Development of Optimum Locations and Scales for an Integrated Multi-feedstock Waste-to-value-added Facility through Geographical Information System Modelling

by

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Absract

Biomass and municipal solid waste (MSW) management have received significant attention globally of late. This study is focused on the utilization of lignocellulosic biomass (agricultural and forest residue) and MSW. The potentials of lignocellulosic biomass and MSW are used to determine the geographical point source locations for the distributed biomass, and optimal locations for waste-to-value-added (W2VA) facilities in a jurisdiction. A case study for the province of Alberta for the production of valuable products is conducted. Precise estimates of the annual availability of agricultural residue, forest residue, and MSW in Alberta show the potential for 4.1 million oven dry tonnes (odt), 2.1 million odt, and 4.3 million wet tonnes, respectively, of these waste sources. The initial step in optimally locating a W2VA facility is identifying feedstock collection points. MSW is transferred from communities to already established transfer stations (TSs) from where it is further distributed for either landfilling or recycling. On the other hand, agricultural and forest residue do not have dedicated TSs, therefore, this study for the first time developed geographic information system (GIS)-based suitability model to identify point source locations, defined as biomass collection points (BCPs), with geographical latitude and longitude for collecting biomass. The developed model also estimated the annual feedstock potential at identified BCPs and MSW TSs. In case study, the developed framework was used to perform a land suitability analysis, which is defined as a GIS-based process to determine the suitability of a given area for a particular use. Suitability analysis uses various geographical constraints chosen based on economic, environmental, and social factors to identify the most suitable area whereas network analysis identifies the most optimal locations out of various candidate sites to set up a W2VA facility. In this study, one W2VA facility was identified in Alberta's Industrial Heartland (AIH) and 10 across the province of Alberta. This study also investigates the integration of three types of feedstock – agricultural residue, forest residue, and MSW – along with waste heat in the AIH W2VA facility.

A techno-economic model, the **FUN**damental E**N**gineering Princip**lE**s-based model for Estimation of **Cost** of Energy from **Biomass and Municipal Solid Waste** (FUNNEL-Cost-Bio-MSW), was then used to assess the technical and economical parameters of converting lignocellulosic biomass and MSW into electricity via gasification technology. The availability of biomass and MSW at corresponding collection points, as well as the transportation distances to the W2VA facility, are the key inputs to the model. A particular case of the AIH was considered to assess the technical and economic feasibility of a proposed 199 MW gasification-based W2VA facility. Two scenarios were defined based on whether waste heat is used from one source or more than one source. Scenario I considered W2VA facility next to a single waste heat source whereas Scenario II identifies optimal location of W2VA facility between two waste heat sources in order to address the case where if the waste heat from one source is not sufficient for drying. A techno-economic assessment of Scenario I and II estimated internal rate of returns (IRRs) of 11.8% and 8.1%, respectively. The cost of generating electricity was estimated to be $21.09/MWh and $33.23/MWh for Scenario I and II, respectively. The model also assessed the sensitivities of the calculated results to the key technical and economic parameters.

This study can be used as a framework by municipalities/communities in any jurisdiction across the world to geographically locate biomass source/collection points along with their annual capacity, the corresponding optimal location for siting a W2VA facility, and the technical and economic feasibility of setting up a W2VA facility.

Preface

This thesis is an original work by Prashant Patel under the supervision of Dr. Amit Kumar.

Chapter 2 of this thesis, titled "The development of a GIS-based framework to locate biomass and municipal solid waste collection points along with waste conversion facility" by Prashant Patel, Mahdi Vaezi, and Amit Kumar will be submitted to the journal *American Society of Agricultural and Biological Engineers.*

Chapter 3 of this thesis, titled "The techno-economic assessment of a biomass-MSW integrated waste-to-value-added facility" by Prashant Patel, Mahdi Vaezi, and Amit Kumar will be submitted to a peer-reviewed journal.

I was responsible for the data collection, data analysis, model development, and manuscript composition. Mahdi Vaezi reviewed the developed models, assessed the results, provided feedback on research structure, and corrected journal papers. Amit Kumar was the supervisory author and provided supervision on concept formulation, models and results validation, and manuscript edits.

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List of Abbreviations

AAC	Annual allowable cut
AB	Alberta
AHP	Analytic hierarchy process
AIH	Alberta's Industrial Heartland
BCP	Biomass collection point
BSP	Biomass source point
CAD	Canadian dollar
CR	Consistency ratio
DA	Dissemination area
ESA	Environment sensitive area
FMA	Forest management agreement
FMU	Forest management unit
FUNNEL-Cost-Bio-MSW	FUNdamental ENgineering PrinciplEs-based model for Estimation of Cost of Energy from Biomass and Municipal Solid Waste
GHG	Greenhouse gas
GIS	Geographic information system
ha	Hectare
IRR	Internal rates of return
MC	Moisture content
MSW	Municipal solid waste
ODT	Oven dry tonnes
SHS	Spatial harvest sequence
TS	Transfer station
W2VA	Waste-to-value-added

Chapter 1: Introduction

1.1 Background

Fossil-based fuels provide the major portion of the world's primary and secondary energy (Weldemichael and Assefa, 2016). With the rise in both population and living standard, energy demand has increased, and with it, fossil fuel consumption. Fossil fuels are a significant source of greenhouse gas (GHG) emissions and associated environmental and health-related concerns are also rising (Campbell-Lendrum and Corvalán, 2007a). Utilization of lignocellulosic biomass and municipal solid waste (MSW) for production of fuels along with industrial waste heat can help in reduction of fossil fuel use. However traditional approaches to lignocellulosic biomass and MSW handling, such as burning lignocellulosic biomass in an open field (Kumar et al., 2003; MacDonald, 2009b; Mani et al., 2006) and dumping MSW into landfills (Khan, 2015), present a significant environmental challenge (Ojha et al., 2007). MSW burning sends emissions directly to the environment, and leachate formation in MSW landfills releases GHGs to the atmosphere. These concerns can be addressed by using lignocellulosic biomass and MSW for energy, an approach that not only displaces fossil fuels but also reduces landfilling- and burning-related emissions (Schmer et al., 2014; Thornley et al., 2015; Weldemichael and Assefa, 2016; Zhang, 2016).

As of 2016, the global GHG emissions from all the sector was 49.3 gigatonnes of CO_2-equivalent out of which methane contributes total of 9.2 Gt CO_2-eq. The main source of CH4 emissions are cattle, crop cultivation, and waste disposal (Olivier et al., 2017). Canada's GHG emissions as of 2016 was 704 megatonnes of CO_2-eq out of which agriculture and waste sector contributed 60 and 19 megatonnes of CO_2-eq, respectively (Government of Canada, 2018). Under the waste sector, solid waste dispotal contributed 84.2% whereas the rest was through activities involving biological treatment of solid waste, wastewater treatment, and incineration and open burning. The province of Alberta is the highest contributor to Canada's annual GHG emissions. Alberta's GHG emissions in 2016 were 262.9 Mt CO_2-eq and contributed 37.3% to Canada's total GHG emissions (Government of Canada, 2018). The reason behind the high GHG emissions is Alberta's dependency on coal and gas for energy purposes. Of the total emissions, the agriculture, forestry, and MSW sectors accounted for 8.8% and the electricity sector for 17% (Government of Canada, 2017).

Lignocellulosic biomass and MSW can be used to produce valuable products (Bradburn, 2014; Enerkem, 2017). Of the provinces, Alberta has the fourth highest biomass and MSW availability and therefore huge potential to produce valuable products from these wastes (Weldemichael and Assefa, 2016). Also, there is significant amount of waste heat facilities due to its large oil and gas industries. The first step towards understanding the untapped potential of biomass, MSW and waste heat, and locating a waste-to-value-added (W2VA) facility, is to obtain an accurate estimate of biomass, MSW and waste heat availability, along with their geographical locations.

Various studies have estimated the agricultural residue (Jacobs' Consultancy, 2013; Mani et al., 2006; Weldemichael and Assefa, 2016), forest residue (Bradley, 2007, 2010; Dymond et al., 2010; Friesen, 2016; Jacobs' Consultancy, 2013; Kumar et al., 2003; Smith and Web, 2015; Weldemichael and Assefa, 2016), and MSW potential (Jacobs' Consultancy, 2013; Khan et al., 2018; Weldemichael and Assefa, 2016) in both Alberta and Canada. Several disparate methods have been used to estimate this potential, with wide discrepancies in results. For example, Khan et al. (2018) used landfill data to estimate 4.1 million wet tonnes for year 2010, Jacobs' Consultancy (2013) used population data and per capita disposal rate to estimate 4.0 million wet tonnes for year 2008, and Weldemichael and Assefa (2016) used future waste diversion percentage predictions to estimate surplus MSW availability of 5.0 million wet tonnes for year 2014. Weldemichael and Assefa (2016) assumed percentages for various losses to estimate surplus agricultural residue of 7.5 million over dry tonnes (odt) for year 2014, and Jacobs' Consultancy (2013) used the straw-to-grain ratio along with several losses to estimate 6.2 million odt for the year 2010. Dymond et al. (2010) used natural disturbances to estimate forest residue availability of 5.6 million odt; others (Jacobs' Consultancy, 2013; Kumar et al., 2003; Weldemichael and Assefa, 2016) used natural harvesting and residue yield to estimate the potential in the range of 0.24 to 4.3 million odt per year. Detailed estimate on MSW, agricultural residue, and forest residue is provided in Chapter 2.

There is no data on biomass and MSW potential after 2012 for the province of Alberta. This study uses census data from 2016 along with the per capita disposal rate to estimate MSW potential, crop production data averages for 2006-15 along with the straw-to-grain ratio less various associated losses to estimate the agricultural residue, and actual forest harvesting data for 2011-15 along with residue yield to estimate annual forest residue availability. The waste heat potential was considered from a study done by Alberta's Industrial Heartland Association (AIHA) on surplus waste heat availability in Alberta's Industrial Heartland (AIH). Detailed methodology and estimates are provided in Chapter 2.

A few studies have used geographic information system (GIS)-based assessment to identify optimal locations for siting a W2VA facility (Khan et al., 2018; Sultana and Kumar, 2012; Tavares et al., 2011) and to calculate biomass and MSW potential, but none identified biomass collection points (BCPs) for the distributed biomass. This study is uses a GIS-based assessment to find optimal geographical locations of BCPs by longitude and latitude for distributed biomass, as well as corresponding biomass availability at each BCP which is a new methdology. For MSW, Khan et al. (2018) used landfill data to reverse-engineer the MSW potential at corresponding transfer stations (TSs), while we used census data, along with variations across the province, and per capita disposal rates to calculate MSW availability at TSs.

A few authors have studied the use of individual feedstocks, mainly MSW (Khan et al., 2016; Rizwan et al., 2018; Ruth, 1998; Weldemichael and Assefa, 2016), agricultural residue (Helwig et al., 2002b; Kumar et al., 2003; Sultana et al., 2010; Urošević and Gvozdenac-Urošević, 2012), and forest residue (Demirbaş, 2001; Kumar et al., 2003; Sultana et al., 2010; Zamora-Cristales and Sessions, 2016), in a W2VA facility to produce valuable products using various waste conversion technologies, but none considered more than one type of feedstock in a single facility. This study is one-of-its-kind on the integrated use of more than one type of feedstock – lignocellulosic biomass (agricultural and forest residue) and MSW – in a single W2VA facility to produce electricity via gasification technology. This study also includes, in a specific case, the use of waste heat to dry the biodegradable content of MSW on a commercial scale. In addition, we examined geographically located BCPs along with real road transportation distances in a techno-economic setting.

This study makes estimates on annual biomass and MSW potential using the most recent government data and reports. The data estimates are correct to the year 2016. This study also developed a GIS-based framework to identify and locate BCPs for the distributed biomass, use existing TSs as MSW collection points, and estimate corresponding annual biomass and MSW availability at collection points. A techno-economic model, **FUN**damental E**N**gineering Principl**E**s-based model for Estimation of **Cost** of Energy from **Biomass and Municipal Solid Waste** (FUNNEL-Cost-Bio-MSW), was developed that considered technical and economical parameters to assess the techno-economic feasibility of a W2VA facility in terms of internal rates of return (IRR) and the cost of generating electricity. Further, in a case study, the developed framework was used to perform a land suitability analysis using set of economic, environmental, and social factors to identify a single, most optimal location of a W2VA facility in AIH and ten across the province of Alberta. The ten W2VA facilities across the province process biomass and MSW as feedstock to produce electricity via gasification technology, whereas the single AIH facility would use biomass and MSW along with 99 MW of waste heat, as reported by the CMC Research Institutes and others (2014), to dry the biodegradable content of MSW.

1.2 Research Objectives

The overall objectives of this study are to develop a framework to assess the optimal locations of the waste-to-value-added facility using lignocellulosic biomass, MSW, and waste heat including techno-economic assessment. The following are the specific objectives:

- To precisely estimate the surplus biomass and MSW potential available annually in the province of Alberta;
- To develop a GIS-based framework to identify the geographical locations of biomass collection points with longitude and latitude for distributed fields, as well as estimate their corresponding annual biomass availability along with MSW availability at transfer stations;
- To study the feasibility of integrating more than one type of waste in a single W2VA facility;
- To develop a techno-economic model to assess the feasibility of a W2VA facility generating electricity;
- To assess the sensitivities of various input variables on the output of the techno-economic assessment;
- To identify a single, most optimal location for siting a W2VA facility in the Alberta Industrial Heartland (AIH) and 10 across the province of Alberta.

This study can be used as a framework to assess MSW and biomass availability along with their geographical locations and to identify the technical and economic feasibility of a W2VA facility. This study can help communities/municipalities to make waste management-related policies, decisions and investments.

1.3 Research Approach

1.3.1 Feedstock Quantification

Feedstock quantification involves estimating the amount of surplus feedstock sustainably available for energy purposes. Three types of feedstock were considered: MSW, agricultural residue, and forest residue. Data from various government sources, such as Statistics Canada and Natural Resources Canada (Government of Alberta, 2016a; National Forest Inventory, 2016; Statistics Canada, 2014b, 2016), were used and analyzed to estimate availability. The potential MSW available was calculated by multiplying Alberta's census population figures for the year 2016 (Statistics Canada, 2016) and Statistics Canada's annual per capita waste disposal rates (Statistics Canada, 2014b). Agricultural residue potential was estimated using the 10-year (2006-2015) average crop production data (Government of Canada, 2016) and straw-to-grain ratios (Li et al., 2012b; Sultana et al., 2010), less losses associated with soil conservation, animal bedding and feeding, harvest machine efficiency, transportation, and moisture content. Forest residue was calculated using the 5-year (2011-2015) average actual harvesting area (National Forest Inventory, 2016) and residue yield of 24.7 odt/ha (Kumar et al., 2003).

1.3.2 Location of BCPs and W2VA Facilities

A GIS-based model was developed to identify feedstock collection point locations and estimate the annual availability of feedstock. The first part of this model uses land suitability analysis to identify the most suitable areas using set of geographical factors chosen based on social, economic, and environmental criteria (Khan et al., 2018; Sultana and Kumar, 2012). The second part involves network analysis, which chooses the most optimal location out of pool of candidate sites for a W2VA facility and connects them with the real road network such that transportation distances are minimized. With respect to MSW collection, there are 285 existing transfer stations across Alberta (Khan et al., 2018). Their annual capacity was calculated using the Thiessen polygon approach along with MSW density maps (Khan et al., 2018). Since agricultural and forest residue fields do not have collection points (such as transfer stations), BSPs and BCPs were identified using the GIS-based model. Geographical data were taken from multiple sources, such as AltaLIS (AltaLIS, 2017), Natural Resources Canada (Government of Canada et al., 2017), Statistics Canada (Statistics Canada, 2017), Agriculture and Agri-food Canada (Government of Canada, 2016), etc. The same GIS model was later used to identify the most optimal location of a W2VA facility in the AIH as well as 10 across the province of Alberta. Further details on the methodology and framework is provided in Chapter 2.

1.3.3 Techno-economic Assessment

A techno-economic model, named **FUN**damental E**N**gineering Princip**lE**s-based model for Estimation of **Cost** of Energy from **Biomass and Municipal Solid Waste** (FUNNEL-Cost-Bio-waste), was developed to assess the technical and economic feasibility of using several different feedstocks in a single gasification-based W2VA facility to generate electricity. The model considered MSW, agricultural residue, forest residue, and waste heat as feedstock inputs. Data on various cost parameters, such as capital cost, operating cost, residue production cost, etc. were developed where transportation distances were calculated through GIS analysis. The values of revenue parameters, such as the gate fee (fee for processing per tonne of waste by facility which otherwise would be charge by landfills for dumping same amount of waste) for MSW, carbon credit, and the selling price of electricity, were collected from the literature. The gasification technology was considered to be a fluidized bed gasifier with a combined cycle gas turbine for generating electricity. The model outputs are developed in terms of the IRR for two scenarios: first scenario focuses on a fixed selling price of electricity and the second scenario focuses on the cost of generating electricity for a fixed IRR. Following this, key sensitivities of various cost and revenue parameters on IRR and the cost of generating electricity were analyzed in a range of ±50%. Further details on the methodology and results are provided in Chapter 3.

1.4 Scope and Limitations of the Study

This study considered data up to the year 2016 to estimate biomass and MSW potential in the province. However, data can be updated in order to estimate current feedstock potential. In order to identify locations for agricultural residue BCPs, geographical maps of wheat, barley, and oats for the year 2016 were used. However, crops can rotate from one year to the next and thus different geographical maps, which may change the location of BCPs identified, are needed. The accuracy of the identified BCPs and W2VA facilities is limited to the most recent geographical information available. All the costs considered here are updated to the base year of 2017. However, any analysis for future years can be done in the FUNNEL-Cost-Bio-MSW model by inflating the costs to the desired year.

1.5 Organization of the Thesis

This thesis consists of four chapters along with a table of contents, list of tables, list of figures, and references. This thesis is written in a paper-based format such that Chapters 2 and 3 are two papers, which is expected to be published in peer-reviewed journals. Therefore, there may be repetition of concepts/work in the chapters.

Chapter 1, the current chapter, describes the research background, objectives, research approach, scope and limitation of the study, and organization of the thesis.

Chapter 2 presents the feedstock quantification process and geographical analysis. It describes the feedstocks considered and the methods used to estimate their annual potential. The GIS-based model is developed to estimate the annual potential of MSW at transfer stations and BCPs along with identification of geographical locations of BCPs. This model also identifies the optimal locations of W2VA facilities in the AIH as well as across the province of Alberta.

Chapter 3 describes the model developed to assess the technical and economic feasibility of the proposed W2VA facilities. The model considers various cost and revenue parameters along with the use of various feedstocks in a single, gasification-based W2VA facility to generate electricity. The gasification technology considers a fluidized bed gasifier with a combined cycle gas turbine to generate electricity. The output of the model is in terms of the IRR for a fixed selling price of electricity and the cost of generating electricity for a fixed IRR.

Chapter 4 presents the conclusion and recommendations for future work.

Chapter 2: The Development of a GIS-Based Framework to Locate Biomass and Municipal Solid Waste Collection Points for an Optimal Waste-to-Value-Added Facility

2.1 Introduction

Alberta's greenhouse gas (GHG) emissions from all sectors were 262.9 Mt CO_2-eq in 2016 (Government of Canada, 2018). Oil sands mining and upgrading, as well as electricity/heat generation, make up a most of these emissions (Government of Alberta, 2018). Additionally, traditional biomass handling practices in Alberta, comprising burning most of the forest and agricultural residue on farms (Kumar et al., 2003; MacDonald, 2009b; Mani et al., 2006) and dumping MSW into landfills (Khan, 2015), contributes towards environmental concerns (Ojha et al., 2007). Alberta diverts only 19.56% of its MSW from landfills to be converted into value-added products (Statistics Canada, 2014a). Proper management and use of lignocellulosic biomass and MSW have the potential to replace a portion of fossil fuel supply, mitigate GHG emissions (Schmer et al., 2014; Thornley et al., 2015; Weldemichael and Assefa, 2016; Zhang, 2016), and ultimately reduce environment and health concerns (The City of Edmonton, 2011).

In recent years, there have been efforts to use first generation biomass (e.g., grains) and MSW to produce various value-added products (Bradburn, 2014; Enerkem, 2017). As of 2013, Alberta has one first-generation ethanol plant, 5 biodiesel plants, and 10 biogas plants using biomass and MSW (Bradburn, 2014; Evans and Gray, 2013). An example is the Enerkem facility in Edmonton that uses MSW to produce methanol and ethanol at a combined capacity of 10 million gallons per year (Enerkem, 2017). Alberta ranks as the fourth Canadian province for lignocellulosic biomass availability after British Columbia, Quebec, and Ontario (Weldemichael and Assefa, 2016); thus there is a huge potential to use lignocellulosic biomass and MSW to produce value-added products in W2VA facilities. The quantification of lignocellulosic biomass and MSW, along with identifying their geographical distributions, are the first steps towards understanding the untapped potential and locating W2VA facilities.

There have been a number of studies on lignocellulosic biomass and its potential in Alberta and Canada. A few studies estimated the potential of MSW (Jacobs' Consultancy, 2013; Khan et al., 2018; Weldemichael and Assefa, 2016), agricultural residue (Jacobs' Consultancy, 2013; Mani et al., 2006; Weldemichael and Assefa, 2016), and forest residue (Bradley, 2007, 2010; Dymond et al., 2010; Friesen, 2016; Jacobs' Consultancy, 2013; Kumar et al., 2003; Smith and Web, 2015; Weldemichael and Assefa, 2016) for the province of Alberta and for Canada. These studies use various methods and report different estimates of lignocellulosic biomass and MSW potential. Khan et al. (Khan et al., 2018) forecasted MSW potential using data from landfills, Weldemichael and Assefa (2016) predicted future waste diversion percentages in order to estimate surplus MSW potential, and Jacobs' Consultancy (2013) used MSW disposal rates and population for the year 2010 to estimate potential. Both Weldemichael and Assefa (2016) and Jacobs' Consultancy (2013) projected agricultural residue potential after taking losses into account; however, in the former study, the losses were assumed as a percentage and in the latter, losses were subtracted from agricultural residue for various categories for the year 2010. Dymond et al. (Dymond et al., 2010) estimated forest residue based on natural disturbances, whereas other researchers (Jacobs' Consultancy, 2013; Kumar et al., 2003; Weldemichael and Assefa, 2016) estimated biomass from natural harvesting using residue yield. There are no data published after 2012 on lignocellulosic biomass and MSW potential in the province. In this paper, we used the 2016 provincial population together with the per capita disposal rate to estimate MSW potential, the 10-year average agricultural production and harvesting areas for the years 2006 to 2015, and the straw-to-grain ratio less additional losses to estimate agricultural residue potential, and actual forest harvesting data for the years 2011-15 along with residue yield to estimate forest residue potential.

A few studies used GIS-based assessment to optimally locate waste-to-value-added facilities (Khan et al., 2018; Sultana and Kumar, 2012; Tavares et al., 2011) and some quantified lignocellulosic biomass and MSW potential (Bradley, 2007, 2010; Dymond et al., 2010; Friesen, 2016; Jacobs' Consultancy, 2013; Kumar et al., 2003; Mani et al., 2006; Smith and Web, 2015; Weldemichael and Assefa, 2016), but none sited point source geographical location for collecting lignocellulosic biomass. This study is the first of its kind and uses GIS to optimally locate biomass (agricultural and forest residue) collection points (BCPs), in the form of geographical point locations with latitude and longitude, for collecting lignocellulosic biomass, together with their corresponding annual availability for distributed fields. In terms of MSW collection points, Khan et al. (2018) used landfill data to reverse-engineer the MSW potential across 285 transfer stations, whereas we used the latest population data and per capita disposal rate to estimate the capacity of nearby transfer stations.

A number of studies have proposed lignocellulosic biomass and MSW use in W2VA facilities. However, none suggests the integrated use of all of these wastes in a single facility. In the present study, for the first time, the integrated use of all types of lignocellulosic biomass (agricultural and forest residues) and MSW in a single facility is investigated. This study also integrates, in a specific case, the use of waste heat in a W2VA facility to dry biodegradable MSW at a commercial scale.

This study estimates current feedstock (MSW, agricultural residue, and forest residue) potential using data available from government reports and the literature. A GIS-based framework was developed to identify and locate biomass collection points for distributed lignocellulosic biomass, and existing MSW transfer stations were considered as MSW collection points. Further, this study identifies optimal locations for W2VA facilities.

The following are the specific objectives of this study:

- To estimate the available MSW, agricultural residue, and forest residue feedstock across the province of Alberta,
- To develop a GIS-based framework to locate biomass collection points along with potential capacity, and to identify MSW potential across transfer stations,
- To identify a single optimal location for a W2VA facility for the AIH and ten across the province of Alberta using the GIS framework developed.

This study can be used as a framework to assess lignocellulosic biomass and waste availability along with their geographical locations anywhere in the world. This study can help various government bodies make waste management-related policies and decisions in their respective communities.

2.2 Method

Identifying lignocellulosic biomass availability and geographical location is the initial step in processing waste in any W2VA facility. The feedstock potential and point location for agricultural and forest residues, as well as MSW, were identified for the province of Alberta. ArcGIS 10.4 (ESRI, 2015), a GIS-based software, was then used to determine the optimal location for the single W2VA facility. This GIS process considered economic, environmental, and social factors. The detailed method is given in subsequent sections.

2.2.1 Feedstock Availability

Different approaches were applied to estimate the annual availability of MSW, agricultural residue, and forest residue throughout the province of Alberta. MSW potential was calculated by multiplying the per capita disposal rate of 1.064 wet tones per year from Statistics Canada (Statistics Canada, 2014b) and the population of Alberta for the year 2016 (Statistics Canada, 2016).

Typically, agricultural straw yield is estimated through the established straw-to-grain ratio. This study considered straw from three major Alberta crops, wheat, barley, and oats. Straw-to-grain ratios of 1.1, 0.8, and 1.1 were used for wheat, barley, and oats to calculate gross straw yield (Li et al., 2012b; Sultana et al., 2010). Net straw yield was calculated by subtracting the losses from soil conservation, livestock feeding and bedding, machine harvesting, handling, transportation and storage, and straw moisture content. With respect to soil conservation, a sufficient amount of straw must be left on the field to maintain soil health and fertility, and to prevent soil erosion. Estimates of the amount to be left have been reported by various authors (Lindstrom et al., 1979; Mani et al., 2006; Stumborgl et al., 1996). This research considers 0.75 tonnes/ha for soil conservation (Sultana and Kumar, 2012). The amount of straw required for animal feeding was calculated based on the total production and demand of dry hay, silage, and straw, and the straw required for animal bedding used data for canola straw. Average numbers of cattle and sheep/lamb across the province of Alberta over the last 10 years (2006-2015) were 5.44 and 0.17 million per year, respectively (Statistics Canada, 2015). The feed demand (dry hay, silage, straw, and other), calculated using the feeding requirement in tonnes per animal per year from Statistics Canada (2003), and feed supply (tame hay, corn fodder) were calculated for Alberta to be 8.71 million dry tonnes and 7.07 million dry tonnes, respectively (see Table 2-1). Based on the literature review for straw requirement for animal bedding (Li et al., 2012b; Mani et al., 2006; Sultana and Kumar, 2012), this study considered a straw requirement of 2.5 kg per head per day for 93 days of bedding (Mani et al., 2006) for a total of 1.27 million tonnes per year. Canola is also one of the main crops in Alberta and its straw, calculated to be around 1.79 million dry tonnes per year, can be used for bedding. Based on feedstock supply and demand, 0.44 green tonnes per ha were considered for the feeding and bedding.

Table 2-1: Livestock feeding and bedding consumption and supply for the province of Alberta

Livestock feeding and bedding			Dry hay	Silage	Other	Total
Demand (dry tonnes)	Feeding		3,280,825	3,552,271	1,882,477	8,715,573
	Bedding		-	-	-	1,271,263
Supply (dry tonnes)	Feeding	Tame hay	6,719,931	-	-	-
		Corn fodder	-	350,096	-	-
	Bedding	Canola straw	-	-	-	1,271,263
Balance to be supplied from wheat, barley, and oat straw						1,645,546
Feeding and bedding requirement (green tonnes/ha)						0.44

Straw yield was further reduced by harvest losses, that is, the straw that a harvesting machine is not capable of collecting. This study considered harvesting machine loss of 30% based on a literature review (Liu, 2008; Perlack et al., 2005; Sokhansanj and Fenton, 2006). There are losses associated with handling, storage, and transportation as well. Based on previous studies (Hamelinck et al., 2005; Liu, 2008), a 15% loss was considered here. These losses are a 3% field loss, 5% handling loss, and 7% storage loss. The last way in which straw can be lost is when the lignocellulosic biomass is dried. This study assumes a moisture content of 14% on a wet basis for all three straw types (Sultana et al., 2010).

The forest residue considered here is the roadside residue left by harvesting companies. Current harvesting practices involve harvesting trees on main sites and skidding the trees to the roadside. On the roadside, the trees are delimbed, mainly removing limbs, branches and tops. These roadside residues are piled and burnt to prevent forest fires. This study assumes a 20% residue yield (i.e., the portion of limbs, tops and branches), which is equivalent to a blended yield of 24.7 dry tonnes of residue per net harvested hectare (Kumar et al., 2003).

2.2.2 GIS Analysis

2.2.2.1 Identification of Feedstock Point Source Location and Capacity

MSW, agricultural residue, and forest residue data were assessed through geographical analysis to determine point source locations along with annual potential at every location. For example, the location of transfer stations (TSs) for MSW was known, but their annual capacity was not. For agricultural and forest residues, both biomass collection points (BCPs) and annual potentials were identified through a GIS-based land suitability and network analysis. Land suitability analysis is a GIS-based process to determine the suitability of a given area for a particular use (GIS Lounge, 2014) whereas network analysis uses actual road network to minimize impedance between candidate sites and demand locations (ESRI, 2018). For waste heat in the AIH, the location of the waste heat sources and their annual potential were both inferred and taken from the study done by the CMC Research Institute et al. (2014).

