Techno-economic Assessment of Utilization of Food Processing Waste for Production of Energy and Chemicals

by

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Abstract

Alberta's food processing industry is the second largest food waste producer after the household sector. Most of the waste currently produced by the food processing industry is landfilled. Decomposing landfill waste emits greenhouse gases (GHG), which contribute to global warming. We estimated the amount of food waste produced by Alberta's food processing industry by developing a geographical information system (GIS)-based model with data from food processing companies in the province. The companies were selected such that all sizes, types, and geographic locations were considered. We gathered information on the amount and characteristics of food waste, the location of the processing facilities, and the food waste disposal method and then estimated the total amount of food waste generated in Alberta. In addition, with the help of ArcGIS software, we created GIS maps to show the distribution of food waste throughout the province and the availability intensity. Finally, we estimated the potential energy that could be produced in the form of biogas and electricity using Alberta's food processing waste and mapped it as well. There is a potential to generate 852 million kWh electricity per year from Alberta's food processing waste, which is about 1% of the province's total electricity generation. This capacity could help in the development of waste-to-value-added facilities in Alberta and Canada.

Alberta's food processing industry produces 500,000 tonnes of food waste every year. As mentioned above, a large portion of this waste is currently landfilled. The cost to transport the waste to the landfill, along with associated disposal fees, make landfilling a costly means of handling food processing waste. Food processing waste can, instead, be converted to energy through anaerobic digestion (AD) technology. A detailed techno-economic analysis model was developed to study the economics associated with anaerobic digestion facilities processing food wastes. The model was afterwards applied to study a food processing facility in Red Deer County, Alberta. For the base case scenario, a techno-economic analysis was carried out for a

proposed facility that would process 100,000 t/yr of food processing wastes. Economic analyses were carried out for three more proposed scenarios as well. In all cases, the gate fee was calculated based on Alberta's current electricity price and a 10% IRR with and without considering carbon credit. The economic viability of each plant was justified by comparing the calculated gate fee with the landfill disposal fee. Finally, a sensitivity analysis was performed to assess the influence of key parameters on the results.

Composting is another means of managing wastes. We developed a techno-economic model to analyze composting of food processing wastes as well. Later, a case in Alberta was studied and the techno-economic model was used for small-, medium-, and large-scale facilities that compost less than 1,000 t/yr, 1,000 to 10,000 t/yr, and 10,000 to 20,000 t/yr food processing waste, respectively. Gate fees and internal rates of return (IRRs) were calculated for all the case scenarios with and without considering carbon credit. The minimum size below which a facility is no longer economically attractive was determined. Finally, we performed a sensitivity analysis to assess the influence of key parameters. We also compared composting with anaerobic digestion technology in converting food processing wastes.

Preface

This thesis is an original work by Mohammad Ahsan Ullah under the supervision of Dr. Amit Kumar. Chapter 2 of this thesis has been submitted as Ullah, M., Vaezi, M., Kumar, A., Bell, J., "Assessment of the waste-to-energy potential from Alberta's food processing industry" to Canadian Biosystems Engineering Journal. Chapter 3 of this thesis is to be submitted as Ullah, M., Vaezi, M., Khan, M., Kumar, A., as "Techno-economic Analysis of Anaerobic Digestion Processes to Convert Food Processing Industry Waste to Energy". Chapter 4 of this thesis is to be submitted as Ullah, M., Vaezi, M., Kumar, A., as "Composting of Food Processing Industry Waste: A Techno-economic Analysis". I was responsible for the data collection, modelling and validation, and manuscript composition. M. Vaezi contributed to model validation and manuscript edits. A. Kumar was the supervisory author and was involved with concept formulation, evaluation, model development and validation, and manuscript edits.

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Chapter 1 : Introduction

1.1. Background

According to the Food and Agriculture Organization (FAO) of the United Nations, 1300 million tonnes of food is wasted annually throughout the world; this figure is one-third of the total food produced (FAO, 2012; Uçkun Kiran et al., 2014). The wastage occurs at different stages of the supply chain, which starts with farm production and continues to food processing, transportation and distribution, retail shops, restaurants and hotels, and finally to household consumption. On a per capita basis, North America (295 kg/year) and Europe (280 kg/year) are the biggest food waste producers compared to sub-Saharan Africa (160 kg/year) and South and Southeast Asia (125 kg/year each) (Gustavsson et al., 2011).

As a developed and North American country, Canada produces significant amounts of food waste. On average, 40% of food produced in Canada is unconsumed every year (Abdulla, 2013; Uzea, 2014). Based on an earlier study, the quantified annual economic value of food waste in Canada is worth $31 billion (Gooch & Felfel, 2014). The breakdown of food waste at different stages in Canada is shown in Fig. 1-1. It shows that household consumers and food processing industries generate the highest (47%) and second highest (20%) percentages of total food waste (Gooch & Felfel, 2014). Although household consumers produce the highest portion of food waste, it is difficult to separate and collect food waste alone, since it is mixed with municipal solid waste. The method of segregation of waste and its collection also depends on the jurisdiction. Food waste produced in food processing industries, on the other hand, is easier to separate and collect. In this study, the focus is on the food waste produced in food processing industries.

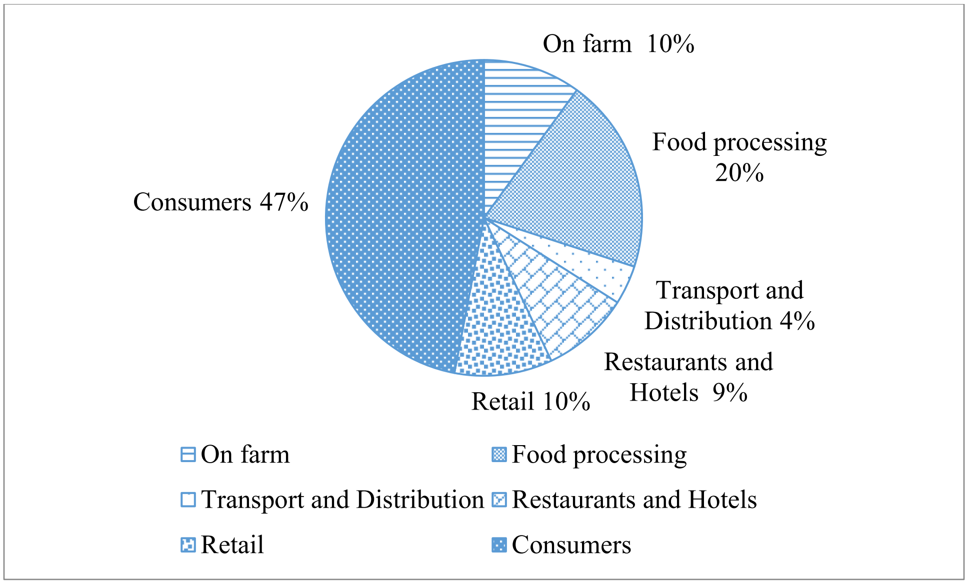


Figure 1-1: Food waste production at different stages in Canada

Alberta's food processing industry is the second largest manufacturing sector in the province and produced $12.6 billion of $74.8 billion in manufacturing goods in 2015 (Alberta Government2, 2015). There are more than five hundred food processing companies in Alberta (Bates, 2015). These companies produce and process a wide variety of foods such as meat, fish, vegetables, fruit, cereal products, baked goods, confectioneries, beverages, etc. These facilities generate a range of wastes from the loss of raw materials while processing, unused leftovers, and by-products of processes. The wastes consist of typical waste of food processing industries (Bell, 2015), which includes left over and chucked out portions of fruits and vegetables; inedible and discarded portions of meat and fish processing; viscous black syrup and dry pulp from sugar refining; cheese whey from dairy farms; residues of alcohol production (stillage) from wineries and breweries; and wastewater from cleaning, boiling, cooling, and cooking operations (Kosseva, 2011; Pham et al., 2015). Quantifying the total amount of this waste is one of the key objectives of this study.

1.2. Research Gap / Motivation

Although Alberta's food processing industry is the second largest manufacturing sector, its waste is not well investigated/characterized. There has not been any research to estimate the total amount of food processing waste produced in the province and its distribution geographically in the province. The amount of the processing waste have been estimated by assuming a certain percentage of the total food is wasted or by assuming the per capita waste generated and then multiplying by total population (Abdulla et al., 2013 ; Moriarty, 2013). But these methods do not ensure the true amount of the processing waste produced. Collecting accurate data from all food processing facilities is a reliable approach to examine the accurate amount of the waste produced. Such a survey has never been conducted across the province of Alberta before.

Landfilling is the most common disposal practice of food processing waste. Landfilling is an expensive disposal method for food processing facilities due to the transportation cost of food waste to distant landfill and corresponding landfilling fees. Moreover, Landfilling is harmful for the environment. The decomposition of food waste in landfills emits methane (CH_4) which is 23 times more potent greenhouse gas than carbon dioxide (CO_2) and hence causes global warming (Pham et al., 2015). To address these economical and environmental concerns with current disposal methods, more efficient waste management approach is needed.

Food processing waste can be converted to energy by a suitable conversion technology. There are a number of waste conversion technologies, i.e., anaerobic digestion (AD), composting, incineration, pyrolysis, gasification, hydrothermal carbonization, and hydrothermal liquefaction. By conducting literature review, anaerobic digestion and composting was found the most appropriate conversion technology for food waste. The others are troublesome for different reasons. Incineration is a combustion process where highly toxic compound and environment pollutant, dioxin, is produced due to high moisture content of food waste (Autret et al., 2007;

Katami et al., 2004). Pyrolysis and gasification is a heating process at very high temperature to produce bio-oil and syngas. High moisture content of food waste make the heating process costly due to the consumption of more power (Arena, 2012; Demirbaş, 2002; Luz et al., 2015; McKendry, 2002; Pham et al., 2015; Yaman, 2004). Hydrothermal carbonization is an emerging technology that produces coal-like product, hydro-char, in the presence of water at 180–350 C temperature, and 4–45 bar pressure. However, It has not matured to process food waste in industrial scale (Berge et al., 2011; Heilmann et al., 2011; Kaushik et al., 2014; Li et al., 2013; Libra et al., 2011; Pham et al., 2015). Hydrothermal liquefaction takes place at high pressure and subcritical water condition to produce bio-oil. Similar to hydrothermal carbonization, it has not matured to process food waste in industrial scale or at commercial stage yet (Déniel et al., 2016; Tekin et al., 2014; Toor et al., 2011).

On the other hand, anaerobic digestion is decomposition process of food waste in the absence of air. The process is enhanced in the presence of anaerobic bacteria. It produces biogas that can be utilized to generate electricity and heat. Food waste is easily biodegradable due to its high moisture content and organic structure. In addition to biogas, anaerobic digestion produces digestive as a by-product that can be used as fertilizer or a soil conditioner. The volume of methane produced from food waste is higher than other organic wastes such as animal manure or organic parts of municipal solid waste. The anaerobic digestion is also considered a carbon neutral process, and thus it reduces greenhouse gas emission (Kim & Oh, 2011; Moriarty, 2013; Uçkun Kiran et al., 2014; Zhang et al., 2014). For such reasons, anaerobic digestion technology is a popular waste management solution in many large cities (Moriarty, 2013; RIS & MacViro, 2005).

In composting, biological decomposition of biodegradable materials is occurred in the presence of oxygen. Though it is not as environmentally-friendly as anaerobic digestion (Alberta

Environment, 2010) but it is relatively cheaper than anaerobic digestion and other technologies (Pham et al., 2015; RIS and MacViro, 2005).

There has been studies on economic analysis of anaerobic digestion and composting for a specific capacity (RIS & MacViro, 2005), but no study has been conducted when the capacity changes and its impact on cost of electricity production (or compost production for composting). In this study, we carried out techno-economic analysis by developing scale factor and investigating how the final results change.

1.3. Research Objectives

The overall objective of the study is to assess the utilization of food processing waste for production of energy and chemicals through development of techno-economic models. The specific objectives are:

- Assessing the total amount of food waste produced in the province of Alberta, Canada;
- Finding out the geographical locations where food processing waste availability is comparatively higher;
- Finding out the type and characteristics of food processing waste and how it is managed at present;
- Estimating the potential energy from food processing waste;
- Developing region-wise GIS maps to illustrate corresponding energy distribution across Alberta;
- Developing scale factor for assessment of capital cost of different components of an anaerobic digestion plant for processing of food waste;
- Developing a comprehensive techno-economic model for assessment of cost of electricity generation from AD of food waste;

- Conducting a case study for Reed Deer County in Western Canada including the development of the transportation cost using geographic information system (GIS);
- Conducting a comparative assessment of two scenarios: (a) separately located food waste production facilities and AD facilities; and (b) co-located food waste producing facilities and AD facilities;
- Assessing the impact of the variation of different technical and economic parameters on the cost of electricity generation from food waste;
- Developing scale factor for assessment of capital cost of different components of composting plant for processing of food waste;
- Developing a comprehensive techno-economic model for assessment of cost of composting of food waste;
- Estimating the economic optimum size of compositing facility;
- Conducting a case study for Alberta, a Western Canadian Province including the development of the transportation cost using geographic information system (GIS);
- Conducting sensitivity analysis to assess the impact of the variation of key parameters on the cost of compost production from food waste;

1.4. Research Methodology

The focus of this study was on assessing the total amount of food processing waste in the province of Alberta, as well as on conducting a techno-economic analysis of anaerobic digestion and composting technologies to study their technical and economic feasibility. The study was conducted as follows:

- Data was collected such as the amount of waste generated, types of waste, disposal methods practised, etc., from food processing facilities across the province of Alberta. The data was collected based on the survey of the facilities in Alberta. Once the data were collected, the amount of the waste availability was developed for county-wise, region-wise and for the whole province. A geographic information system (GIS) map was developed to show the intensity of waste throughout the province and major areas of waste availability were afterwards identified. The potential energy from food processing waste was estimated and GIS map was developed to show the energy distribution across the province of Alberta. Detailed discussions are provided in Chapter 2 of the thesis.

- In the next step, detailed techno-economic analysis of anaerobic digestion was conducted. With survey data and using ArcGIS software and exclusion, preference, and location-allocation analyses, a site was selected for a proposed AD facility. All the cost components (capital, operating, maintenance, transportation) of the facility were estimated using data reported in literature. Operating costs were estimated for staff using Alberta salaries. Transportation costs were estimated by calculating the travelling distance using Alberta's actual road network and considering the unit transportation costs. Total biogas yield was calculated for the standard value of biogas production from food waste by anaerobic digestion. Electricity generation was calculated for the combined heat and power (CHP) unit considering the heating value of biogas and efficiency of the CHP unit. The revenue components (electricity sale, gate fee, carbon credit) of the facility were also estimated. The parameters used in the techno-economic model (plant size, plant parasitic load, plant life time, IRR, inflation rate) were estimated. The model was afterwards applied to study a food processing facility in Red Deer County, Alberta. For the base case scenario, the techno-economic analysis was carried out for a proposed facility that would process 100,000 t/yr of food processing waste. Economic analyses were carried out for three more proposed scenarios as well. In all cases, the gate fee was calculated based on Alberta's current electricity price and 10% IRR with and without considering carbon credit. The economic viability of each plant was justified by comparing the calculated gate fee with the landfill disposal fee. Finally, a sensitivity analysis was performed to assess the influence of key parameters on the results. The details are discussed in chapter 3 of the thesis.

- In the last step, a techno-economic analysis was conducted for composting following the procedure described for anaerobic digestion. Windrow composting was considered for the analysis since this is the predominant composting practice in Alberta. The results were compared with the outcomes of the anaerobic digestion analysis. The details are discussed in chapter 4 of the thesis.

1.5. Thesis Organization

This thesis is comprised of five chapters as well as a table of contents, a list of tables, a list of figures, and a list of references. The thesis is in a paper-based format. Chapters 2, 3, and 4 are stand-alone papers that are expected to be published in peer-reviewed journals. Since each chapter is intended to be read independently, there is some repetition of concepts, data, and assumptions.

Chapter 1 provides the background, research motivation, research methodology, and organization of the thesis. A brief summary of the current status of food processing waste in Alberta is described in the background section. The research motivation section describes the need to conduct this study. In the research methodology section, the procedures of the whole study were described briefly.

In Chapter 2, Alberta's food processing waste was assessed. The chapter describes how the survey was conducted, the results of the survey, and the development of GIS maps.

In Chapter 3, a detailed techno-economic analysis of anaerobic digestion was presented. The chapter describes how the facility site was selected, the cost and revenue components of the facility were estimated, and the model was developed. Chapter 3 also includes the justification of the results for the base case scenario and a few other scenarios.

In Chapter 4, the techno-economic analysis of composting is discussed and the results compared with those of anaerobic digestion.

Chapter 5 summarizes the research outcomes and makes recommendations for future work.

Chapter 2 : Assessment of the Waste-to-Energy Potential from Alberta's Food Processing Industry

2.1. Introduction

Organisation for Economic Co-operation and Development (OECD) carried out a study to collect available data of food waste of all countries (OECD, 2014). They found that Canada is not amongst the nations whose food waste data are available. In some literature, the total percentage of food wasted in all sectors in Canada were assumed 30% (Gooch & Felfel, 2014) to 40% (Abdulla, 2013; Nicoleta Uzea, 2014). Among all sectors, household consumers and food processing industries generate the highest and second highest percentages of food waste. Although household consumers produce the highest portion of food waste, it is difficult to separate and collect food waste alone, since it is mixed with municipal solid waste. Food waste produced in food processing companies, on the other hand, is easier to separate and collect. Therefore, as the second-largest food waste producing sector, the food processing industry should be studied thoroughly.

An earlier study assumes that 20% of Canada's food waste is generated in food processing facilities (Gooch & Felfel, 2014). However, they do not mention province wise percentage of food processing waste. Among all provinces, Ontario is the highest food processing waste producer followed by Alberta and British Colombia (Saville, 2014). However, this data excludes the smaller facilities. We focused on Alberta's food processing industries and have not found any estimation of the total amount of food waste produced in this sector.

The province of Alberta in Canada has over five hundred food processing companies (Bates, 2015). Food processing facilities in Alberta produce/process a wide variety of food such as meat, fish, vegetables, fruit, cereal products, baked goods, confectioneries, beverages, etc., which generate an equally wide range of waste through the loss of raw materials during processing, unused leftovers, and by-products of processes (Bell, 2015). The disposal of this waste wastes energy, labour, and other resources that have been invested to produce and process the food. Environmentally speaking, when landfilled, the decomposition of food processing waste emits methane (CH_4), which is 25 times more powerful a greenhouse gas (GHG) than carbon dioxide (CO_2) and contributes significantly to global warming (Alberta Government1, 2015). In addition, the transportation cost of waste to landfills and tipping fees (i.e., disposal fees) impose immense costs to food processing companies. Landfill tipping fees vary from one county to another and depend on the county's waste management policy and regulations. Some notable landfill tipping fees in 2015 were $110/tonne in the City of Calgary (Bell, 2015; The City of Calgary 2015), $110/tonne in Taber (Municipal District of Taber, 2015; Bell, 2015), $70/tonne in the City of Edmonton (Bell, 2015; The City of Edmonton, 2015), $65/tonne in Red Deer County (Bell, 2015; The City of Red Deer, 2015), and $60/tonne in Lethbridge County (Bell, 2015; The City of Lethbridge, 2015). The environmental concerns and the costs indicate the need to manage food processing waste efficiently.

Food processing waste can be used as a source of energy. Electricity can be produced from food waste by anaerobic digestion (AD) technology (Kiran et al., 2014; Moriarty, 2013; Pham et al., 2015; Zhang et al., 2014). In this process, food waste is decomposed in a digester with the help of anaerobic bacteria in absence of air to produce biogas. This biogas can be combusted in a combined heat and power (CHP) unit to generate electricity. There are a number of food waste conversion facilities in North America that produce electricity through AD technology, i.e., the 40,000 t/yr AD facility in Toronto, Canada (Moriarty, 2013), the 35,000 t/yr AD facility in East Bay Municipal Utility District (EBMUD) Oakland, USA (Institute for Local Self-Reliance, 2010), and the 40,000 t/yr AD facility in Everett, USA (Moriarty, 2013). There are also AD facilities where food waste is co-processed together with other residues. Examples of those are food and yard waste AD facilities at the University of Wisconsin, USA (Moriarty, 2013), in Richmond, Canada (Natural Resources Canada, 2016), in San Jose, USA (Institute for Local Self-Reliance, 2010), and in Lethbridge, Canada (Lethbridge Biogas LP, 2013).

There are several approaches to estimate food waste from food processing industries. Common approaches are collecting information by conducting surveys among food manufacturers (Moriarty, 2013) and calculating per capita food waste generation (Abdulla et al., 2013) by measuring the waste sent to landfills, composting, etc. (Moriarty, 2013). Food waste is also estimated by identifying the sectors where the wastage takes place (e.g., fields, processing and packaging, transportation and distribution, hotels and restaurants, etc.) and associating a certain percentage of the total food waste to every specific sector. On that note, in an earlier study, 20% of total food waste produced in Canada was assumed to be associated with the food processing sector (Gooch and Felfel, 2014). Except for the survey approach (i.e., collecting accurate data from all food processing companies), none of the approaches ensures an accurate amount of produced waste. Such a survey has never been conducted across the province of Alberta before. This study is an effort to address this gap.

The overall aim of this study is to carry out a comprehensive research study on food processing waste of Alberta. The specific objectives are:

- To assess the total amount of food waste produced in the province of Alberta, Canada;
- To find out the geographical locations where food processing waste availability is comparatively higher;
- To find out the type and characteristics of food processing waste and how it is managed at present;
- To estimate the potential energy from food processing waste; and
- To develop region-wise GIS maps to illustrate corresponding energy distribution across Alberta.

This study would help to select the location of future food processing waste conversion facilities in Alberta.

2.2. Methodology

2.2.1. Data collection

In an earlier study it was assumed that 20% of Canada's food waste is generated in food processing facilities (Gooch and Felfel, 2014). However, there is no organized survey conducted so far to estimate the amount of food waste produced by food processing facilities in Alberta. The initiative was taken for the first time here to collect data on food waste from all of Alberta's food processing facilities. Figure 2-1 shows the data collection and waste estimation steps taken for this research.

Out of 503 food processing companies in Alberta, 200 companies were selected in such a way to include a range of facility sizes (small, medium, large), food type (meat, fish, vegetables, fruits, cereal products, baked goods, confectioneries, beverages, etc.), and geographic locations. The survey questionnaire were sent out to these companies to ask about the types of products, the types of waste or underused by-products, the characteristics of the waste, the volume of the waste produced per day/week/month, the current use for the waste and/or the disposal method, the waste disposal cost, and anything else the company wanted to add. In the end, responses were received from 181 companies.

