Development of a Decision Model for the Techno-economic Assessment of Municipal Solid Waste Utilization Pathways

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Abstract

Economic competitiveness is one of the key factors in making decisions towards the development of waste conversion facilities and devising a sustainable waste management strategy. The goal of this study is to develop a framework, as well as to develop and demonstrate a comprehensive techno-economic model to help county and municipal decision makers in establishing waste conversion facilities. The user-friendly data-intensive model, called the **FUN**damental E**N**gineering Principl**E**s-based Mode**L** for Estimation of **Cost** of Energy and Fuels from **MSW** (FUNNEL-Cost-MSW), compares nine different waste management scenarios, including landfilling and composting, in terms of economic parameters such as gate fees and return on investment. In addition, a geographic information system (GIS) model was developed to determine suitable locations for waste conversion facilities and landfill sites based on integration of environmental, social, and economic factors. Finally, a case study on Parkland County and its surrounding counties in the province of Alberta, Canada, was conducted and a sensitivity analysis was performed to assess the influence of the key technical and economic parameters on the calculated results.

Key Words: WTE; waste conversion; landfilling; GIS; sensitivity analysis

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Nomenclature

AD	Anaerobic digestion
AHP	Analytic hierarchy process
BDT	Bone dry tonne
CO_2	Carbon dioxide
CO_2-eq	Equivalent carbon dioxide
ESA	Environmentally sensitive areas
FUNNEL-Cost-MSW	**FUN**damental E**N**gineering Principl**E**s-based Mode**L** for Estimation of **Cost** of Energy and Fuels from **MSW**
GHG	Greenhouse gas
GIS	Geographic information system
IRR	Internal rate of return
kWh	Kilowatt hour
MSW	Municipal solid waste
OPEX	Operating expenditure
WA	Waste availability
WTE	Waste-to-energy

1. Introduction

The management of municipal solid waste (MSW) is a big concern today for city authorities and planners due to increasing population, urbanization, and limited land space. MSW is one of the major concerns to environmental health (Javaheri et al., 2006) and the traditional treatment and dumping of solid waste has some key environmental challenges such as leachate generation and air pollution (Ojha et al., 2007). Such environmental challenges, combined with political, social, and economic issues, as well as the availability of land, are major concerns to be addressed in land evaluation and management (Lein, 1990). On the other hand, increasing population leads to increased fossil fuel consumption and corresponding increase in energy and fuel demands and greenhouse gas (GHG) emissions. Converting solid waste to energy provides an option, not only to produce cleaner energy, but also to contribute to offsetting GHG emissions.

In 2010, 19 out of 32 European countries (EU-27 member states, Croatia, Iceland, Norway, Switzerland, and Turkey) landfilled more than 50% of their municipal solid waste (European Environment Agency, 2013). In 2006, 212 million tonnes of solid waste was generated in China (Zhang et al., 2010), and India generates around 45 million tonnes of waste every year (Shekdar, 2009). These two countries open dump 50% and 90% of their total MSW, respectively (Visvanathan and Trankler, 2003). In 2012 the United States discarded 53.8% of the total generated MSW in landfills (United States Environmental Protection Agency, 2014) and currently many landfills have either reached or nearly reached their capacity (Palmer, 2011). In Canada, most of the waste ends up at landfills as well. About 30% of Canada's landfills either reached or surpassed their capacity at 2010 (PPP Canada, 2014). These landfills produce a sizable portion (about 25%) of Canada's methane emission (Environment Canada, 2012). Obviously, it has become necessary to research and implement more environmentally friendly waste management options to divert wastes from landfills.

There have been many studies conducted on solid waste utilization techniques. A few of these studies focussed on the energy and economic assessment for specific technologies (Bonk et al., 2015; Emery et al, 2007). Others provided current solid waste scenarios and future possibilities for some specific regions only (Boukelia and Mecibah, 2012; Hossain et al., 2014; Kimambo and Subramanian, 2014). Environmental impact and life cycle assessment (LCA) have also been the focus of many research studies, e.g., Fruergaard and Astrup (2011) and Bozorgirad et al. (2013). A number of research studies also used geographic information systems (GIS) to find out a suitable location for solid waste disposal (Sener et al. 2011; Yesilnacara et al. 2012; Gorsevski et al. 2012). However, the available information for solid waste conversion facility site selection is not comprehensive. Furthermore, although some location-specific and technology-specific waste-to-energy (WTE) techno-economic studies have been conducted (Lemea et al. 2014; Bonk et al. 2015), there is no techno-economic study on solid waste utilization that considers the spatial variation of solid waste, uses real road networks, and compares waste conversion technologies for a wide range of waste availabilities.

There is a need to develop a decision-making model to help small counties/towns/municipalities decide whether to dispose of waste at out-of-county or town landfills, use waste in a waste conversion facility, or make their own landfills and dispose of their waste there. Each option has a set of economic and technical parameters and needs to be evaluated. The overall objective of this work is to develop a comprehensive decision-making model to help municipalities make informed decisions on the disposal and use of their waste. The specific objectives are to:

- Develop a framework and conduct a site selection by spatial analysis of waste availability and considering environmental parameters
- Develop a decision-making model based on economic, environmental, and other parameters to select optimal waste disposal
- Calculate transportation cost using a real road networks incorporating GIS and other attributes (road speed limits, direction of traffic, etc.)
- Determine the optimum size and location of an MSW processing facility for a particular municipality
- Compare nine different waste conversion technologies over a wide range of waste availabilities to provide a clear idea about the cheapest technology for a certain amount of waste availability
- Conduct a specific case study on Alberta's Parkland County to find out the optimal waste disposal option for the county.

2. Methodology

The geographic information system (GIS) software ArcGIS 10 (ESRI, 2015) and its geodatabase were used to find suitable locations for a waste conversion facility based on environmental, social, and economic factors. Then, a user-friendly data-intensive model called the **FUN**damental E**N**gineering Principl**E**s-based Mode**L** for Estimation of **Cost** of Energy and Fuels from **MSW** (FUNNEL-Cost-MSW) was developed. This model can compare various waste conversion technologies and landfilling approaches. The current version of FUNNEL-Cost-MSW calculates the gate fees (the payment that the waste conversion facilities take per tonne of waste received) and internal rate of return (IRR - the interest disbursed or earned on the unrecovered balance such that the net present value of the initial payment is zero) for nine waste management scenarios and helps the user to understand and compare the economic feasibility of every scenario. There are some other considerations that affect waste management decision making, such as the remaining landfill life, available spaces for future landfills, and current rules and regulations. Nevertheless, comparison of different waste management scenarios in terms of economic assessment is considerably valuable in waste management decision making.

2.1. Site selection

The suitable and optimal location of a waste conversion facility depends on some environmental, social, and economic factors as well as waste availability. In this study, site selection was performed in two stages through an exclusion analysis and preference analysis (Sultana and Kumar, 2012). The exclusion analysis screens out unsuitable lands from the study area based on social and environmental factors as shown on Table 1. For every 12 constraints stated in Table 1, a buffer zone was created and the areas inside and outside the buffer zones were assigned value of "0" and "1", respectively. Accordingly, a binary map was generated for every constraint. A final constraint map was developed by multiplying all the binary values from whole the maps. Figure 1 shows an example of final constraint maps.

Figure 1: Example of final constraint map

Table 1: Identified constraints and corresponding buffer zones

Preference analysis was performed to find the relative preference of different regions within the study area. Eight factors were considered to find the most preferable sites for a waste conversion facility building. These factors are as follows:

i) Waste availability
ii) Urban area
iii) Water availability
iv) Roads
v) Transmission lines
vi) Power substations
vii) Land cover and
viii) Slope

These eight factors have been selected based on literature review and experts working in the field (Ma et al., 2005; Page and Pate, 2013; Sultana and Kumar, 2012; Tavares et al., 2011). The weights of the preference factors were calculated using the analytic hierarchy process (AHP) (Saaty, 2002). Using the AHP, we compared the preference factors with each other and assigned each factor a value on a 9-point scale. The weight of each factor was calculated using these assigned values. The AHP methodology is explained in detail in the supplementary materials.