2.2.2.1.1 Point source locations of MSW

MSW has dedicated transfer stations across Alberta. Waste from various residential and non-residential sources is transferred to the TSs and then either to landfills or a waste conversion facility. Suitability analysis requires point location of MSW transfer stations along with their annual potential. Since there are no current data on MSW potential by transfer station, a mathematical approach using Thiessen polygons was used to estimate MSW potential. Thiessen polygons are shaped around a sample point, such that any location inside the polygon is closer to that point than to all other points (ESRI, 2017). The area of each polygon is multiplied by the density of the MSW measured in gross tonnes per unit area. This gives the amount of MSW available inside each polygon. Since each polygon represents a particular TS, its MSW potential represents the available MSW at the corresponding TS.

2.2.2.1.2 Point source locations of agricultural residue

Transfer stations do not exist for agricultural and forest residues. Agricultural residues come from fields and there are no dedicated biomass supply points. Therefore, biomass collection points (BCPs) are defined and identified here. A BCP is equivalent to a transfer station except that it is identified through geographical analysis and is a source of large quantities of agricultural residue.

A GIS-based framework was developed based on work done by Khan et al. (2018), Sultana and Kumar (2012), to perform the land suitability analysis. As the name suggests, this process helps identify the most suitable locations for BCP. Suitability analysis comprises exclusion and preference analyses. Exclusion analysis helps screen out all unsuitable land, based on social and environmental factors, from the study area. Twelve constraints, shown in Table 2-2, were considered in such a way that they do not interfere with siting the collection point. A buffer distance, based on government norms and the literature, was created around each constraint and the maps were then converted to raster maps with a cell size 30 m X 30 m. The raster maps were then converted to binary maps in which the values “0” and “1” represent areas inside and outside the buffer zone, respectively. Binary maps of all the constraints were combined as per Eq. 1 to obtain the final constraint map, called the exclusion analysis map:

$$C_{E,i} = \prod_{j=1}^{n} C_{i,j} \tag{1}$$

where $C_{E,i}$ is the cell value in Boolean (0,1) for the i^{th} cell of the final constraint map; $C_{i,j}$ is the cell value in Boolean (0,1) for the i^{th} cell in jth constraints considered in this study; n is the total number of constraints. Binary values of “0” and “1” in the final constraint maps show areas not suitable and suitable for locating BCPs.

Table 2-2: Identified constraints and corresponding buffer zone distances for the exclusion analysis

Criteria	Specification	Source
Rivers, lakes, and other water bodies	Buffer of 300 m from water bodies	(Government of Alberta, 2010)
Rural and urban areas	Buffer of 1 km from rural and urban areas	(Eskandari et al., 2012; Ma et al., 2005)
Airports and heliports	Buffer of 8 km from international airports and 3 km from local airports	(Ma et al., 2005; Southern Alberta Energy From Waste Association (SAEWA), 2012)
Industrial and mining zones	Buffer of 1 km from industrial and mining zones	(Sultana and Kumar, 2012)
Environmentally sensitive areas (ESAs) (conservation areas, habitat sites)	Buffer of 1 km from ESAs	(Eskandari et al., 2012)
Natural gas pipelines	Buffer of 100 m from natural gas pipelines	(Ma et al., 2005; Sultana and Kumar, 2012)
Park and recreational areas	Buffer of 500 m from these sites	(Sultana and Kumar, 2012)
Wetlands	Buffer of 200 m	(Sultana and Kumar, 2012)
Roads	More than 30 m	(Sultana and Kumar, 2012)
Power plants and substations	Buffer of 100 m	(Sultana and Kumar, 2012)
Transmission lines	Buffer of 100 m	(Sultana and Kumar, 2012)
Land surface gradient	Land having slopes larger than 15% are removed	(Sultana and Kumar, 2012)

In preference analysis, relative preferences were given to different regions within the study area. Multiple buffer rings were generated around each preference factor (e.g., point, line, or polygon) and each buffer ring was assigned a grading value on a scale of 0-10 depending on its distance from the corresponding factor. For preference factors (e.g., land cover, slope), where multiple buffer rings were not possible, the raster values were re-classified on a 0-10 scale for spatially varied available data (Khan et al., 2018). All the preference maps were finally combined as per individual weightage calculated using the Analytic Hierarchy Process (AHP) (Saaty, 2001). The AHP is a mathematical approach that uses grading values to identify the weights of each preference factor such that the net sum totals 100%. The final preference map was created as per Eq. 2:

$$C_{P,i} = \sum_{j=1}^{m} W_j C_{i,j} \quad (2)$$

where $C_{P,i}$ is the preference value of the i^{th} cell in final preference map, $C_{i,j}$ is the preference value of the i^{th} ith cell in j^{th} preference factor, and *m* is the total number of preferences considered here. Higher cell values indicate higher preference for the facility siting. Following a literature review (Khan et al., 2016; Ma et al., 2005; Sultana and Kumar, 2012; Tavares et al., 2011), we used three preference factors – waste availability, road network, and land cover – to optimally locate the most preferable sites for BCPs.

For the preference analysis, a BCP close to biomass source points (BSPs) and roads is preferred in order to minimize transportation distance. BSPs provide small amounts of residue and transfer their waste to nearby BCPs. A single BCP takes residues from more than one BSP.

For land cover, preference factors were assigned based on the type of land used. For example, grassland and exposed land were given preference over water, coniferous forest, etc. Preference grading values for BSPs are shown in Table 2-3.

Table 2-3: Preference grading for distance from BSPs

Grading value Factors	0	1	2	3	4	5	6	7	8	9	10
Waste availability (km)	<0.03		> 2.0		1.0-2.0		0.5-1.0		0.2-0.5		0.03-0.2
Roads (km)	< 0.03		> 6		4.5-6		3-4.5		1.52-3.0		0.03-1.5
Land cover	Water, snow/ ice	Mixed forest	Rock/ Rubble				Agricultural land	Shrub land	Developed /Exposed land		Grassland

The weights of all the three parameters were calculated using the AHP with the highest weight for waste availability, followed by roads and then land cover, as shown in Table 2-4. The consistency ratio (CR) calculated for this comparison matrix is 7.93%; a CR below 10% indicates the correct weightages have been calculated (Saaty, 2001).

Table 2-4: Pairwise comparison matrix and weights of preference factors to locate agricultural BCPs

Preference factor	BCP	Roads	Land cover	Weightage
Waste availability – BSPs	1	3	9	0.66
Roads	0.33	1	6	0.28
Land cover	0.11	0.17	1	0.06

Exclusion and preference maps were then combined to make the land suitability map. Cell values of land suitability maps are shown in the form of suitability indices (*SI*), which are calculated as per Eq. 3. *SI* ranges from 0-10, where "10" is the most suitable location and "0" the least suitable for BCP siting.

$$SI_i = C_{E,i} \times C_{P,i} \quad (3)$$

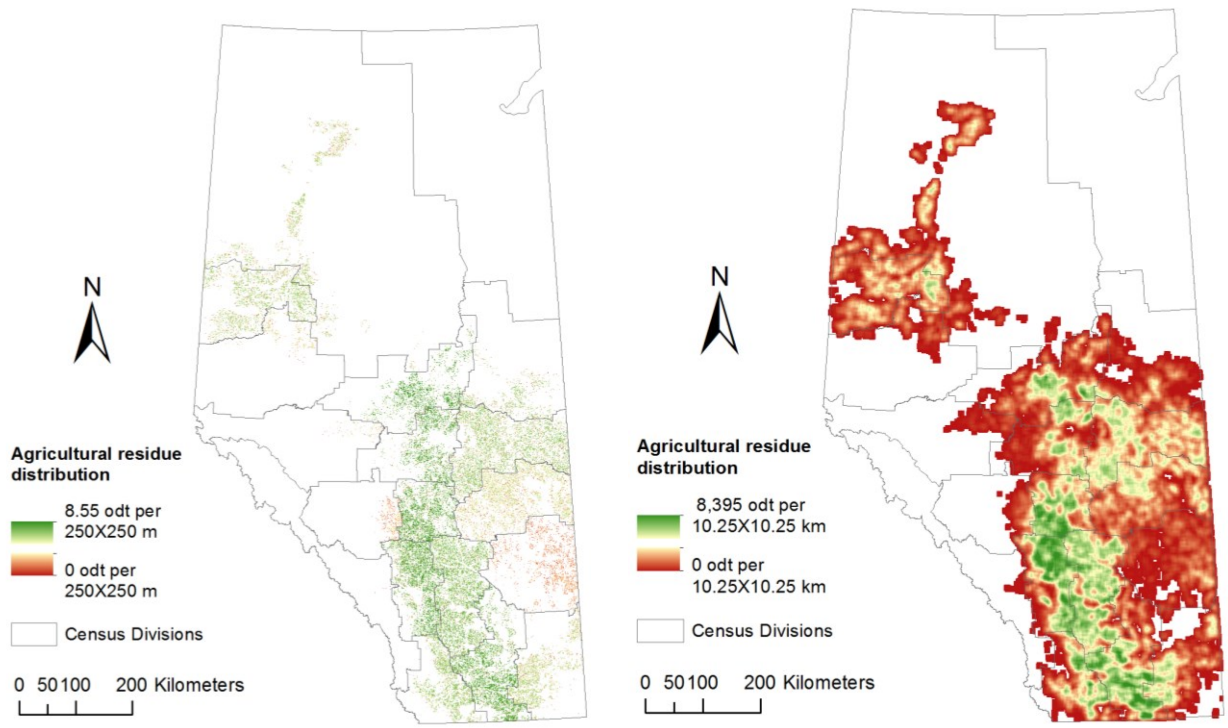
where SI_i is the suitability index of the i^{th} cell in the land suitability map.

Areas with high *SIs* (*SI* 10 and 9) were considered suitable for BCPs. Centroids from high *SI* (*SI* 10 and 9) polygons were chosen as the candidate sites for BCPs. These candidate sites were used in location-allocation analysis to find the optimal locations of BCPs. Location-allocation analysis uses actual road networks along with constraints such as one-way roads, U-turn junctions, and dead ends. The option of "maximize capacitated average" in network analysis minimizes the product of demand weight (i.e., biomass potential in this study) and the impedance (the distance between the W2VA facility and biomass supply points) (ArcGIS Resource Centre, 2012).

A raster map of agricultural residue yield with the smallest possible cell size of 250m X 250m, as shown in Figure 2-1(a), was developed for higher accuracy results. The yield ranges from ~0 to 8.55 oven dry tonnes (odt) [1] per 250m X 250m area per year. In order to collect distributed residue, a point source has to be identified. This was done by overlaying a 10.25km X 10.25km grid on the agricultural residue map. The total yield was calculated for each square and ranges from 0 to 8,395 odt per 10.25km X 10.25km per year, as shown in Figure 2-1(b). The overlain grid picks up the agricultural residue potential beneath each point. These points are called biomass source points (BSPs). The BSPs with an annual capacity of more than 300 odt were considered for further analysis as shown in Figure 2-2.

The identified agricultural BSPs need to connect with the central biomass supply point, i.e., biomass collection points (BCPs). The locations of the BCPs were identified by performing suitability and network analyses, as mentioned previously. Exclusion analysis for the BCPs considered all 12 constraint factors, and preference analysis only considered biomass availability, roads, and land cover. The suitability analysis also indicates the BCPs' individual capacities on an annual basis.

[1] Oven dry tonnes (odt) is defined as lignocellulosic biomass having 0% moisture content



(a) **(b)**

Figure 2-1: Agricultural residue yield (a) 250 X 250 m grid; (b) 10.25 X 10.25 km grid in Alberta

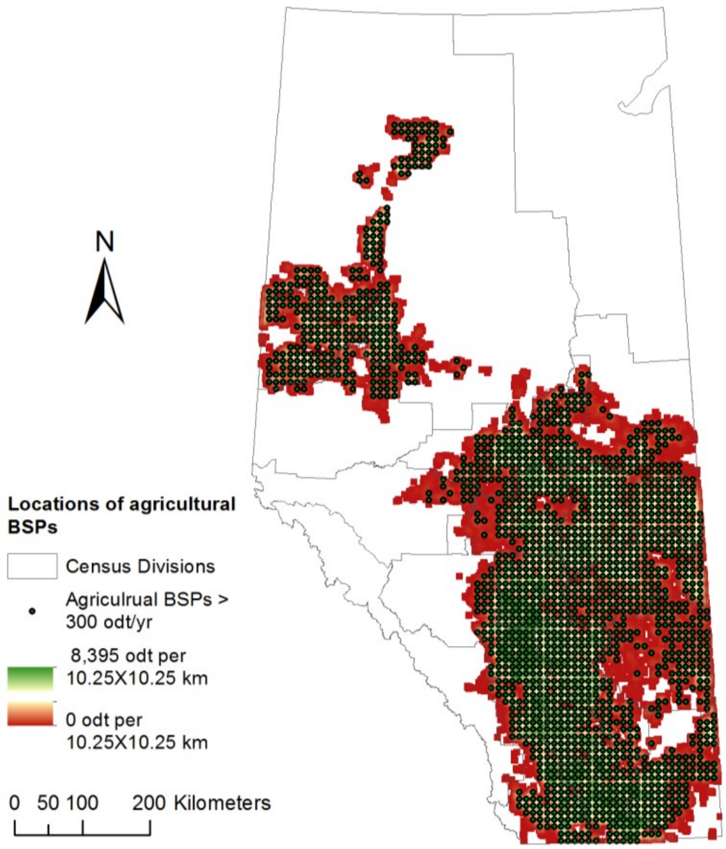


Figure 2-2: Identified locations of agricultural BSPs with annual potential greater than 300 odt

2.2.2.1.3 Point source locations of forest residue

The Government of Alberta signs long-term (generally 20-year) agreements, called Forest Management Agreements (FMAs), with forest harvest companies (Government of Alberta, 2016c). FMA holders are given rights to perform harvesting operations in small units called forest management units (FMUs). There are 21 FMA holders with 42 FMUs in Alberta (Government of Alberta, 2016d). Each FMA holder operates a mill, i.e., sawmill, pulp mill, panelboard mill, or other integrated facility. There are 38 mills in Alberta (Government of Alberta, 2012). FMA holders either use the harvested trees in their own mills or sell them to other companies.

Since harvesting locations change every year, there are no fixed lignocellulosic biomass location points for roadside forest residues comparable to MSW TSs, hence there is a need to determine how to choose future harvesting locations. The average life of a lumber mill is at least 30 years, and mill owners like to maintain a uniform production cost throughout the life of the plant. Production costs include harvesting, transportation, plant operation, etc. Since the forest area allocated to FMA holders is much larger than the actual area harvested, FMA holders have to plan cut block locations such that production costs, mainly the transportation cost component, remain relatively constant for all the future years (Fulton Smyle, Alberta Innovates, personal communication, 8 Jun 2017). FMA holders consider sustainability and environmental protection in selecting cut block locations. A special harvest sequence (SHS) provided by each FMA holder can be used to make a judgement on possible harvesting locations. Figure 2-3 shows an example of SHS for West Fraser (Edson area) (Government of Alberta, 2001).

In order to keep production costs constant, this study assumed 2 or 3 biomass source points (BSPs), depending on the area, for each FMU. BSPs are located such that one point is close to the FMA holder's mill and the other is the farthest distance from the mill. Figure 2-3 shows the location of 2 BSPs in West Fraser's FMU near Edson (Government of Alberta, 2001). These BSPs were connected to the West Fraser mill via secondary roads specially made by the company to connect primary highways to the harvesting locations. A tortuosity factor[2] of 1.22 was considered to simulate the straight-line distance to the actual road distance. Similar BSPs were located for all 21 FMA holders and their corresponding FMUs. 76 BSPs were identified throughout the province. Figure 2-9 shows the location and distribution of the BSPs and corresponding mills. Mills are referred to here as biomass collection points (BCPs), as this study assumes that roadside harvest residues from BSPs were transferred to the corresponding mills and then to the nearby

[2] The tortuosity factor is the ratio of actual road distance to the shortest straight-line distance

W2VA facility. Figure 2-4 shows the process flow for locating BCPs and connecting them to a W2VA facility.

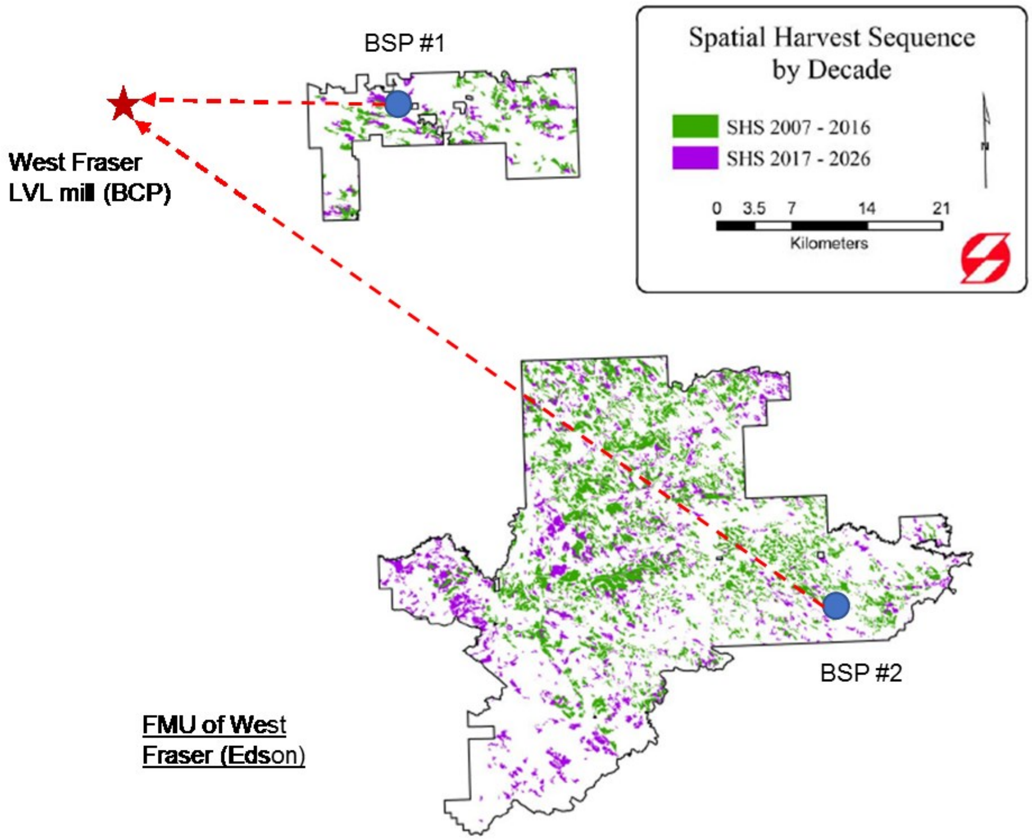


Figure 2-3: Special harvest sequence (SHS) and location of BCPs in West Fraser's (Edson-area) FMU and their connection with the West Fraser LVL mill (Government of Alberta, 2001)

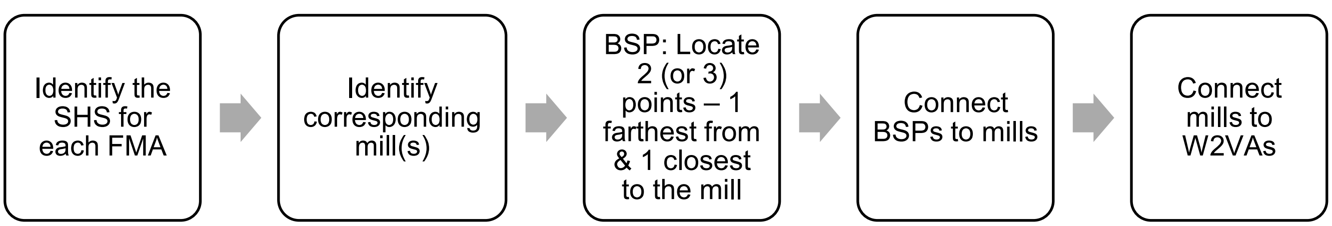


Figure 2-4: Process flow for the identification of BCPs for forest roadside residue

2.2.2.2 Facility Site Selection

Site selection for locating a W2VA facility was performed using suitability analysis, as mentioned in the previous section. The 12 geographical constraints mentioned in section 2.2.2.1.2 were considered in exclusion analysis, and preference analysis considered the following 8 factors chosen based on work done by Khan et al. (2016) and Sultana and Kumar (2012):

i. Waste availability
ii. Location of urban and rural areas
iii. Water availability
iv. Road network
v. Transmission lines network
vi. Location of power substations
vii. Land cover
viii. Slope

The suitability analysis approach mentioned in section 2.2.2.1.2 was followed to obtain optimal locations for facility siting. The procedure used to locate a W2VA facility has been discussed in detail elsewhere (Khan et al., 2018; Sultana and Kumar, 2012).

2.3 Results

2.3.1 Feedstock Quantification and Distribution in Alberta

2.3.1.1 Municipal Solid Waste Availability and Distribution

The average MSW disposal rate in the province of Alberta is 1.064 wet tonnes per capita per year, of which residential and non-residential disposals are 0.291 and 0.773 wet tonnes/capita/year, respectively (Statistics Canada, 2014b), or 27.3% and 72.7% of the waste from the respective waste sources. The total amount of MSW disposed in landfills, calculated using census data and disposal rates, is 4,327,474 wet gross tonnes per year and is shown in Table 2-5. Figure 2-5 shows MSW disposal ranges based on dissemination areas (DAs), i.e., the smallest population areas, across the province. The density of the DAs around Calgary, Edmonton, and Red Deer is much higher than in the rest of the Alberta.

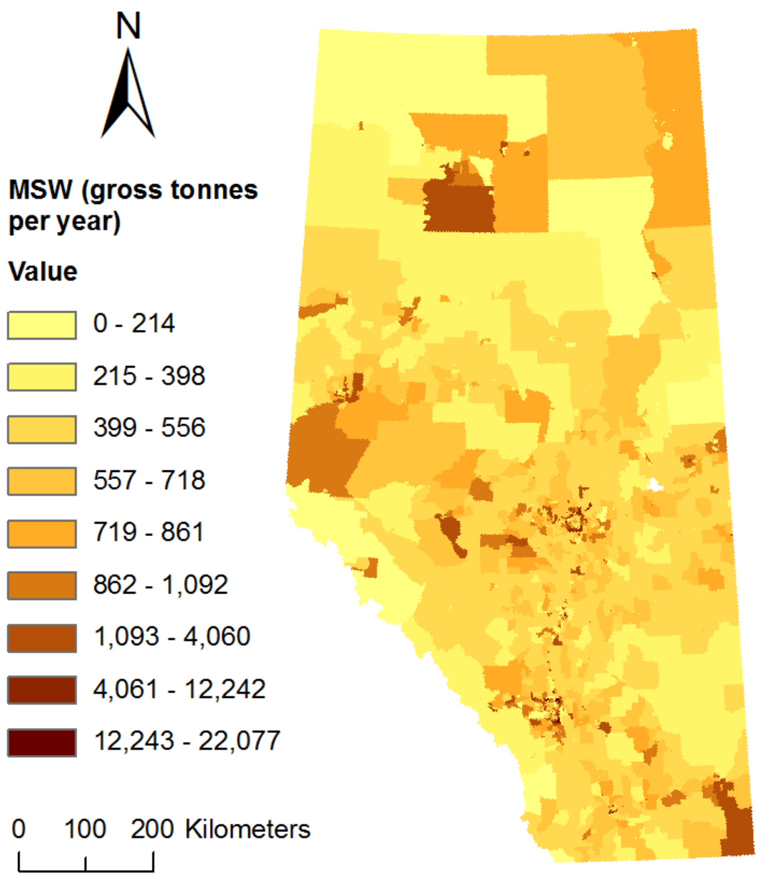


Figure 2-5: Distribution of MSW in gross tonnes across Alberta

Alberta has 285 transfer stations where MSW is sorted. Using the Thiessen polygon approach described in section 2.2.2.1.1, we identified the annual potential of each MSW TS, as shown in Figure 2-6. TSs in Edmonton, Calgary, and Red Deer have the highest MSW availability per year.

Table 2-5: Estimate of annual MSW disposal in Alberta for the year 2016

Parameter		Value	Source
Population (year 2016)		4,067,175	(Statistics Canada, 2016)
Per capita disposal rate (tonnes/capita/year)	Residential sources	0.291	(Statistics Canada, 2014b)
	Non-residential sources	0.773	
	Total	1.064	
Estimated total provincial waste disposed (gross tonnes)	Residential sources	1,183,548	-
	Non-residential sources	3,143,926	-
	Total	4,327,474	-

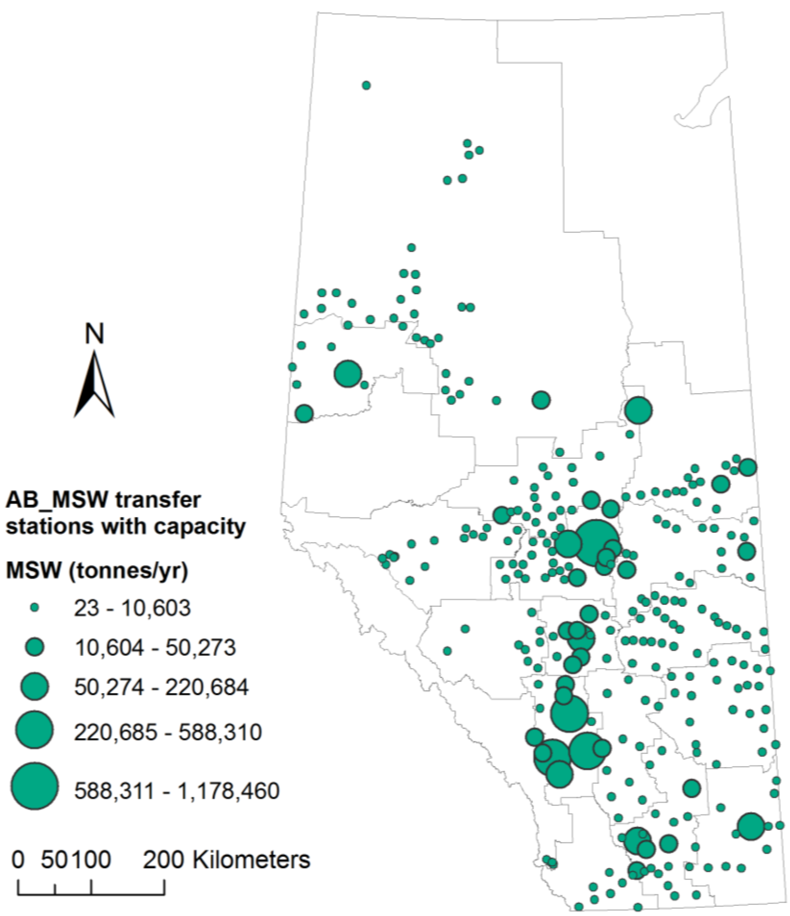


Figure 2-6: MSW transfer stations with their annual capacity in Alberta

2.3.1.2 Agricultural Residue Availability and Distribution

This study considered straw from three major Alberta crops (wheat, barley, and oats) as agricultural residue. The total average production of wheat, barley, and oats during the 10-years period 2006-2015 was 8.41, 4.64, and 0.56 million tonnes per year, respectively, and the crop harvest areas were 2.71, 1.34, and 0.19 million ha, respectively (Government of Alberta, 2016a).

All the losses associated with soil conservation, livestock feeding and bedding, machine harvesting, handling, transportation and storage, and moisture content were removed from the gross yield, as described in section 2.2.1. The gross straw yield considers no losses whereas the net straw yield considers all the losses mentioned. Gross straw yields for wheat, barley, and oat straw are 3.48, 2.78, and 3.16 gross tonnes per ha, respectively, as shown in Table 2-6 and net straw yields are 1.08, 0.72, and 0.92 odt per ha, respectively, as shown in Table 2-7. The total net straw production is 4.06 million odt per year, as shown in Table 2-8.

Table 2-6: Average grain yield (wet tonnes/ha) and gross straw yield (odt/ha) for wheat, barley, and oats in Alberta

Crop	Average grain yield (wet tonnes/ha)	Straw to grain ratio	Gross straw yield	
			(wet tonnes/ha)	(odt/ha)
Wheat straw	3.16	1.1	3.48	2.99
Barley straw	3.47	0.8	2.78	2.39
Oat straw	2.88	1.1	3.17	2.73

Table 2-7: Straw intermediate losses and net straw yield (odt/ha) for wheat, barley, and oats in Alberta

Crop straw	Reduction in straw yield					Net straw yield
	Gross straw yield	Straw level left for soil conserva-tion	Fraction of straw harvest machine loss	Straw level removed for animal feeding and bedding	Losses associated with storage and transportation	

	(odt/ha)	(odt/ha)	(odt/ha)	(odt/ha)	(odt/ha)	(odt/ha)
Wheat straw	2.99	2.35	1.64	1.27	1.08	1.08
Barley straw	2.39	1.75	1.22	0.84	0.72	0.72
Oat straw	2.73	2.08	1.46	1.08	0.92	0.92

.

Table 2-8: Annual agricultural residue potential of Alberta

Crop	Area harvested (ha)	Net straw production (odt/year)
Wheat straw	2,711,746	2,916,844
Barley straw	1,343,355	962,790
Oat straw	196,879	180,427
Total	4,251,999	4,060,060

In order to determine the location of agricultural BCPs, suitability analysis was carried out. Exclusion and preference analyses were performed as described in section 2.2.2.1.2 and the resulting maps are shown in Figure 2-7(a) and (b). Similarly, suitability analysis was carried out and the resulting map is shown in Figure 2-7(c). Here, polygons with suitability indexes (*SI*s) 9 and 10 were further considered with their centroids as candidate sites for BCPs. 2006 identified candidate sites were used with BSPs in a location-allocation analysis as shown in Figure 2-7(d). The optimal locations of BCPs were identified based on the "maximize capacitated coverage" concept mentioned in section 2.2.2.2. A maximum distance of 50 km between any BSP and BCP and a maximum capacity of 30,000 odt per year for BCPs are assumed in "maximum capacitated coverage." This capacity is considered based on trial and error in order to have minimal errors between theoretical agricultural residue potential and actual residue collection from the identified BCPs. 190 optimal locations for BCPs were identified and are shown in Figure 2-8 along with their annual potential. The number of BCPs was optimized such that more than 90% of the total available agricultural residue was collected from BCPs.