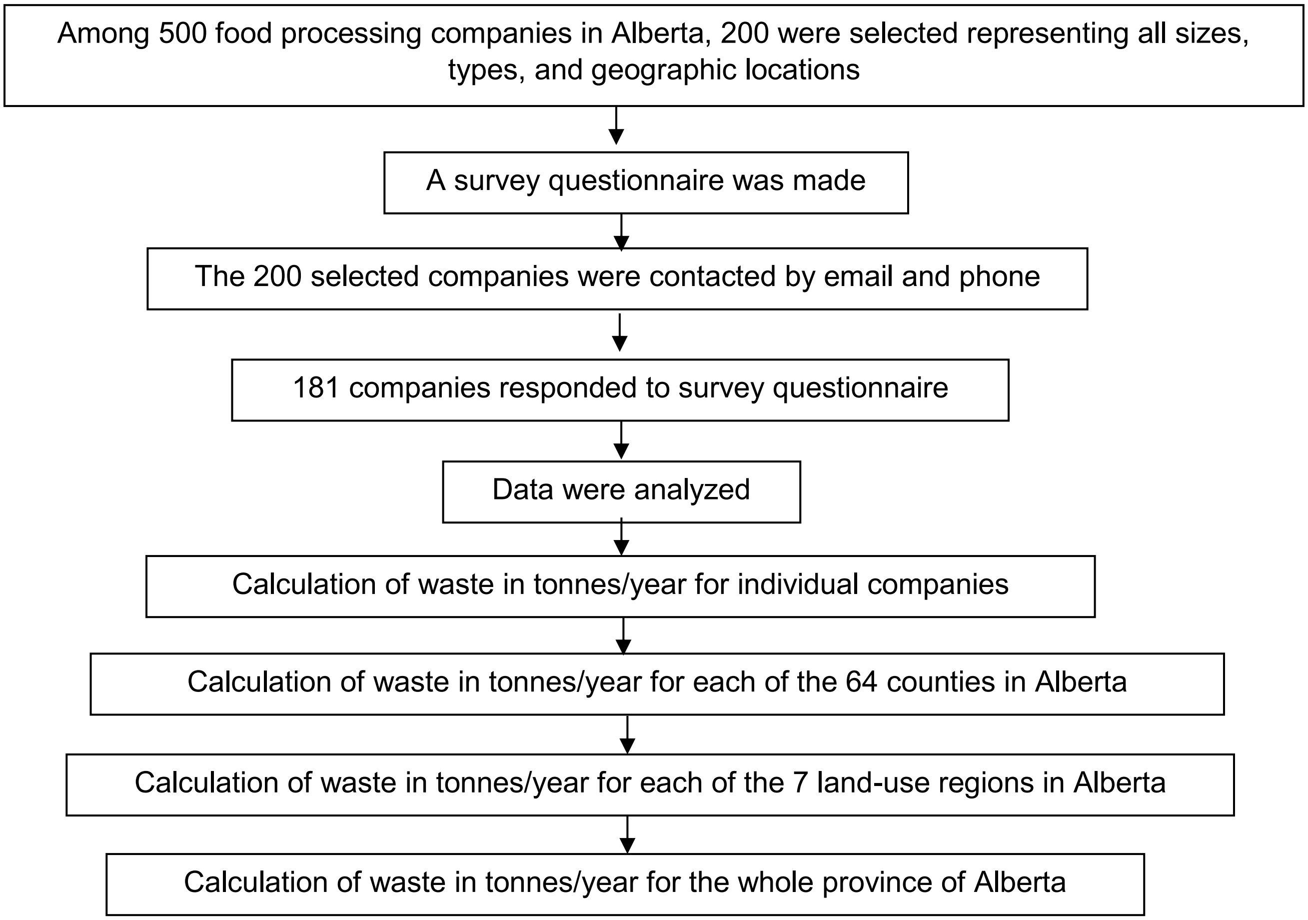


Figure 2-1: Flow chart of data collection process and waste estimation

The waste data provided by the companies were reported in different units such as kg/month, dumpster/week, etc. Some companies provided the waste amount by dumpster size (i.e., small, medium, large) and filling schedule (daily or weekly). In such cases, the average volume of a standard dumpster was considered and the corresponding weight of the waste was then calculated by multiplying the volume and the waste density. The value of the waste density was mainly provided by the processing companies. However, in some cases, it was collected from the literature as well (Krokida, Karathanos, and Maroulis 1998; Krokida and Maroulis 1997). Similarly, the waste moisture content was collected from both the companies and the literature. In cases of mixed waste, since it was not possible to determine the dominant waste in the mixture, 70% moisture content was assumed as this is considered to be typical for food waste (Miller 2000). The moisture contents for different waste streams are shown in Table 2-1.

Table 2-1: Average moisture content of different waste streams

Waste type	Moisture content	Reference
Vegetables	90%	(Bastin and Henken, 2011; Sipahioglu and Barringer, 2003)
Fruit	85%	(Bastin and Henken, 2011; Sipahioglu and Barringer, 2003)
Potato	76%	(Bastin and Henken, 2011; Krokida and Maroulis, 1997; Sipahioglu and Barringer, 2003)
Wet distilled grain	70%	(Leu, 2011)
Mixed food waste	70%	(Miller, 2000)
Meat	60%	(Yalçın and Şeker, 2016; USDA, 2011)
Unusable bread dough	60%	(estimated)
Syrup (stillage)	60%	(Cardona, Sanchez, and Gutierrez 2009)
Filter grain or skimming	50%	(provided by companies)
Bean hulls	50%	(estimated)
Oat hulls	20%	(Clarke, 2011)
Flour	14%	(Canadian Grain Commission, 2013)

We then estimated county- and region-wise food processing waste for the province. Alberta has sixty-four counties and seven land-use regions (Alberta Environment and Parks, 2011; AltaLIS, 1998). The 181 companies that responded were allocated to their own counties and the total amount of food processing waste in each county was calculated. The estimates of the counties were used to estimate the respective potential in the different land-use regions and the total amount of food processing waste produced in every region, as well as the potential for the entire province of Alberta.

2.2.2. GIS mapping

A geographic information system (GIS) can store, retrieve, and display spatially referenced data (Noon and Daly, 1996). The GIS software ArcGIS 10.1, released in 2011, developed by the Environmental Systems Research Institute (ESRI, 2011), was used in this study to develop GIS maps. Geospatial information for the processing facilities is available in both GCS North American 1983 and GCS North American 1983 CSRS, which are found in the Canadian Spatial Reference System (Sultana and Kumar, 2012). A map was prepared for Alberta showing land-use region boundaries and county boundaries (Fig. 2-2) based on collected standard shape files for land-use regions and counties from AltaLIS (AltaLIS, 1998) and Alberta Environment and Parks (Alberta Environment and Parks, 2011).

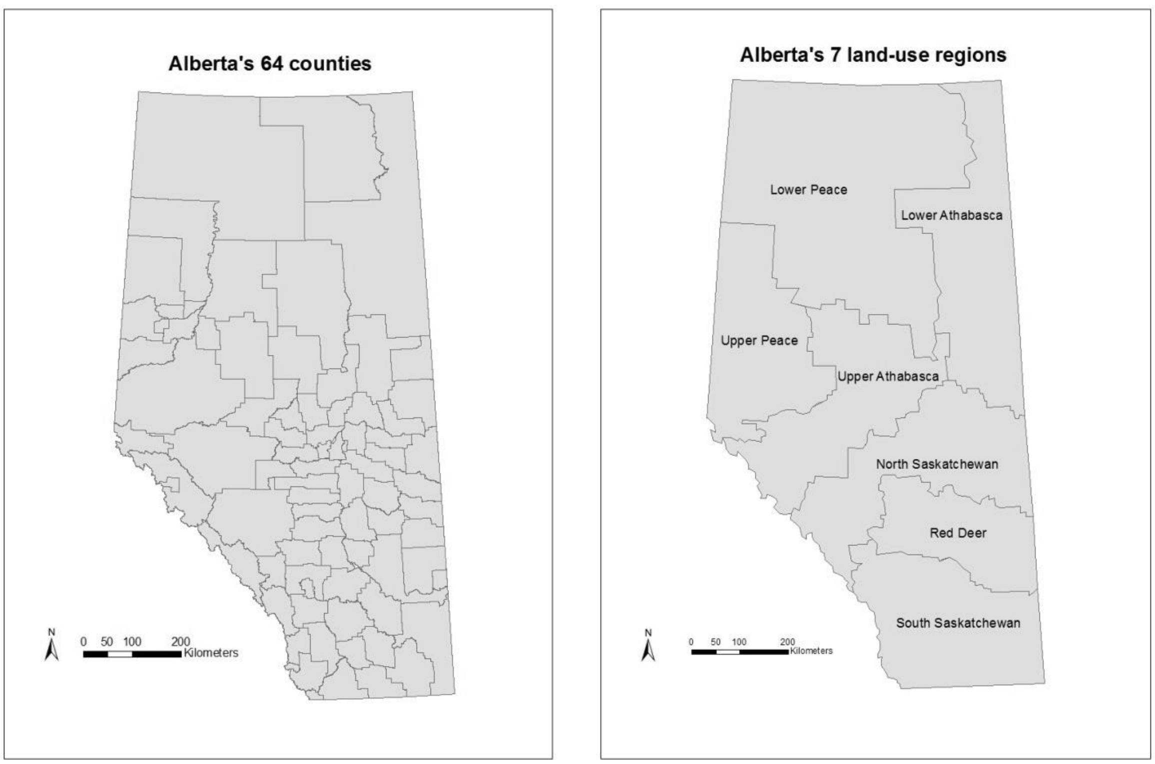


Figure 2-2: Shape file boundaries for Alberta's counties (left) and land-use regions (right)

2.2.3. Extrapolation of data

There are 503 food processing companies in Alberta. After collecting data from 181 of them, we estimated the amount of food waste for the remaining 322 companies based on the data from the facilities surveyed. Those companies that provided data were categorized into three size classes (small, medium, and large) based on the number of employees: 1-25 is small, 26-100 is medium, and 100+ is large. The average food processing waste produced by size class were calculated. The 322 companies not surveyed were also categorized into small, medium, and large size classes using similar criteria, and the corresponding amount of waste produced was estimated by multiplying the size class with the corresponding average waste production. Thus the total amount of food processing waste was estimated for the entire province.

2.3. Results

2.3.1. Estimation of the potential of food processing waste

The total amount of food waste in the 181 surveyed companies was 250,570 dry tonnes/year. The amount of food waste for each land-use region was calculated for these companies and is shown in Table 2-2. The Red Deer and South Saskatchewan regions produce the most food processing waste.

Table 2-2: Food processing waste by land-use region

Land-use region	Tonnes/year (dry)
Lower Peace	-
Upper Peace	-
Lower Athabasca	-
Upper Athabasca	3,997.07
North Saskatchewan	36,114.04
Red Deer	113,184.78
South Saskatchewan	97,231.91
Total	**250,570**

2.3.2. Development of GIS maps

To learn the location of food processing waste generating regions and the distribution of waste throughout the province, we created GIS maps. Figure 2-3 shows a land-use region-wise GIS map of Alberta's food processing waste. Most of the waste is concentrated in southern Alberta, primarily in Red Deer County, Taber County, Lethbridge County, Sturgeon County, the City of Calgary, Parkland County, and the City of Edmonton. It also shows the intensity of the food waste availability for different regions. The higher intensity regions are favourable for the establishment of a waste-to-value-added facility.

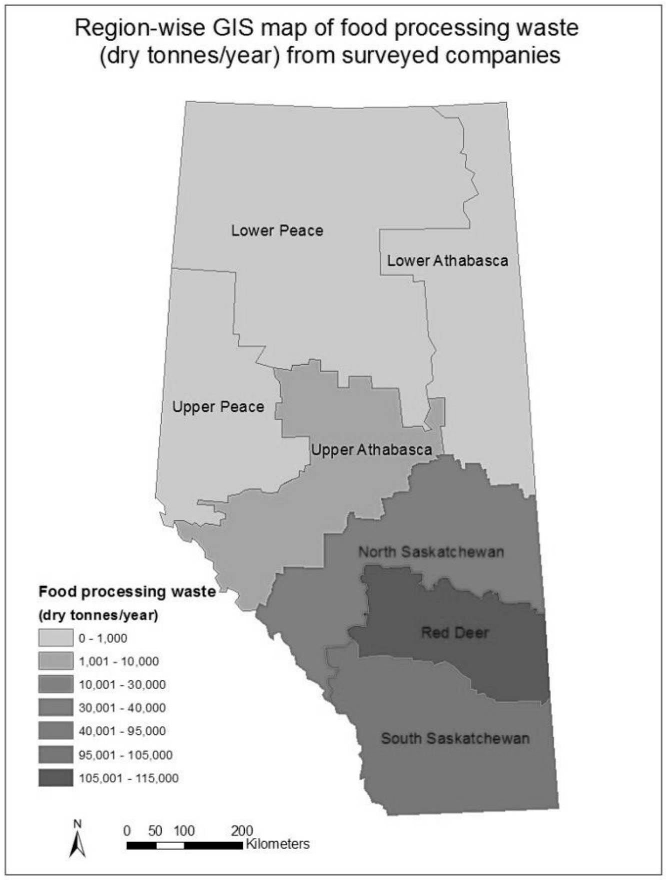


Figure 2-3: Land-use region-wise GIS map of Alberta's food processing waste

2.3.3. Estimate of total waste

The waste generated by the 181 surveyed companies was 250,000 tonnes/year (dry). The waste from the remaining 322 companies was calculated by extrapolation. The total amount of food processing waste from all 500 companies in Alberta was estimated as 503,171 tonnes/year (dry) and is shown in Table 2-3.

Table 2-3: Potential of total waste by food processing industries across Alberta

	Small companies	Medium companies	Large companies	TOTAL
Surveyed companies	85	69	27	181
Collected amount (dry tonnes/year)	28,874	135,287	86,408	250,569
Companies not surveyed	252	46	24	322
Extrapolated amount (dry tonnes/year)	85,603	90,191	76,807	252,602
Total number of companies in Alberta	337	115	51	503
Total amount of waste (dry tonnes/year)	114,478	225,479	163,215	503,171

2.3.4. Disposal of waste

The surveyed companies provided information on how they handled their waste. Some companies have several waste streams and many waste disposal methods including landfilling, animal feeding, composting, land application, rendering, recycling, etc. The different disposal methods and the number of times they are cited by the companies are shown in Fig. 2-4.

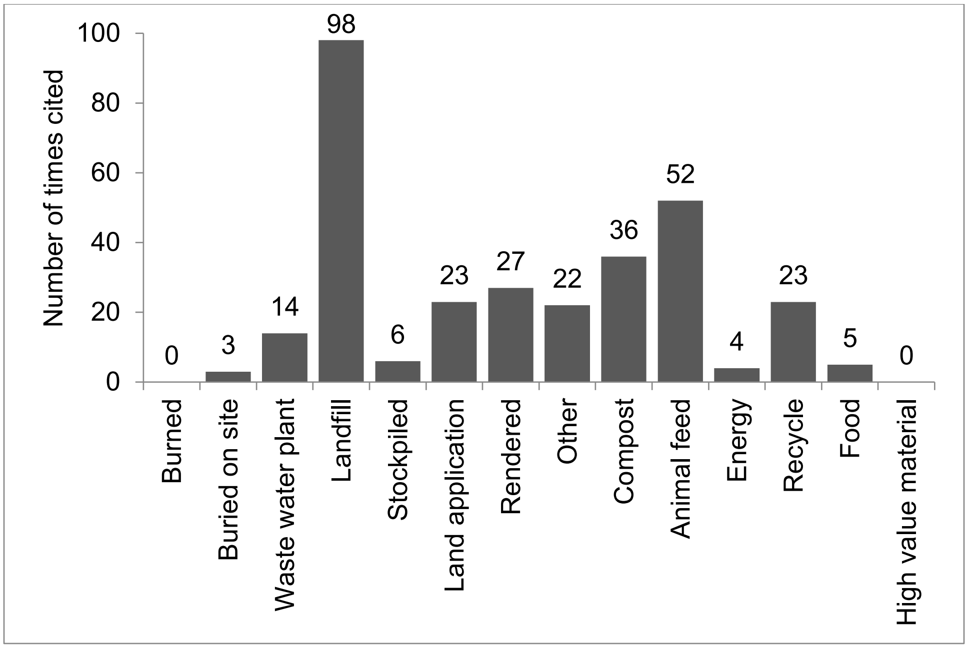


Figure 2-4: Types of disposal methods and number of times cited by the companies

The disposal of waste may be a cost to the company or may be a revenue stream. Table 2-4 shows some comparative values based on various disposal methods. It shows that whatever method the company applies, there is little or no value in the waste. In many cases, the company pays hauling and tipping fees that yield a negative earning from waste disposal. Sometimes the company hires a waste management company to handle the waste. Some large companies incur significant cost to dispose of waste.

Table 2-4: Net value of different disposal methods

Disposal method	Total number of times cited	Possible cost/gain	Net value gain
Burned, buried on site, waste water plant, landfill, stockpiled	121	Hauling cost, staff cost, tipping fee	Negative value
Land application	23	Hauling cost by others	No value
Rendered, other, compost, animal feed	137	May or may not pay for material, hauling fee, may or may not receive payment	Low value
Energy, recycle	27	Valuable commodity	Medium value
Food	5		High value
High value material	0		Very high value

2.3.5. Potential application of food waste diverted from the landfill

Food waste can be used to produce biogas through conversion technologies such as anaerobic digestion and fermentation and thus can be diverted from landfills. Anaerobic digestion of food waste yields higher volumes of biogas than other organic wastes such as animal manure, organic parts of municipal solid waste (MSW), and garden waste (Zhang et al., 2014). Anaerobic digestion of food waste can generate 0.936 m^3 of biogas for every kilogram of volatile solid destruction (Moriarty, 2013). Assuming 88% volatile solids in total food waste (Moriarty, 2013), 824 m^3 of biogas can be produced from each tonne of solid food waste. Hence, Alberta has the potential to generate 412 Mm^3 of biogas per year from 500,000 dry tonnes food waste. Considering the composition of biogas to be 65% methane and 35% carbon dioxide, and the heating value of biogas to be 20.7 MJ/m^3 (Ghafoori, 2007), 8,528 million MJ energy would be available in Alberta each year. If electricity is produced from the biogas using a combined heat and power (CHP) unit with 36% electrical efficiency, Alberta has the potential to generate 852 million kWh electricity in a year. The total amount of electricity generation from all sources (i.e., coal, natural gas, hydro, wind, biomass etc.) in Alberta is 81,621 million KWh in a year (Alberta

Energy, 2015). Hence, the amount of electricity produced from food waste would be 1% of the total generated. Table 2-5 shows the biogas, energy, and electricity potential in Alberta from food waste.

2.3.5.1. Sample Calculation

$$Biogas\ potential\ by\ AD$$

$$= amount\ of\ volatile\ solid\ in\ dry\ food\ waste$$

$$\times\ biogas\ production\ from\ volatile\ solid\ by\ AD$$

$$= (0.88 \times 500{,}000)\ tonnes \times 0.936\ \frac{m^3}{kg} = 412\ million\ m^3$$

$$Energy\ potential\ of\ biogas\ = biogas\ potential \times unit\ energy\ potential\ of\ biogas$$

$$= 412\ million\ m^3 \times 20.7\ \frac{MJ}{m^3}\ = 8{,}528\ million\ MJ$$

$$Electricity\ potential\ = energy\ potential \times conversion\ efficiency\ = 8{,}528\ million\ MJ \times 0.36$$

$$= 3070\ million\ MJ\ = 852\ million\ kWh$$

Table 2-5: Biogas, energy, and electricity potential from food waste in Alberta

	Amount of waste (dry tonnes/year)	Biogas potential by AD (million m^3/year)	Energy potential (million MJ/year)	Electricity potential (million KWh/year)
Based on 181 companies surveyed				
Lower Peace	-	-	-	-
Upper Peace	-	-	-	-
Lower Athabasca	-	-	-	-
Upper Athabasca	4,000	3.3	68	6.8
North Saskatchewan	36,000	29.8	616	61.6
Red Deer	113,000	93.3	1,930	193
South Saskatchewan	97,000	80.1	1,660	166
For whole province of Alberta				
Alberta	500,000	412	8,528	852

A region-wise GIS map was developed (see Fig. 2-5) that shows the available energy and electricity generation based on the waste data for different regions.

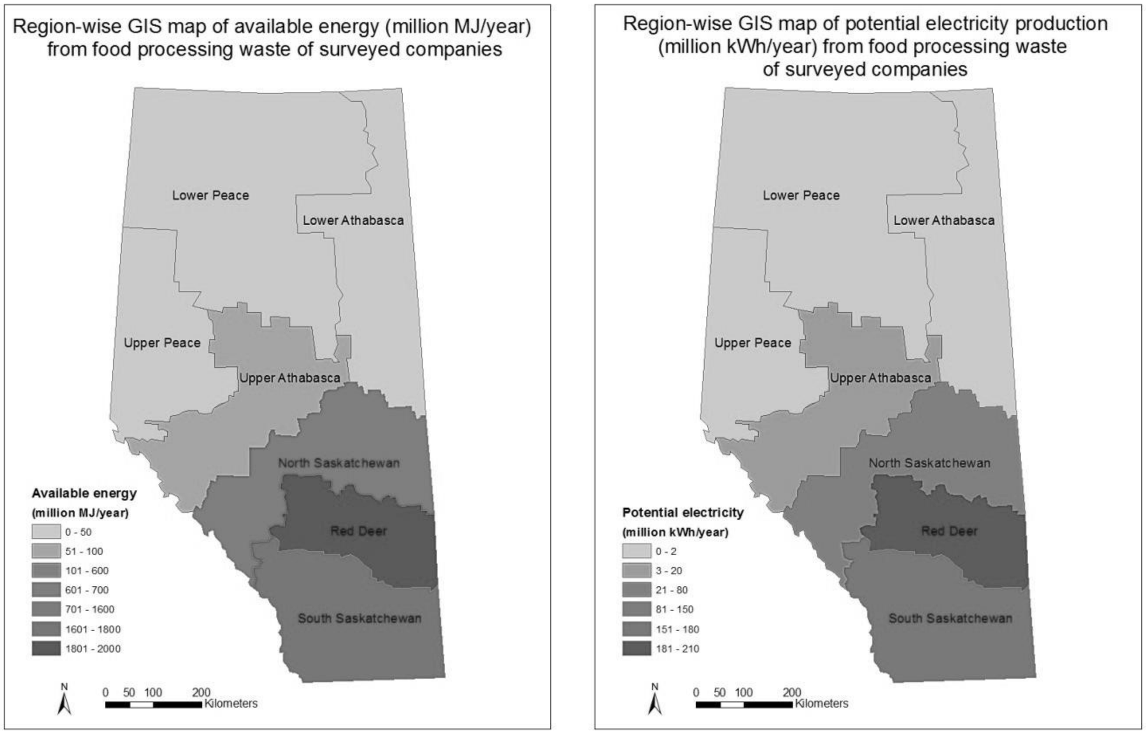


Figure 2-5: Region-wise GIS map of available energy (million MJ/year) and electricity production (million kWh/year) from the food processing waste of surveyed companies

The use of food waste can mitigate GHG through its diversion from landfills and its use for electricity production, which can replace coal or natural gas-based electricity. Hence we estimated GHG reduction via the anaerobic digestion of waste through its diversion from the landfill as well as via electricity production from biogas and its replacement of coal or natural gas-based electricity.

GHG reduction via the AD of food waste (rather than landfilling) was estimated by ICF Consulting to be 0.9 tonne CO_2-eq/tonne of waste (ICF Consulting, 2005). The total food waste potential in Alberta is 500,000 dry tonnes/year, which is equivalent to 1,600,000 wet tonnes/year considering 70% moisture content. Hence, the total amount of GHG reduction in AD (compared to landfilling the waste) is estimated at 1,500,000 tonnes CO_2-eq/year (shown in Table 2-6).

Table 2-6: Calculation of total GHG reduction in AD compared to landfilling

Amount of waste (dry tonnes/year)	Amount of waste considering 70% moisture (wet tonnes/year)	GHG reduction in AD compared to landfill (tonne CO_2-eq / tonne waste)	Total GHG reduction in AD compared to landfill (tonne CO_2-eq / year)
500,000	1,600,000	0.9	1,500,000

GHG reduction through the displacement of coal-based electricity and natural gas-based electricity by biogas-based electricity is 0.00097 tonne CO_2-eq/kWh and 0.0003 tonne CO_2-eq/kWh, respectively (Ghafoori, 2007). Thus the total amount of GHG reduction is 820,000 and 250,000 tonne CO_2-eq/year, respectively, through the displacement of coal- and natural gas-based electricity (shown in Table 2-7).

Table 2-7: Calculation of total GHG reduction in a biogas power plant compared to coal and natural gas power plants

Amount of waste (dry tonnes/year)	**Electricity potential of biogas plant (KWh/year)**	**GHG reduction in a biogas power plant compared to coal (tonne CO_2-eq / kWh)**	**Total GHG reduction in a biogas power plant compared to coal (tonne CO_2-eq /year)**	**GHG reduction in a biogas power plant compared to natural gas (tonne CO_2-eq / kWh)**	**Total GHG reduction in a biogas power plant compared to natural gas (tonne CO_2-eq / year)**
500,000	$852x10^6$	0.00097	820,000	0.0003	250,000

2.4. Conclusion

The food processing industry in Alberta, Canada, produces around 500,000 dry tonnes of food waste annually. The Red Deer region produces the highest amount of waste, followed by the South Saskatchewan and North Saskatchewan regions. Unlike household sector food waste, food processing waste does not require sorting/separation. However, the waste is not disposed economically or environmentally and, in most cases, little or no value is gained from disposal. Such waste, however, could be converted into energy. An estimated 412 million cubic meters of biogas can be produced from these wastes through anaerobic digestion, and 852 million kWh electricity can be produced through combined heat and power. We also estimated the potential for GHG mitigation by diverting landfill waste and displacing the coal or natural gas for electricity generation. The amount of GHG mitigation was estimated to be 1,500,000, 820,000, and 250,000 tonne CO_2-eq/year for diverting landfill, replacing a coal power plant, and replacing a natural gas power plant, respectively.