Multiple buffer zones were created around each preference factor, and scores (on a scale of 0 to 10) were assigned to the buffer zones depending on their distance from the corresponding factor and afterwards multiplied by the corresponding weights to calculate the relative preference of the corresponding region of the study area. In this study, places with a suitability index (a value that indicates how suitable each location is on the map, taking into account the criteria entered into the model) of 7, 8, 9, and 10 were considered suitable sites for a waste conversion facility. Figure 2 shows an overview of the methodology of this study.

Figure 2: Methodology for waste management facility site selection and development of FUNNEL-Cost-MSW

After determining the candidate sites, the final facility location can be chosen by one of the following two options:

i) Location-allocation analysis (ArcGIS Resource Center, 2012) with ArcGIS can be done using the actual road network. Location-allocation analysis was done in this study to locate the facility/facilities in such a way that waste supply from the transfer stations to the facility/facilities has the lowest transportation cost. For a location-allocation analysis, road networks, candidate facility site locations, and transfer station locations are needed as input. In this study, a “minimize impedance (P-median)” network analysis was performed in order to conduct a location-allocation analysis. For a “minimize impedance (P-median)” analysis, facilities are located such that the transportation cost between waste supply points and facilities is minimized (ArcGIS Resource Center, 2012). This approach uses ArcGIS and gives a more detailed and accurate result (since it uses actual longitude and latitude), but since it uses ArcGIS, this approach cannot be used by the county planners if they do not have ArcGIS in their system.

ii) A spreadsheet-based model was used to determine the actual driving distance travelled from the transfer station to the candidate facility sites. This custom function in the spreadsheet model uses the Google Maps Application Programming Interface (API - a set of routines, protocols, and tools for building software applications [Google, 2015]) to calculate the distance. To find the distances between the transfer stations and candidate facility sites, the address of each location is needed. Once the addresses are entered, the model shows the candidate site with shortest total travel distance as the chosen facility site. This approach can be used by the county planners easily if they have Microsoft Excel and an Internet connection, but since this approach might be used without exact longitude and latitude, the result might not be as accurate as the "Location-allocation analysis" approach.

2.2. Transportation cost calculation

Waste collection and transportation cost can be divided into three segments:

i) Collection cost from residences, industries, and institutions

ii) Waste transportation cost from transfer stations to waste conversion facilities

iii) Ash transportation cost from a waste conversion facility to a landfill

In FUNNEL-Cost-MSW, collection cost can be input either in \$/t or total collection cost (cumulative \$) as chosen by the user. Waste transportation cost from transfer stations to waste conversion facilities and ash transportation cost from waste conversion facility to landfill were calculated using the actual road network using ArcGIS and Google maps. The truck transportation cost consists of two components. The first is the fixed cost of loading/unloading (\$/t) and does not change with the travel distance. The second component is the distance variable cost (\$/t/km) consisting driver cost, fuel cost, etc., and depends on the transport distance. The total transportation cost was calculated by adding the fixed cost and the distance variable cost.

2.3. MSW conversion technology-based scenarios

The model, FUNNEL-Cost-MSW, compares nine MSW conversion technology-scenarios, as shown in Table 2.

Table 2: MSW conversion technology-based scenarios

It was assumed that an existing landfill was used for both the disposal of the remaining waste (waste left after being treated at the facilities) and the ash left following thermal or biological treatment. These scenarios are discussed further in subsequent sections.

2.3.1. Scenario 1: Gasification (producing biofuel)

Gasification is a thermo-chemical partial oxidation process that converts organic or fossil fuel based carbonaceous materials into carbon monoxide, hydrogen, and methane by reacting the material at high temperatures (>700 °C) with a controlled amount of oxygen and/or steam (Luque and Speight, 2015; Yang and Chen, 2015). Biofuel (e.g., methanol, ethanol) can be produced from such synthetic gas through reactions such as methyl carbonylation and hydrogenolysis (Jacobs Consultancy, 2013).

The use of gasification to produce syngas and biofuel has been investigated by several researchers. For instance, Yang and Chen (2015) studied the gasification of biomass to produce synthetic liquid fuel production and focussed on the development of biomass gasification techniques to reduce tar and produce high purity hydrogen, and Luque and Speight (2015) described the application of biomass gasification for power generation and synthetic fuel production. In this study, gasification of MSW followed by the catalytic transformation of syngas to ethanol has been considered. Similar technology is currently being used by Enerkem Co. (Enerkem, 2015; Jacobs Consultancy, 2013). Enerkem made its first commercial start-up in 2013 and has been able to produce biofuel in its pilot plant.

Here it was assumed that solid waste is transported from transfer stations to a waste sorting facility. The waste is sorted and the waste suitable for thermal treatment goes to a gasification facility and the rest goes to a landfill. The ash collected after gasification is also transported to landfill. The waste suitable for thermal treatment goes through gasification and is converted to ethanol. The biofuel production rate and the GHG reduction rate (CO_2-eq saved by not landfilling waste) was assumed to be 380 litres/BDT (Arena et al., 2015; Jacobs Consultancy, 2013) and 2 tonnes of CO_2-eq/tonnes of MSW (Chornet, E., 2012; Nguyen et al., 2007; Sultana and Li, 2014;

Zaman, 2010). This study did not include a thorough calculation of GHG emissions (life cycle assessment), and a separate comprehensive LCA for the different pathways needs to be done. .

2.3.2. Scenario 2: Gasification (producing electricity)

Gasification technology can be used to produce electricity as well. Many studies have been conducted on generating electrical energy from gasified biomass. For instance, Pereira et al. (2012) presented a number of latest gasification technologies available for biomass gasification for producing electricity and Yassin et al. (2009) studied the technical and economic performance of fluidized bed gasification processes to produce energy from waste. Yassin et al. (2009) reported on the implication of fluidized bed gasifier combined with either of gas engine, combined cycle gas turbine or steam turbine in terms of costs and efficiencies and found fluidized bed gasifier combined with combined cycle gas turbine as the most attractive option.

In this study, a fluidized bed gasifier coupled with a combined cycle gas turbine (CCGT) was considered to produce electric energy. The electricity production rate and the GHG reduction rate (CO_2-eq saved by not landfilling waste) was assumed to be 1800 kWh/BDT (Arena et al., 2015; Jacobs Consultancy, 2013) and 2 tonnes of CO_2-eq/tonnes of MSW (Fruergaard et al., 2009; Sultana and Li, 2014; Zaman, 2010). For electricity generation technology, this model only considered CCGT plants. This model uses a scale factor of 0.6 to scale up or down the capital and operating cost of the same technology. However, since this model provides the option of inserting new technologies or replacing technologies (if the user knows the capital cost, operating cost, and production rate of electricity), other technologies can be compared by the user with the remaining nine technologies.

2.3.3. Scenario 3: Anaerobic digestion

The biodegradable fraction of solid waste is a sizable portion of Alberta's total waste composition and therefore treatment of this waste has a significant part in an integrated solid waste management system. Anaerobic digestion is an attractive solution for biodegradable waste treatment. This technology is a collection of processes in which micro-organisms break down organic material in an enclosed vessel in the absence of oxygen (DeBruyn and Hilborn, 2007). Three principle products of anaerobic digestion are biogas, digestate, and water. Biogas consists primarily of methane and carbon dioxide, and can be combusted to produce heat and to run a generator producing electricity. Among several investigators, Mao et al.(2015) and Mata-Alvarez et al. (2000) have reviewed the research and industrial achievements of anaerobic digestion of organic solid wastes.

