat production is considered and the energy and emission during wheat production were allocated between wheat grain and straw based on mass ratio. However a number of earlier studies do not consider emissions related to farming (Hartmann and Kaltschmitt, 1999; Cherubini and Ulgiati, 2010) because they considered wheat straw production is incidental of wheat grain production.

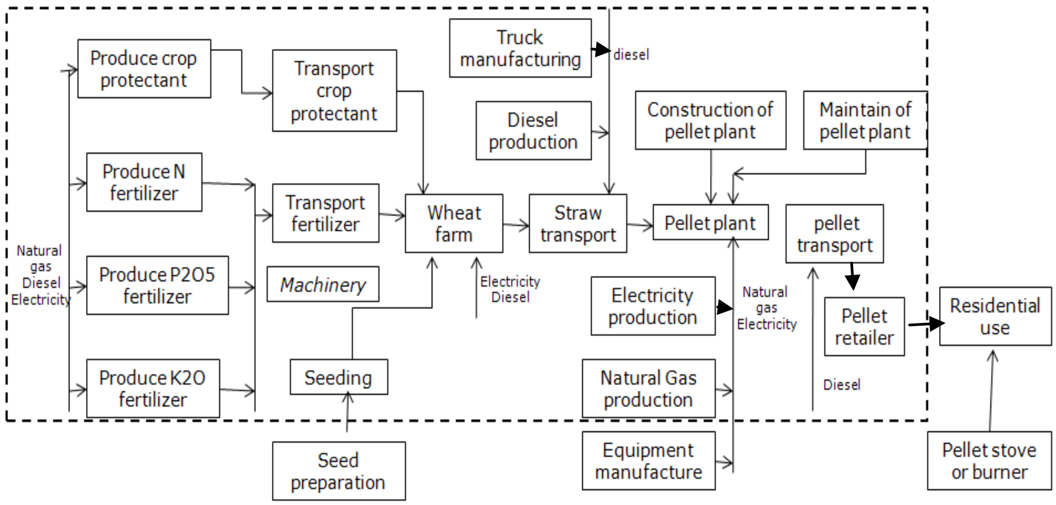


Figure 4-1: System boundary for life cycle analysis of agricultural pellet production

The later concept is analyzed in one of the scenarios. The estimated economic optimum size of the agri-pellet production plant is taken from an earlier study by the authors (Sultana *et al*., 2010). The economic optimum size of the agri-pellet plant in Western Canada is 150,000 tonnes/year and collection radius of the biomass for the plant is 94 km (Sultana *et* al., 2010). Wheat straw is assumed to be collected from the field in the form of bales. These bales are transported to the agri-pellet production plants on trucks. In a pellet plant, pellet production is a combination of sequential steps including preprocessing, drying, grinding, pelleting, cooling, screening, and bagging. Different scenarios (scenario 1-6) were developed by changing key assumptions and methodological choices while keeping other parameters and assumptions same as the base case. Scenarios are shown in Table 4-1.

Table 4-1: Developed life cycle analysis scenarios

Phases	Scenario Description	Scenarios
Field	*Starting point of life cycle chain* • Start from wheat farming and allocation of energy and emission between grain and straw based on mass ratio. *Fertilizer* • Synthetic fertilizer *Tillage system* • Conventional tillage	Base Case
Pellet plant	*Drying fuel* • Natural Gas	
Pellet transport	*Mode of transport* • Truck transport	
Field	*Starting point of life cycle chain* • Consider straw as by-product; all energies and emissions before straw harvest are omitted.	Scenario 1
Field	*Fertilizer* • Organic fertilizer	Scenario 2
Field	*Tillage system* • Zero tillage	Scenario 3
Pellet plant	*Drying fuel* • Biomass (straw)	Scenario 4
Pellet plant	*Drying fuel* • Without drying	Scenario 5
Pellet transport	*Mode of transport* • Truck and train combination	Scenario 6

In this study, the total energy requirement and resulted emission of the whole process is the sum of the energy requirement and emissions of unit processes respectively. The emission attributed to pellet production were evolved using existing data on emission factors and material flow input of the unit processes from published literature. Wherever data was not available, these were assumed or calculated. To develop a quantitative input estimate of energy requirement for each process, input per functional unit and energy coefficients (MJ per unit) were used. Energy co-efficient are the energy used from primary production to end user (Nagy, 1999). Data to develop energy co-efficients were taken from the published literature. In field processes, input data were usually location-specific information data. These data were estimated by developing a data intensive model which was ultimately used to estimate the total emissions for agri-pellet production.

4.2.1. Inventory assessment

Agronomic input data and assumptions

The usual practice for use of straw in Western Canada till today is either to leave it in field to rot or to collect for animal feed. If the straw is left in the field it provides some nutrient for the soil. Nutrient replacement by applying fertilizer is necessary if straw is removed. We assumed that nutrient requirement of soil due to removal of residue is compensated by application of fertilizer and therefore there would be no change in the yield of straw.

Agricultural inputs such as fuel, fertilizers, electricity, herbicides and machineries contribute to GHG emission to atmosphere. Alberta's soil contains abundance of calcium and some minerals so nitrogen, phosphorous, potassium and sulfur are the only fertilizers that need to apply in soil (Kumar *et al*., 2003). Agricultural practices including resource usage and emissions, vary widely by location and crops (O'Donnell *et al.,* 2009). The factors which influence the inputs to the soil for any crop production includes crop rotation, soil characteristics, the sequence of soil preparation and culturing steps, and type and application rate of fertilizers.

Uptake rates of fertilizers and insecticides are region-dependent and vary due to soil types and available nutrients (Fernandez-Cornejo and Jans, 1999). Nutrient uptake (total nutrient taken up by the crop) and removal value (nutrient removed in the harvested portion of the crop) are given in Table 4-2 based on typical nutrient concentrations and yield for good growing condition for Western Canada (CFI, 2001). Actual uptake and removal may vary with time (year) and depend on crop yield, crop variety, soil fertility (CFI, 2001). In this study all fertilizer, seeding, pesticides used in Western Canada were reviewed. In this region, demand is the greatest for two nitrogen based fertilizers: urea and anhydrous ammonia (Nagy, 1999). Urea consumption in the prairies represents 81% of the total used fertilizers. The amount of N fertilizer required depends on the level of soil nitrate-nitrogen ($NO_{3-}N$). Less fertilizer is needed if the level of soil nitrogen is high (Mckenzie, 2001). Wheat has traditionally been grown using conventional tillage in the southern prairie of Western Canada. However, with increasing concerns about decline in soil quality, farmers have been shifting to continuous cropping system coupled with reduced or zero tillage (Bryan, 2004). Hence, we have considered continuous cropping of wheat with conventional tillage system in our base case analysis.

Effect on land Use change

The effect of removal of agricultural residues from the field is still being debated by many researchers (Cherubini and Ulgaiati, 2010). Since straw need to be removed from soil top for agri-pellet production, an in-depth consideration of the issues including affects to soil organic matter turnover, soil erosion, crop yield, N_2O emission and others. The impact can vary from location to location with climate, soil type and crop management. The issue of land–use-change effects induced by agricultural residue collection have been partially investigated in earlier studies (Cherubini and Ulgaiati, 2010; Lal, 2004; Lal, 2008). Agriculture soil has exclusive property that it can store C and also emit it as CO_2. The use of biomass may lead to alteration of carbon stored above and below the ground in the field (Cherubini and Ulgaiati, 2010). Most of the life cycle analyses do not consider the changes except few (Lal, 2004; Gabrielle and Gagnaire, 2008; Cherubini and Ulgaiati, 2010). Any disturbances of soil organic matter (SOM) increase the rate of decline of the SOM until equilibrium is reached. The factors which affect the soil carbon pool are very site-specific (Sauve, 2000). Soil characteristics, climate, agronomic practices such as tillage, crop rotation, residue management, fertilizer application affect the soil carbon pool (Cherubini and Ulgaiati, 2010). A detailed assessment of carbon dioxide and nitrous oxide emissions and sequestration from agricultural soil in Alberta was done by Alberta Agriculture, Food and Rural development (Sauve, 2000). Data from this study was used in the current analysis.

Emissions associated with land use changes are mainly carbon dioxide and nitrous oxide. N_2O emission evolves from organic matter decomposition in soil and from nitrogen fertilizer. Emission is very site-specific, depends on soil type, climate, crop type, tillage method, application rate of fertilizer. The majority of the N_2O production from agricultural soil can attribute to dentrification and nitrification process. Dentrification is the major process of N_2O production which increases at moist soil conditions with low oxygen availability (Sauve, 2000). N_2O has higher (310 times) global warming potential than CO_2 over a 100-year period. Moreover, a part of the nitrogen fertilizer used in soil is converted to N_2O and some may run off the site (Cherubini and Ulgaiati, 2010). The IPCC soil emission estimates are based upon linear extrapolation between N_2O emission and N fertilizer application without considering soil type and climate (Sauve, 2000).

Soil organic carbon (SOC) is decreased in soil due to removal of straw during harvesting. Straw if not removed would otherwise decompose in soil. On average 0.75 tonne/ha stubble is kept in field for protection against wind and water erosion and for improving soil moisture conservation (Stumborg *et. al*, 1996; Sultana *et al*., 2010). The amount of residue retained for soil conservation varies with field slope, soil texture, residue type, weather condition, soil aggregation and tillage practice (Saskatchewan Agriculture, 2008). About 30% of straw yield (i.e. 2.96 tonne/ha) of the loose residue is retained on the soil surface after harvesting is complete due to inefficient machine((Sultana *et al*., 2010). Total amount kept in soil (i.e., 1.5 tonne/ha), decomposes in soil. Similar amount is reported by in an earlier study (for Western Canada (Saskatchewan Agriculture, 2008). Total N content of straw is 6 kg N/tonne with 10 percent moisture (Hartman, 2008). Hence, total of 9 kg N is decomposed per hectare of soil when straw is harvested based on total amount of straw kept in soil. About 27.5 kg N/ha (Table 4-1) is removed during the harvesting from the soil (CFI, 2001). The difference 18.5 kg N/ha should be adjusted by nutrient replacement. If the fertilizer requirement of wheat crop is adjusted for the removal of nutrients in the straw then there should be no wheat yield changes and thus no changes in N content of soil. It is assumed in this study that the amount of nutrient removed during harvest is compensated by applying more nutrient to the soil so net yield would not change (Levelton Engineering Ltd., 2000). IPCC (2006) estimated a factor of 1.325% of N/ kg N fertilizer is released as N_2O. This value is more generic without considering soil texture, climate, temperature and other factors in consideration (Sauve, 2000). The denitrification potential and capacity to produce N_2O increase with the decomposition of straw. The manufacturing and application of additional fertilizer also takes into account energy and emission assessment. Using IPCC (2006) estimate, the calculated N_2O emission was 1.619 kg N_2O/ha (or 0.0006 kg N_2O/kg of straw.)

Another effect of harvesting straw is the decrease in soil organic carbon (SOC) due to changes in soil carbon stock. Loss of soil carbon occurs through emission of CO_2. The removal of straw from the field causes a reduction of SOC to be 0.27

tonnes C/ha per year (Cherubini and Ulgaiati, 2010). Gabrielle and Gagnaire (2008) estimated SOC decrease rate of 0.15 to 0.75 tonnes C/ha depending on the soil and climatic condition. Sauve (2000) considered similar value from 0.15 to 0.45 tonne C/ha for Alberta. In order to supply 150,000 tonnes/year of straw to the pellet production plant, 1,228,000ha of land is required (Sultana *et al*., 2010). About 30% of this land is used for wheat cultivation. Based on these input values, an amount of 99.46 ktonne C/year is lost from SOC to atmosphere and hence 358 ktonne CO_2/year emission which accounts 0.159 kg CO_2/MJ of pellet.

Fertilizer

Three primary nutrients N fertilizer, P_2O_5 and K_2O are considered in the analysis. Sulfur application in the field was omitted as the amount of application rate is very low in Western Canada. Lime is usually applied to acidic soil to neutralize the excess acidity of soil which might cause reduction in yields but only 5% of the total area of Alberta lies in the acidic region so the lime application was omitted from the analyses. Different nitrogen based fertilizer (e.g., urea (46-0-0) (i.e., urea contains 46% N), ammonium nitrate (34-0-0), ammonium sulphate (21-0-24)(i.e.,ammonium sulphate contains 21% N and 24% sulfur), anhydrous ammonium can be applied to wheat production areas. Mainly urea and ammonium nitrate are used in wheat production in Western Canada (Nagy, 1999) and the use of urea is prevalent. The application rate of nitrogen based fertilizer (kg/ha) and its energy co-efficient is low in North America than in Europe (Mortimer *et al*., 2004; Punter *et al.,* 2004). In the current analysis, GHG emissions during production of fertilizers, transportation of fertilizers and its application in the field are considered. The average transport distance of the fertilizer from production plant to the farm was taken as 500 km (Gasol *et al*., 2007). The uptake rate of fertilizer was taken from the Canadian Fertilizer Institute as shown in Table 4-2 (CFI, 2001). The fossil fuel usages for the production of fertilizer, transportation and application of fertilizer was taken from previous studies (Zenter *et al*., 1989, Nagy, 2000, Coxworth *et al.,* 1995). The estimation of energy co-efficient varies considerably with the type of fertilizer, time and estimation procedure. The energy co-efficient was calculated by considering energy requirement during manufacturing of raw material for production of fertilizer. Energy required in manufacturing of machinery used for producing fertilizers was not considered. Fossil fuels used for the production of fertilizer contribute to GHG emissions. This is due to the energy requirement during processes of mineral extraction and fertilizer manufacturing. Fertilizers input in wheat production and its energy co-efficients are shown in Table 4-3. The 'value used' shown in Table 4-3 are taken based on values suitable for Western Canada.

Table 4-2: Average nutrient uptake and removal by 40bu/ac wheat crop under western Canadian conditions (derived from CFI, 2001)

Crops	N		P_2O_5		K_2O		S	
	Kg/ha							
	Uptake[a]	Removal[b]	Uptake[a]	Removal[b]	Uptake[a]	Removal[b]	Uptake[a]	Removal[b]
Spring wheat	94.72	27.46	35.87	9.53	81.27	61.65	10.09	5.05
Winter wheat	75.67	17.38	34.19	5.62	79.59	60.53	11.21	3.36
Barley	124.43	37.55	49.88	12.33	118.82	89.67	14.57	6.72
Oat	120.51	51.57	45.40	16.81	163.10	142.36	14.57	9.53

[a] total nutrient taken up by crop
[b] nutrient removed during harvesting straw.

Pesticides

The total energy input for pesticide includes energy required in manufacturing of the raw materiala used for pesticides and the direct energy input during making of fetilizers. The energy related to packaging, transporting and application of pesticides was considered. The energy requirement in manufacturing of different fossil fuels used for these processes involved in production of pesticide were reported in literature (Green,1987); Bhat *et al*., 1994;Audsley, 2009). The average energy requirements of 23 different pesticides listed by Green (1987) were used in the analysis. The pesticides application rates were taken from Piringer and Steinberg (2006) and this rate varies from 0.33 to 0.49 kg/ha. Pesticide input for wheat production and its energy co-efficients are shown in Table 4-3.

Seeding

The energy used for seed production, packaging and distribution was estimated based on earlier studies (Nagy,1999; West and Marland, 2002). The optimum seeding rate for Alberta varies from 138 to 144 kg/ha for durum wheat and 112 to 135 kg/ha for spring wheat (Dunn and Mckenzie, 2006). Input of seeding rate and its energy coefficients are shown in Table 4-3.

Machinery

The energy requirements for manufacturing, transportation and repair of machinery were taken from Coxworth *et al.* (1995). The energy required for manufacturing and repair of farm equipment was considered to be 158.9 MJ/kg and for transportation of the equipment was 8.6 MJ/kg (Coxworth *et al.,* 1995). The estimation of the amount of material required for manufacture of the proportional faction of tractors and agricultural utensils used in the agricultural phase are estimated based on previous study (Gasol *et al.,* 2007).

Table 4-3: Inputs and energy co-efficient for wheat production

Operation	Input quantity				Energy co-efficient			
	unit	Used value	Low-high	Reference	Unit	Used value	Low-high	Reference
Fuel and oil								
Diesel use					MJ/kg	45.25		[h]
Sowing	kg/ha	3.0	0.9-21.6	[a][b][c][d]	MJ/kg	45.25		[h]
Fertilizer and liming								
Spreading fertilizer	kg/ha	2.0	0.9-4.7	[a][e][f][g]	MJ/kg	45.25		[h]
Liming	kg/ha		1.5	[h]	MJ/kg	45.25		[h]
Plant protection								
Pesticide spraying	kg/ha	1.5	0.8-1.7	[a][e][f][g]	MJ/kg	45.25		[h]
Harvesting and baling								
Combine harvesting	kg/ha	14.0	7.0-19	[a][e][f][g]	MJ/kg	45.25		[h]
Baling and handling	kg/ha	1.5	1.3-1.7	[a][e][f][g]	MJ/kg	45.25		[h]
Transport								
Machine transport	kg/ha	0.04	0.3-0.4	[a][e][f][g]	MJ/kg	45.25		[h]
Loading and handling								
Loading and handling	kg/ha	1.3	0.3-3.8	[a][e][f][g]	MJ/kg	45.25		[h]
Electricity	kWh/ha	37.07		[h]	MJ/kWh	9.89		[h]
Gasoline	L/ha	9.35		[h]	MJ/L	43.19		[h]
LPG	L/ha	2.81		[h]	MJ/L	26.72		[h]
Natural gas	M^3/ha	0.007		[h]	MJ/m^3	40.43		[h]
Seeds and agrochemicals								
Seeds	kg/ha	125	35-175.27	[a][b][c][d]	MJ/kg	7.2	5.57-7.2	[a][e]
Fertilizer								
Urea-N(46-0-0)	kg/ha	94.72	85.19-104.25	[i]	MJ/kg	67.03	90.6-45.6	[f][h][l][m]
Ammonium nitrate	kg/ha	94.72	85.19-104.25	[i]	MJ/kg	63.00	42.8-75.63	[f][h][l][n]

Phosphate (P_2O_5)	kg/ha	35.87	32.51-39.23	[i]	MJ/kg	13.11	2.11-20.3	[e][f][o][p]
Potassium (k_2O)(0-0-60)	kg/ha	81.27	72.86-89.68	[i]	MJ/kg	9.85	4.6-12.35	[e][h][m][q][r]
Sulfur	Kg/ha		8.96-11.21	[h]	MJ/kg	1.12		[a][h][m]
Lime stone	kg/ha		44.83	[h]	MJ/kg	0.17		[a][h]
Pesticides	kg/ha	0.49	0.33-0.49	[a][h][j][k]	MJ/kg	308	297-474	[l][m][s]
Farm machinery								
Tractor	kg/ha	8.60		[e][f][h]	MJ/kg	158.9		[h][m]

[a] Bhat *et al*., 1994; [b] Dunn and Mckenzie, 2006; [c] GHG Registries, 2010; [d] AESO, 2010; [e] EPA, 2009;
[f] Levelton Engineering Ltd., 2000; [g] Ali, 2002; [h] Green, 1987; [i] Kumar *et al.,* 2003; [j] Boerma *et al*., 1980;
[k] Graboski, 2002; [l] Coxworth *et al.,* 1995; [m] IPCC, 2006; [n] Tompkins *et al.,* 1991; [o] AAFRD, 2006;
[p] Dalgaard *et al.,* 2001; [q] DOE, 2000; [r] Gianessi and Marcelli, 2000; [s] Gasol, 2007.

The proportion fraction of machinery or utensils was estimated using (Gasol *et al.,* 2007):

$$M_F = \frac{WxT_0}{L_T} \quad (4\text{-}1)$$

M_F= fraction for the amount of machinery (kg/Fu) used in the field work.
Fu = functional unit selected for this chapter.
W= weight of the tractor or other utensils (kg)
T_o = operation time for each field operation (hour/Fu)
L_T =life time of tractor or utensils (hours).

Fuels and Electricity

The emission from combustion of fuels and that associated with production and delivery of the fuels to the farm were considered. The estimates include field operations such as seeding, harvesting and hauling of harvested material to the roadside, application of fertilizer, herbicides and other farming operations. Application of lime was not included in the analysis. The estimate of the energy co-efficient of fuels was considered based on previous study (Nagy, 1999). Data for diesel emission was taken from previous studies (GHG Registries, 2009). Carbon dioxide attributed to electricity consumption are based on mix of fuel to produce electricity which comes mainly from coal (46%), gas (40%), hydro (7%), wind (5%) and biomass (2%) (AESO, 2010). There are also emissions during the construction of a power plant but this is negligible when averaged over the life cycle of the power plant (Hartmann and Kaltschmitt, 1999; Kumar *et al.*, 2003). Fuel and electricity input in production of wheat and its energy co-efficients are shown in Table 4-3.

4.2.2. Transportation of straw bale from field to pellet plant

Straw in the form of bales are usually transported by truck (Sokhansanj *et al*., 2010; Sultana *et al*., 2010). In this analysis, bales were loaded onto a truck and transported to a pellet plant throughout the year. The weight of each bale was considered to be 500 kg (based on weights reported in earlier studies; Sokhansanj *et al*., 2010; Sultana *et al*., 2010). Bales were stacked on a flatbed trailer with payload capacity of 16.8 tonne. Assumptions considered for truck transport were shown in Table 4-4. Based on an earlier study by the authors (Sultana *et al.,* 2010), the highest yield area of Alberta is Census Division 5. It is considered in this study that the location of the pellet plant is at the center. Census division 5 is 138 km north from Calgary (Figure 4-2). For an optimum plant capacity of 150,000 tonne per year (Sultana *et. al.,* 2010) the biomass requirement for a pellet plant is 157,000 tonne per year considering the 5% loss in the plant. Optimum capacity is defined as the capacity of the plant at which the cost of production of pellets is the minimum.

Different capacities of truck and trailer are shown in Table 4-5 (Volvo, 2006). For this capacity the numbers of truck trips were 17,045 per year. We considered the fuel consumption of a single fully loaded truck and empty truck are 0.25 and 0.20 litre/km, respectively. The fuel requirements of trucks with different capacities are shown in Table 4-5. Energy consumed to haul 1 kg of straw to a distance of 94 km is 0.115 MJ considering the higher heating value of diesel is 45.25 MJ/litre. We considered diesel as the fuel for truck transport since 46% of heavy-duty truck operates by diesel (Gaines *et al.,* 1998). Table 4-6 gives the biomass transport forms and truck carrying capacities.

Figure 4-2: Map of Alberta (derived from AAFRD, 2006)

Table 4-4: Assumptions for truck transport

Capacity of the plant (tonnes/year)	150,000	Sultana *et al.,* 2010
Amount of biomass transport	157,500	
Material loss in plant	5%	Sultana *et al.,* 2010
Capacity of the truck (tonnes)	16.8	Gaines *et al*., 1998
Distance from field to pellet plant (km)	94	Sultana *et al.,* 2010
Fuel consumption of a truck (full load)(l/km)	0.25	Volvo Truck Corporation, 2006
Fuel consumption of a truck (empty)(l/km)	0.20	Volvo Truck Corporation, 2006
Travel speed of heavy-duty truck in high-way of Alberta (km)	50	Sokhansanj *et al.,* 2010
Life time of a truck (hours)	12,000	Gasol *et al.,* 2007
Steel and iron composition in truck	65%	Gaines *et al.,* 1998
Moisture content of straw*	14%	Sultana *et al.*, 2010

- Moisture content in wet basis.

Table 4-5: Capacities and fuel requirements of heavy-duty trucks (derived from Volvo Truck Corporation, 2006)

Type of truck	Gross Vehicle weight(GVW) (tonne)	Payload (tonne)	Fuel requirement l/km (empty)	Fuel requirement l/km (full load)
Truck, distribution traffic	14	8.5	0.20-0.25	0.25-0.30
Truck, regional traffic	24	16.8	0.25-0.30	0.30-0.40
Tractor and semi-trailer, long-haul traffic	40	26	0.21-0.26	0.29-0.35
Truck with trailer, long-haul traffic	60	40	0.27-0.32	0.43-0.53

Table 4-6: Biomass transport forms and capacity

Forms of biomass for transport	Bulk density (tonne/m^3) (a)	Amount to be transported (tonne) (b)	Payload (tonne) (c)	Volume capacity of truck(m^3) (d)	Actual weight carry Min{c, (axd)}	No of trucks loads
Bale	0.11	157,500	16.8	84	9.24	17,045
Chop	0.16	157,500	11	70	11	14,318
Pellet	0. 60	150,000	40	70	40	3,750

The actual load a truck can carry is limited by the weight or volume limit of the truck. Thus actual load of truck was estimated by

$$W_a = min\ \{W_p,\ (b\ x\ V)\} \qquad (4\text{-}2)$$

Where,

W_a = actual load a truck can carry (kg);

W_p = Payload of a truck (kg)

b = bulk density of bale (kg/m^3)

V = volume capacity of a truck (m^3)

Actual fuel consumption of truck with a certain load can be estimated as (Gasol *et al.,* 2007).

$$F_c = F_0 + \left\{ (F_f - F_0) x \frac{W_a}{W_p} \right\} \qquad (4\text{-}3)$$

Where,

F_c = Actual fuel consumption of a vehicle with W_a load (litre/km).

F_o = fuel consumption of an empty vehicle (litre/km).

F_f = fuel consumption of a fully loaded vehicle (litre/km).

W_p = Payload of a truck (kg)

W_a = Actual transportable load of a truck (kg).

In equation (4-3), the fuel consumption (litre per km) during hauling is F_c and fuel consumption at the time of back hauling is F_o (litre/km). The data for truck transport is shown in Table 4-6.

To estimate the energy and emission in manufacturing of a truck of capacity 22 tonnes the composition of truck material was considered. The material used for truck manufacturing included steel (51.29%), iron (12.98%), wrought aluminum (12.17%), rubber (9.01%), plastic (3%) and rest covered by copper, lead and glass (Gaines *et al.*, 1998). A reference speed of 50 km/hour was considered for our analysis. The life time of a truck is typically 12,000 hour and energy intensity of steel is 37 MJ/kg (Gasol et al., 2007; Markas Engineering Service, 2002). The life cycle emissions data for steel production was derived from literature (Markas Engineering Service, 2002). The tailpipe emission from heavy-duty truck for diesel fuel and the life cycle emission analysis of diesel production was also derived from earlier studies (GHG Registries, 2009; Furuholt,1995).

4.2.3. Straw pellet production

In a pellet plant, production of pellets is a combination of sequential steps including preprocessing, drying, grinding, pelleting, cooling, screening, and bagging. All of the equipment are operated by electric motor. The power requirement for straw-based pellet production is 865 kW (Sultana *et al.,* 2010). This electrical energy was converted to thermal energy by considering the efficiency of power plant is 35% (assumed to be for coal in case of Alberta). Unlike wood pellet production, pellet mill is the highest energy consuming equipment (34%) in straw-based pellet production followed by dryer (19%). This is different than wood pellet production where the dryer consumes the maximum portion of electricity (Pastre, 2002) because the moisture content of woody biomass is 45-50% compared to 15-20% of agricultural biomass. The feedstock species, particle size, pellet size and moisture level are important factors in determining how much horsepower is needed. Straw pelletization requires less electrical power than pelletization of wood, even though it requires extra power for chopping compared to wood (Sultana *et al.,* 2010). The power requirement for all the equipments used for pellet production was taken from previous study (Sultana *et al.,* 2010).

If straw is delivered to the pellet plant with moisture content lower than 12%, drying may not be required (Campbell, 2007). In spring harvesting moisture content of straw is 40% less than fall harvesting. The rotary drum dryer is generally used in a pellet production plant (Campbell, 2007; Karwandy, 2007) and this was considered in this analysis. The pellet plant with capacity of 150,000 tonnes per year operates for 7200 hours annually (about 24 hours/day, 310 days /year, hence at a capacity factor of 85%) (Sultana *et al.,* 2010). The energy required for pellet production was estimated at be 0.15 $MJ_{thermal}$/kg of pellet. The GHG emission factors for electricity used were taken as 905g CO_2/KWh, 0.028g CH_4/KWh and 0.02g N_2O/KWh (Environment Canada, 2009).

In this analysis moisture content of straw was considered to be 14% (Sultana *et al.,* 2010). Straw arriving at pellet plant typically have moisture content of 13 to 20% which is reduced to 8-10% using dryer. Natural gas is commonly used fuel for drying (Magelli *et al.,* 2009). This was considered in the base case scenario. Another scenario considered for the analysis was the use of biomass straw as drying fuel. The reduction of moisture content of biomass was from 14% to 8%.
Straw requires conditioning to provide durable pellets and to minimize fines (Karwandy, 2007). Conditioning is done with steam or hot water to soften the fibrous material of straw. The requirement of steam for conditioning purpose is

approximately 4% (by mass) of total amount of dry biomass feedstock used (Thek and Obernbergern, 2004). Conditioned feedstock is then fed to the pellet mill. Steam generation for conditioning is produced by burning natural gas in a boiler. Boiler efficiency was considered to be 80% and heating value of the natural gas was 40.43 MJ/m^3 (Dias *et al.*, 2004; Kristensen and Kristensen, 2004). Thus the energy requirement for conditioning of pellet is 0.12 MJ/MJ of pellets. The assumptions considered in this study for drying and conditioning of straw is shown in Table 4-7.