Chapter 3 : Techno-economic Analysis of Anaerobic Digestion Processes to Convert Food Processing Industry Waste to Energy

3.1. Introduction

According to the Food and Agriculture Organization (FAO) of the United Nations, one-third of the food produced globally is wasted (Gustavsson et al., 2011). The wastage occurs at different stages of the supply chain, which starts with farm production and continues to food processing, transportation and distribution, retail shops, restaurants and hotels, and finally to household consumption. Among these sectors, household consumers and food processing industries generate the highest (47%) and second highest (20%) percentages of total food waste (Gooch & Felfel, 2014), respectively. Although household consumers produce the highest portion of food waste, it is difficult to separate and collect food waste alone, since it is mixed with municipal solid waste. The method of collection, transportation and disposal varies in different jurisdictions around the world. Food waste produced in food processing companies, on the other hand, is easier to separate and collect. In this study, we focused on the food waste from the food processing industries.

Food processing industries produce/process a wide variety of foods such as meat, fish, vegetables, fruit, cereal products, baked goods, confectioneries, beverages, etc. These facilities generate a range of wastes sourcing from the loss of raw materials while processing, unused leftovers, and by-products of processes. The wastes are comprised of fruit and vegetable left-overs and cast-off portions; viscous black treacle and dry pulp from sugar refining; inedible and discarded portions of meat and fish processing; residues of alcohol production (stillage) from wineries and breweries; cheese whey from dairy farms; and wastewater from cleaning, boiling, cooling and cooking operations (Kosseva, 2011; Pham et al., 2015).

As a common practice, a large portion of the food processing waste is landfilled. Sometimes it is burned, buried, or spread on agricultural land (Alberta Agriculture and Rural Development, 2006). Landfilling these wastes means wasting the energy, labour, and other resources spent to produce and process the food. Transporting these wastes to distant landfills and the disposal fees come at a high cost to food processing companies. Landfill disposal fee varies with jurisdiction. Some notable landfill disposal fees in 2015 were $110/tonne in the City of Calgary (Bell, 2015; The City of Calgary, 2015), $110/tonne in Taber (Municipal District of Taber, 2015; Bell, 2015), $70/tonne in the City of Edmonton (Bell, 2015; The City of Edmonton, 2015), $65/tonne in Red Deer County (Bell, 2015; The City of Red Deer, 2015), and $60/tonne in Lethbridge County (Bell, 2015; The City of Lethbridge, 2015). Moreover, landfilling is an environmental hazard. The decomposition of the food waste in landfills produces methane (CH_4) which is 23 times more powerful a greenhouse gas than carbon dioxide (CO_2) and hence contributes substantially to the climate change (Pham et al., 2015). Burning the wastes causes environmental issues, and burying and prolonged spreading of waste on land can destroy soil productivity by overloading the soil with nutrients (Alberta Agriculture and Rural Development, 2006). These economic and environmental concerns demand the food processing waste to be managed more efficiently.

There are several waste-to-energy conversion technologies available: anaerobic digestion (AD), incineration, pyrolysis, gasification, composting, hydrothermal carbonization, and hydrothermal liquefaction. Anaerobic digestion is considered to be the most suitable technology to process food waste on an industrial scale. The others are problematic for various reasons. In incineration, heat and energy is produced by combustion of waste. The problem with incineration is, food waste contains high level of moisture and this may lead to the production of dioxins which is a highly toxic compound and environment pollutant (Autret et al., 2007; Katami et al., 2004). It has been banned in many countries due to environmental concern (Pham et al., 2015). In pyrolysis and gasification, waste is heated at very high temperature to produce bio-oil and syngas. However, the waste should have some specific characteristics such as low moisture content. Since food waste contains high moisture, pyrolysis and gasification is not a good option to process it (Arena, 2012; Demirbaş, 2002; Luz et al., 2015; McKendry, 2002; Pham et al., 2015; Yaman, 2004). In composting, biological decomposition of biodegradable materials is occurred in the presence of oxygen. Though it is relatively cheaper than anaerobic digestion (Pham et al., 2015; RIS and MacViro, 2005), it is not as environmentally-friendly as anaerobic digestion (Alberta Environment, 2010). Hydrothermal carbonization is an emerging technology that takes place in the presence of water at 180–350 C temperature, and 4–45 bar pressure. It produces coal-like product which is called hydro-char. It has not been found to process food waste in industrial scale (Berge et al., 2011; Heilmann et al., 2011; Kaushik et al., 2014; Li et al., 2013; Libra et al., 2011; Pham et al., 2015). Hydrothermal liquefaction is carried out at high pressure and subcritical water condition to produce bio-oil. It has not been found to process food waste in industrial scale or at commercial stage yet (Déniel et al., 2016; Tekin et al., 2014; Toor et al., 2011).

On the other hand, in anaerobic digestion, anaerobic bacteria decompose biodegradable substances without the presence of oxygen and produce biogas. Biogas can potentially be combusted to generate electricity and heat. Food waste is high in moisture and macromolecular organic matters and is thus easily biodegradable. In addition to biogas, anaerobic digestion produces a nutrient-rich digestive that can be used as fertilizer or a soil conditioner. The volume of methane produced from food waste is higher than other organic wastes such as animal manure or organic parts of municipal solid waste (Kim & Oh, 2011; Moriarty, 2013; Uçkun Kiran et al., 2014; Zhang et al., 2014). For such reasons, anaerobic digestion technology is a popular waste management solution in many large cities (Moriarty, 2013; RIS & MacViro, 2005).

There has been studies on economic analysis of anaerobic digestion for a specific capacity (RIS & MacViro, 2005), but no study has been conducted when the capacity changes and its impact on cost of electricity production. In this study, we carried out techno-economic analysis by developing scale factor and investigating how the final result (i.e. cost of energy) changes.

The overall aim of this study is to conduct a comprehensive techno-economic of converting food waste to electricity through anaerobic digestion (AD). The specific objectives include:

- Development of scale factor for assessing the capital cost of different components of an anaerobic digestion plant for processing of food waste;
- Development of a comprehensive techno-economic model for assessment of cost of electricity generation from AD of food waste;
- Conduct a case study for Reed Deer County in Western Canada including the development of the transportation cost using geographic information system (GIS);
- Conduct a comparative assessment of two scenarios: (a) separately located food waste production facility and AD facility; and (b) co-located food waste producing facility and AD facility;
- Assessment of the impact of the variation of different technical and economic parameters on the cost of electricity production from food waste;

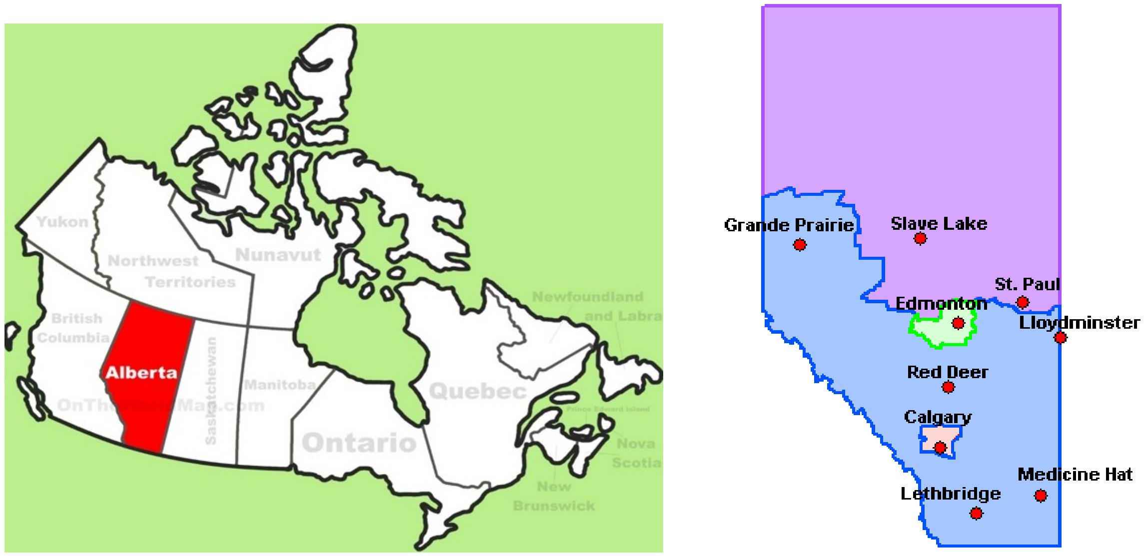
3.2. Methodology

In this paper, we conducted a comprehensive techno-economic analysis on anaerobic digestion (AD) technology to convert food processing waste to energy. The analysis was comprised of feedstock evaluation, facility site selection, cost estimation (capital, operating, maintenance and transportation), biogas yield as well as electricity generation estimations, gate fee calculation, and GHG and carbon credit calculation. Afterwards, a case study in Red Deer County, Alberta was conducted where a financial model was developed for a base case of 100,000 t/yr AD facility. Three additional scenarios were analyzed wherein (i) the waste availability is lower than that of the base case scenario, (ii) the facility is located at a food processing company rather than a distant location, and (iii) the facility is located in Taber County, AB, where the waste availability and landfilling fee are much different from Red Deer County's. The results were presented with and without considering the carbon credit[1]. In addition, we performed sensitivity analyses to assess the influence of key parameters on the final results. Ultimately food processing industry will benefit by the less costly waste management approach proposed here. The environment will be also benefited through the reduction in landfilled food processing wastes and GHG emissions.

3.2.1. Feedstock evaluation

Assessment of availability of feedstock is critical for the techno-economic assessment of utilization of food waste. In this study amount of feedstock availability was evaluated by understanding the number of food processing companies, locations, the amount of food waste per year produced in every company, the characteristics of the food waste, and the size of the area where the food waste is collected in the Red Deer County in Western Canada as shown in Fig.3-1. About 200 companies were surveyed to collect the relevant data. The details on the data collection and availability is discussed in an earlier study (Ullah et al., 2016). The total amount of the waste available and corresponding transportation distance is estimated using the collected data.

[1] A permit that allows a country or organization to produce a certain amount of carbon emissions and that can be traded if the full allowance is not used



(a) (b)

Figure 3-1: (a) Province of Alberta, Western Canada (b) Red deer County, Southern part of Alberta

3.2.2. Site Selection for Anaerobic Digestion Facility

The geographic information system (GIS) software ArcGIS 10.1, developed by the Environmental Systems Research Institute (ESRI, 2011), was used to find suitable locations for the facility. Site selection was performed in three stages, through exclusion analysis, preference analysis, and location-allocation analysis (Sultana & Kumar, 2012; Ma et al., 2005). The exclusion analysis screens out unsuitable lands (also known as constraints) from the study area such asrivers, lakes, rural and urban areas, airports, industrial and mining zones, etc. (Khan et al., 2016). A buffer zone was then created for each constraint and values of “0” and “1” were attributed to the areas within and beyond the buffer zone, respectively. A binary map was developed for each constraint and a final constraint map was created by multiplication of all binary values. Figure 3-2 is an example of a final constraint map.

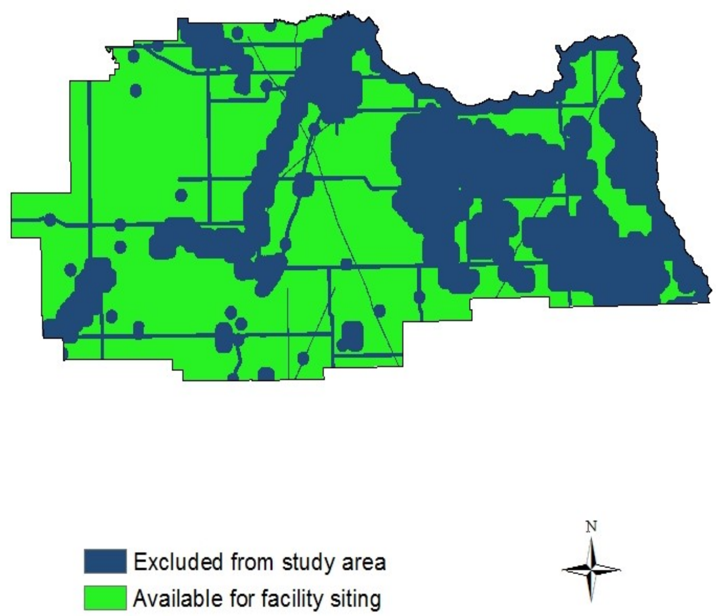


Figure 3-2: Results of the exclusion analysis for Red Deer County

Following the exclusion analysis, a preference analysis was performed by taking into account eight factors: (i) waste availability, (ii) urban area, (iii) water availability, (iv) roads, (v) transmission lines, (vi) power substations, (vii) land cover, and (viii) slope. The analytic hierarchy process (AHP[2]) was used to calculate the weight of each preference factor (Saaty, 2000). Multiple buffer areas were generated around every preference factor, and scores of 1 to 10 were attributed to the buffer areas based on their distance from the respective factor. A suitability index was then calculated by multiplying the value of the constraint map (from the exclusion analysis) with corresponding weights of the preference analysis. A location-allocation analysis was then conducted using the actual road network. The facility location was ultimately determined based on the shortest transportation distance. The details of the approach could be found elsewhere (Khan et al., 2016). The supplementary materials are added in Appendix.

[2] AHP is a structured technique for organizing and analysing complex decisions where the factors are ranked by assigning weights based on their relative importance.

3.2.2.1. Optimization of transportation cost

In this study, we calculated transportation cost for one source points of waste (i.e. for one company). If there are several source points of waste (i.e. several companies) as represented by solid dots in Fig 3-3, then following the methodology described above we might found three facility locations as presented as F1, F2, and F3 that have higher suitability indices. Then total transportation distance is calculated from all source points to F1, F2 and F3. The final facility selected is the one which has the shortest transportation distance.

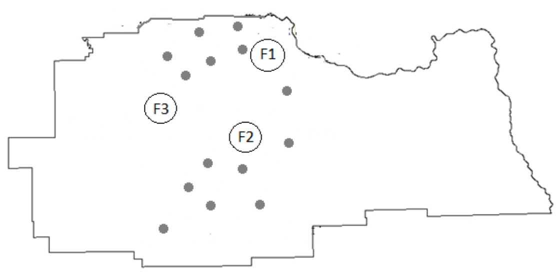


Figure 3-3: Optimization of facility location for multiple companies

3.2.3. Anaerobic Digestion Facility Cost Estimate

Anaerobic digestion process comes in two variations: wet and dry. For feedstock moisture content of 60% to 80%, dry AD is preferable and wet AD is recommended for moisture content above 80% (Chaoran, 2015; Davis, 2014; Moriarty, 2013; RIS & MacViro, 2005). A flowchart of the wet AD process, from food waste collection to electricity generation, is presented in Fig. 3-4. As observed, food waste is collected from different food processing facilities and is then transported to an AD facility. The transportation cost is, therefore, part of the total cost to be considered. Food waste is afterwards processed in several steps including washing to remove unsuitable materials for AD, mixing with co-digestion, and equalization with chemicals to dampen or neutralize the impact of inhibitory or toxic compounds or contaminants and to adjust pH (Layne, 2016; Chaoran, 2015). An anaerobic digestion reaction then takes place in the digester, and biogas is produced. The mass balance of anaerobic digestion process is shown in Fig. 3-5. The biogas is later combusted in a combined heat and power (CHP) unit to produce electricity.

The total cost of AD facility includes the cost to transport food waste to the facility, equipment capital costs, and facility operating and maintenance costs (Chaoran, 2015; Luning et al., 2003; RIS & MacViro, 2005).

3.2.3.1. Estimation of Transportation Cost

Transportation cost was calculated for transporting food waste from source points to AD facilities. Trucking, the mode of transportation chosen here, has two components: a fixed cost and a variable cost. The fixed cost ($/tonne) is for waste loading/unloading. This cost was assumed to be $6/tonne for the province of Alberta based on an earlier study (Ghafoori, 2007). The variable cost ($/tonne/km) includes driver cost, fuel cost, etc., and depends on traveling distance. This cost was assumed to be $0.2/tonne/km based on earlier study (Khan et al., 2016). The traveling distance was calculated by ArcGIS using the actual road network. The total transportation cost was then calculated by adding the fixed cost and the variable cost (Ghafoori, 2007; Khan et al., 2016).

The equations 1(a), 1(b), 1(c) were used to calculate the transportation cost:

Fixed cost = available waste (t/yr) x loading/unloading rate ($/tonne) 1(a)

Variable cost = total transportation distance (km) x unit variable cost ($/tonne.km) 1(b)

Total transportation cost = fixed cost + variable cost 1(c)

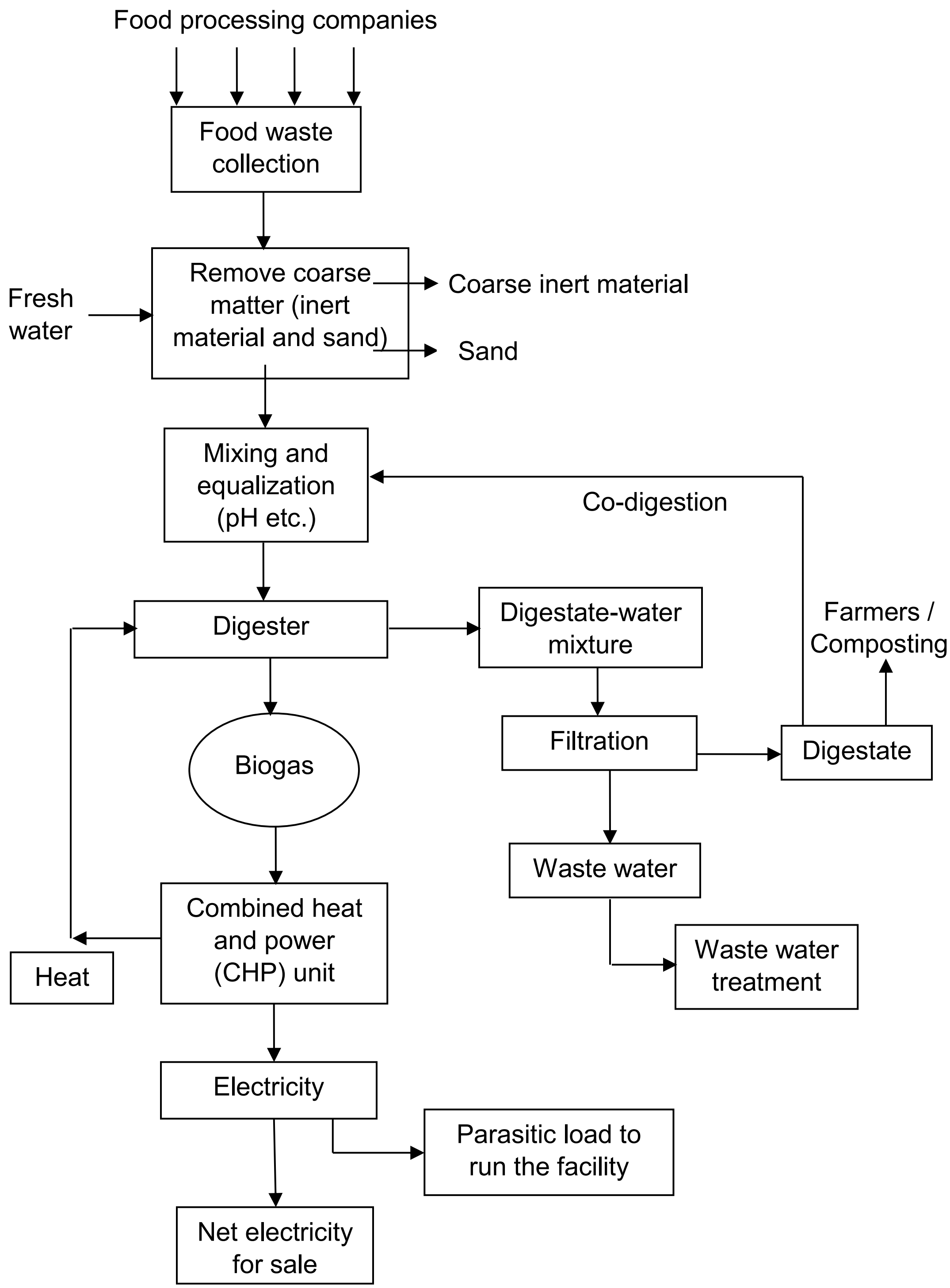
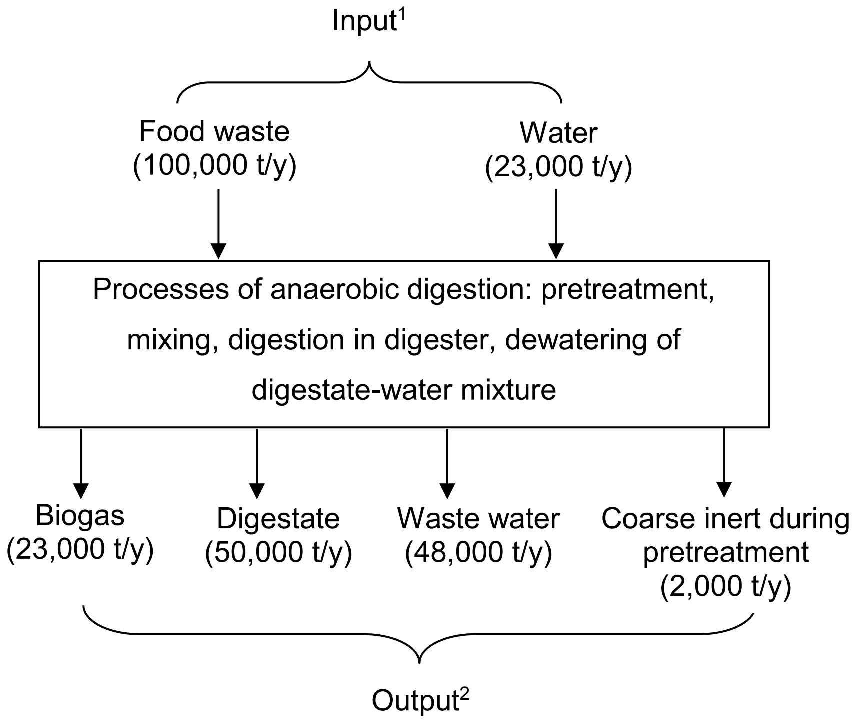


Figure 3-4: Flowchart of wet AD process



[1] Input: food waste (100,000 t/y) + water (23,000 t/y)

[2] Output: biogas (23,000 t/y) + digestate (50,000 t/y) + waste water (48,000 t/y) + coarse inert during pretreatment (2,000 t/y)

Figure 3-5: Mass balance of anaerobic digestion

3.2.3.2. Capital cost estimate

The capital cost consists of the costs associated with general site works, new buildings (tip floor, wet processing building, dewatering building, scale house, etc.), major tankage (digester, gas storage tank, process water storage tank), processing equipment (compressor, mixer, screw press, pump, piping, etc.), flaring and odour control, electrical generation, and other miscellaneous costs.

The capital cost data was collected for plant processing different feedstocks with various capacities from several sources (see Table 3-1) (CAD was converted to USD with the conversion rate 1 USD = 1.2 CAD. In this paper, dollar ($) always refers to USD unless otherwise mentioned). Next, by fitting a curve to the collected data points (see Fig. 3-6), we developed the following equation (Eq. 2):

$$\text{Capital cost} = 0.010750\ (\text{capacity}^{0.7117}) \tag{2}$$

To justify the capital cost, it was compared with the capital cost reported by Khan et al. (Khan et al., 2016). They estimated the capital cost for a small-scale AD municipal solid waste (MSW) plant in Alberta and reported capital costs of $9.45 million and $7.41 million for 15,000 t/yr and 10,000 t/yr capacities, respectively. Similar values of $9.91 million and $7.44 million were calculated here using Eq. 2; a deviations of 4.6% and 0.4%, respectively.