In this study, the Dranco process was considered for biodegradable waste treatment (OWS, 2015). The Dranco process is a high-solids, single-stage anaerobic digestion system. The biogas yield, electricity production rate, and GHG reduction rate (CO_2-eq saved by not landfilling waste) were assumed to be 181.4 m^3/tonne (Akbulut, 2012; Sultana and Li, 2014; Verma, 2002), 2.14 kWh/ m^3 (Akbulut, 2012; Sultana and Li, 2014), and 2 tonnes of CO_2-eq/tonnes of MSW (DiStefano and Belenky, 2009; Sultana and Li, 2014), respectively. Here, the input is entirely MSW throughput (after removing the recyclable portion).

2.3.4. Scenario 4: Composting

The biological decomposition of biodegradable materials under controlled and mainly aerobic conditions is known as composting. The sole product of the composting process is compost. Windrow composting is the most used composting method in Alberta (Government of Alberta, 2012) and is considered in this study. Ruggieri et al. (2009) and Emery et al. (2007) studied the environmental and economic modelling of composting process.

Capital cost and OPEX for composting were calculated here using Eqs. 1 and 2. These two equations were developed from the data available from the Government of Alberta (2010) and Ruggieri et al.(2009). Compost production rate and the GHG reduction rate were assumed to be 0.3 tonne/tonne of waste (Verma, 2002) and 0.63 tonnes of CO_2/ tonnes of MSW (Keystone Environmental, 2014).

$$\text{□□□□□□□□ □□□□}\ (\$) = (457.55 \times \text{□□}\ (\text{□□□□□□□□□}(\text{□□□□□□})) - 2742) \times 1000 \tag{1}$$

$$\text{□□□□}\ (\$/\text{□□□□}) = (41.831 \times \text{□□}\ (\text{□□□□□□□□□}(\text{□□□□□□})) - 234.72) \times 1000 \tag{2}$$

According to Sustainable Resources Development's (AESRD) regulations and composting facility standards in Alberta, facilities that compost more than 20,000 tonnes/year are regulated differently than those that compost less than 20,000 tonnes/year (Environmental Assurance, 2007) and there are different costs associated with each facility (Environmental Assurance, 2007). In this study, the maximum unit size of the composting facility was assumed to be 20,000 tonnes/year. For the capacities more than 20,000 tonnes/year, it was assumed that a new composting facility was built.

2.3.5. Scenario 5: New landfill

Landfills have been an integral part of waste management systems and the final destination of waste till now, since it is the simplest and cheapest option for many scenarios (Allen, 2001). Obersteiner et al.(2007) studied on life cycle assessment of landfilling based on empirical data. Sumathi et al. (2008) studied the siting of a new landfills through a multi-criteria decision-making analysis and a GIS. In this study, capital cost, OPEX, and post-closure cost for landfilling were calculated using Eqs. 3 to 5. These equations were developed using cost data available for landfills with different capacities from Municipal Solid Waste Options (2006), Government of Alberta (2012), Sultana and Li (2014), Zhang et al.(2011).

$$\text{Capital cost }(\$) = 875.51 \times \text{capacity (tonne)} + 6{,}000{,}000 \tag{3}$$

$$\begin{aligned} OPEX\left(\frac{\$}{tonne - yr}\right) &= 3\times 10^{-9}(capacity\ (tonne))^2 - 0.0003 \\ &\quad \times capacity\ (tonne) + 31.989 \end{aligned} \tag{4}$$

$$\begin{aligned} Post\ closure\ cost\left(\frac{\$}{tonne - yr}\right) &= 7\times 10^{-10}(capacity\ (tonne))^2 - 5\times 10^{-5} \\ &\quad \times capacity\ (tonne) + 2.2039 \end{aligned} \tag{5}$$

These cost data include site development, pre-development, operating, gas capturing cost, and post-closure cost. Here capital cost includes pre-development (site selection allowance, land acquisition allowance and approval allowance) and site development costs (site clearing and preparation, utilities allowances, site infrastructure allowances, cell excavation and base preparation, engineered leachate containment and collection system, leachate recirculate system, landfill gas collection and flaring system, cap system construction, environmental monitoring infrastructure allowances). OPEX includes administration and support staff, waste disposal operations, daily cover placement, leachate treatment, reporting. Post-closure cost includes post-closure staffing and administration cost, leachate treatment and maintenance allowance of the landfill.

2.3.6. Scenario 6-9: Integrated facilities

At integrated facilities, waste from transfer stations is sorted and distributed within the facility. Waste suitable for thermal treatment goes to a gasification facility, waste applicable to biological treatment goes to either an anaerobic digestion or a composting facility, and the remaining waste goes to the landfill. Waste unsuitable for either thermal or biological treatment goes to the landfill. Figures 3(a) and 3(b) show the flow charts showing the waste flow at an integrated facility.

Figure 3: (a) Flow of waste from transfer stations to an integrated gasification and anaerobic digestion facility, (b) Flow of waste from transfer stations to an integrated gasification and composting facility

2.4. Decision model (FUNNEL-Cost-MSW)

A user-friendly model was developed to help make MSW management decisions. Initially, the user inputs waste availability and associated variables into the model. Since there are some counties/municipalities that do not have detailed data on how much waste will be useful for either thermal or biological treatment, this model offers three options at the waste availability input stage. The three options are:

i) Input only total waste: This option is suitable if the user does not know how much waste is suitable for thermal and biological treatment but knows the total available waste amount. For this option, the model assumes that 40% of the waste is suitable for thermal treatment, 40% for biological treatment, and 20% will be landfilled (TRI Environmental Consulting Inc., 2014).

ii) Input total waste with classification: This option is suitable if the user knows the total waste along with how much waste is suitable for thermal and biological treatment. The user does not need to know the detailed breakdown of available waste composition.

iii) Input total waste with detailed breakdown of waste composition: This option is suitable if the user knows the detailed breakdown of the total available waste composition.

Waste suitable for thermal and biological treatment is considered to have, on average, 15% and 50% moisture content, respectively. In addition, an average ash content of 15% has been assumed for all the scenarios (Wilson et al., 2013). In addition to waste availability information, the model asks the user the following information:

a) Selling price of biofuel ($/liter)
b) Selling price of electricity cost ($/kWh)
c) Selling rate of compost ($/t)
d) Carbon credit/offset rate ($/t)
e) Existing landfill's tipping fee ($/t)
f) Incentives available (if any) for each scenario

Once this information is entered, the user can indicate whether or not the facility owner pays the transportation cost from the transfer station to the waste conversion facility to be included in the total cost.

For the first two scenarios (gasification to produce biofuel and gasification to produce electricity), only waste suitable for thermal treatment goes to the gasification facility. Waste with very high moisture content cannot be directly treated in a gasification facility and requires either pre-drying or diversion to some other waste management facility (e.g., biological treatment, landfill). Hence, the model provides the option of selecting the thermal or biological treatment of waste in standalone gasification facilities. Depending on the moisture content of the waste, biological treatment (which can handle high moisture content) or gasification (which requires low moisture content) can be selected. Default values of required moisture contents are available in the model for making the decision.

The amount of capital cost of the waste use facility is critical for its economic viability. The model input includes a database with the capital costs of the various waste conversion facilities. However, these can also be input by the user. The model also has the option of considering capital cost alternatives, if available. For each scenario, separate modules were developed that include a flow chart, assumptions, cost components, and revenue components. This model provides the option of choosing the revenue components (for example, consideration of the carbon credit). Revenue components available for each scenario are shown in Table 3. A default value for the CO_2 saved by diverting waste from landfills to other options has been assumed for each scenario. These default values can be changed by the user.

Table 3: Revenue components available for the nine scenarios

For each scenario except landfilling, it was assumed that a waste sorting facility was built close to the waste conversion facility. Economic factors of the sorting facility, together with the factors for the first three standalone scenarios, are shown in Table 4. Table 4 shows the data that were used in the case study. However, any other capital and operating costs associated with other waste management strategies can be input in this model and be compared with other technologies. For the other two scenarios, capital cost and operating expenditure (OPEX) were calculated using equations developed from empirical data. A 30-year project life was assumed for all the scenarios except for landfilling, which was assumed to have a 25-year lifetime. The project life was assumed according to Municipal Solid Waste Options (2006) and Sultana and Li (2014). The model provides two types of comparison: comparison of calculated gate fees with a specified IRR and comparison of IRRs with a specified gate fee. Both outputs can be obtained for all the nine scenarios.