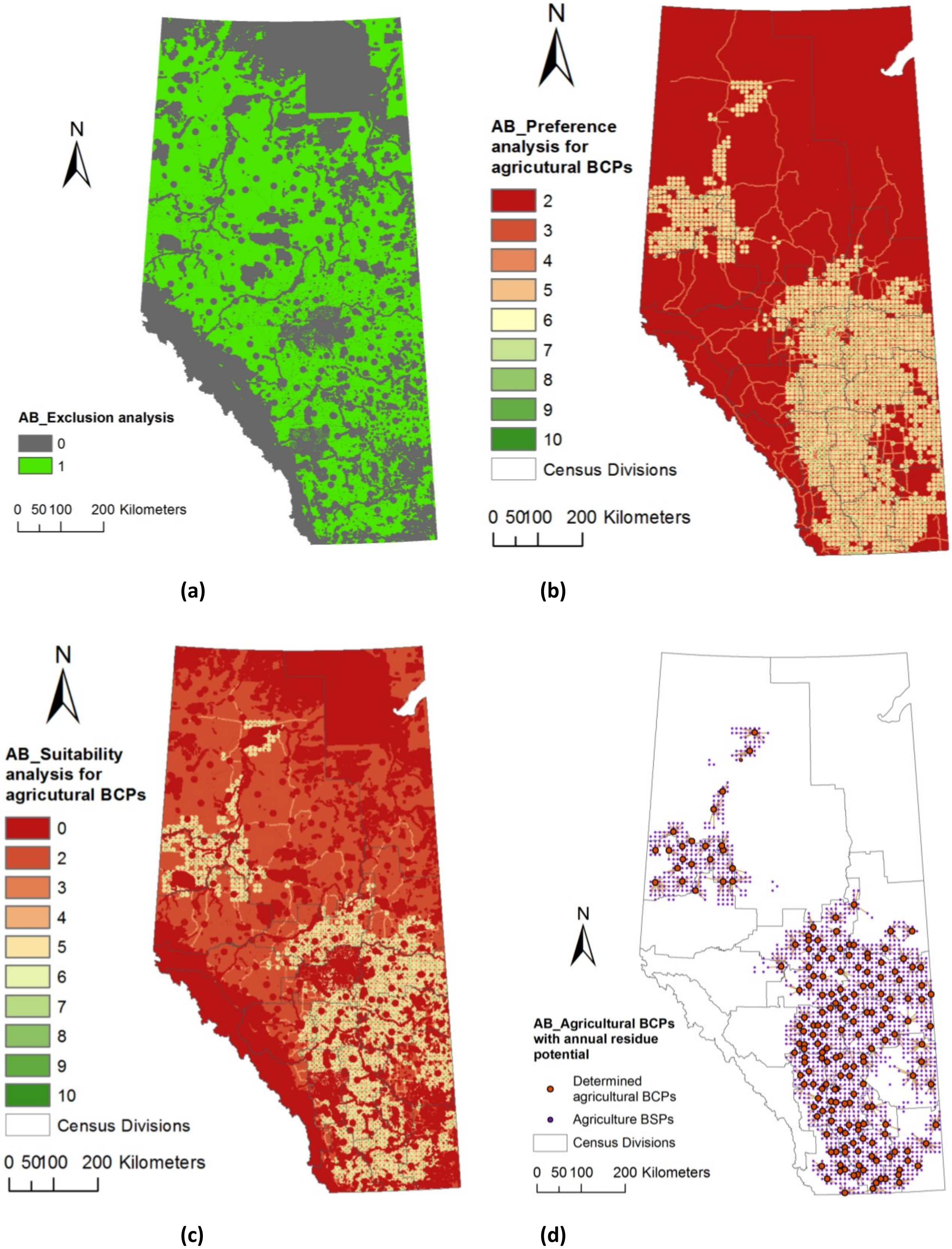


Figure 2-7: (a) Exclusion analysis map; (b) Preference analysis map; (c) Suitability analysis map; and (d) Determined locations for agricultural BCPs across Alberta

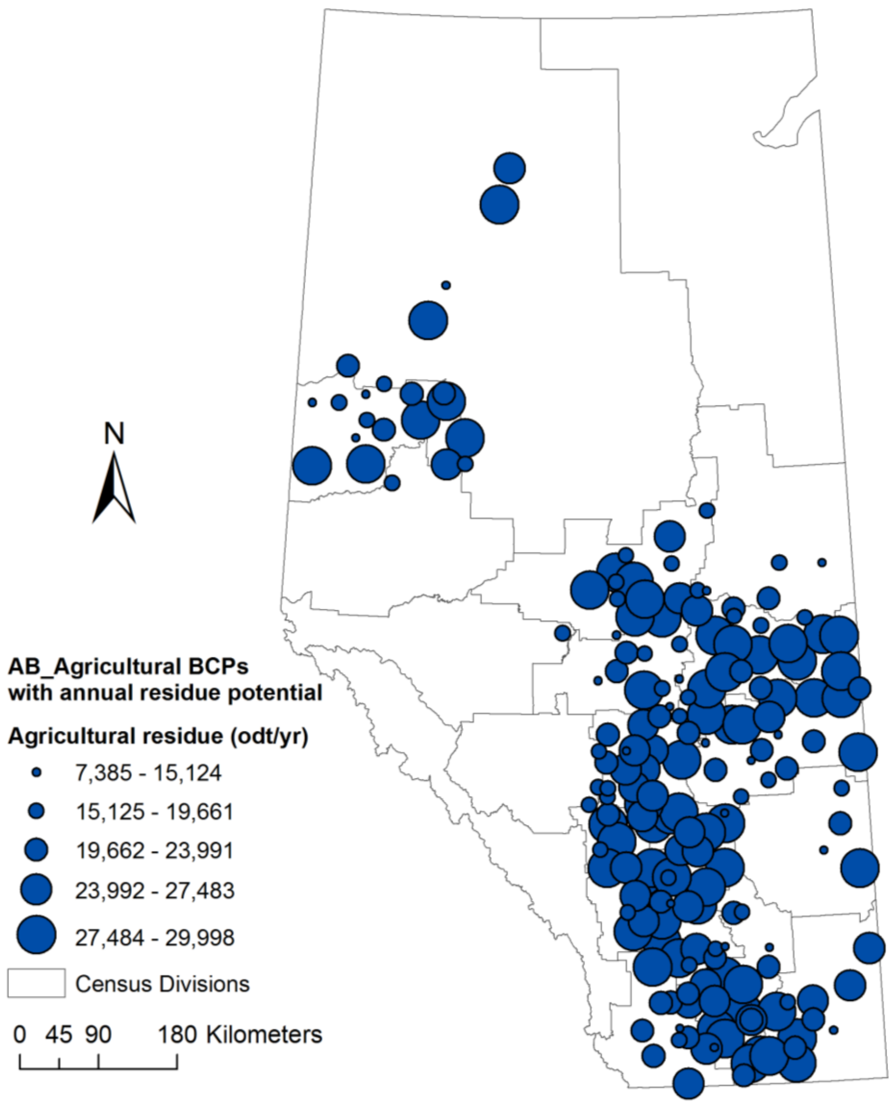


Figure 2-8: Location of agricultural BCPs along with their annual potential

2.3.1.3 Forest Residue Availability and Distribution

As of 2015, Alberta had around 20 million ha of forest area, of which an average 84,106 ha had been harvested annually in the 5 years prior (2011-2015) (National Forest Inventory, 2016). Assuming a harvesting yield of 24.7 dry tonnes of residue per net harvested hectare, the annual forest residue potential is 2.07 million odt per year. The Annual Allowable Cut (AAC) by the Government of Alberta from 2009-2013 was 30.43 million cubic meters per year, whereas the actual average harvested volume during that time was 20.20 million cubic meters per year, approximately 66.38% of the AAC (Government of Alberta, 2016b). The AAC and actual volume harvested over the past 10 years show increasing trends.

Harvesting locations, known as harvesting cut blocks, change every year and there is no specific information available publicly on the location of cut blocks for each year, though FMA holders predict harvest sequences on a 10-year basis. Using the method mentioned in section 2.2.2.1.3, we predicted the location of forest BSPs for all the FMA holders. Figure 2-9 shows the location of BSPs with the corresponding FMA holders' mills. 50 BSPs were identified for 21 FMA holders' mills. Each mill location was considered a forest residue BCP in this study.

The annual residue availability of the mills was calculated based on harvesting volume as a percentage of the annual harvesting volume of all of Alberta. The harvesting volume of each FMA holder for year the 2017 are extrapolated from the FMA document available from Government of Alberta (2016c). Figure 2-10 shows the location of forest BCPs (i.e., mills) with their annual roadside residue potential.

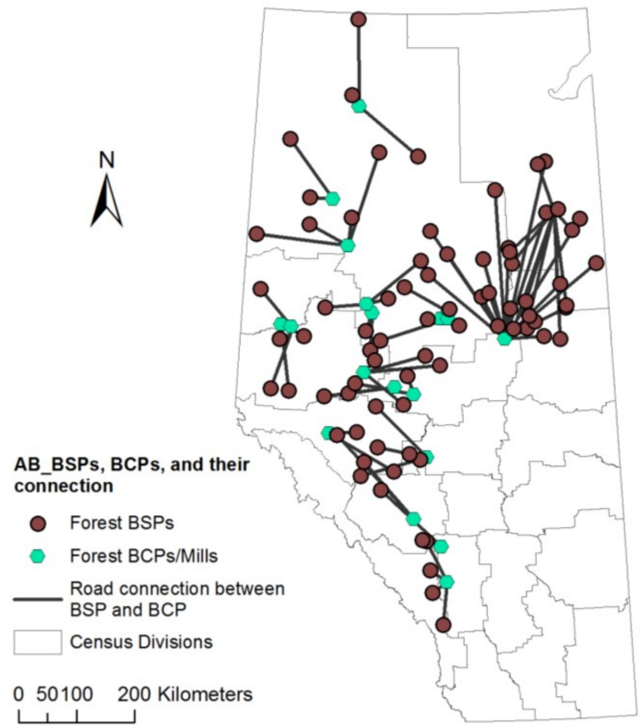


Figure 2-9: Location of forest BSPs and their corresponding mills (BCPs)

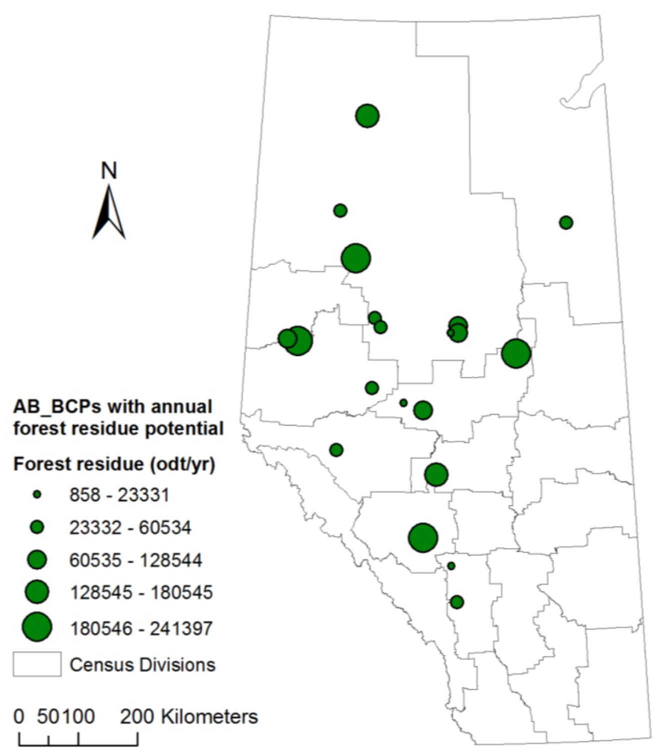


Figure 2-10: Locations of identified mills (BCPs) along with their annual roadside residue potential

2.4 Case Study I: Alberta's Industrial Heartland (AIH)

Many industries in the AIH emit high temperature exhaust streams into the environment. In order to use the waste heat stream in this region, a proposal is made here to locate a W2VA facility. The study area was defined by considering a 50 km transportation ring around the AIH boundary, as shown in Figure 2-11 (Alberta's Industrial Heartland, 2014).

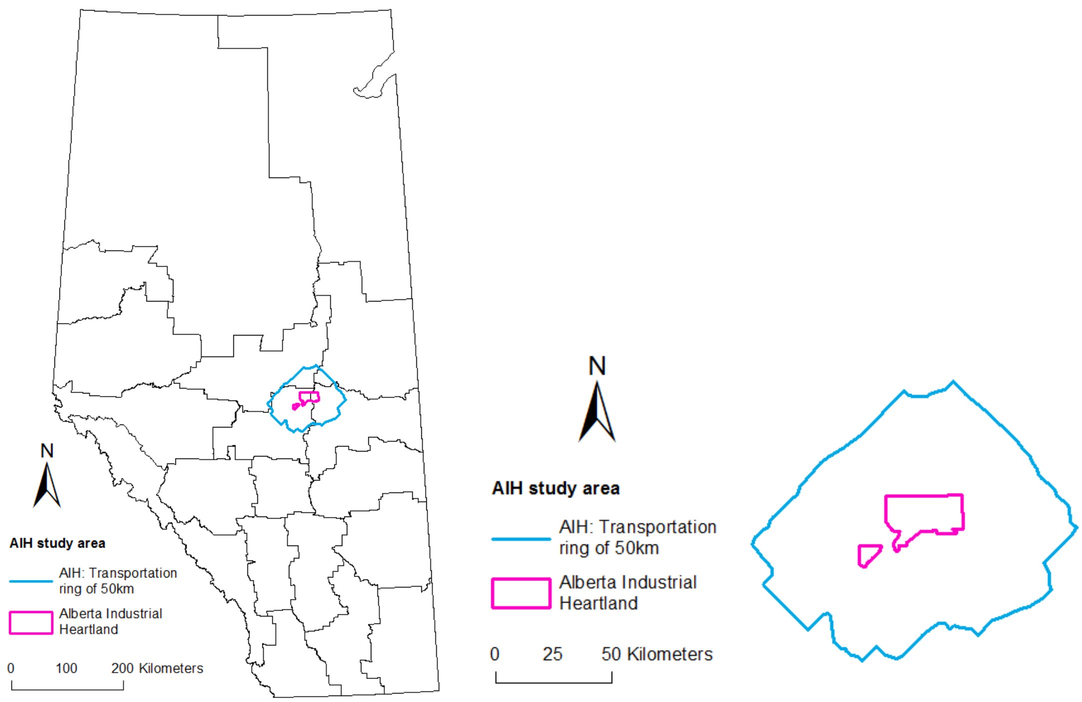
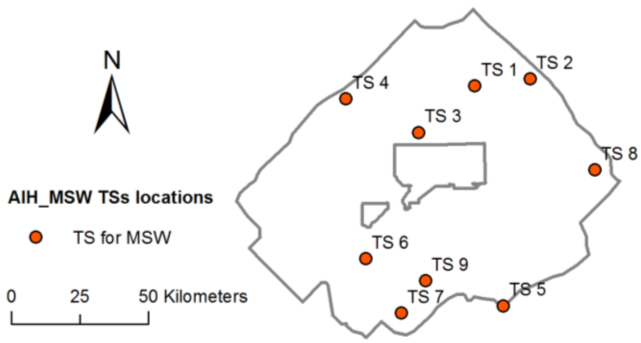


Figure 2-11: The AIH study area showing the AIH boundary along with the transportation ring of 50 km around the AIH boundary (Alberta's Industrial Heartland, 2014)

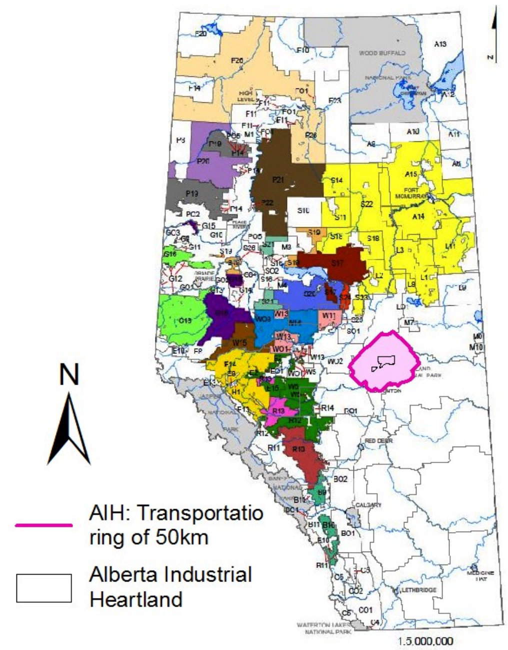
2.4.1 Feedstock Potential in the AIH

MSW available in the AIH study area was calculated by locating TSs inside the study area. There are nine TSs in the study area and their cumulative MSW potential is 1,266,851 gross tonnes per year, as shown in Figure 2-12 and

Table 2-9. There is no forest residue available because no green area lies within the study area; hence, no harvesting operations take place inside the study area. Waste heat available in the study area is 47 MW (CMC Research Institute et al., 2014).



(a)



(b)

Figure 2-12: (a) Location of MSW TSs in the AIH study area; (b) Forest management area for the province of Alberta and the AIH study area ([Government of Alberta, 2016d](#))

Table 2-9: Location of MSW transfer stations along with their annual MSW availability

TS #	TS Name	Longitude	Latitude	Annual MSW availability (gross tonnes/year)
TS 1	Waskatenau	-112.784	54.097	4,283
TS 2	Smoky Lake	-112.474	54.113	3,003
TS 3	Redwater	-113.106	53.948	20,576
TS 4	Vimy	-113.506	54.064	19,461
TS 5	Tofield	-112.666	53.370	6,091
TS 6	Lindale	-113.416	53.536	1,178,460
TS 7	Looma	-113.226	53.355	12,632
TS 8	Willingdon	-112.133	53.805	3,443
TS 9	Half Moon Lake	-133.090	53.459	18,903
Total capacity (gross tonnes per year)				1,266,851

The amount of agricultural residue available in the AIH study area is 264,130 wet tonnes (~227,152 odt) per year. Agricultural BCPs for the AIH study area were identified using the method mentioned in section 2.2.2.1.2. The same factors were used to determine the locations of agricultural BCPs. Figure 2-13 shows the locations of 8 optimum locations of identified BCPs and Table 2-10 shows their corresponding residue availability.

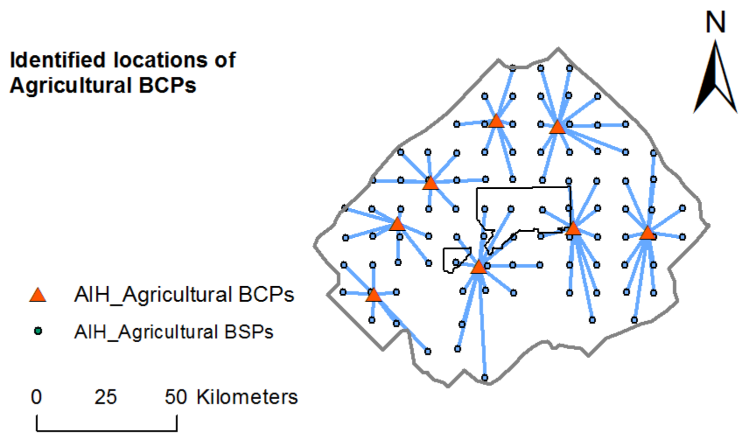


Figure 2-13: (a) SI 9 & 10 candidate sites for agricultural BCPs; (b) Eight identified optimal BCP locations

Table 2-10: Geographical locations of agricultural BCPs along with their annual residue potential

Agricultural BCP	Latitude	Longitude	Annual potential (odt/year)
BCP 1	53.931	-113.493	29,220
BCP 2	53.659	-113.243	30,962
BCP 3	54.124	-113.127	24,646
BCP 4	54.100	-112.799	32,969
BCP 5	53.803	-113.676	28,273
BCP 6	53.773	-112.730	28,099
BCP 7	53.751	-112.332	39,554
BCP 8	53.577	-113.811	13,429
	Total		227,152

2.4.2 Waste Heat Availability in the AIH

This paper considered the waste heat that is available only in the Alberta's Industrial Heartland (AIH) area. The industrial area houses approximately 40 industries from various operations such as refineries, bitumen upgraders, chemical and fertilizer production, etc.

According to the CMC Research Institute et al. (2014), 99 MW of waste heat currently exhausted to the environment is available for potential use. Based on the location of the industrial area, the temperature of the waste heat, and the operations of the industries involved, five major waste heat producers were identified with a total capacity of 86 MW, as shown in Table 2-11. This study assumes that waste heat from these companies would be used to dry the biodegradable content of MSW, which has a high moisture content. Waste heat is not used for agricultural residue as the residue has the optimum moisture content of 14% required for energy conversion.

Table 2-11: Waste heat sources along with their potential and temperature range in the AIH area (CMC Research Institute et al., 2014)

Inferred company	Location	Type of operation	Estimated potential	Temp range
Waste Heat I	(-113.182, 53.718)	Mining	8 MW	230^0-650^0C
Waste Heat II	(-113.091, 53.797)	Refinery	19 MW	230^0-650^0C
Waste Heat III	(-113.163, 53.728)	Petrochemicals	20 MW	120^0-230^0C
Waste Heat IV	(53.559, -113.356)	Chemicals	12 MW	650^0-1100^0C
Waste Heat V	(53.553, -113.35)	Oil Processing	27 MW	230^0-650^0C

2.4.3 Suitability Analysis for Identifying One W2VA Facility in the AIH

Two scenarios were considered for siting the optimal location of a W2VA facility in the AIH. The two scenarios are as follows.

2.4.3.1 Scenario I: W2VA Facility Next to Waste Heat Source

The location of the W2VA facility was assumed to be next to the available waste heat source. This case considered a W2VA facility next to Waste Heat II (see Table 11) such that its waste heat is directly used in the drying facility. The scenario considered one-stage feedstock transportation, i.e., feedstock would be transported to the W2VA facility. Both waste sorting and drying were considered at the W2VA facility location; both waste sorting and drying facilities were considered to be located at the W2VA facility location. The geographical location of the W2VA facility is 53.797^{0}N, 113.091^{0}W and has an annual capacity of 911,252 odt/year, as shown in Figure 2-14.

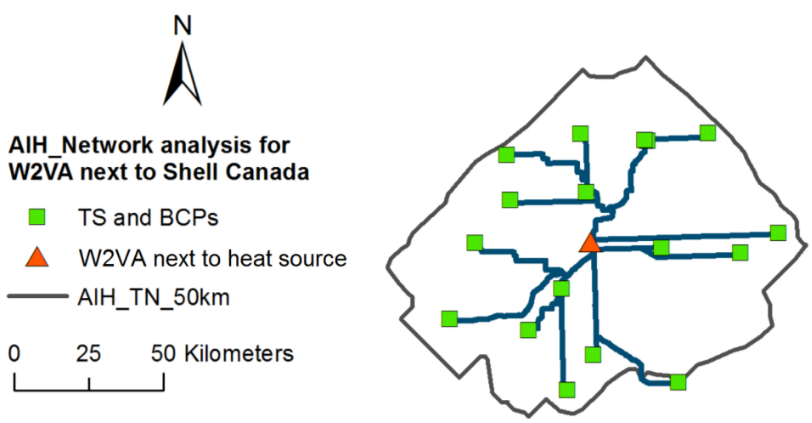


Figure 2-14: TSs, BCPs, and W2VA facility in Scenario I

2.4.3.2 Scenario II: W2VA Facility Location Optimized for More Than One Waste Heat Source

Scenario II assumed that if there is a shortage of waste heat at a particular location, MSW could be dried at more than one location. This scenario considered two-stage feedstock transportation, i.e., first MSW was transported to the waste heat source for drying and then taken to the W2VA facility. Each waste heat source has one waste sorting facility and one drying facility. Two major waste heat sources were considered in this scenario, Waste Heat I and Waste Heat II, chosen based on the waste heat quantity and quality (~230-650 ^{0}C) emitted. In this scenario, optimal location of W2VA facility was identified using land suitability analysis model. Exclusion analysis considered the 12 constraints mentioned in Table 2-2 whereas preference analysis considered the eight preference factors described in section 2.2.2.2, except waste availability (MSW and agricultural BCPs) replaced waste heat sources. Figure 2-15 shows the exclusion analysis results for the AIH case.

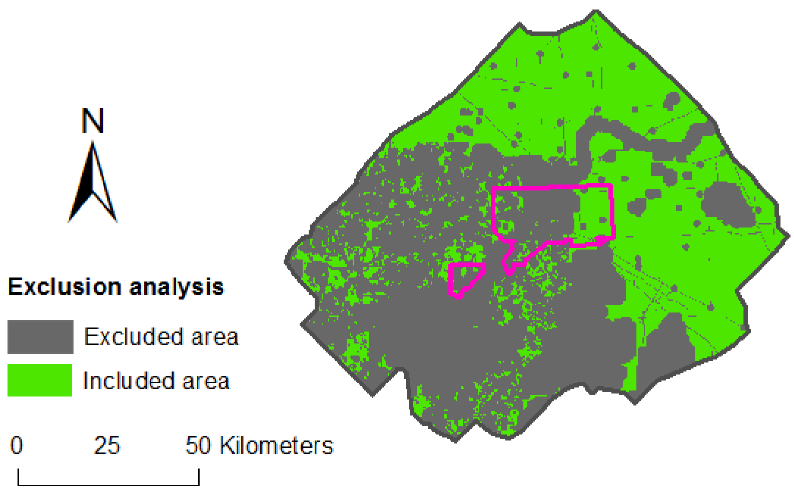


Figure 2-15: Exclusion analysis map of the AIH study area

The preference analysis of all eight constraints, mentioned in section 2.2.2.2, was performed with waste availability replaced by waste heat source. Multiple buffer rings, along with their grading values for each preference factor, were created, as per the information given in Table 2-12. These eight preference factors were combined according to weightage, shown in Table 2-13, and calculated using the AHP to get the preference map. Exclusion and preference maps were combined to get the suitability maps shown in Figure 2-16 (a). Using the higher *SI*s in a network analysis, an optimal location for W2VA facility was identified between both waste heat sources, as shown in Figure 2-16 (b).

Table 2-12: Grading values for preference factors (Khan et al., 2018)

Grading value Factors	0	1	2	3	4	5	6	7	8	9	10
Waste availability (km)			> 20		15-20		10-15		5-10		<5
Urban (km)	< 1				1-2		2-3		3-4		>4
Water (km)	< 0.3		> 2.5		1.5-2.5		1-1.5		0.5-1		0.3-0.5
Roads (km)	< 0.03		> 2		1-2		0.5-1		0.2-0.5		0.03-0.2
Transmission (km)	< 0.1		> 5		3-5		2-3		1-2		0.1-1
Substation (km)	< 0.1	> 5	4-5		3-4		2-3		1-2		0.1-1
Land cover	Water, snow/ ice	Mixed forest	Rock/ Rubble				Agricultural land	Shrub land	Developed /Exposed land		Grassland
Slope (%)	> 15										< 15

Table 2-13: Pairwise comparison matrix and weights of preference factors to locate one W2VA facility (Khan et al., 2016)

Preference factors	WA	Urban	Water	Roads	Transmission	Substation	Land cover	Slope	Weight
Waste availability	1	3	5	7	8	9	9	9	0.44
Urban	0.33	1	2	3	4	4	5	6	0.19
Water	0.2	0.5	1	2	3	3	4	5	0.13
Roads	0.14	0.33	0.5	1	2	2	3	3	0.08
Transmission	0.13	0.25	0.33	0.5	1	1	2	2	0.05
Substation	0.11	0.25	0.33	0.5	1	1	2	2	0.05
Land cover	0.11	0.2	0.25	0.33	0.5	0.5	1	1	0.03
Slope	0.11	0.17	0.2	0.33	0.5	0.5	1	1	0.03

Later, MSW TSs were optimally connected to waste heat sources (to dry the biodegradable portions of MSW) and agricultural BCPs to the identified W2VA facility directly (as agricultural residues do not require drying). MSW delivery from TSs was directed to both waste heat sources to use waste heat. The division was done using network analysis, which considers the shortest transportation distances between the chosen TSs and the waste heat source. Since the capacity of the Lindale TS is high (~93% of the total MSW available in the AIH study area), 30% of the MSW available is sent to waste heat I and the remaining 70% to the Waste Heat II. The percent distribution was chosen such that almost 90% of the waste heat potential of Waste Heat I was used for drying. Figure 2-17(a) shows the real road connection between MSW TSs and waste heat sources, and Table 2-14 shows the distribution of MSW between two waste heat sources. Since agricultural residues do not require drying, agricultural BCPs were directly connected with a W2VA facility, as shown in Figure 2-17(b). The geographical location of the W2VA facility is 53.726^{0}N, 113.154^{0}W with an annual capacity of 911,252 odt/year. The biodegradable contents (40%) of the MSW available at Waste Heat I and II are 164,250 and 343,491 wet tonnes/year, respectively. The amount of waste heat required to dry the MSW at both locations is 6.89 MW and 14.36 MW, respectively.