The specific emission from combustion of natural gas was 1918 g CO_2/m^3, 0.0372 g CH_4/m^3 and 0.0332 g N_2O/m^3 (NETL, 2008). The emissions during natural gas recovery including well drilling testing and processing emission were 0.1339 kg CO_2/m^3, 0.0019 kg CH_4/m^3 and 46 x 10-6 kg N_2O/m^3 (IPCC, 2003).

Table 4-7: Assumptions for drying and conditioning biomass for pellet production

Drying		Sources
Total amount of biomass for drying (tonnes/year)	157,500	
Moisture reduction	14% to 8%	Thek and Obernberger, 2004
Temperature increase (^{0}C)	25^{0}C to 110^{0}C	Thek and Obernberger, 2004
Specific heat of water (KJ/kg ^{0}C)	4.2	
Specific enthalpy of steam at standard atmosphere (KJ/kg)	2676	
Conditioning		
Percentage of water required for conditioning biomass (%)	4%	Thek and Obernberger, 2004
Temperature increase of water for conditioning(^{0}C)	20^{0}C to 100^{0}C	
Boiler efficiency (%)	80%	

4.2.4. Transportation of pellet from plant to consumer

The truck considered for transporting pellet from the plant to retailer or end-user has a capacity of 40 tonnes (70 m^3 capacity). This pellet can be used in small scale combustor by residential users or large scale CHP plants. It is assumed that pellets are transported from plant to nearby location (e.g., Edmonton or Calgary as these two are the nearby big cities) in Alberta (Figure 4-2). Two locations for the consumers were considered at distances of 140 km and 280 km between production plant and consumer. We assumed that the retailer stores are within these two cities from which residential user purchases 250 kg of pellets at a time (15 kg bag each) (Sikkema *et al.,* 2010). The distance between the retailer shop and the residence of small user was assumed to be 5 km to 15 km in two different scenarios. The approximate radius of city of Edmonton and Calgary are 14 km and 15 km, respectively. Including suburbs the approximate radius can be increased to 54 km and 40 km respectively. Sikkema *et al.* (2010) considered the distance of 93 km from retailer to the residential user in European setting. Assumptions considered for pellet transport are shown in Table 4-8.

Table 4-8: Assumptions for pellet transport from pellet plant to consumer

Heavy-duty truck transport		Sources
Pellet truck capacity (tonne)	40	Sokhansanj *et al.,* 2010
Fuel consumption (litre/km)	0.25	Volvo Truck Corporation, 2006
Highest yield area	Census division 5	
Distance from center of census division 5 to		
Calgary (km)	140	
Edmonton (km)	280	
Passenger car transport		
Distance travel by customer (km)	5	
Fuel consumption (litre/km)	0.066	EPA, 2000
Pellet bag size (kg)	15	Sikkema *et al.,* 2010

The GHG emissions from the passenger car, which is used to transport pellets from retailer store to customer, were considered 0.258 kg CO_2/km and 8.6 x 10^{-4} kg N_2O/km (EPA, 2000). The fuel consumption of passenger car is considered to be 0.066 litre/km (EPA, 2000). Pneumatic trucks are used in Europe for delivering pellet to households or medium size users and trucks are used for delivery to large scale user (Senechal and Grassi, 2009). Unlike Europe pneumatic truck with automated loading system is not common in North America, so truck and combination of truck and train transport are used here. The average transported volume is about 0.25 tonnes/year for residential user but for users of large loads can be between 500 to 1000 kg (Sikkema *et al.,* 2010). For industrial bulk users such as CHP plants, pellets are transported through wholesale merchants or directly from the pellet plant.

4.2.5. End user

There are two main end-uses of pellet including residential and industrial. The residential pellet biomass trade in Canada is local or regional while currently industrial wood pellets are traded internationally. In case of agricultural pellet we have considered that pellet is used in CHP plants in Canada. For residential users small scale combustor such as pellet stove or burner is considered. The efficiency of this type of combustor is usually 60% but these days high efficiency combustor of efficiency 85% are available (US Department of Energy, 2010). The emissions per unit energy output from small scale combustor are generally high due to incomplete combustion which depends on temperature during combustion, excess air and other factors (Johansson, 2003). In large scale plants combustion occur at high temperature and complete combustion is possible due to proper technical design and hence lower emissions per unit energy output. CO_2 emission due to combustion of pellet was considered zero because pellet is considered as a carbon neutral fuel, i.e., the amount of CO_2 released during its combustion is same as the amount taken up by plants during its growth (Raymer, 2006; Sikkema *et al*., 2010; Kumar *et al.*, 2003). Other GHG emission, e.g., CH_4 and N_2O are considered in the analysis. There is also GHG emissions during the construction of a power plant but that is likely to be small when averaged over the lifetime of the power plant. We have not considered the emissions during manufacturing of small-scale combustor in our analysis.

4.3. Introduction to Scenarios

Scenario analyses were done to examine the sensitivity of different assumptions and parameters on the life cycle emission and energy of agricultural pellet production and utilization. Different scenarios were developed by changing various assumptions of the base case. The details on the scenarios are given below.

Scenario 1- The analysis starts from harvesting of straw from the field assuming that straw is the by-product of wheat production. The upstream activities of wheat farming were not taken into consideration. In the base case all emission and energy required for wheat farming were allocated to the grains and straw on mass basis. In this scenario, nutrient replacement required due to the removal of straw from the field was included. Other assumptions are same as the base case.

Scenario 2- This scenario was developed to distinguish the primary energy used and GHG emission between inorganic (or synthetic) and organic fertilizers. Recently there has been an increase in organic fertilizer usage at an annual rate of 20% (ERS, 2002). Other advantages of using organic fertilizer are increased soil quality, and enhanced biodiversity (Mader *et al*., 2002). Nutrient sources are different in inorganic and organic wheat but it is assumed that the nutrient requirement per kg of harvested wheat is same (Meisterling *et al.*, 2009). It was also assumed organic fertilizers requirements are met by manure and other crop organics (Meisterling et al., 2009). GHG from manure may vary with manure management, storage and allocation. In the current analysis GHG emission from manure management in wheat production system were adapted from Hoeppner *et al*. (2005) and Meisterling *et al*. (2009). The yearly availability of beef cattle manure, hog manure, dairy manure in Alberta are 51.9, 2.5 and 3.9 million tonnes, respectively (Navartnasamy *et al*., 2008), which is sufficient for organic wheat farming in the province.

Scenario 3- Wheat has traditionally been grown using conventional tillage in the southern prairie of Western Canada. However, farmers are shifting from conventional to reduced or zero tillage system to retain soil quality and to reduce cost. The zero tillage is still used for wheat production. So it was assessed in terms of GHG emissions and energy consumption in Scenario 3.

Scenario 4 – Solid biomass can be used as a dryer fuel instead of natural gas (Mani *et al*., 2006; Campbell, 2007). In this scenario it was assumed that straw would be used as fuel for drying during pellet production. If biomass was used as dryer fuel, 187,000 tonne/year straw are needed annually, of which 30,000 tonne/year (20% of biomass) is used as dryer fuel and rest, 157,000 tonne of straw feedstock for making pellets.

Scenario 5 – Drying can be omitted if the moisture content of biomass is less than 12% (Pastre, 2002). Spring wheat harvesting in August-September in western Canada can reduce moisture content by 40% so drying can be omitted. This case was evaluated in this scenario.

Scenario 6 – Trucking is the usual means of biomass transport and this is the only transport accessed in rural areas (Mahmudi *et al.,* 2005). For the considered area (from Calgary to Edmonton) biomass can be transported by train as the infrastructure is already in place. Earlier studies on LCA conclude that emissions are reduced substantially by using trains (Mahmudi *et al.,* 2005). Truck transport is considerably more energy intensive than rail transport (Coxworth *et al.,* 1995). Energy required for rail and truck are 0.47 MJ/t-km and 2.0 MJ/t-km, respectively (Coxworth *et al.,* 1995). Sixty percent of the total volume of land freight shipment in Canada is by rail and the remaining by truck (Mahmudi *et al.,* 2005) to reduce road congestion and cost of delivery. The size of the train considered was equivalent to 100 cars with capacity 190 m^3 per car. Typical train capacity is 26.6 tonne/car (Mahmudi *et al.,* 2005).

4.4. Impact Assessment and Interpretation - Results and Discussion

The energy requirements and associated emissions for base case are shown in Table 4-9. In the base case energy and emission are allocated between wheat grain and straw on mass basis. The nutrient replacement was also considered in the base case to compensate for the nutrients removed due to straw harvesting. The energy and emission due to nutrient replacement is completely assigned to straw. It is seen from Table 4-9 that the total energy use for the base case (after allocation to wheat and straw) is 0.21642 MJ/MJ of pellet e.g. the amount of energy used is 0.21642 MJ for 1 MJ of pellets. Field activities of wheat straw production is 21.07 gm CO_{2eq}/MJ of pellet. The highest energy use and emission comes from fertilizer production, transportation and application which is 84% of the total used energy and 94% of total emissions.

Energy use and emission in base case occurred during transport of straw (baled form) from field to the pellet plant (distance 94 km), pellet production and pellet transported to consumer is shown in Table 4-10. The tailpipe emission of the truck contributes 67% of the total emission by using 80% of the total energy. This operation consumes highest amount of energy compared to other operations in transportation phase. In base case, the total energy use of pellet production is 0.048 MJ/MJ of pellet and 60% of the energy is used in pelleting process. Total emission in pellet production is 7.76 gm CO_{2eq}/MJ of pellet of which 93% of emissions comes from the equipment which are operated by electric motors.

In the base case, the pellet use was considered for residential users. The pellet plant is assumed to be located in the centre of census division 5 of Alberta and the pellets can be transported to the retailers in the nearby big cities such as Calgary and Edmonton. The residential users get the pellets from the retailers who are on an average a driving distance of 5 km. The energy used to transport to the retailer of Calgary and Edmonton are 0.002 MJ/MJ of pellet and 0.005 MJ/MJ of pellet, respectively. Emission to transport to Edmonton is higher due to longer distance of transport as compared to Calgary.

Table 4-9: Energy use and emission for straw production

Input	Energy requirement	Emission				Sources/Comments
	MJ/MJ_{pellet}	kg CO_2/MJ_{pellet}	kg CH_4/MJ_{pellet}	kg N_2O/MJ_{pellet}	kg CO_{2eq}/MJ_{pellet}	
Base Case						
Fertilizer						
N	0.1574	0.00151 [a]	4.43×10^{-6} [b]	2.25×10^{-5} [c]	0.008575	[a]: Total carbon requirement for urea fertilizer is 1.225 kg CO_2/kg N [46]. In case of ammonium nitrate fertilizer the carbon requirement is 1.904 ± 0.275 kg CO_2/kg N [a1]. [b]: Total methane requirement for nitrogen fertilizer is $3.6 \times 10^{-3} \pm 0.6 \times 10^{-3}$ kg CH_4/kg N [a1]. [c]: Total nitrous oxide requirement for nitrogen fertilizer is 0.0183 kg N_2O/kg N [a1].
P_2O_5	0.0117	0.00012 [d]	1.07×10^{-8} [e]	1.96×10^{-8} [f]	0.000124	[d]: Total carbon requirement for phosphate fertilizer is 0.253 kg CO_2/kg P_2O_5 [b1]. [e]: Total methane requirement for phosphate fertilizer is 2.3×10^{-5} kg CH_4/kg P_2O_5 [a1]. [f]: Total nitrous oxide requirement for phosphate fertilizer is 4.2×10^{-5} kg N_2O /kg P_2O_5 [a1].
K_2O	0.0198	0.00022 [g]	2.22×10^{-8} [h]	9.92×10^{-9} [i]	0.000227	[g]: Total carbon requirement for potash fertilizer is 0.212 kg CO_2/kg K_2O [b1]. [h]: Total methane requirement for potash fertilizer is 2.1×10^{-5} kg CH_4/kg K_2O [a1]. [i]: Total nitrous oxide requirement for potash fertilizer is 9.4×10^{-6} kg N_2O /kg K_2O [a1].
Pesticide	0.0045	0.00004 [j]	1.10×10^{-9} [k]	9.61×10^{-9} [l]	0.000045	[j]: Total carbon requirement for pesticides (average of 23 pesticides) is 3.73 kg CO_2/kg pesticides [a1]. [k]: Total methane requirement for general pesticides is 1.8×10^{-4} kg CH_4/kg pesticides [a1]. [l]: Total nitrous oxide requirement for general pesticides is 1.51×10^{-3} kg

						N_2O /kg pesticides [a1].
Seed	0.0223	0.00021 [m]	0.00000 [n]	1.62×10^{-6} [o]	0.000714	[m]: Total carbon requirement for sowing is 0.212 kg CO_2/kg seeds [c1]. [n]: Total methane requirement for sowing is 2.1×10^{-5} kg CH_4/kg seeds [a1]. [o]: Total nitrous oxide requirement for sowing is 9.4×10^{-6} kg N_2O /kg seeds [a1].
Fuel	0.0419	0.00035 [p]	8.18×10^{-8} [q]	1.63×10^{-7} [r]	0.000399	[p]: Total carbon requirement for diesel fuel is 0.01926 kg CO_2/MJ of diesel fuel in Western Canada [d1]. [q]: Total methane requirement for diesel fuel is 4.42×10^{-6} kg CH_4/MJ for diesel fuel in Western Canada [d1]. [r]: Total nitrous oxide requirement for diesel fuel is 1.95×10^{-7} kg N_2O /MJ of diesel fuel in Western Canada [d1].
Machinery	0.0337	0.00018 [s]	1.0×10^{-8} [t]	3.78×10^{-15} [u]	0.000177	[s]: Total carbon requirement for machinery is 2.046 kg CO_2/kg steel [e1]. [t]: Total methane requirement for machinery is 0.0001 kg CH_4/kg steel [e1]. [u]: Total nitrous oxide requirement for machinery is 0.0027 kg N_2O /kg steel [e1].
Total	**0.2914**	**0.00240**	**4.52×10^{-6}**	**1.77×10^{-5}**	**0.01026**	
Nutrient Replacement						
N	0.112	0.00204	6.0×10^{-6}	3.05×10^{-5}	0.01162	[a1][b1]
P_2O_5	0.009	0.00017	2.0×10^{-8}	2.74×10^{-8}	0.00017	[a1][b1]
K_2O	0.005	0.00010	1.0×10^{-6}	4.50×10^{-9}	0.00010	[a1][b1]
Total	**0.125**	**0.00231**	**0.00001**	**0.000031**	**0.01190**	
			Organic Farming			
Fertilizer production	0	-	-	-	0	[f1][g1]
Pesticide production	0	-	-	-	0	[f1][g1]
Seed	0.0117	-	-	-	0.00071	[f1][g1]
Fuel	0.0105	-	-	-	0.00052	[f1][g1]
Machinery	0.0176	-	-	-	0.00017	[f1][g1]
Manure storage	0				0.0005	[f1][g1]
Total	**0.0398**				**0.00141**	

[a1] Mortimer *et al*., 2004; [b1] Coxworth *et al*., 1995; [c1] West and Marland, 2002; [d1] GHG Registries, 2010; [e1] Markas Engineering Services, 2002; [f1] Meisterling *et al*., 2009; [g1]Hoeppner *et al*., 2005.

Table 4-10: Energy and emission during transportation and pellet production

Operations	Energy requirement	Emissions			
	MJ/MJ$_{pellet}$	kg CO_2/MJ$_{pellet}$	kg CH_4/MJ$_{pellet}$	kg N_2O/MJ$_{pellet}$	kg CO_{2eq}/MJ$_{pellet}$
Transport of straw from field to pellet plant					
Truck run (95 km)[a]	0.012	0.00046	3.39×10^{-8}	6.79×10^{-8}	0.000485
Diesel production[b]	0.0003	0.00002	0.0000	9.67×10^{-8}	5.03×10^{-5}
Truck manufacture[c]	0.0023	0.0001	0.0000	0.0000	0.000179
Sub Total	0.015	0.00061	4.01×10^{-8}	3.32×10^{-7}	0.000714
Pellet production					
Pelleting	0.02847	0.00716	2.21×10^{-7}	1.58×10^{-8}	0.00721
Drying[d]	0.01311	0.00062	1.2×10^{-8}	1.07×10^{-8}	0.00063
Conditioning	0.00851	2.0×10^{-5}	3.9×10^{-10}	3.4×10^{-10}	2.03×10^{-5}
Sub Total	0.05009	0.00780	2.37×10^{-7}	2.68×10^{-8}	0.00786
Transport pellet from plant to the Consumer					
Transport to Calgary[e]	0.002	15.93×10^{-5}	1.16×10^{-8}	2.33×10^{-8}	16.67×10^{-5}
Transport to Edmonton[e]	0.005	31.85×10^{-5}	2.33×10^{-8}	4.67×10^{-8}	33.35×10^{-5}
Car transport[f]	0.0663	5.70×10^{-9}	0	1.26×10^{-12}	6.12×10^{-9}

[a]: The tailpipe emissions of diesel are 2.73 kg CO_2/litre, 2.0×10^{-4} kg CH_4/litre, and 4.0×10^{-4} kg N_2O/litre (GHG Registries, 2010).

[b]: Emissions during diesel production are 0.12 kg CO_2/l, 57.0×10^{-4} kg N_2O/l (Furuholt, 1995).

[c]: Emission for steel production 2.045 kg CO_2/kg, 0.0001 kg CH_4/kg, and 0.0027 kg N_2O/kg (Markas Engineering Service, 2002).

[d]: Emissions from burning of natural gas are 1.918 kg CO_2/m^3, 3.72×10^{-5} kg CH_4/ m^3 and 3.32×10^{-5} kg NO_2/m^3 (NETL, 2008).

[e]: Diesel fuel emission from heavy-duty truck are 2.73 kg CO_2/litre, 2.0×10^{-4} kg CH_4/litre and 4.0×10^{-4} kg N_2O/litre (GHG Registries, 2010).

[f]: Emission from passenger car are 0.258 kg CO_2/km and 8.6 x 10-4 kg N_2O/litre (EPA, 2000).

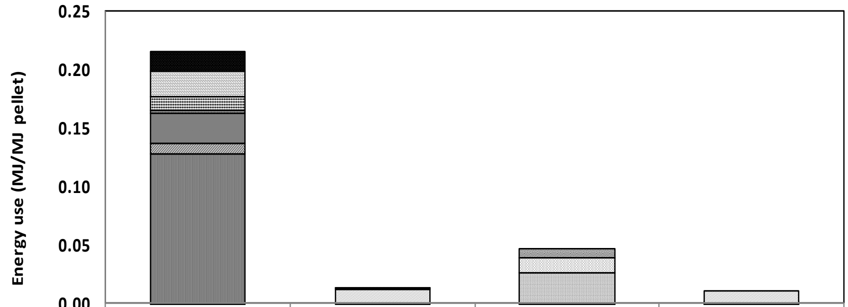
Emissions from pellet burning are shown in Table 4-11. These results are similar to earlier studies (Johansson *et al.*, 2003; Kjallstrand and Olsson, 2004; Caserini *et al.,* 2010). Pellet burning in a small scale combustor results in higher emissions than the CHP plant. This is because of the efficiency of the combustion units are lower than the CHP plants. In CHP plants, technical design of the combustor support complete combustion of fuel by controlling amount of air intake in combustor unit. In case of small scale combustor, such as a pellet furnace of stove, efficiency of combustion is less due to incomplete combustion.

Table 4-11: Emissions from pellet burning (derived from Jungmeier, 2010)

Operations	**Emission**			
	g CO_2/MJ_{pellet}	**g CH_4/MJ_{pellet}**	**g N_2O/MJ_{pellet}**	**g CO_{2eq}/MJ_{pellet}**
Small scale combustor	0[a]	5.01×10^{-3}	3.01×10^{-3}	1.03684
CHP plant	0[a]	1.65×10^{-3}	6.61×10^{-4}	0.23965

[a] The assumption is that the amount of CO_2 released during combustion is the same as taken up by the plant during its growth.

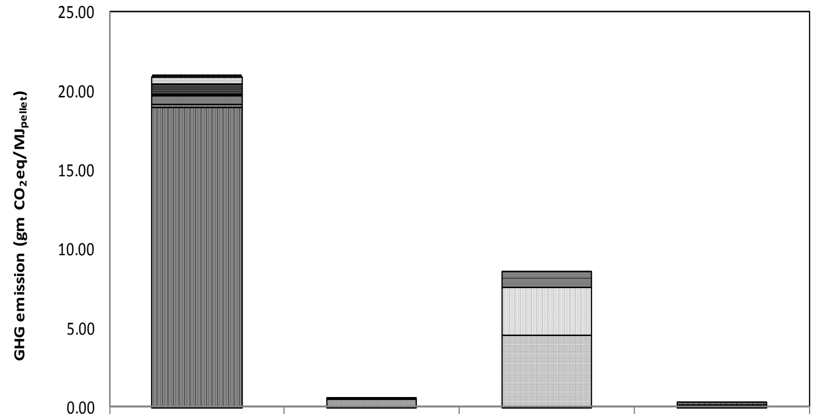
Energy use in the life cycle of pellet production is shown in Figure 4-3. Energy use in each phase of pellet production, starting from wheat farming till delivery to the plant is shown in Figure 4-3. Total energy used for pellet production and distribution is 0.286 MJ/MJ of pellet. The highest energy used is in farming (76%) especially for all fertilizer production, transportation and application. From this amount, about 62% energy is used in the production of nitrogen fertilizer, transportation and application. Similar result was also observed in an earlier study for this unit operation (Hartmann and Kaltschmitt, 1999).



	Field	Transport	Pellet production	Transport to residential user
Truck + car transport	0.0000	0.0000	0.0000	0.0092
Pellet conditioning	0.0000	0.0000	0.0080	0.0000
Drying with NG	0.0000	0.0000	0.0131	0.0000
Pellet, equipment and electricity manufacture	0.0000	0.0000	0.0263	0.0000
Truck Manufacturing	0.0000	0.0000	0.0000	0.0000
Diesel production	0.0000	0.0003	0.0000	0.0008
Truck run including backhauling	0.0000	0.0120	0.0000	0.0000
Machinery	0.0176	0.0000	0.0000	0.0000
Fuel	0.0220	0.0000	0.0000	0.0000
seeding	0.0117	0.0000	0.0000	0.0000
Pesticide	0.0024	0.0000	0.0000	0.0000
K2O	0.0254	0.0000	0.0000	0.0000
P2O5	0.0092	0.0000	0.0000	0.0000
N	0.1280	0.0000	0.0000	0.0000

Figure 4-3: Energy use for pellet production and distribution

Total emission during pellet production and distribution are shown in Figure 4-4 and is 30.34 gm CO_{2eq}/MJ of pellet. About 70% of the total emission occurs during field activities especially in all fertilizer production, transportation and application. About 92% from this amount came from nitrogen fertilizer production, transportation and application.

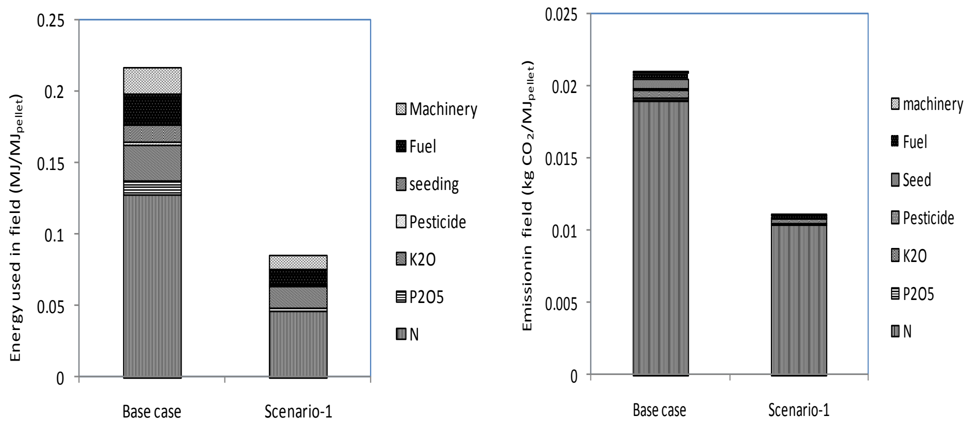


	Field	Transport	Pellet production	Transport to residential user
Truck + car transport	0.00	0.00	0.00	0.17
Pellet conditioning	0.00	0.00	1.00	0.00
Drying with NG	0.00	0.00	3.05	0.00
Pellet, equipment and electricity manufacture	0.00	0.00	4.52	0.00
Truck Manufacturing	0.00	0.00	0.00	0.00
Diesel production	0.00	0.05	0.00	0.12
Truck run including backhauling	0.00	0.48	0.00	0.00
Machinery	0.18	0.00	0.00	0.00
Fuel	0.40	0.00	0.00	0.00
seeding	0.71	0.00	0.00	0.00
Pesticide	0.04	0.00	0.00	0.00
K2O	0.55	0.00	0.00	0.00
P2O5	0.19	0.00	0.00	0.00
N	18.99	0.00	0.00	0.00

Figure 4-4: Emission from pellet production and distribution

4.4.1. Scenario analysis

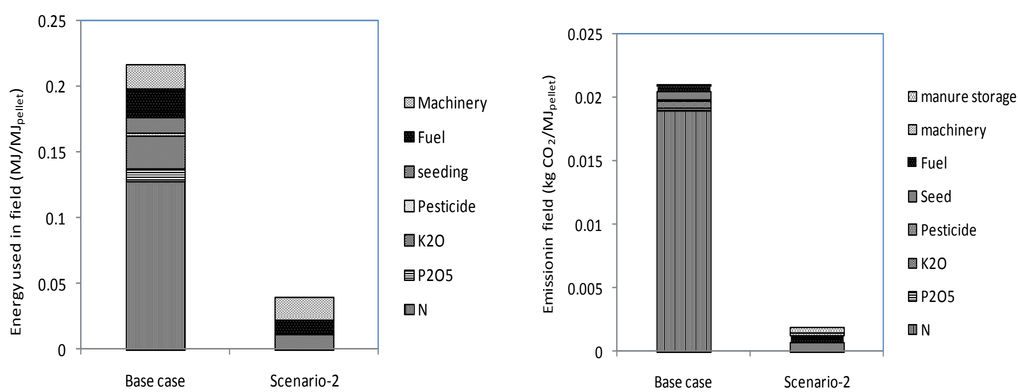
In scenario 1, nutrient replacement was considered for removal of straw from the field. Considering straw as a by-product resulted in an energy consumption of 0.154 MJ/MJ of pellet production which was 46.31% lower than the base case. Life cycle GHG emission was also reduced by 64.79% compared to the base case and was 10.68 gm CO_{2eq}/MJ of pellet production (Figure 4-5).



(a) **(b)**

Figure 4-5: Energy (a) and emission (b) from field activities in scenario 1.