All currency figures in this paper are expressed in USD and the base year is 2014 unless otherwise noted. Conversion between the Euro and USD was done at the rate of 1 Euro= USD 1.38 and conversion between Canadian and US$ was done at the rate of USD 1= CAD 1.09. Costs have been adjusted to the year 2014 using historical inflation rates (Bank of Canada, 2014). An inflation rate of 2% was assumed for 2015 and onward. In this paper, OPEX includes variable, fixed, and sustaining capital. Fixed OPEX is the OPEX that is independent of any increase or decrease in production. Variable OPEX increases or decreases as the production changes. Sustaining capital is the expenditure to sustain/maintain an existing asset. This techno-economic assessment does not include other financial components such as debt/equity financing, depreciation, taxes etc.

Table 4: Economic parameters of various facilities

3. Case Study: Parkland County

There is a considerable focus in various jurisdictions in Alberta and Canada on the use and disposal of MSW. Throughout Alberta (and other parts of Canada), municipalities focus variously on waste reduction at source, collection services, waste diversion from landfill, reuse, recycling and composting of diverted waste, and recovery and generation of energy from residual waste. Alberta has 17 cities, 108 towns, 74 rural municipalities, and 64 municipal and other districts. Alberta's municipalities dispose their MSW at around 166 landfills (Page and Pate, 2013). Though the City of Edmonton's public landfill began with a capacity for 13.2 million tonnes of waste in 1975, the city's landfill has been rapidly filling; so the city decided to divert as much waste as possible (Edmonton Sun, 2013).

In 2011, Parkland County had a population of 30,568 (Statistics Canada*,* 2011). Currently the county generates approximately 15,098 tonnes of waste per year (Sultana and Li, 2014) and does not have any landfill sites; former sites were closed and converted into transfer stations. Currently, the county transports its waste to the Beaver Regional Landfill and has a contract rate of 62.50 $/t with the Beaver Regional Waste Management Commission (Stantec, Integrated waste management plan, 2010). This rate provides for disposal at 26 $/t and hauling at $36.50/tonne (Stantec, Integrated waste management plan, 2010). Figure 4(a) shows Parkland County's current waste transportation system. As shown in Fig. 4(a), Parkland County has six existing transfer stations and waste is currently transported from these stations to the Beaver Regional Landfill. Building a waste conversion facility to treat both the county's and part of the neighboring county's waste could help Parkland County move toward a sustainable waste management system. Waste availability in Parkland County and its neighboring counties is shown on Table 5.

Figure 4: (a) Parkland County's current waste transportation scenario, (b) Identified facility locations within Parkland County, (c) Chosen facility location and waste transportation scenario for up to 39,598 tonne/year waste availability, (d) Chosen facility location and waste transportation scenario for waste availability of more than 39,598 tonne/year, (e) Transportation of ash and unsuitable waste from facility to landfill

Table 5: Waste availability in Parkland and surrounding counties (Sultana and Li, 2014)

3.1. Site selection and transportation cost calculation

Exclusion and preference analyses were conducted and municipal zoning data from Parkland County were used to determine candidate sites. For exclusion and preference analyses, 12 exclusion criteria and 8 preference factors were selected based on environmental and social considerations for Alberta. These analyses are described in detail in the methodology section. In the preference analysis, the AHP was used to assign weights to the preference factors. The values assigned to each factor after pairwise comparison and weights of these factors are shown in Table 6.

Figure 4(b) shows the four candidate facility locations within Parkland County as identified by this study.

After exclusion and preference analyses were done and municipal zoning was considered, a facility location was chosen based on a location-allocation analysis. Figure 4(c) shows the chosen facility location and selected transportation system for up to 39,598 tonne/year waste. This capacity is the sum of the waste available at Parkland County, Spruce Grove, and Stony Plain.

Table 6: Pairwise comparison matrix and weights of preference factors

Typical truck loading and unloading cost was considered to be 5.45 \$/t (Kumar et al., 2003; Chornet, 2012) and the variable cost (related to distance traveled) was considered to be 0.2 \$/t-km (Chornet, 2012). The average truck size considered in this study is a 6.5 tonne/load (Sultana and Li, 2014).

Travel distance was taken as the distance from the existing six transfer stations in Parkland County, Spruce Grove, and Stony Plain to the chosen waste conversion facility location. The distance travelled was calculated using the actual road network provided through ArcGIS. As shown in Fig. 5, transportation costs increase as available waste increases. Equation (6) was developed using the correlation shown in Fig. 5 and was used to calculate the transportation cost corresponding to the input waste availability for this case study.

$$\begin{aligned} Transportation\ cost\ (\$) \\ = 0.5335 \times Waste\ availability\ (tonne)^{1.2966} \end{aligned} \tag{6}$$

Figure 5: Correlation between transportation cost and waste availability of less than 39,598 tonne/year

Since only 39,598 tonnes of waste are available per annum within Parkland County, Spruce Grove, and Stony Plain, additional adjoining counties are taken into consideration to increase waste. Among the surrounding counties, Leduc's landfill has the lowest remaining life (around 6-14 years) (Chomlak, 2013). Therefore, for waste availability greater than 39,598 tonne/year, another correlation of transportation cost with plant capacity was developed, one that includes the waste available from Leduc. Figure 4(d) shows the transfer stations and facility location when Leduc's transfer stations are taken into account.

Figure 6 shows the correlation of transportation cost and plant capacity. Equation (7) was developed using the correlation shown in Fig. 6 and was used for this case study when the waste availability was more than 39,598 tonne/year. However, though the two curves of Figs. 5 and 6 seem to be linear, they should not be so, since the transfer stations are not equally distant from the facility. Moreover, the fitted curves have a higher R^2 value than the linear ones.

$$\text{[illegible] [illegible]}\ (\$) = 4.0695 \times \text{[illegible] [illegible]}\ (\text{[illegible]})^{1.1221} \qquad (7)$$

Figure 6: Correlation between transportation cost and waste availability for capacities more than 39,598 tonne/year

After treating the waste, ash and the remaining unsuitable waste are landfilled (see Fig.4(e)). For this case study, ash and unsuitable waste were considered to be landfilled at the Beaver Regional Landfill (currently used by Parkland County [Stantec, 2010]).

Since for this case study the chosen facility location does not change when the waste availability goes above 39,598 tonne/year, the correlation between ash and unsuitable waste transportation cost and waste availability remains the same. Figure 7 shows the correlation between ash and unsuitable waste transportation cost and waste availability. This equation was developed using the correlation (showed in Fig. 7) and was used for this case study to calculate ash and unsuitable waste transportation cost.

$$\text{[illegible] [illegible] [illegible] [illegible] [illegible] [illegible]}\ (\$) = 35.565 \times \text{[illegible] [illegible]}\ (\text{[illegible]}) \qquad (8)$$

Figure 7: Correlation between ash and unsuitable waste transportation cost and waste availability

3.2. Economic comparison of scenarios

The key input variables considered in the model are the amount of waste available, selling rate of biofuel, selling rate of electricity, selling rate of compost, and carbon credit value. Based on these variables, the model estimates the gate fee and IRR. In this section, comparison of gate fees and comparison of IRRs are discussed in 3.2.1 and 3.2.2, respectively. These comparisons are based on the values listed in Table 7.

Table 7: Input data considered for economic comparison of various scenarios for the case study

Though there is an option in the model to input waste availability for different waste management strategies, to simplify scenario comparison in this section, it was assumed that 40%, 40%, and 20% of the available waste were directed to thermal treatment, biological treatment, and landfilling, respectively. This assumption has been made on waste charaterization studies carried out for some regions of Alberta (TRI Environmental Consulting Inc., 2014).