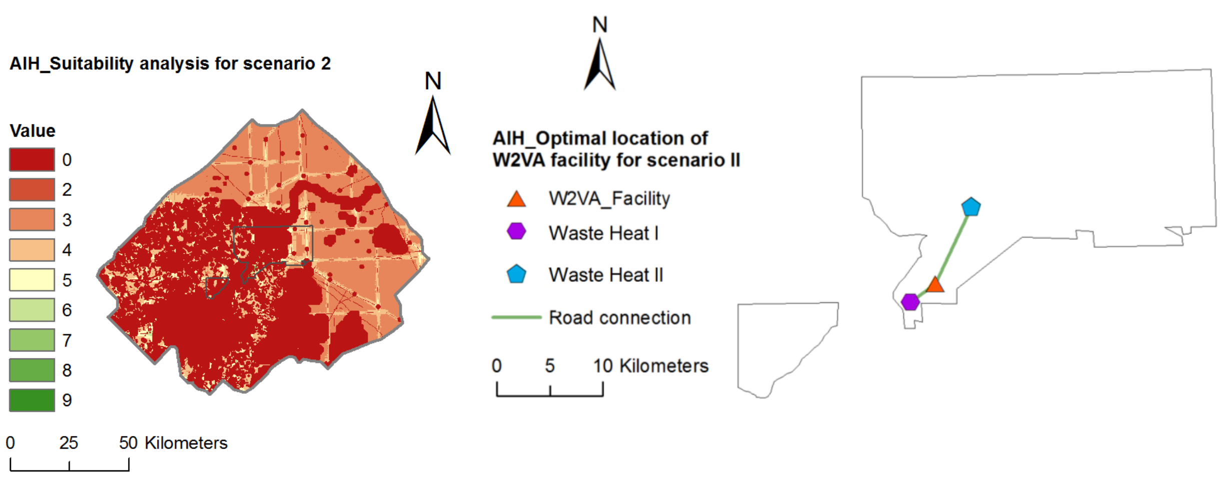
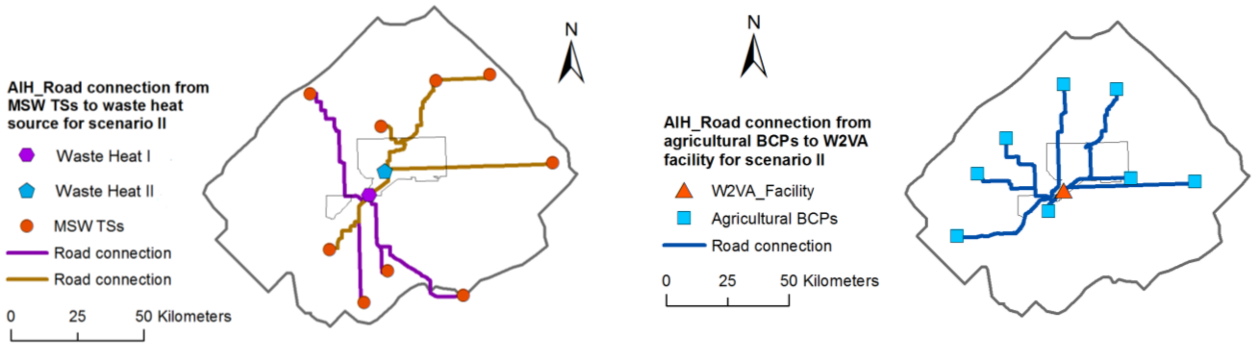


Figure 2-16: (a) Suitability analysis map for Scenario II; (b) Identified location of the W2VA facility



(a) (b)

Figure 2-17: Network analysis connecting (a) MSW TSs to the waste heat sources; (b) Agricultural BCPs to W2VA facility in Scenario II

Table 2-14: Distribution of MSW between two waste heat sources

Waste heat source	TS Name	TS #	MSW transferred for drying (wet tonnes/yr)
Waste Heat I	Vimy	TS 4	19,461
	Tofield	TS 5	6,091
	Lindale	TS 6	353,538 (30% of the total capacity)
	Looma	TS 7	12,632
	Half Moon lake	TS 8	18,903
	Total MSW transferred		**410,625**
Waste Heat II	Waskatenau	TS 1	4,283
	Smoky Lake	TS 2	3,003
	Redwater	TS 3	20,576
	Lindale	TS 6	824,922 (70% of the total capacity)
	Willingdon	TS 8	3,443
	Total MSW transferred		**856,227**

2.5 Case Study II: Province of Alberta

A study similar to the AIH study was conducted for the entire province of Alberta. The objective was to determine ten optimal locations of W2VA facilities across the province. Three types of feedstocks were considered on a provincial scale: MSW, agricultural residue, and forest residue. The potential and spatial distribution of each across the province has been described in section 2.3. The locations of MSW TSs, agricultural BCPs, and forest BCPs are shown in Figure 2-18.

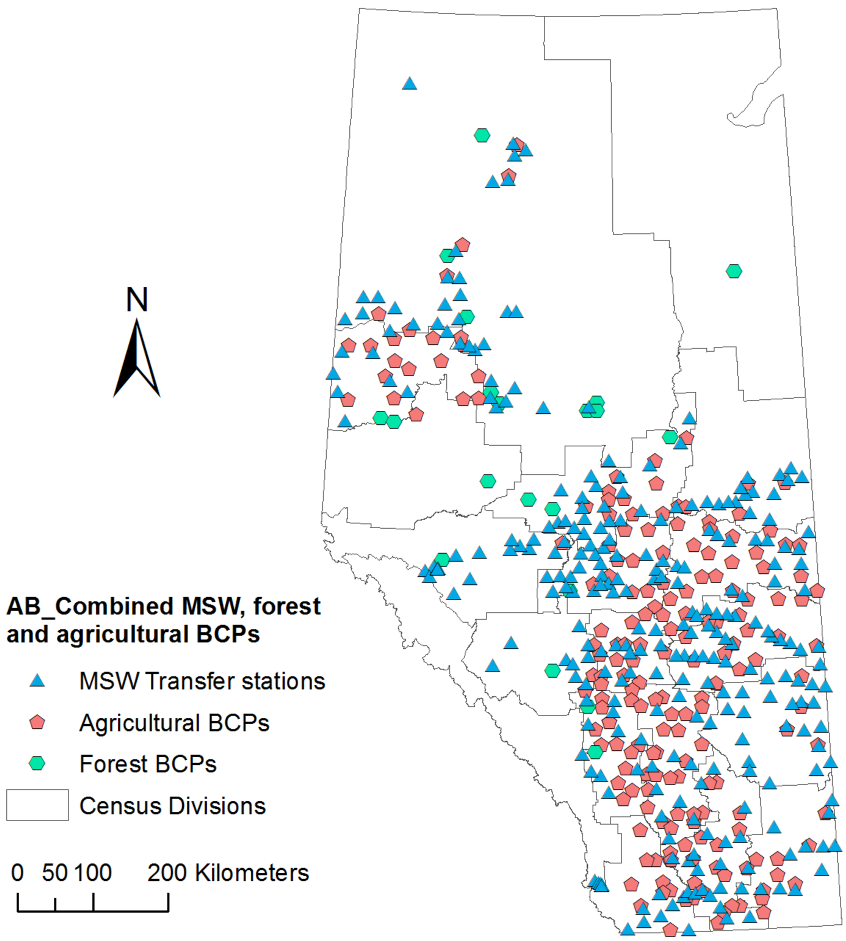


Figure 2-18: Locations of MSW TSs and agriculture and forest residue BCPs across the province of Alberta

The exclusion analysis map for the Alberta is shown in Figure 2-7(a). Preference maps were created for all eight preference factors mentioned in section 2.2.2.2 and all preference maps were combined as per the weightage calculated in Table 2-12 to get the final preference map. Combining exclusion and preference maps gave the suitability analysis map. Figure 2-19(a) and (b) shows the preference and suitability analysis maps.

Areas with suitability indices of 10 and 9 were chosen for locating the W2VA facilities. A centroid of *SI* 10 and 9 polygons with areas greater than 10 ha were chosen as candidate sites for 10 W2VA facilities. Using the concept of “minimize impedance,” network analysis (location-allocation analysis) (ESRI, 2017) was performed to obtain 10 optimal locations for a W2VA facility. These 10 facilities are connected with all types of lignocellulosic biomass and MSW sources. Table 2-15 shows the geographical coordinates of 10 W2VA facilities along with their annual individual biomass collection potential. Figure 2-20 shows the network analysis for the whole province.

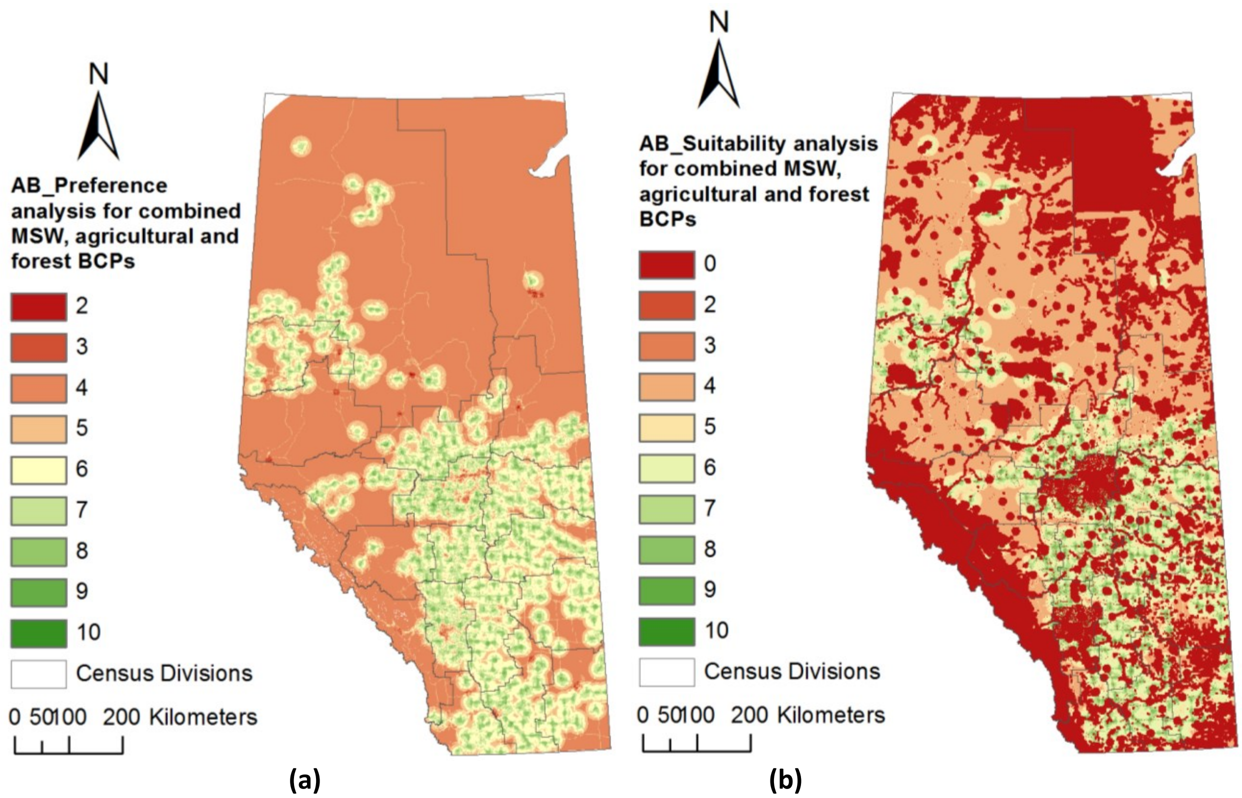


Figure 2-19: (a) Preference analysis map; (b) Suitability analysis map for the combined MSW TSs and agricultural and forest residue BCPs in Alberta

Table 2-15: Geographical locations and annual waste collection of 10 W2VA facilities in Alberta

W2VA facility	Latitude	Longitude	Annual waste collection			
			Total[3] (odt/year)	MSW (wet tonnes/yr)	Agricultural residue (odt/yr)	Forest residue (odt/yr)
W2VA 1	56.556	-117.676	676,842	56,367	167,130	479,274
W2VA 2	55.773	-118.697	786,380	118,186	317,182	405,378
W2VA 3	55.290	-114.563	300,808	29,464	-	284,897
W2VA 4	54.111	-112.797	867,222	245,083	477,303	257,575
W2VA 5	53.606	-115.214	503,006	112,001	64,619	377,906
W2VA 6	53.389	-113.267	1,108,866	1,416,284	344,073	-
W2VA 7	52.648	-111.253	688,603	89,318	640,371	-
W2VA 8	52.291	-113.982	1,065,548	305,268	665,112	235,591
W2VA 9	50.982	-113.877	1,627,319	1,637,238	706,414	36,798
W2VA 10	49.946	-112.623	1,197,827	319,800	1,025,134	-

[3] Wet tonnes of MSW are converted to odt based on thermal content (40%) with MC of 15% and biodegradable content (40%) with MC of 50%

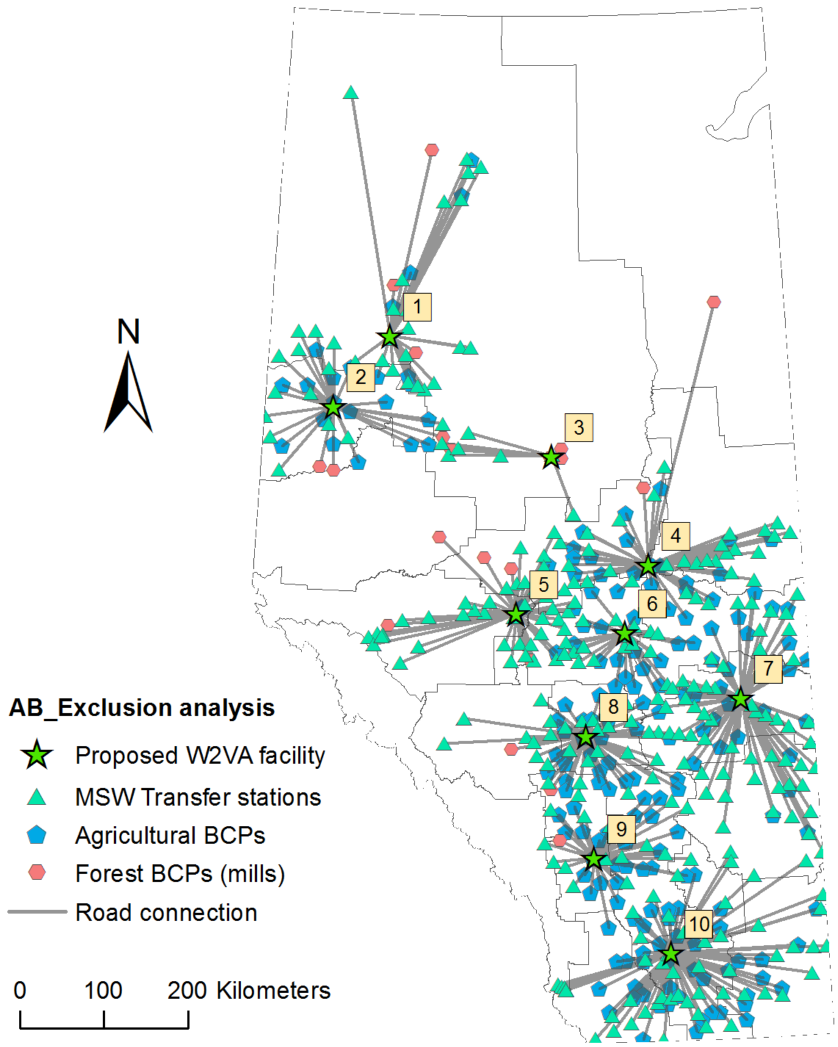


Figure 2-20: Optimal locations of 10 W2VA facilities in Alberta

2.6 Conclusion

Three types of feedstock – MSW, agricultural residue, and forest residue – were considered in this study. A precise estimate of their availability shows an annual potential, as of 2016, of 4,097,584 wet tonnes, 4,060,060 odt, and 2,077,418 odt for MSW, agricultural residue, and forest residue, respectively. A GIS-based land suitability model was developed to identify geographical locations, along with longitude and latitude, for agricultural and forest residue, as well as their annual potential. The developed GIS model was also used to identify the optimal location for siting a W2VA facility. Later, a specific case study was done for Alberta's Industrial Heartland (AIH) to identify an optimal location for a single W2VA facility. This case study considered the AIH boundary along with a 50 km transportation ring from its boundary as the study area. The study considered the use of waste heat for drying the biodegradable portion of MSW to bring its moisture content from 50% to 15%. The annual potential of MSW, agricultural residue, forest residue, and waste heat in AIH study area is 1,266,851 gross tonnes, 227,152 odt, 0 odt, and 47 MW, respectively. Depending on whether one or two waste heat sources are used for drying MSW, Scenario I and Scenario II were developed, respectively. Scenario I considered a W2VA facility next to waste heat source and one-stage feedstock transportation, i.e., MSW and lignocellulosic biomass were transferred directly to the W2VA facility. Scenario II considered MSW drying at two waste heat sources and then transporting dried MSW to a W2VA facility optimally located between waste heat sources through a land suitability model. This scenario uses two-stage feedstock transportation. The land suitability model identified geographical locations 53.797^{0}N, 113.091^{0}W and 53.797^{0}N, 113.154^{0}W for W2VA facilities for Scenario I and Scenario II, respectively, with an annual capacity of 911,252 odt/year.

Similar work was done in a second case study to identify 10 optimal W2VA facility locations across the province of Alberta. The locations are at gasification facilities, which integrate all types of waste in a single facility. The developed model can be used by private companies or government to understand feedstock potential along with collection point locations and optimal locations in the province for siting any W2VA facility.

Chapter 3: Assessment of Biomass-MSW Integrated Waste-to-Value-Added Facility

3.1 Introduction

Today, fossil fuels are major sources for providing primary and secondary energy across the world (Weldemichael and Assefa, 2016). The increasing consumption of fossil fuels results in increased emissions of greenhouse gas (GHG) emissions and have raised environmental and health concerns globally (Campbell-Lendrum and Corvalán, 2007b). Traditional treatments of landfilling or burning solid residues, including municipal solid waste (MSW), agricultural residue, and forest residue, is also causing a challenge for the environment (Kumar et al., 2003; MacDonald, 2009a; Mani et al., 2006; Ojha et al., 2007). Landfilling MSW leads to leachate formation and ultimately GHG emissions. These concerns can be addressed by using lignocellulosic biomass residues and MSW for energy production purposes, not only to substitute fossil fuels but also to prevent landfilling- and burning-related emissions (Schmer et al., 2014; Thornley et al., 2015; Weldemichael and Assefa, 2016; Zhang, 2016).

Alberta, a western Canadian Province, has an oil and coal-based economy and supplies 85% of its primary and secondary energy from fossil fuels (Weldemichael and Assefa, 2016). In year 2015, Alberta's total GHG emissions was 266.9 Mt CO_2-eq (Government of Canada, 2017). Agriculture, forestry, and MSW sector accounted for 8.8% whereas electricity sector accounted for 17% of the total GHG emissions in year 2015. Converting lignocellulosic biomass residue and MSW to value-added products, as well as replacing fossil fuels by renewable energies could potentially mitigate GHG emissions provincially. Currently, however, burning agricultural and forest residues on the field as well as landfilling MSW are the common waste management approaches followed by Albertans (only 19.56% of the total MSW is being diverted from the landfills to convert into value-added products) (Kumar et al., 2003; Statistics Canada, 2014a). Current practices not only contribute towards GHG emissions, but also cause loss of valuable assets of the province. Apart from lignocellulosic biomass and MSW, quality waste heat with high temperature range from energy intensive industries is directly exhausted into the atmosphere (CMC Research Institute et al., 2014). For example, the Alberta's Industrial Heartland (AIH) exhausts approximately 99 MW of heat into the atmosphere (CMC Research Institute et al., 2014). There exists a need to develop and implement environmentally friendly waste management pathways to address these issues.

There have been many studies conducted on biomass and MSW utilization pathways. Few studies have been on MSW utilization using various waste conversion technologies (Khan et al., 2016; Rizwan et al., 2018; Ruth, 1998; Weldemichael and Assefa, 2016). Some authors studied agricultural (Helwig et al., 2002a; Kumar et al., 2003; Sultana et al., 2010; Urošević and Gvozdenac-Urošević, 2012) and forest residue utilization techniques (Demirbaş, 2001; Kumar et al., 2003; Zamora-Cristales and Sessions, 2016). A few studies investigated techno-economic aspects of specific technologies (Bonk et al., 2015; Emery et al., 2007; Yassin et al., 2009). There are some studies, which considered geographic information systems (GIS)-based model for waste-to-value-added (W2VA) facility siting (Gorsevski et al., 2012; Khan et al., 2018; Şener et al., 2011; Yesilnacar et al., 2012). All of these studies have looked at single type of waste processed in a single facility. There is no study which considered integrated utilization of more than one waste in a single W2VA facility or considering geographically-identified biomass collection points (BCPs) for agricultural and forest residue, as well as real road network transportation distances in a techno-economic setting.

This study develops a framework to analyze the overall economy of a W2VA facility processing multiple types of feedstock via gasification technology to generate electricity. Four types of feedstock considered here are MSW, agricultural residue, forest residue, and waste heat. A techno-economic model, named **FUN**damental E**N**gineering Princip**lE**s-based model for Estimation of **Cost** of Energy from **Biomass and Municipal Solid Waste** (FUNNEL-Cost-Bio-MSW), developed here analyzes the technical and economical parameters associated with feedstock, conversion technology, investment, logistics, and transportation cost to assess the economic feasibility of W2VA facility in terms of Internal Rates of Return (IRR) and cost of generating electricity. In conjunction, a previously-developed geographic information systems (GIS)-based model defined in Chapter 2: was used as well to estimate the annual biomass and MSW availability at corresponding collection points, to optimally locate the W2VA facility, and to calculate the actual transportation distances. The following are the specific objectives of this study:

- To develop a techno-economic model to study the technical and economic feasibility of integrated waste-to-value-added (W2VA) facility;
- To study the feasibility of integrating more than one type of feedstock in a single W2VA facility;
- To perform a case study for technical and economical assessment of proposed 200 MW gasification facility in the Alberta's Industrial Heartland (AIH);
- To conduct sensitivity analysis to study the impact of the parameters on the overall results.

This model can help communities/municipalities to take investment related decisions on processing various types of wastes in a single W2VA facility to generate electricity. The developed model can be applied in any jurisdiction across the world.

3.2 Method

Developed GIS-based framework given in Chapter II was used to identify the geographical location of biomass collection points, as well as to quantify their corresponding feedstock availability at collection points. Same framework also identifies the optimal location of a W2VA facility and actual transportation distance between collection points and the facility. Proposed W2VA location was then economically assessed using the **FUN**damental E**N**gineering Princip**lE**s-based model for Estimation of **Cost** of Energy from **Bio-Municipal Solid Waste** (FUNNEL-Cost-Bio-MSW), based on various technical and economic parameters associated with feedstock, conversion technology, transportation, logistics, etc. This model takes agricultural residue, forest residue, MSW, and waste heat to generate electricity using gasification technology. The economic viability of the facility is finally presented in terms of IRR for fixed selling price of electricity and the cost of generating electricity for a fixed IRR.

3.2.1 GIS-based Model

The first step before techno-economic assessment of the W2VA facility is finding an optimal location to site the facility. Previously developed GIS-based model defined in Chapter II was used to identify the most optimal location for siting a W2VA facility. GIS-based model performs land suitability and location-allocation (network) analyses to identify areas for possible facility siting (Sultana and Kumar, 2012). Suitability analysis is a two-step process involving exclusion and preference analyses. Exclusion analysis screens out unsuitable lands from the study area. Various geographical constraints chosen based on governmental regulations and literature reviews were removed to filter only the areas suitable for facility siting. Preference analysis gives relative importance to areas surrounding geographical factors. Multiple buffer rings were created around each factor with grading values assigned on the scale of their relative importance. All the individual preference factors maps were combined as per the weightages, calculated using analytical hierarchy process (AHP), to get a single preference map (Saaty, 2001).

At the end, both the exclusion and preference analysis maps were combined to get the suitability map. The centroids of suitable areas were considered as candidate sites for W2VA facility.

Location-allocation analysis (network analysis) was afterwards performed to find out the most optimal location of W2VA (ArcGIS Resource Centre, 2012) using actual road network to connect feedstock collection points to the W2VA facility such that the transportation distance is minimized (ArcGIS Resource Centre, 2012).

3.2.1.1 Transportation Distances

Transportation distance is one of the major inputs into the developed FUNNEL-Cost-Bio-MSW model. GIS model helps measuring all those transportation distances required. Depending on the specific scenario being discussed, combination of transportation distances can be considered in the economic model. A few possible options are listed below:

i. Transportation distance between biomass collection point (BCP) to W2VA facility (for agricultural and forest residues);
ii. Transportation distance between waste sorting facility to landfill (for landfilling a portion of sorted MSW)
iii. Transportation distance between W2VA facility to landfill (for landfilling the ash residue)

3.2.2 Techno-economic Model

The developed model; FUNNEL-Cost-Bio-MSW, analyzes costs (e.g., feedstock cost, transportation cost, capital cost, operating cost, etc.) associated with generating electricity via gasification technology in a W2VA facility using various feedstock (MSW, agricultural residue, forest residue, and waste heat). The model assesses the economic feasibility of the proposed W2VA facility in terms of Internal Rates of Return (IRR) for fixed selling price of electricity and cost of generating electricity for a fixed IRR. The costs were all calculated in US dollar for the base year of 2017, where an inflation rate of 2% was assumed to bring all the costs to the year 2017 (Bank of Canada, 2017b).

3.2.2.1 Transportation Cost

Transportation cost mainly have two components: fixed and variable costs. The fixed component is the cost of loading/unloading ($/tonnne) material and does not vary with distance. The variable component ($/tonne/km) consists of fuel cost, driver cost, etc., and is a function of the distance travelled (Sultana and Kumar, 2012). The total transportation cost is sum of fixed and variable costs, and can be calculated by summing the multiplication of fixed transportation cost with feedstock availability at each collection point/transfer station and multiplication of variable transportation cost with real road distance between collection points/transfer stations to disposal location.

3.2.2.2 Feedstock Availability and Location

The techniques used to identify the feedstock availability and location are different for different types of feedstock. If a feedstock source is not in the form of point source (i.e., concentrated in one place), series of techniques are implemented to convert unevenly distributed sources into a point source. However, if it is in the form of point source, only its potential is required to be calculated.

MSW potential across Alberta was calculated using the 2016 census data and the average waste disposal rate of 1.064 wet tonnes per capita per year (Statistics Canada, 2014b). Annual MSW capacity of each of the 285 transfer stations across Alberta was then calculated using Thiessens polygon approach and population density variation in Alberta.

The agricultural residue considered here is straw coming from three major crops of Alberta: wheat, barley, and oats. Gross yield of straw was calculated using average grain production over the years 2006-2015 (Government of Canada, 2016) and straw-to-grain ratios (Sultana et al., 2010). Various losses associated with soil conservation, harvest machine efficiency, animal feeding and bedding, storage and transportation, and moisture content (MC) were removed from the gross yield to calculate net yield (Sultana et al., 2010). Average harvesting area was later multiplied with net straw yield to estimate the annual potential of agricultural residue in the area. The locations of agricultural residue BCPs were identified as per previously developed methodology given in Chapter 2:.

The forest residue considered here is roadside harvesting residue coming from harvesting operations. The net annual roadside residue across the province was calculated using blended yield of 24.7 oven dry tonnes (odt[4])/ha (Kumar et al., 2003) and the annual harvested forest area. Every forest mill in Alberta, which belongs to one of the forest management agreement (FMA) holders, was considered as a BCP, where the FMA holder collects and stores the roadside residue at. The annual capacity of those BCPs were calculated by multiplying provincial forest residue estimation with the ratio of FMA holders' harvesting volume to provincial harvesting volume. Further details are provide in Chapter 2.

Waste heat potential was considered only for a specific case of the Alberta's Industrial Heartland (AIH). Its availability was not provincially estimated since waste heat is difficult to transfer over long distances and, hence, its local availability is only considered here. Five waste heat sources along with their locations were identified in AIH. An earlier study (CMC Research Institute et al., 2014) suggests surplus availability of 99 MW of waste heat in the AIH. This study considered excess flue gas available in the AIH with temperature greater than 120 ^{0}C for drying higher MC feedstock.

[4] Oven dry tonnes can be defined as biomass having 0% moisture content

3.2.2.3 Energy Conversion Technology

This study considered gasification technology to generate electricity from lignocellulosic biomass and MSW. Many studies have been carried out on generating electricity via gasification technology using MSW and lignocellulosic biomass along with techno-economical assessment of the process (Dornburg and Faaij, 2001; Khan et al., 2016; Rizwan et al., 2018; Yassin et al., 2009). For example, Pereira et al. (Pereira et al., 2012) talks about governing parameters for producing various value-added products from gasification process, Khan et al. (Khan et al., 2016) suggested using fluidized bed gasifier with combined cycle gas turbine to produce electricity, and Yassin et al. (Yassin et al., 2009) shared details on technical and economic aspects along with study on combining fluidized bed gasifier with either of gas turbines, steam turbines, or combined cycle gas turbines. Out of the various possible combinations, fluidized bed gasifier with combined cycle gas turbine is an attractive option because of relatively lower cost and higher overall efficiency (Yassin et al., 2009).

Accordingly, this study considered fluidized bed gasifier joined with combined cycle gas turbine to generate electricity from lignocellulosic biomass and MSW. Since the waste suitable for gasification comes with MC of 15% or less (Wilson et al., 2013), feedstock with higher MC will be dried, using internal/external waste heat sources, until 15% or lower MC is achieved. All other necessary inputs are given in Table 3-12.

3.2.2.4 Cost and Revenue Parameters

The model takes various cost parameters as inputs. Major cost parameters considered are capital cost, operating cost, transportation cost, landfill tipping fee, and feedstock cost. The costs were taken from literature and developed as needed. A scale factor of 0.6 was used to scale up the capital and operating cost from the base prices (Khan et al., 2016; Kumar et al., 2003). Dumping landfill portion of MSW as well as ash from the proposed W2VA facility incurs landfill tipping cost. Feedstock cost is the cost associated with purchase and collection. On the other hand, revenue can be made by selling electricity to the grid, earning carbon credits, and receiving gate fee from municipalities for using their MSW. For all the calculations, plant life of 30 years is assumed in this study.

3.3 Case Study: Alberta's Industrial Heartland (AIH)

The present study is a specific case of the AIH, 30 km NW of Edmonton. The AIH is home to almost 40 petrochemical industries along with fertilizer companies, chemical factories, etc (Alberta Indsutrial Heartland, 2017). The AIH region along with 50 km transportation ring from the AIH boundary is considered here as the study area for this case as shown in Figure 2-11. In the presented case study, an optimal location of W2VA facility is being proposed using previously developed GIS-based model. The proposed location receives feedstock from collection points in the study area and generates electricity via gasification technology. Later, proposed W2VA facility is being assessed on its technical and economic performance. This case study can be a benchmark for communities/municipalities across the world to make waste management related decisions involving investment in a W2VA facility to generate electricity or any other value-added products. Figure 3-2 shows the flow diagram of overall process for this case study.