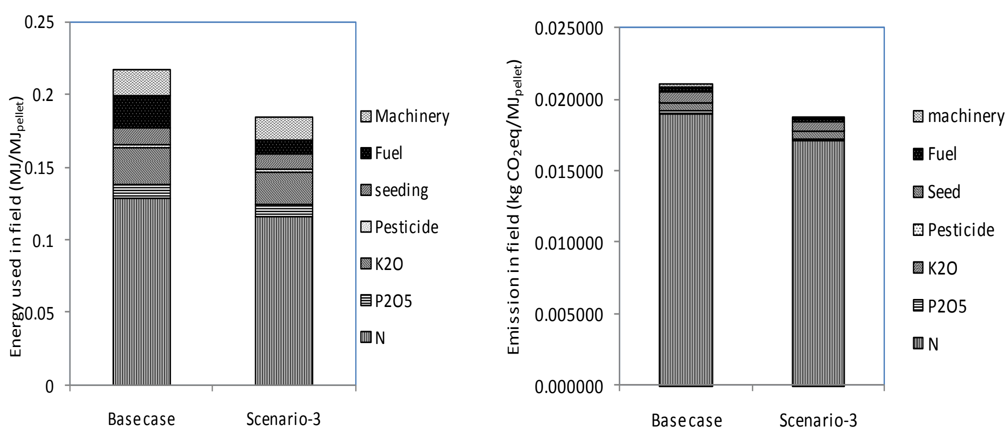
As inorganic fertilizer is the highest contributor both for the energy usage and the resulting emission, so to reduce energy use and emission one option could be to use organic fertilizer instead of inorganic fertilizer. The energy use is generally lower if organic fertilizer is used compared to inorganic fertilizer in farming system, but the yield of straw produced are lower (Dalgard *et al.,* 2001). Hoeppner *et al.* (2005) showed that energy use was 50% lower with organic farming than conventional farming where inorganic fertilizer was used. Production of wheat using inorganic fertilizer had the highest energy use, whereas the organic wheat production has the highest energy efficiency (Dalgard *et al.,* 2001). Inorganic fertilizers are produced employing fossil energy. On the other hand, the nitrogen nutrient for the organic systems is obtained from cattle manure. As the manure is used for organic farming, so energy and emission due to fertilizer production can be omitted for this type of farming. Seeding and machinery manufacturing impacts can be assumed to be the same for both organic and inorganic system. Organic farms usually plow or till as a mechanical method of controlling weeds, instead of using pesticides (Meisterling *et al.,* 2009). So the pesticide production and transport impact is not considered in the analysis. The fuel used in farm equipments depends on the type of equipment. Based on Madler *et al*. (2002) and Hoeppner *et al*. (2005), we considered that the organic farming is less fuel intensive. Wheat yields for organic agriculture are typically lower than inorganic system (Meisterling *et al.,* 2009). Madler *et al*. (2002) and Meisterling *et al*. (2009) reported organic wheat yield as 80% and 75%, respectively, of the conventional wheat yield. We assumed 80% in our study. The LCA study of organic and inorganic wheat by Meisterling *et al*. (2009) showed that the shifting from inorganic to organic fertilization can save energy of 0.61 KJ/kg of wheat production and reduce emissions by 30 g CO_{2eq}/kg of wheat production. . The data for this scenario was adopted from previous studies (Hoeppner *et al.*, 2005; Meisterling *et al*., 2009) which are shown in Table 4-9. Figure 4-6 shows that fertilizer contributed the most to the difference in energy input between inorganic and organic system. The energy and emissions for scenario 2 accounted for 36% and 35% of the total energy and emission compared the base case scenario.



(a) **(b)**

Figure 4-6: Energy (a) and emission (b) from field activities in scenario 2.

The tillage system has a significant effect on the yield of spring wheat (Lafond *et al.,* 1992). Several studies reported the increase of yield due to zero tillage on stubble averaged, e.g., Lafond *et al.* (1992), 21%, Brandt (1989) 13%, Wright (1990) 12%, Stobbe *et al.* 5% (1970). In case of the fallow management practice, the yield of spring wheat is not affected (Lafond *et al.,* 1992). In our study we have assumed that 10% of the yield change due to change from conventional tillage to zero tillage. By using zero tillage system (scenario 3), both energy use and emissions were reduced compared to the conventional tillage. This was due to less use of machinery and fuel in this scenario compared to base case. Fuel and machinery emission reductions were larger than the small increase in emissions associated with higher herbicide used in zero tillage (Coxworth *et al.,* 1995). In conventional method, multiple tillage are used for seed bed preparation, seeding, fertilizer, pesticide application and weed control, whereas, in zero tillage soil is disturbed only during planting. The life cycle energy used in zero tillage was reduced to 0.274 MJ/MJ of pellet production. The reduction of energy requirement and emissions in zero tillage were observed in previous studies (Zentner *et al.,* 1998; West and Marland, 2002). In this study, the reduction is 4.19% of the energy requirement for pellet production compared to the base case (conventional tillage). Similarly, life cycle emission was 30.09 gm CO_{2eq}/MJ which is a reduction of 1% from the base case (Figure 4-7). Farmers continue to adopt zero tillage in Alberta. The 2006 Census of Agriculture shows that 27% of farmers adopted zero tillage compared to 16.5% in 2001. Thus zero tillage acres have gone from about 5 million in 2001 to nearly 9 million in 2006 (Gamache, 2007).



(a) **(b)**

Figure 4-7: Energy (a) and emission (b) in scenario 3.

The usual practice of pellet production in Western Canada is to use natural gas as dryer fuel. By replacing this with biomass (straw) (Scenario 4), the emission was reduced (Figure 4-8). In scenario 5, the drying process was omitted assuming that moisture content of straw brought to the pellet plant has a moisture content of less than 12%. The amount of moisture in straw which is harvested in spring contains approximately 40% moisture. A reduced life cycle emission (29.92 gm CO_{2eq}/MJ of pellet production, 4.2 % of base case) resulted due to use of straw as the dryer fuel. Similar analysis of replacing natural gas by sawdust was done by Magelli *et al.,* (2009) during making of wood pellets and found that the emission by using sawdust is far less compared to natural gas. This emission was 29.82 gm CO_{2eq}/MJ when drying operation was omitted and this is similar to using straw. The comparison of scenario 4 and scenario 5 with base case is shown in Figure 4-8.

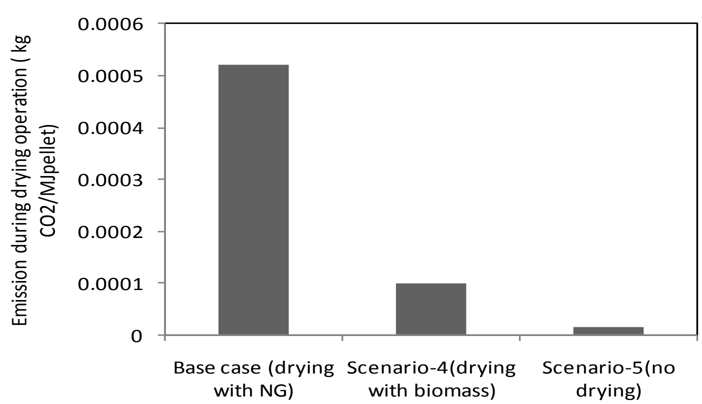


Figure 4-8: Comparison of emission of scenario 4 and 5 with base case.

The truck transport is considerably more energy intensive than rail transport (Coxworth *et al.,* 1995). Energy required for rail and truck are 0.47 MJ/t-km and 2.0 MJ/t-km, respectively (Coxworth *et al.*, 1995). The corresponding emission for truck transport is higher than train transport (Mahmudi *et al.,* 2005). The CO_2 emissions for truck and train transport are 41.3gm/Km-tonne and 21.8 gm/km-tonne respectively (Mahmudi *et al.,* 2005). By considering 140 km total travel distance,, the amount of energy for truck transport and combined train and truck transport (40 km by truck and remaining by train)in scenario 6 is shown in Figure 4-9.

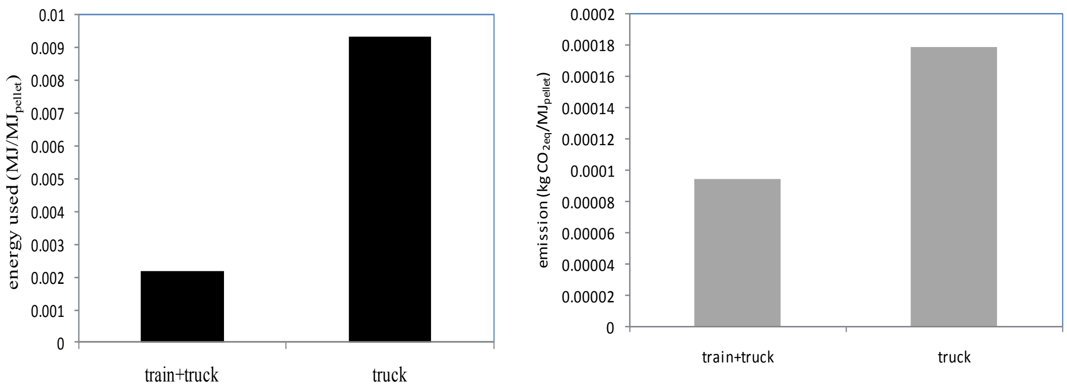


Figure 4-9: Energy used and emissions for different mode of transport

If pellet is burned in a CHP plant, the emission per MJ of pellet is reduced significantly compared to small scale combustor because of the complete burning in CHP combustor. The resultant emissions in both cases are shown in Figure 4-9 (Johansson *et al.,* 2003; Kjallstrand and Olsson, 2004). Figure 4-10 shows that emission from CHP plant is 76.88% less than small-scale combustor.

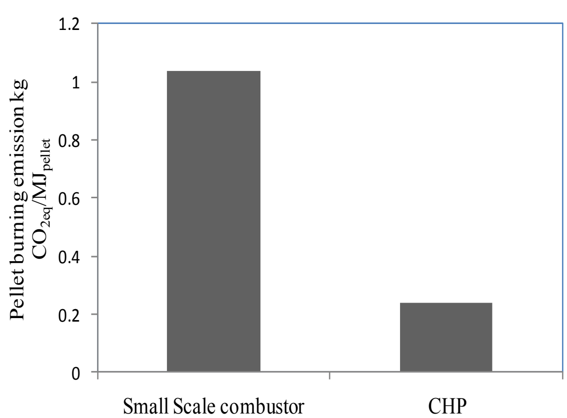
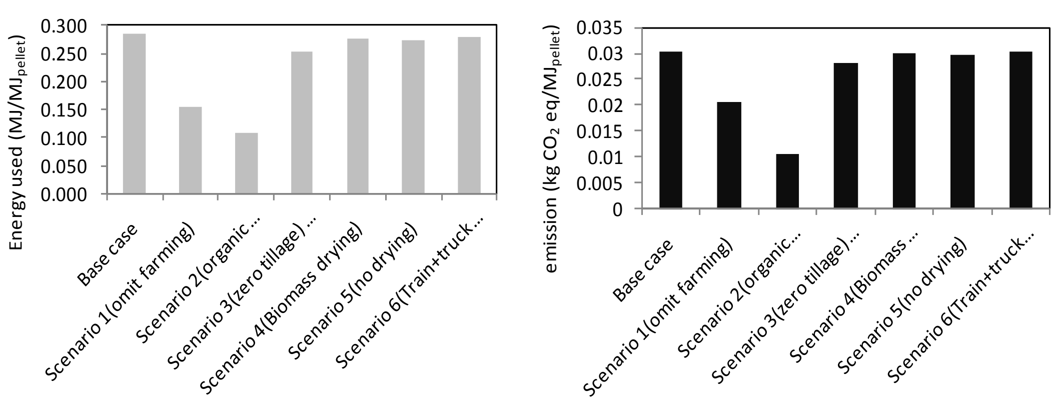


Figure 4-10: Emissions in end use of pellets

If base case is compared with all other scenarios, energy used and emissions for all scenarios except scenarios 1 and 2, are close to base case and the difference is within ±4% and ±2%, respectively. Energy use and emissions are 53.84% and 35.20% of the base case, respectively, if farming practice is omitted (Figure 4-11). Organic farming (scenario 2) provided large reduction of energy use and emission compared to base case i.e., 64.33% and 65.08%, respectively. Effects of changing either dryer fuel (scenario 4) or omitting drying (Scenario 5) or changing tillage system (Scenario 3) or changing mode of transport (scenario 6) are not significant on energy use and emission. In straw pellet production, drying is used to reduce moisture content from 14% to 8%. For this small reduction of moisture content, both the energy requirement and emissions are less. This is unlikely the case in wood pellet production where moisture content is reduced from 40% to 10% (Mani *et al.,* 2006), and the total emissions (Samson *et al.,* 2008) are 43% higher than straw pellet production. The change of tillage system only reduces the machinery and fuel use but fertilizer applications are same for both tillage systems. So the alternate tillage option did not change the life cycle energy use and emission of pellet production appreciably. Finally, it can be stated that organic fertilizer use can reduce energy requirement and emission but change of wheat yield due to the use of organic fertilizer and its economic aspect should be taken into account.

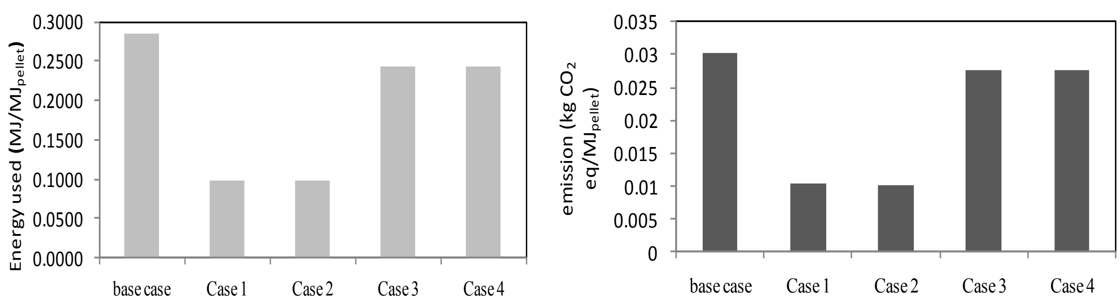


(a) **(b)**

Figure 4-11: Energy (a) and emission (b) comparison of scenario 1 to 6.

4.4.2. Emission and energy analysis for composite cases

The base case was considered based on the current practices of wheat farming, biomass transport and pellet production in Western Canada such as wheat farming by conventional tillage, straw transport by truck, drying process perform in plant with natural gas and again transport to the consumer by truck. By changing one of these option at a time and keeping other option same different scenarios developed which is discussed in section 4.1.1 (scenario analysis). By taking other additional cases together some composite cases developed. These composite cases are: *case-1* (organic farming- truck transport to plant- biomass drying in plant and truck transport to consumer), *case-2* (organic farming- truck transport to plant-no drying in plant and truck transport to consumer), *case-3* (organic farming- truck transport to plant- biomass drying in plant- train and truck combination transport to consumer), *case-4* (organic farming- truck transport to plant- biomass drying in plant- train and truck combination transport to consumer), *case-5* (zero tillage farming- truck transport to plant- biomass drying in plant and truck transport to consumer), *case-6* (zero tillage farming- truck transport to plant- no drying in plant and truck transport to consumer), *case-7* (zero tillage farming- truck transport to plant- biomass drying in plant- train and truck combination transport to consumer), *case-8* (zero tillage farming- truck transport to plant- no drying in plant- train and truck combination transport to consumer). Farmers of Western Canada are adopting zero tillage system due to higher yield and less energy and fuel requirements. It is increased 63% (16.5% in 2001 to 27% in 2006) within six years (Brandt, 1989). So zero tillage is a potential option against conventional tillage. The spring wheat harvesting period of Western Canada is from August to September (Edwards *et al*., 2007), there is a potential of natural-air drying of straw during this time in Canadian prairie (University of Saskatchewan, 2010). However, the actual moisture content depends on the relative humidity and temperature at that time of collection of straw from field. The use of biomass drying to no drying impact on energy and emission of agri-pellet production is very low as the straw has to dry from moisture content 14% to 8%. It has not much effect on total energy requirement and emission of agri-pellet production. As this depends on weather condition so pellet plant operator may keep the option for drying of straw before pellet production. Figure 4-12 shows the energy requirement and emission for composite cases. It is seen from Figure 4-12 that energy requirement and emission for *case-1* to *case-4* is only 31 to 34% and 65 to 66% of the base case, respectively. This is because of organic farming considered in *case-1* to *case-4*. The energy and emission of organic farming is discussed in section 3.1(scenario 2). The energy requirement and emission of the other phases such as transport and in pellet plant is negligible. The variation of energy and emission within *case-1* to *case-4* is only 2% and 1%, respectively. Variation of energy requirement and emission from *case-5* to *case-8 is* 82-85% and 90% of the base case, respectively. The variation of energy and emission within case-*5* to *case-8 is* 3% and 1%, respectively. These four cases are based on zero tillage farming so energy and emission variation is not much with conventional tillage which is discussed in section 4.1.1 in scenario 3.



(a) (b)

Figure 4-12: Energy (a) and emission (b) for composite cases

4.5. Emission Comparison of Agricultural Pellet with Other Fuel Sources

Figure 4-13 shows emissions for the agricultural pellet and other fuel sources which are commonly used for heating and electricity production purposes. Emission of coal, natural gas and wood pellet has been taken from previous studies (Jungmeier and Spitzer, 2001; Magelli *et al.,* 2009). It is obvious that the emission from biomass pellet is far less than other fuel sources.

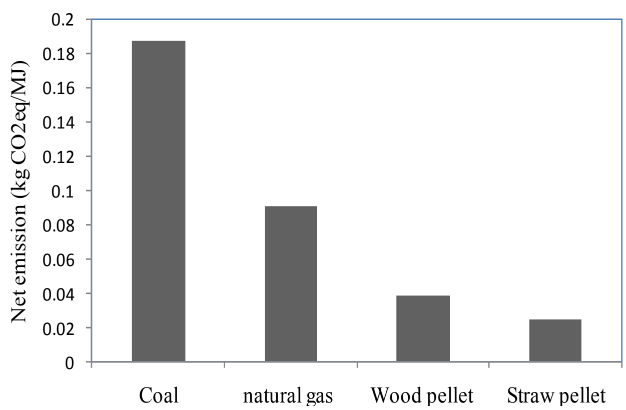


Figure 4-13: Comparison of agri-pellet with other fuel sources. (Sources of coal, natural gas and wood pellet data: Jungmeier and Spitzer, 2001; Magelli *et al.*, 2009).

For Western Canada, net emissions for coal, natural gas and wood pellet are, respectively, 350%, 250% and 50% higher than straw pellet. However, these numbers may vary from location to location and due to adopted technology in fuel production but the comparative emission trend is expected to be same.

In the Province of Alberta, the total production of biomass (i.e., straw from wheat, barley and oat) is about 12.47 million tonnes per year (12 years average) (Sultana *et al.,* 2010). The potential of recoverable agricultural biomass for bioenergy purposes after accounting for current usage is about 6.2 million dry tonnes per year for Alberta. This biomass has an energy content of about 0.11 EJ per year (considering lower calorific value of straw to be 17.5 GJ/dry tonnes), which can generate about 10 TWh of electrical power (assuming a large scale power plant efficiency of 35% efficiency). The same content of energy, 0.11 EJ per year, can be obtained from 4 million tonnes of coal (considering energy content 27.45 GJ/dry tonne). If energy from coal is substituted by energy from straw pellets, about 17.6 million tonnes of CO_{2eq} per year could be mitigated.

4.6. Estimated cost of Greenhouse Gas Credits for Pellets

Greenhouse gas (GHG) credits would be required to develop biomass fuel competitive to the fossil fuels. GHG credits for making agri-pellet economic in Alberta were estimated as a function of fossil fuel (natural gas and coal) prices. The pellet production cost was estimated $7.2 per tonne (Chapter 3). Based on an assumed transportation distance of $200 km, the total delivered cost of pellets would be $1.71 per GJ. At this deliverd cost of pellets, a carbon credit of $31.67 to $81.67 per tonne of CO_{2eq} would be required for it to be competitive with natural gas an average price of $4 to $7 per GJ. If agric-pellets are used to reaplce energy from coal, the carbon credit value would be $26 to $39.33 per tonne of CO_{2eq} at an average coal price of $3 to $5 per GJ.

4.7. Conclusions

The life cycle analysis of energy use and associated emission of agri-pellet were carried out by considering field operations, transport of straw to pellet plant, operations in pellet plant and transport of pellet to user. The energy use and emissions are highest in field activities. Nitrogen-based fertilizer production, transportation and application are the highest contributor among the field activities. A large reduction of energy use (64%) and emission (65%) is possible if organic fertilizer is used. The utilization of biomass as dryer fuel in pellet production or omitting the drying, adopting no-tillage option instead of conventional tillage or adopting a combination of train and truck transport for pellet delivery causes less emission and energy use but only by less than 5%. Agri-pellets have the potential to offset substantial amounts of GHG emission compared to other fuel sources as energy source. The emission is reduced approximately by 50%, 250% and 350% if compared to wood pellets, natural gas and coal, respectively. Greenhouse gas (GHG) credits would be required to develop agri-pellet competitive to the fossil fuels. A carbon credit of \$31.67 to \$81.67 per tonne of CO_{2eq} would be required for it to be competitive with natural gas an average price of \$4 to \$7 per GJ. If agric-pellets are used to reaplce energy from coal, the carbon credit value would be \$26 to \$39.33 per tonne of CO_{2eq} at an average coal price of \$3 to \$5 per GJ.

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Chapter 5. Multiple Lignocellulosic Biomass Feedstocks Delivery: An Assessment of Supply and Logistics

5. 1. Introduction

The lignocellulosic biomass is considered as a major renewable energy option due to nearly zero carbon emissions over life cycle; However, its usage is very limited today for fuels and chemicals production. Low conversion efficiency, availability and logistical constraints are the major challenges to the large scale development of biomass-based facilities for the production of fuels and chemicals (Caputo *et al*., 2005). Biomass supply and logistics is influenced by its complex texture, limited period of availability and scattered distribution. The low bulk density and the complex texture also create delivery issues for biomass during its transportation to a biorefacility.

The delivered cost of biomass is a key component of the overall cost of recovering fuels or chemicals from biomass. It constitutes 35 - 50% of the total production cost of production of biofuel (Kumar *et al.*, 2006). Biomass can be transported in various forms with different bulk densities. Possible forms of the woody biomass at the point-of-origin are stems, chips, bundles and pellets. Agricultural biomass (e.g. corn stover, straw, energy crops) can be transported as loose material, chops, bales and pellets. The transportation cost of biomass depends on the type of biomass, the form, bulk density, distance to be travelled and road infrastructure of the location (Badger, 2003).

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The options available for transporting biomass feedstocks to the plant for energy purposes are by trucks, rails or pipelines. Comparisons of different modes of transport of biomass have been reported in previous studies (Kumar *et al*., 2005a; Searcy *et al*., 2007). The rail transport of biomass is viable where the required infrastructure is already available, and the pipeline transport is more suitable for large scale and longer distance of biomass transportation (Kumar *et al*., 2005b; Kumar and Sokhansanj, 2007). Trucks are used almost exclusively in North America (e.g., ninety percent of pulpwoods delivered to US mills arrive by trucks (Ashron *et al.,* 2007). However, a large-scale facility cannot depend on truck delivery of fuel because of the high cost of transport and consequent traffic congestion (Kumar *et al*., 2005a; Kumar *et al*., 2005b). This issue is further investigated in this paper.

Agricultural activities produce large amount of biomass around the world. As an example, about 37 million tonnes of agricultural biomass are produced each year in Western Canada over an area of 16.3 million hectare (Sokhansanj *et al*., 2006). In the Province of Alberta, the total production of biomass is about 12.47 million tonnes per year (12 years average) (Sultana *et al.,* 2010). The potential of recovering agricultural residues (i.e., straw from wheat, barley and oats) for bioenergy purposes after accounting for current usage is about 6.2 million tonnes per annum for Alberta (Sultana *et al.,* 2010)]. Currently, most of these biomass resources are not utilized and left to rot in the field. The agricultural biomass could potentially be used as a feedstock for biorefinery. In Canada, an estimated 22 million dry tonnes of wood harvest residues are available annually. About 90% of these are available on the road side and these are the potential feedstock for bioenergy production (Bradley, 2010). In most of the Provinces in Canada, slash is 20 to 25% of the harvest volume. Alberta produces 2.5 million dry tonnes of slash which is about 10% of total harvest volume of wood (Bradley, 2010) .The harvesting methods in Alberta, British Columbia and Ontario are primarily full-tree harvesting, which leaves the slash at easily accessible roadsides and these slash could be potential feedstocks for a biorefinery.

Both forest and agricultural biomass are the main feedstock for biorefineries in North America. However, wood resources have competing use in wood processing industries e.g., pulp and paper, particle board, plywood, fiber wood. Canadian lumber production fell from 83.5 million tonnes in 2004 to 45 million tonnes in 2009 due to the financial crisis and recession (Bradley, 2010) Also the use of paper is on decline due to more use of electronic media. This gives an opportunity for diversification of the forest industry to bio-industry. Mill residues (such as sawdust, shaving, bark) of pulpwoods and sawmills also decreased from 21.22 million tonnes in 2004 to 10.89 million tonnes in 2009. Alberta's mill residue production was 1.9 million tonnes in 2009 which was about 21% less from 2004 (Bradley, 2010). The lower availability also eventually raises cost of mill residue. The combined effect of reduced mill residue production and high demand for feedstocks would lead to use forest residues for biorefineries. One of the prominent pellet plant uses 20-30% of forest residue feedstock for pellet production in BC, Canada (Bradley, 2010). The limited availability of wood resources for biorefinery is a key driver for interest in utilization of harvest residue as another fuel source, currently most of which is burned at the roadside to prevent forest fire.

For large scale biorefinery, only one biomass source alone cannot support the total feedstock requirement as there are constraints on the availability of the different feedstocks locally. In this case the multiple feedstock delivery to a biorefinery might be a solution. There are also significant challenges in multiple feedstock delivery to a biorefinery as there are different forms of both woody and agricultural biomass available. The concept of multiple feedstock utilization in a biorefinery is in its preliminary stage as observed in different power plants in

Europe and North America; for example, Shasta and Colmac in California, USA, Ridge in Florida, USA, Lahti in Finland (Wiltsee, 2000). The combination of two or more biomass types and forms could be more feasible feedstock supply solution for large scale applications. Currently, many plants around the world burn biomass to make heat, power or a combination of the two. Many of these plants are based on single biomass such as mill residue and hence are built on a small size because of feedstock scarcity. Most of the biomass based plants have capacity less than 100 MW. For example, William Lake power plant of capacity 60 MW in British Columbia uses sawmill feedstock 780,000 tonne per year. The size of these biomass plants are constrained by mill residue supply and also by their nature of being a demonstration project. However, it is reported by many publications (Kumar *et al*., 2005a; Jenkins, 1997; Jenkins 2005) that economy of scale benefit can be achieved for large scale plants and the cost of production of biomass based fuels and chemicals could be reduced at larger scale as there is an economic optimum size of the plants. Power cost per MWh rises dramatically for plants at sizes below 100 MW (Kumar *et al*., 2005c). In this case feedstock supply for large scale bioenergy facility can be accomplished using both woody biomass such as mill residue, harvest residue and agricultural residue i.e., wheat, barley and oat straws or corn stover for the same plant.

There are several studies on the assessment of total delivery system of biomass in different forms. Supply systems for both woody biomass in the chipped form and agricultural biomass in the bale form were analyzed in earlier studies (Badger 2003; Kumar *et al*., 2005a; Kumar *et al.,* 2005b; Searcy *et al*., 2007; Sokhansanj *et al.,* 2009) and these studies have discussed different systems of biomass transport in the form of whole tree, bales and pellets. Angus-Hankin *et al.* (1998) analyzed the woody biomass transportation from forest to the facility in the form of chipped material, logging residue and tree sections. They discussed how load of the transport vehicle and terminal time can be optimized. Allen *et al*. (1998) described the logistics management system and estimated total delivery costs for both woody and agricultural biomass. Transportation cost analysis of woody biomass has been performed by several authors (Kumar and Sokhansanj, 2007; Ashron *et al*., 2007; Surr, 2002; Badger, 2002, Spinelli *et al*., 2007, Afzal *et al.,* 2010). Hess *et al*. (2007) developed a detailed analysis of cellulosic feedstock supply systems and logistics of the baled biomass for ethanol productions. A number of studies have presented techno-economic and cost analyses for supply, transportation, storage and handling of different agricultural biomass in the form of bales (Jose and Brown, 1996; Epplin, 1996; Glassner *et al*., 1998; Perlack and Turhollow, 2002; Sokhansanj *et al*., 2002; Gallagher *et al*., 2003; Sokhansanj and Fenton, 2006; Duffy, 2007; Holmgren *et al*., 2007; Brechbill and Tyner, 2008; Kumar and Illeji, 2009; Morey *et al*., 2010). Sokhansanj *et al.* (2010) discussed the cost analysis of the corn stover considering bales, chops and pellets for a combined heat and power production system. Kumar and Sokhansanj (2007) and Sokhansanj *et al* (2009) estimated cost of baled, loafed and chopped biomass productions, storage and transportation for switchgrass. Hess *et al*. (2006) performed a feasibility analysis of ground straw feedstock supply system. The pelleted form of biomass supply systems have been discussed by Forsberg (2000) and Hamelinck *et al.* (2005). The biomass logistics and supply system were analyzed in detail in the study by Cundiff *et al*. (2009) for containerized handling. Rentizelas *et al*. (2009) and Stephen *et al.* (2010) have studied multiple biomass and selection of scale, location and technology, respectively.

However, none of these studies explicitly analyzed and compared the effects of bulk density and different forms of biomass on the total delivery cost of biomass as feedstock to the end-use biorefinery. The assessment of the delivery cost of multiple biomass feedstocks and different forms of woody and agricultural biomass to a biorefinery has not been done. This chapter investigates the total delivery cost of different forms of multiple feedstocks (i.e., woody and agricultural biomass mainly wheat straw and corn stover) to a biorefinery. Baled, chopped and pelletized forms are considered for the agricultural biomass.

Chipped, bundled and pelletized forms were selected for the woody biomass. Following are the key objectives of this study.