3.2.1. Comparison in terms of calculated gate fee

An IRR of 10% was assumed for comparative assessment of the scenarios. Figures 8(a) and 8(b) show the gate fees for different scenarios as the waste availability changes.

Generally, the term “gate fee” is used for the charge levied on the waste material coming into a waste management facility. In this paper, however, the term “gate fee” has been used as the charge levied by a waste conversion facility and the term “tipping fee” has been used as the charge levied by the landfills. Gate fee/tipping fee calculation formula used in this model:

$$\text{[illegible]} \left(\frac{\$}{\text{[illegible]}}\right) = \frac{\text{[illegible]}\ (\$) + \text{[illegible]}(\$) - \text{[illegible]}\ (\text{[illegible]}}{\text{[illegible]}\ (\text{[illegible]})} \qquad (9)$$

For landfilling, the tipping fee is the only revenue component considered (unless power from landfill gas is considered), whereas for waste conversion facilities, there are other revenue components (i.e., biofuel sale, electricity sale, etc.). With an increase in waste availability, total cost and all revenue components accordingly increase. As a result, the landfilling tipping fee increases as the landfill size increases and the gate fee (associated with other waste conversion scenarios) decreases with an increase in waste availability (for waste conversion scenarios, the total revenue increase rate is higher than the total cost increase because there are more revenue components, e.g. biofuel sale, electricity sale, available for waste conversion scenarios). As Figs. 8(a) and 8(b) show, landfilling tipping fees decrease with an increase in waste availability up to a certain capacity (around 50,000 tonne/year), due to the decrease in operating and post-closure costs (e.g., leachate treatment cost); beyond this capacity, tipping fees increase with an increase in waste availability due to increased operating and post-closure costs. This study used cost data generated through the study Municipal Solid Waste Options (2006). In this study, it was assumed that smaller sites are natural attenuation sites and rely on natural mechanisms to treat contaminants in the leachate; for larger sites, on the other hand, it was assumed that all of the generated leachate is contained, collected, and treated before being discharged to the environment. Due to the addition of leachate engineering and treatment cost, operating and post-closure costs are higher for larger landfills.

For a waste availability of 25,000-50,000 tonne/year, composting is the cheapest solution (77 to 86 $/t gate fee). This is mainly due to the higher capital cost of the other waste conversion and landfilling scenarios. When waste availability is low, scenarios with higher capital costs would come with higher gate fees. As waste availability increases, gate fees associated with waste conversion scenarios decrease. For a waste availability of 50,000-150,000 tonne/year, a gasification (producing electricity) facility integrated with composting becomes the cheapest solution with a gate fee of 42 to 77 $/t.

Moreover, calculated gate fees change with changes in capital investment. Capital investment is the investment made by the owner and decreases when incentives are available. The impact on gate fees with changes in capital investment for a waste availability of 100,000 tonne/year and a 10% IRR is shown in Figs. 8(c) and 8(d).

Figure 8: Comparison of gate fees for (a) standalone waste conversion scenarios with landfilling for different waste availability, (b) integrated waste conversion scenarios with landfilling for different waste availability, (c) standalone waste conversion scenarios with landfilling for different capital investment, and (d) integrated waste conversion scenarios with landfilling for different capital investment

Landfilling and integrated waste conversion facility’s gate fees decrease by 65% when capital investment decreases from 100% to 25%. On the other hand, gasification (producing biofuel) gate fees decrease from 116 to 71 $/t (38.8% decrease) when capital investment decreases from 100% to 25%. Similarly, gasification (producing electricity) gate fees decrease from 90 to 60 $/t (33.8% decrease) with a decrease in capital investment from 100% to 25%. The anaerobic digestion and composting gate fees decrease from 79 to 70 $/t (11.7% decrease) and from 72 to 69 $/t (4.16% decrease), respectively, with a decrease in capital investment from 100% to 25%. The relationship between gate fee and capital investment (%) can be shown as follows:

$$\begin{aligned}
&\square\square\square\square\ \square\square\square\ \square\square\ \square\square\square\square\square\square\square\square\ \square\square\square\ (\$/\square)\\
&\quad = (\square\square\square.\ \square\square\square\square\square\square\square.(\%) \times \square\square\square.\ \square\square\square\square\ (\$) + \square\square\square.\ \square\square\square\square(\$) + \square\square\square\square\square\square\square(\$)\\
&\quad - \square\square\square\square\square\square\square\square\ \square\square\square\square\square\square\square\square\square\square\square\square\ (\square\square\square\square\square\square\square\ \square\square\square\square\square\ \square\square\square)(\$))\\
&\quad /(\square\square\square\square\square\square\ \square\square\square\square\square\square\square\square\square\square\square\square\square\square\ (\square\square\square\square\square\square))
\end{aligned} \tag{10}$$

Hence, for a specific waste availability, the rate of change in gate fee due to changes in capital investment depends on the capital cost of the corresponding scenario. The higher the capital cost, the higher the rate of the change of the gate fee for a change in capital investment. Since integrated waste conversion scenarios have a higher capital cost than standalone waste conversion scenarios, integrated waste conversion scenarios have higher rate of change of gate fee for a capital investment change. With regard to landfilling, since the capital cost of a landfill with 100,000 tonne/year capacity is very high, it shows a higher rate of change of gate fee for capital investment change.

3.2.2. Comparison in terms of calculated IRR

For comparative analysis based on the IRR, a gate fee of 70 $/t has been assumed. The reason for the 70 $/tonne gate fee is because the City of Edmonton and Parkland County currently spend 70-75 $/tonne for disposing their waste. As Figures 9(a) and 9(b) show, for a gate fee of 70 $/t, integrated gasification (electricity) with composting has the highest IRRs (an IRR range from

8.87% to 13.17% for waste availability of 50,000-100,000 tonne/year). After this scenario, integrated gasification (producing electricity) with anaerobic digestion has the second highest IRR (an IRR range of 6.79% to 11.49% for waste availability of 50,000-150,000 tonne/year). Landfill has the lowest IRR for waste availabilities greater than 70,000 tonne/year for a 70 $/t tipping fee. Within a range of 50,000 to 70,000 tonne/year waste availability, gasification (producing biofuel) shows the lowest IRR.

Here, a higher IRR is an indication of higher growth rate of the scenario with a gate fee of 70 $/t against a comparatively lower total cost. Since the integrated waste conversion scenarios have higher earnings than the corresponding total cost, integrated waste conversion scenarios show higher IRRs. Moreover, since composting has a lower capital cost than the earning with 70 $/t gate fee, composting shows a higher IRR (comparatively higher than other standalone waste conversion scenarios) as well.

A high rate of change of IRR indicates higher growth rate of the scenario because of the higher selling rate of any revenue component (e.g., 0.67 $/liter for biofuel compared to 0.08 $/kWh for electricity) associated with that scenario. In this study, no revenue components were considered for landfilling, which resulted in a decreasing IRR trend with increases in the total cost due to increases in waste availability.

Moreover, calculated IRRs change with changes in capital investment. Changes in calculated IRRs with changes in capital investment are shown in Figures 9(c) and 9(d) for a waste availability of 100,000 tonne/year and gate fee of 70 $/t.

Figure 9: Comparison in terms of IRRs for (a) standalone waste conversion scenarios with landfilling, (b) integrated waste conversion scenarios with landfilling for different waste availability scenarios, (c) standalone waste conversion scenarios with landfilling and (d) integrated waste conversion scenarios with landfilling for different capital investment scenarios

As the capital investment decreases, the IRR increases. Landfilling shows the highest IRR increase (from -4.76% to 21.46%) for a decrease in capital investment from 100% to 25%, whereas anaerobic digestion and composting show the lowest IRR increases (from 5.28% to 9.97% and from 8.26% to 10.46%, respectively) for a decrease in capital investment from 100% to 25%.