Table 3-1: Capital costs of wet AD facilities of various capacities

Location	**Feedstock**	**Capacity** (t/yr)	**Capital cost** (2015 million USD)	**Reference**
California	Garden waste	100,000	$39.68	(RIS & MacViro, 2005)
South Carolina	Organic waste	48,000	$24.7	(Moriarty, 2013; Soberg, 2011)
Ontario	HSSOW	43,000	$19.69	(Sanscartier et al., 2012)
Ontario	HSSOW	86,000	$34.68	(Sanscartier et al., 2012)
Ontario	HSSOW	43,000	$25.95	(Sanscartier et al., 2012)
Toronto	Food waste	40,000	$19.33	(City of Atlanta, 2010; Moriarty, 2013)
Belgium	SSO + Green waste	50,000	$20.44	(RIS & MacViro, 2005)

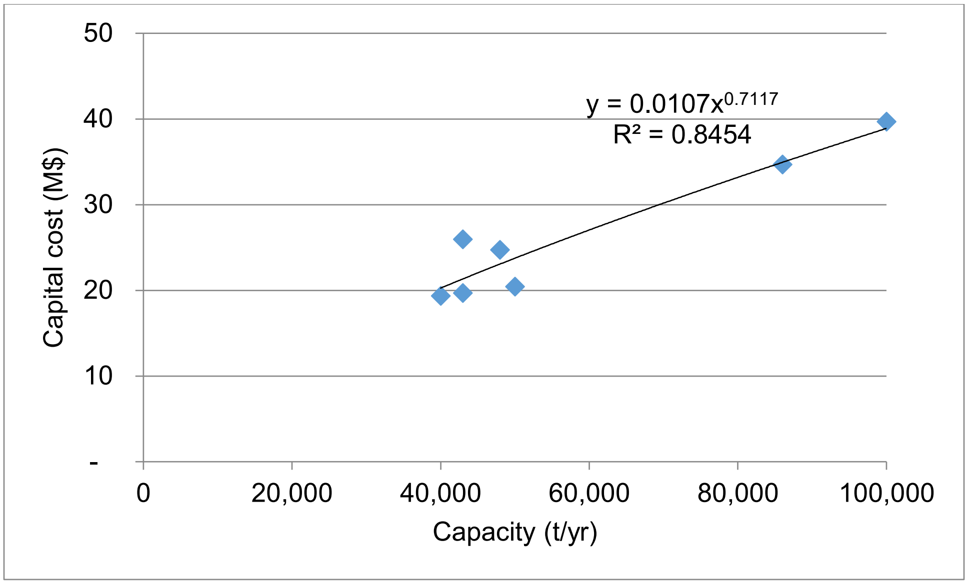


Figure 3-6: Capital cost vs. capacity for wet AD facilities

3.2.3.3. Operating & maintenance cost estimate

Operating costs refer to the cost of all operational activities, i.e., employment, feedstock processing, chemicals. The anaerobic digestion plant in Sacramento, California estimated detailed staff requirements for a 100,000 t/yr AD facility (RIS & MacViro, 2005). The operating costs was calculated following the estimates and based on Alberta's pay scale for different job titles/positions (Payscale Inc, 2016). The detailed operating cost estimate is presented in Table 3-2. The maintenance cost was assumed to be 3% of the capital cost (Kumar et al., 2003).

Table 3-2: Operating cost estimate of wet AD facility

Staff position	Salary($/year)
1 Plant manager	1 x 100 K = 100 K
1 Marketing manager	1 x 70 K = 70 K
3 Process control operators	3 x 70 K = 210 K
2 Tip floor operators	2 x 60 K = 120 K
2 Maintenance technicians	2 x 60 K = 120 K
1 Lab technician	1 x 60 K = 60 K
2 Scale House operators	2 x 50 K = 100 K
1 Receptionist	1 x 40 K = 40 K
6 General laborers	6 x 40 K = 240 K
Total salary	**$1,060,000**
Fuel cost for rolling equipment (80,000 l/yr at 0.9 $/l)	72,000
Water, start-up electricity, and gas	10,000
Wastewater treatment	500,000
Subtotal	1,642,000
10% Unforeseen, 10% estimating allowance	328,400
Total operating cost	**1,970,400**

To scale the operating cost to various capacities, the operating cost data was collected for a wet AD facility at different capacities (see Table 3-3) (Murphy & McKeogh, 2004; Tsilemou & Panagiotakopoulos, 2006). With the scale factor of 0.65, derived from Fig. 3-7, and Eq. 3, we estimated operating and maintenance costs for various capacities:

$$\text{Cost} = \text{cost of base case} \times (\text{capacity} / \text{capacity of base case})^{0.65} \qquad (3)$$

To justify the cost, it was compared with Khan's results (Khan et al., 2016). Khan et al. (2016) estimated operating and maintenance costs to be $635,083 and $810,000 for 10,000 t/yr and

15,000 t/yr capacity AD facilities, respectively. Our estimates were $678,990 and $883,736, respectively, showing deviations of 6.5% and 8.3%, respectively.

Table 3-3: Operating & maintenance costs of wet AD facility of different capacities

Capacity (t/yr)	Operating & maintenance cost (2015 USD)
2,500	250,435
5,000	333,913
10,000	500,870
15,000	1,202,087
20,000	834,783
25,000	1,043,479
30,500	1,395,765
50,000	1,669,566
50,500	1,681,203
100,000	2,504,349

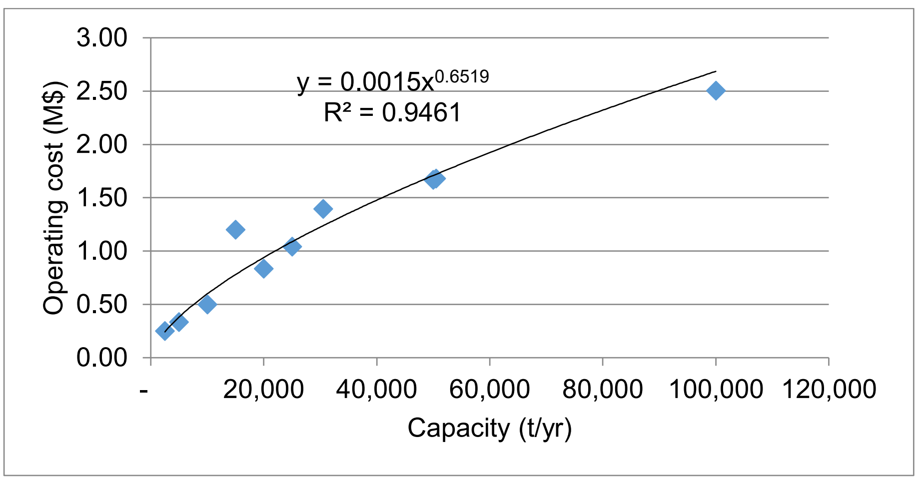


Figure 3-7: Scale factor derived for operating & maintenance costs of wet AD facility

3.2.4. AD facility revenue estimate

The final product of the AD facility studied here is the electricity generated from the biogas produced. Selling the electricity earns revenue. Before estimating the amount of electricity produced, the biogas yield was calculated. Two revenue components were calculated: electricity selling price and gate fee. In a separate section, carbon credit, as a revenue component, was also considered.

3.2.4.1. Biogas yield estimate

Biogas yield in the anaerobic digestion process is a function of the type of feedstock and retention time. Anaerobic digestion of food waste yields higher volumes of biogas than other organic wastes such as animal manure, organic parts of MSW, and garden waste (Zhang et al., 2014). Based on earlier studies, the biogas production rate is 225 m^3 per tonne of food waste (Moriarty, 2013). In other studies, Nagao et al. reported the average rate of biogas production to be 192 m^3 per tonne of food waste (Nagao et al., 2012) and another study found the production rate of biogas from maize silage to be about 180 m^3 per tonne of feedstock (The Andersons Centre & Redman, 2010). Taking the average values reported in these studies, the biogas production in AD was considered to be 200 m^3 per tonne of food waste. Khan et al. found the biogas production rate to be 181 m^3 per tonne of MSW (Khan et al., 2016), which is reasonable since biogas production from MSW is lower than from food waste. We also assumed 10% of biogas was used to generate the heat required to operate the plant (Moriarty, 2013). The remaining 90% was used to generate electricity.

3.2.4.2. Electricity generation estimate

Electricity is produced, among other means, through the combustion of gas. The energy potential of biogas was considered to be 6.7 kWh/m^3 (The Andersons Centre & Redman, 2010), electrical efficiency to be 37% (Ghafoori, 2007), and the plant capacity factor to be 0.7 in year 1, 0.8 in year 2, and 0.85 afterwards (Kumar et al., 2003). Accordingly, electricity production from 1

m^3 of biogas was calculated to be 1.73 kWh in year 1, 1.98 kWh in year 2, and 2.11 kWh afterwards. Khan et al.'s estimated electricity production from 1 m^3 of biogas was 2.14 kWh (Khan et al., 2016). The plant's parasitic power[3] consumption was considered to be 20% of the generated electricity (Ghafoori, 2007). The remaining 80% electricity was considered to be available for sale.

3.2.4.3. Gate fee

The gate fee is the charge levied by the waste conversion facility on receiving waste. Food processing companies pay a gate fee to a waste conversion facility for taking their waste. This fee should be equal or less than the landfill disposal fee to encourage waste producing companies to send their waste to an AD facility. The landfill disposal fee for some counties in Alberta, as compiled by Alberta Agriculture and Forestry, is shown in Fig. 3-8 (Bell, 2015). The landfill disposal fees for Red Deer and Taber counties are $65/tonne and $110/tonne, respectively.

[3] Parasitic power is onsite energy consumption by the plant.

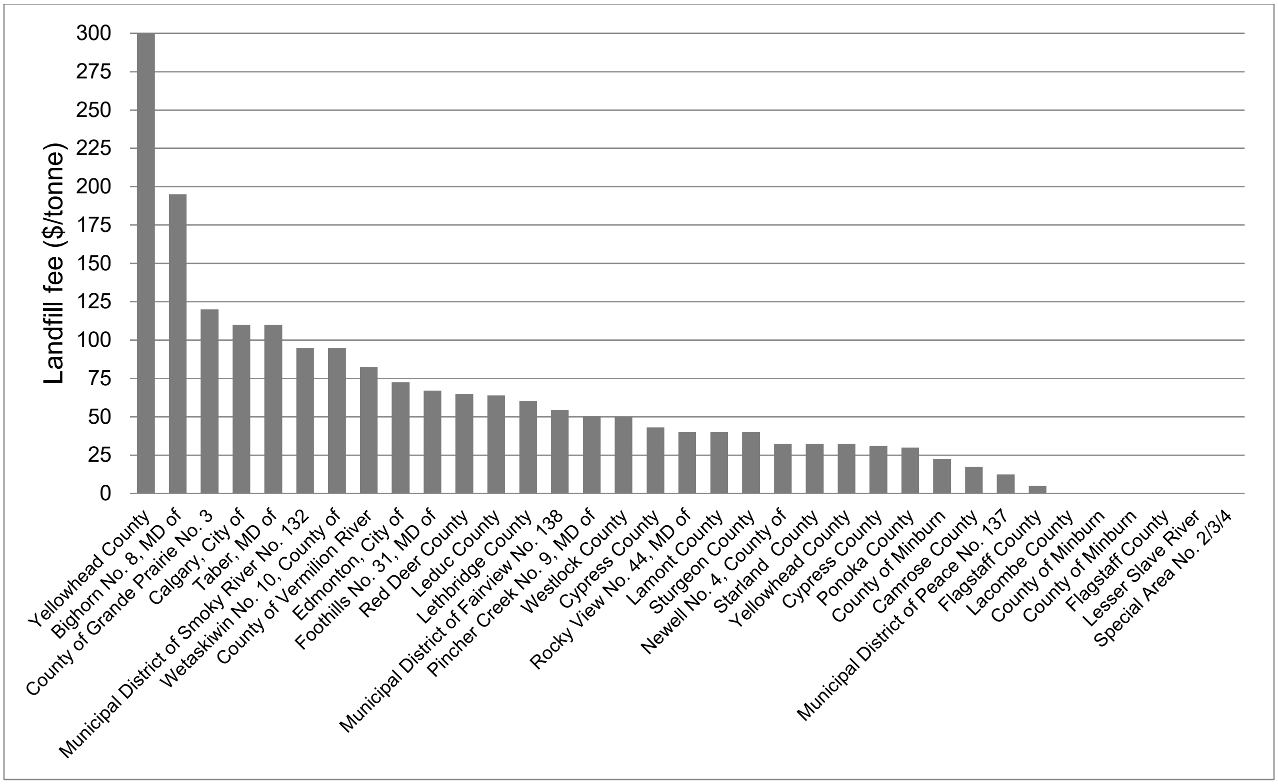


Figure 3-8: Landfill disposal fees for mixed waste for selected Alberta jurisdictions

3.2.4.4. Carbon credit

A carbon credit (often called a carbon offset) is a financial instrument that represents a tonne of CO_2 or CO_2e (carbon dioxide equivalent gases) removed or reduced from the atmosphere through an emission reduction project (Carbon Planet Limited, 2016). It is also known as greenhouse gas (GHG) reduction. GHG reduction in biogas power plant is 0.00097 tonne CO_2-eq/KWh compare to coal power plant (Ghafoori, 2007). Based on this assumption, the revenue was calculated from the carbon credit for the current price of carbon $13/tonne of CO_2 for the province of Alberta (Preferred Carbon Group, 2011).

3.3. Case study: Red Deer County

An earlier study shows that (Fig. 3-9) Red Deer region produces the largest amounts of food waste in the province of Alberta (Ullah et al., 2016). A large portion of this waste is currently landfilled. Hence, Red Deer is a potential area to build an AD facility.

3.3.1. Economic analysis of base case scenario

An evaluation of the feedstock available in Red Deer County (number of companies, locations, amount of food waste generation) confirms that 100,000 t/yr food waste is available for AD. Hence an economic analysis was conducted for the purpose of developing a centralized AD facility in Red deer with 100,000 t/yr capacity. The location of the facility was determined using ArcGIS as described in section 2.2. Then the transportation cost of the food waste from all source points to the facility was calculated considering \$6/tonne for loading/unloading (fixed cost) and \$0.2/tonne/km for variable cost. The other cost components (capital, operating, maintenance) and revenue components (electricity sale, gate fee) were estimated as described in methodology sections.

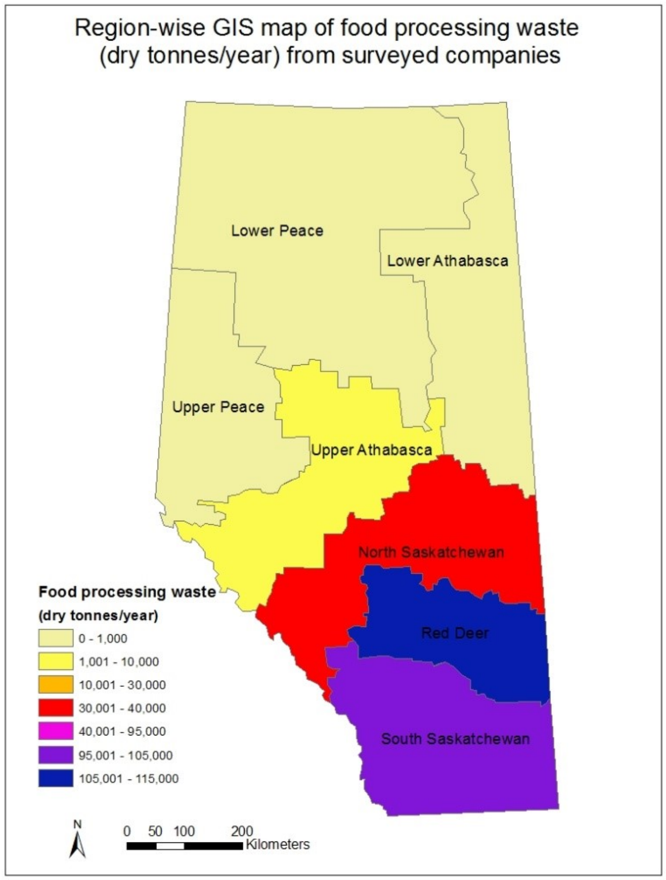


Figure 3-9: Region-wise GIS map of Alberta's food processing waste

Afterwards, a spreadsheet model was developed to conduct the techno-economic analysis. The input data of the model is shown in Table 3-4. The project lifetime was assumed to be 30 years with a 2% inflation rate. There were three variables – electricity price, gate fee, and internal rate of return (IRR). Based on the electricity price and IRR, the minimum gate fee that should be charged from the waste producers were calculated. Similarly, by using the gate fee and IRR, the minimum electricity price was calculated, and by using the electricity price and gate fee, the IRR was obtained. The results are presented in Table 3-5.

Table 3-4: Input data of the model

Food waste (t/y): 100,000	Biogas yield (m3/t): 200
Capital cost ($): 38,142,439	Total biogas yield (m3/yr): 20,000,000
Spread of capital costs during construction:	Biogas composition: 65% methane, 35% carbon dioxide
Year 1: 20%	Heating value of biogas (MJ/m3): 20.7
Year 2: 35%	For electricity generation: Use 90% of biogas
Year 3: 45%	Electrical efficiency: 37%
Inflation: 2%	For heat generation: Use 10% of biogas
Maintenance cost: assumed 3 % of capital cost	Capacity factor:
Fixed transportation cost ($): 600,000	Year 1: 0.7
Variable transportation cost ($): 350,000	Year 2: 0.8
IRR: 10%	Year 3 onwards: 0.85

The current rate of electricity in Alberta is $0.035/kWh (Alberta Utilities Commission, 2016). At this rate and for 10% IRR, the gate fee at plant's break-even point was calculated to be $67/tonne. Since the current landfill disposal fee in Red Deer is $65/tonne, food processing companies would probably not agree to pay a $67/tonne gate fee. Hence, the facility is not economically viable with a 10% IRR and $0.035/kWh electricity price. When we consider a gate fee of $65/tonne and IRR of 10% in the model, the electricity price calculated at plant's break-even point was found to be $0.041/kWh. At this higher rate of electricity, an AD project is economically viable. For a $0.035/kWh electricity price and $65/tonne gate fee, the IRR was calculated to be 9.4%.

Table 3-5: Economic factors for a 100,000 t/yr AD facility in Red Deer County

Input	Calculated
Electricity price = $0.035/kWh (current rate), IRR = 10%	Gate fee = $67/tonne
Gate fee = $65/tonne (current landfill fee), IRR = 10%	Electricity price = $0.041/kWh
Electricity price = $0.035/kWh (current rate), Gate fee = $65/tonne (current landfill fee)	IRR = 9.4%

3.3.2. Economic analysis of other scenarios

3.3.2.1. Scenario 1 (centralized AD plant in Red Deer if waste availability is less than 100,000 t/yr)

Scenario 1 is the case where 100,000 t/yr waste is not available and the minimum optimal (and still economically viable) plant size is determined. Noticing the unit cost of the plant to increase with the decrease in the plant size (Ghafoori, 2007; Kumar et al., 2003), we calculated the gate fee for small plants (i.e., 90,000 t/yr, 80,000 t/yr); the results are presented in Fig. 3-10. If the calculated gate fee is less than $65/tonne, we consider the project to be economically viable. The minimum plant size was found to be 110 thousand t/yr (corresponds to a $65/tonne gate fee) to achieve economic viability. This scenario was true when other parameters remained unchanged, i.e., IRR of 10% and electricity price of $0.035/kWh. If the IRR reduced or if the electricity price increased, the minimum size would be smaller.

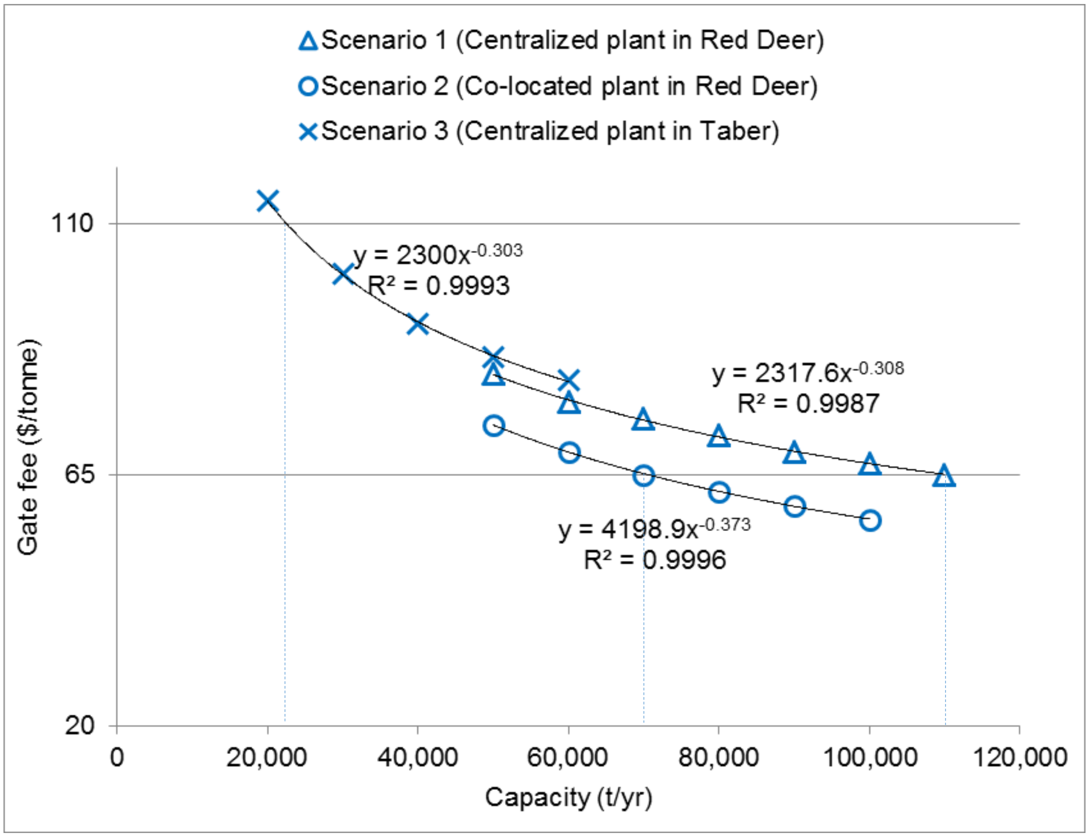


Figure 3-10: Gate fee vs. plant size for a centralized plant in Red Deer (scenario 1), a co-located plant in Red Deer (scenario 2), and a centralized plant in Taber (scenario 3)

3.3.2.2. Scenario 2 (co-located plant in Red deer)

In the base case, it was assumed that the AD facility is located away from the processing company. In scenario 2, it was assumed that the AD facility is co-located with the food waste processing facility and determined the economic viability for a 100,000 t/yr capacity plant. The minimum plant size was also determined below which the plant is no longer economically feasible. For this scenario, there is of course no transportation cost and thus the total cost will drop. The calculated gate fee at the plant's break-even point for a 100,000 t/yr facility dropped to $57/tonne, thus making waste disposal from AD more economical than landfilling.

The gate fee for smaller plants was also calculated and the results are also included in Fig. 3-10. To achieve economic viability, the minimum plant size should be 70,000 t/yr (corresponds to a $65/tonne gate fee). This scenario holds true when the other parameters remain unchanged, i.e., IRR of 10% and electricity price of $0.035/kWh.

3.3.2.3. Scenario 3 (centralized plant in Taber, Alberta)

Scenario 3 is the case in which the facility is located in Taber County and the waste availability and landfilling fees are different from those of Red Deer County. Using waste availability data, an economic analysis was conducted for the AD facility in this scenario. The advantage of building an AD facility in Taber County is that the facility owner can set a high gate fee because the landfill disposal fee here is very high (about $110/tonne). All costs (other than transportation) associated with the facility were calculated using the model developed for Red Deer County. The transportation distance was calculated by ArcGIS specifically for this scenario. The maximum size of the facility was 50,000 t/yr based on waste availability. For this plant's capacity, the calculated gate fee at the plant's break-even point was $86/tonne. Hence the disposal of the AD-processed waste is economically attractive. We also calculated gate fees for smaller plants to determine the minimum size below which a facility is no longer economically viable. We incorporated the results in the graph as shown in Fig. 3-10. To achieve economic viability, the minimum plant size should be 22,000 t/yr, corresponding to a $110/tonne gate fee.

3.3.3 Economic analysis considering carbon credit

The techno-economic analysis was conducted for the base case as well as the three developed scenarios to take into consideration carbon credit. For the base case scenario, the calculated gate fee was found to be $63/tonne, which is lower than the landfill disposal fee of $65/tonne. The base case, which was not economically viable before considering carbon credit, is now economic. The corresponding economic factors are shown in Table 3-6.