- To investigate the multiple feedstock delivery to a biorefinery in combination of different forms.
- To examine the effect of bulk density on total delivery cost to a biorefinery for different forms of agricultural and woody biomass.
- To investigate the relationship between transportation cost and bulk density of different forms of agricultural and woody biomass.
- To determine the optimal delivery combination of different forms of multiple biomass feedstock to a large scale biorefinery.
- To investigate the traffic congestion of multiple biomass feedstock delivery in different forms to a biorefinery.

5.2. Forms and Bulk Densities of Biomass along with the Factors Affecting It

The bulk density of biomass is not an intrinsic property of material due to its different forms. Generally, bulk density depends on material composition, particle size distribution, particle shapes, orientation of particles, specific density, moisture content and the applied axial pressure (Chevanan, 2008). Various compaction and comminuting methods change the bulk density of biomass. Bulk densities of different woody and agricultural biomass are shown in Table 5-1.

The form in which biomass is transported depends on the type of biomass, quantity, distance of transport, road infrastructure, end use and available technology at the site. Woody biomass can be transported to the plant in loose uncomminuted form, as chips, bundles or processed pellets. Forest residues are available at forest landing at the time the trees are processed. Loose uncomminuted residue is a mixture of tops, discarded logs and fine slash. The main disadvantage of the uncommunited residue is that it has low bulk density and hence when loaded on to a truck it is difficult to reach the payload (Rawling *et al*., 2004). However, it is still used in some European countries such as Austria, Finland (Ranta and Rinne, 2006) and Italy (Spinelli *et al.,* 2007). The advantage of transporting this type of residue is to save investment cost of chipper or bundler. In this case, the plant should have an in-plant chipper (Spinelli *et al.,* 2007). Consequently, there is a critical decision to be made whether to comminute before or after transport.

Table 5-1: Bulk densities of different forms of biomass

Form of biomass	Moisture content (%)	Bulk density (kg/m^3)	Sources
Wood			
Forest residue	50	80	Loo and Koppejan, 2008
Wood chip (wet)	50	180- 340	Loo and Koppejan, 2008
Woodchip (pre-dry)	30	240	Loo and Koppejan, 2008
Sawdust	50	120	Loo and Koppejan, 2008
Bundle	45	170	Loo and Koppejan, 2008
Pellets	10	560-650	Obernberger and Thek, 2004
Solid wood	12	865	Loo and Koppejan, 2008
Straw			
Loose	20	40-60	Mckendry, 2002
Chopped	15	80-110	Mckendry, 2002
Baled	15	110-190	Mckendry, 2002
Cube	8	320-670	Mckendry, 2002
Pellet	6	560-710	Obernberger and Thek, 2004

Large scale in-plant chipper can reduce chipping cost due to the benefit from the economy of scale (Spinelli *et al*., 2007). For in-wood chipping, mobile chippers are used for chipping and then chips are collected in a container and transferred to roadside or chipping is done on the roadside where the forest residues are piled.

Bundling is a relatively new method compared to chipping which is extensively used in Finland and Sweden these days. This is usually a slower process than chipping. From logistics point of view, bundling is a better option than chipping as the bundler can stack the bundles on the ground for collection later whereas the chipper needs a truck to receive the chips. Bundles can be stored for 11 months which can result in lower moisture contents and higher energy values (Taylor *et al*., 2010). Chipped biomass should be used as soon as possible after chipping to avoid fungal growth (Johansson *et al*., 2006) and the maximum time for storage is about 2 months (Taylor *et al*., 2010). In general, bundles have lower bulk density than wood chips (Table 5-1). The densified biomass such as the pellet is a potentially good option of biomass transport and handling because of its uniform shape, size and densified form. In pellet production, biomass is compacted and the bulk density is increased to 500-700 kg/m^3.

Most of the reported collection option of agricultural biomass includes collection in the form of square or round bales (Cundiff 1996; Bransby and Downing, 1996). Almost 20% of the loading space in truck becomes unutilized during transport of round bales because of its shape. Other options for biomass collection are ensiling and loafing (Kumar *et al*., 2006). These options are not very prevalent and are out of the scope of this chapter.

Generally, the moisture content is an important factor for bulk density. High moisture content results in higher bulk density of biomass due to high density of water (1000 kg/m^3). Higher moisture content of biomass adversely affects the efficiency of transportation and storage. Biomass with higher moisture content is also prone to decomposition and fungal growth (Taylor *et al.,* 2010). Compaction of biomass can increase bulk density which would reduce moisture content making them more suitable for transport and handling.

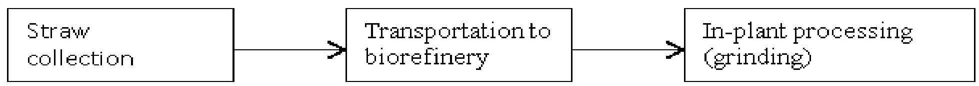
Another important property of the biomass fuel which is affected by the moisture content is its heating value. Impact on heating value of biomass as a function of moisture content was studied earlier by Kumar *et al.* (2005b). Transpirational drying is an economic way to reduce the moisture content of biomass which helps in increasing the efficiency of transport and handling (Stokes *et al.,* 1993). In case of agricultural biomass, whenever weather and time permits, in-field drying saves cost of artificial drying to better serve as fuel. From the above description and Table 5-1, it is obvious that the bulk density of biomass can vary significantly for various forms with different moisture contents. The storage and transportation cost as well the quality of biomass are directly related to the bulk density.

5.3. Methodology

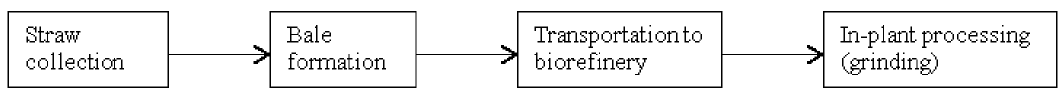
Biomass supply chain and input data

A biomass supply chain involves a range of interconnected unit operations which depend on several factors including characteristics of biomass, biorefinery and the employed technology. The delivery system of biomass includes collection, storage, pre-processing (if required), transportation from field/forest to plant and in-plant processing before final use. Decisions taken at any stage of the interdependent unit operations effect the available options in the subsequent stages.

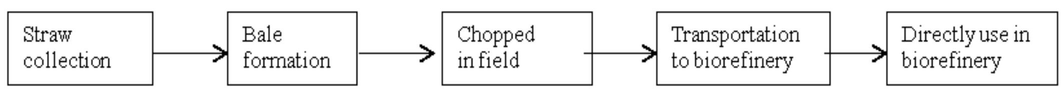
Parameters related to local weather (such as, average daily temperature, humidity, precipitation), the average yield of biomass, proportion of land that is cultivated with the crop of interest, harvest duration, moisture content of biomass, operating conditions of different agricultural machineries have impact on the harvesting process. Following subsections briefly describe relevant features of different steps of the delivery system which are considered for calculation of the total delivery costs of a combination of multiple feedstocks to a biorefinery. The supply chains used in this study for delivery of different forms of agricultural and woody biomass are shown in Figure 5-1 and Figure 5-2, respectively. Costs of different operations are shown in Table 5-2.



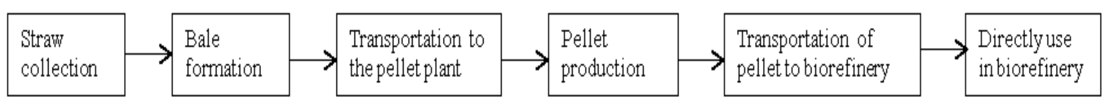
(a) Supply chain of loose-cut straw to a biorefinery



(b) Supply chain of bales to a biorefinery

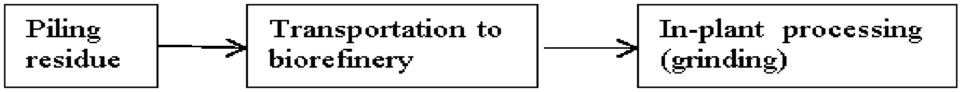


(c) Supply chain of chopped straw to a biorefinery

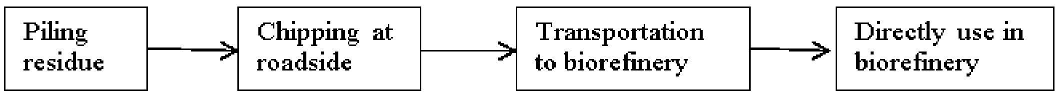


(d) Supply chain of pellet to a biorefinery

Figure 5-1: Delivery chain of agricultural biomass at different forms of transport

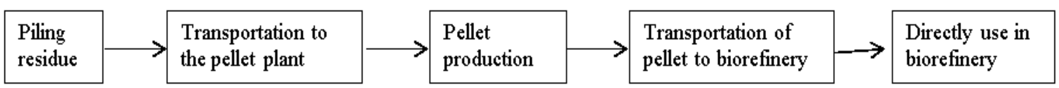


(a)Supply chain of biomass residue to a biorefinery



(b) Supply chain of chipped woody biomass to a biorefinery

(c) Supply chain of bundle form of woody biomass to the biofacility



(d)Supply chain of pellet to a biorefinery

Figure 5-2: Delivery chain of woody biomass at different form of transport

Table 5-2: Cost input for biomass delivery (base case 2009)

	Wheat Straw		Corn Stover		Woody biomass		
Operations	**Base case $/tonne**	**Sources**	**Base case ($/tonne)**	**Sources**	**Operations**	**Base case $/tonne**	**Sources**
Collection and preprocessing					Collection and preprocessing		
Shredding	3.67	Sultana *et al.,* 2010	4.95	Sokhansanj *et al*., 2009	Piling	2.64	Bradley, 2010
Raking	2.31	Sultana *et al.,* 2010	2.31	Sokhansanj *et al*., 2009			
Storage and	1.90	Sultana *et al.,* 2010	1.90	Sokhansanj *et al*., 2009	Sawdust cost	23.60	Bradley, 2010
storage premium	5.50	Sultana *et al*., 2010	12.50	Sokhansanj *et al*., 2009			
Farmer premium							
Nutrient	22.60	Sultana *et al*., 2010	15(10-				
replacement			20)	Sokhansanj et al., 2009			
Baling					Chipping	13.04	Bradley, 2020
Bale collection	4.25	Sultana *et al.,* 2010	9.78	Sokhansanj *et al.,* 2009	Bundling	16.20	Bradley, 2010
Bale wrapping	0.49	Sultana *et al.,* 2010	1.73	Sokhansanj *et al*., 2009	Pelleting (sawdust)	69.67	Sokhansanj *et al.,* 2010
Feeding bale in tub							
Grinder[a]	2.08	Morey *et al.,* 2010	2.08	Morey *et al.,* 2010	Pelleting (forest residue)[C]	104.26	Estimated
Tub-grinding of							
bales	5.18	Morey *et al.,* 2010	5.18	Morey *et al.,* 2010			
Pelleting[b]	129.42	Sultana *et al.,* 2010	129.42	Sultana *et al*., 2010			
On-site fuel preparation					On-site fuel preparation		
Bale form				Sokhansanj *et al*., 2010			
Grinding in plant				Sokhansanj *et al*., 2010	Bundle form	1.1	Sokhansanj *et al*., 2010
Receiving	4.75	Sokhansanj *et al.,* 2010	4.75	Sokhansanj *et al*., 2010	Receiving	13.04	Sokhansanj *et al*., 2010
Storing	2.22	Sokhansanj *et al*., 2010	2.22		Bundle grinding	6.62	Sokhansanj *et al*., 2010
	4.77	Sokhansanj *et al*., 2010	4.77	Sokhansanj *et al*., 2010	Storing		
Chopped form				Sokhansanj *et al*., 2010			
Receiving	1.10	Sokhansanj *et al.,* 2010	1.10		Chipped form		
Storing	6.62	Sokhansanj *et al.,* 2010	6.62		Receiving	2.22	Sokhansanj *et al*., 2010
				Sokhansanj *et al.,* 2010	Storing	4.77	Sokhansanj *et al*., 2010
Pellet form							
Storing	1.27	Sokhansanj *et al.,* 2010	1.27		Pellet form		
					Storing	1.27	Sokhansanj *et al.,* 2010

a: chop size of 10 m.m (Morey, 2010). b: The optimum size of the pellet plant capacity is 150,000 tonnes per year (Sultana *et al.*, 2010); c: The optimum size of pellet plant using forest residue is estimated 290,000 tonnes per year with net yield of forest residue is 0.248 tonnes/ha.

Total delivery cost of biomass

The total cost of biomass feedstock delivery is determined by considering costs incurred in different steps of supply chain before its utilization in a biorefinery.

$$\begin{aligned} &\textit{Total delivery cost of biomass} \left(\$/_{\text{tonne}}\right) \\ &= \textit{Harvest and collection cost} \left(\$/_{\text{tonne}}\right) \\ &+ \textit{storage cost} \left(\$/_{\text{tonne}}\right) \\ &+ \textit{preprocessing cost} \left(\$/_{\text{tonne}}\right) (\textit{if any}) \\ &+ \textit{transportation cost from field to plant} \left(\$/_{\text{tonne}}\right) \\ &+ \textit{inplant processing cost} \left(\$/_{\text{tonne}}\right) \end{aligned} \quad (5\text{-}1)$$

In this study the transportation cost of selected forms of biomass is estimated based on the bulk density of the material and the resulting actual load that a truck can carry. All the cost data in this cahpter are in 2009 US dollar.

The actual amount of biomass, a truck can carry is limited by the maximum weight and the volume capacities of the truck. So, the actual load (W) of a truck was estimated by using Eq. (5-2).

$$W = \min\{\textit{Payload of truck}, (\textit{bulk density x volume capacity of truck})\} \quad (5\text{-}2)$$

Every truck has the limits related to its weight and volume. The bulk density of material is the determining factor whether it will run out of volume before reaching the payload or if weight reaches the payload before the truck is full. Table 5-3 shows the volume and weight limits of selected trucks for agricultural and woody biomass in different forms. Reaching the volume limit first means the capacity remains underutilized and in these cases compaction of the biomass could be a solution. For example, based on data in Table 5-3, though the payload of truck is 22.7 tonne, the truck can actually carry 5.1 tonne of loose biomass because of its low bulk density. In case of pellets, the truck can carry same weight of biomass as the payload of the truck because of its higher bulk density.

Table 5-3: Weight carried by trucks for various forms of biomass (Payload of truck =22.7 tonnes, volume capacity of truck =70m^3)

Forms of biomass for transport	Bulk density of biomass (tonne/m^3)	Actual weight carried by truck (tonne)	Limiting factor
Agricultural biomass			
Loose	0.06	5.1	volume
Chopped	0.11	9.2	volume
Bale	0.16	11.2	volume
Pellet	0.60	22.7	weight
Woody biomass			
Forest residue	0.08	6.7	volume
Chipped	0.22	16.8	volume
Bundle	0.17	14.3	volume
Pellet	0.65	22.7	weight

Truck operating cost

The biomass transportation cost ($/tonne) is evaluated as the sum of the variable and fixed transportation costs. For trucking, the fixed cost (also called terminal cost) mainly includes costs related to loading and unloading of biomass, depreciation, insurance, interests and the administrative cost of biomass transport which is independent of the distance traveled or the time required for that travel. Variable costs depend on the location. These include costs for fuel, repair, tire, lubrication and labor. Different locations have different fuel or labor rates. The distance related variable cost depends on the type of biomass being transported, form of biomass, the equipment used for loading-unloading and any existing contractual agreement (Searcy *et al*., 2007). The specific form of biomass transport affects the fixed cost more than the variable cost.

The truck operating cost can vary a wide range because most of the cost components are region specific. A small change in the equipment use would have large impact on the costs (Berwick, 1997). Driver and fuel costs have wider range of tolerance within them (By Ray Barton Associates Ltd., 2008). The firm size from where truck or trailer are rented also effect the cost. Some costs are lower for small farms (such as wages, administrative costs) but these are offset by economics of scales of costs for equipment, tire and consumables which lead to large variations of total costs.

There are many different sizes and types of trucks available. However, we estimated a single value to account for these in our study. No precise cost estimations are available for different types of trucks in literature. Berwick (1997) considered single trailer and double trailer van, flatbed and hopper and compared their operating costs. It was found that only 6% variations in costs occur when shifting from single trailer to double trailer of the same capacity (24 tonnes GWV).

The total variable cost for Alberta is $1.365 per km (Table 5-4). This cost is more or less same for all types of trucks in Alberta and can be varied up to 6% (Berwick, 1997). Similar value is also given by Bassett (2010). The fixed cost has been taken from previous studies given in Table 5-5.

Table 5-4: Variable cost of truck transport

Cost component	Cost ($/km)	Comments and references
Driver cost	0.62	Driver cost for Alberta, Canada are-19.50 – 30.06 $/hour for bulk commodity and 20.00 – 30.06 $/hour for general commodity (By Ray Barton Associates Ltd., 2008). $600/8 hour day (Illeji, 2007). $250/trip (Illeji, 2007).
Fuel cost (including provincial fuel tax and federal tax)	0.413	Best year round fuel efficiency for any truck in Canada is 0.33 litre /km (8.5 mpg) (NRC, 2009). The fuel consumption of truck 0.30 – 0.40 litre /km (full loaded) and 0.25 – 0.30 litre /km (empty) and of trailer 0.29 – 0.30 litre/km (full loaded) and 0.21 – 0.26 km/litre (empty) (Volvo, 2003). The average speed of truck is considered 50 km/hour (Sokhansanj *et al.,* 2009). The retail price of diesel in Alberta in 2009 was $1.18/litre (including provincial fuel tax 9.0 cents/litre and federal tax 4.0 cents/litre) (BY Ray Barton Associates Ltd., 2008)
Road expenses	0.062	Mainly considered are for paid parking, tolls etc (BY Ray Barton Associates Ltd., 2008).
Maintenance and repair	0.23	The cost varies from 6 cents/km to 31 cents/km converted in 2009 value (Berwick, 1997; Faucett Associates, 1991, Roth, 1993; Volvo, 2003; Branes and Langworthy, 2003; Edward, 2010). We considered the cost based on a Canadian study (Berwick, 1997).
Tire	0.04	The cost varies from 1 cents/km to 5 cents/km Roth, 1993; Volvo, 2003; Branes and Langworthy,2003; Edward, 2010; Trimac Logistics Ltd., 2001;OOIDA, 2010).
Total variable cost	1.365	

Total cost of transport

Values of fixed and variable cost parameters are shown in Table 5-5. For a fixed capacity truck of payload 22.7 tonnes, the loaded amount of biomass will be different for various forms due to variation of the bulk density. The amount of load that a 22.7-tonne truck can actually carry based on the bulk density of material is shown in Table 5-5. Assuming the variable cost of truck transport is approximately constant in Alberta and is \$1.365 per km, by using this cost and actual load carrying capacity of truck in tonne, variable cost (\$/tonne-km) can be calculated as shown in Eq. (5-3). In this calculation, bulk densities were used from Table 5-3.

$$Cost\ per\ tonne - km = \left. Operating\ cost\ of\ truck\ \left(\frac{\$}{km}\right) \middle/ Actual\ load\ carried(tonne) \right. \tag{5-3}$$

Table 5-5: Values of parameters related to fixed transportation costs and variable costs

Biomass form	Fixed cost (\$/tonne)	Sources	Actual load carried by 22.7 tonne truck (tonne)	Variable cost (\$/tonne-km)
		Woody biomass		
Logging residue	6.96	Perez-Verdin *et al.*, 2007	6.7	0.20
Chipped	5.27	Mahmudi and Flynn, 2006	16.8	0.08
Bundle	6.41	Bradley, 2010	14.28	0.10
Pellet	3.61	Sokhansanj and Fenton, 2006	22.7	0.06
		Agricultural biomass		
Loose	5.66	Kumar and Sokhansanj, 2007	5.1	0.27
Chopped	5.30	Kumar and Sokhansanj, 2007	9.2	0.15
Bale	6.06	REAP-Canada, 2008	13.4	0.10
Pellet	3.61	Sokhansanj and Fenton, 2006	22.7	0.06

The transport distance is a function of the quantity of biomass feedstock required for a biorefinery, biomass yield in the drawn area, percentage of biomass available for biorefinery compared to total production of biomass, percentage of farmers willing to sell their biomass (in case of agricultural biomass) and winding factor. The configuration of the truck used for biomass transport depends on the form of the biomass being carried. Weights and dimensions of heavy-duty trucks differ substantially around the world and sometimes vary within the country also (Wideberg *et al*., 2006). Annual travel distance of a truck for biomass transport is shown by Eq. (5-4).

$$X = {(0.75 * M^{1.5} * \tau)}/{(Q * (\rho * \varphi)^{1.5})} \quad (5\text{-}4)$$

Where, M = total biomass flow rate per year (tonne/year); Q = vehicle capacity (tonne/vehicle); φ = fraction of area where biomass is available (%); ρ = yield of biomass (tonne/km^2), considered uniform; τ = winding factor. For any specific area, $X = K/Q$; where K is a constant. Distance is inversely proportional to truck capacity. The assumptions in this study are based on earlier analysis by the authors (Sultana *et al*., 2010). The area used for biomass production is 30% and the winding factor is 1.27 (Sultana *et al*., 2010).

5.4. Results and Discussions

Transportation cost

Based on Eq. (5-3) total transportation costs of agricultural and woody biomass are computed considering different densities of various forms of biomass. The transportation cost increases with the increase of the size of the biorefinery. Biomass for a large-scale biorefinery is drawn from a larger area and hence results in a longer transportation distance. The transportation cost is calculated based on net wheat straw yield of 0.51 tonne/ha, with the land utilization factor of 0.3 (Sultana *et al.*, 2010). The net yield of forest residue considered in this study is 0.248 tonnes/ha. The truck payload was considered 22.7 tonnes.

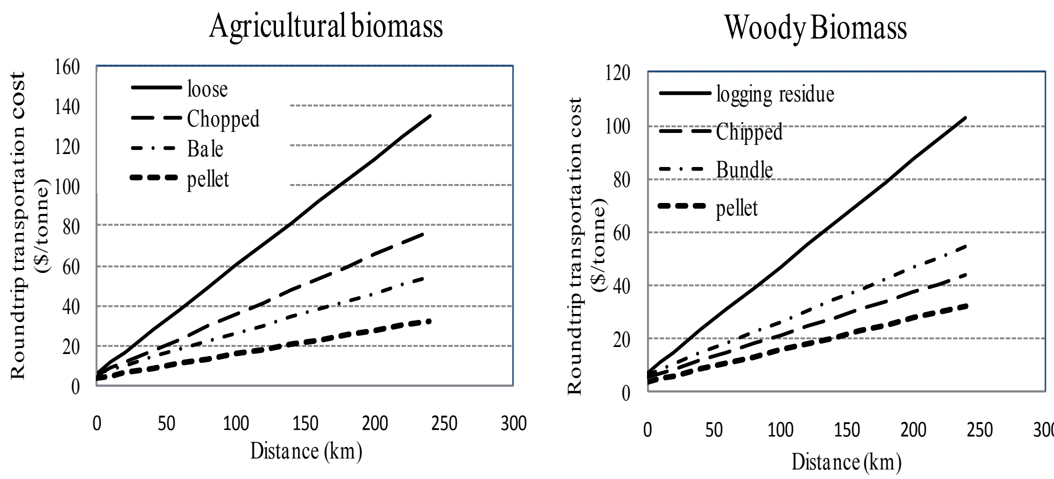


Figure 5-3: Variation of transportation cost with distance for both woody and agricultural biomass

Figure 5-3 shows the variation of roundtrip cost of transportation with distance of hauling for different forms for biomass. The cost curves for pellets stay well below the cost curves for transportation of bales, chips or chops indicating that pellet is a better form for transportation of both woody and agricultural biomass. For woody biomass, transportation cost of pellets are followed by transportation costs of bundles, chips and forest residues, respectively. Similarly for agricultural biomass, transportation cost of agri-pellets are followed by the transportation cost of bales, chops and loose biomass, respectively. The reason for this variation is the high bulk density of pellets compared to other forms. The transportation cost of loose agricultural or woody biomass are much higher than other forms due to their low bulk densities. Another important observation is that the difference between costs of transportation of various forms of biomass becomes larger at longer distances. This indicates, pellets are preferable form of transport especially for large-sized biorefineries because of the longer transportation distances of biomass to support these facilities based on field or forest based biomass.

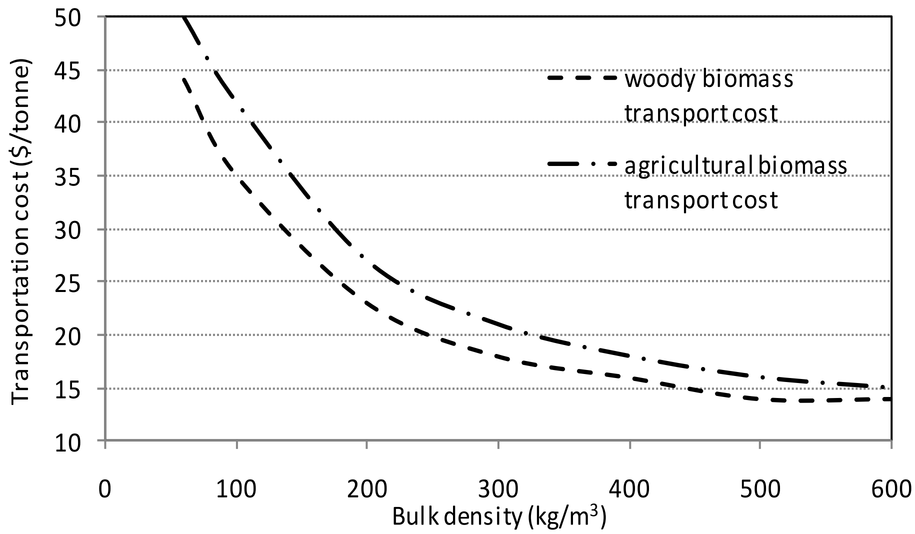


Figure 5-4: Variation of transportation cost with bulk density

The variation of roundtrip transportation cost with bulk density (for an arbitrary distance of 100 km) is shown in Figure 5-4. It is observed that the transportation cost decreases quickly with the increase in the bulk density. If the bulk density is high, trucks can transport material near to the payload. So the number of trips of trucks are less and the transportation cost is lower. For materials with a low bulk density, the volume limit is reached before the payload limit and more trips are necessary to deliver required weight of biomass. In Figure 5-4, the curve for agricultural biomass indicate that the transportation cost of agricultural biomass is higher compared to woody biomass. This is due to its low bulk density compared to woody biomass in general. The flat curves at higher bulk densities also indicate that the transportation cost of both biomass is less sensitive to the high bulk density at this range.

Truck capacity has an impact on the transportation cost. Using a large size truck can reduce vehicle kilometers, increase fuel consumption efficiency per trip and hence reduce the total transportation cost. The number of trips would be lower for a larger size truck. By increasing truck capacity from 22.7 to 40 tonnes and keeping other parameters constant (Eq. 5-4), the transportation cost can be reduced by 5 to 10%. However, the increase in capacity of trucks is limited by road weight regulations of a region or a country.

5.4.1. Total delivery cost for biorefinery

In this study we analyzed delivery costs for three different forms of agricultural and woody biomass. The total delivery cost for different biomass are calculated using data for unit operations as discussed (Table 5-2) earlier.