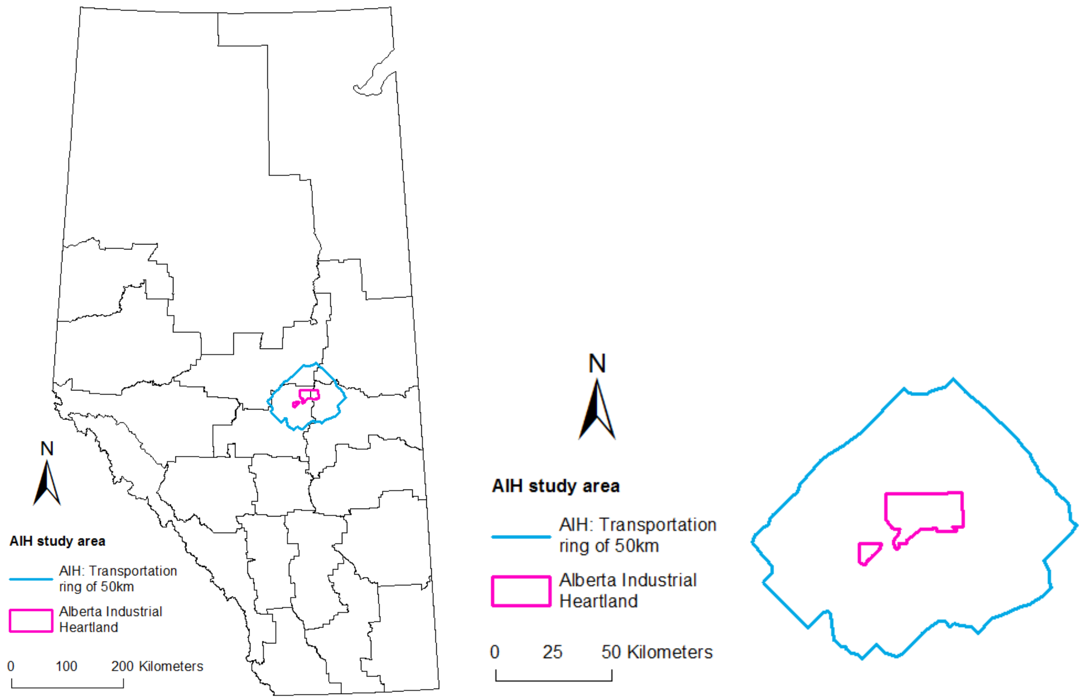


Figure 3-1: The AIH study area showing the AIH boundary along with the transportation network of 50 km from the AIH boundary

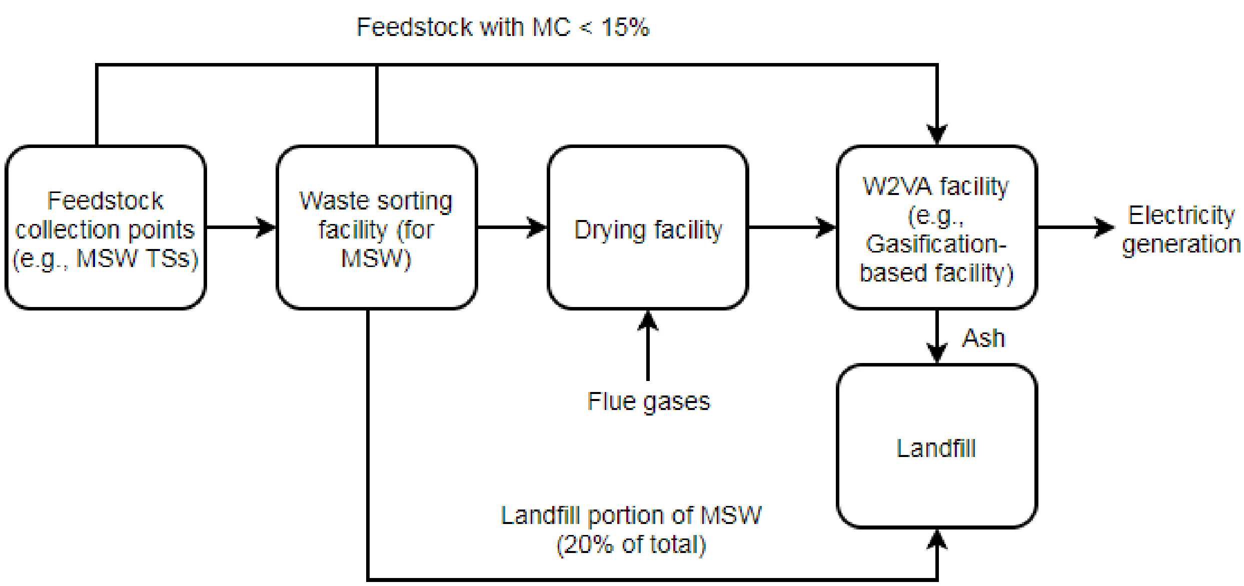


Figure 3-2: Process flow diagram from feedstock collection points to electricity generation

3.3.1 Feedstock Availability, Distribution, and Properties

No forest management agreement unit exists within the case study area. Therefore, there is no harvesting taking place; hence, no forest residue is available. However, remaining three types of feedstock: MSW, agricultural residue, and waste heat, are available. The potential of MSW and agricultural residue estimated using the approach discussed in section 3.2.2.2 is 1,266,852 wet tonnes (~684,100 odt) and 264,130 wet tonnes (~227,152 odt) per year, respectively, whereas surplus waste heat, as reported in the literature (CMC Research Institute et al., 2014) is 47 MW. Table 3-1 shows the feedstock properties considered for converting wet tonnes to odts and calculating plant capacity.

Table 3-1: Feedstock properties used for the case study

Feedstock		% distribution	Moisture content	Ash content	Calorific value (GJ/odt)	Comments/ Remarks
MSW	Thermal portion	40%	15%	15%	21.6	(Arena et al., 2015; Jacobs' Consultancy, 2013; Khan et al., 2016; Wilson et al., 2013)
	Biodegradable portion	40%	50%			
	Landfill	20%	-			
Agricultural residue	Wheat	-	14%	8%	17.8	(Bailey-Stamler et al., 2007; Chico-Santamarta et al., 2009; Sultana et al., 2010)
	Barley	-	14%	8%	19.2	
	Oats	-	14%	7%	18.1	

Nine MSW transfer stations (TSs) exists within the AIH study area as shown in Figure 3-3(a). Annual availability of MSW at each TS was estimated using Thiessens polygon approach where Thiessens polygon's area and MSW density were multiplied to calculate the MSW potential. City of Edmonton is the major source of MSW supply in the study area.

This study considered waste heat with its temperature more than 120^{0}C for drying purpose. Table 3-2 shows the three major waste heat source identified in the AIH whereas Figure 3-3(b) shows their location in the AIH (CMC Research Institute et al., 2014). Based on availability of waste heat in the AIH, the flue gas temperature of 350 ^{0}C was selected to be the operating temperature for drying purposes.

Table 3-2: Identified waste heat sources along with their geographical locations, waste heat potential, and temperature range in the AIH

Inferred company	Location	Estimated potential	Temperature range
Waste Heat I	(-113.182, 53.718)	8 MW	230-650 ^{0}C
Waste Heat II	(-113.091, 53.797)	19 MW	230-650 ^{0}C
Waste Heat III	(-113.163, 53.728)	20 MW	120-230 ^{0}C

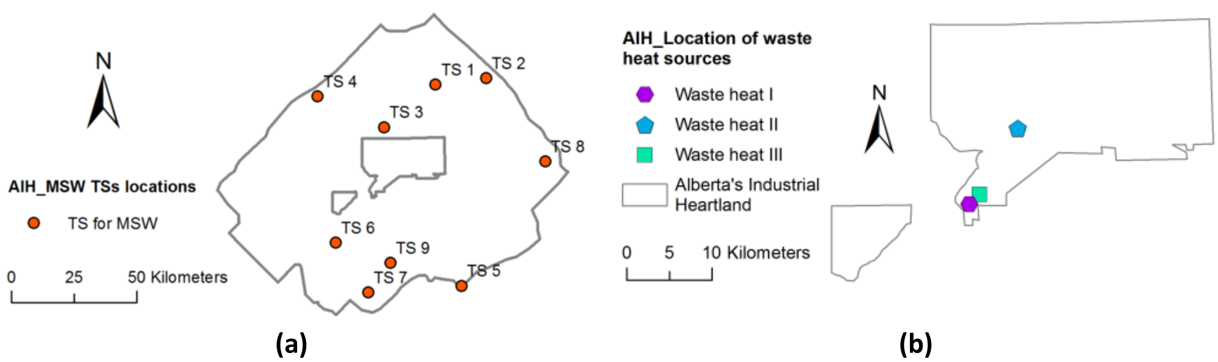


Figure 3-3: Locations of (a) MSW transfer stations; and (b) waste heat sources in the AIH

Agricultural biomass source points (BSPs) are the source of residue supply for BCPs. BSPs locations were identified as per the methodology given in Chapter 2:. Since agricultural residue is distributed across the whole study area, their BCPs, unlike MSW transfer stations, are not known. Therefore, a separate suitability analysis was performed to find the geographical locations of BCPs along with their annual capacity. Exclusion and preference analyses were performed as per the method mentioned in section 3.2.1. The exclusion constraints along with their buffer distances are listed in Table 3-3. Three preference factors considered for preference analysis along with their relative weights are presented in Table 2-4. These relative weights were calculated using Analytic Hierarchy Process (AHP). The combination of exclusion and preference analyses maps presents suitability analysis map showing areas suitable for locating BCPs in Figure 3-4(a), (b), and (c). Eventually, the network analysis gives the most optimal locations of agricultural BCPs from the pool of candidate sites as shown in Figure 3-4(d).

Table 3-3: Identified constraints and corresponding buffer zone distances for the exclusion analysis

Constraints	Specification	Source
Rivers, lakes, and other water bodies	Buffer of 300 m from water bodies	(Government of Alberta, 2010)
Rural and urban areas	Buffer of 1 km from rural and urban areas	(Eskandari et al., 2012; Ma et al., 2005)
Airports and heliports	Buffer of 8 km from international airports and 3 km from local airports	(Ma et al., 2005; Southern Alberta Energy From Waste Association (SAEWA), 2012)
Industrial and mining zones	Buffer of 1 km from industrial and mining zones	(Sultana and Kumar, 2012)
Environmentally sensitive areas (ESAs) (conservation areas, habitat sites)	Buffer of 1 km from ESAs	(Eskandari et al., 2012)
Natural gas pipelines	Buffer of 100 m from natural gas pipelines	(Ma et al., 2005; Sultana and Kumar, 2012)
Park and recreational areas	Buffer of 500 m from these sites	(Sultana and Kumar, 2012)
Wetlands	Buffer of 200 m	(Sultana and Kumar, 2012)
Roads	More than 30 m	(Sultana and Kumar, 2012)
Power plants and substations	Buffer of 100 m	(Sultana and Kumar, 2012)
Transmission lines	Buffer of 100 m	(Sultana and Kumar, 2012)
Land surface gradient	Land having slopes larger than 15% are removed	(Sultana and Kumar, 2012)

Table 3-4: Pairwise comparison matrix and weights of preference factors to locate agricultural BCPs

Preference factor	**BCP**	**Roads**	**Land cover**	**Weightage**
Waste availability – BSPs	1	3	9	0.66

Preference factor	BCP	Roads	Land cover	Weightage
Roads	0.33	1	6	0.28
Land cover	0.11	0.17	1	0.06

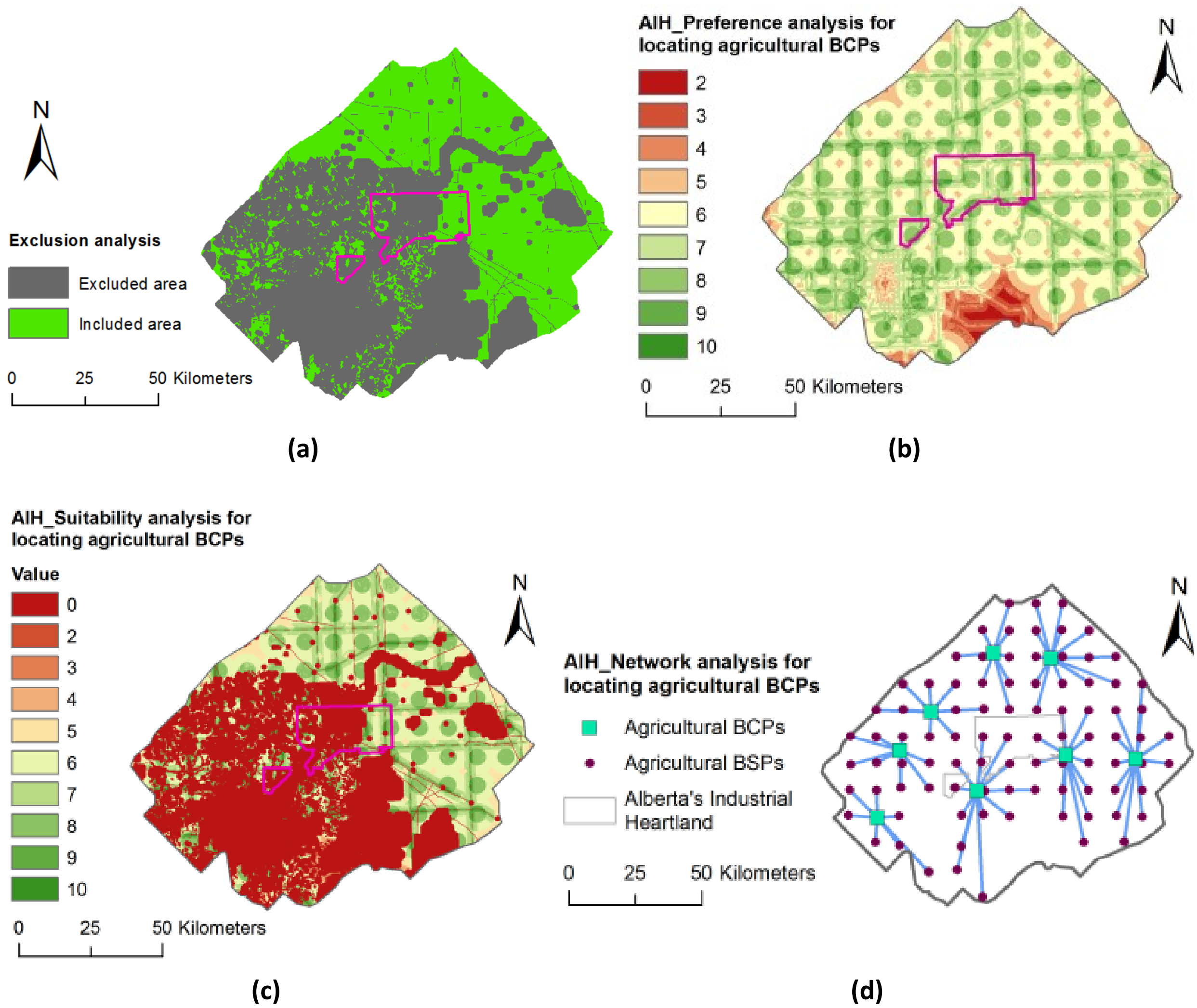


Figure 3-4: (a) Exclusion analysis map; (b) Preference analysis map; (c) Suitability analysis map; and (d) Location of agricultural BCPs for the AIH study area

Biodegradable content of MSW amounts for 40% of the total with MC of ~50%. However, 15% or less MC is suitable for gasification process (Khan et al., 2016). In order to bring the MC of MSW down to 15%, waste heat from neighboring industrial sources is used. Therefore, higher MC MSW is directly sent to drying facility to reduce the MC to 15% or less. The dried feedstock is then transported to W2VA facility for gasification. Since agricultural residue comes with approximate MC of 15%, no drying is needed. Therefore, agricultural residue is directly sent to W2VA facility. Table 3-5 shows the properties of different feedstock considered in this study.

Table 3-5: Properties of feedstock used in this case study

Property \ Feedstock	MSW	Agricultural Residue			Reference
		Wheat straw	**Barley straw**	**Oat straw**	
Moisture content (%)	Non-biodegradable MSW: 15% Biodegradable MSW: 50%	14%	14%	14%	(Kumar et al., 2003; Sultana et al., 2010)
Thermal heating value (Gj/odt)	21.60	17.80	19.20	18.10	(Arena et al., 2015; Bailey-Stamler et al., 2007; Chico-Santamarta et al., 2009)
Ash content (%)	15%	8%	8%	7%	(Bailey-Stamler et al., 2007; Wilson et al., 2013)

3.3.2 Transportation Cost

In this case study, fixed and variable costs are considered $6.51 per tonne (Chornet, 2012; Kumar et al., 2003) and $0.24 per tonne per km (Chornet, 2012), respectively. The average truck size considered is 6.5 tonnes per trip (Sultana and Li, 2014).

3.3.3 Facility Site Selection

In this study, facility site selection depends majorly on the location of waste heat source, and that is because biodegradable content of MSW requires drying, hence, W2VA location is required to be near the waste heat sources in order to reduce transportation distances and thus, costs. Therefore, two different scenarios were developed as follows:

Scenario I: In this scenario, W2VA facility was considered right next to a waste heat source so that waste heat transportation over a long distance is avoided to retain the waste heat quality. This scenario assumes waste heat from single source is enough for MSW drying purpose. Based on availability of waste heat and temperature range of flue gas, W2VA was placed next to waste heat source II (see Table 3-2) along with the biomass drying and waste sorting facility. MSW was transported from transfer stations to waste sorting facility. In this case, transportation distances between (1) waste supply points (MSW TSs and agricultural BCPs) to W2VA facility, and (2) W2VA facility to landfill, where ash and MSW (the portion to be landfilled) are landfilled, were considered in the economic model. Figure 3-5 shows the location of W2VA facility and real road connection between W2VA facility and waste supply points. The identified location of W2VA facility is (-113.091, 53.797) with annual capacity of 911,252 odt/year.

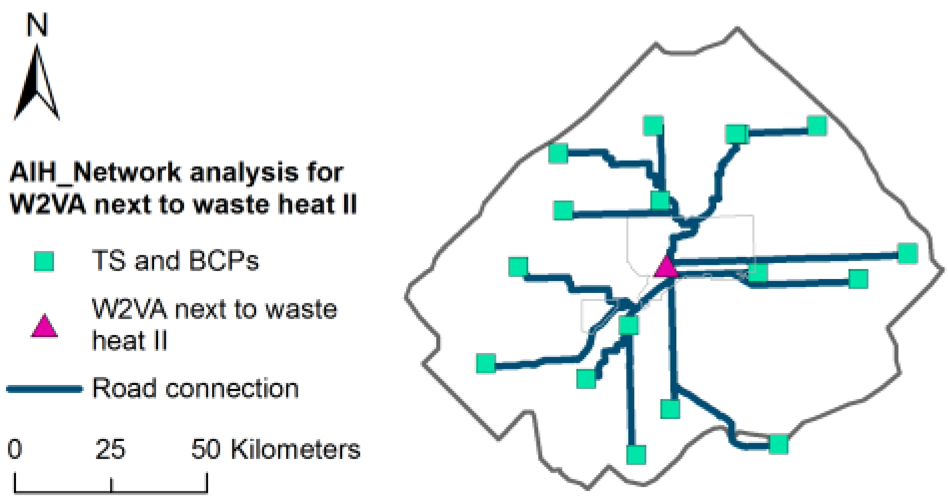


Figure 3-5: Real road network connecting W2VA facility to MSW TSs and agricultural BCPs

Scenario II: This is a more realistic scenario where waste heat is used at two different locations. If waste heat is not enough at one source, a second or third source can be brought into picture. Based on the amount of waste heat available and the temperature of flue gas, waste heat source I and II were considered in this scenario. MSW from nine transfer stations were distributed between two waste heat sources such that each heat source utilizes more than 75% of their available heat for MSW drying.

The transportation distances between (1) MSW TS to waste heat source I and II, (2) Agricultural BCP to W2VA facility, (3) waste heat source I and II to the W2VA facility for dried MSW transport, (4) waste heat sources I and II to the landfill for transport of 20% of MSW which is to be landfilled, and (5) W2VA to the landfill for ash transport were considered here in the economic model.

The location of W2VA facility was identified using suitability analysis. The 12 constraints previously listed in Table 3-3 were used here in exclusion analysis. Following eight preference factors, chosen based on literature reviews (Khan et al., 2016; Ma et al., 2005; Sultana and Kumar, 2012; Tavares et al., 2011), were used for preference analysis.

i. Waste heat source locations
ii. Location of urban and rural areas
iii. Water availability
iv. Road network
v. Transmission lines network
vi. Locations of power substations
vii. Land cover
viii. Slope

All the individual preference maps were combined as per the relative weights given in Table 2-13 to get the final preference map. Suitability analysis was performed by combining exclusion and preference analyses maps. Later, network analysis helped identifying the most optimal location for siting W2VA facility in the vicinity of both the waste heat sources such that transportation distances are minimized. Figure 3-6(a) and (b) shows the result of suitability analysis with the most optimal location of W2VA facility connecting heat sources to the facility. The identified location is (-113.154, 53.726) with annual capacity of 911,252 odt/year.

Figure 3-7 shows the network analysis between MSW TSs and waste heat sources I and II, and agricultural BCPs to proposed W2VA facility. In this case study, the amount of MSW processed by waste heat source I and II is 410,625 wet tonnes per year and 856,227 wet tonnes per year, respectively. However, the biodegradable content (40%) of MSW available at Waste Heat I and II is 164,250 and 343,491 wet tonnes/year, respectively. The corresponding waste heat required at both sources are 6.89 MW and 14.36 MW, respectively.

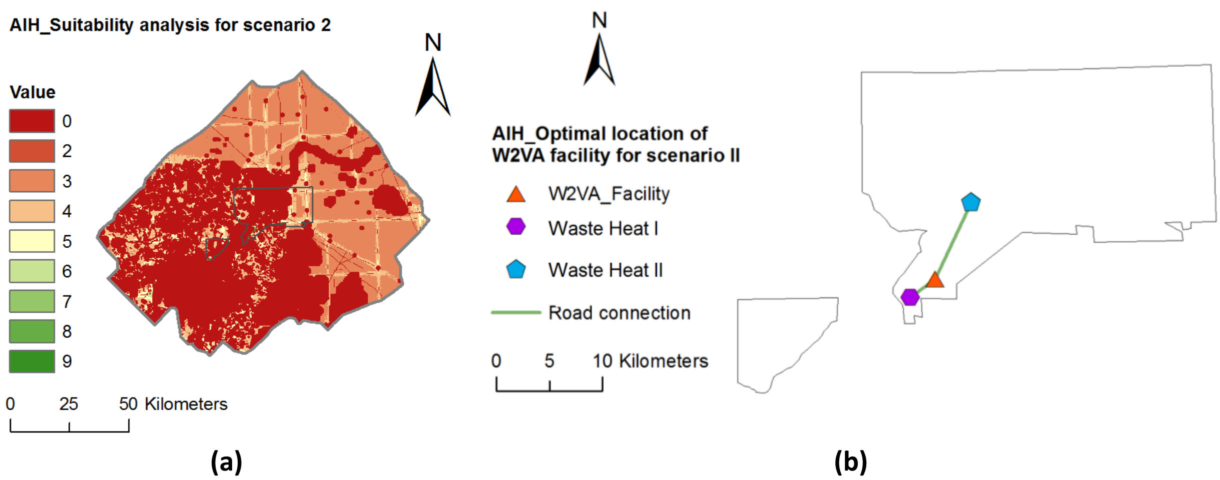


Figure 3-6: (a) Suitability analysis results; (b) Network analysis between waste heat sources and W2VA facility in scenario II

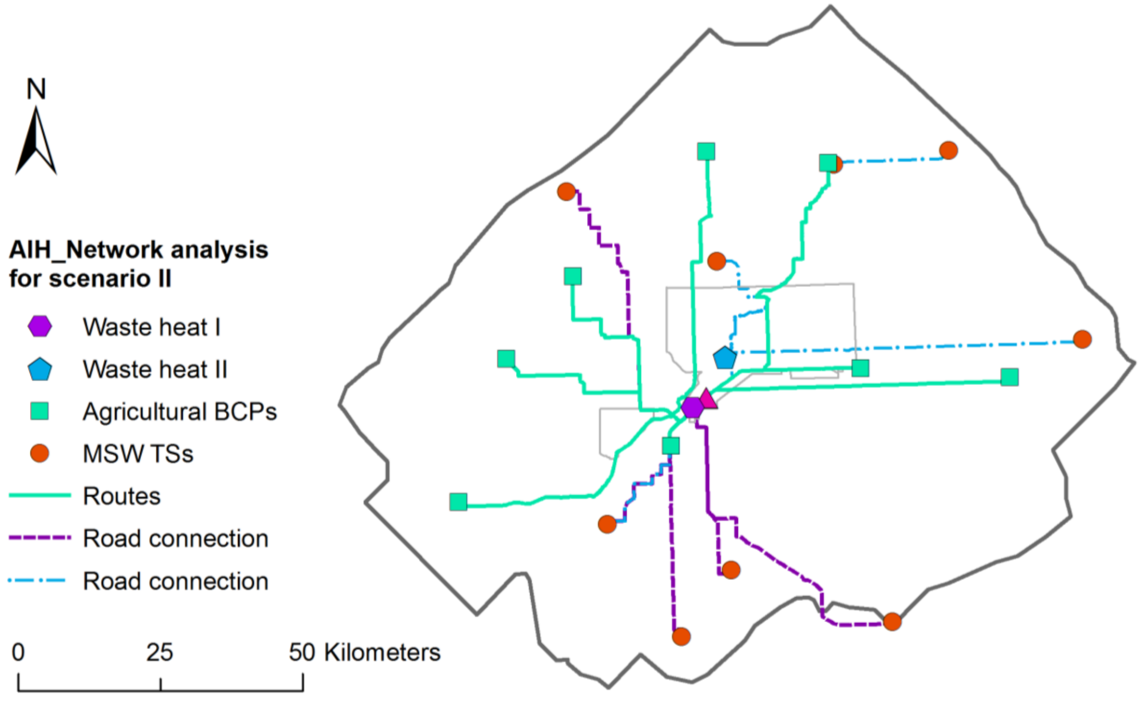


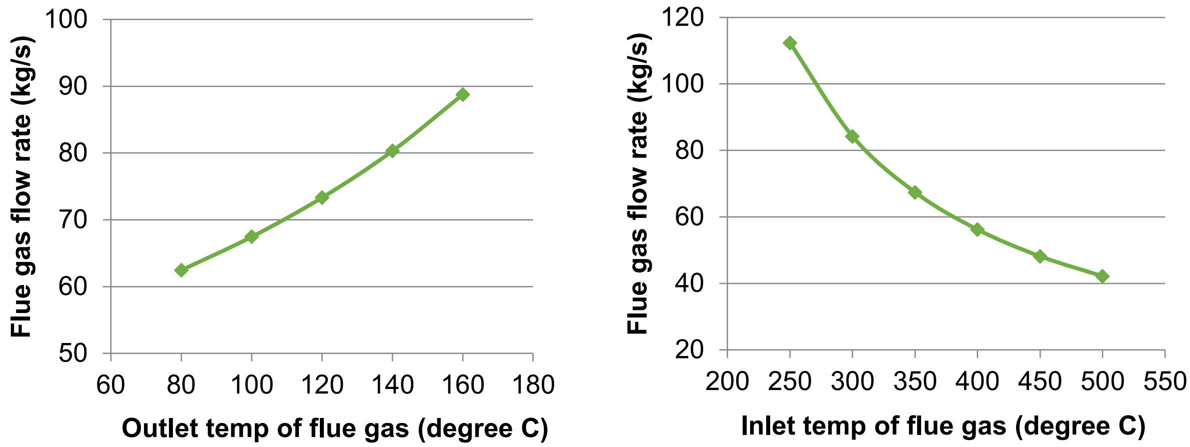
Figure 3-7: Network analysis map with roads connecting MSW TSs to waste heat sources and agricultural BCPs to W2VA facility in Scenario II

3.3.4 Biomass Drying Using Flue Gases

For the purpose of calculating the amount of flue gas required for drying the biodegradable portion of MSW, flue gas composition is important. It was taken from literature since the exact composition was not reported by the waste heat sources. Based on the W2VA capacity, MSW flow rate was calculated 17.6 wet kg/s. Hot flue gas removes moisture as well increases the temperature of MSW. It is assumed that inlet temperature of flue gas is 350 ^{0}C whereas MSW enters the dryer at 15 ^{0}C and exits at 100 ^{0}C. Using basic energy balance equation, total energy required for drying MSW from 50% to 15% MC is calculated 21.24 MJ/s. The mass flow rate of flue gas required for inlet and exit temperatures of 350 ^{0}C and 100 ^{0}C is 67.44 kg/s. Table 3-6 shows the properties and drying specification of MSW and flue gas. Variation in required flue gas flow rate with (a) outlet temperature of flue gas for fixed inlet temperature of 350 ^{0}C; and (b) inlet temperature of flue gas for fixed outlet temperature of 100 ^{0}C is shown in Figure 3-8 (a) and (b), respectively.