Table 3-6: Economic factors while taking carbon credit into account for a 100,000 t/yr AD facility in Red Deer County, Alberta

Input	Calculated
Electricity price = \$0.035/kWh (current rate), IRR = 10%	Gate fee = \$63/tonne
Gate fee = \$65/tonne (current landfill fee), IRR = 10%	Electricity price = \$0.028/kWh
Electricity price = \$0.035/kWh (current rate), Gate fee = \$65/tonne (current landfill fee)	IRR = 10.5%

For scenario 1, the gate fee was calculated for smaller plants considering carbon credit and the results are shown in Fig. 3-11. The minimum size below which a plant is no longer economically viable is 90,000 t/yr (corresponds to a \$65/tonne gate fee).

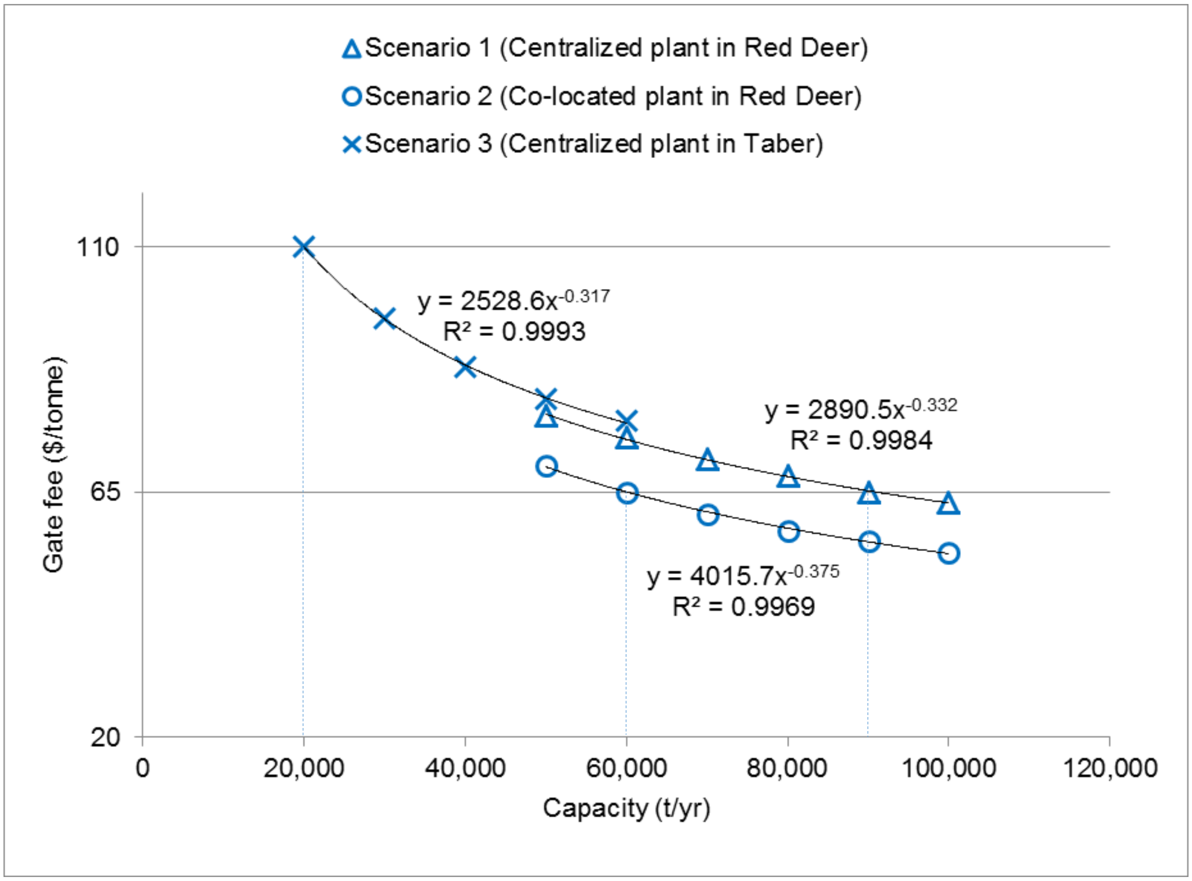


Figure 3-11: Gate fee vs. plant size considering carbon credit for a centralized plant in Red Deer (scenario 1), a co-located plant in Red Deer (scenario 2), and a centralized plant in Taber (scenario 3)

In scenario 2, the situation in which the AD facility is co-located with a food processing company, the gate fee was calculated for different plant sizes considering carbon credit. The results are included in Fig. 3-11. The minimum size below which a plant is no longer economically viable would be 60,000 t/yr, corresponding to a $65/tonne gate fee.

For scenario 3, the case in which the facility is located in Taber County where waste availability and landfilling fees are different from those of Red Deer County, the gate fee was calculated for different plant sizes considering carbon credit. These results are also shown in Fig. 3-11. The minimum plant size was found to be 20,000 t/yr, corresponding to a $110/tonne gate fee, below which the plant is no longer economically viable.

It can be concluded from the results (see Table 3-7) that building a 100,000 t/yr capacity AD facility in Red Deer County is not economically feasible without a carbon credit. A larger plant (110,000 t/yr or higher) is needed to achieve economic feasibility. Yet if carbon credit is taken into account, a 100,000 t/yr capacity AD facility would be profitable. Even a smaller plant (minimum 90,000 t/yr capacity) is economically viable if carbon credit is considered.

If the facility is co-located in Red Deer with a food processing company, a 100,000 t/yr plant is profitable even without a carbon credit. If a smaller plant is desired, it is poosible to build as small as a 70,000 t/yr and not generate economic loss. The plant can be even smaller (60,000 t/yr) if carbon credit is considered. In Taber, where waste availability is much lower and the landfilling fee much higher than in Red Deer County, the minimum AD plant sizes that can be built without economic loss are 22,000 t/yr and 20,000 t/yr with and without considering carbon credit, respectively. These results are valid for the current electricity price in Alberta ($0.035/kWh) and a 10% IRR.

Table 3-7: Summary of the results

	Red Deer County			**Taber County**
	Base case	**Scenario 1**	**Scenario 2**	**Scenario 3**
	Gate fee	Minimum plant size		
Without carbon credit	$67/t	110,000 t/yr	70,000 t/yr	22,000 t/yr
With carbon credit	$63/t	90,000 t/yr	60,000 t/yr	20,000 t/yr

In summary, the following AD plant sizes are economically feasible without considering carbon credit as revenue:

- ❑ Centralized 110,000 t/yr or larger AD plant in Red Deer County
- ❑ Food processing waste facility-based (co-located with food waste producing facility) 70,000 t/yr or larger AD plant in Red Deer County
- ❑ Centralized 22,000 t/yr or larger AD plant in Taber County

The following AD plant sizes are economically feasible considering carbon credit as revenue:

- ❑ Centralized 90,000 t/yr or larger AD plant in Red Deer County
- ❑ Company-based (co-located with company) 60,000 t/yr or larger AD plant in Red Deer County
- ❑ Centralized 20,000 t/yr or larger AD plant in Taber County

3.3.4. Sensitivity analysis

A sensitivity analysis was performed to better understand the impact of key parameters on the calculated gate fee. The parameters included electricity selling price, IRR, transportation distance, capital cost, operating cost, waste availability, parasitic load, biogas yield, and carbon credit. The base values of the parameters are presented in Table 3-8. One parameter was changed at a time, keeping all others constant, and calculated the gate fee. The extent of the change of each parameter is also presented in Table 3-8. The greatest change is considered in the electricity selling price, from -50% to +100%, simply because the price of electricity in Alberta has changed considerably in the last few years and currently is very low.

Table 3-8: Base value and extent of variation of the model's economic parameters

Parameters	Base value	Changed value
Selling price of electricity	$0.035/kWh	-50% to +100%
IRR	10%	-20% to +20%
Transportation distance	17.5 km	-40% to +40%
Waste availability	100,000 t/yr	-20% to +20%
Capital cost	$38,142,439	-5% to +5%
Operating cost	$1,970,400	-10% to +10%
Biogas yield	200 m^3/tonne	-20% to +20%
Parasitic load	20%	-40% to +40%

For the base case scenario, a sensitivity analysis was performed (see Fig. 3-12) and discerned that the selling price of electricity and the IRR have the highest impact on calculated gate fee.

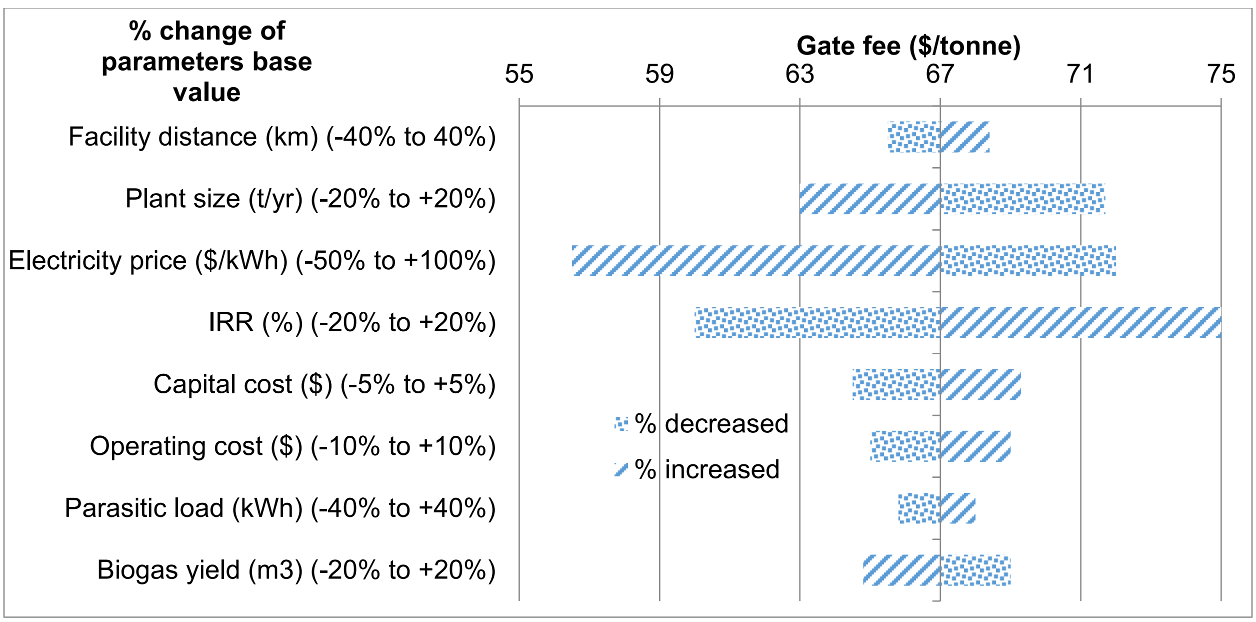


Figure 3-12: Sensitivity of the calculated gate fee to major economic factors

3.4 Application of the model in other jurisdiction

The techno-economic model that we developed here could be applied in other jurisdictions by customizing some features. The methodology described here remains the same, i.e. feedstock evaluation, facility site selection, transportation cost, capital cost, operating cost and maintenance cost estimation, biogas and electricity generation estimation, gate fee and carbon credit calculation. However, outcomes would not be the same as we found here. Amount of the feedstock production is different in different jurisdiction. Facility site location depends on several environmental, social and geographical factors. Hence, transportation cost would be different. Capital and maintenance costs might vary a little bit for different jurisdiction. However, operating cost would be different in different jurisdiction since a big portion of operating cost is staff salary. Again, for the same amount of feedstock, the amount of biogas and electricity generation should be same irrespective of location. But the price of electricity largely varies in different territories. Carbon tax and landfill disposal policies is different in different jurisdictions. Hence, gate fee and carbon credit would be changed.

This model is applicable to any jurisdiction. Though the final outcome of the model i.e. IRR or gate fee or electricity price, whichever is required, would be different in different jurisdiction. Based on that outcome decision could be made whether building AD plant is economically feasible or not.

3.5. Conclusion

Food processing industry is the second largest food waste producing sector after household. However, the waste, in most cases, is not disposed economically and/or environmentally. Such waste can be converted into energy through anaerobic digestion conversion technology. A techno-economic model is developed here to study the economy of anaerobic digestion (AD) facilities. Using the model to study a case in Red Deer County, Alberta, shows that if a centralized AD facility of 100,000 t/yr capacity is built in Red Deer, with the current selling price of electricity ($0.035/kWh) and a 10% IRR, the calculated gate fee would be $67/tonne, which is higher than the current landfill disposal fee in Red Deer County ($65/tonne). However, considering carbon credit will lower the gate fee to $63/tonne, thus making the AD facility economically viable. We also considered three scenarios - (a) if the waste availability is less than expected amount, (b) plant is co-located with waste producer facility, and (c) plant is located in a different jurisdiction where waste availability is lower but gate fee is higher. For each case, the minimum plant size was determined below which an AD facility is no longer economically viable. Finally, a sensitivity analysis was perfomed on the base case to better understand the impact of key parameters on the calculated gate fee. It was found that the selling price of electricity and the IRR are the most influential factors. A new approach to waste management that is less costly and more environmentally-friendly than landfilling was developed in this study.

Chapter 4 : Composting of Food Processing Industry Waste: A Techno-economic Analysis

4.1. Introduction

According to the Food and Agriculture Organization (FAO) of the United Nations, 1300 million tonnes of food is wasted annually throughout the world; this figure is one-third of the total food produced (FAO, 2012; Uçkun Kiran et al., 2014). Food processing industry is the second largest sector after household where the most wastage takes place. A wide range of food products are produced and processed in food processing industries and accordingly, a variety of wastes are produced due to unused leftovers, loss of raw materials during processing, and by-products of the processes. The wastes consist of chucked out and left over portions of fruits and vegetables; viscous black syrup and dry pulp from sugar refining; inedible and discarded portions of meat and fish processing; residues of alcohol production (stillage) from wineries and breweries; cheese whey from dairy farms; and wastewater from cleaning, boiling, and cooling and cooking operations (Kosseva, 2011; Pham et al., 2015). A large portion of this food processing waste is disposed in landfills. Landfilling comes with high costs associated with transportation and disposal (i.e., landfilling fee). Moreover, outdoor decomposition of waste in a landfill produces methane gas (CH_4) which is 23 times more powerful greenhouse gas than carbon dioxide (CO_2) and hence causes substantial climate change (Pham et al., 2015). To overcome the economic and environmental concerns of landfilling, a better waste management approach needs to be in place.

There are a number of waste conversion technologies available including anaerobic digestion (AD), composting, incineration, pyrolysis, gasification, hydrothermal carbonization and hydrothermal liquefaction. As discussed in Chapter 1 (section 1.2), we found anaerobic digestion and composting is the most suitable energy conversion technology. We also found that composting is relatively cheaper than anaerobic digestion.

Composting is a controlled aerobic microbiological process that decomposes organic wastes. There are several types of composting, i.e., windrow composting, aerated static pile (ASP) composting, enclosed channel composting, and container/tunnel composting (Alberta Environment, 2010). Among these, windrow and ASP are carried out outdoors and the others are indoor processes and have much higher capital and operating costs (Recycling Council of Alberta, 2006). In the windrow composting process, a windrow or pile of waste is created and regularly turned/moved so that the material is uniformly exposed to fresh air. In the present study, we focussed on windrow composting since it is widely used and relatively cheaper than ASP, enclosed channel, and container/tunnel composting (Alberta Environment, 2010).

The overall objective of this research was to conduct a comprehensive techno-economic assessment to analyze composting of food processing wastes. The specific objectives are:

- Development of scale factor for assessing the capital cost of different components of composting plant for processing of food waste;
- Development of a comprehensive techno-economic model for assessment of cost of composting of food waste;
- Estimation of economic optimum size of compositing facility;
- Conducting a case study for Alberta, a Western Canaddian Province including the development of the transportation cost using geographic information system (GIS);
- Conducting sensitivity analysis to assess the impact of the variation of key parameters on the cost of compost production from food waste;

4.2. Methodology

4.2.1. Food waste evaluation and site selection

Food processing waste is evaluated to determine the amount and the type of the waste available for composting. This is done by determining the number of food processing facilities, their locations, the amount of food waste produced per year in every facility, the characteristics of the food waste (e.g., moisture content, density etc.), and the area where the food waste is collected from.

A suitable site for composting facility is selected using the Geographic Information System (GIS) software ArcGIS 10.1, developed by the Environmental Systems Research Institute (ESRI, 2011). Site selection was performed in three stages, exclusion, preference, and location-allocation analyses (Sultana & Kumar, 2012). An exclusion analysis screens out unsuitable lands (also known as constraints) such as rivers, lakes, rural and urban areas, airports, industrial and mining zones, etc. (Khan et al., 2016). Figure 1 is an example of the exclusion analysis map. We then performed a preference analysis considering eight preference factors. These factors are (i) waste availability, (ii) urban area, (iii) water availability, (iv) roads, (v) transmission lines, (vi) power substations, (vii) land cover, and (viii) slope. We used the analytic hierarchy process (AHP) to calculate the weight of the preference factors (Saaty, 2000) and then calculated the suitability index by multiplying the value of exclusion analysis with the corresponding weight of the preference analysis. Finally, we conducted a location-allocation analysis using the actual road network. The facility location was ultimately determined based on the shortest transportation distance. The supplementary materials is added in Appendix.

4.2.2. Cost estimation of composting

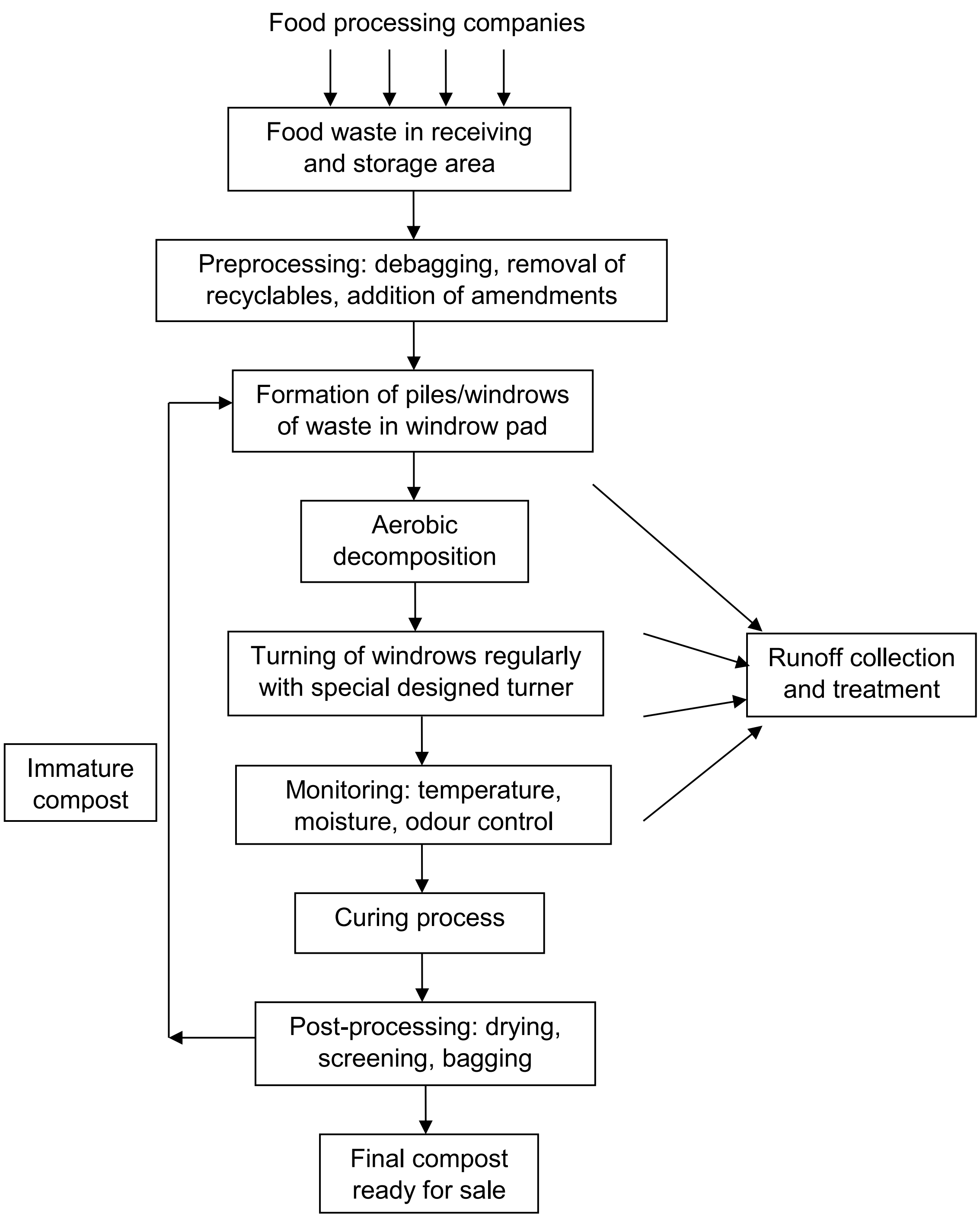


Figure 4-1: Flowchart of composting processes

A Flowchart of composting processes is presented in Fig. 4-1. As observed, food waste, coming from food processing facilities, is stored in storage area. Some pre-processing is done such as debagging, removal of recyclables, and addition of amendment. Then windrows/files are built in windrow pad; where aerobic decomposition of waste starts. The windrows are turned and moved regularly with special designed turner. Continuous monitoring is conducted to control temperature, moisture and odour. Then it goes through curing processes. Afterwards post-processing is done to achieve quality compost.

4.2.2.1. Transportation cost

Trucking is the means of transporting food wastes from source points to composting facility, and it has two components, fixed cost and variable cost. The fixed cost ($/tonne) is the cost of loading/unloading waste; we assumed this to be $6/tonne for Alberta (Ghafoori, 2007; Kumar et al., 2003). The variable cost ($/tonne/km) includes driver cost, fuel cost, etc., and depends on the traveling distance. We considered $0.2/tonne/km variable cost (Chornet, 2015; Khan et al., 2016). The traveling distance was calculated through ArcGIS using the actual road network. The total transportation cost was then calculated by adding the fixed cost and the variable cost.

4.2.2.2. Capital cost

Capital cost consists of the costs associated with general site works, access roads, receiving and grinding buildings, windrow/curing/compost pad, surface water detention pond, biofilters, equipment such as front-end loaders, windrow turners, hard-hose reels and pumps, monitoring equipment, firefighting and water addition equipment (Recycling Council of Alberta, 2006). The capital cost of windrow composting varies with the size of the facility. Three sizes were considered – small, medium, and large. The capital cost of typical facilities of such sizes is presented in Table 4-1. A curve (Fig.4-2) was developed considering data at different capacities and a logarithmic capital cost equation (Eq.1) was obtained, as follows:

$$\text{capital cost (US \$)} = 508{,}330 \times \ln(\text{capacity}) - 3E{+}06 \quad (1)$$

Table 4-1: Capital cost of windrow composting facilities of different sizes

	Small-scale facility	Medium-scale facility	Large-scale facility	Reference
Capacity (t/yr)	500	4,000	15,000	(Alberta Environment, 2010; Government of Alberta, 2012)
Capital cost (2015 $)	136,338	1,117,522	1,877,436	(Alberta Environment, 2010; Government of Alberta, 2012)

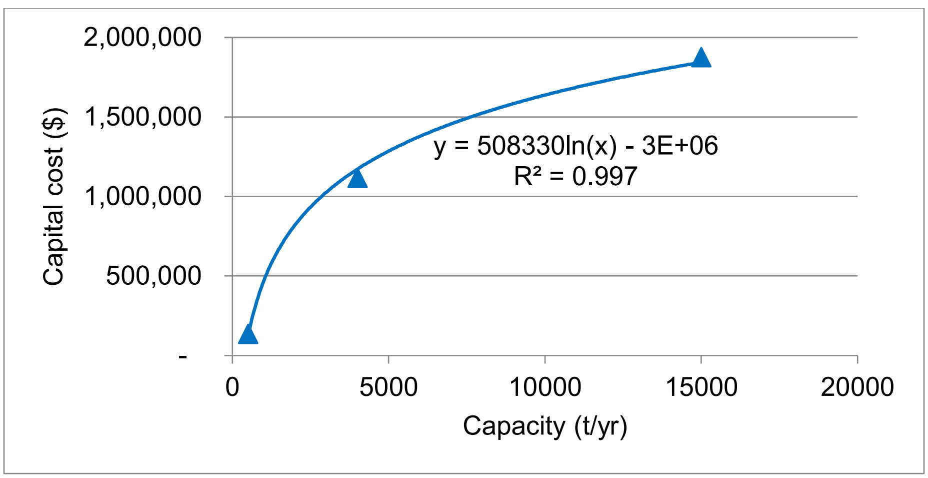


Figure 4-2: Capital cost vs capacity for windrow composting

The logarithmic relations is applicable up to 20,000 t/yr capacity. According to Alberta's composting facility standard, facilities that process more than 20,000 t/yr are regulated differently than those that process less than 20,000 t/yr (Alberta Environment, 2007; Khan et al., 2016).