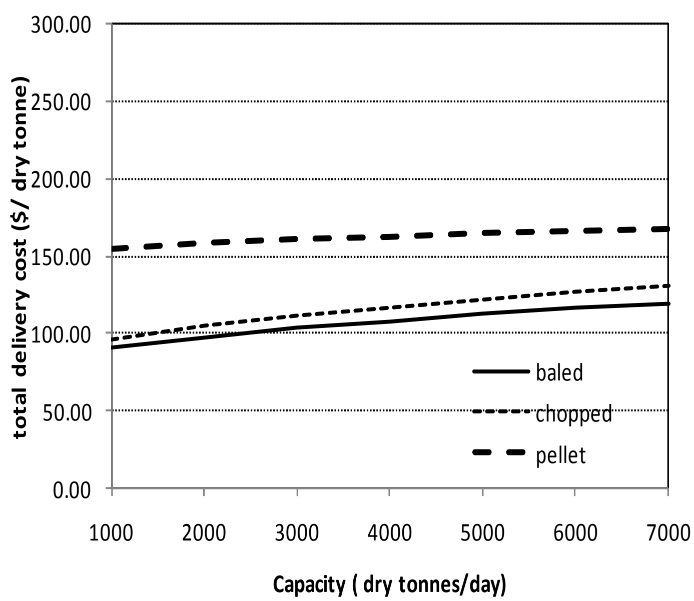


Figure 5-5: Total delivery cost of different forms of agricultural biomasses

The variation of the total delivery cost (from the field to the plant) with plant capacity for agricultural biomass is presented in Figure 5-5. The intercepts of these curves with cost axis are fixed costs. Pellets have higher (~ 1.5 times) fixed cost than other forms of biomass. This is because of the high cost of production of pellets from agricultural biomass. The result shows that bales are the least expensive form of biomass delivery (Figure 5-5). Theoretically, pellets have the lowest delivered cost for capacities of biorefineries higher than 60,000 dry tonnes per day and chopped form of feedstock shows better performance than pellet till 30,000 dry tonnes per day capacity. However, till 60,000 dry tonnes per day capacity bale shows best performance. But this size of plant is practically difficult to operate due to the availability of feedstock and road congestion issue in feedstock supply. The world's largest ethanol plant (Jilian Tianhe) in China uses 6,223 dry tonnes corn per day. The half of this capacity is transported by truck (Stephen *et al*., 2010). The largest pulp and paper mill (Aracruz Celulose, SA) in Brazil has a capacity of 3.3 million tonnes (5750 dry tonnes per day) whole tree logs per year. About 45% of its feedstock is transported by truck (Stephen *et al.,* 2010). The rest capacity of feedstock is transported by train or ship (Panamax) (Stephen *et al.,* 2010). Stephen *et al.* (2010) estimated that the maximum required number of deliveries in this plant is 169,907 trucks per year (a truck delivery every 3 minutes) to meet feedstock demand. If we compare these existing sizes of the plants to the optimum size to get benefits of economy of scale, we found that these existing large capacity plants have the capacities close to the probably optimum size. Kumar *et al*. (2003) estimated the optimum size of agricultural residue based power plant to be 6,846 dry tonne per day. Brown (2005) mentioned optimal plant size of ethanol plant (using sugarcane as feedstock) is 5,325 dry tonnes per day. However, almost all of the existing large size plants are located in other continents than North America. However, North American mills are smaller in capacity compared to the other continents of the world (Stephen *et al*., 2010). Most of the plants are within the capacities of 2000 - 3000 dry tonnes per day in Canada. Biorefinery larger than 7000 dry tonnes per day capacity is still non-existent because of the feedstock availability and traffic congestion issues. However, the world largest solid handling plant (power plant, 5,780 MW capacity) in Taiwan can handle 44,435 tonnes bituminous coal per day because of its location where 100% of its raw material is transported by ship (Stephen *et al.,* 2010).

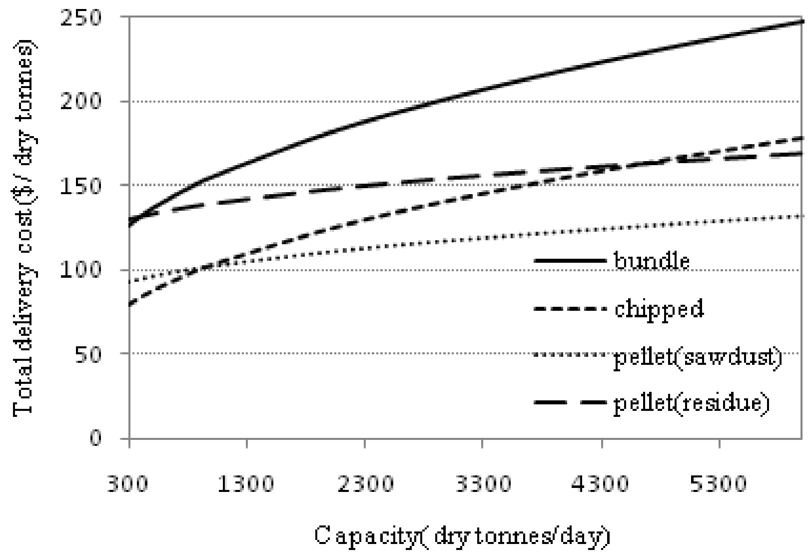


Figure 5-6: Total delivery cost of woody biomass

Figure 5-6 shows the variation of total delivery cost of woody biomass with capacity. The total delivery cost changes faster with capacity in case of chipped biomass and bundle biomass compared to pellets. The chipped form of biomass transport is a better option than other forms for biorefinery having capacities less than 1,000 dry tonnes/day. Above 1000 dry tonnes per day capacity sawdust pellet is the economic form compared to other forms. Above 300 dry tonnes/day capacity plant, the delivery cost of bundled biomass becomes the highest over other forms. For the intermediate plant sizes, e.g., 1000 to 4300 dry tonnes/day capacity, the chipped form of biomass delivery shows better performance than forest residue pellet. For larger size plant, e.g., greater than 4300 dry tonnes/day, the pellet (made up of sawdust and forest residue) becomes more economic than other forms. Kumar *et al*. (2003) estimated feedstock requirement of optimal size

(137 MW) of power plant using forest residue as 2,040 dry tonnes per day. At this capacity sawdust pellet is the most economic form followed by chipped form.

5.4.2. Total delivery cost in GJ

In case of power plant, it is more relevant to find delivery cost per GJ basis. Heating values of different forms of biomass are different due to the variation in their moisture and ash contents. The chemical composition of different forms of biomass is shown in (Table 5-6).

Table 5-6: Chemical compositions of different forms of biomass

	Wood pellet	Wood bundle	Wood chip	Straw pellet	Straw bale	Straw chopped
C (wt%, d.b) [a][b][c]	50.3	50	50	45	45	45
H (wt%, d.b) [a][b][c]	6.1	5.9	5.9	5.5	5.5	5.5
O (wt%, d.b) [a][b][c]	43.09	44	44	43	43	43
N (wt %, d.b) [a][b][c]	0.5	0.8	0.8	0.54	0.54	0.54
S (wt%, d.b) [a][b][c]	0.04	0.08	0.08	0.2	0.2	0.2
Ash (wt%, d.b) [a][b][c]	0.51	2.5	1.4	5.5	5.5	5.5
Moisture (wt%, w.b) [[a][b][c]	6	45	50	6	15	13
GCV(MJ/kg, d.b)	20.28	19.80	19.82	17.64	17.64	
NCV(MJ/kg, w.b)	17.23	9.08	8.05	14.93	13.61	

[a] Loo and Koppejan, 2008;
[b] Obernberger and Thek, 2004;
[c] Melin, 2008.

The high calorific value (HCV) of biomass is calculated by using the following empirical equation (Loo and Koppejan, 2008).

$$HCV = 0.3491X_c + 1.1783X_H + 0.1005X_S - 0.0151X_N - 0.1034X_o - 0.0211X_{ash} \qquad (5\text{-}5)$$

where, HCV is in MJ/kg (d.b); *X* is the content of C, H, S, N, O and ash in wt% (d.b).

The low calorific value (LCV) can be calculated from the HCV taking into account the moisture and hydrogen contents of fuel by applying the following equation (Loo and Koppejan, 2008).

$$LCV = HCV\left(1 - \frac{W}{100}\right) - 2.444.\frac{w}{100} - 2.444.\frac{h}{100}.8.936.\left(1 - \frac{w}{100}\right) \quad (5\text{-}6)$$

LCV is in MJ/kg (w.b.) fuel, 'w' is the moisture content of the fuel in wt% (w.b.) and 'h is concentration of hydrogen in wt% (d.b.). HCV and LCV are calculated based on data on Table 5-6. The ash content of wood bundle and wood chips are higher because the forest residue is contaminated with soil and dirt during skidding of the whole tree to the roadside from the stand (Obernberger and Thek, 2004; Ohman *et al*., 2004). In case of production of pellets, the feedstock is cleaned before grinding.

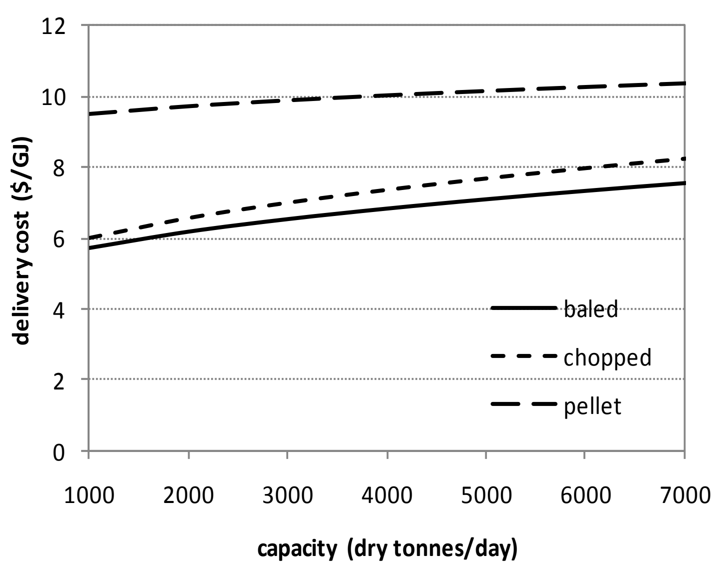


Figure 5-7: Delivery cost of agricultural biomass per GJ

In the delivery cost in GJ basis (Figure 5-7), till 7000 dry tonnes per day capacity, the bales are the most economical form of delivery of feedstock followed by chopped form. Theoretically, pellets have least delivery cost having capacity of power plant 50,000 dry tonnes per day which is not practical in terms of feedstock availability and traffic congestion issues. The optimum size and the largest size of power plant in Canada using forest residue biomass having capacities of 2,040 dry tonnes per day and 2,500 dry tonnes per day, respectively, which are very close (Wiltsee, 2000; Kumar *et al.,* 2003). At these capacities, bales are the most economic form of delivery.

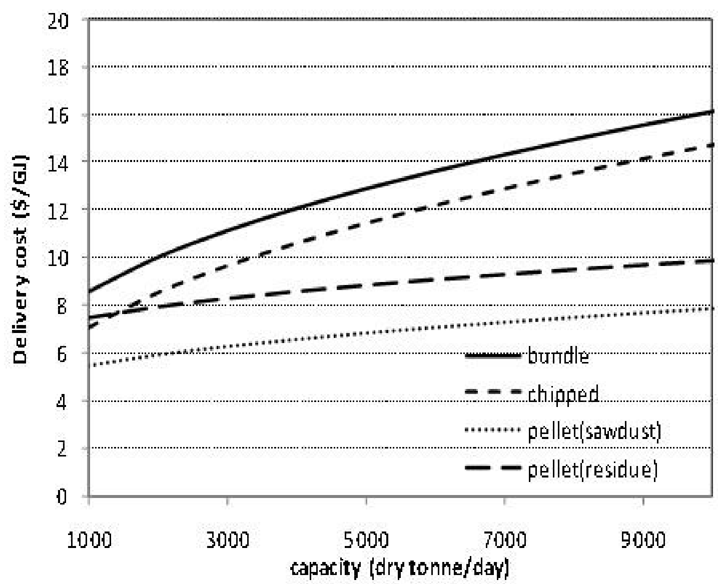


Figure 5-8: Delivery cost of woody biomass per GJ

In case of woody biomass (Figure 5-8), pellets made of sawdust are the most economical form of delivery for use in the power plants. The key reason is the low cost of manufacturing of sawdust pellets. The cost of pellets manufactured from forest residues are much higher than the pellets from sawdust as there are additional costs for collecting, processing and transporting these residues.

5.4.3. Delivery cost of multiple forms of biomass feedstocks to a biorefinery

Based on several studies done earlier, the optimum size of the biomass based facilities (i.e., the size at which the cost of production of fuels or chemicals is minimum) is typically in the range of 5,000 to 7,000 dry tonnes of biomass per day (Kumar *et al*., 2003; Brown 2005). This size depends on a number of factors and these factors are detailed in the literature (Kumar *et al*., 2003; Brown 2005). Many jurisdictions have scarcity of such large amount of biomass. In most of these cases, only one feedstock may not be sufficient due to its limited availability. These large scale biorefineries can operate at such scales by using a combination of agricultural and woody biomass forms as feedstocks. Due to the high cost of delivery of chopped form of agricultural biomass and bundle form of woody biomass, these two forms are not included in this assessment. Delivery costs of other forms of biomass in different combinations are shown in Figure 5-7. Figure 5-7 is based on feedstock supply to a biorefinery having a capacity of 5,000 dry tonnes/day.

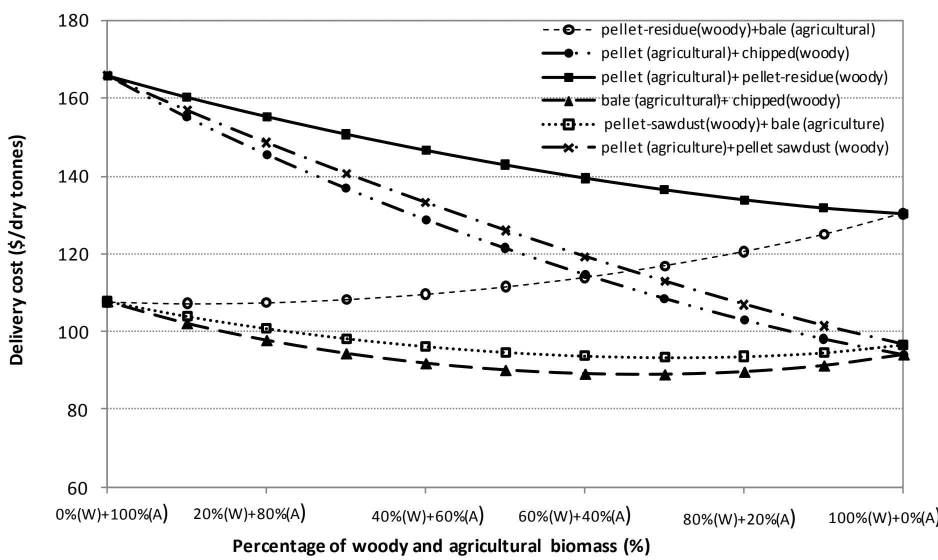
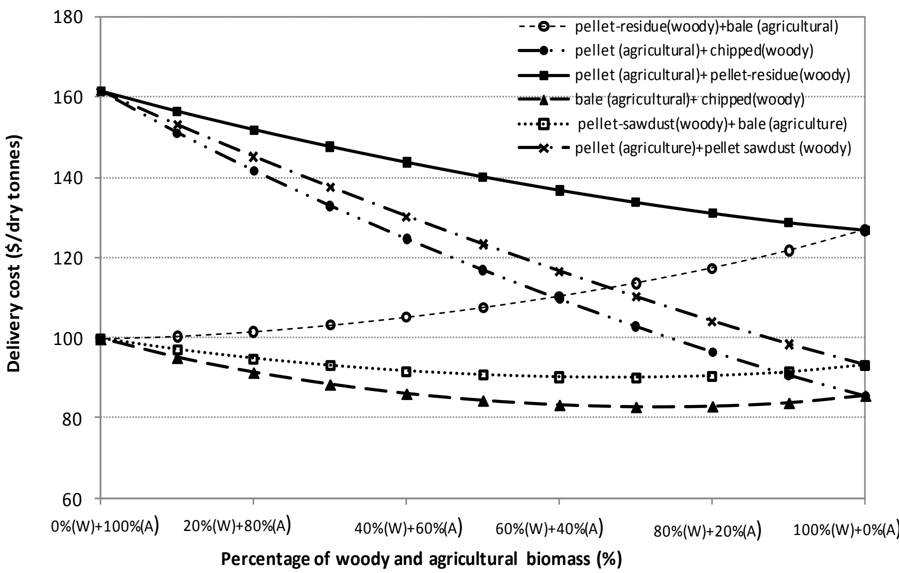


Figure 5-9: Delivery cost of mixed form of transport to a biorefinery having capacity of 5000 dry tonnes/ day (W = woody biomass, A= agricultural biomass)

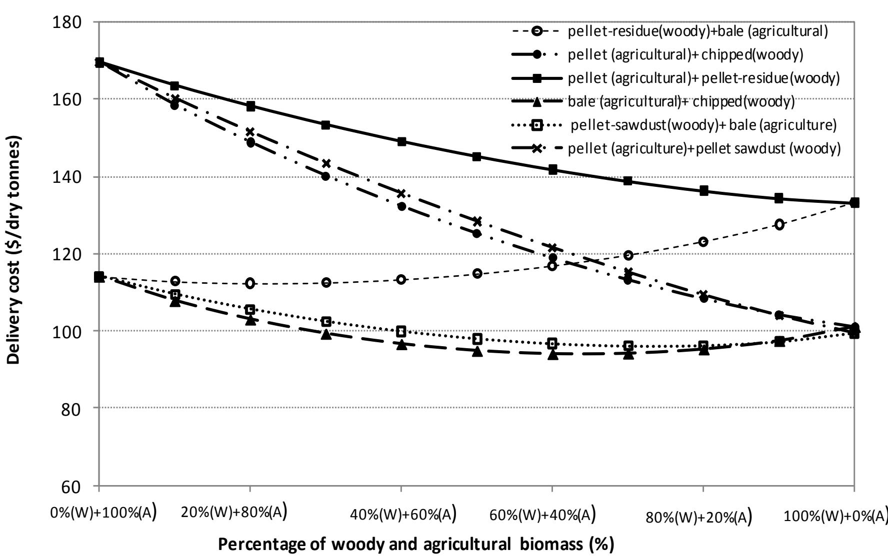
The delivery cost of agriculture biomass in form of bales together with chipped form of woody biomass is the most economical combination of feedstock delivery. This is consistent with observation from Figure 5-5 where we have seen that bale is the cheapest form of delivery of agricultural biomass at the considered capacity. Though chipped form of woody biomass could not show better performance than pellets, it's combination with agricultural residue bale shows better performance. The shape of the curve in Figure 5-9 indicates that hundred percent agriculture or woody form of delivery incurs higher delivery cost than combination of woody and agricultural forms. A combination delivery of seventy percent of woody chips and thirty percent of agriculture bales shows least cost followed by the combination of seventy percent sawdust pellets and thirty percent agri-bales.

Figure 5-9 also shows that as the percentage of woody biomass increases the delivery cost decreases for the mixed feedstock including agricultural pellets with woody pellets, sawdust pellet with forest residue pellet and also for agricultural pellets with chipped (woody) forms. This is because delivery costs of woody biomass forms are less than agricultural biomass on per tonne basis. The delivery cost for the combination of pellets (woody) and bale (agriculture) forms increases with increase of percentage of woody biomass because agricultural biomass in the form of bales has lower cost in dollar per tonne than pellets from woody biomass.

By changing the capacity of the biorefinery to 3000 dry tonnes per day and 7000 dry tonnes per day (Figure 5-10), the pattern of the graphs and the combination of least cost forms of feedstock delivery is same, only the delivery cost varies because the distance to travel to collect feedstock increases with the capacity.



(a)



(b)

Figure 5-10: Delivery cost of mixed form of transport for (a) 3000 dry tonnes per day and (b) 7000 dry tonnes per day

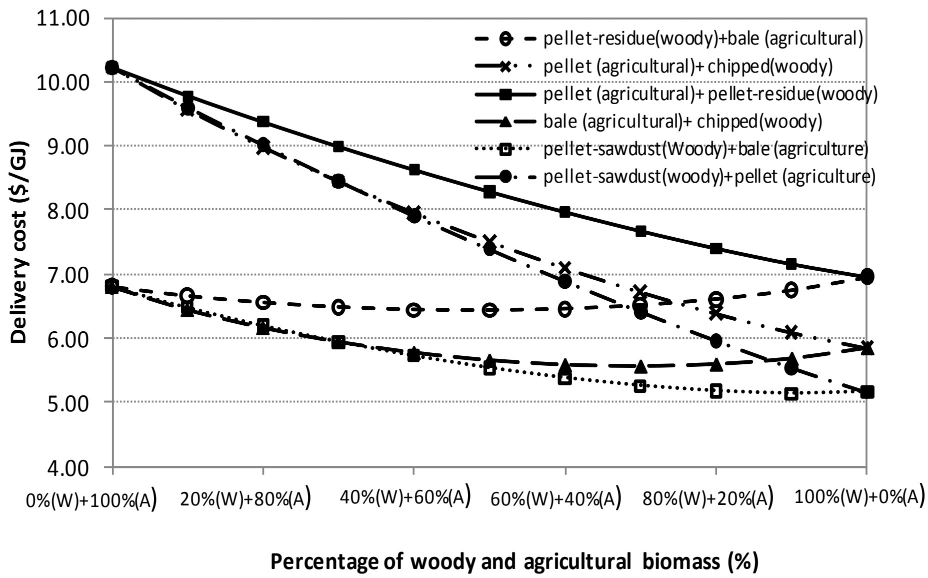


Figure 5-11: Delivery cost of mixed form of transport for power plant having capacity of 5000 dry tonnes/ day (W = woody biomass, A = agricultural biomass)

A similar pattern of delivery cost is also observed on GJ basis (Figure 5-11). This figure would be more useful for power plant feedstock delivery. For a 5,000 dry tonnes per day capacity plant, the combination of the bale (agriculture) with pellet from sawdust is the most economic option compared to other mixed forms of biomass delivery. The minimum cost in this case occurs at 10% bales and 90% sawdust pellet combination. The curve of agricultural bale and chipped form of woody biomass delivery does not show as economic as the curve in Figure 5-9 because here costs are in per GJ basis and chips usually have high moisture content i.e., 45 to 50%. The delivery cost of pellet (agriculture) with pellet (woody), pellet (sawdust) with pellet (agriculture) and also pellet (agriculture) with chip (woody) decreases sharply as the percentage of woody biomass increases because of lower cost of woody biomass.

5.4.4. Traffic congestion for multiple feedstock transport

Another constraint of large scale biorefinery build up is the traffic congestion. As biomass has lower bulk density as well as lower energy density compared to fossil fuel, significantly more feedstock is required to transport to the bioenergy plant to get same energy value from the fuel. The number of trucks of biomass feedstock delivered per day or per hour depends on the capacity of the plant (tonnes per year), capacity of the truck (tonnes per load), bulk density of the biomass feedstock (tonnes/m^3) and the form at which it is transported. Table 5-5 shows the minimum cost combinations of different forms of feedstock transport and probable traffic congestion for 5,000 dry tonnes per day capacity plant considering the capacity of trucks which are usually used for biomass transport in Western Canada. It is assumed that agricultural residue bales are transported with flatbed trailer having capacity 23 tonnes (110 m^3), woody chips are transported with B-train of capacity 21.5 tonnes (70m^3) and pellets with truck boxes of capacity 40 tonnes (70m^3) (Sokhansanj *et al.,* 2010).

Table 5-7 shows that traffic congestion is less for the pellets' combinations (both agricultural and woody). Only 5 trucks per hour i.e., the truck should deliver feedstock every 12 minutes. However, in case of bales (agriculture) with chips (woody), bales (agriculture) with pellets- (forest residue), pellets (agriculture) with chips (woody) and bales (agriculture) with pellets (sawdust -woody) combinations, traffic congestion is higher which is 12, 10, 13 and 9 trucks per hour, respectively i.e., there will be feedstock truck delivery at every 4, 5, 4, 8 minutes, respectively (Figure 5-12). If we compare these combinations (woody and agriculture) with single biomass feedstock delivery, it is seen that at 5,000 dry tonnes per day capacity of a biorefinery, single feedstock such as bale, chips and pellets truck delivery per hour is 11, 13 and 5, respectively. It is important to note here that in multiple biomass delivery case, biomass has to be collected fromtwo different sources including forest and agricultural areas. So the traffic congestion might reduce in combined delivery of woody and biomass feedstocks compared to delivery of biomass from a single source.

Table 5-7: Impact of delivery of combined forms of lignocellulosic biomass on traffic congestion (A=agricultural biomass and W= woody biomass)

Combination form	Minimum cost combination (A)	Minimum cost combination (W)	Actual tonnes carried per truck (A)	Actual tonne carried per truck(W)	No of trucks per day (A)	No of trucks per day (W)	total trucks per hour	min/truck
Bale(A)+Chip (W)	30%	70%	17.6	15.4	85	227	12	4
Bale(A) + Pellet-residue(W)	90%	10%	17.6	40	255	12	10	5
Pellet(A)+ Chip(W)	0%	100%	40	15.4	0	324	13	4
Pellet(A)+Pellet-residue (W)	0%	100%	40	40	0	125	5	12
Bale (A)+ Pellet-sawdust (W)	30%	70%	17.6	40	85	87	9	8
Pellet (A)+ Pellet-sawdust (W)	0%	100%	40	40	0	125	5	12

The present analysis uses cost values from North American perspective which might change in other regions of the world. However, it is inferred that the findings of this study, specifically the comparative results of different densities of biomass would be same for everywhere.

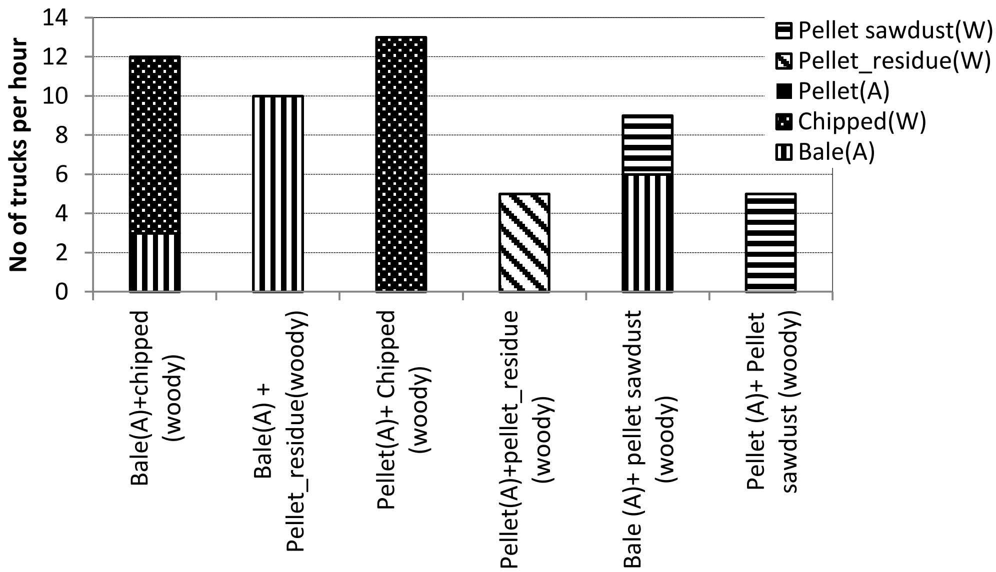


Figure 5-12: Traffic congestion for different combination of feedstock delivery to 5000 dry tonnes/day plant (W= woody biomass and A = agricultural biomass)

5.5. Conclusions

Multiple types and forms of biomass feedsock delivery is a viable option of fuel supply system for large-scale biorefinery. It is found that multiple types and forms of biomass feedstock delivery give lower delivery cost than single type and form of biomass feedstock. In biorefinery feedstock delivery system, the combined transport of agricultural residue in form of bales and wood chips shows lowest cost of delivery compared to others combinations. Delivery of seventy percent of wood chips and thirty percent of agriculture bales result in the most economic option for biorefinery. In case of power plant, mixed mode delivery of agricultural residue bale and sawdust pellet is best option.

For a single biomass such as agricultural residue, the bale is the best option for delivery for biorefinery. In case of woody biomass, the chipped form of delivery could be used for small plant sizes, e.g., less than 1,000 dry tonnes/day. The bundle is not a good option for any plant sizes at current state. For larger plant capacities (greater than1,000 dry tonnes/day), the sawdust pellet is the most economic option for delivery. Forest residue based pellets becomes more economical than chipped form of biomass for plant sizes greater than 4,300 dry tonnes per day. If we consider only the transport cost then the pellet is a good option followed by the bale. The transportation cost and overall delivery cost of the agricultural biomass are higher than the woody biomass for similar capacity plants.

By increasing the bulk density, the transportation cost and traffic congestions can be reduced. Transport of agricultural and woody biomass in pellet form is the best in terms of traffic congestion. Traffic congestion would not increase when biomass is transported in the form of combination of forms and types of multiple feedstocks compared to the single type and form of biomass feedstock transport. The present analysis uses cost values from North American perspective which might change in other regions of the world. However, it is inferred that the findings of this study, specifically the comparative results of different densities of biomass would be same for everywhere.

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Chapter 6. Optimal Siting and Size of Bioenergy Facilities using Geographic Information System

6.1. Introduction

Biomass is a highly disperse and geographically dependent renewable energy source. Biomass can be used for production of a number of fuels and chemicals. The transportation cost of feedstock constitutes a significant part (35 – 50%) of the total cost of production of these fuels and chemicals (Kumar *et al.*, 2006). Consequently, establishment of biomass-based facilities in suitable locations by minimizing transportation cost is one of the key issues for biofuel economy and its sustainability. In addition, location and size of a biomass-based facility for fuels and chemical is dependent on different issues e.g., steady supply of feedstocks, environmental regulations, stakeholders interests etc.