As mentioned above, a higher IRR is an indication of higher growth rate compared to corresponding lower total cost. Since integrated waste conversion scenarios have higher earnings (because they have more revenue components) compared to their corresponding total cost, integrated waste conversion scenarios show higher IRRs than standalone waste conversion scenarios.

In addition, a higher IRR change indicates higher earnings because of the higher selling rate of any revenue component. Moreover, it has been mentioned earlier that scenarios with a higher capital cost show a higher rate of change in the total cost and hence a higher rate of change of IRR as the capital investment changes.

3.3. Sensitivity analysis

The sensitivity analysis presented in this section provides a better understanding of the key parameters' impacts on the overall cost. Here, impacts of the key parameters are shown on the calculated gate fees for each scenario. A sensitivity analysis for the gate fee was done for a constant IRR of 10% and for the base values of the key parameters shown in Table 7. The values of the selling rate of biofuel and waste availability were changed by ±40% and ±50%, respectively; the values of the selling rate of electricity, the selling rate of compost, carbon credit rate, and existing landfill's tipping fee were changed by ±20%. Figure 10 shows the impact of this change for all of the scenarios. The main reason behind performing the sensitivity analysis within the above mentioned ranges is the historical range of change of the parameters. The rate of electricity fluctuated over the last two years (from October 2012 to February 2015) between 0.6 $/kWh and 0.95 $/kWh (Alberta Government, 2015). And the rate of ethanol fluctuated over the last 10 years (January 2006 to September 2015) between 1.574 $/gal and 3.5 $/gal (Nasdaq, 2015). Changing the parameters' value by the above mentioned ranges of the base value helps us to do the sensitivity analysis with credible values of the parameters. These diagrams show us which parameter has greater impact.

Figure 10: Sensitivity analysis using a 10% IRR and the base values of the key parameters shown in Table 7 for (a) gasification (producing biofuel), (b) gasification (producing electricity), (c) anaerobic digestion, (d) composting, (e) gasification (producing biofuel) integrated with anaerobic digestion, (f) gasification (producing electricity) integrated with

anaerobic digestion, (g) gasification (producing biofuel) integrated with composting, and (h) gasification (producing electricity) integrated with composting

For the gasification (producing biofuel) scenario, the selling rate of the biofuel is the dominating factor. This is mainly due to the high conversion rate of biofuel (380 liters/BDT - Jacobs Consultancy, 2013). A 40% change in biofuel cost results in a gate fee change of around 29 $/t, whereas a 50% increase in waste availability decreases the gate fee by 20 $/t and a 50% decrease in waste availability increases the gate fee by 42 $/t.

For the gasification (producing electricity) scenario, waste availability and the selling rate of electricity are the most influential variables because of the high rate of change in waste availability (±50%) and the high conversion rate (1800 kWh/BDT). A 20% change in the selling rate of electricity changes the gate fee by around 8 $/t and a 50% change in the waste availability changes the gate fee by around 22 $/t.

For the anaerobic digestion scenario, waste availability and an existing landfill's tipping fee have more influence than other parameters. A 20% change in an existing landfill's tipping fee changes the gate fee by 3 $/t, whereas a 50% increase in waste availability decreases the gate fee by 5 $/t and a 50% decrease in waste availability increases the gate fee by 10 $/t.

For the composting scenario, a 20% change in an existing landfill's tipping fee and a 50% change in waste availability changes the gate fee by 3 $/t.

For gasification (biofuel) integrated with anaerobic digestion, the selling rate of biofuel and the waste availability are the most influential parameters; a 40% change in the selling rate of biofuel changes the by 29 $/t. A 50% increase in waste availability decreases the gate fee by 23 $/t and a 50% decrease in waste availability increases the gate fee by 51 $/t.

For the gasification (electricity) integrated with anaerobic digestion scenario, waste availability and the selling rate of electricity are the most influential variables. A 20% change in the selling rate of electricity changes the gate fee by 12 $/t. Waste availability is the second most influential parameter for this scenario. A 50% increase in waste availability decreases the gate fee by 14 $/t gate fee and a 50% decrease in waste availability increases the gate fee by 32 $/t.

For the gasification (biofuel) integrated with composting scenario, the selling rate of biofuel and waste availability are the most influential parameters; a 40% change in the selling rate of biofuel changes the gate fee by 29 \$/t. A 50% increase in waste availability decreases the gate fee by 20 \$/t, and a 50% decrease in waste availability increases the gate fee by 43 \$/t.

For the gasification (electricity) integrated with composting scenario, a 20% change in electricity cost changes the gate fee by 10 \$/t. Waste availability is the second most influencing parameter for this scenario. A 50% increase in waste availability decreases the gate fee by 25 \$/t, and a 50% decrease in waste availability increases the gate fee by 11 \$/t.

To summarize, waste availability is an influential factor for each scenario. Selling rates of biofuel and electricity are the dominating factors for gasification (producing biofuel) and gasification (producing electricity) scenarios, respectively. Waste availability and existing landfill tipping fee are the most influencing factors for anaerobic digestion and composting scenarios, respectively.

4. Conclusions

A suitable location for a facility was determined through a suitability analysis and a location-allocation analysis using ArcGIS. Then a model (FUNNEL-Cost-MSW) was developed that compares different waste management scenarios and recommends the best option based on waste availability and some cost specifications and cost parameters. The comprehensive FUNNEL-Cost-MSW model is a generic framework that can be used in any county or city. The model compared nine scenarios, including landfilling and composting, with respect to calculated gate fees and calculated IRRs. A case study was conducted on waste management in Parkland County in Alberta, Canada. In the case of Parkland County, it was found that for a 10% (IRR) and a waste availability of 25,000-50,000 tonne/year, composting is the cheapest solution (77 to 86 \$/t gate fee). For a waste availability of 50,000-150,000 tonne/year, on the other hand, a gasification (producing electricity) facility integrated with composting is the most economical solution with a gate fee of 77 to 42 \$/t. In the economical comparison of the nine waste management scenarios it was found that waste conversion scenarios become more economical with an increase in the capacity; landfilling becomes expensive as the capacity increases due to the higher post-closure and operating costs; and landfilling and integrated waste conversion scenarios are more sensitive to capital investment than the standalone scenarios. A sensitivity analysis was also performed to better understand the impact of key parameters on gate fees and it was found that waste availability is an influential factor in each scenario. Waste availability is an influential parameter for each scenario. Selling rates of biofuel and electricity are dominating factors for gasification (producing biofuel) and gasification (producing electricity) scenarios, respectively. This comprehensive decision-making FUNNEL-Cost-MSW model can be used for assessing the waste management options for different jurisdictions taking into account economic, social, and environmental factors.