Using Eq. 1, the capital cost per unit output for a 20,000 t/yr facility was estimated to be \$102/tonne. This is similar to the capital cost per unit output of \$104/tonne as suggested in the literature based on a survey of North American facilities (Recycling Council of Alberta, 2006). If the feedstock to be processed is more than 20,000 t/yr, the same unit capital cost per unit was considered that was calculated for 20,000 t/yr (i.e., \$102/tonne) and the total capital cost was calculated by Eq. 2. It means the economy of scale is found up to 20,000 t/yr, and after that the cost is linear. The reason is when the capacity is an integer multiplication of 20,000 t/yr (i.e. 40,000 t/yr, 60,000 t/yr etc.), we considered several 20,000 t/yr parallel units of composting facilities and hence took the unit capital cost be the same as that calculated for a 20,000 t/yr capacity (i.e., \$102/tonne). Table 4-2 summarizes the capital cost calculation for different capacities.

$$\text{capital cost (\$)} = 102\ (\$/t) \times \text{capacity (t)} \tag{2}$$

Table 4-2: Capital cost for different capacities

Capacity	Capital cost
Up to 20,000 t/yr	508,330 × ln(capacity) – 3E+06
More than 20,000 t/yr	102 (\$/t) × capacity (t)

4.2.2.3. Operating costs

Operating costs are the costs associated with all operational activities that include employment, processing feedstock, chemicals, etc. The operating cost data of windrow composting facilities in North America with various capacities are shown in Table 4-3 (Recycling Council of Alberta, 2006). A curve was developed considering the data available for different sizes (Fig.4-3) and the following equation (Eq. 3) was developed to estimate the operating cost:

operating cost (\$) = 47.878 (capacity) - 0.6667 (3)

Table 4-3: Operating costs of windrow composting facilities of various sizes

Capacity (t/yr)	Operating cost (2015 \$)
6,000	287,270
24,000	1,149,082
60,000	2,872,706

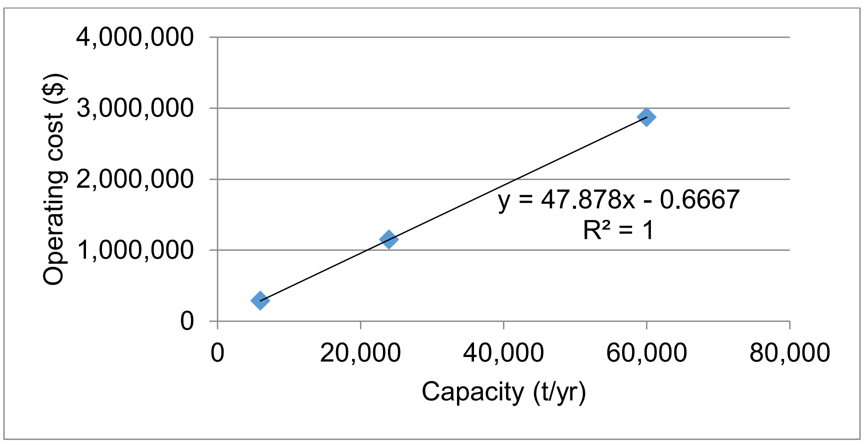


Figure 4-3: Operating cost vs capacity of windrow composting

4.2.3. Estimation of revenues from composting

4.2.3.1. Sale of compost

The final product of composting is compost. The amount of yield of compost produced varies from 0.3 to 0.5 tonne of compost per tonne of feedstock (Alberta Environment, 2010; Government of Alberta, 2012; Khan et al., 2016; Recycling Council of Alberta, 2006). In this study, an average of 0.4 tonne of compost per tonne of feedstock was considered and it was assumed that the compost could be used as fertilizer to improve soil characteristics such soil nutrients (nitrogen, phosphorous, potassium), water conserve and retain ability, to reduce erosion and the negative impact of synthetic chemical fertilizers (Illinois Food Scrap Coalition, 2015). The average selling price of compost is $24/tonne (Alberta Environment, 2010; Government of Alberta, 2012).

4.2.3.2. Gate fee

Food processing companies pay a fee to the composting facility owner for taking their waste. This is called gate fee. This gate fee should be equal to or less than the landfill disposal fee to encourage companies to send their waste to a composting facility. Landfill disposal fee varies with jurisdiction and depends on the policies and regulations of individual counties. Landfill disposal fees for some counties in Alberta were compiled by Alberta Agriculture and Forestry and are shown in Fig. 3-6 in Chapter 3.

4.2.3.3. Carbon credit

Earlier studies have calculated net emissions reduction for composting compared to landfilling to be 0.27 tonne of CO_2 for each tonne of feedstock (ICF consulting, 2005). The revenue from the carbon credit for the current price of carbon, $13/tonne of CO_2 (Preferred Carbon Group, 2011) was calculated.

4.3. Case study for Red Deer, Alberta

There are 64 composting facilities in Alberta and these are classified by the type of feedstock processed. 37 of these facilities process leaf and yard waste, 11 process manure, 9 process several feedstocks together, and 7 process biosolids. Altogether, the facilities process 539,029 tonnes of waste every year. Facilities are also classified based on the capacity of the feedstock processed. Small-, medium-, and large-scale facilities process less than 1,000, 1,000 to 10,000, and 10,000 to 20,000 t/yr feedstock. There is no facility in Alberta that processes food waste alone (Alberta Environment, 2010; Government of Alberta, 2012).

There are five hundred food processing facilities in Alberta, Canada. These facilities produces 500,000 tonnes/year food waste. Red Deer region produces the largest amounts of food waste (Ullah et al., 2016a). A large portion of this waste is currently landfilled. Hence, Red Deer is a potential area to build composting facility. A techno-economic analysis by calculating all cost components (capital, operating, transportation) and revenue components (compost sale, gate fee, carbon credit) as described in methodology section was conducted. Afterwards, a techno-economic model was developed for three different scales of composting facilities - small, medium, and large. The total cost of the facility was calculated by adding capital, operating, and transportation costs. The total revenue was then calculated using the compost selling price and the gate fee. A 20-year project lifetime and 2% inflation rate was assumed.

4.3.1. Gate fee and IRR of three facilities

In the model, there were two variables – IRR and gate fee. By assuming IRR, a gate fee was calculated, and vice versa. The input value of IRR and gate was 10% and $65/tonne (current landfill fee in Red Deer), respectively. The results are presented in Table 4-4. The calculated gate fees at a plant's break-even point are $85/tonne, $69/tonne, and $61/tonne for small (500 t/yr), medium (10,000 t/yr), and large (20,000 t/yr) facilities, respectively. The calculated IRRs at a plant's break-even point are 1.2%, 7.4%, and 13.7% for similar facilities. The results indicate that small- and medium-scale facilities are not economically attractive since their gate fees are higher than the current landfill fee in Red Deer, and the IRR is quite low as well. On the other hand, large-scale facilities appear to be profitable since their gate fee is lower than the current landfill fee in Red Deer and they have a quite high IRR of 13.7%.

Table 4-4: Economical factors for various composting facilities in Red Deer County

Input	Calculated		
	Small-scale facility (500 t/yr)	**Medium-scale facility (10,000 t/yr)**	**Large-scale facility (20,000 t/yr)**
IRR = 10%	Gate fee = $85/t	Gate fee = $69/t	Gate fee = $61/t
Gate fee = $65/t	IRR = 1.2%	IRR = 7.4%	IRR = 13.7%

4.3.2. Minimum size of facility for economic viability

In previous section, it was observed that with the decrease of facility size the gate fee increases and the IRR decreases, both of which make medium- and small-scale facilities economically unattractive. The economic optimum size of the facility was determined. This is the size below which a facility would not be economically viable. It was found that the gate fee should not exceed $65/tonne and the IRR should not be below 10%. After calculating the gate fee for different capacities, a curve was developed for gate fee vs. facility size (shown in Fig. 4-4). Then the minimum size of the facility was determined which is 14,000 t/yr (corresponds to $65/tonne gate fee) for economic viability.

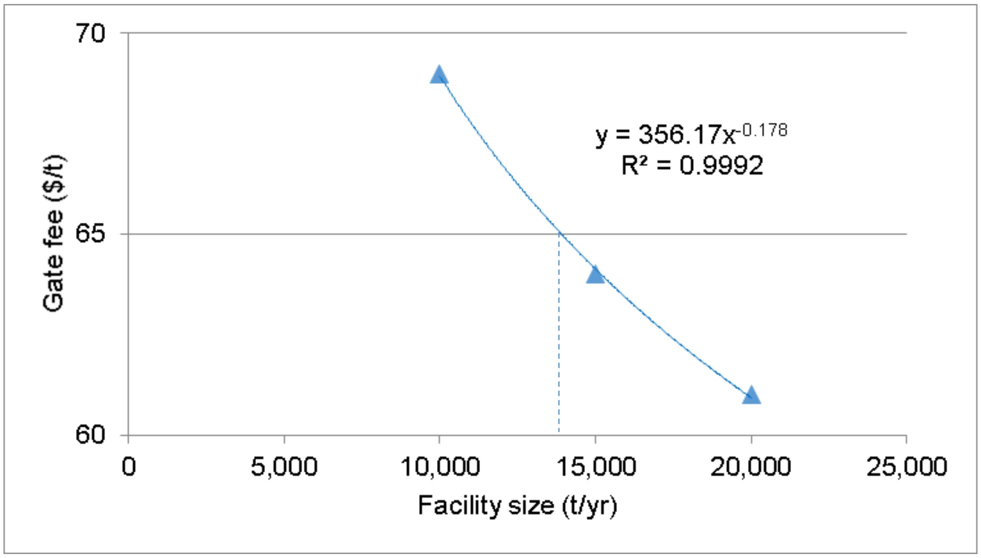


Figure 4-4: Gate fee vs facility size

4.3.3. Large-scale facilities which is integer multiplication of 20,000 t/yr (i.e. 40,000 t/yr; 60,000 t/yr etc.)

The gate fee (when the IRR is 10%) and IRR (when the gate fee is $65/tonne) for large-scale facilities which is integer multiplication of 20,000 t/yr (i.e. 40,000 t/yr; 60,000 t/yr etc.) was calculated. It was found that the same gate fee ($61/tonne for 10% IRR) and IRR (13.7% for $65/tonne gate fee) as for a 20,000 t/yr capacity plant. The results are the same since several 20,000 t/yr parallel units of composting facilities was considered and hence the capital cost would change linearly with respect to capacity. Since all other cost and revenue components follow a similar trend, the gate fee and IRR remain the same for facilities that process 20,000 t/yr or higher.

4.3.4. Economic analysis considering carbon credit

Since composting is intended to reduce GHG emissions compared to landfilling, a techno-economic analysis was done considering carbon credit. The results, given in Table 4-5, show that the calculated gate fee for a medium-scale facility with 10,000 t/yr capacity is $64/tonne, which is less than the landfilling fee. The medium-scale facility, which is not economically viable without considering carbon credit, is economical in this scenario. The results also indicate that a large-scale facility with 20,000 t/yr can achieve an attractive IRR of 17.8%.

Table 4-5: Economical factors for three composting facilities in Red Deer County considering carbon credit

Input	Calculated		
	Small-scale facility (500 t/yr)	**Medium-scale facility (10,000 t/yr)**	**Large-scale facility (20,000 t/yr)**
IRR = 10%	Gate fee = $81/t	Gate fee = $64/t	Gate fee = $57/t
Gate fee = $65/t	IRR = 3.6%	IRR = 10.5%	IRR = 17.8%

Gate fees were calculated for facilities with other capacities as well to determine the minimum size below which a facility is no longer economically viable. By developing a curve for gate fee vs facility size, it was found that the minimum size of such a facility is 9,000 t/yr (see Fig. 4-5).

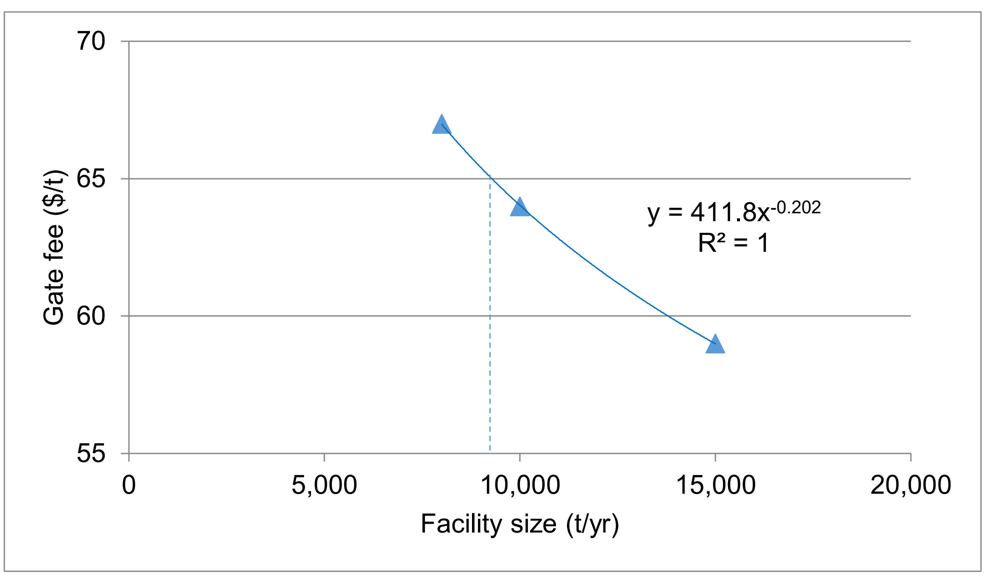


Figure 4-5: Gate fee vs facility size considering carbon credit

4.4. Sensitivity analysis

A sensitivity analysis was performed to better understand the impact of key parameters on the calculated gate fee. The parameters included compost selling price, IRR, facility distance, capital cost, operating cost, carbon price, and carbon credit. The base values of the parameters are presented in Table 4-6. The extent of the variation of each parameter is also shown in the same table.

Table 4-6: Base value and the extent of variation of economic parameters

Parameters	Base value	Changed value
Compost price	\$22/tonne	-20% to +20%
IRR	10%	-20% to +20%
Facility distance	17.5 km	-40% to +40%
Capital cost	\$10,211,206	-10% to +10%
Operating cost	\$4,690,197	-10% to +10%
Compost production	0.4 tonne/tonne waste	-20% to +20%
Carbon price	\$12/tonne of CO_2	-20% to +20%
Carbon credit	0.27 tonne co2/tonne	-40% to +40%

A sensitivity analysis was performed (see Fig. 4-6) and it was found that the operating cost is the most influential parameter on the calculated gate fee. Compost price is the second most influential parameter followed by IRR.

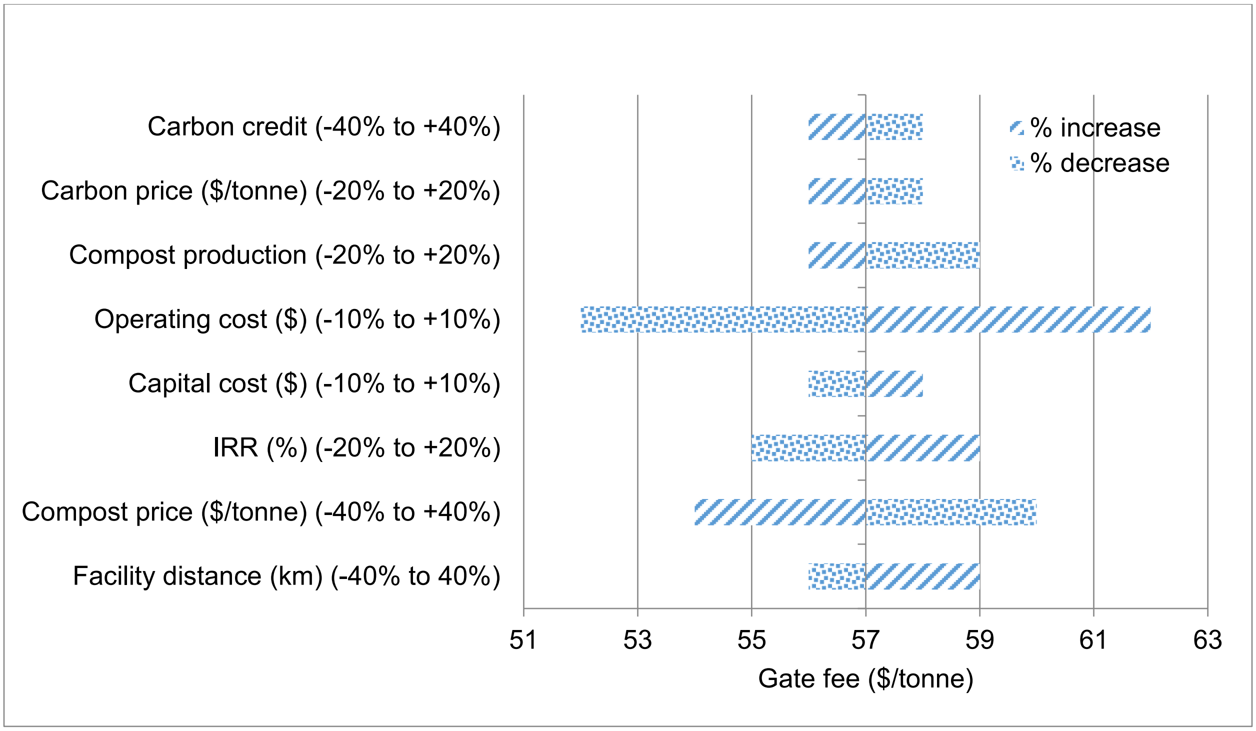


Figure 4-6: Analyzing the sensitivity of the calculated gate fee to large economic factors

4.5. Comparison with anaerobic digestion technology

In a separate study, a techno-economic analysis on anaerobic digestion (AD) technology for the same feedstock in the same region (described in Chapter 3) was conducted. The gate fee for a 20,000 t/yr AD facility was calculated $102/tonne considering carbon credit. In the current study, it was found that the respective value for windrow composting is $57/tonne. However, the gate fee for a large-scale (100,000 t/yr) AD facility is $63/tonne; this figure is lower due to economies of scale. The minimum size of composting and AD facilities below which they are not economically viable was determined to be 9,000 t/yr and 90,000 t/yr, respectively. Thus, composting is economically more viable if the amount of feedstock is 9,000 t/yr to 100,000 t/yr and AD is economically more viable if the amount of feedstock is more than 100,000 t/yr. However, the selection of one technology over the other would depend not only the cost but also relative demand of the end products, i.e., electricity and compost.

4.6. Conclusion

Alberta's food processing industry produces 500,000 tonnes of food waste annually. In most cases, this waste is not disposed of economically or environmentally. The waste can be better managed through composting. The techno-economic analysis of composting shows that if a large-scale facility with 20,000 t/yr capacity is built in Red Deer County, Alberta, the calculated gate fee will be $61/tonne, which that is below the current local landfilling fee ($65/tonne). In this case, the facility can earn 13.7% IRR. If carbon credit is taken into account, the facility becomes more attractive with a $57/tonne gate fee and 17.8% IRR. It was also found that the minimum size below which a facility is no longer economically viable. Sensitivity analysis was performed to better understand the impact of key parameters on the calculated gate fee. It was found that operating cost is the most influential factor followed by compost selling price and IRR. From the comparison of composting and anaerobic digestion technology it was found that composting is cheaper if the amount of the feedstock is less than 100,000 t/yr.

Chapter 5 : Conclusion and Recommendations for Future Work

5.1. Conclusion

Food processing industry is one of the key manufacturing sector globally. It is the second largest manufacturing sector in Alberta. There are more than 500 food processing facilities in Alberta. These facilities produce a significant amount of food waste, a large portion of which is landfilled at high cost to food processing facilities due to transportation costs and landfilling fees. Landfilling also has adverse impact to the environment. To address the problems with the current disposal method, two waste management approaches were proposed – anaerobic digestion and composting. A detailed techno-economic analysis was conducted for both technologies. An assessment of Alberta's food processing waste was carried out for the techno-economic analysis of anaerobic digestion and composting.

5.1.1. Assessment of waste

Alberta’s total food processing waste was assessed based on data from the food processing facilities. About 200 facilities were surveyed, and they reported about 250,000 dry tonnes of food waste per year. The total amount of waste generated by all 500 facilities was estimated through extrapolation. It was estimated that Alberta’s food processing industry produces 500,000 dry tonnes of waste annually. It was also found that most of the waste is generated in the southern half of Alberta, specifically Red Deer County, Taber County, Lethbridge County, Sturgeon County, the City of Calgary, Parkland County, and the City of Edmonton.

5.1.2. Anaerobic digestion

A techno-economic analysis of anaerobic digestion was carried out to understand the economic viability of the technologies as a potential waste management method. A range of scenarios were assessed to understand the viability in different situation..

Base case scenario

The base case was developed for a 100,000 t/yr capacity AD plant for Red Deer County based on waste availability. It was calculated that all cost and revenue components of the facility through development of a techno-economic model. An analysis was performed assuming a 30 year plant life time and 10% IRR. For the current rate of electricity in Alberta ($0.035/kWh), the gate fee at the plant's break-even point was calculated to be $67/tonne. Since the current landfill disposal fee in Red Deer County is $65/tonne, The estimated gate fee required for production of electricity is higher than currently being paid by the facilities. Hence, the facility is not economically viable with a 10% IRR and $0.035/kWh electricity price. When a gate fee of $65/tonne was considered, the electricity price calculated at the plant's break-even point was $0.041/kWh. At this higher electricity rate, the project is economically viable a. For a $0.035/kWh electricity price and $65/tonne gate fee, the IRR is 9.4%. With a lower IRR, the project would also be economically viable.

Scenario 1

Scenario 1 is the case in which 100,000 t/yr waste is not available in Red Deer County. The economic optimum size of a plant below which the plant is no longer economically feasible was estimated. The unit capital cost of the plant increases when the plant size decreases and vice versa. A range of sizes were explored and required gate fees were assessed for electricity production. If the calculated gate fee is equal to or less than $65/tonne, the project was considered to be economically viable. It was found that the minimum size of the plant would be 110,000 t/yr (corresponds to $65/tonne gate fee) to achieve economic viability.

Scenario 2

Scenario 2 is the case in which the AD facility is co-located with the food processing company. The economic optimum size of the plant was determined. There is no transportation cost in this scenario and thus the total cost is low. In this scenario, the calculated gate fee at a plant's break-even point for a 100,000 t/yr facility dropped to $57/tonne, thus making the disposal of the waste through AD more economically attractive than landfilling. The economic optimum size of the plant to achieve economic viability is 70,000 t/yr (corresponds to $65/tonne gate fee) in this scenario.

Scenario 3

Scenario 3 is the case in which the facility is located in Taber County, Alberta. The advantage of building an AD facility in Taber County is that the facility owner can set a high gate fee because the landfill disposal fee in this county is is about $110/tonne which is very high. Based on waste availability, the maximum facility size was assumed to be 50,000 t/yr. For a plant with this capacity, the calculated gate fee at the plant's break-even point is $86/tonne. It means that the disposal of the waste via AD processes is economically viable. The plant capacity below which it is not economically viable is 22,000 t/yr, corresponding to a $110/tonne gate fee..

Economic analysis considering carbon credit

A techno-economic analysis was conducted for the base case as well as the three scenarios considering carbon credit of $13/tonne of CO_2. For the base case scenario, the calculated gate fee was found to be $58/tonne, which is below the landfill disposal fee ($65/tonne). Thus a project that can be economically viable with carbon credit. The minimum plant sizes, with carbon credit, is estimated to be 73,000 t/yr, 50,000 t/yr, and 17,500 t/yr for scenarios 1, 2, and 3, respectively.

In summary, the following AD plant sizes are economically feasible without considering carbon credit as revenue:

- ❑ Centralized 110,000 t/yr or larger AD plant in Red Deer County in western Canada as shown in Fig. 3-1;
- ❑ Company-based (co-located with company) 70,000 t/yr or larger AD plant in Red Deer County;
- ❑ Centralized 22,000 t/yr or larger AD plant in Taber County.