Siting bioenergy plants in optimal locations at optimum capacities is a challenging task. Due to high geographical dependence of biomass feedstocks, implementation of spatial information technologies such as remote sensing and geographical information system (GIS) in addressing this issue appears to be an appropriate methodology. In the past, GIS has been used for assessing biomass availability in some studies, for instance, Noon and Daly (1996), Baccali *et al.* (2009), Stephen *et al.* (2010). A number of studies used the spatial information tool especially GIS to identify the location of biomass plants e.g., Mielenz (1997), Graham *et al.* (2000), Voivontas *et al.* (2001), Papadopouloas and Katsigiannis

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(2002), Noon *et al.* (2002), Ranta (2005), Zhan *et al.* (2005), Haddad and Anderson (2008), Panichelli and Gnansounou (2008), Dubuc (2010), Zhang *et al.* (2010), Youshioka *et al.* (2011). Majority of these studies are aimed at identifying locations of bioenergy plants and investigating the economic aspect. Other studies incorporated the location-allocation modeling to find optimum biomass-based facility locations (e.g., Venema and Calamai, 2003; Ranta, 2005; Zhan *et al.*, 2005; Dong, 2008; Shi *et al.*, 2008; Perpina *et al.*, 2009). Two prime aspects of analysis with geospatial tools are: determining the suitability of different locations of the study area for plants, and, finding an optimal solution. An optimal location determined based only on economics may not comply with local environmental regulations or other social criteria. The available information in the current literature on combining socio-environmental suitability and economic optimality in local geospatial scale is not adequate. There is a requirement for further research on optimal size and location of biomass-based facilities.

One of the important tasks in the suitability analysis is the integration of different preference criteria by providing weightage factors to the criteria. One approach of incorporating weightage factor in the preference criteria is by employing the Analytic Hierarchy Process (AHP) introduced by Saaty in 1970s (Saaty, 1977 and 2008). It is a potential tool which integrates qualitative and quantitative criteria systematically for complex decisions. The method has been used successfully in many fields but it's application in bioenergy facility location is very limited (e.g., Madlener, 2001; Ma *et al.*, 2005). There is no study which reports on the variation of optimal capacity of biomass-based facilities in a region and its relation to the average optimal size and number of facilities by considering both the real road network and spatially varied biomass yield.

The aim of this research was to develop a model in GIS environment to locate bio-energy facility through integration of environmental and economic constraints. The specific objectives were:

- To develop a land suitability model for biomass-based facility development using the Analytic Hierarchy Process (AHP) in order to integrate selected spatial and environmental criteria.
- To find suitable locations with transport cost optimization and the number of biomass-based facilities in an area considering spatially varied biomass yield and the road network.
- To develop a methodology to compute optimal size and the minimum cost of biomass-based facility considering location of biomass sources and the existing road network.

Results using this approach are compared with those estimated from generic (GEN) method developed earlier (Chapter 3). The presented methodology is implemented by performing a case study for the Province of Alberta.

6.2. Methodology

The current study involves assessment of biomass availability, suitability analysis of candidates for biomass facility and spatial optimization of the considered facilities. Figure 6-1 shows the conceptual model and various analyses performed under this study. In this type of research, it is imperative to develop a proper geospatial database in addition to statistical information for subsequent analysis. The ArcGIS software, version 10 (ESRI, 2011) and it's geodatabase environment were used in this study.

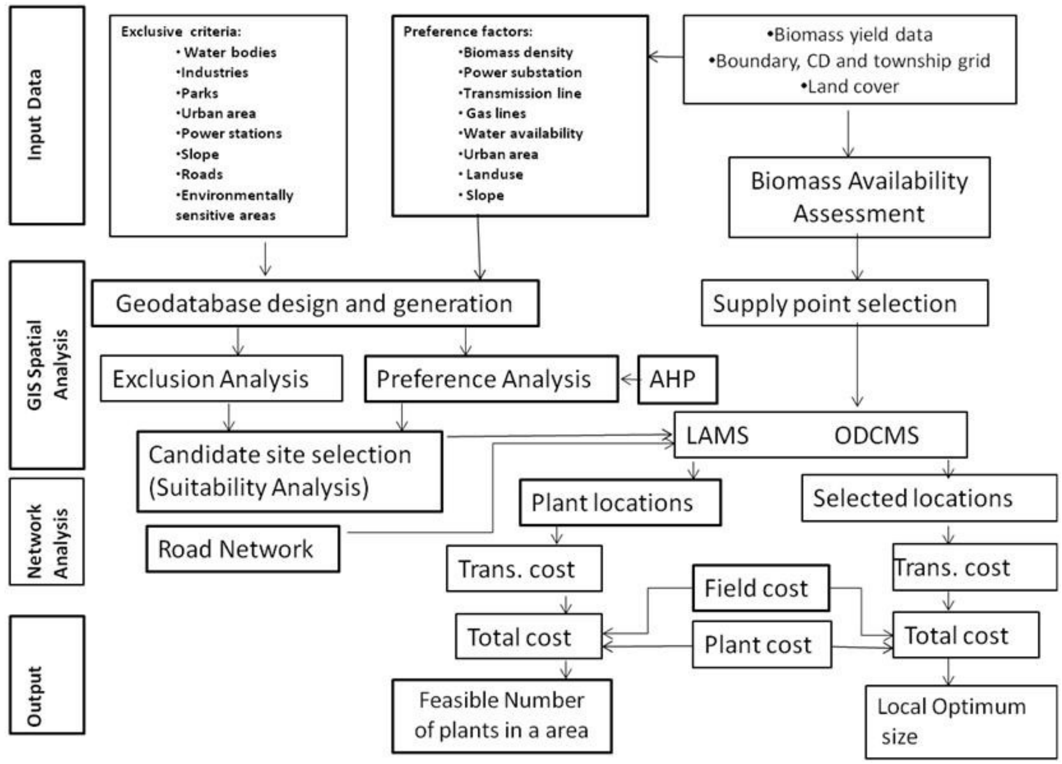


Figure 6-1: Flowchart of the conceptual model and different analyses (AR-agricultural regions, CD- census divisions, ATS-Alberta township system, SLC- soils landscape of Canada, AHP – Analytic Hierarchy Process, LAMS – location-allocation model solver, ODCMS – origin-destination cost matrix solver)

Geospatial information for the current study was collected mainly in vector format from different sources including GeoBase Portal (CCOG, 2011), Altalis (Altalis, 2011). Majority of the data were available in either of the geographical coordinate systems: GCS North American 1983 and GCS North American 1983 CSRS (Canadian Spatial Reference System). Both refer to the North American datum of 1983 with geodetic reference system GRS 80 ellipsoid. Only few of the features were available in projected UTM (Universal Transeverse Mercator) coordinate system. Both vector-based and raster analyses were carried out in this study. Landcover and elevation data were available in multiple files for 1:50,000 NTS (National Tophographic System of Canada) tiles (CCOG, 2011). The digital elevation data (8 – 23 m resolution) were used to develop a new land slope layer. In some cases several layers of data were integrated to create a single layer. For example, spatial information for urban areas, rural residential areas in different feature classes (points, lines and polygons) were merged to a single layer. Eventually a large number of data files were analyzed. To ensure quality of data and raster operations of multiple files, all spatial information was transformed to a projected local coordinate system.

6.2.1. Assessing spatial variation of biomass

Biomass availability is characterized by year to year variability and spatial non-homogeneity. In this study data on production of wheat, barley and oat were collected from Alberta Agricultural Food and Rural Development (AAFRD, 2011). The annual volume of straw that potentially could be procured in a particular region was assessed considering the variability of production and crop supply. The actual amount depends on many factors which include biomass species, biomass yield, location, climate, time of harvest, and the technology used for harvesting and collection of biomass (Kumar and Sultana, 2010). In Alberta, the total average production of wheat, barley and oats over the last 12 years (1997–2008) has been 6.8, 6.3 and 0.72 million tonnes per year, respectively. The available straw production volumes are determined by measuring and applying straw to grain mass ratios. The average yields of wheat, barley and oats are 2.66, 3.03 and 2.49 green tonnes ha^{-1}, respectively. Different levels of straw to grain mass ratios were recommended in different studies which are summarized in Sultana *et al.* (2010) and the ratios adopted in this study for estimating crop residue for wheat, barley and oats are 1.1, 0.8 and 1.1, respectively. To determine the net yield of straw, additional factors were considered. These include: (i) straw required for livestock feeding, bedding and mulching, (ii) residue retained for soil conservations, (iii) material left on the field in accordance with the removal efficiency of the harvesting machine, (iv) straw lost through handling, transport and storage, (v) material retained on the field to prevent soil erosion and to maintain soil health and fertility. The quantity of straw is further reduced in accordance with its moisture content. Details on the estimation procedure are available in Sultana *et al.* (2010) and Kumar and Sultana (2010).

Geospatial information of agricultural areas including their probability of using for agricultural crop production (high, medium and low) was obtained from the Soil Landscape of Canada (SLC) database version 3.2 (AAFC, 2011). Other useful information for the assessment of annual crop production were obtained from land cover data (CCOG, 2011) and from the AGRASID version 3.0 database on soil landscape of the agricultural areas of Alberta (Brierley *et al.*, 2001). All the information were combined and processed with appropriate geo-processing tools to derive the representative spatial distribution of net biomass over the studied area. The biomass attributes of small cells were then integrated to larger representative collection areas to use as potential sources of feedstock for biomass-based facilities. Each collection unit area was defined by a polygon around source points such that any location within that area was closer to that particular biomass source point compared to other sources. The resulting polygons for biomass gathering are also known as Voronoi cells.

6.2.2. Finding suitable candidate sites for biomass-based facility development

In order to locate optimal sites for biomass-based facilities; environmental, economic and social factors are generally considered. The environmental constraints are based on areas which has restriction on biomass-based facility development. In addition to finding an available area the implication of the constraints is that the new plants would not interfere with the existing facilities while complying with the current environmental and conservation practices. Important constraints which were considered in this study are summarized in Table 6-1. This includes man-made, natural, and environmental elements. Social acceptability of establishing a plant largely depends on the proper treatment of these three elements.

In the exclusion analysis, a buffer zone was developed for each of the constraints to define the minimum distance of development sites to the selected geographic entities. The buffer extents were selected based on the conditions of the study area and guidelines available from previous literature (e.g., Fischer and Fischenich, 2000; Ma *et al.*, 2005; Foud *et al.*, 2008; Carolinian Canada, 2011). From the geospatial data a raster map (30 m x 30 m cell size) was created for each constraint element. The image data was transformed into a binary image by reclassifying cells within the constraint area by “0” and cells outside the area by “1”. The final binary constraint map was produced by multiplying relevant layers of data which can be expressed by the following equation:

$$C_{E,i} = \prod_{j=1}^{n} C_{i,j} \qquad (6\text{-}1)$$

Where $C_{E,i}$ is the cell value i of Boolean value (0, 1) assigned to the i^{th} cell in the final exclusion map; $C_{i,j}$ is the Boolean cell value (0, 1) assigned to the i^{th} cell value in the j^{th} constrained grid layer; n is the number of constraints considered for the analysis. In the final raster file a “0” value indicates the cell is not suitable for plant build up. The cells with value “1” represent probable locations for building bioenergy plant. The exclusion analysis was used to reduce the study area for subsequent analysis. In the following step the preference analysis was carried out where certain factors that influence the selection of a potential site are assessed.

In the preference analysis spatially defined data were used to find out location of the biomass-based facility employing spatial analysis techniques and AHP method. The influences of all factors in the selection of potential sites are not equal. So, the AHP is used to estimate appropriate weights to the factors reflecting their relative importance. The AHP method is a theory of measurement through pair-wise comparisons and expert judgments play the key role to derive the priority scale (Saaty, 2008). The method is explained in detail in Appendix C-1.

Table 6-1: Identified constraints and their specifications for creating buffer zones

Constraints	Specifications
Rural and urban areas	A distance of 1 km from residential and urban areas.
Industrial and mining zones	The zones and areas falling within a buffer of 1 km are avoided.
Airport and heliport	Sites falling within such areas and a buffer zone of 1 km are avoided.
Park and recreational areas	Sites falling within these areas and a buffer of 500 m are avoided.
Rivers, lakes and other waterbodies	Sites within buffer zone of 200 m are avoided.
Wetlands	Wetland areas and a buffer zone of 200 m are avoided.
Environmentally sensitive areas (flood plains, conservation areas, habitat sites)	Sites falling within such areas and a buffer zone of 500 m are avoided.
Roads	Sites falling within a buffer of 30 m are avoided.
Power plant and substation	Sites falling within a buffer of 100 m are avoided.
Transmission line	Sites falling within a buffer of 100 m are avoided.
Natural gas and oil pipelines	Sites falling within a buffer of 100 m are avoided.
Land surface gradient	Areas with slopes larger than 15% are avoided.

For preference analysis, multiple buffers were generated around the influencing physical elements (footprints in the form of polygons, lines or point features). Each buffer region is then re-classed assigning a score representing the relative influence of individual zones. For other factors where buffering is not possible but their spatially varied data are available (e.g., biomass yield, slope of land, water availability), the values of raster cells were directly re-classified to assign relative scores. In the process of analysis a range of uniform scoring (e.g., score values 1 to 10; 10 representing the most preferable site and 1 is the least preferable) was devised for all the spatial data layers related to preference analysis. A single grid or preference map was calculated by using weighted overlay method including all grid layers. The final preference map was developed based on the equation below:

$$C_{P,i} = \sum_{j=1}^{m} w_j C_{i,j} \qquad (6\text{-}2)$$

Where, $C_{P,i}$ is the preference score of the i^{th} cell value in the final criteria grid; w_j is the weight assigned to j^{th} criterion from AHP analysis; $C_{i,j}$ is the i^{th} cell value in the grid of the j^{th} preference criteria layer; m is the total number of preferable criteria considered for the analysis. A higher value for a cell indicates higher preference for the site. The final preference analysis map values indicate the overall ranking preferences of each cell for all criteria.

Considering the constraints and preference factors, a land suitability model (LSM) was developed. This LSM produced a siting suitability index (*SI*), which was a quantitative measure of preference of land use for development. The final constraint map from exclusion analysis and preference map were used to create the land suitability map and the value in each cell of the map represents suitability index. The suitability index is expressed by

$$SI_i = C_{E,i} * C_{P,i} \qquad (6\text{-}3)$$

Where, SI_i is the suitability index for the *ith* cell in the final land suitability map; $C_{E,i}$ is the Boolean value (0,1) assigned to the *ith* cell of the final constraint map in exclusion analysis; $C_{P,i}$ is the value assigned to the cell in the final map of selective analysis. The values of cells in land suitability map is 0 to 10 where "0" represents the unsuitable site, "10" represents the most suitable location and "1" is the least suitable location for siting a bioenergy facility.

6.2.3. Determining number and locations of biofacilities

The location-allocation analysis was performed with the road network data layer of the study area to deliver biomass feedstock to the facility with the minimum transportation cost and by allocating all collectable biomass to the facilities. In this approach, the shortest route network distances were computed for delivering and allocating biomass to the facilities using location-allocation problem solver. The goal of this problem was to determine *p* biofacilities in a predefined set with *n* (*n* > *p*) candidate facilities in order to satisfy a set of demands so that the total sum of weighted distances between each demand point and facility is minimized.

$$\min \sum_{i}^{m} \sum_{j}^{n} w_i x_{ij} d_{ij} \qquad (6\text{-}4)$$

Subject to

$$\sum_{j}^{n} x_{ij} = 1; \; i \in U \qquad (6\text{-}5)$$

$$x_{ij} \leq y_j \; ; \quad j \in V \qquad (6\text{-}6)$$

$$x_{ij} \leq y_j \; ; \quad j \in V \qquad (6\text{-}7)$$

$$\sum_{j}^{n} y_j = p \qquad (6\text{-}8)$$

$$x_{ij,} \, y_j \in \{0,1\} \qquad i \in U \quad j \in V$$

Where, $V = \{1,2,\ldots..,n\}$ is the set of possible facility locations from where p sites will be selected to allocate total biomass; $U = \{1,2,\ldots..,m\}$ is the set of biomass source points in the network.

i = index of biomass source points;

m = total number of biomass source points in the network;

j = index of potential facility sites;

n = total number of potential facility locations;

w_i = weight associated with each source point i;

d_{ij} = distance between source area i and potential facility j;

x_{ij} = 1 if source i is assigned to facility j , = 0 otherwise;

y_j =1 if the facility is located at candidate point j, = 0 otherwise.

The first constraint (6-5) forces biomass of each source to be assigned to only one facility. The second constraint (6-6) allows source point i to assign to j only if there is an open facility in this location. The third constraint (6-7) dictates the total number of assigned facilities to be equal to p.

The ArcGIS-based network analysis was used in this study to find the optimal location of a fixed number (p) of facilities in the study area. Figure 6-2 shows method for finding out the average optimal size and the number of plants. This analysis was performed by using location-allocation solver of network analyst tool of ArcGIS software. The location-allocation solver generates an origin-destination matrix of the shortest-path costs between facilities and source points by using the Dijkstra's algorithm. A detail on the algorithm is illustrated in Daskin (1995). It combines several techniques including a vertex substitution heuristic and a refining metaheuristic to achieve a near optimal solution (ESRI, 2011). The location-allocation solver working procedure is given in Appendix D.

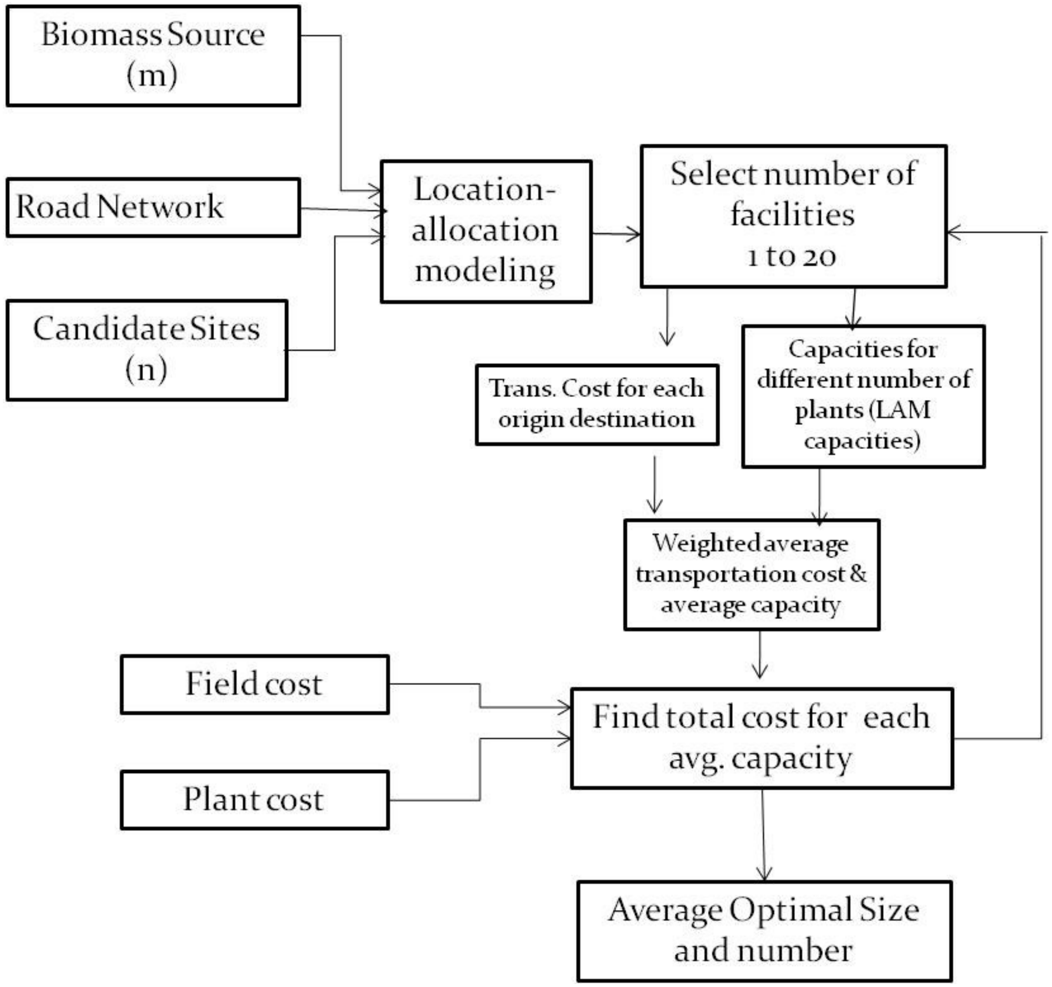


Figure 6-2: Schematic diagram for determination of the average optimal size and number using location-alocation solver (LAM= location-allocation model)

The distance travelled along the optimal route was used to calculate the transportation cost. The weighted average unit transportation cost for a facility *j* (UTC_j) is calculated as:

$$UTC_j = \left(\sum_{i=1}^{M} C_{ij} Q_i\right) / Q_t \quad (6\text{-}9)$$

with

$$C_{ij} = a + 2b \sum_{k=1}^{N} d_k \qquad (6\text{-}10)$$

Where C_{ij} is the total transportation cost ($ per dry tonne of biomass) for the optimal route between the facility *j* and biomass source *i*;

Q_i is the total biomass at source *i*;

M is the total number of biomass sources assigned to facility *j*;

Q_t is the total biomass assigned to facility *j*;

a is the fixed cost related to loading and unloading of biomass ($ per dry tonne);

b is the variable cost related to distance traveled ($ per tonne-km);

d_k and *N* are the length of the travelled road segment (km) and number of total segments along the optimal route between the facility (*j*) and the biomass source (*i*), respectively. The values of *a* and *b* were taken from Sultana *et al.* (2010).

6.2.4. Optimal size of plants

The optimal size of a biomass-based facility, in this case a pellet plant, was determined in Chapter 3 by a generic *(GEN)* approach. Henceforth the total cost estimation and optimal sizes mentioned in this chapter would be referred to this method identifying as generic (*GEN*) approach. A 30 years plant operating period and all life cycle costs of pellets were considered in this approach. This included cost of obtaining the straw, transporting to pellet plant, and its conversion to pellets. Costs incurred by the plant for the production of pellets consisted of capital cost, energy cost, employee cost, and consumable cost. The scale factors for all the equipment related to pellet production were determined based on the data of previous studies. All costs associated with pellet production were added to the field and transportation costs to obtain the total cost of pellets production. Iterations were carried out to obtain the minimum cost of producing pellets. In this part of the study, the optimal size was calculated in the suitable sites considering biomass transportation via actual road network and distributed biomass sources. The procedure to determine the optimal size is shown in Figure 6-3. The origin-destination (OD) cost matrix comprising of the shortest paths combining all biomass sources and candidate biomass-based facility locations were used for this purpose. The weighted average total cost for incremental capacities were derived using the above method. Optimal sizes of plants and the minimum costs from this analysis were then compared with the estimated values by the *GEN* approach.

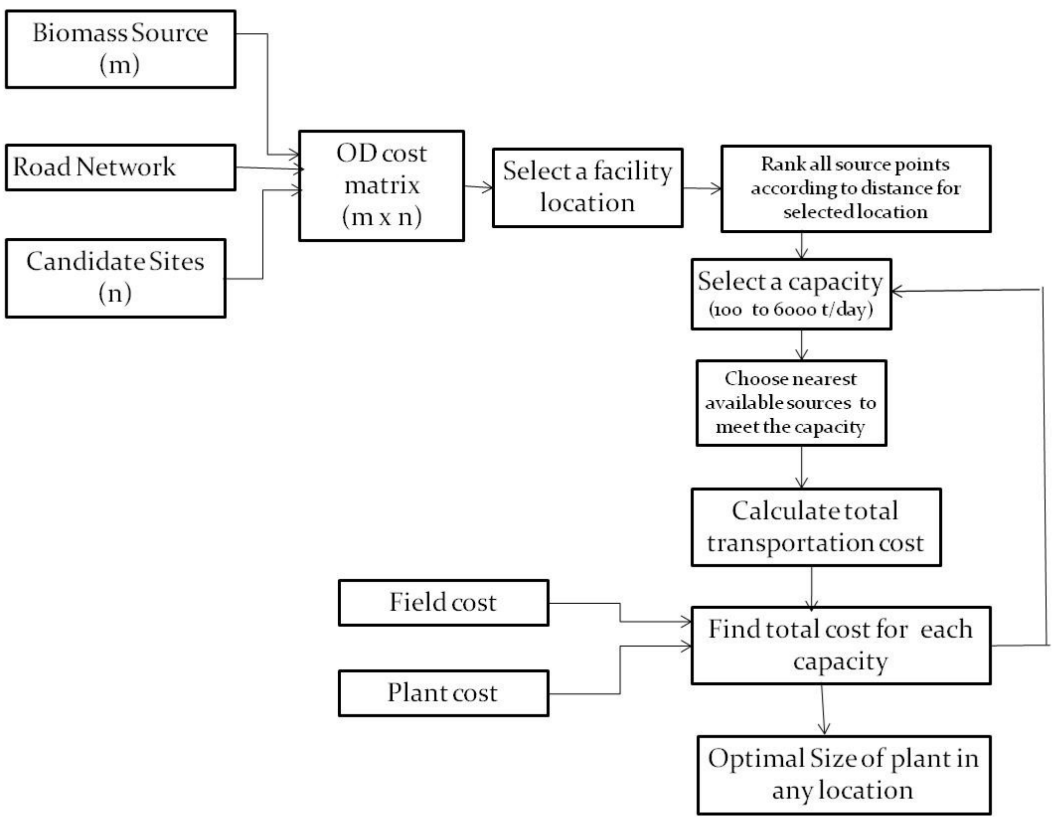


Figure 6-3: Schematic diagram to determine optimal size plant in any location (OD = origin-destination)

6.3. Case Study: The province of Alberta

6.3.1. Input data and assumptions

The study area and biomass availability

The methodology as described in the previous sections was applied for Alberta with particular reference to agri-biomass (wheat, barley and oat). The province has a large biomass resource base which could be used as feedstock of bioenergy facility. Besides 22.5 million hectare of harvestable wood forest, Alberta has a large agricultural resource base. Total farmland in Alberta is 21.1 Mha of which 46% area produces crops (Wood and Layzell, 2003). It is the second largest producer of wheat and the largest producer of barley in Canada. The net biomass available for processing were determined based on the methodology described earlier (Section 6.2.1). The distribution of straw biomass yield (tonne/km^2) is shown in Figure 6-4. The yield varies from < 1 tonne/km^2 to 60 tonne/km^2. The net availability of biomass is high in the middle part of the southern and central regions, and also in some parts of the north western region. For the location-allocation model, total 2,717 biomass sources were identified by constructing Voronoi cells. About 20% of these cells were located in the Peace River region. To facilitate description in the following texts, the Peace River region is described separately and the rest of the agricultural regions is together termed as southern regions.

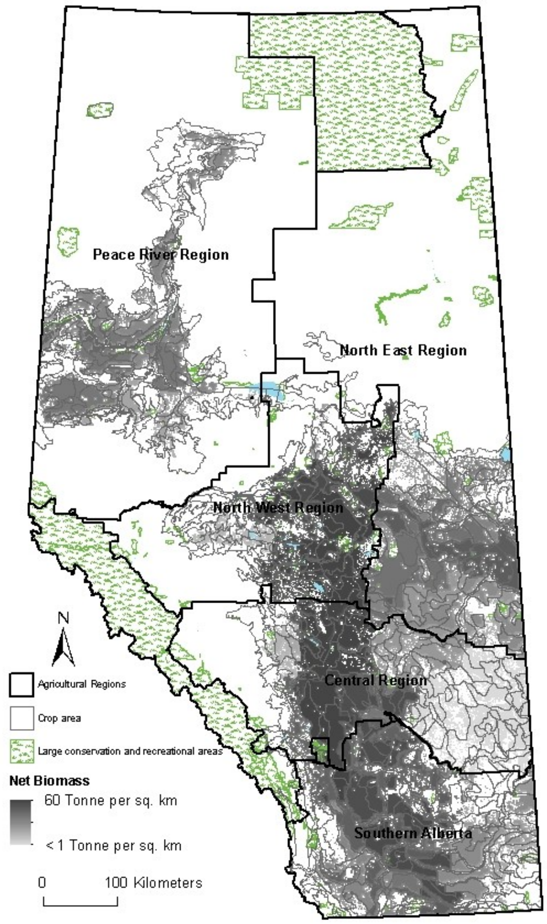


Figure 6-4: Cropping area and agri-biomass net yield in different regions of Alberta

Selection of factors and criteria for land suitability assessment

The exclusion analysis was performed with selected criteria to identify unsuitable and unavailable areas for locating bioenergy plants. The selection of constraints (Table 6-1) for Alberta was based on the concern to avoid possible impact on environment, public health and safety, and to evade any interaction with other natural and man-made elements. In the preference analysis, eight factors were identified for selecting potential sites. These factors were selected based on their importance in the study area which was consistent with other previous studies (e.g., Dikshit *et al.*, 2000-2001; Ma *et al*., 2005; Perpina *et al*., 2009). Relevant organizations in Alberta were also contacted for this purpose (e.g., Bell, 2011). The factors and their weight by the AHP analysis are given in Table 6-2. The consistency ratio (*CR*) of the AHP estimation of weights can be calculated using the procedure explained in Appendix C-1. The value of *CR* is 0.015 for the estimation of Table 6-2 which indicates that the weight values are acceptable.