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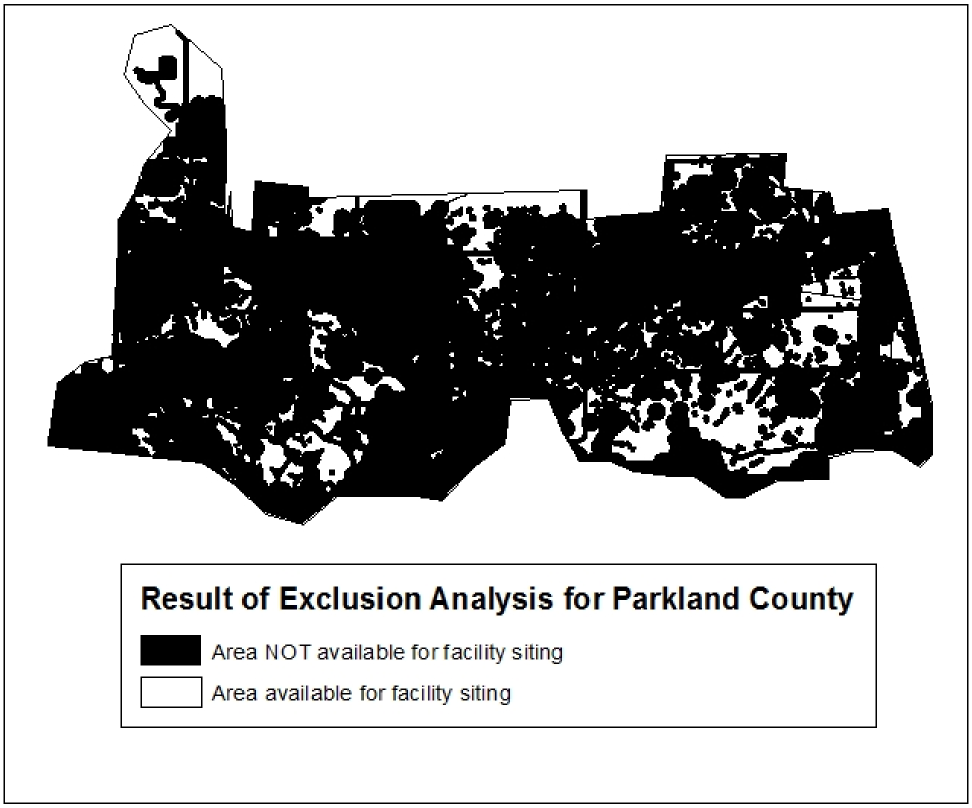


Figure 1: Example of final constraint map

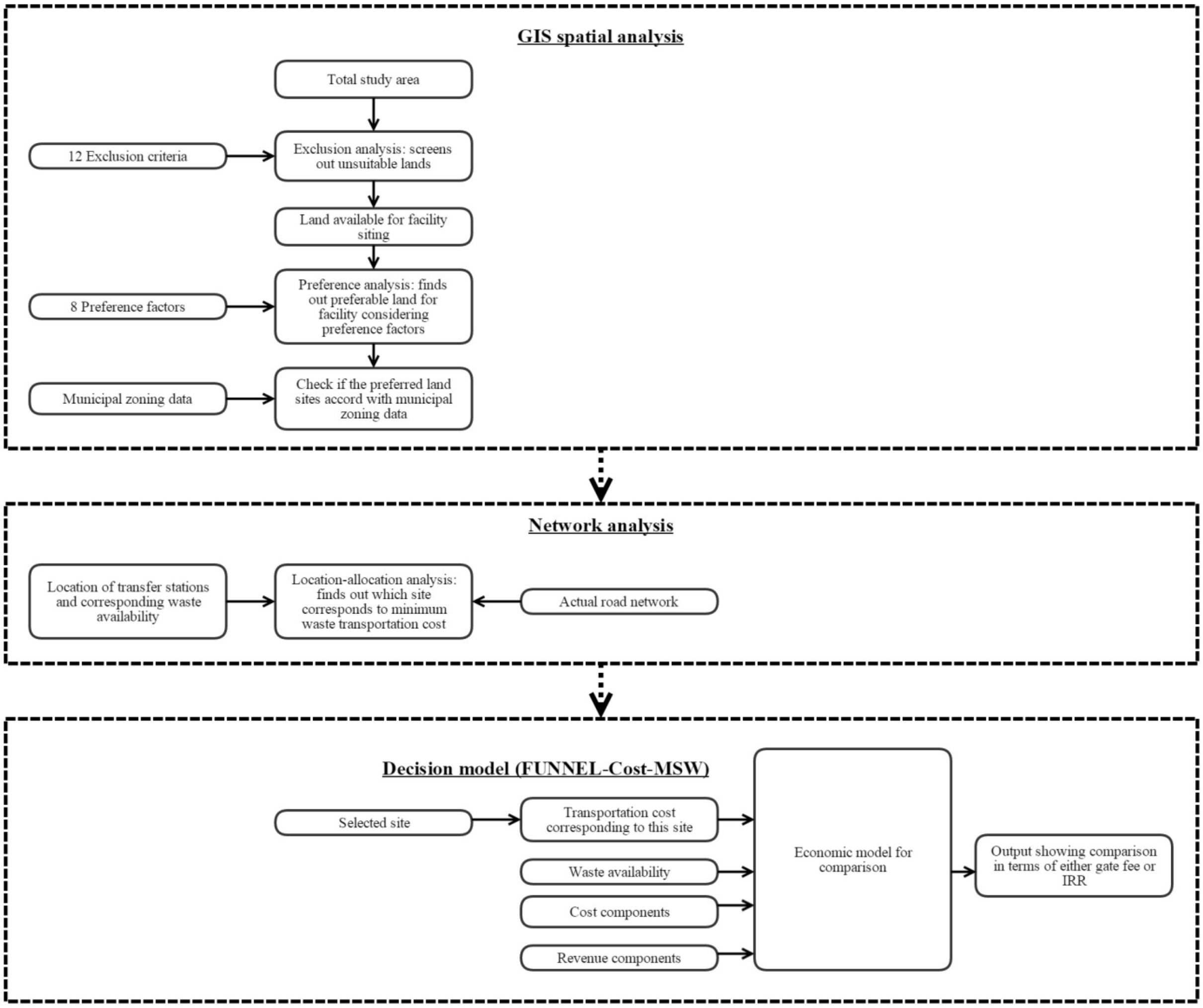


Figure 2: Methodology for waste management facility site selection and development of FUNNEL-Cost-MSW

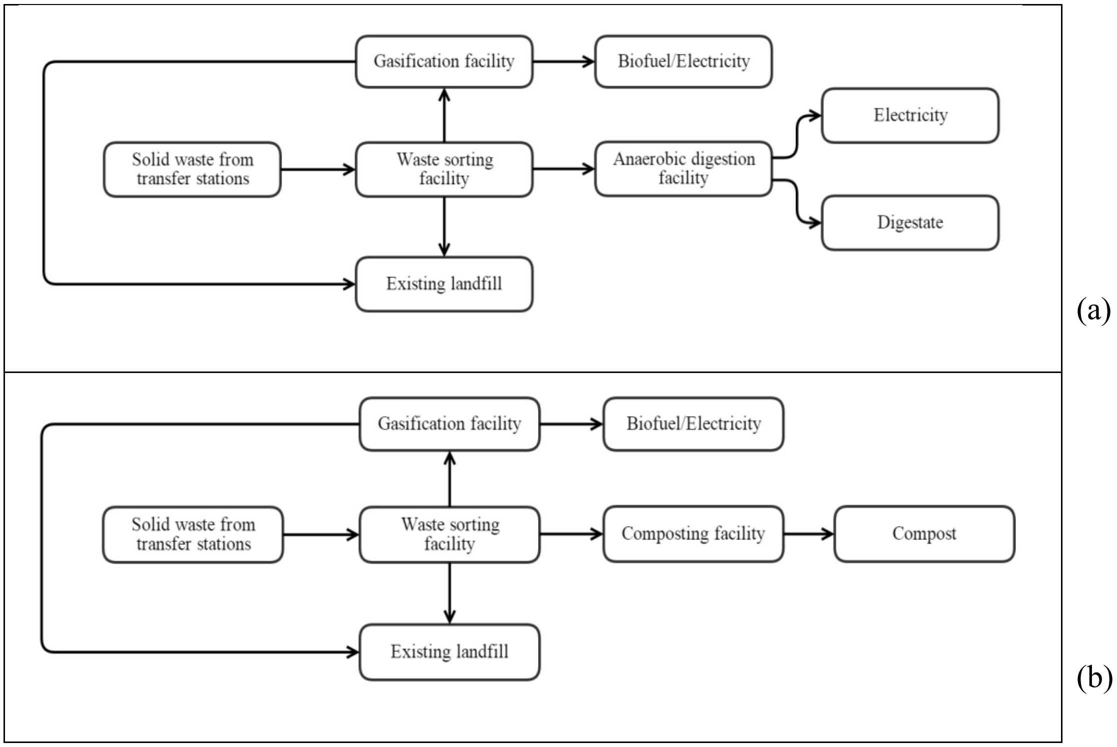


Figure 3: (a) Flow of waste from transfer stations to an integrated gasification and anaerobic digestion facility, (b) Flow of waste from transfer stations to an integrated gasification and composting facility