The following AD plant sizes are economically feasible considering carbon credit as revenue:

- ❑ Centralized 90,000 t/yr or larger AD plant in Red Deer County;
- ❑ Company-based (co-located with company) 60,000 t/yr or larger AD plant in Red Deer County;
- ❑ Centralized 20,000 t/yr or larger AD plant in Taber County.

Sensitivity analysis

A sensitivity analysis was performed to better understand the effects of key parameters on the calculated gate fee. The selling price of electricity and the IRR have the highest impact on calculated gate fee.

5.1.3. Composting

Gate fee and IRR of small-, medium- and large-scale facilities

A techno-economic analysis was conducted for windrow composting. A financial model was developed for small-, medium-, and large-scale composting facilities with sizes less than 1,000 t/yr, 1,000 to 10,000 t/yr, and 10,000 to 20,000 t/yr, respectively. The model was based on a project life of a 20-years and 10% IRR. The calculated gate fees at a plant's break-even point were $85/tonne, $69/tonne, and $61/tonne for small (500 t/yr), medium (10,000 t/yr), and large (20,000 t/yr) facilities, respectively. For a gate fee of $65/tonne (the current landfilling fee in Red Deer County), the calculated IRRs at a plant's break-even point were 1.2%, 7.4%, and 13.7% for similar facilities. The results indicate that small- and medium-scale facilities are not economically attractive since their gate fees are higher than the current landfill fee in Red Deer County, and the IRR is quite low as well. On the other hand, large-scale facilities appear to be profitable since their gate fee is lower than the current landfill fee in Red Deer County and they have quite a high IRR of 13.7%.

Minimum size of facility for economic viability

The minimum size was determined below which a facility is no longer economically viable. The determining criteria were that the gate fee should not be above $65/tonne (since the landfilling fee in Red Deer County is $65/tonne) and the IRR should not be below 10%. The minimum size of the facility was determined to be 14,000 t/yr which is economic viabile.

Economic analysis considering carbon credit

An economic analysis was conducted considering carbon credit. The calculated gate fees for small (500 t/yr), medium (10,000 t/yr), and large (20,000 t/yr) facilities were $81/tonne, $64/tonne, and $57/tonne, respectively. IRRs for the same facilities were also calculated and the values were 3.6%, 10.5%, and 17.8%, respectively. The results indicate that a medium-scale facility is economical with carbon credit.

Sensitivity analysis

A sensitivity analysis was performed for windrow composting and it was observed that the operating cost is the most influential parameter on the calculated gate fee. Compost price is the second most influential parameter followed by the IRR.

Comparison with anaerobic digestion

The calculated gate fee for a 100,000 t/yr AD facility is $63/tonne considering carbon credit. However, the gate fee for a 20,000 AD facility is much higher ($102/tonne) due to economies of scale. It was also calculated that the gate fee for a 20,000 t/yr composting facility is $57/tonne. The minimum size of AD and composting facilities was determined to be 90,000 t/yr and 9,000 t/yr, respectively for economic viability. Thus, composting is economically attractive if the size of the facility is 9,000 t/yr to 100,000 t/yr and AD is economically attractive if the size of the facility is more than 100,000 t/yr. However, the selection of one technology over the other would depend not only the cost but also the relative demand of the end products, i.e., electricity and compost.

5.2. Recommendations for Future Work

Food processing waste data was collected from 200 of 500 facilities. The waste data of the remaining facilities were extrapolated based on the data received. This extrapolation could easily lead to a deviation from the amount of total waste as well as region-wise, county-wise, and company-wise waste. Hence, by surveying more faclities, the actual amount of waste could be determined and the new information will affect the facility site location, travelling distance, transportation cost, and hence total cost.

Assessment of conversion of food processing waste using other technologies that AD and composting should b evaluated.

References

Abdulla, M., Martin, R. C., Gooch, M., & Jovel, E. 2013. The importance of quantifying food waste in Canada. *Journal of Agriculture, Food Systems, and Community Development*, **3**(2), 137–151.

Alberta Agriculture and Rural Development. 2006. Impact of soil phosphorus loading on water quality in Alberta: A review. http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/sag11864/$FILE/vol-5-impact-of-p-loading.pdf. Date accessed : May 22, 2016.

Alberta Energy. 2015. http://www.energy.alberta.ca/electricity/682.asp. Date accessed: November 16, 2016.

Alberta Environment. 2010. Leaf and Yard Waste Diversion Strategy Feasibility Study. CH2M HILL Canada Limited. https://extranet.gov.ab.ca/env/infocentre/info/library/8668.pdf . Date accessed : June 30, 2016.

Alberta Environment and Parks. 2011. Maps and shapefiles. https://landuse.alberta.ca/RESULTSRESOURCES/Pages/MapsandShapefiles.aspx. Date accessed: April 22, 2016.

Alberta Government1. 2015. Carbon offset emission factors handbook. Version 1.0. http://aep.alberta.ca/climate-change/guidelines-legislation/specified-gas-emitters-regulation/documents/CarbonEmissionHandbook-Mar11-2015.pdf. Date accessed: November 16, 2016.

Alberta Government2. Highlights of the Alberta Economy 2015, Alberta Innovation and Advanced Education. 2015. https://www.albertacanada.com/files/albertacanada/SP-EH_highlightsABEconomyPresentation.pdf. Date accessed : June 12, 2016

Alberta Environment, Environmental Policy Branch,. 2007. Standards for composting facilities in Alberta. http://aep.alberta.ca/waste/waste-management-facilities/documents/StandardsCompostingFacilitiesAlberta-2007.pdf . Date accessed: July 14, 2016.

Alberta Utilities Commission. 2016. Alberta, Canada. http://www.auc.ab.ca/Pages/Default.aspx. Date accessed : June 10, 2016.

AltaLIS. 1998. Municipal boundaries http://www.altalis.com/products/property/municipal_boundaries.html. Date accessed: April 20, 2016.

Arena, U. 2012. Process and technological aspects of municipal solid waste gasification. A review. *Waste Management*, **32**(4), 625-639.

Allen Kani Associates with Enviros RIS Ltd. 2001. Implications of Different Waste Feed Streams (Source-Separated Organics and Mixed Waste) On Collection Options and Anaerobic Digestion Processing Facility Design, Equipment and Costs. Ontario Waste Diversion Organization. Prepared for the CIty of Toronto. https://nerc.org/documents/toronto_report.pdf. Date of accessed : July 12, 2016.

Bastin, S. and K. Henken. 2011. Water amounts in fruits and vegetables http://www.rrtcadd.org/resources/Advocacy/Water-Amounts-in-Fruits-and-Vegetables---Handout-Week-10.pdf. Date accessed: April 26, 2016.

Bates, J. 2015. Agricultural processing industry directory, Alberta Agriculture and Rural Development http://www.agric.gov.ab.ca/app68/foodindustry. Date accessed: April 10, 2016.

Bell, J. 2015. An organic waste inventory for alberta's agrifood sector. Final report published by Alberta Agriculture and Forestry, Alberta Innovates Energy and Environment Solutions, and Alberta Livestock and Meat Agency. http://www.saewa.ca/. Date accessed: February 17, 2016.

Canadian Grain Commission. 2013. Wheat methods and tests used to measure quality https://www.grainscanada.gc.ca/wheat-ble/method-methode/wmtm-mmab-eng.htm. Date accessed: April 22, 2016.

Carbon Planet Limited. 2016. Carbon Planet. http://www.carbonplanet.com/. Date accessed : July 11, 2016.

Cardona, C.A., Sanchez, O.J., Gutierrez, L.F. 2009. *Process Synthesis for Fuel Ethanol Production* CRC Press, Taylor & Francis Group, Boca Raton, Florida, USA.

Chaoran, L. 2015. Wet and Dry Anaerobic Digestion of Biowaste and of Co-substrates. PhD thesis, Department of Civil Engineering, Karlsruhe Institute of Technology, Germany.

Chornet, E. 2015. Valorizing residual carbon: an important link between energy and environment. http://www.ai-ees.ca . Date accessed: June 11, 2015.

City of Atlanta, I.f.L.S.R. 2010. Update on Anaerobic Digester Projects Using Food Wastes in North America. Division of Sustainability, City of Atlanta, Georgia.

Clarke, S. 2011. Biomass burn characteristics, http://www.omafra.gov.on.ca/english/engineer/facts/11-033.htm. Date accessed: April 25, 2016.

Davis, R.C. 2014. Anaerobic digestion: Pathways for using waste as energy in urban settings. Prepared for the City of Vancouver. https://sustain.ubc.ca/. Date accessed : February 21, 2016.

Demirbaş, A. 2002. Gaseous products from biomass by pyrolysis and gasification: effects of catalyst on hydrogen yield. *Energy Conversion and Management*, **43**(7), 897-909.

Déniel, M., Haarlemmer, G., Roubaud, A., Weiss-Hortala, E., Fages, J. 2016. Energy valorisation of food processing residues and model compounds by hydrothermal liquefaction. *Renewable and Sustainable Energy Reviews*, **54**, 1632-1652.

Eskandari, M., Homaee, M., Mahmodi, S., 2012. An integrated multi criteria approach for landfill siting in a conflicting environmental, economical and socio-cultural area. Waste Management. 32(8): pp. 1528-1538.

ESRI. 2011. ArcGIS for Desktop http://www.esri.com/software/arcgis/arcgis-for-desktop. Date accessed: April 22, 2016.

FAO. 2012. Towards the future we want: End hunger and make the transition to sustainable agricultural and food systems. Food and agriculture organization of the United Nations Rome; 2012. http://www.fao.org/docrep/015/an894e/an894e00.pdf. Date accessed: May 18, 2016.

Ghafoori, E. 2007. The economics of energy from animal manure for greenhouse gas mitigation. PhD Thesis, Department of Mechanical Engineering, University of Alberta, Edmonton.

Gooch, M. and A. Felfel. 2014. $27 Billion revisited. The cost of Canada's annual food waste. Value Chain Management International Inc. Final report. http://vcm-international.com/wp-content/uploads/2014/12/Food-Waste-in-Canada-27-Billion-Revisited-Dec-10-2014.pdf. Date accessed: May 15, 2016.

Government of Alberta. 2016. Alberta Agriculture and Forestry. http://www.agric.gov.ab.ca. Date accessed : May 15, 2016.

Government of Alberta. 2012. Leaf & yard waste diversion targets in Alberta: A Benefit cost analysis. https://extranet.gov.ab.ca/env/infocentre/info/library/8667.pdf. Date accessed: May 28, 2016.

Government of Alberta, 2010. Standards for landfills in Alberta, in Landfill development and siting. http://environment.gov.ab.ca/info/library/7316.pdf. Date of accessed: May 14, 2015.

Government of Canada. 2016. http://srv129.services.gc.ca/rbin/eng/alb.aspx. Date of accessed: December 15, 2016.

Gustavsson, J., C. Cederberg and U. Sonesson. 2011. Global food losses and food waste – extent, causes and prevention. Food and Agriculture Organization of the United Nations. http://www.fao.org/docrep/014/mb060e/mb060e.pdf. Date accessed: April 10, 2016.

ICF Consulting. Determination of the impact of waste management activities on greenhouse gas emissions: 2005. Update final report. Submitted to Environment Canada and Natural Resources Canada by ICF Consulting, October 31, 2005. http://www.rcbc.ca/files/u3/ICF-final-report.pdf . Date accessed : June 20, 2016.

Illinois Food Scrap Coalition. 2015. Food scrap composting challenges and solutions in Illinois. http://illinoiscomposts.org/images/pdfs/IFSC-FoodScrapReportFINAL-Jan2015.pdf. Date accessed: May 28, 2016.

Institute for Local Self-Reliance. 2010. Update on anaerobic digester projects using food wastes in North America. Division of Sustainability, City of Atlanta, Georgia. http://ilsr.org/wp-content/uploads/2012/03/atlanta-adreport.pdf. Date accessed : May 18, 2016.

Jeff Bell. 2015. An organic waste inventory for Alberta's agrifood sector. Final report published by Alberta Agriculture and Forestry. http://www.saewa.ca/public/download/documents/15033 . Date accessed: February 17, 2016.

Katami, T., Yasuhara, A., Shibamoto, T. 2004. Formation of dioxins from incineration of foods found in domestic garbage. *Environmental Science & Technology*, **38**(4), 1062-1065.

Kaushik, R., Parshetti, G.K., Liu, Z., Balasubramanian, R. 2014. Enzyme-assisted hydrothermal treatment of food waste for co-production of hydrochar and bio-oil. *Bioresource Technology*, **168**, 267-274.

Khan, M.M.-U.-H., Jain, S., Vaezi, M., Kumar, A. 2016. Development of a decision model for the techno-economic assessment of municipal solid waste utilization pathways. *Waste Management*, **48**, 548-564.

Kim, D.-H., Oh, S.-E. 2011. Continuous high-solids anaerobic co-digestion of organic solid wastes under mesophilic conditions. *Waste Management*, **31**(9–10), 1943-1948.

Kiran, U.E., Trzcinski, A.P., Ng, W.J., Liu, Y. 2014. Bioconversion of food waste to energy: A review. Fuel, 134, 389-399.

Kosseva, M.R. 2011. *Management and processing of food wastes. second ed*.

Krokida, M.K., Karathanos, V.T., Maroulis, Z.B. 1998. Effect of freeze-drying conditions on shrinkage and porosity of dehydrated agricultural products. *Journal of Food Engineering*, **35**(4), 369-380.

Krokida, M.K., Maroulis, Z.B. 1997. Effect of drying method on shrinkage and porosity. *Drying Technology*, **15**(10), 2441-2458.

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

Layne. 2016. http://www.layne.com/en/solutions/construction/anaerobic-digestion.aspx. Date accessed: April 08, 2015.

Lethbridge Biogas LP. 2013. 2.85 MW Lethbridge biogas / cogeneration facility. http://ccemc.ca/wp-content/uploads/2012/12/G101234-Lethbridge-Biogas-Final-Report.pdf . Date accessed : March 07, 2016.

Leu, B. 2011. Using distillers grains in alternative cow-calf production systems, http://www.iowabeefcenter.org/Cows_Plows/IBC43.pdf. Date accessed: April 22, 2016.

Luning, L., van Zundert, E.H.M., Brinkmann, A.J.F. 2003. Comparison of dry and wet digestion for solid waste. *Water Science and Technology*, **48**(4), 15-20.

Luz, F.C., Rocha, M.H., Silva Lora, E.E., Venturini, O.J., Andrade, R.V., Vicente Leme, M.M., Almazan del Olmo, O. 2015. Techno-economic analysis of municipal solid waste gasification for electricity generation in Brazil. *Energy Conversion and Management*, **103**, 321-337.

Ma, J., Scott, N.R., DeGloria, S.D., Lembo, A.J. 2005. Sitting analysis of farm-based centralized anaerobic digester systems for distributed generation using GIS. Biomass and Bioenergy, **28**, 591–600.

Massachusetts Department of Environmental Protection, 2002. Identification, characterization, and mapping of food waste and food waste generators in Massachusetts. Draper/Lennon, Inc.. http://www.mass.gov/eea/docs/dep/recycle/priorities/foodwast.pdf. Date accessed: October 29, 2016.

Miller, C. 2000. Profiles in garbage: Food waste http://waste360.com/mag/waste_profiles_garbage_food. Date accessed: April 18, 2016.

Moriarty, K. 2013. Feasibility Study of Anaerobic Digestion of Food Waste in St. Bernard, Louisiana. NREL/TP-7A30- 57082. http://www.nrel.gov/docs/fy13osti/57082.pdf. Date accessed : July 10, 2016.

Municipal District of Taber, Alberta, Canada. Official website. http://www.mdtaber.ab.ca/181/Transfer-Station-Landfill-Services. Date accessed: July 14, 2015.

Murphy, J.D., McKeogh, E. 2004. Technical, economic and environmental analysis of energy production from municipal solid waste. *Renewable Energy*, **29**(7), 1043-1057.

Nagao, N., Tajima, N., Kawai, M., Niwa, C., Kurosawa, N., Matsuyama, T., Yusoff, F.M., Toda, T. 2012. Maximum organic loading rate for the single-stage wet anaerobic digestion of food waste. *Bioresource Technology*, **118**, 210-218.

Natural resources Canada, Government of Canada, 2016. http://www.nrcan.gc.ca/energy/funding/current-funding-programs/cef/4963. Date accessed: October 30, 2016

Nicoleta Uzea, M.G.a.D.S. 2014. Developing an industry led approach to addressing food waste in Canada.

Noon, C.E., Daly, M.J. 1996. GIS-based biomass resource assessment with BRAVO. *Biomass and Bioenergy*, **10**(2–3), 101-109.

OECD. 2014. Food Waste Along the Food Chain, OECD Trade and Agriculture Directorate. http://www.oecd.org/officialdocuments/publicdisplaydocumentpdf/?cote=TAD/CA/APM/WP(2013)4/FINAL&docLanguage=En. Date of accessed: February 10, 2015

Payscale Inc. 2016. Payscale human capital. Seattle, USA. http://www.payscale.com/. Date accessed : January 15, 2016.

Pham, T.P.T., Kaushik, R., Parshetti, G.K., Mahmood, R., Balasubramanian, R. 2015. Food waste-to-energy conversion technologies: Current status and future directions. *Waste Management*, **38**, 399-408.

Preferred Carbon Group. 2011. http://preferredcarbongroup.ca/. Date accessed: June 02, 2016.

Recycling Council of Alberta. 2006. Municipal solid waste (MSW) options: integrating organics management and residual treatment/disposal. https://recycle.ab.ca/wp-content/uploads/2016/01/MSW_Options_Report.pdf. Date accessed : July 01, 2016.

RIS, I.L., MacViro, C.I. 2005. Feasibility of Generating Green Power through Anaerobic Digestion of Garden Refuse from the Sacramento Area, California, USA. Sacramento Municipal Utility District. https://nerc.org/documents/sacramento_feasibility_study.pdf. Date accessed: July 08, 2016.

Saaty, T.L. 2000. *Fundamentals of Decision Making and Priority Theory with the Analytic with the Analytic Hierarchy Process*. RWS Publications, Pittsburg, USA.

Sanscartier, D., MacLean, H.L., Saville, B. 2012. Electricity Production from Anaerobic Digestion of Household Organic Waste in Ontario: Techno-Economic and GHG Emission Analyses. *Environmental Science & Technology*, **46**(2), 1233-1242.

Saville, B. 2014. Industrial and Agricultural Anaerobic Digestion Potential in Canada. http://www.gtmconference.ca/site/index.php/2014-presentations/doc_download/83-b4d-3-savel. Date accessed: July 4, 2015.

Sipahioglu, O., Barringer, S.A. 2003. Dielectric properties of vegetables and fruits as a function of temperature, ash, and moisture content. *JOURNAL OF FOOD SCIENCE*, **68**(1), 234 - 239.

Soberg, M. 2011. W2E to build $23 WtE facility in SC. *Biomass Magazine*. USA. http://biomassmagazine.com/articles/5774/w2e-to-build-23-million-wte-facility-in-sc. Date accessed : August 17, 2016.

Southern Alberta Energy-From-Waste Alliance, 2012. Phase 2, Task 3: Waste Collection, Handling and Transportation. http://www.saewa.ca/pdf/engineering_study/Task3.pdf. Date of accessed: May 14, 2015.

Sultana, A., Kumar, A. 2012. Optimal siting and size of bioenergy facilities using geographic information system. *Applied Energy*, **94**, 192-201.

The Andersons Centre, Redman, G. 2010. A detailed economic assessment of anaerobic digestion technology and its suitability to UK farming and waste system. Report, 2nd Edition, Project No: NNFCC 10-010. http://www.organics-recycling.org.uk/uploads/category1060/10-010%20FINAL_Andersons_NNFCC_AD2010.pdf. Date accessed : June 11, 2016.

The City of Calgary, Alberta, Canada. Official website. http://www.calgary.ca/UEP/WRS/Pages/Landfill-information/Landfill-Rates.aspx. Date accessed: October 25, 2015.

The City of Edmonton. Official website. https://www.edmonton.ca/programs_services/garbage_waste/disposal-rates.aspx. Date accessed: October 10, 2015.

The City of Lethbridge. Official website. http://www.lethbridge.ca/living-here/Waste-Recycling/Pages/2016-Tipping-Rates.aspx. Date accessed: October 20, 2015.

The City of Red Deer. Official website. http://www.reddeer.ca/city-services/garbage-and-recycling/landfill-waste-management-facility/. Date accessed: October 24, 2015.

Tsilemou, K., Panagiotakopoulos, D. 2006. Approximate cost functions for solid waste treatment facilities. *Waste Management & Research*, **24**(4), 310-322.

Uçkun Kiran, E., Trzcinski, A.P., Ng, W.J., Liu, Y. 2014. Bioconversion of food waste to energy: A review. *Fuel*, **134**, 389-399.

Ullah, M., Vaezi, M., Kumar, A., Bell, J., 2016. Assessment of the waste-to-energy potential from Alberta's food processing industry. Canadian Biosystems Engineering Journal.

USDA. 2011. Water in meat and poultry, United States Department of Agriculture Food Safety and Inspection Service http://www.fsis.usda.gov/wps/wcm/connect/42a903e2-451d-

40ea-897a-22dc74ef6e1c/Water_in_Meats.pdf?MOD=AJPERES. Date accessed: april 11, 2016.

Uzea N, Gooch M and Sparling D. Developing an industry led approach to addressing food waste in Canada. 2014. https://www.provisioncoalition.com/Assets/website/PDFs/Provision-Addressing-Food-Waste-In-Canada-EN.pdf. Date accessed: June 03, 2016.

Yalçın, M.Y., Şeker, M. 2016. Effect of salt and moisture content reduction on physical and microbiological properties of salted, pressed and freeze dried turkey meat. *LWT - Food Science and Technology*, **68**, 153-159.

Zhang, C., Su, H., Baeyens, J., Tan, T. 2014. Reviewing the anaerobic digestion of food waste for biogas production. *Renewable and Sustainable Energy Reviews*, **38**, 383-392.