The biomass yield is the most important factor which is reflected in its highest weighing factor. The influence of roads, rails, power transmission lines, substations and gas pipelines were included by creating 5 buffer rings around these features. The criteria here was that the closer a location is to these, the better it is because the cost of relevant services used by the facility would be lower. Water availability was quantified as the difference between the naturally available water in the area and allocated water. The data were collected from the Alberta Environment (Alberta Environment, 2011) and through personal communication (Kienzle, 2011). Except direct use of water in the facility, water availability has also indirect significance because sufficient availability of water is always necessary for target crop yield and biomass productions. For proper siting of biomass plants landcover types are also important. There are total 44 categories and sub-categories of covers in this data including agricultural lands, forest areas, grasslands, and other vegetation covers, non-covered areas, barren lands etc. A suitability score (0, 1-10) was given to each of these categories in relation to building a plant on the pertinent lands.

The significance of *SI* could be realized from the considered preference factors and their weights (Table 6-2). In addition to socio-environmental values, it also includes some elements which are related to cost. For example, biomass yield, proximity to facilities like roads or railways, substations, transmission lines, gas pipelines would contribute to final cost. Similarly, low availability of water or higher terrain slope could increase the total cost.

Table 6-2: Pair-wise comparison matrix and weights of preference factors with AHP

Preference factors	Biomass supply	Roads	Urban areas	Transmission & Gas lines	Sub stations	Water Availability	Land cover	Slope	Weights, w_j
Biomass supply	1	3	5	7	8	9	9	9	0.44
Roads and Rail	0.33	1	2	3	4	4	5	6	0.20
Urban areas	0.20	0.50	1	1	2	3	3	5	0.11
Transmission & Gas lines	0.14	0.33	1	1	1	2	2	3	0.07
Substations	0.13	0.25	0.50	0.83	1	1	1	2	0.05
Water Availability	0.11	0.25	0.33	0.67	1	1	1	1	0.04
Landcover	0.11	0.20	0.33	0.67	1	1	1	1	0.04
Slope	0.11	0.17	0.20	0.33	0.50	1	1	1	0.03

Road network of Alberta

For location-allocation analysis detailed data on road network is essential. The road network data of Alberta consists of segments (total 473,566) and nodes. The attribute data contains connectivity of nodes, their relative elevations, names of roads, speed limits and direction of traffic. The roads are classed as expressway, primary highway, secondary highway and local roads (Figure 6-5). Roads which are classed as trail are unsuitable for truck movements. These were excluded from the analysis. The information on turn restrictions and restrictions of truck movement on particular roads were considered during transport calculation.

6.3.2. Results and Discussions

Locations of bioenergy plants

Applying the exclusion criteria, the study area was reduced to a smaller size. Thus, the actual study area was about 62% of the total area after exclusion analysis. Computed suitability index (*SI*) values resulting from the suitability analysis of each 30 m cell of Alberta is shown in Figure 6-5(a). The white cells in this figure indicate unsuitable spaces where no biomass-based facility would be sited. Almost all locations where $SI \geq 5$ are located in the high biomass yield zones of the province. The most suitable areas ($SI = 9$) are found in the census divisions CD-11, CD-5 and CD-8. No similar sites are available in the Peace River region (CD–19) and north east region (CD–10). Table 6-5 gives a summary of these locations with their suitability indices. The highest number of sites with $SI \geq 8$ are available in the CD-5 followed by available sites in the CD-11. The majority of highly suitable sites ($SI \geq 8$) are located in CD-5 in the southern region. The north east and central regions also share comparable number of sites. The southern Alberta has also been identified as the optimal region for biorefinery development in the macro-scale conceptual study by Luk *et al.* (2010).

Due to larger weightage of biomass yield (Table 6-2), a high suitability is attributed to a high-yield areas. If biomass production is sufficient, suitable sites tend to exist near the urban fringe but beyond the restricted urban buffer and low preference zones. This is due to the fact that other facilities and preference elements (e.g., roads, power lines, gas pipelines, water etc.) co-exist near the urban areas. However, a reduced preference of zones around urban areas was created by constructing multi-buffers and by providing gradually smaller scores away up to a distance of 5 km. In general, plant sites need to be located near the biomass producing agricultural lands but should not be located on the land parcels producing the crops. Considering that a large area (> 10 ha) is required to build a facility including required storage spaces, so a barren land or an unused grass land would be a better choice than an agricultural or a forested area. Similar criteria were fulfilled by providing preference scores based on the land cover types. The suitable sites also need to be located near the transport network and preferably near major roads and junctions which would facilitate easy transportation. The highly suitable areas from this analysis (Figure 6-5) indicate that these criteria are satisfied.

In general, the plants should be built in areas with high *SI* values in order to incorporate strong socio-environmental consciousness in the process and thereby enhance social acceptability which is important for the Province of Alberta. Consequently, areas with $SI = 8$ and 9 were selected as candidates for facility locations. $SI = 10$ value was not found in the analysis. In selecting the candidate sites some additional criteria were applied: (i) the contiguous area of a site should be larger than a minimum value (e.g., 10 hactres for large plants), (ii) if multiple patches of high *SI* exist in nearby locations (distance ≤ 10 km) only one site is chosen from this locality, (iii) if large biomass producing area exists but no sites with $SI \geq 8$ is available within ~ 50 km then sites are chosen from lands with $SI = 7$. The last condition was required only for few points, e.g., in the Peace River region. Thus total selected candidate sites were 68 for location-allocation modeling which are shown in Figure 6-5(b).

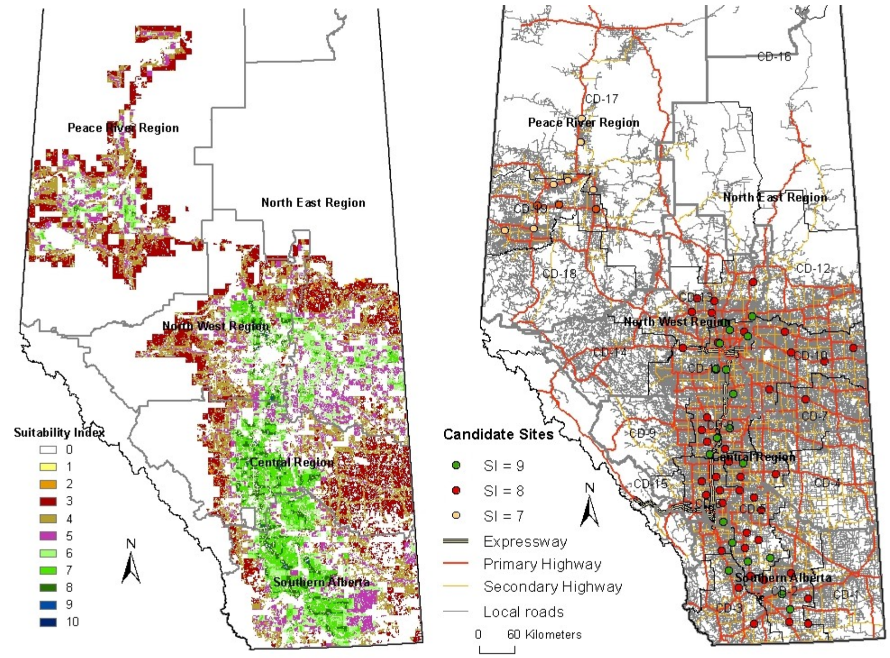


Figure 6-5: (a) Land suitability model for biomass-based facility development; (b) Candidate sites for plants and transport network in Alberta (SI=9: most suitable; SI=1: least suitable; cell size for analysis, 30m x 30m)

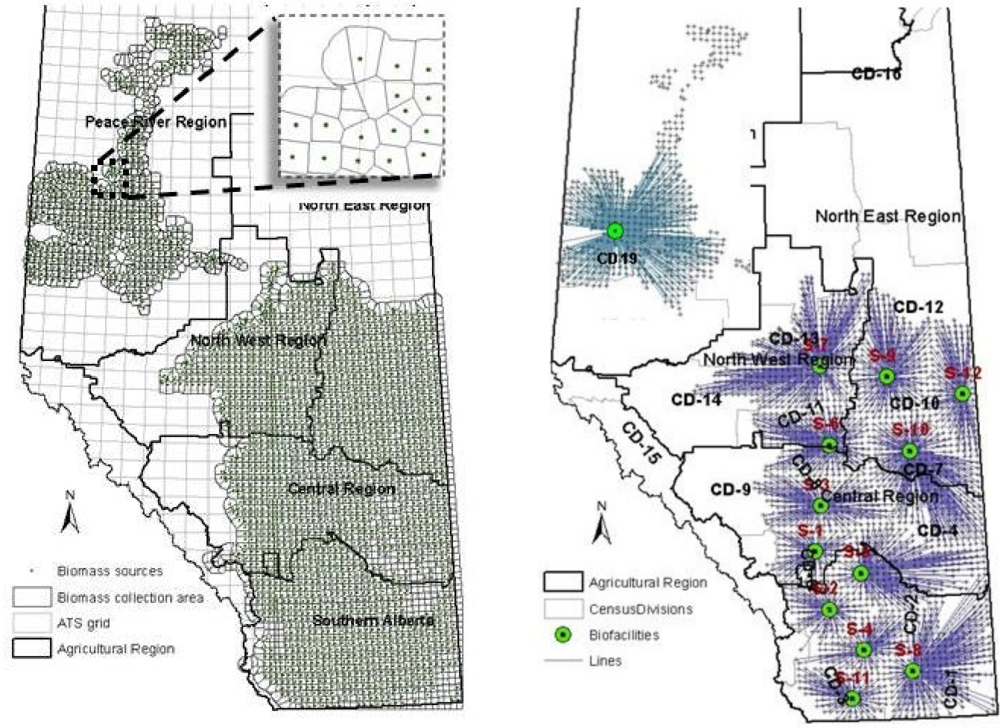
Table 6-3: Summary of candidate sites for bioenergy facility development

Site ID	Number of Sites			Census Division	Agricultural Region
	SI = 9	*SI* = 8	Total		
PS-1 to PS-8	2	6	8	CD-2	
PS-9 to PS-11	1	2	3	CD-3	S
PS-12 to PS-24	4	9	13	CD-5	
PS-25 to PS-31	1	6	7	CD-6	S & C
PS-32 to PS-38	3	4	7	CD-8	C
PS-39 to PS-42	0	4	4	CD-10	NE
PS-43 to PS-52	7	3	10	CD-11	NW
PS-53 to PS-58	5	1	6	CD-13	NW
PS-59 to PS-61	0	3	3	CD-19	PR

* S - Southern; C - Central; NE - North East; NW – North West; PR – Peace River region; CD – Census Division; *SI* – Suitability Index; PS- potential site.

From the location-allocation modeling, the weighted unit transportation costs (Eq. 6-9) were calculated by increasing number of facilities (*p* in the p-median problem 6-4). An example of selecting 12 sites in the southern regions from the candidate sites solving the p-Median Problem (PMP) using 2,194 biomass sources [Figure 6-6(a)] is shown in Figure 6-6(b). If biomass from all the sources of the southern regions are processed in a single facility, the solution yields a very high weighted average unit transportation cost (*UTC* = $93 per tonne) due to a high transportation distance of total biomass. By increasing the number of facilities, the transportation distance decreases rapidly and so do the *UTC*. It is apparent from biomass distribution and *SI* result that to cover most of the southern regions of Alberta (excluding Peace River region) biomass-based facilities need to be installed at least in three remote zones. This general observation is tested by solving the location-allocation model and the resulting optimal three sites are located in the CD-11 (NW region), CD-5 (central region) and CD-2. (Southern region). Their weighted average unit transportation cost is $49 per tonne i.e., a reduction of transportation cost by 47% compared to a single centralized facility.

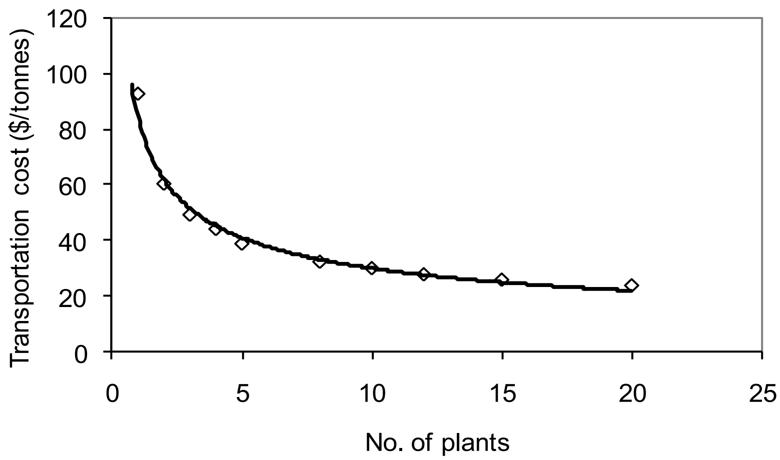
The unit transportation cost (*UTC*) reduces rapidly at the beginning followed by a slower reduction with increasing number of plants [Figure 6-7(a)]. The values of *UTC* were used to calculate total costs by applying the methodology of Section 6.2.4. Figure 6-7(b) shows the total cost variation with plant capacity. An optimum capacity (~200,000 tonne/year) can be identified from this total cost curve which corresponds to 12 plants for all the southern regions of Alberta. However, there are opportunities to adjust this number with a small cost penalty which is obvious from the total cost curve. For example, the total cost variation in the range of <1% from the optimum cost is obtained for number of plants varying from 7 – 14. At this stage, other socio-economic factors such as local resources,



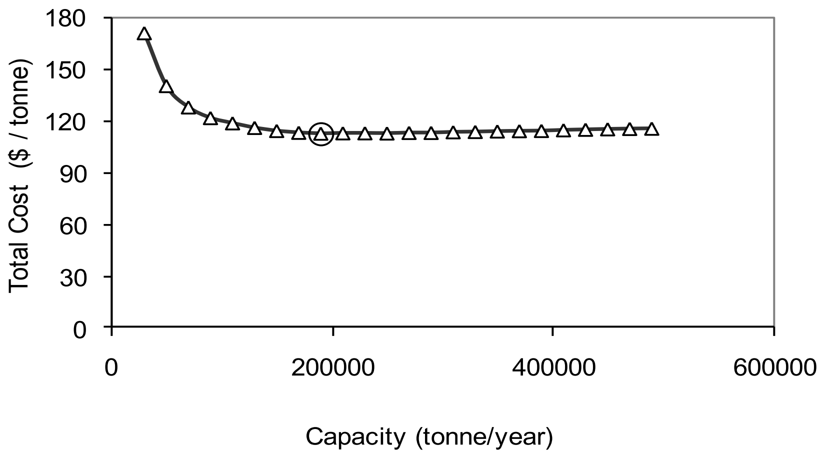
(a) (b)

Figure 6-6: (a) Discreatization of the study area into smaller polygons (Voronoi cells) around biomass collection points; (b) Optimal number and locations of probable biofacilities [empty polygons in (a) indicate very low net biomass production; straight lines in (b) showing origin-destination connectivity, actual transportation via the road network is considered in the analysis]

government support, social indicators etc. (e.g., Luk *et al.*, 2010) could come into play to influence the decision for sites and number of plants. Taking into considerations the year to year variability of biomass productions, building smaller size plants i.e., higher number of plants, is a safer approach. Thus it can be stated here that for biomass plant (e.g., for pellets) siting, absolute optimum solution is not directly necessary but the range of capacities or the range of total number of plants is critical.



(a)



(b)

Figure 6-7: (a) Variation of unit transportation cost with number of plants; (b) Total cost of pellet production with different plant capacities

If multiple biomass-based facilities are considered in a region with the objective of optimal utilization of available resources, a resource competition exists between neighboring candidates. The biomass collection area for each of the plant [Figure 6-6(b)] differs from that of a single plant. An overall cost optimization is achieved with multiple facilities even though some plants are required to source biomass from remote locations. This type of analysis for multiple biobiofacilities could be useful for large regional or provincial integrated planning where the objective could be to maximize total benefit or optimize the use of all available resources.

The analysis for the Peace River region was carried out separately because the cropping area of this region is completely separated from the cropping areas of the southern regions. From the transportation cost and total cost analysis, it was found that only one facility is feasible in this region. The position of the site is shown in Figure 6-6(b) which incurs the least transportation cost.

Variation of the optimal size of biomass plants at different locations

Without considering multiple sites, an optimum size and corresponding optimal cost can be identified for each site. Using existing road network and all biomass sources (total 2,717), the origin-destination (OD) cost matrix was developed for each combination of the minimum cost paths. Figure 6-8 shows the results of computed weighted average transportation costs at different capacities for the twelve sites [Figure 6-6 (b)]. For all cases, the average transportation cost increases gradually at decreasing rate with incremental capacity which is similar to the trend computed by the *GEN* approach. In the latter case, the transportation cost values are conservative.

As plotted in Figure 6-8, the transportation cost of S-1 [Figure 6-6(b)] is lower than other facility locations for the exhibited capacity range. This site is located near the common boundary of CD-5 and CD-6 where yield is high over a large area. So biomass feedstock could be collected in larger amount from an area encompassing smaller distances. For other locations like S-7 (in CD-13), the transportation cost is initially low due to high biomass yield in nearby (southern) areas of CD-13 and in the northern part of CD-11 but over capacity of 500 tonne

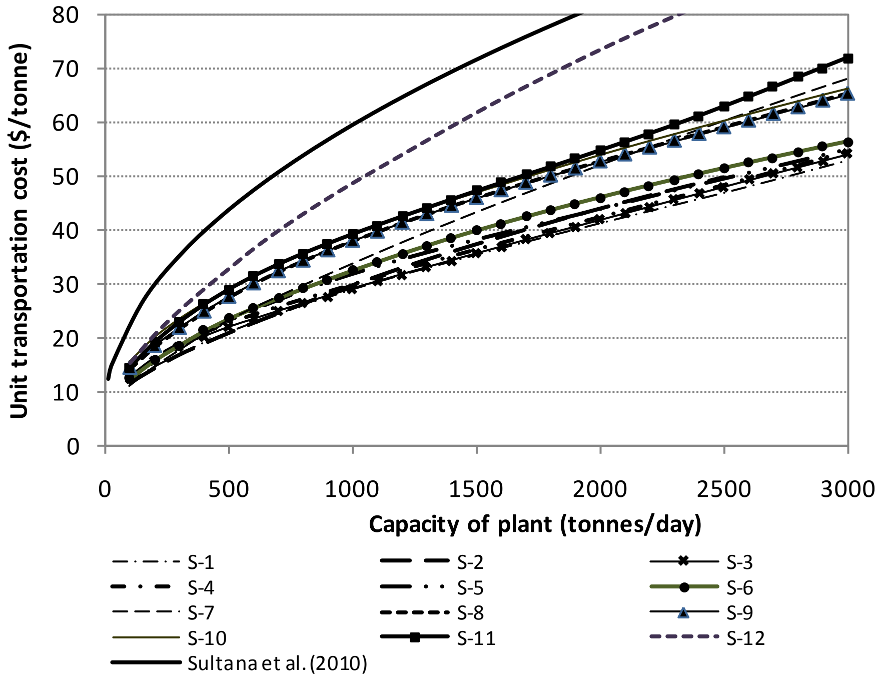


Figure 6-8: Unit transport costs of selected suitable sites for biofacility development

per year, biomass need to be collected from areas where cropping intensity is low. The transportation cost is the highest for S-12 (in CD-10) due to restricted eastern boundary which requires collecting feedstock from low-yield lands of CD-7 and CD-12.

The information on transportation costs (Figure 6-8) were used to calculate total costs and optimum sizes at 12 sites. Figure 6-9 shows selected total cost curves. In majority cases cost curves are almost flat after the minimum cost point, e.g., for sites S-1, S-5, and S-10. In this condition, the plant could be built with a minimum cost penalty for a range of capacities around the optimal point (marked by a large symbol in the figure). This feasible capacity range changes in different locations.

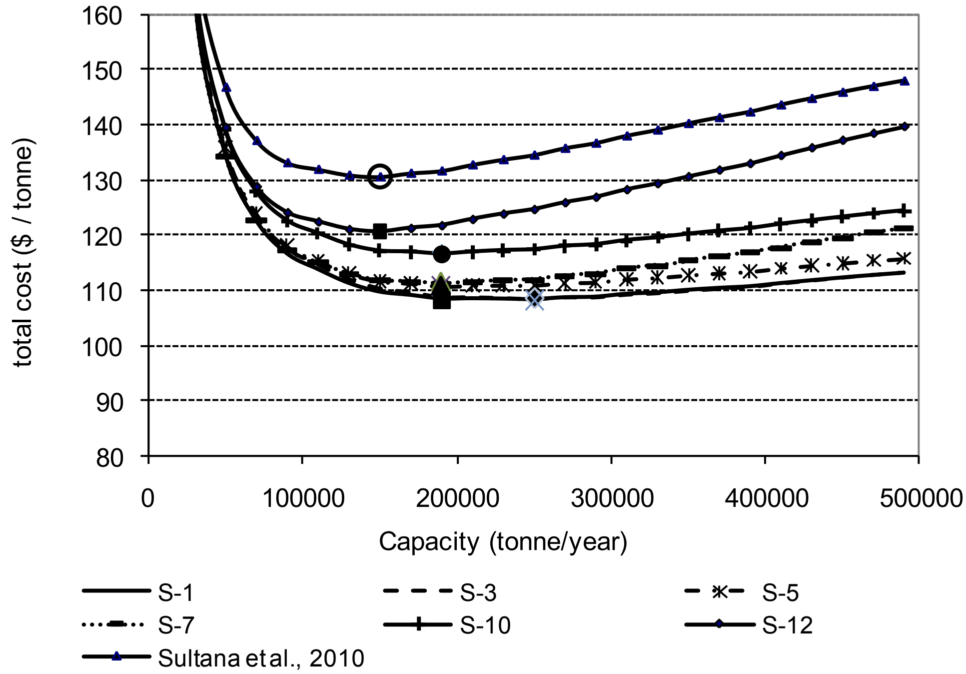


Figure 6-9: Minimum cost curve with capacity and optimum sizes

Table 6-4 shows the comparison of optimal sizes and the minimum costs from network analysis results for different locations. By using the *GEN* approach the optimum size of the pellet plant and the minimum cost of pellet production were 150,000 dry tonnes per year and $129.42 per dry tonnes, respectively. This is an average conservative estimation for the whole region (Sultana *et al.*, 2010). Considering the minimum cost path along the existing road network and the spatially varied yield of biomass i.e., using more localized information, the optimum sizes become larger in most cases. As shown in the Table 6-4, the optimal capacities could vary upto 67% from the *GEN* estimated size. Similarly, the minimum cost could be reduced by 6% to 16% from the estimated value. The difference between the cost of production at different locations differs by upto 10%. The optimal capacity and the minimum cost for the optimal site in Peace River region [Fig. 6-6 (b)] were 180,000 tonne/yr and $110 per tonne, respectively. For other locations the cost was as high as $132 per tonne. Because of the uncertainty involved in the production of biomass in different years, smaller capacities of facilities are generally preferred. Taking into consideration of this fact the *GEN* estimation appears to be a practical option for a design period of 25 – 30 years.

Table 6-4: The minimum cost, optimum size and location of pellet plants considering road network and spatially varied biomass yield.

Site	*SI*	Allocated biomass* tonne/year	Local optimal capacity tonne/year	Min total cost $/tonne	Nearest Road Intersection	County location of plant
S-1	8	176,860	250,000	108.21	Hwy 72 Hwy 791	Rocky view 44
S-2	9	185,095	190,000	108.31	Hwy23 RR263	Foothills no. 31
S-3	8	254,203	250,000	108.48	Hwy590 RR264	Red Deer
S-4	8	216,493	250,000	109.37	Hwy843 Hwy520	Lethbridge
S-5	8	201,858	190,000	110.71	TR 244 RR211	Wheatland
S-6	9	235,145	190,000	110.96	Hwy2A Hwy611	Ermineskin
S-7	9	277,113	190,000	111.08	Hwy2 TR582	Westlock
S-8	8	261,186	190,000	111.72	Hwy877 Hwy513	Taber
S-9	8	169,317	190,000	115.35	Hwy45 TR560	Twohills county no. 21
S-10	8	210,683	190,000	116.58	TR440 RR120	Flagstaff
S-11	8	106,486	190,000	116.68	Hwy 5 RR234A	Cardston
S-12	8	134,650	150,000	120.57	Hwy45 RR30	Vermilion River County no. 24

SI: Suitability index; * from LAM: Location-Allocation Model

6.4. Conclusions

A model was developed under this study to analyze suitable locations of biomass-based facilities, optimal plant sizes and number of facilities. In the case-study for Alberta, the constraints and influencing factors for siting biomass-based facilities were analyzed and a land suitability model was derived using Analytic Hierarchy Process (AHP). Multiple sites with the highest suitability index are located in the specific areas with high biomass-yield (e.g., Census Divisions 2, 5, 8, 11 and 13).

The location-allocation modeling results with actual road network show that the unit cost of transportation reduces rapidly with increase in number of facilities followed by a slower reduction. In the Alberta province 13 plants (8 – 15 plants with <1% cost penalty) could be sited in different regions.

In order to compute the optimal size of plants in suitable sites, a method has been introduced which considers the total cost including the transportation cost for the optimal routes via the actual road network. The results show that the optimal capacity and the minimum unit cost of plants varies considerably in different suitable sites. Compared to these results, the optimal size computed by the approach by Sultana et al. (2010), illustrated in Chapter 3, provides a conservative estimation. Considering the year to year variability of biomass production and uncertainty involved over the total operating period of a biomass-based facility the latter approach is suitable for design purpose. However, more a accurate estimation could be obtained by the GIS approach if detailed local data and resources are available.

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Chapter 7. Conclusions and Recommendations for Future Research

7.1. Conclusions

This research was focused on using lignocellulosic biomass resources to produce green energy resulting in both reduced GHG emissions and enhanced energy security. This study incorporated both techno-economic and emission modeling approaches. Agricultural residues available in Alberta were analyzed for biomass-based facility development. A techno-economic model was developed to estimate the optimum size and the cost of pellet production. Three different agricultural residues (i.e., wheat, barley and oat straw), which are abundant in Alberta, were considered as feedstocks for producing pellets. The life cycle assessment (LCA) of pellets was performed by considering both energy and emissions. A multi-criteria decision model was developed to rank agri-pellets with respect to other pellets from woody biomass, energy crop and poultry waste. For large-scale bioenergy plants, the delivery logistics and costs of combined use of agricultural biomass and woody biomass were analyzed. Finally, a GIS-based model was developed to determine suitable locations of biofacilities, number of facilities and optimal plant sizes using real road network and distributed biomass sources. The methodologies were applied for the Province of Alberta.

7.1.1. Multi-criteria assessment of different pellets

The multi-criteria assessment model was developed to rank different biomass pellets and it showed the importance of environmental, economical and technical factors in making decision about pellets. Five pellet alternatives, each produced from a different sustainable biomass feedstock i.e., wood, straw, switchgrass, alfalfa and poultry litter, were ranked according to thirteen criteria, using the Preference Ranking Organization Method for Enrichment and Evaluation (*PROMETHEE*). Both quantitative and qualitative criteria were considered, including environmental, technical and economic factors. Three scenarios, namely, the base case, environmental scenario and economic scenario were developed by changing the weight assigned to different criteria. In the base case scenario, equal weights were assigned to each criterion. In the economic and environmental scenarios, larger weights were given to the economic and environmental factors, respectively. Based on the results, wood pellets are the best source of energy for all scenarios followed by switchgrass, straw, poultry litter and alfalfa pellets. Only in the economic scenario, straw pellets were at higher position than switchgrass pellets. In the environmental scenario, NOx, and SOx emissions were assigned higher importance than other criteria. The ranking order of pellets in this scenario was same as in base case apart from the interchange of the ranking positions of alfalfa and poultry pellets. The order of the ranking was not modified considerably compared to the base case scenario if the values of preference threshold, indifference threshold and production cost were changed by ±10%, ±20% and ± 25%, respectively. The performance of the selected alternatives in all scenarios remained the same when qualitative criteria were omitted, showing stronger influence of quantitative counterparts. The sensitivity analysis indicated that the ranking was stable. Overall, this study proved the suitability and competence of agri-biomass to use as feedstock.