Table 3-6: Properties and drying specifications of MSW and flue gas

Type	Property		Value	Remarks
MSW	Flow rate		17.6 wet kg/s	Calculated based on plant capacity
	Initial MC		50%	-
	Final MC		15%	-
	Inlet temperature		15 ^{0}C	Assumption
	Outlet temperature after drying		100 ^{0}C	Assumption
	Specific heat, $C_{p,MSW}$		1.8 kJ/kg-K	(Luk et al., 2013)
Flue gas	Composition	CO_2	8.7%	(Reddy et al., 2014)
		N_2	70.7%	
		O_2	1%	
		H_2O	19.6%	
	Specific heat, $C_{P,flue}$		1.26 kj/kg▪K	(Increase Performance, 2017)
	Flue gas density, ρ_{flue}		0.498 kg/m^3	
	Pressure		5 bar	Assumption
	Inlet temperature		350 ^{0}C	(CMC Research Institute et al., 2014)



(a) (b)

Figure 3-8: Direct drying using flue gas: Variation in required flue gas flow rate with (a) outlet temp of flue gas from heat exchanger; (b) inlet temp of flue gas to the heat exchanger

3.3.5 Techno-Economic Assessment

A techno-economic model was developed to assess the technical and economic viability of the proposed integrated W2VA facility. This model considered few assumptions as listed below:

- W2VA facility is not responsible for the MSW collection and transportation cost from residences to MSW TSs.
- The cost of MSW transportation from transfer stations (TSs) to the W2VA facility is covered in the gate fee charged by municipalities. Hence, this cost would not be incurred by the W2VA facility.
- The agricultural residue production cost along with cost of transporting agricultural residue from the field to the W2VA facility is incurred by the W2VA facility.
- All the feedstock available within the study area is transported to the optimally located W2VA facility.

3.3.5.1 Feedstock Availability and Plant Capacity

Optimally located W2VA facility takes dried MSW and agricultural residue for gasification. Using the total MSW and agricultural residue with availability of 684,100 and 227,152 odt per year, respectively, along with their thermal heating value, the total thermal capacity of the plant was calculated 5.3 TWh. Considering 8,000 hours of facility operation and 30% plant efficiency, net plant capacity was estimated 199 MW. Table 3-7 shows the net annual feedstock supply along with thermal and electric capacity of the proposed W2VA facility.

Table 3-7: Annual feedstock supply and plant capacity

Parameter		Values
Feedstock availability in AIH	MSW	684,100 odt/yr
	Agricultural residue	227,152 odt/yr
Max thermal power available	MSW	4,137,437 MWh
	Agricultural residue	1,168,167 MWh
	Total	5,305,604 MWh
Efficiency of gasification plant		30%
Net energy production		1,591,681 MWh
Facility operating hours		8,000 hours
Net plant capacity		199 MW

3.3.5.2 Capital and Operating Costs

Three major units contribute to the overall capital cost of the plant. These are gasification plant with steam turbines, the waste sorting facility, and the biomass drying facility. The capital and operating costs for this case study were calculated based on previously published studies and are shown in Table 3-8 and Table 3-9. All the capital and operating costs were scaled up by a scale factor of 0.6 from base case costs. Base case is a reference case for which we already have the costs available from previously published literature.

This study considered belt dryer with hot flue gases as a medium for drying biodegradable content of MSW. Dimension and equipment cost of dryer were calculated using ASPEN software (AspenTech, 2018). The capital cost of drying facility was calculated using a multiplication factor of 5.16 that covers costs associated with installation, electricity, instrumentation, civil work, etc. The operating cost was assumed as 10% of the total capital cost (Hosseinizand et al., 2017). Dryer size depends on the biomass residence time and it varies inverse proportionally. The mass flow rate of MSW passing through the dryer is 16.53 kg/s, calculated using the available MSW (biodegradable content). Table 3-10 shows the dryer dimensions along with corresponding capital and operating cost for various residence times.

Table 3-8: Capital cost of gasification and waste sorting facilities

Facility type	Case			Year	Plant size	Capital cost (million $)	Comments/ Remarks
Gasification facility	Base case			2006	250 MW	383.10	Calculated using cost rate of $1,532/k (Cameron et al., 2007)
	AIH study			2017	199 MW	415.40	-
Waste sorting facility	Base case			2017	45,000 wet tonnes/yr	10.50	Calculated using cost rate of $177/tonne of MSW (Li, 2017b)
	AIH study	Scenario I		2017	1,266,852 wet tonnes/yr	58.93	-
		Scenario II	At Waste Heat I	2017	856,227 wet tonnes/yr	46.58	-
			At Waste Heat II	2017	410,625 wet tonnes/yr	29.97	-

Table 3-9: Operating cost of gasification and waste sorting facilities

Facility type	Case			Year	Plant size	Operating cost (million $/yr)	Comments/Remarks
Gasification facility	Base case			2015	18,214 odt/yr	1.53	Considered as 4% of capital cost (Cameron et al., 2007)
	AIH study			2017	911,252 odt/yr	16.60	-
Waste sorting facility	Base case			2017	45,000 wet tonnes/yr	1.80	Calculated using cost of $40/tonne of MSW (Li, 2017b)
	AIH study	Scenario I		2017	1,266,852 wet tonnes/yr	10.10	-
		Scenario II	At Waste Heat I	2017	410,625 wet tonnes/yr	5.14	-
			At Waste Heat II	2017	856,227 wet tonnes/yr	7.99	-

Table 3-10: Flue gas dryer capital and operating cost

Equipment	Parameter	Value	Comments/Remarks
Flue gas dryer	MSW flow rate	16.53 kg/s	Calculated using biodegradable portion of MSW available from study area for drying
	Equipment cost	417,000 ($)	Calculated using MSW drying rate and temperature difference between input and output in ASPEN Plus
	Multiplication factor	5.16	Covers cost associated with installation, electricity, instrumentation, civil work
	Total capital cost	2.23 (million $)	-
	Total operating cost	0.07 (million $/yr)	Considered as 3% of the capital cost (Li et al., 2012a)

3.3.5.3 Agricultural Residue Production Cost

Agricultural residue production cost was calculated based on several previously published studies. This cost includes harvesting cost, bale wrap cost, bale collection, bale on-field storage, farmer's premium, and nutrient replacement cost (C. Brechbill et al., 2011; Campbell, 2007; Kumar et al., 2003; Liu, 2008). All the costs were calculated based on the current technologies and common farming practices. Therefore, tillage management practices were not considered for estimating straw recovery. It is also assumed that farmers are willing to sell all the straw available within the study area after removing all the losses associated with soil retention, animal bedding and feeding, harvest machine efficiency losses, and transportation losses. Here, round shape bales weighing in the range of 360-500 kg (Liu, 2008) were considered. Table 10 shows individual along with total agricultural residue production cost.

Table 3-11: Agricultural residue production and collection costs

Parameters	Component	Value ($/tonne)	Comments/ Remarks
Harvesting cost	Shredding, Raking, and Baling	11.51	(C. Brechbill et al., 2011)
Collection cost	Bale picker & Tractor	5.08	(Liu, 2008)
Bale wrap	Twine wrap	0.59	(C. Brechbill et al., 2011)
Bale storage cost	On-field-storage Storage premium	2.15 0.12	(Campbell, 2007)
Farmer premium cost	-	6.57	(Kumar et al., 2003)
Nutrient replacement cost	-	27.03	Calculated by multiplying the amount of nutrient required with cost of fertilizer containing the nutrient (Kumar et al., 2003)
Total Cost		53.05	

3.3.5.4 Economic Inputs

Selling rate of electricity, carbon credit offset rate, landfill-tipping fee, and gate fee variables are the other inputs of the model. Selling price of electricity was taken as three-year average between 2015-17. Landfill tipping fee is the charge levied by landfills for dumping any kind of waste whereas gate fee is the fee levied by waste management facility for processing the waste. It is assumed that plant construction duration is spread over three years with construction completion phase at the rate of 20%, 35%, and 45% (Sultana et al., 2010). Similarly, plant capacity factor at which plant will operate for year 1, year 2, and year 3 onwards is 70%, 80%, and 85%, respectively (Sultana et al., 2010). Table 3-12 shows all the input parameters considered in the model.

Table 3-12: Inputs for the economic model

Parameters	Value	Comments/ Remarks
Plant capacity	199 MW	Calculated using available feedstock within study area and their electrical potential
Scale factor	0.6	(Khan et al., 2016; Kumar et al., 2003)
Carbon credit (tonnes of CO_2/MT of MSW)	2	(Chornet, 2012; Nguyen et al., 2007; Sultana and Li, 2014; Zaman, 2010)
Carbon credit (tonnes of CO_2/MT of agricultural residue)	1	(Bhattacharya et al., 1999; Kadiyala et al., 2016; Shafie et al., 2014; Urošević and Gvozdenac-Urošević, 2012)
Selling rate of electricity	\$18.94/MWh (~CA\$ 25/MWh – 2015-2017 average data)	(Alberta Electric System Operator, 2017)
Carbon credit/offset rate	\$15.15/tonne (~CAD 20/tonnes – 2017 data)	(Government of Alberta, 2016e; Li, 2017b)
Landfill tipping fee	\$60/tonne (2017 data)	(Li, 2017b; The City of Edmonton, 2017)
Gate fee	\$56/tonnes (~CAD 70/tonne - 2017 data)	(Li, 2017b)
Inflation rate	2%	(Bank of Canada, 2017b)
Plant life	30 years	Assumption
Spread of cost		(Sultana et al., 2010)
Year 1	20%	
Year 2	35%	
Year 3	45%	
Plant capacity factor		(Sultana et al., 2010)
Year 1	70%	
Year 2	80%	
Year 3	85%	

3.3.5.5 Results

The developed economic model, FUNNEL-Cost-Bio-MSW, analyzed the cost of generating electricity using multiple feedstock via a gasification technology. The revenue components of the model are coming from carbon credit, collecting gate fee, and selling electricity whereas cost components are capital cost, operating cost, transportation cost, and tipping fee of landfills. Transportation costs were calculated using transportation distances previously obtained in GIS-based model in chapter 2. The output of the cost model is in terms of IRR for a fixed selling price of electricity and cost of generating electricity for a fixed IRR. The observed IRRs for scenario I and II is 11.18% and 8.09%, respectively.

Revenue component from gate fee constitute the major portion and is equal to 52.9% of the total revenue as shown in Figure 3-9. This means MSW is a major contributor in overall economics of the plant. Further, higher carbon offset rate for MSW (2 tonnes of CO_2-eq/tonnes of MSW (Chornet, 2012; Nguyen et al., 2007; Sultana and Li, 2014; Zaman, 2010)) than agricultural residue (1 tonnes of CO_2-eq/tonnes of agricultural residue (Bhattacharya et al., 1999; Kadiyala et al., 2016; Shafie et al., 2014; Urošević and Gvozdenac-Urošević, 2012)) shows importance of MSW over agricultural residue with respect to W2VA facility's economic performance. The IRR for scenario II is less than scenario I because of extra costs associated with waste sorting facility, drying facility, and transportation distances. Since scenario II considers more than one waste heat source along with W2VA location optimized in between the heat sources, there are extra set of transportation distances that the trucks need to cover. Total transportation costs for scenario II is 69% more than scenario I whereas there are also costs associated with one extra waste sorting facility and flue gas dryer in scenario II. Further, if the capacity of the plant is increased and single waste heat source is not enough for drying the MSW, more than one waste heat source would be used. Hence, the IRR of the facility would be compromised. In this study, since, in scenario I, sufficient waste heat is available at waste heat II, one waste heat source is enough for drying the biodegradable portion of MSW required in proposed 199 MW W2VA facility.

Similarly, using IRR of 12% based on earlier studies, cost of generating electricity for scenario I and II was calculated to be \$21.90 and \$33.23 per MWh, respectively. Against the current selling price of electricity of \$18.94/MWh, both scenarios had higher cost of producing electricity. Again, scenario II had higher costs because of extra transportation cost, waste sorting and drying facility cost. The electricity generation costs were calculated after considering carbon credit rate of \$15.15/tonne of CO_2-eq. However, with the projected increase in carbon credit, the cost of generating electricity can significantly decrease whereas IRR can increase.

Figure 3-9 & Figure 3-10 show the cumulative cash flow diagram for scenario I and II, respectively, along with individual contribution by various costs and revenues over the 30 years of plant life. The cumulative cash flow decrease to zero at the end of plant life meaning investment would be recovered in 30 years at an IRR of 11.18% in scenario I and 8.09% in scenario II.

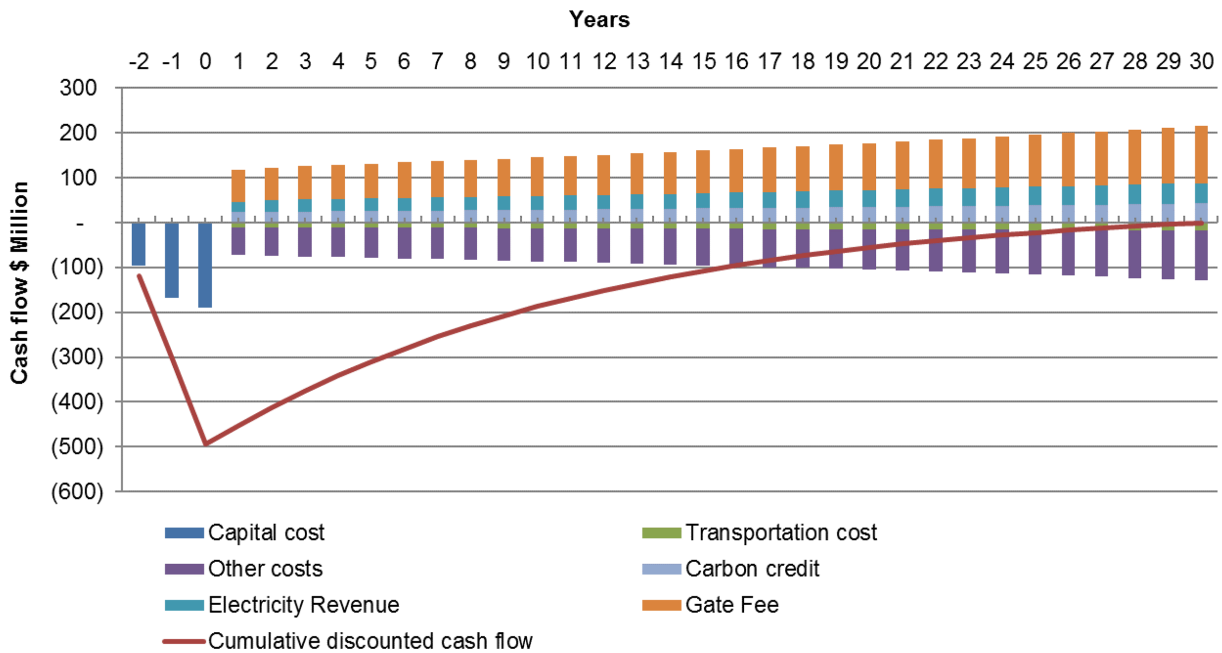


Figure 3-9: Discounted cash flow analysis of 199 MW gasification plant capacity for scenario I

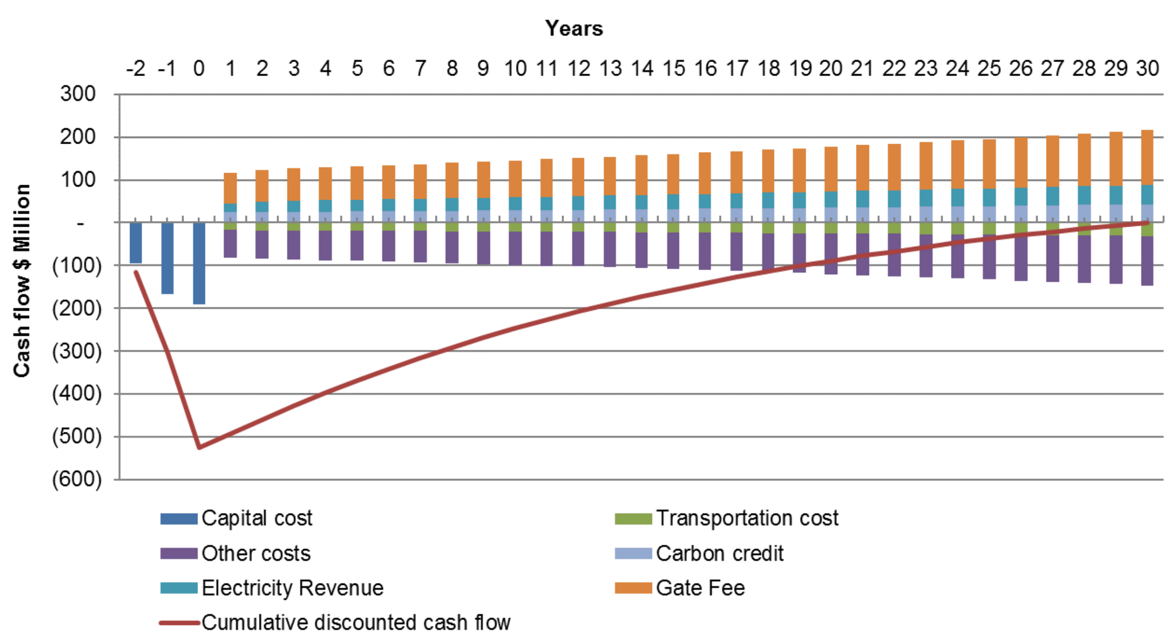


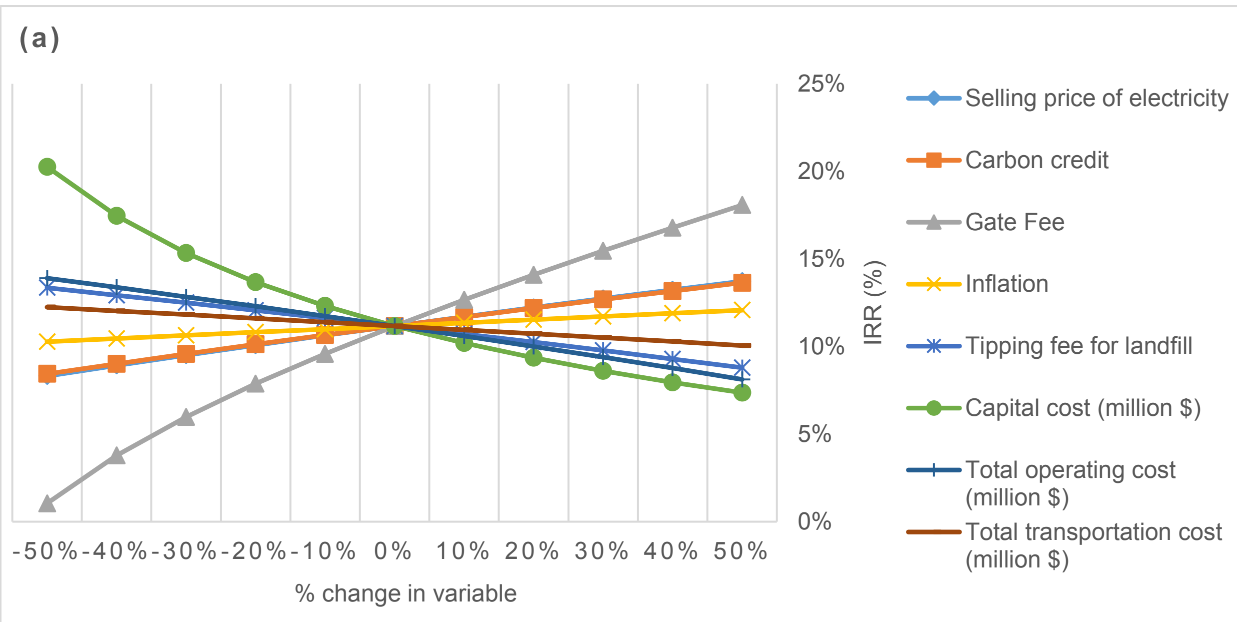
Figure 3-10: Discounted cash flow analysis of 199 MW gasification plant capacity for scenario II

3.3.6 Sensitivity Analysis

In order to understand the effect of input variables (cost and revenue parameters) on IRR and cost of producing electricity, sensitivity analysis technique was used. The sensitivity analysis involved understanding the effect of ±50% variation of input variables on the outputs.

Capital cost and the gate fee affect the IRR the most in scenario I, which considered W2VA facility next to Waste Heat I, whereas total operating cost and gate fee affect the IRR the most in scenario II, which considered W2VA facility optimally located in between Waste Heat I and II. Inflation and total transportation cost has the least impact on IRR in both the scenarios. For a change in capital cost by -50% and +50%, IRR changes by 81.03% and -34.09%, respectively in scenario I, and by 92.27% and -40.19%, respectively in scenario II. Similarly, by changing the gate fee by -50% and +50%, IRR changes by -90.63% and 61.76%, respectively in scenario I, and by -180.29% and 86.86%, respectively in scenario II. Future technological advancement in gasification technology may reduce the capital cost that may lead to increase in IRR. Revenue from the gate fee for taking waste from municipalities contributes 59.2% to the total revenue of the plant. Hence, change in gate fee affects IRR more than any other input variable. Figure 3-11 shows the sensitivity analysis of IRR for set of input variables for scenario I and II.

Similarly, for a fixed IRR of 12%, the cost of generating electricity was calculated to be $21.90 and $33.23 per MWh in scenario I and II, respectively. This cost was calculated after considering carbon credit offset rate of $15.15 per tonnes of CO_2. Without carbon credit, the cost of generating electricity is $40.17 and $51.49 per MWh in scenario I and II, respectively, which is way more than current electricity pool price of $18.94/MWh (Alberta Electric System Operator, 2017). Without carbon credit, biomass-based gasification for generating electricity is not economical. If the carbon credit rate increases in near future, cost of generating electricity can very well decrease which can make it more competitive with fossil fuel-based electricity. Figure 3-12 shows the sensitivity analysis of selling price of electricity with respect to other input variables for scenario I and II. All the input variables are same as mentioned above except IRR. Gate fee has the most effect on cost of generating electricity followed by capital cost, and then carbon credit. On the other hand, inflation affects least followed by transportation cost. On changing gate fee by -50% and +50%, cost of generating electricity changes by ±124.19% in scenario I, and 81.85% and -451.05%, respectively, in scenario II, whereas on changing capital cost by -50% and +50%, cost of generating electricity changes by -91.26% and +91.26%, respectively in scenario I and -65.46% and 39.56%, respectively, in scenario II.



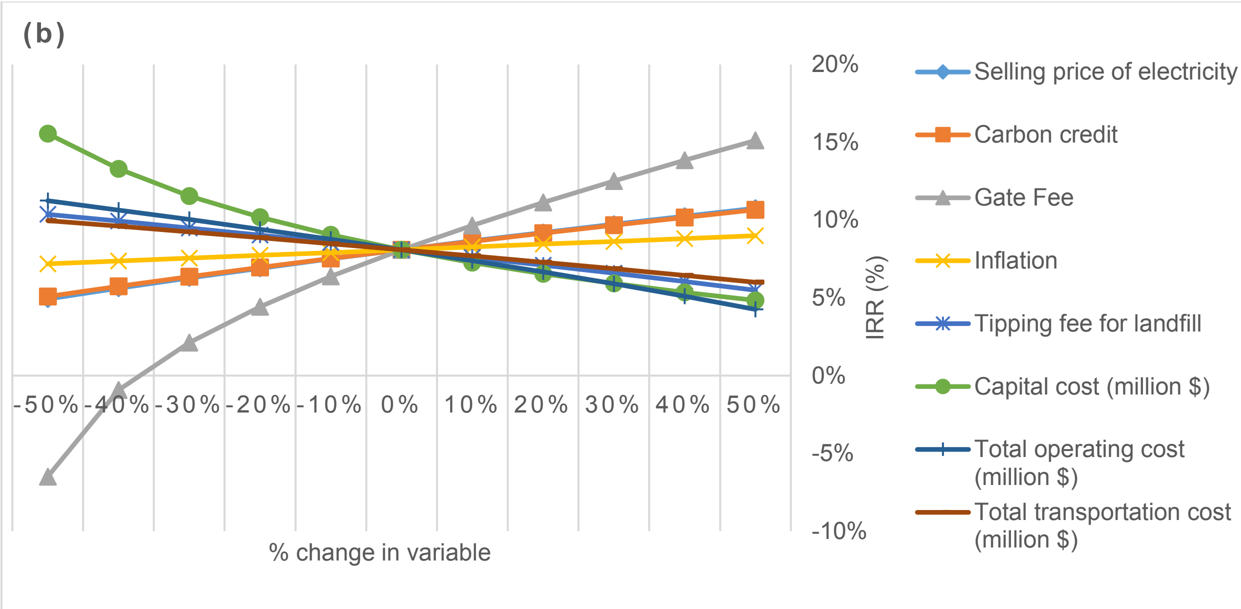
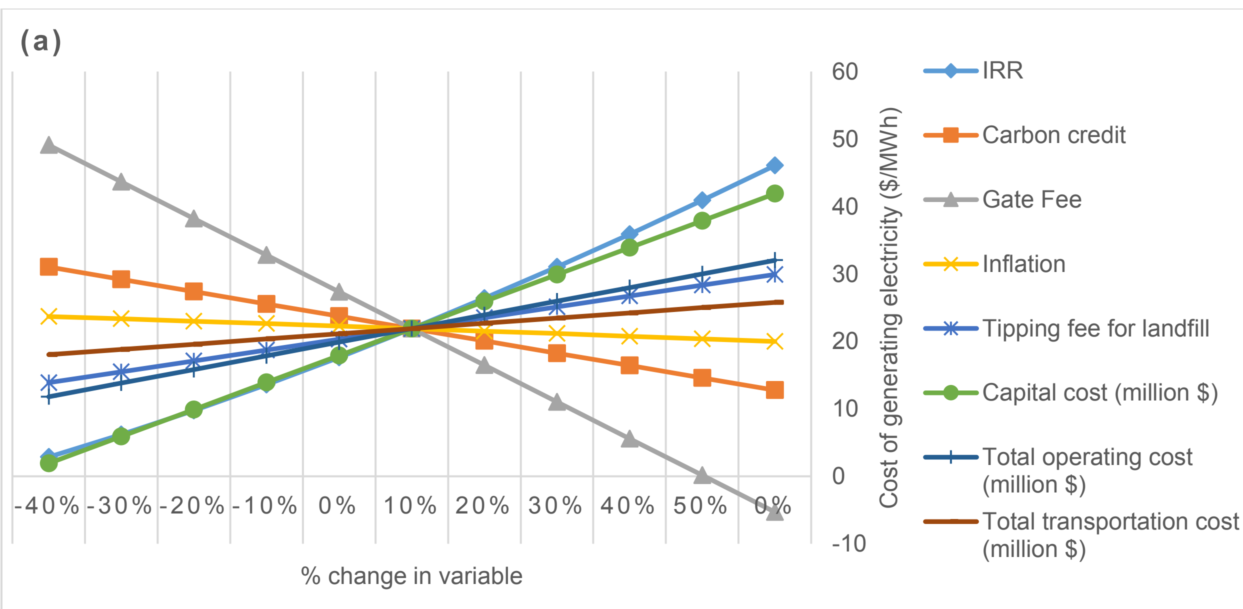


Figure 3-11: Sensitive analysis of IRR with respect to other input variables for (a) scenario I, and (b) scenario II



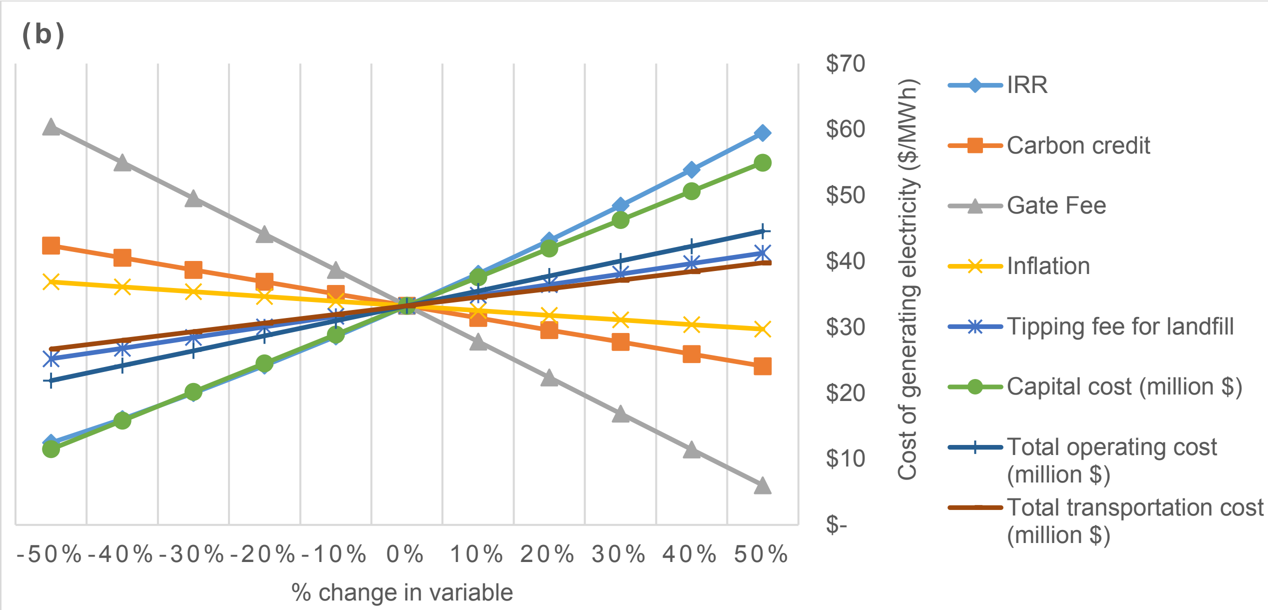
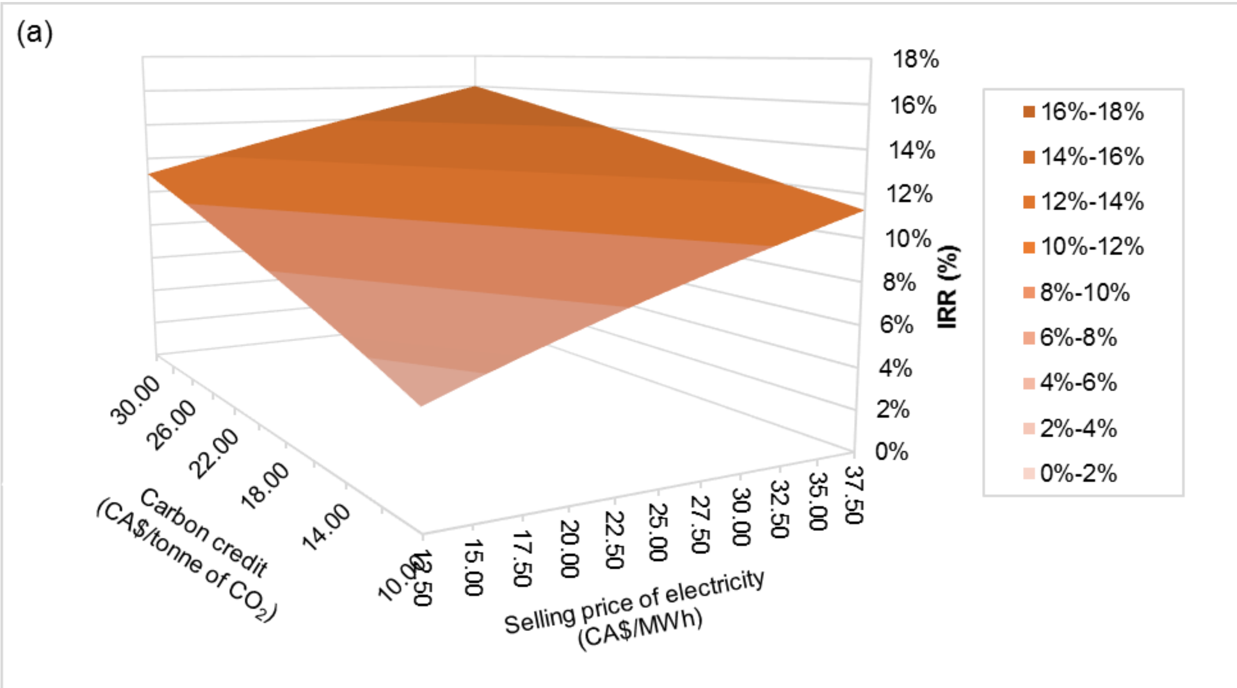


Figure 3-12: Sensitive analysis of cost of generating electricity with respect to other input variables for (a) scenario I, and (b) scenario II

In order to understand the simultaneous effect of carbon credit and selling price of electricity on IRR, surface graph was created for both the scenarios I and II as shown in Figure (1) and (2). Higher values of carbon credit and selling price of electricity results in IRR greater than 12%. The highest IRR observed is 20.30% in scenario I and 13.07% in scenario II for carbon credit rate of $22.72 per tonnes of CO_2 and electricity selling price of $28.40 per MWh. Generating electricity in this plant is economical if its production cost is less than the current electricity pool price. For a sound investment return of 12% in scenario I, cost of generating electricity should be less than $18.94 per MWh for carbon credit rate greater than $18.18 per tonne of CO_2 in case of scenario I and greater than $27.27 per tonnes of CO_2 in scenario II. However, scenario II can give investment return of 10% with cost of generating electricity less than $18.94 per MWh for carbon credit greater than $21.21 per MWh.