Appendices

Appendix A: List of surveyed food processing facilities

Appendix B: AD plant site selection by ArcGIS

Appendix C: Power cost calculation: Base case of AD

Appendix A: List of surveyed food processing facilities

Company name	County/City/Town
Select Ready Foods Inc.	Edmonton
Sons Bakery	Calgary
Sunfresh Farms Ltd.	Edmonton
Permolex Ltd.	Red Deer County
Prairie Gold Produce	Municipal District of Taber
Rahr Malting Canada Ltd.	Lacombe County
Rocky Mountain Flatbread Company	M.D. of Bighorn No. 8
Richardson Milling (Viterra Food Processing)	County of Barrhead No. 11
Viterra, Alberta Bean Division	County of Forty Mile No. 8
Wing's Foods of Alberta Ltd.	Edmonton
Mountain Creek Farms (XL Fine Foods)	Calgary
Edmonton Meat Packing (XL Grinding)	Edmonton
Let's Pasta Food Services Ltd.	Lethbridge
Coca-Cola Bottling Ltd.	Lethbridge
Hi Pro Feeds, LP	Lethbridge
Sudo Farms Ltd.	Lethbridge
All Seasons Mushrooms Inc.	Rocky View County
Olds SoftGels	Mountain View County
Bunge Canada	Edmonton
Canada Bread Frozen Bakery Ltd.	Calgary
Canada Malting Co. Limited	Calgary
El Dorado Vegetable Farms Ltd.	Cypress County
Lantic Inc.	Municipal District of Taber
McCain Foods Canada	Lethbridge County
Parmalat Canada	Calgary
Red Hat Co-operative Ltd.	Cypress County
Sun Gro Horticulture Canada Ltd.	Parkland
ADM Milling Company	Calgary
Alberta Processing Co.	Calgary
Archer Daniels Midland	County of Vermilion River
Bee Maid Honey Limited	Parkland County
Byblos Bakery Ltd.	Calgary
Calahoo Meats Ltd.	Sturgeon County

Company name	County/City/Town
Calgary Italian Bakery Ltd.	Calgary
CB Constantini Ltd.	Lethbridge County
Champion Feed Services Ltd.	Westlock County
Culligan	Edmonton
Edmonton Potato Growers 1971 Ltd.	Edmonton
Engel's Bakeries Ltd.	Calgary
Sliced FC	Calgary
Gouw Quality Onions Ltd.	Municipal District of Taber
Heritage Frozen Foods Ltd.	Edmonton
Hi Pro Feeds, LP	Lethbridge County
Vauxhall Meats 2004 Ltd.	Municipal District of Taber
Alberta Sugar Beet Growers	Municipal District of Taber
Alberta Vegetable Growers (Processing)	Municipal District of Taber
Kayben Farms	Municipal District of Foothills No. 31
Kitchen Partners Limited	Edmonton
Kuhlmann's Market Gardens & Greenhouses Ltd.	Edmonton
Norac Technologies Inc.	Edmonton
PARMX Cheese Co.	Calgary
Bunge Canada	Municipal District of Wainwright No. 61
MacKay's Cochrane Ice Cream Ltd.	Rocky View County
Big Rock Brewery	Calgary
Richardson Oilseed Limited	Lethbridge County
Dpb Baking Company	Calgary
Lucerne Foods Ltd., A Div. of Canada Safeway	Lethbridge County
Bunge Canada	Sturgeon County
Brooks Meat Packers 1995 Ltd.	Brooks County of Newell
Edmonton Custom Packers Ltd.	Edmonton
Johnny's Sausage & Meats Ltd.	Municipal District of Peace No. 135
Judy G Foods Inc.	Calgary
Lethbridge Meats & Seafoods Ltd.	Lethbridge County
Masterfeeds	Mountain View County
Masterfeeds Inc.	Municipal District of Taber
Prairie Meats Ltd.	Lethbridge County
Prairie Mill Bread Co.	Edmonton
Pure Country Meats	Wheatland County

Company name	**County/City/Town**
Rockport Flour Mills Inc.	Cardston County
Bouvry Exports Calgary Ltd.	Calgary
Agropur Lethbridge Plant	Lethbridge County
Sunny Boy Foods Ltd.	Edmonton
Sylvan Star Cheese Ltd.	Red Deer County
Sylvia's Essential Sauces Ltd.	County of Wetaskiwin No. 10
H&M Meats	Grande Prairie
King's Crown Farm and Meats	Lethbridge County
Irricana Meat Market	MD Rockyview
South Edmonton Produce Co. 1978 Ltd.	Edmonton
Wow Factor Desserts	Strathcona County
Big Bend Market, North	Red Deer County
Big Bend Market, South	Red Deer County
Columbia Seed Company Ltd.	Municipal District of Taber
De Fazio Gourmet	Edmonton
East-Man Feeds	Lethbridge County
East-Man Feeds - Red Deer	Red Deer County
Fratello Coffee Co. Ltd.	Calgary
Landmark Feeds, Nutreco Canada Inc.-Strathmore	Wheatland County
Landmark Feeds, Nutreco Canada Inc.-Medicine Hat	Cypress County
Le Chocolatier	M.D. of Bighorn No. 8
Masterfeeds LP-Picture Butte	Lethbridge County
Olds College Meat Processing Program	Mountain View County
Parkland Packers 1976 Ltd.	Parkland County
Peace Country Milling and Grain	County of Grande Prairie No. 1
Rocky Mountain Meats 1999 Ltd.	Clearwater County
Scholing's Produce Inc.	Lacombe County
Sunrise Poultry Processors Ltd.	Lethbridge County
Maple Leaf Poultry	Wetaskiwin (city)
Bassano Growers Ltd.	Calgary
Canadian Premium Meats Inc.	Lacombe County
Canyon Creek Food Company Ltd.	Edmonton
Cargill Animal Nutrition	Camrose County
Cococo Chocolatiers Inc. o/a Chocolaterie Bernard Callebaut	Calgary
Family Meats 2011 Ltd.	Ponoka County

Company name	County/City/Town
Mountain Top Foods Ltd.	Municipal District of Willow Creek No. 26
Transcend Coffee	Edmonton
Triple D Produce	Municipal District of Taber
KSL Foods Inc.	Municipal District of Taber
Bar Al Beef and Bison	Municipal District of Taber
Sunrise Poultry Processors Ltd. Taber	Municipal District of Taber
Lilydale Hatchery	Edmonton
High River Chicken	High River
Cargill Feed & Nutrition-Lethbridge Plant	Lethbridge
Pepsico	Taber
Old Dutch Foods Ltd.-Calgary	Calgary
Old Dutch Foods Ltd. -Airdrie	Airdrie
Lucerne Foods	Calgary
Champion Feed Services Ltd - Barrhead	Barrhead
Olymel S.E.C./L.P.	Red Deer
Beck Farms Ltd.	Red Deer
Blue Rock Minerals 2002 Inc.	Red Deer
Sungold Specialty Meats Ltd.	Red Deer
Ben's Quality Meats Ltd.	Lethbridge County
Trophy Foods Inc.	Calgary
Aliya's Foods Limited	Edmonton
Awake Cereals Corporation	Strathcona County
Baba Jenny's Ukrainian Foods Ltd.	County of Vermilion River
Bles-Wold Yogurt Inc.	Lacombe County
Cadcan Marketing & Sales Inc.	Calgary
Canadian Nurs-Ette Distributors Ltd.	Camrose County
Copper Pot Creations Inc.	Calgary
Crystal Springs Cheese	Lethbridge County
Dehnamar Inc.	Sturgeon County
Delizia's Pasta Ltd.	Calgary
Richardson Oilseed Limited	Lethbridge
Lucerne Foods Ltd. Lethbridge	Lethbridge
PepsiCo Foods Canada	Lethbridge
New-Life Feeds	Lethbridge
Clover Leaf Cheese Ltd.	Calgary
Foothills Creamery Ltd.	Calgary

Company name	County/City/Town
Sudo Farms Ltd.	Lethbridge County
The Happy Camel Inc.	Edmonton
Tiras Dairies Inc.	Camrose County
Troika Foods 2000 Ltd.	Strathcona County
Canada Malting Co.	Calgary
Canadian Oats	Sturgeon
Alberta Feed & Consulting Ltd.	Red Deer
Y B Quality Meat	Red Deer
Nossack Fine Meats Ltd.	Red Deer
Alberta Prairie Meats Ltd.	County of Newell
Balzac Meat Processing	Rocky View County
Barrhead Custom Meats 1990 Ltd.	County of Barrhead No. 11
Bauer Meats	Kneehill County
Pearson's Berry Farm Ltd.	Red Deer
Nossack Gourmet Foods	Red Deer
Nestle Purina Pet Care	Red Deer
Cargill Feed and Nutrition	Lethbridge
Wilbur-Ellis Company of Canada Ltd.	Lethbridge
Westway Feed Products	Lethbridge
Champion Feed Services Ltd.	County of Grande Prairie No. 1
Seabrook Meats Ltd.	Athabasca County
Mountain Dog Enterprises Inc.	Edmonton
Penteco Foods Ltd.	Strathcona County
CB Constantini Ltd.	Lethbridge
Masterfeeds Inc.	Municipal District of Taber
Prairie Gold Produce	Municipal District of Taber
Lethbridge Meats & Seafoods Ltd.	Lethbridge
Sunrise Poultry Processors Ltd. Lethbridge	Lethbridge
Gouw Quality Onions Ltd.	Municipal District of Taber
East-Man Feeds	Lethbridge
Maple Leaf Pork, a division of Maple Leaf Foods	Lethbridge
Lantic Inc.	Municipal District of Taber
From The Earth Naturally Ltd.	Sturgeon County
Kirschenman Farms	Cypress County
Lynn Thacker Ag. Corp.	County of Forty Mile No. 8
Rock Ridge Dairy Ltd.	Ponoka County

Company name	County/City/Town
Lakeview Bakery 2001 Ltd.	Lethbridge
NAFTAC Commodities Inc.	Lethbridge
Rollover Premium Petfood Limited	Municipal District of Foothills No. 31
Ben's Beef Jerky	Lethbridge
Transfeeder - An Agricultural Corporation	Mountain View County
Vermilion Packers Ltd.	County of Vermilion River
Y B Quality Meat	Red Deer County
Alberta Greenhouse Growers Association	Edmonton
Green Prairie International Inc.	Lethbridge
Parmalat Canada	Lethbridge
Hilton Stone Distribution Corp	Calgary
Hi-Pro Feeds	Mountain View County
Inovata Foods Corp.	Edmonton
L.A. Grains	Lethbridge
Lucerne Foods Ltd., Taber	Municipal District of Taber
Potato Growers of Alberta	Municipal District of Taber
Sakai Spice Canada Corp.	Lethbridge
Viterra, Special Crops	Lethbridge
Columbia Seed Company Ltd.	Municipal District of Taber
PEPSICO	Municipal District of Taber
Normerica Inc.	Lethbridge
P & H Milling Group	Lethbridge
The Black Velvet Distilling Company	Lethbridge
Chin Ridge Seeds Ltd.	Municipal District of Taber
Cavendish Farms	Lethbridge

Appendix B: AD plant site selection by ArcGIS

Supplementary materials for site selection

Analytic Hierarchy Process (AHP)

The analytic hierarchy process is a widely accepted multi-criteria decision-making method. Through this method a weightage factor from a pairwise comparison can be derived. Paired elements are compared, and each element is assigned a value on a 9-point scale derived from Saaty (Saaty, 2002). The fundamental scale of relative importance is shown in Table B1.

Table B1: The fundamental scale of relative importance in the AHP (Sultana and Kumar, 2012; Ma et al., 2005)

Definition	Relative importance
Equal importance	1
Moderately more important	3
Strongly more important	5
Very strongly more important	7
Extremely more important	9
Intermediate values to reflect compromise	2, 4, 6, 8

The first step is to make a hierarchy of the considered influencing factors that provides an overall view of the complex relationship between the factors. After defining the structure, for each pair of criteria, rating on the basis of relative priority is done by assigning a weight between "1" (equally important) and "9" (extremely more important). An $n \, x \, n$ matrix "A" is developed where $a_{i,j}$ is the extent of preferring factor i to factor j and $a_{j,i} = \frac{1}{a_{i,j}}$. Then the sum of each column in the matrix is calculated and each matrix element is divided by its corresponding column sum. Finally, relative weight is calculated by taking the average across each row.

The final steps of the AHP are to calculate the consistency ratio (CR) and to check the consistency of the pairwise comparison. The consistency ratio is calculated using the following mathematical relation:

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}} \qquad \text{(SP.1)}$$

where CR= Consistency Ratio, RI= Mean/Average consistency index, and CI= Consistency Index. The consistency index is calculated using the following relation:

$$CI = \frac{\lambda max - n}{n - 1} \qquad \text{(SP.2)}$$

where n= Order of matrix and λ_{max}= maximum eigenvalue of the matrix.

<u>Exclusion Analysis</u>

In exclusion analysis, unsuitable areas for the building of facility are deducted. The facility should not be built near some environmental, social and economic factors, which is called constraints, as shown in Table B2. The table also shows that each constraints has a corresponding buffer zone, which means the facility is not safe within that distance.

Table B2: Constraints and corresponding buffer zones

Constraints	Buffer zone	Reference
Rivers, lakes, and other water bodies	More than 300 m	(Government of Alberta, 2010)
Rural and urban areas	More than 1 km	(Eskandari et al., 2012; Ma et al., 2005)
Airports and heliports	More than 8 km from international airports and 3 km from local airports	(Southern Alberta Energy-From-Waste Alliance, 2012; Ma et al., 2005)
Industrial and mining zones	More than 1 km	(Sultana and Kumar, 2012)
Environmentally sensitive areas (ESA) (flood plains, conservation areas, habitat sites)	More than 1 km	(Eskandari et al., 2012)
Natural gas pipelines	More than 100 m	(Sultana and Kumar, 2012; Ma et al., 2005)
Park and recreational areas	More than 500 m	(Sultana and Kumar, 2012)
Wetlands	More than 200 m	(Sultana and Kumar, 2012)
Roads	More than 30 m	(Sultana and Kumar, 2012)
Power plants and substations	More than 100 m	(Sultana and Kumar, 2012)
Transmission lines	More than 100 m	(Sultana and Kumar, 2012)
Land surface gradient	Areas with slopes larger than 15% are screened out	(Sultana and Kumar, 2012)

Preference Analysis

In preference analysis, relative importance of eight factors is considered to identify the most preferable location. The factors are waste availability (WA), urban areas, water availability, roads, transmission line, power substation, land cover and slope as shown in Table B3. Here waste availability and slope is the most and least important factor respectively for site selection. Then weight of each preference factor was determined using AHP.

Table B3: Pair-wise comparison matrix and weights of preference factors

Preference factors	WA	Urban	Water	Roads	Transmi ssion	Subst ation	Land cover	Slope	Weights
WA	1	2	3	4	5	7	8	9	0.36
Urban	0.5	1	2	3	4	4	5	6	0.22
Water	0.33	0.5	1	2	3	3	4	5	0.15
Roads	0.25	0.33	0.5	1	2	2	3	3	0.09
Transmission	0.2	0.25	0.33	0.5	1	1	2	2	0.06
Substation	0.14	0.25	0.33	0.5	1	1	2	2	0.06
Land cover	0.13	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

Suitability Index

The determination of suitability index of different location of the study area is shown in Table B4. The weight of each preference factor is multiplied with its grading value, which gives a cell value for each factor. Then values of all factors is added, that gives total preference cell value. Then it is multiplied with the exclusion analysis value to get the suitability index.

Table B4: Sample calculation of suitability index values

Preference factors	Grading values (C)	Weight of preference factors (w)	Cell value for each factor, $C_p=C\times w$	Preference cell value (ΣC_p)	Constraint map value for corresponding cell, C_E= 0 or 1	Suitability index, $SI=C_E\times C_p$
Waste availability	9	0.36	3.24	7.25	1	7.25 ≈ 7
Water availability	8	0.22	1.76			
Urban and rural areas	7	0.15	1.05			
Roads	6	0.09	0.54			
Transmission lines	5	0.06	0.3			
Substations	4	0.06	0.24			
Land cover	3	0.03	0.09			
Slope	1	0.03	0.03			

Alberta road network map

Alberta road network map is shown in Fig. B1. It is used to determine the distance from waste producing points to higher suitability index location. The the location with shortest distance is selected for site of the facility.

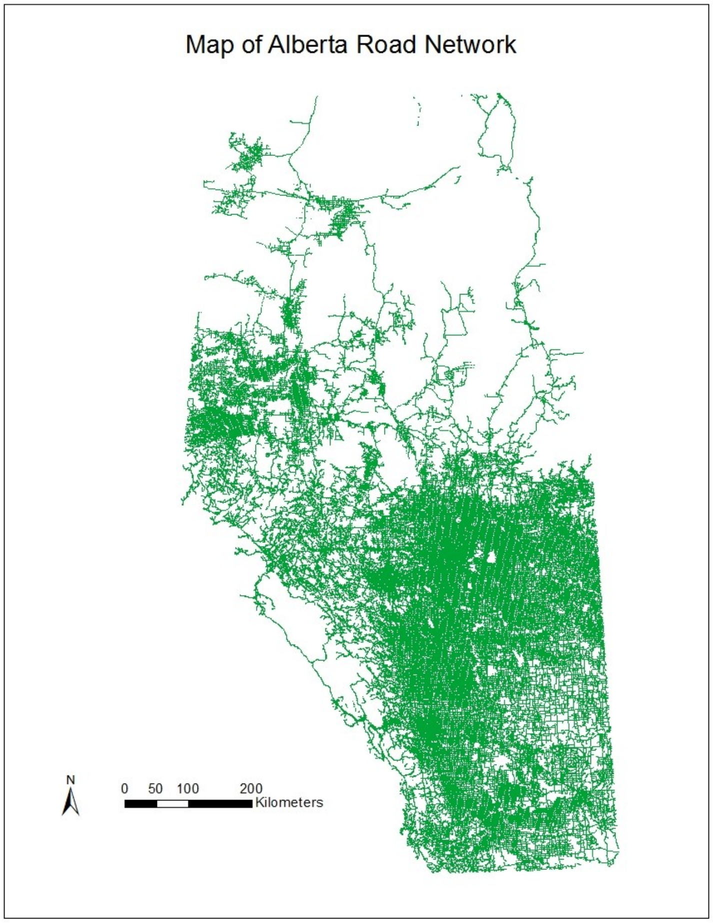


Figure B1: Alberta road network map

Appendix C: Power cost calculation: Base case of AD

Table C1: Value of different factors related to power cost calculation

Capacity (t/y) : 100,000
Capital cost ($) : 38,142,439
Spread of capital costs during construction:
Year 1 : 20%
Year 2 : 35%
Year 3 : 45%
Inflation : 2%
Maintenance cost : assumed 3 % of capital cost
Fixed transportation cost ($) : 600,000
Variable transportation cost ($) : 350,000
IRR : 10%
Biogas yield (m3/t) : 200
Total biogas yield (m3/yr) : 20,000,000
Heating value of biogas (kWh/m3) :6.7
For electricity generation: Use 90% of biogas
Electrical efficiency : 37%
For heat generation: Use 10% of biogas
Capacity factor:
Year 1 : 0.7
Year 2 : 0.8
Year 3 onwards : 0.85

Table C2: Spreadsheet table of power cost calculation for base case of AD facility

Year	Capital cost ($)	Operating cost ($)	Maintenance cost ($)	Transportation cost ($)	Total cost ($)	PV of total cost at 10% IRR ($)	Gross Electricity generation (kWh)	Net Electricity generation (kWh)	Price of electricity ($/kWh)	Revenue from electricity ($)	Gate fee ($/t)	Revenue from tipping fee ($)	Total revenue ($)	PV of total revenue at 10% IRR ($)	Net income ($)	Net income at 10% IRR ($)
-2	7,628,488	0	0	0	7,628,488	9,230,470	0	0	0	0	0	0	0	0	(7,628,488)	(9,230,470)
-1	13,349,854	0	0	0	13,349,854	14,684,839	0	0	0	0	0	0	0	0	(13,349,854)	(14,684,839)
0	17,164,098	0	0	0	17,164,098	17,164,098	0	0	0	0	0	0	0	0	(17,164,098)	(17,164,098)
1		1,970,400	1,144,273	950,000	4,064,673	3,695,157	31,235,400	24,988,320	0.035	874,591	66.90	6,689,592	7,564,183	6,876,530	3,499,510	3,181,372
2		2,009,808	1,167,159	969,000	4,145,967	3,426,419	35,697,600	28,558,080	0.036	1,019,523	68.23	6,823,383	7,842,907	6,481,741	3,696,940	3,055,322
3		2,050,004	1,190,502	988,380	4,228,886	3,177,225	37,928,700	30,342,960	0.036	1,104,909	69.60	6,959,851	8,064,760	6,059,173	3,835,874	2,881,949
4		2,091,004	1,214,312	1,008,148	4,313,464	2,946,154	37,928,700	30,342,960	0.037	1,127,007	70.99	7,099,048	8,226,055	5,618,506	3,912,591	2,672,352
5		2,132,824	1,238,598	1,028,311	4,399,733	2,731,888	37,928,700	30,342,960	0.038	1,149,547	72.41	7,241,029	8,390,576	5,209,887	3,990,843	2,477,999

Table C2: (continued)

6		2,175,481	1,263,370	1,048,877	4,487,728	2,533,205	37,928,700	30,342,960	0.039	1,172,538	73.86	7,385,850	8,558,387	4,830,987	4,070,660	2,297,781
7		2,218,990	1,288,637	1,069,854	4,577,482	2,348,972	37,928,700	30,342,960	0.039	1,195,989	75.34	7,533,567	8,729,555	4,479,642	4,152,073	2,130,670
8		2,263,370	1,314,410	1,091,251	4,669,032	2,178,138	37,928,700	30,342,960	0.040	1,219,908	76.84	7,684,238	8,904,146	4,153,850	4,235,114	1,975,712
9		2,308,638	1,340,698	1,113,076	4,762,412	2,019,728	37,928,700	30,342,960	0.041	1,244,306	78.38	7,837,923	9,082,229	3,851,752	4,319,817	1,832,024
10		2,354,810	1,367,512	1,135,338	4,857,661	1,872,838	37,928,700	30,342,960	0.042	1,269,193	79.95	7,994,681	9,263,874	3,571,624	4,406,213	1,698,786
11		2,401,907	1,394,863	1,158,045	4,954,814	1,736,632	37,928,700	30,342,960	0.043	1,294,576	81.55	8,154,575	9,449,151	3,311,870	4,494,337	1,575,238
12		2,449,945	1,422,760	1,181,206	5,053,910	1,610,332	37,928,700	30,342,960	0.044	1,320,468	83.18	8,317,666	9,638,134	3,071,007	4,584,224	1,460,675
13		2,498,944	1,451,215	1,204,830	5,154,988	1,493,217	37,928,700	30,342,960	0.044	1,346,877	84.84	8,484,020	9,830,897	2,847,661	4,675,909	1,354,444
14		2,548,923	1,480,239	1,228,926	5,258,088	1,384,619	37,928,700	30,342,960	0.045	1,373,815	86.54	8,653,700	10,027,515	2,640,558	4,769,427	1,255,939
15		2,599,901	1,509,844	1,253,505	5,363,250	1,283,919	37,928,700	30,342,960	0.046	1,401,291	88.27	8,826,774	10,228,065	2,448,517	4,864,815	1,164,598
16		2,651,899	1,540,041	1,278,575	5,470,515	1,190,543	37,928,700	30,342,960	0.047	1,429,317	90.03	9,003,309	10,432,627	2,270,443	4,962,112	1,079,900
17		2,704,937	1,570,842	1,304,146	5,579,925	1,103,958	37,928,700	30,342,960	0.048	1,457,903	91.83	9,183,376	10,641,279	2,105,320	5,061,354	1,001,362
18		2,759,036	1,602,259	1,330,229	5,691,524	1,023,671	37,928,700	30,342,960	0.049	1,487,061	93.67	9,367,043	10,854,105	1,952,206	5,162,581	928,536
19		2,814,216	1,634,304	1,356,834	5,805,354	949,222	37,928,700	30,342,960	0.050	1,516,803	95.54	9,554,384	11,071,187	1,810,227	5,265,832	861,006

Table C2: (continued)

20		2,870,501	1,666,990	1,383,971	5,921,461	880,187	37,928,700	30,342,960	0.051	1,547,139	97.45	9,745,472	11,292,610	1,678,575	5,371,149	798,387
21		2,927,911	1,700,330	1,411,650	6,039,891	816,174	37,928,700	30,342,960	0.052	1,578,081	99.40	9,940,381	11,518,463	1,556,496	5,478,572	740,323
22		2,986,469	1,734,336	1,439,883	6,160,688	756,816	37,928,700	30,342,960	0.053	1,609,643	101.39	10,139,189	11,748,832	1,443,297	5,588,144	686,481
23		3,046,198	1,769,023	1,468,681	6,283,902	701,775	37,928,700	30,342,960	0.054	1,641,836	103.42	10,341,973	11,983,809	1,338,330	5,699,906	636,555
24		3,107,122	1,804,404	1,498,054	6,409,580	650,736	37,928,700	30,342,960	0.055	1,674,673	105.49	10,548,812	12,223,485	1,240,997	5,813,905	590,260
25		3,169,265	1,840,492	1,528,015	6,537,772	603,410	37,928,700	30,342,960	0.056	1,708,166	107.60	10,759,788	12,467,954	1,150,742	5,930,183	547,332
26		3,232,650	1,877,301	1,558,576	6,668,527	559,526	37,928,700	30,342,960	0.057	1,742,329	109.75	10,974,984	12,717,313	1,067,052	6,048,786	507,526
27		3,297,303	1,914,847	1,589,747	6,801,898	518,833	37,928,700	30,342,960	0.059	1,777,176	111.94	11,194,484	12,971,660	989,448	6,169,762	470,615
28		3,363,249	1,953,144	1,621,542	6,937,936	481,100	37,928,700	30,342,960	0.060	1,812,720	114.18	11,418,373	13,231,093	917,488	6,293,157	436,389
29		3,430,514	1,992,207	1,653,973	7,076,694	446,111	37,928,700	30,342,960	0.061	1,848,974	116.47	11,646,741	13,495,715	850,762	6,419,020	404,651
30		3,499,124	2,032,051	1,687,052	7,218,228	413,666	37,928,700	30,342,960	0.062	1,885,953	118.80	11,879,676	13,765,629	788,888	6,547,401	375,222
Total	38,142,439	79,935,343	46,420,965	38,539,675	203,038,423	86,613,578				42,832,314		271,383,880	314,216,194	86,613,578	111,177,771	(0)