7.1.2. Optimum size and the minimum cost of agri-pellet production

A techno-economic model was developed to estimate the minimum cost of producing pellets and the optimum size of pellet plants based on agricultural biomass. Agricultural residues, including wheat, barley and oat straw, were considered at average, maximum and minimum yield cases. All costs from the harvest of straw to pellet production were calculated. The field costs were for straw acquisition, nutrient replacement and farmer premium. The expenditure of transportation and pellet plant cost including capital, maintenance, and operating costs (labor, energy and consumable items) were taken into account. The model was applied to Alberta conditions. The result shows that total cost ($ per tonne) curves are quite flat for a wide range of plant sizes over 70,000 tonnes $year^{-1}$ for the average and maximum yield cases. The reason is that the benefit in the plant's capital cost per unit output due to economy of scale is offset by the increased cost of transporting the agricultural biomass. The implication is that plants smaller than the economically optimum size can be built with minor cost penalties. The economically optimum size of plant for the average yield case is 150,000 tonnes $year^{-1}$, but agri-pellet production cost remains within 10% of the optimum value from 70,000 tonnes $year^{-1}$ to more than 500,000 tonnes $year^{-1}$. For the minimum yield scenario, above 70,000 tonnes $year^{-1}$, any increase in capacity will considerably raise the cost of production. In this case, an increase in transportation cost outweighs the reduction of capital cost per unit of output. Above 70,000 tonnes $year^{-1}$, reduction in capital cost is 5% for the minimum yield case, but the biomass must be collected from a very large area. The agri-pellet plant can be built at a capacity of 70,000 tonnes $year^{-1}$ which will result in pellet production cost of $130 $tonne^{-1}$ to $132 $tonne^{-1}$. It is evident that agri-pellets (at $7.2 GJ^{-1}) are still not economical as a fuel compared to fossil fuel (e.g., natural gas at $6.5 GJ^{-1}). Among different costs, transportation contributes the most to total cost, followed by the field cost. Transportation alone contributes almost 40% of the total cost. The main reason for the cost of transportation being high is that the biomass feedstock is geographically very dispersed due to natural low yield. Straw harvesting requires nutrient replacement, which is a significant field cost in all cases. From the sensitivity analysis it can be concluded that total cost of production of pellet is very sensitive to field cost followed by the transportation cost.

7.1.3. Energy and emissions analysis of agri-pellets

The environmental performance of production and distribution of densified form of lignocellulosic biomass (i.e., agri-residue based pellets) was assessed for Western Canada in terms of energy and GHG emissions. An energy and emissions model was developed to estimate energy consumption and emissions over the life cycle of biomass pellet from agricultural residues. This included key stages of energy use and emission during crop production and harvesting, transport of crop residue from field to the pellet plant, pellet production and transportation to the user. Results show that used energy and consequent emissions are the highest in field activities especially if emission and energy credits are given to straw in farming stage where nitrogen fertilizer is the highest contributor. Total energy used for pellet production and distribution is 0.286 MJ/MJ of pellet. The highest energy is used in farming (76%) especially for all fertilizer production, transportation and application. From this amount, about 62% energy is used in the production of nitrogen fertilizer, transportation and application. Total emission during pellet production and distribution is 30.34 g CO_{2eq}/MJ of pellet. About 70% of the total emission occurs during field activities especially in fertilizer production, transportation and application. About 92% from this amount come from activities related to nitrogen fertilizer.

Significant reductions of energy use (64%) and emissions (65%) are possible if organic fertilizer is used in farming. From the scenario analysis it is evident that using biomass as an energy source after drying, no drying at all in pellet production stage and shifting from conventional tillage to zero tillage in farming result in less than 5% reduction of the energy use and emissions. Similar effects were also observed by considering alternate mode of transport (i.e., truck and train combination) for pellet delivery. The agri-pellet has the potential to offset substantial amount (about 50 – 350 %) of GHG emission compared to other fuel sources i.e., wood pellets, natural gas and coal. The energy and emission of the production chain of agri-pellets may vary between countries but overall trend of energy used and emission compared to other fuel sources would be similar to current findings.

7.1.4. Multiple feedstock delivery for large-scale biofacilities

Biomass availability and transportation are major challenges in establishing a large-scale biofacility. A model was developed to assess the optimum delivery cost of multiple forms of lignocellulosic feedstock to biofacility and to analyze the effect of bulk density on total delivery cost of selected forms of agricultural and woody biomass. The issue of traffic congestion was also investigated. Three types of biomass i.e., corn stover, wheat straw and forest biomass were considered in different forms i.e., loose biomass, bales/bundles, chopped/chipped and pellets. It was found that the delivery cost of a combination of woody and agricultural biomass feedstock was lower than that for a single type of biomass delivery to a biorefinery. The optimal combination for delivery of lignocellulosic biomass consists of 30% of agricultural biomass in the form of bales and 70% of forest biomass in the form of wood chips. Supply of a combination of agricultural biomass in the form of bales and sawdust-based pellets is the most favorable option for delivering biomass to the power plants. When considering a single biomass feedstock for a biorefinery, the agricultural straw bales are the preferable option of transport for short transportation distances but the agricultural straw-based pellet becomes more economic as the transportation distance increases. For woody biomass, the chipped form is better for delivery to a small-capacity (e.g., below 1,000 dry tonnes/day) plant and the sawdust pellet is the most economic option for larger plants. Delivery of forest residues in the form of pellets is a more economic option than chipped form for large capacity biorefinery e.g., above 4300 dry tonnes/day. Delivery costs of agricultural biomass are higher than woody biomass due to low bulk density of the former. The anticipated traffic congestions resulting from biomass supply to a large biomass facility could be reduced significantly by increasing the density of biomass. Traffic congestion is lower for a mixed mode delivery of biomass.

7.1.5. GIS-based methodology for biofacility development

Under the GIS environment a procedural model was developed to determine bio-energy facility locations integrating environmental and economic factors. The methodology included suitability assessment for biofacility sites by constructing a suitability model with the help of geoprocessing tools and the Analytic Hierarchy Process (AHP). A new methodology was developed to compute optimal capacities of biofacilities considering spatially varied biomass yield and the real road network. The procedure was applied to the Province of Alberta.

In the first step of this study the detailed spatial distribution of biomass was assessed by using statistical data of available straw production and GIS vector data for agricultural areas and land cover. In the case-study of Alberta the constraints and factors for siting a biofacility were analyzed and the land suitability model was derived integrating selected factors. The preference factors were biomass yield, road, rails, environmentally sensitive areas, power transmission lines, gas supply pipelines and water availability. The result shows that the sites with high suitability index are located in the specific regions with high biomass yield. In Alberta, multiple sites with the highest suitability index are available in Census Divisions 2, 5, 8, 11 and 13.

The location-allocation modeling results with actual road network show that the unit cost of transportation (UTC) reduces initially rapidly with increase in number of facilities which is followed by a low rate of reduction of UTC. By constructing total cost curve an optimal number of plants could be identified. In the Province of Alberta 13 plants (8 – 15 plants with < 1% cost penalty) could be sited in different regions. The detailed analysis show that the optimal capacity and the minimum unit cost of plants may vary considerably in different suitable sites. The optimal size computed by the generic (*GEN*) approach by Sultana et al (2010) provides a conservative estimation. Considering the year to year variability of biomass production and uncertainty involved over the total operating period of a biofacility the *GEN* approach is suitable for design purpose.

The methodology developed within the GIS environment is applicable for different types of facilities using other biomass sources. In final decision making in regional scale further analysis could be performed by incorporating other criteria such as social issues, government support, community impact, etc.

7.2. Policy Implications of Results

Climate change benefits, energy security and rural economic development make the pellet an attractive option to use as a fuel source to policy makers, investors and consumers. Pellets can be integrated with existing fossil fuel infrastructure. As determined in this research, the agri-pellet has the potential to offset a significant amount of GHG by substituting the energy use from fossil fuel sources. GHG credit would be necessary to make pellets competitive with fossil fuels in Alberta. The carbon credit required to sustain agri-pellets varies with the fossil fuel price. This study estimates the cost of production of agri-pellets. If pellets are used for replacing the fossil fuel, transportation cost of agri-pellets to the consumer needs to be added to the production cost to get the total delivered cost of agri-pellets. Based on an assumed transportation distance of 200 km, the total delivery cost of pellets would be $1.71 per GJ. At this delivered cost of pellets, a carbon credit of $65 per tonne of CO_{2eq} would be required for it to be competitive with an average price of natural gas $5 per GJ. If agri-pellets are used to replace energy from coal, the carbon credit value would be $32.67 per tonne of CO_{2eq} at an average coal price of $4 per GJ. Due to the large capital investement required to build a bioenergy plant, security of fuel supply is a critical issue.

Secure long term fuel supply of agricultural residue from diverse owners is a challenge. This could be addressed through suitable policy.

7.3. Recommendation and Future work

This study focused on the techno-economic modeling, energy and emission analysis, logistics and location analysis of densified agri-biomass pellets. The methodologies were applied for the Province of Alberta. Some opportunities for future research are given below.

- Production cost of pellet is estimated for a pellet plant which operates with only one type of biomass feedstock throughout the plant life. It might be interesting to investigate the techno-economics of pellet production from multiple biomass feedstocks (i.e., blend of straw and forest residues). This will help in further increasing the scale of the pellet production plant. This topic would merit research, and experimental studies using other biomass feedstocks.

- The techno-economic, energy and emission analyses of pretreatment-based pellet production such as, torrefaction and steam explosion pellet could be performed to compare the quality of pellet with respect to cost and emission.

- Large-scale transport of agricultural biomass by rail should be studied in details. Train transport is being used in some countries for biomass transport. Economics of rail transport of biomass should be evaluated for Western Canada.

- A study on large-scale transport of torrefied pellets through pipeline would be useful as torrefied pellets are hydrophobic.

- Biomass power is not economic compared to the fossil fuel in Alberta. The security of supply of biomass feedstock is a critical issue for building a biofacility because large investment of capital is involved with low return. Government could play a role to secure a long-term fuel supply. To make biomass competitive with fossil fuel a study on policy issue could be recommended.

- The GIS methodology incorporating real transportation network (road) was presented in this study which could be further extended and applied for other regions of Canada and for finding optimal sizes of other biofuel facilities.

- A comparative analysis of pellets with other densification form of biomass and its logistics could give some more information in developing a bioeconomy.

Appendices

- **Appendix A : Discounted cash flow for pellet production**
- **Appendix B : The PROMETHEE Method**
- **Appendix C : Analytic Hierarchy Process**
- **Appendix D : Location-Allocation Solver for ArcGIS**

Appendix A.

Discounted Cash Flow Analysis for agricultural Biomass Feedstocks and Pellet Production Processes at Optimum Plant Size

The distribution of capital cost in pelleting processes is shown in Table A-1. Costs are in the US$ in the year of 2008. Discounted cash flow analysis for optimum size (150,000 dry tonnes per year) pelletization of agricultural residue is shown in Table A-1. If the construction of pellet production plant had started in the year of 2008, it would have produced pellet for a plant life of 30 years starting in the year of 2011. Therefore, costs are shown accordingly in different years of plant construction and pellet production. Pellet production process will start in the year of 2011 and will end in the year of 2040.

Table A-1: Summary of discounted cash flow of agri-pellet production at optimum size (150,000 tonne/year at average yield case)

Cost items ($1000)/year	-2	-1	0	1	2	3	4	5	6	7
Capital cost	4336.11	7588.19	9756.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Maintenance cost				393.31	401.17	409.20	417.38	425.73	434.24	442.93
Field cost				6493.69	7421.36	7885.19	8042.89	8203.75	8367.83	8535.18
Transportation cost				5982.57	7243.68	7902.20	7902.20	7902.20	7902.20	7902.20
Employee cost				1309.55	1335.74	1362.46	1389.70	1417.50	1445.85	1474.77
Energy cost				942.58	961.43	980.66	1000.27	1020.28	1040.68	1061.50
Consumable item cost				1569.94	1601.34	1633.36	1666.03	1699.35	1733.34	1768.00
Site recovery and reclamation cost				0.00	0.00	0.00	0.00	0.00	0.00	0.00
Other costs				108.40	110.57	112.78	115.04	117.34	119.69	122.08
Total cost	4336.11	7588.19	9756.25	16800.04	19075.29	20285.85	20533.52	20786.15	21043.83	21306.66
Present value (PV) of total cost at 10% IRR	5246.69	8347.01	9756.25	15272.76	15764.70	15241.06	14024.67	12906.56	11878.69	10933.69
Amount of pellet sold (tonnes)				123529	141176	150000	150000	150000	150000	150000
Price required for 10% return ($/tonnes)				157.45	160.60	163.81	167.09	170.43	173.84	177.32
Revenue required for 10% return				19450.04	22673.19	24572.07	25063.51	25564.78	26076.08	26597.60
PV of revenue at 10% return				17681.86	18738.17	18461.36	17118.72	15873.72	14719.27	13648.77
Net revenue	4336.11	7588.19	9756.25	2650.00	3597.90	4286.22	4529.99	4778.63	5032.25	5290.94

Table A-1: Summary of discounted cash flow of agri-pellet production at optimum size (150,000 tonne/year at average yield case) (cont.)

Cost items ($1000)/year	8	9	10	11	12	13	14	15	16	17
Capital cost	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Maint. cost	451.79	460.82	470.04	479.44	489.03	498.81	508.79	518.96	529.34	539.93
Field cost	8705.89	8880.00	9057.60	9238.76	9423.53	9612.00	9804.24	10000.33	10200.33	10404.34
Transt. cost	7902.20	7902.20	7902.20	7902.20	7902.20	7902.20	7902.20	7902.20	7902.20	7902.20
Employee cost	1504.26	1534.35	1565.03	1596.33	1628.26	1660.83	1694.04	1727.92	1762.48	1797.73
Energy cost	1082.73	1104.38	1126.47	1149.00	1171.98	1195.42	1219.33	1243.71	1268.59	1293.96
Consumable item cost	1803.36	1839.43	1876.22	1913.75	1952.02	1991.06	2030.88	2071.50	2112.93	2155.19
Site recovery & reclamation	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Other costs	124.52	127.01	129.55	132.14	134.79	137.48	140.23	143.04	145.90	148.81
Total cost	21574.75	21848.20	22127.12	22411.62	22701.81	22997.80	23299.71	23607.66	23921.77	24242.16
Present value (PV) of total cost at 10% IRR	10064.78	9265.77	8530.96	7855.14	7233.50	6661.64	6135.54	5651.49	5206.07	4796.18
Amount of pellet sold (tonnes)	150000	150000	150000	150000	150000	150000	150000	150000	150000	150000
Price required for 10% return ($/tonnes)	180.86	184.48	188.17	191.93	195.77	199.69	203.68	207.76	211.91	216.15
Revenue required for 10% return	27129.55	27672.14	28225.59	28790.10	29365.90	29953.22	30552.28	31163.33	31786.59	32422.33
PV of revenue at 10% return	12656.14	11735.69	10882.18	10090.75	9356.88	8676.38	8045.37	7460.25	6917.69	6414.58
Net revenue	5554.80	5823.94	6098.46	6378.48	6664.09	6955.41	7252.57	7555.66	7864.82	8180.16

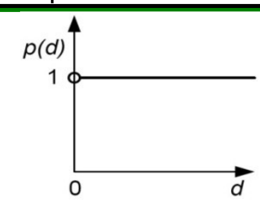
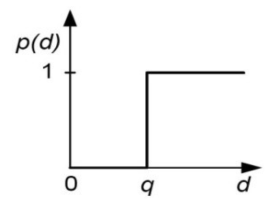
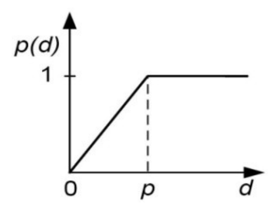
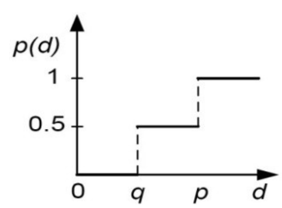
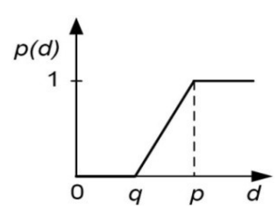
Table A-1: Summary of discounted cash flow of agri-pellet production at optimum size (150,000 tonne/year at average yield case) (cont.)

Cost items ($1000)/yr	18	19	20	21	22	23	24	25	26	27	28	29	30
Capital cost	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Maintenance cost	550.73	561.74	572.98	584.44	596.12	608.05	620.21	632.61	645.26	658.17	671.33	684.76	698.45
Field cost	10612.43	10824.68	11041.17	11261.99	11487.23	11716.98	11951.32	12190.34	12434.15	12682.83	12936.49	13195.22	13459.12
Transportation cost	7902.20	7902.20	7902.20	7902.20	7902.20	7902.20	7902.20	7902.20	7902.20	7902.20	7902.20	7902.20	7902.20
Employee cost	1833.69	1870.36	1907.77	1945.92	1984.84	2024.54	2065.03	2106.33	2148.46	2191.42	2235.25	2279.96	2325.56
Energy cost	1319.84	1346.24	1373.16	1400.62	1428.64	1457.21	1486.35	1516.08	1546.40	1577.33	1608.88	1641.05	1673.88
Consumable item cost	2198.29	2242.26	2287.10	2332.84	2379.50	2427.09	2475.63	2525.15	2575.65	2627.16	2679.71	2733.30	2787.97
Site recovery and reclamation	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1734.44
Other costs	151.79	154.83	157.92	161.08	164.30	167.59	170.94	174.36	177.85	181.40	185.03	188.73	192.51
Total cost	24568.96	24902.30	25242.30	25589.10	25942.84	26303.65	26671.68	27047.07	27429.97	27820.53	28218.89	28625.23	29039.69
Present value (PV) of total cost at 10% IRR	4418.94	4071.72	3752.11	3457.87	3186.97	2937.54	2707.86	2496.34	2301.52	2122.09	1956.79	1804.52	1664.22
Amount of pellet sold (tonnes)	150000	150000	150000	150000	150000	150000	150000	150000	150000	150000	150000	150000	150000
Price required for 10% return ($/tonnes)	220.47	224.88	229.38	233.97	238.65	243.42	248.29	253.25	258.32	263.48	268.75	274.13	279.61
Revenue required for 10% return	33070.77	33732.19	34406.83	35094.97	35796.87	36512.80	37243.06	37987.92	38747.68	39522.63	40313.09	41119.35	41941.73
PV of revenue at 10% return	5948.07	5515.48	5114.36	4742.40	4397.50	4077.68	3781.12	3506.13	3251.14	3014.69	2795.44	2592.14	2403.62
Net revenue	8501.81	8829.89	9164.53	9505.86	9854.03	10209.15	10571.38	10940.85	11317.71	11702.11	12094.19	12494.12	12902.05

Appendix B.

The PROMETHEE Method

Table B-1: Common preference functions

<table>
<tr><th>Preference function</th><th>Shape</th></tr>
<tr><td>Usual</td><td>
</td></tr>
<tr><td>U Shape</td><td>
</td></tr>
<tr><td>V Shape</td><td>
</td></tr>
<tr><td>Level</td><td>
</td></tr>
<tr><td>Linear</td><td>
</td></tr>
</table>

$* \; d = f(a) - f(b)$

PROMETHEE I Partial Ranking

PROMETHEE I provides partial ranking of alternatives. In PROMETHEE I, alternative *a* is preferred to alternative *b*, if alternative *a* has a greater leaving flow than that of alternative *b* and a smaller entering flow than that of alternative *b*.

$$a \text{ is preferred over } b \text{ if } \begin{cases} \varphi^+(a) \rangle \varphi^+(b) \text{ and } \varphi^-(a) \langle \varphi^-(b), \text{or} \\ \varphi^+(a) \rangle \varphi^+(b) \text{ and } \varphi^-(a) = \varphi^-(b), \text{or} \\ \varphi^+(a) = \varphi^+(b) \text{ and } \varphi^-(a) \langle \varphi^-(b). \end{cases} \quad \text{(B-1)}$$

Indifference and incomparability situation can be addressed through PROMETHEE I which allows partial ranking of alternatives. In the indifference situation, two alternatives *a* and *b* has the same leaving and entering flow.

$$a \text{ is indifferent to } b \text{ if } \varphi^+(a) = \varphi^+(b) \text{ and } \varphi^-(a) = \varphi^-(b) \quad \text{(B-2)}$$

Incomparable situation of two alternatives arises if alternative *a* is better than alternative *b* in terms of leaving flow, while reverse situation arise for entering flows.

$$a \text{ is incomparable to } b \text{ if } \begin{cases} \varphi^+(a) \rangle \varphi^+(b) \text{ and } \varphi^-(a) \rangle \varphi^-(b), \text{or} \\ \varphi^+(a) \langle \varphi^+(b) \text{ and } \varphi^-(a) \langle \varphi^-(b). \end{cases} \quad \text{(B-3)}$$

In comparable cases PROMETHEE I do not decide which alternative is best. The analysis of incomparability often helps in decision making where decision makers intervention is needed.

PROMETHEE II Complete Ranking

PROMETHEE II provides a complete ranking of alternatives. PROMETHEE II ranking is based on net flows, $\varphi(a)$. In this method, ranking increases with flow i.e., the greater the value of net flow, the higher the ranking.

$$\begin{cases} a \text{ is preferred over } b \text{ if } \varphi(a) > \varphi(b). \\ a \text{ is indifferent to } b \text{ if } \varphi(a) = \varphi(b). \end{cases} \quad \text{(B-4)}$$

All alternatives are comparable in PROMETHEE II. Main disadvantage of PROMETHEE II is some information may get lost in the process. PROMETHEE I and PROMETHEE II, both analysis need to be considered by the decision maker to take final decision.

Appendix C.

Analytic Hierarchy Process (AHP)

AHP evaluates the relative importance of a set of criteria in a multi-criteria decision making (Saaty 1970). Both qualitative and quantitative criteria can be combined with this method to determine useful weightage information which provide a mechanism of decision making.

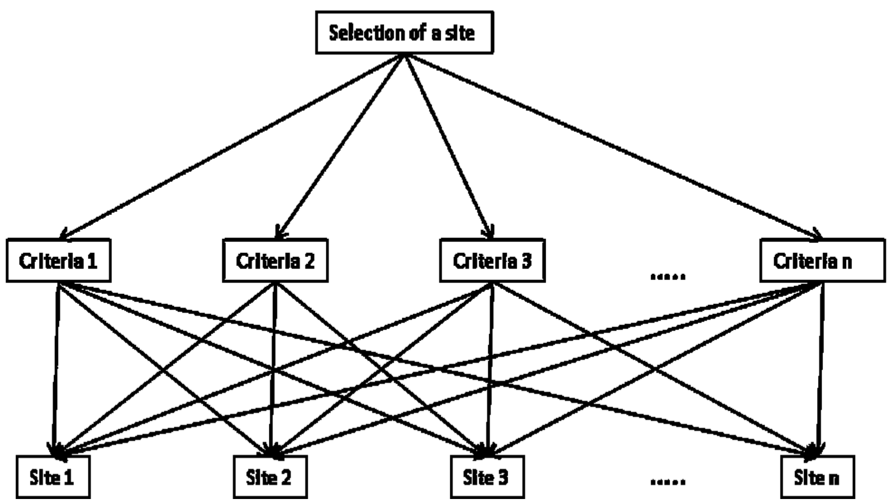


Figure C-1: Decision problem as a hierarchy

In the first step of the AHP, a model is structured in hierarchy using objective, criteria, decision alternatives. After defining the hierarchy, all alternatives and criteria are compared one to one in order to determine the relative importance of the criteria within each level. The pair-wise comparison is performed according to their level of influence and based on the specified criteria in the higher level. It starts from the second level and finishes to the alternative levels at the bottom. A standardized comparison scale is used to find the relative importance of the criteria exhibit in Table C-1.

Table C-1: Scale of relative importance (Saaty, 1977)

Definition	Relative importance	Explanation
Equal importance	1	Two activities contribute equally to the objective
Moderately more important	3	Experience and judgment slightly favor one activity over another
Strongly more important	5	Experience and judgments strongly favor one activity over another
Very strongly more important	7	An activity is strongly favored and its dominance is demonstrated in practice
Extremely more important	9	The evidence favoring one activity over another is of the highest possible order of affirmation
Intermediate values	2,4,6,8	When compromise is needed between the two adjacent judgment
Reciprocal of above	If activity i has one of the above non-zero numbers assigned to its when compared with activity j , then j has the reciprocal value when compared with i	

The result of the pair-wise comparison on n criteria can be summarized in an n x n evaluation matrix **A** in which every element $a_{i,j}$ (i,j = 1, 2, 3……n) is the intensity of relative importance between criteria i and criteria j, such that $a_{i,j} = 1$, $a_{i,j} = 1/a_{j,I}$ and $a_{i,j} \neq 0$.

$$A = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix} \quad a_{ii} = 1, a_{ji} = {}^{1}/_{a_{ij}}, \; a_{ij} \neq 0 \qquad (C-1)$$

The weight vector w_j can be computed as follows:

1. Let a_{ij} means the intensity of relative importance between criteria and criteria and $a_{ji} = \frac{1}{a_{ij}}$
2. Compute the each column of **A** where $A_j = 1/n \sum_{i=1}^{n} a_{i,j}$
3. Normalize matrix **A** by dividing each element a_{ij} in **A** by A_j, $a'_{.,j} = \imath_{i,j} / A_j$
4. Average across row to get relative weight, w_i i.e.,

   $w_i = 1/n \sum_{j=1}^{n} a'_{i,j}$

   where is the total number of criteria.

To check the consistency of the pair-wise comparison and credibility of weights the consistency ratio (CR) is calculated as:

1. Calculate the maximum eigen value λ_{max} of matrix
2. Compute the consistency index (CI) for the matrix

$$CI = \frac{\lambda_{,max} - n}{n - 1}$$

3. Consistency ratio can be computer through following formula

$$CR = \frac{CI}{RI} \qquad \text{(C-2)}$$

Where CI is the the consistency index for the matrix; RI is the the random index for different n is available in Satty and Thomas (2000). Table C-2 shows the value of the Random Index (RI) for matrices of order 1 to 10 obtained using sample size of 500 (Saaty, 2000). The smaller (< 1) the value of CR the better is the judgments of decision makers indicating the pair-wise comparison matrix and the computed weights are reasonable. Larger values require the decision maker to reduce inconsistencies by revising judgment.

Table C-2: Average random Index (*RI*) at different matrix size (Saaty, 2000)

n	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
RI	**0**	**0**	**0.52**	**0.89**	**1.11**	**1.25**	**1.35**	**1.4**	**1.45**	**1.49**

Appendix D.

Location-Allocation Solver in ArcGIS

The location-allocation solver in the ArcGIS starts by generating an origin-destination matrix of the shortest path cost using Dijkstra's Algorithm between all facilities and sources in the network (ESRI, 2011). The detail of the Dijkstra's algorithm is available in Daskin (1995). By using Hillman editing (Densham and Rushton, 1991) an edited version of the cost matrix is constructed. Then the location–allocation solver generates a set of semi-randomized solutions. A vertex substitutution heuristic (Teitz and Bart, 1968) is applied to refine these and to obtain a group of good solutions. The best solution is found by using a metaheuristic resulting in a global near-optimal solution (ESRI, 2011).

The semi-randomized solution is generated by the Greedy Randomized Adaptive Search Procedure (GRASP) metaheuristic (e.g., Gendreau and Potvin, 2010). Following ESRI (*personal communication*), a simplistic implementation of GRASP would create a semi-randomized starting solution set in the following manner:

1. Create an empty list of facilities in the solution set.
2. For each facility not in the solution set determine how advantageous it is to add this facility to the current list of facilities in the solution set.
3. Sort this list of facilities from the most advantageous to the least advantageous.
4. Randomly pick a facility from the top X percent of facilities, add this facility to the list of facilities in the solution set. (X is determined by how many times we have called the GRASP routine, see below)
5. If our solution set is not full go to step 2.
6. Use this semi randomized solution in a follow on heuristic.

There are three distinct steps in solving a location-allocation problem. A pseudo code overview of the algorithm is:

1. Create an empty list of superior solutions.
2. For i = 0; i < 128; i++
    a. Generate an initial solution set using GRASP
        i. If i = 0 then X = 0 (GRASP construction is perfectly greedy, there is no randomization)
        ii. Else If i < 32 then X = 10% (choose randomly from the best 10% of facilities to add)
        iii. Else If i < 64 then X = 20% (choose randomly from the best 20% of facilities to add)
        iv. Else If i < 96 then X = 30% (choose randomly from the best 30% of facilities to add)
        v. Else If i < 128 then X = 40% (choose randomly from the best 40% of facilities to add)
    b. Perform Teitz and Bart greedy swap heuristic on the initial solution until we reach a local optima (also called a "vertex substitution heuristic"). Details of the vertex substitution method is available in Church and Sorensen (1994).
    If i = 0 then add this solution to the list of superior solutions and go to step
    c. Find a solution from a previous iteration that is unlike the solution from step b and apply the path relinking metaheuristic. Details of the path relinking algorithm is available in Gendreau and Potvin (2010).
    d. If the result of step c is good enough, add this solution to a list of superior solutions.
3. Find the best solution in the list of superior solutions and return it as the result.

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