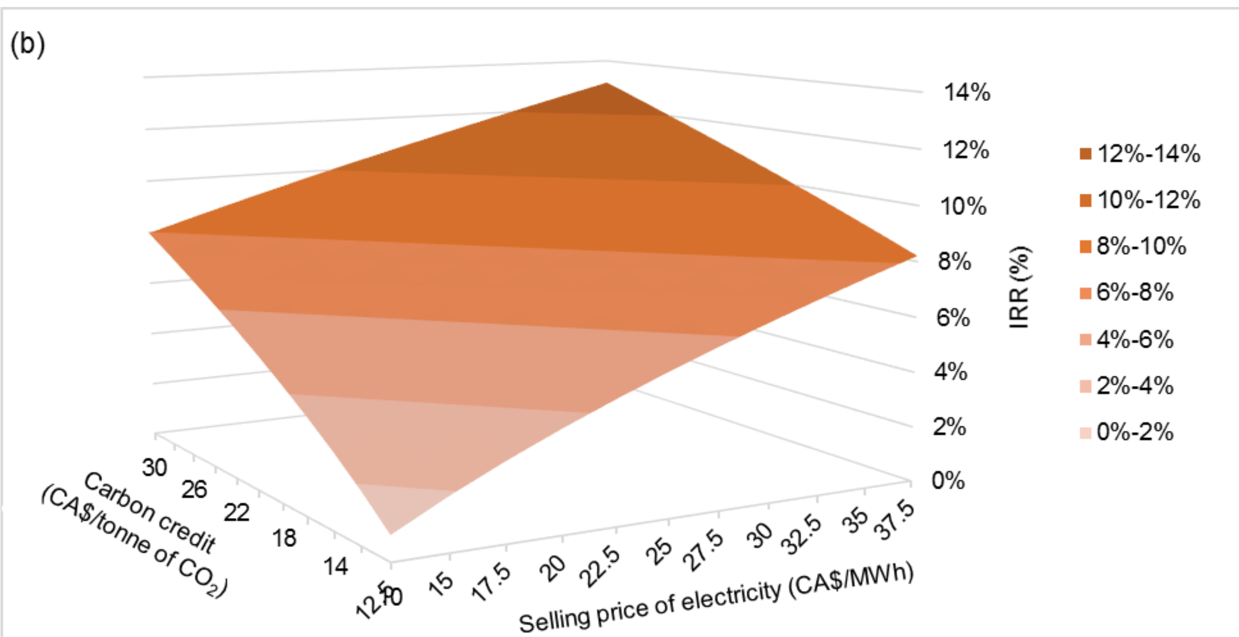


Figure 3-13: Cumulative effect of carbon credit and selling price of electricity on IRR for (a) scenario I, and (b) scenario II

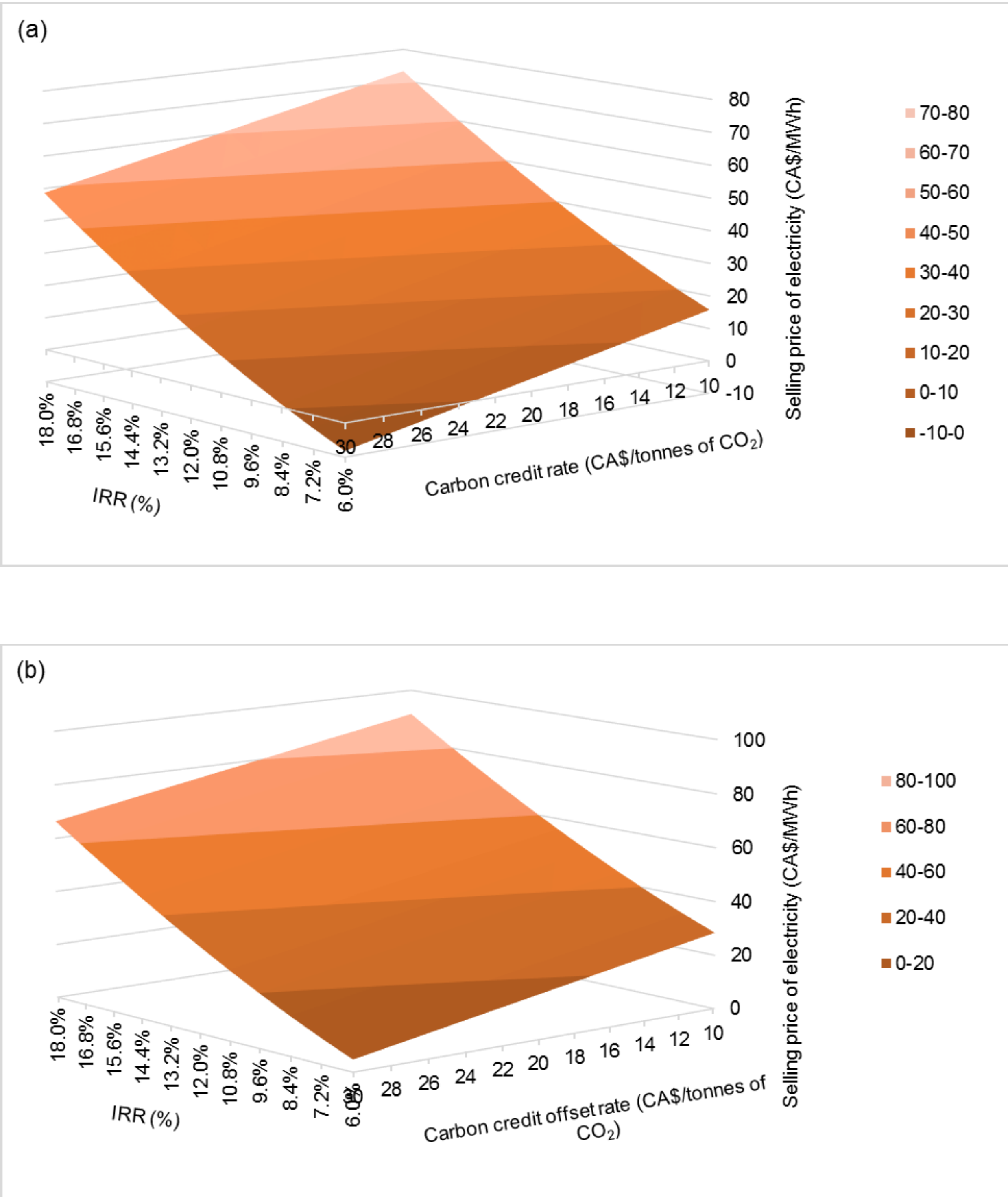


Figure 3-14: Cumulative effect of carbon credit and IRR on selling price of electricity for (a) scenario I, and (b) scenario II

3.4 Conclusion

This study is about using various types of wastes to produce value-added products in an integrated conversion facility. Four types of feedstock: municipal solid waste (MSW), agricultural residue, forest residue, and waste heat were considered in a single gasification-based facility to produce electricity. Developed GIS-based model was used to identify the geographical point source locations of agricultural biomass collection points (BCPs) and forest BCPs along with their annual availability, as well as, annual potential of MSW at their respective transfer stations (TSs). Later, a techno-economic model, named **FUN**damental E**N**gineering Principl**E**s-based model for Estimation of **Cost** of Energy from **Biomass and Municipal Solid Waste** (FUNNEL-Cost-Bio-MSW), was developed to process the technical and economic parameters of converting the feedstock into electricity via gasification technology.

A specific case study of Alberta's Industrial Heartland (AIH) was conducted to techno-economically assess the proposed 199 MW W2VA facility based on gasification technology. AIH boundary along with surrounding 50 km transportation ring was considered as the study area. Since there is no forest management agreement (FMA) area inside the study area, there is no forest residue available. However, annual availability of MSW, agricultural residue, and waste heat in the AIH is 1,266,852 wet tonnes (~684,100 odt) and 264,130 wet tonnes (~227,152 odt) per year, and 46 MW, respectively. W2VA facility location was proposed in two different scenarios, which were developed to incorporate waste heat utilization in a facility. Scenario I considered facility siting right next to one waste heat source whereas scenario II considered facility siting optimized using suitability analysis approach with two waste heat sources. The FUNNEL-Cost-Bio-MSW model uses transportation cost, feedstock availability, capital and operating costs, and other basic parameters as input variables. This model assesses the economy of the facility in terms of Internal Rates of Return (IRR) for fixed selling price of electricity as well as cost of generating electricity for fixed IRR. The observed IRR for scenario I and II is 11.08% and 8.09%, respectively, whereas cost of generating electricity for fixed IRR of 12% for scenario I and II is $21.90 and $33.23 per MWh, respectively. Key sensitive analysis shows that capital cost and the gate fee affect the most the IRR in scenario I and total operating cost and gate fee affect the most the IRR in scenario II. Similarly, gate fee and capital cost affect the most on cost of generating electricity for scenario I and II.

The developed model is applicable across all the jurisdictions to techno-economically assess the feasibility of processing multiple feedstock in a single W2VA facility to produce electricity using gasification technology.

Chapter 4: Conclusions and Recommendations for Future Work

4.1 Conclusion

This study was conducted to quantify the annual potential of various feedstocks and their geographical locations, as well as to identify the most optimal locations of waste-to-value-added (W2VA) facilities and assess their technical and economic feasibility. Three types of feedstock – municipal solid waste (MSW), agricultural residue, and forest residue – were considered. Their estimated annual potential for the year 2016 in the province of Alberta, Canada was 4,097,584 wet tonnes, 4,060,060 odt, and 2,077,418 odt, respectively. A geographic information system (GIS)-based framework was developed to perform land suitability analysis, which is the process of determining suitable area for a particular use, using various geographical factors chosen based on social, economic, and environmental factors. This land suitability model is used to identify the point source locations (defined as biomass collection points (BCPs) with longitude and latitude) along with their annual capacity for collecting lignocellulosic biomass (agricultural and forest residue). The same framework also identifies the annual potential of MSW at existing transfer stations (TSs) for collecting MSW. TSs are used to collect MSW from the community and to distribute them to respective facilities for recycling, composting, landfilling, etc. Figure 4-1 shows the location of existing MSW TSs and identified locations of agricultural and forest BCPs residue along with their annual potential across Alberta. The same model can also can also be used to identify the optimal locations for siting W2VA facilities.

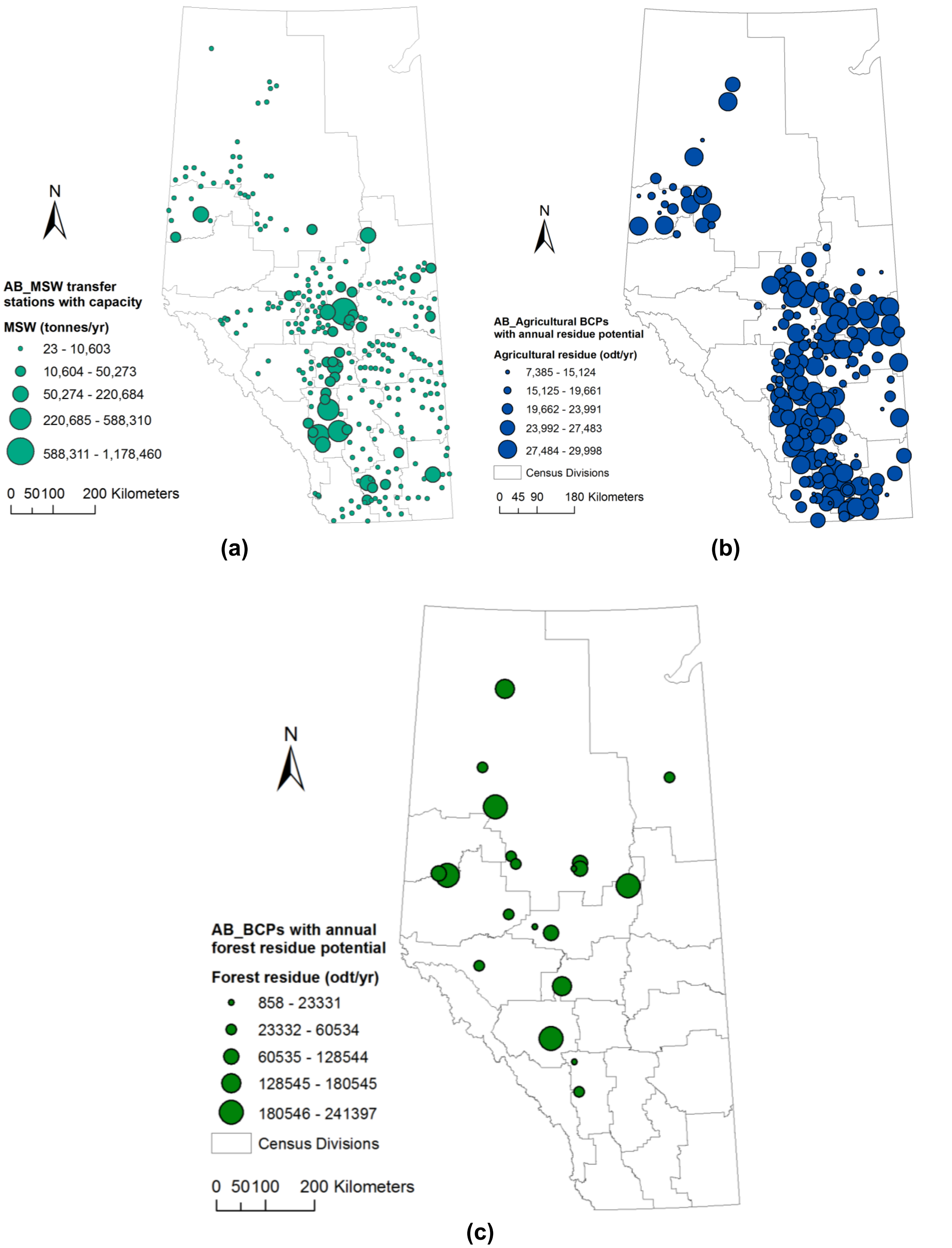


Figure 4-1: (a) Locations of existing MSW TSs along with their annual availability; Identified locations of (b) agricultural and (c) forest BCPs along with their annual availability

An excel-based techno-economic model, the **FUN**damental E**N**gineering Princip**lE**s-based model for Estimation of **Cost** of Energy from **Biomass and Municipal Solid Waste** (FUNNEL-Cost-Bio-MSW), was developed to assess the technical and economic parameters of converting feedstock into electricity via gasification technology. With various inputs such as transportation cost, agricultural production cost, capital and operating cost, etc., the model assesses the techno-economic feasibility of the W2VA facility in terms of internal rates of return (IRR) for a fixed selling price of electricity and in terms of the cost of generating electricity for a fixed IRR. The model is also capable of performing sensitivity analysis to understand individual parameter's influence on the economic output of the facility.

A specific case of Alberta's Industrial Heartland (AIH) was studied to identify the optimal location of a single W2VA facility and included a techno-economic assessment of generating electricity at the facility using gasification. The AIH boundary along with the surrounding 50 km transportation ring was considered as the study area for this case. Three types of feedstock – MSW, agricultural residue, and waste heat – were considered. Since there is no Forest Management Agreement (FMA) area inside the study area, there was no forest residue available. The MSW, agricultural residue, and waste heat available in the AIH were estimated to be 1,266,852 wet tonnes (~684,100 odt) per year, 264,130 wet tonnes (~227,152 odt) per year, and 46 MW, respectively. Using the developed GIS model, we identified the optimal location of one W2VA facility for two scenarios, both incorporating waste heat for drying the biodegradable content of MSW to reduce its moisture content from 50% to 15% or less. Scenario I considered W2VA facility next to a waste heat source, Waste Heat II, whereas Scenario II used land suitability model to determine the optimal location of W2VA facility in between the two waste heat sources, Waste Heat I and II. The land suitability model identified geographical locations 53.797^{0}N, 113.091^{0}W and 53.797^{0}N, 113.154^{0}W for W2VA facilities for Scenarios I and II, respectively, with an annual cumulative capacity of 911,252 odt/year. Figure *4-2* and Figure *4-3* shows the location of identified W2VA facility for Scenario I and II.

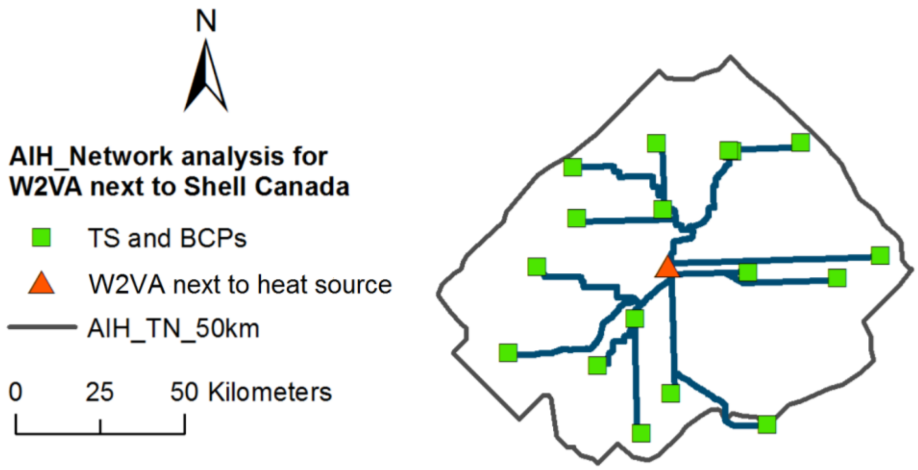


Figure 4-2: Actual road connection between feedstock supply points and W2VA facility located next to Waste Heat I in Scenario I

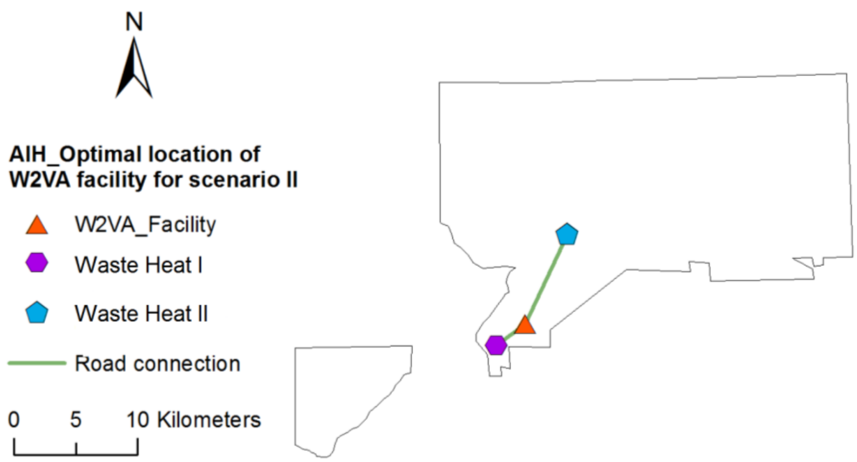


Figure 4-3: Optimal location of W2VA facility identified between Waste Heat I and II using GIS model in Scenario II

The FUNNEL-Cost-Bio-MSW model calculated IRRs of 11.08% and 8.09% for a fixed selling price of electricity of \$18.94/MWh for Scenarios I and II, respectively. The cost of generating electricity, against the current selling price \$18.94/MWh, for a fixed IRR of 12% was calculated to be \$21.90

and \$33.23 per MWh in Scenarios I and II, respectively. With the current carbon credit rate of \$15.15/tonnes of CO2-eq and fossil fuel-based electricity, both the scenario does not look promising. However, with the increase in both the parameters, both the scenario can be very competitive. For example, for carbon credit offset rate of \$22.27/tonnes of CO_2-eq, cost of generating electricity changes to \$12.8/MWh and \$24.09/MWh for Scenarios I and II, respectively, making Scenario I as economical while Scenario II is still non-economical. In addition, with the increase in fossil fuel-based electricity cost, both the scenarios can be very competitive in the market. Table 4-1 shows the economic results of both the scenarios for various inputs.

Table 4-1: Economic results of Scenario I and II in terms of IRR and cost of generating electricity for various inputs

Scenario	**IRR for fixed electricity selling price of \$18.94/MWh (%)**		**Cost of electricity for fixed IRR of 12% (\$/MWh)**	
	Carbon credit: \$15.15/MT-CO_2-eq	Carbon credit: \$22.27/MT-CO_2-eq	Carbon credit: \$15.15/MT-CO_2-eq	Carbon credit: \$22.27/MT-CO_2-eq
Scenario I	11.18%	13.65%	28.91	16.90
Scenario II	8.09%	10.66%	43.86	31.80

Sensitive analyses of various cost and revenue parameters were later performed on the IRR and the cost of generating electricity. The capital cost and gate fee have the largest effect on the IRR in Scenario I, and the total operating cost and gate fee have the largest effect on the IRR in Scenario II. The gate fee and capital cost have the largest effect on the cost of generating electricity for a fixed IRR in both scenarios. Similar work was done in another case study to identify the 10 most optimal locations of W2VA facilities across the province of Alberta as shown in Figure SS. This case study considered using MSW, agricultural, and forest residue in identified W2VA facilities. Identified locations of W2VA facilities were not influenced by the location of waste heat sources.

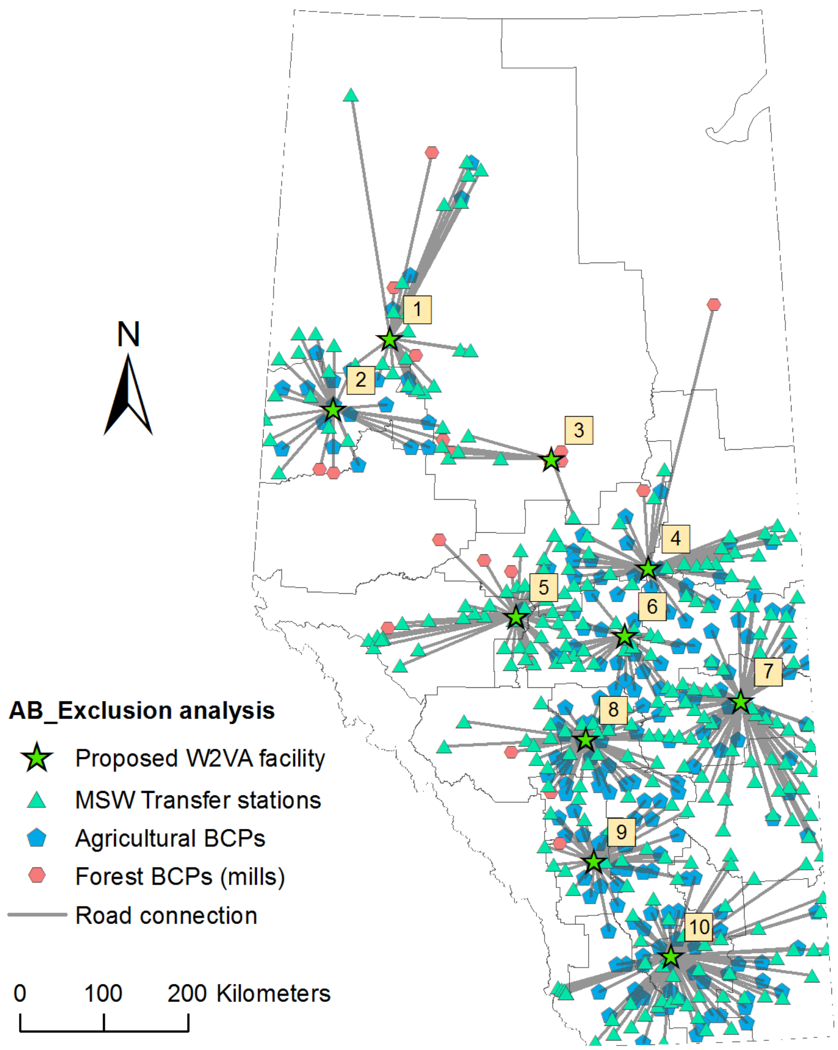


Figure 4-4: Optimal locations of W2VA facilities that uses MSW, agricultural residue, and forest residue across Alberta

The developed model can be used by governments/municipalities/investors to understand feedstock potential along with their collection point locations across any jurisdiction. These models can also be used to identify the optimal location of W2VA facilities and assess their technical and economic feasibility.

4.2 Recommendations for future work

The following are recommendations to promote biomass and MSW use in Canada:

1. This study was done only for the province of Alberta. However, it can be broadened to all of Canada. The GIS model can be extended to estimate the MSW potential of all the transfer stations that exist in Canada and to identify the location of BCPs for agricultural and forest residue along with their annual potential.
2. Using a similar framework for land suitability analysis, optimal locations of W2VA facilities can be found all across the Canada for proper waste management
3. This study used only gasification technology for electricity production. Various other energy conversion technologies such as combustion, anaerobic digestion, composting, gasification for producing biofuels, etc. can be used to produce value added products. A techno-economic assessment can be done for these technologies in order to identify the best energy conversion option.
4. This study used agricultural maps from 2016. However, each year, crops rotate and their locations may change, which can affect the location of the agricultural BCPs identified. A statistical or geographical model that can predict future crop seeding types and location could be developed to help identify long-term optimal locations of BCPs.
5. Update the GIS and techno-economic model if the geographic features or regulations changes in the future

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Appendix A: Feedstock Locations and its Annual Potential

Table A1: MSW transfer stations with their annual potential and geographical locations in Alberta

SN	Name of transfer station	Latitude	Longitude	Annual potential (gross tonnes per year)
1	Whispering Hills, Smith, Perryvale, Colinton	54.607	-113.308	10,268
2	Wandering River Transfer Site	55.159	-112.449	83,106
3	Grassland Transfer Site	54.864	-112.656	5,078
4	Cold lake	54.384	-110.187	19,861
5	Hilda lake	54.500	-110.409	2,403
6	La Corey	54.430	-110.640	1,563
7	Ardmore	54.355	-110.480	2,107
8	Bonnyville	54.199	-110.780	11,967
9	Therien	54.240	-111.210	1,803
10	Goodridge	54.410	-111.297	1,010
11	Blueberry Mountain	55.898	-119.149	1,188
12	Bonzana	55.887	-119.808	592
13	Gundy	55.620	-119.972	112
14	Woking	55.578	-118.757	87,298
15	Cadotte Lake	56.454	-116.300	916
16	Little Buffalo	56.450	-116.109	2,226
17	Harmon Valley	56.062	-116.800	116
18	Reno	55.989	-116.983	1,474
19	Marie Reine	56.062	-117.296	2,827
20	Nampa	56.029	-117.107	2,366
21	Town of Elk Point	53.897	-110.897	2,959
22	Bellis	54.143	-112.150	1,923

SN	Name of transfer station	Latitude	Longitude	Annual potential (gross tonnes per year)
23	Ashmont	54.130	-111.568	844
24	Mallaig	54.210	-111.361	847
25	Vilna	54.116	-111.921	1,665
26	Spedden	54.139	-111.726	2,037
27	Waskatenau	54.098	-112.784	4,283
28	Smoky Lake	54.113	-112.474	3,003
29	St. Lina	54.296	-111.454	1,449
30	St. Paul	53.993	-111.297	8,089
31	Banana Belt	55.302	-116.495	2,724
32	Enilda	55.375	-116.309	1,002
33	Faust/Kinuso	55.302	-115.514	4,111
34	Grouard	55.538	-116.123	2,619
35	Gilwood	55.422	-116.623	5,541
36	Heart River	55.625	-116.614	1,031
37	Marten Beach.	55.311	-114.551	12,648
38	Flatbush	54.665	-114.160	819
39	Hawk Hills	57.166	-117.471	770
40	Manning	56.846	-117.625	1,961
41	Sunny Valley	56.643	-117.332	365
42	Deadwood	56.843	-117.359	325
43	Dixonville	56.523	-117.670	428
44	Weberville	56.353	-117.354	7,753
45	Warrensville	56.290	-117.800	1,529
46	Grimshaw	56.191	-117.600	5,069
47	Blue Hills	58.010	-116.688	5,713
48	Buffalo Head	58.039	-116.349	5,246
49	Bluemenort	58.329	-116.206	1,323

SN	Name of transfer station	Latitude	Longitude	Annual potential (gross tonnes per year)
50	Fort Vermilion	58.388	-115.955	7,546
51	Rocky Lane	58.470	-116.241	1,005
52	Zama	59.143	-118.690	2,469
53	Worseley	56.566	-119.119	554
54	Bear Canyon	56.279	-119.800	736
55	Cleardale	56.363	-119.425	741
56	Deerhill/Whitehall	56.262	-118.324	4,939
57	Eureka River	56.451	-118.746	391
58	Royce	56.175	-118.818	1,140
59	Clear Prairie	56.556	-119.438	448
60	Redwater	53.949	-113.107	20,576
61	Demmitt Transfer Station	55.407	-119.850	1,761
62	Teepee Creek Transfer Station	55.450	-118.385	8,521
63	Elmworth Transfer Station	55.058	-119.650	13,673
64	Jarvie	54.470	-113.910	1,371
65	Busby	53.950	-113.924	6,178
66	Pibroch	54.287	-113.880	7,518
67	Vimy	54.065	-113.507	19,461
68	Tiger Lily	54.228	-114.700	896
69	Meadowview	53.980	-114.653	936
70	Manola	54.123	-114.250	6,644
71	Neerlandia/Vega	54.374	-114.408	1,562
72	Thunder Lake	54.112	-114.702	1,073
73	Dunstable	53.948	-114.157	1,213
74	Lindbrook	53.396	-112.807	3,543
75	Tofield	53.370	-112.667	6,091
76	Kinsella	53.001	-111.525	1,264

SN	Name of transfer station	Latitude	Longitude	Annual potential (gross tonnes per year)
77	Viking	53.090	-111.736	2,701
78	Kingman/Round Hill/Hay Lakes	53.190	-112.810	23,172
79	Kelsey & Area	52.830	-112.525	1,680
80	Meeting Creek & Area	52.682	-112.713	2,615
81	Breton	53.117	-114.483	3,141
82	Buck Creek	53.104	-114.896	2,092
83	Cynthia	53.280	-115.420	936
84	Easyford	53.286	-115.147	720
85	Lindale	53.537	-113.416	1,178,460
86	Lodgepole	53.100	-115.300	2,287
87	Rocky Rapids	53.280	-114.950	9,372
88	Violet Grove	53.160	-115.037	2,422
89	Sedgewick	52.770	-111.690	1,777
90	Daysland	52.865	-112.250	2,428
91	Killam	52.789	-111.850	1,459
92	Alliance	52.436	-111.780	597
93	Forestburg	52.580	-112.068	1,251
94	Galahad	52.500	-111.900	400
95	Heisler	52.670	-112.220	567
96	Strome	52.800	-112.060	748
97	Rosalind	52.787	-112.440	612
98	Hardisty	52.675	-111.300	2,184
99	Cherhill	53.800	-114.670	914
100	Darwell	53.660	-114.549	2,348
101	Hillcrest	53.630	-114.278	6,862
102	Mayerthorpe	53.930	-115.200	2,435
103	Onoway	53.730	-114.156	5,467

SN	Name of transfer station	Latitude	Longitude	Annual potential (gross tonnes per year)
104	Rich Valley	53.870	-114.330	1,711
105	Rochfort Bridge	53.947	-115.049	987
106	Sangudo	53.875	-114.869	1,168
107	Bentley	52.454	-114.050	24,715
108	Spruceville	52.460	-113.849	12,643
109	Prentiss	52.400	-113.580	3,775
110	Eckville	52.390	-114.340	5,107
111	Blackfalds	52.360	-113.777	105,235
112	Alix/Mirror	52.450	-113.178	3,805
113	St. Francis	53.298	-114.318	584
114	Sunnybrook	53.200	-114.178	849
115	Warburg	53.178	-114.340	1,696
116	Thorsby	53.250	-114.000	4,095
117	Mission Beach	53.090	-114.100	3,659
118	Rolly View	53.239	-113.269	48,108
119	Looma	53.356	-113.227	12,632
120	New Sarepta	53.268	-113.129	3,680
121	Wizard Lake	53.108	-113.829	26,564
122	Castor	52.230	-111.916	1,464
123	Halkirk	52.277	-112.148	596
124	Coronation	52.128	-111.439	1,713
125	Ponoka	52.656	-113.600	17,954
126	Mecca Glen	52.637	-113.270	5,633
127	Horn Hill	52.130	-113.790	28,228
128	Gaetz Creek	52.110	-113.267	3,868
129	Yankee Flats	52.144	-114.269	3,359
130	Innisfail	52.033	-113.950	13,592

SN	Name of transfer station	Latitude	Longitude	Annual potential (gross tonnes per year)
131	Cline	52.206	-116.459	1,351
132	Nordegg	52.479	-116.118	836
133	Caroline	52.086	-114.840	2,006
134	Cow Lake	52.290	-115.030	8,471
135	Crammond	51.998	-114.650	1,670
136	Crossroads	52.460	-114.600	2,338
137	Everdell	52.230	-114.900	2,969
138	Faraway	52.687	-114.770	1,627
139	Leslieville	52.319	-114.600	2,259
140	Stettler	52.320	-112.719	7,189
141	Erskine	52.321	-112.880	1,759
142	Byemoor	51.980	-112.285	667
143	Donalda	52.583	-112.570	780
144	Botha	52.307	-112.520	993
145	Gadsby	52.296	-112.360	652
146	Big Valley	52.034	-112.757	1,244
147	Willingdon	53.806	-112.134	3,443
148	Hairy Hill	53.740	-111.966	7,568
149	Two Hills	53.672	-111.746	3,285
150	Myrnam	53.670	-111.212	2,023
151	Derwent	53.657	-110.965	705
152	Clandonald / Dewberry	53.559	-110.620	1,661
153	Kitscoty	53.350	-110.320	24,706
154	Marwayne	53.526	-110.350	1,496
155	Paradise Valley	53.030	-110.279	2,707
156	Preston	53.160	-110.864	8,663
157	Tulliby Lake	53.719	-110.135	2,326

SN	Name of transfer station	Latitude	Longitude	Annual potential (gross tonnes per year)
158	Vermilion	53.365	-110.848	6,102
159	Anselmo	53.883	-115.380	12,370
160	Goose Lake	54.317	-115.132	2,764
161	Doris Creek	54.483	-114.518	319
162	Bodo	52.132	-110.080	228
163	Hayter	52.346	-110.080	2,081
164	Cadogan	52.317	-110.440	1,645
165	Metiskow	52.405	-110.635	665
166	Czar	52.448	-110.820	772
167	Hughenden	52.496	-110.988	603
168	Amisk	52.565	-111.060	1,745
169	Tomahawk	53.396	-114.760	1,692
170	Half Moon Lake	53.460	-113.090	18,903
171	Kapasiwin	53.546	-114.445	3,405
172	Parkland County	53.530	-114.006	79,954
173	Keephills	53.440	-114.340	2,405
174	Seba Beach	53.560	-114.737	2,230
175	Bindloss	50.870	-110.280	399
176	Cereal	51.416	-110.800	381
177	Cessford	51.006	-111.557	165
178	Compeer	51.859	-110.010	68
179	Consort	52.017	-110.760	1,069
180	Empress	50.950	-110.006	255
181	Esther	51.680	-110.260	139
182	Hand Hills	51.497	-112.263	772
183	Hemaruka	51.783	-111.083	477
184	Hanna	51.653	-111.920	3,015

SN	Name of transfer station	Latitude	Longitude	Annual potential (gross tonnes per year)
185	Jenner	50.747	-111.180	438
186	Kirriemuir	51.898	-110.264	117
187	Monitor	51.958	-110.530	164
188	New Brigden	51.700	-110.490	92
189	Oyen	51.350	-110.470	1,282
190	Richdale	51.610	-111.600	175
191	Scapa	51.860	-111.983	334
192	Sedalia	51.675	-110.665	139
193	Sibbald	51.388	-110.150	177
194	Spondin	51.850	-111.616	276
195	Sunnynook	51.283	-111.660	280
196	Veteran	52.004	-111.124	571
197	Wardlow	50.905	-111.546	557
198	Acadia	51.157	-110.210	318
199	Stand Off	49.460	-113.310	7,615
200	Cardston	49.203	-113.300	5,980
201	Hill Spring	49.290	-113.620	7,862
202	Mountain View	49.132	-113.600	845
203	Del Bonita	49.020	-112.788	502
204	Spring Coulee	49.330	-113.070	1,081
205	Magrath	49.420	-112.868	3,475
206	Welling	49.478	-112.785	20,857
207	Raymond	49.460	-112.650	4,759
208	Stirling	49.500	-112.517	1,832
209	Milk River	49.149	-112.087	1,533
210	New Dayton	49.427	-112.379	753
211	Warner	49.283	-112.207	857

SN	Name of transfer station	Latitude	Longitude	Annual potential (gross tonnes per year)
212	Wrentham	49.516	-112.183	899
213	Masinasin	49.152	-111.676	568
214	Waterton	49.046	-113.900	521
215	Coleman	49.635	-114.500	1,950
216	Blairmore	49.608	-114.440	2,389
217	Frank	49.600	-114.390	444
218	BELLEVUE	49.581	-114.366	2,354
219	Hillcrest	49.569	-114.376	1,228
220	Hussar	51.010	-112.662	1,250
221	Michichi	51.579	-112.519	10,017
222	Rumsey	51.838	-112.840	1,346
223	Standard	51.110	-112.980	4,161
224	Strathmore	50.997	-113.400	18,387
225	Three Hills	51.678	-113.271	9,253
226	Priddis	50.890	-114.371	588,310
227	Black Diamond/Turner Valley	50.688	-114.232	220,684
228	Picture Butte	49.847	-112.760	84,716
229	Nobleford	49.888	-113.050	7,256
230	Coaldale	49.740	-112.600	11,675
231	Iron Springs	49.930	-112.649	1,312
232	Bassano	50.779	-112.470	2,344
233	Gem	50.950	-112.230	2,004
234	Tilley	50.470	-111.680	20,508
235	Taber	49.800	-112.170	12,651
236	Vauxhal	50.060	-112.058	3,064
237	Enchant	50.168	-112.399	1,423
238	Hays and Grassy Lake	49.746	-111.659	4,825

SN	Name of transfer station	Latitude	Longitude	Annual potential (gross tonnes per year)
239	Foremost	49.479	-111.440	1,225
240	Etzikom	49.483	-111.100	432
241	Orion	49.450	-110.810	733
242	SKIFF	49.500	-111.790	704
243	Irvine	49.949	-110.255	771
244	Schuler	50.350	-110.096	378
245	Langdon	50.970	-113.679	396,388
246	Bragg Creek	50.950	-114.560	13,746
247	Crossfield	51.430	-114.030	313,605
248	Irricana	51.328	-113.597	6,573
249	Scott Lake	51.149	-114.716	50,273
250	Carmangay	50.130	-113.114	6,349
251	Milo	50.570	-112.880	2,035
252	Lomond	50.350	-112.640	746
253	Vulcan	50.397	-113.239	7,512
254	Mossleigh	50.720	-113.320	3,715
255	Wildwood	53.570	-115.250	1,076
256	Niton	53.617	-115.776	484
257	Peers	53.646	-115.970	834
258	Parkcourt	53.700	-115.057	2,030
259	Pinedale	53.599	-116.160	10,603
260	Marlboro	53.559	-116.783	4,257
261	Obed	53.515	-117.250	457
262	Entrance	53.370	-117.690	249
263	Brule	53.320	-117.850	1,337
264	Overlander	53.250	-117.760	4,339
265	Hattonford	53.730	-115.690	2,280

SN	Name of transfer station	Latitude	Longitude	Annual potential (gross tonnes per year)
266	Bear Lake	53.719	-116.130	1,911
267	Robb	53.236	-116.957	426
268	Cadomin	53.060	-117.268	220
269	Hinton Regional	53.350	-117.590	8,525
270	Hinton Regional	53.350	-117.609	1,996
271	Hinton Regional	53.340	-117.609	23
272	Olds	51.793	-114.100	12,637
273	Sundre	51.797	-114.640	7,029
274	Didsbury	51.660	-114.130	12,378
275	Water Valley	51.506	-114.610	5,009
276	Rolling Hills (Hays)	50.120	-111.779	1,218
277	Dunmore	49.960	-110.579	70,145
278	Elkwater	49.669	-110.304	998
279	Hilda	50.500	-110.033	166
280	Seven Persons	49.877	-110.874	7,986
281	Suffield	50.210	-111.142	873
282	Walsh	49.949	-110.030	239

Table A2: Identified agricultural BCPs along with their annual potential and geographical coordinates

SN	Name	Annual potential (odt per year)	Longitude	Latitude
1	Agricultural BCP 1	20,622	-119.084	56.363
2	Agricultural BCP 2	17,169	-118.398	56.194
3	Agricultural BCP 3	27,690	-117.239	56.043
4	Agricultural BCP 4	16,707	-118.684	55.816
5	Agricultural BCP 5	23,991	-118.367	55.726
6	Agricultural BCP 6	16,435	-116.868	55.405
7	Agricultural BCP 7	17,470	-112.525	54.917
8	Agricultural BCP 8	17,381	-113.986	54.477
9	Agricultural BCP 9	11,637	-110.536	54.322
10	Agricultural BCP 10	16,964	-113.181	54.383
11	Agricultural BCP 11	27,786	-114.621	54.124
12	Agricultural BCP 12	16,661	-112.741	54.102
13	Agricultural BCP 13	16,960	-114.149	54.031
14	Agricultural BCP 14	29,745	-113.371	53.832
15	Agricultural BCP 15	17,313	-110.894	53.769
16	Agricultural BCP 16	17,570	-111.662	53.715
17	Agricultural BCP 17	13,692	-114.165	53.659
18	Agricultural BCP 18	28,464	-111.208	53.511
19	Agricultural BCP 19	28,491	-112.161	53.531
20	Agricultural BCP 20	22,421	-114.000	53.477
21	Agricultural BCP 21	28,350	-112.316	53.253
22	Agricultural BCP 22	13,759	-113.096	53.194
23	Agricultural BCP 23	22,677	-111.716	53.070
24	Agricultural BCP 24	20,436	-110.031	53.008
25	Agricultural BCP 25	29,131	-112.634	53.084

SN	Name	Annual potential (odt per year)	Longitude	Latitude
26	Agricultural BCP 26	17,254	-112.957	53.000
27	Agricultural BCP 27	13,396	-113.271	52.910
28	Agricultural BCP 28	29,260	-112.657	52.815
29	Agricultural BCP 29	28,973	-112.062	52.703
30	Agricultural BCP 30	26,502	-113.731	52.731
31	Agricultural BCP 31	22,545	-110.864	52.493
32	Agricultural BCP 32	27,483	-113.580	52.462
33	Agricultural BCP 33	14,969	-114.026	52.464
34	Agricultural BCP 34	17,473	-114.487	52.464
35	Agricultural BCP 35	20,540	-111.336	52.232
36	Agricultural BCP 36	27,118	-113.722	52.273
37	Agricultural BCP 37	21,078	-112.531	52.252
38	Agricultural BCP 38	16,106	-111.654	52.127
39	Agricultural BCP 39	19,239	-114.502	52.095
40	Agricultural BCP 40	26,667	-113.898	52.093
41	Agricultural BCP 41	16,424	-110.447	52.000
42	Agricultural BCP 42	25,336	-113.602	52.000
43	Agricultural BCP 43	20,139	-110.500	51.638
44	Agricultural BCP 44	29,345	-112.722	51.610
45	Agricultural BCP 45	29,498	-114.201	51.534
46	Agricultural BCP 46	29,759	-114.200	51.532
47	Agricultural BCP 47	29,285	-112.437	51.243
48	Agricultural BCP 48	12,752	-111.763	50.399
49	Agricultural BCP 49	26,161	-112.935	50.415
50	Agricultural BCP 50	20,452	-112.641	50.317
51	Agricultural BCP 51	29,889	-112.505	50.126
52	Agricultural BCP 52	28,423	-112.210	50.031
53	Agricultural BCP 53	21,440	-113.087	49.956

SN	Name	Annual potential (odt per year)	Longitude	Latitude
54	Agricultural BCP 54	23,211	-113.370	49.873
55	Agricultural BCP 55	22,489	-113.528	49.870
56	Agricultural BCP 56	25,048	-113.081	49.865
57	Agricultural BCP 57	29,810	-112.244	49.760
58	Agricultural BCP 58	20,978	-112.101	49.669
59	Agricultural BCP 59	23,456	-111.117	49.641
60	Agricultural BCP 60	13,347	-112.698	49.396
61	Agricultural BCP 61	28,271	-111.841	49.289
62	Agricultural BCP 62	22,592	-113.661	49.325
63	Agricultural BCP 63	24,977	-113.122	49.028
64	Agricultural BCP 64	24,866	-116.155	58.456
65	Agricultural BCP 65	28,224	-116.339	58.079
66	Agricultural BCP 66	13,964	-117.326	57.236
67	Agricultural BCP 67	28,581	-117.636	56.866
68	Agricultural BCP 68	21,172	-117.288	56.126
69	Agricultural BCP 69	22,633	-117.884	56.110
70	Agricultural BCP 70	11,948	-118.726	56.081
71	Agricultural BCP 71	14,423	-119.689	55.965
72	Agricultural BCP 72	16,602	-119.208	55.983
73	Agricultural BCP 73	29,401	-117.696	55.842
74	Agricultural BCP 74	14,872	-118.861	55.627
75	Agricultural BCP 75	28,012	-116.882	55.671
76	Agricultural BCP 76	29,956	-118.656	55.367
77	Agricultural BCP 77	27,397	-117.197	55.396
78	Agricultural BCP 78	29,986	-119.623	55.313
79	Agricultural BCP 79	19,661	-118.170	55.186
80	Agricultural BCP 80	25,431	-113.199	54.662
81	Agricultural BCP 81	16,495	-111.291	54.345

SN	Name	Annual potential (odt per year)	Longitude	Latitude
82	Agricultural BCP 82	29,908	-114.161	54.302
83	Agricultural BCP 83	16,475	-114.162	54.206
84	Agricultural BCP 84	29,116	-113.841	54.207
85	Agricultural BCP 85	11,349	-112.585	54.095
86	Agricultural BCP 86	23,461	-111.506	53.986
87	Agricultural BCP 87	27,100	-113.064	54.023
88	Agricultural BCP 88	28,453	-113.665	54.022
89	Agricultural BCP 89	23,240	-112.125	53.903
90	Agricultural BCP 90	27,000	-112.765	53.892
91	Agricultural BCP 91	17,471	-112.121	53.819
92	Agricultural BCP 92	28,523	-113.838	53.843
93	Agricultural BCP 93	15,757	-115.105	53.683
94	Agricultural BCP 94	28,589	-110.600	53.591
95	Agricultural BCP 95	28,577	-110.324	53.566
96	Agricultural BCP 96	28,922	-112.458	53.630
97	Agricultural BCP 97	17,851	-113.080	53.554
98	Agricultural BCP 98	15,937	-113.684	53.463
99	Agricultural BCP 99	29,331	-111.709	53.408
100	Agricultural BCP 100	29,972	-111.073	53.335
101	Agricultural BCP 101	22,839	-114.167	53.287
102	Agricultural BCP 102	20,125	-112.038	53.254
103	Agricultural BCP 103	28,178	-110.331	53.200
104	Agricultural BCP 104	7,385	-114.493	53.191
105	Agricultural BCP 105	18,811	-113.402	53.099
106	Agricultural BCP 106	29,521	-113.713	53.088
107	Agricultural BCP 107	28,726	-111.437	52.954
108	Agricultural BCP 108	29,844	-110.817	52.942
109	Agricultural BCP 109	28,238	-110.359	52.917

SN	Name	Annual potential (odt per year)	Longitude	Latitude
110	Agricultural BCP 110	20,096	-113.458	52.818
111	Agricultural BCP 111	16,798	-113.112	52.810
112	Agricultural BCP 112	27,286	-111.598	52.773
113	Agricultural BCP 113	29,997	-112.226	52.709
114	Agricultural BCP 114	21,588	-112.965	52.641
115	Agricultural BCP 115	13,783	-111.457	52.585
116	Agricultural BCP 116	22,265	-114.336	52.634
117	Agricultural BCP 117	15,003	-112.684	52.532
118	Agricultural BCP 118	22,262	-111.747	52.433
119	Agricultural BCP 119	25,064	-113.883	52.467
120	Agricultural BCP 120	29,366	-110.131	52.356
121	Agricultural BCP 121	29,351	-113.098	52.362
122	Agricultural BCP 122	12,303	-111.932	52.329
123	Agricultural BCP 123	21,952	-114.363	52.350
124	Agricultural BCP 124	25,993	-114.043	52.278
125	Agricultural BCP 125	17,507	-114.342	52.082
126	Agricultural BCP 126	15,954	-112.121	51.965
127	Agricultural BCP 127	19,592	-114.350	51.992
128	Agricultural BCP 128	29,356	-113.748	51.914
129	Agricultural BCP 129	18,880	-114.659	51.912
130	Agricultural BCP 130	29,467	-113.166	51.825
131	Agricultural BCP 131	15,124	-112.405	51.799
132	Agricultural BCP 132	29,971	-113.304	51.800
133	Agricultural BCP 133	21,292	-114.339	51.813
134	Agricultural BCP 134	27,052	-113.768	51.796
135	Agricultural BCP 135	29,979	-113.588	51.719
136	Agricultural BCP 136	29,962	-112.402	51.696
137	Agricultural BCP 137	29,848	-114.341	51.712

SN	Name	Annual potential (odt per year)	Longitude	Latitude
138	Agricultural BCP 138	25,071	-112.995	51.615
139	Agricultural BCP 139	18,384	-114.472	51.451
140	Agricultural BCP 140	14,351	-110.797	51.373
141	Agricultural BCP 141	27,344	-113.156	51.432
142	Agricultural BCP 142	25,589	-112.875	51.421
143	Agricultural BCP 143	26,282	-114.056	51.265
144	Agricultural BCP 144	29,257	-114.363	51.264
145	Agricultural BCP 145	29,171	-113.637	51.258
146	Agricultural BCP 146	29,998	-110.230	51.169
147	Agricultural BCP 147	29,501	-113.780	51.169
148	Agricultural BCP 148	28,910	-113.313	51.160
149	Agricultural BCP 149	18,135	-113.361	51.153
150	Agricultural BCP 150	29,015	-112.747	51.046
151	Agricultural BCP 151	24,811	-113.906	50.975
152	Agricultural BCP 152	23,729	-113.497	50.906
153	Agricultural BCP 153	13,051	-113.337	50.888
154	Agricultural BCP 154	29,218	-112.900	50.870
155	Agricultural BCP 155	26,785	-113.054	50.855
156	Agricultural BCP 156	16,055	-112.179	50.779
157	Agricultural BCP 157	17,445	-114.039	50.804
158	Agricultural BCP 158	22,610	-112.325	50.772
159	Agricultural BCP 159	29,822	-113.481	50.717
160	Agricultural BCP 160	26,402	-113.778	50.712
161	Agricultural BCP 161	29,466	-113.948	50.605
162	Agricultural BCP 162	29,904	-113.496	50.504
163	Agricultural BCP 163	11,157	-112.472	50.428
164	Agricultural BCP 164	25,467	-110.163	50.341
165	Agricultural BCP 165	17,054	-112.630	50.410

SN	Name	Annual potential (odt per year)	Longitude	Latitude
166	Agricultural BCP 166	28,897	-113.219	50.325
167	Agricultural BCP 167	16,239	-113.060	50.251
168	Agricultural BCP 168	28,625	-113.648	50.235
169	Agricultural BCP 169	21,362	-111.787	50.204
170	Agricultural BCP 170	24,911	-112.810	50.044
171	Agricultural BCP 171	26,970	-110.507	49.971
172	Agricultural BCP 172	24,868	-112.668	49.873
173	Agricultural BCP 173	26,159	-111.113	49.834
174	Agricultural BCP 174	19,166	-111.506	49.834
175	Agricultural BCP 175	28,458	-111.687	49.740
176	Agricultural BCP 176	26,438	-112.101	49.664
177	Agricultural BCP 177	13,902	-113.237	49.601
178	Agricultural BCP 178	29,320	-112.657	49.580
179	Agricultural BCP 179	22,532	-113.826	49.583
180	Agricultural BCP 180	12,451	-110.812	49.519
181	Agricultural BCP 181	22,600	-113.106	49.506
182	Agricultural BCP 182	29,911	-111.388	49.459
183	Agricultural BCP 183	29,169	-112.527	49.482
184	Agricultural BCP 184	18,042	-113.251	49.476
185	Agricultural BCP 185	23,775	-111.430	49.363
186	Agricultural BCP 186	26,404	-112.823	49.386
187	Agricultural BCP 187	29,455	-111.982	49.295
188	Agricultural BCP 188	29,382	-111.417	49.202
189	Agricultural BCP 189	28,473	-112.139	49.214
190	Agricultural BCP 190	23,221	-112.247	49.097

Table A3: Forest mills (or BCPs) of each FMA holders with annual roadside residue potential

<table>
<tr><th>SN</th><th colspan="2">Name of mill
(same as FMA holder)</th><th>Harvested area (ha)</th><th>Harvested vol (m^3)</th><th>% of total harvested vol in Alberta</th><th>Residue potential (odt/yr)</th><th>No of BSPs in an FMA</th></tr>
<tr><td>1</td><td rowspan="2">Alpac Forest Products Incorporated (Boyle)</td><td>Alpac</td><td>7,874</td><td>2,204,731</td><td>10.67%</td><td>221,757</td><td>19</td></tr>
<tr><td>2</td><td>Northland Forest Products</td><td>1,272</td><td>356,108</td><td>1.72%</td><td>35,818</td><td>10</td></tr>
<tr><td>3</td><td colspan="2">ANC Timber Ltd. (Whitecourt)</td><td>1,227</td><td>231,957</td><td>1.12%</td><td>23,331</td><td>2</td></tr>
<tr><td>4</td><td colspan="2">Blue Ridge Lumber Inc. (Whitecourt)</td><td>3,643</td><td>1,020,000</td><td>4.94%</td><td>102,594</td><td>2</td></tr>
<tr><td>5</td><td colspan="2">Canadian Forest Products Ltd. (Grande Prairie)</td><td>4,564</td><td>1,278,000</td><td>6.19%</td><td>128,544</td><td>2</td></tr>
<tr><td>6</td><td colspan="2">Daishowa-Marubeni International Ltd. -East</td><td>5,286</td><td>1,480,000</td><td>7.17%</td><td>148,862</td><td>2</td></tr>
<tr><td>7</td><td colspan="2">Daishowa-Marubeni International Ltd. -West</td><td>3,286</td><td>920,000</td><td>4.45%</td><td>92,536</td><td>2</td></tr>
<tr><td>8</td><td colspan="2">Gordon Buchanan Enterprises Ltd., and Tolko Industries Ltd.</td><td>2,300</td><td>485,000</td><td>2.35%</td><td>48,782</td><td>2</td></tr>
<tr><td>9</td><td colspan="2">Manning Diversified Forest Products Ltd.</td><td>2,662</td><td>570,000</td><td>2.76%</td><td>57,332</td><td>2</td></tr>
<tr><td>10</td><td colspan="2">Millar Western Forest Products Ltd. (Whitecourt)</td><td>2,950</td><td>601,837</td><td>2.91%</td><td>60,534</td><td>4</td></tr>
<tr><td>11</td><td colspan="2">Spray Lake Sawmills (1980) Ltd. (Cochrane)</td><td>1,932</td><td>365,846</td><td>1.77%</td><td>36,798</td><td>4</td></tr>
<tr><td>12</td><td colspan="2">Sundre Forest Products Inc. (Sundre)</td><td>560</td><td>106,945</td><td>0.52%</td><td>10,757</td><td>2</td></tr>
<tr><td>13</td><td colspan="2">Tolko Industries Ltd. (High Prairie)</td><td>3,100</td><td>577,312</td><td>2.80%</td><td>58,067</td><td>3</td></tr>
<tr><td>14</td><td colspan="2">Tolko Industries Ltd., Footner Forest Products Ltd. and La Crete Sawmills Ltd.</td><td>15,566</td><td>1,795,000</td><td>8.69%</td><td>180,545</td><td>3</td></tr>
<tr><td>15</td><td colspan="2">Tolko Industries Ltd., Vanderwell Contractors (1971) Ltd., and West Fraser Mills Ltd. (Slave Lake)</td><td>4,328</td><td>1,211,910</td><td>5.87%</td><td>121,897</td><td>2</td></tr>
<tr><td>16</td><td colspan="2">Vanderwell Contractors (1971) Ltd. (Slave Lake)</td><td>587</td><td>8,534</td><td>0.04%</td><td>858</td><td>1</td></tr>
<tr><td>17</td><td colspan="2">West Fraser Mills Ltd. (Edson)</td><td>1,900</td><td>446,590</td><td>2.16%</td><td>44,919</td><td>2</td></tr>
<tr><td>18</td><td colspan="2">West Fraser Mills Ltd. (Hinton)</td><td>10,047</td><td>2,235,325</td><td>10.82%</td><td>224,834</td><td>2</td></tr>
</table>

SN	Name of mill (same as FMA holder)	Harvested area (ha)	Harvested vol (m^3)	% of total harvested vol in Alberta	Residue potential (odt/yr)	No of BSPs in an FMA
19	West Fraser Mills Ltd. (Slave Lake)	5,313	1,127,034	5.46%	113,360	2
20	Weyerhaeuser Company Limited (Grande Prairie)	13,600	2,175,000	10.53%	218,766	3
21	Weyerhaeuser Company Limited (Pembina Timberland)	5,745	1,456,796	7.05%	146,528	5
	Total	**97,742**	**20,653,925**	**100.0%**	**2,077,418**	**76**