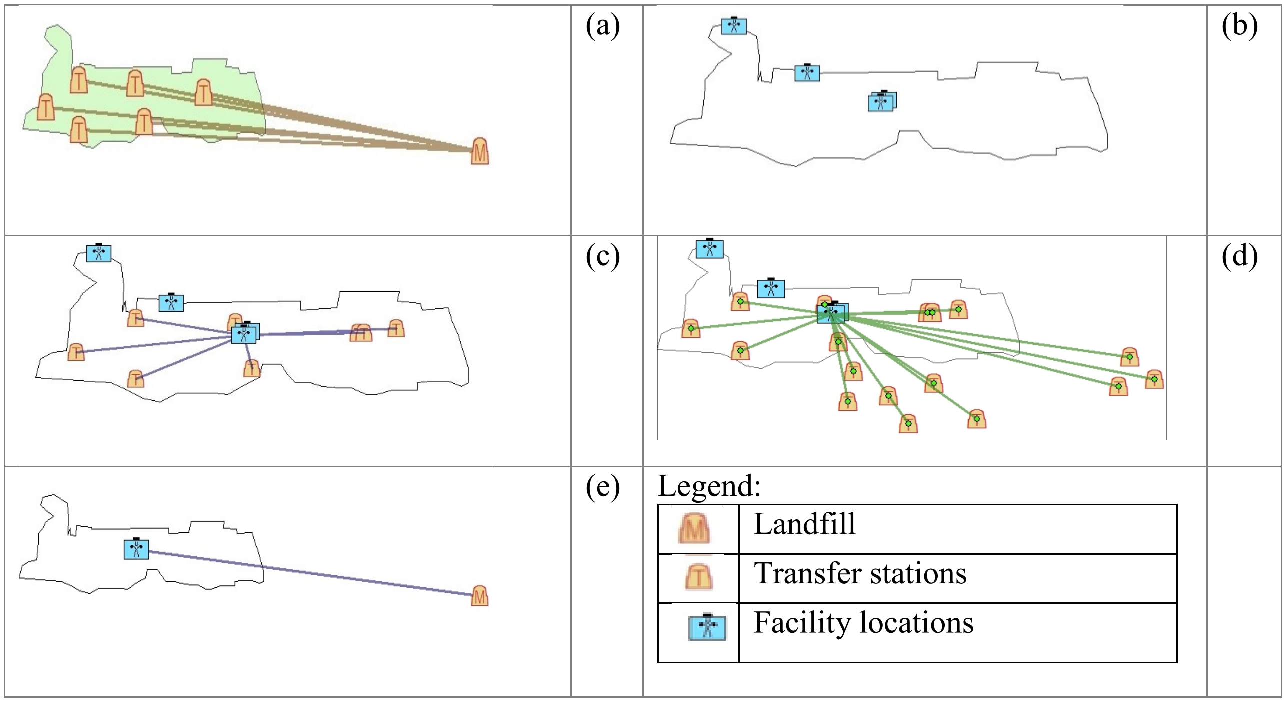


Figure 4: (a) Parkland County's current waste transportation scenario, (b) Identified facility locations within Parkland County, (c) Chosen facility location and waste transportation scenario for up to 39,598 tonne/year waste availability, (d) Chosen facility location and waste transportation scenario for waste availability of more than 39,598 tonne/year, (e) Transportation of ash and unsuitable waste from facility to landfill

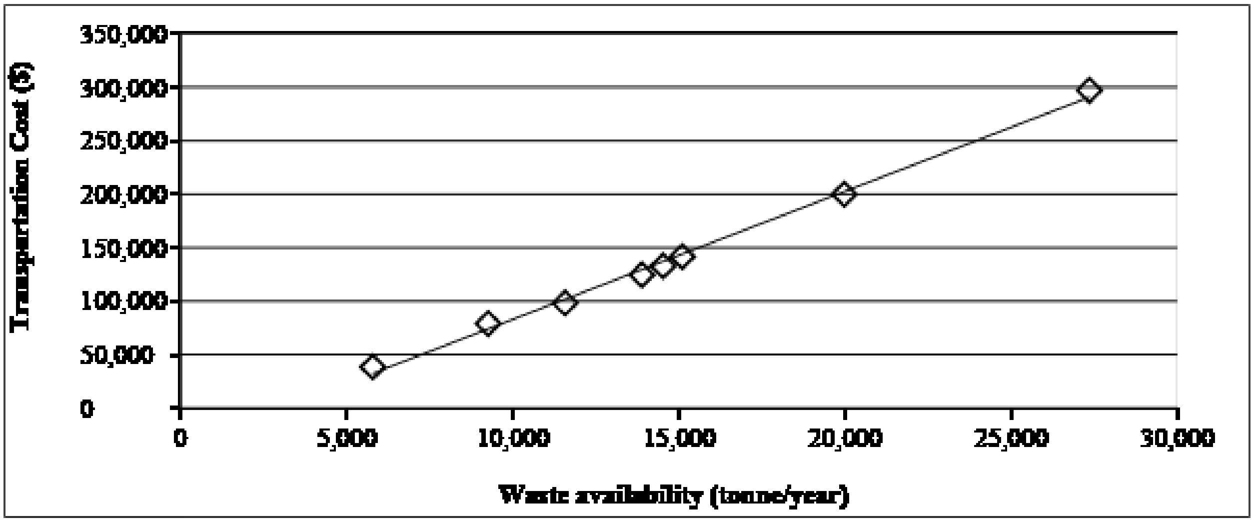


Figure 5: Correlation between transportation cost and waste availability of less than 39,598 tonne/year

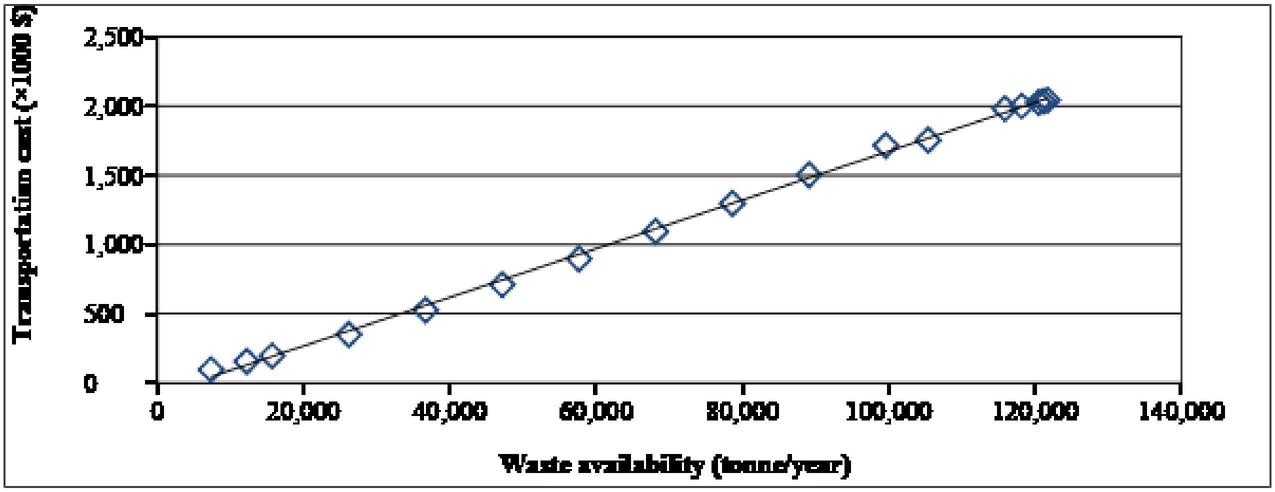


Figure 6: Correlation between transportation cost and waste availability for capacities more than 39,598 tonne/year

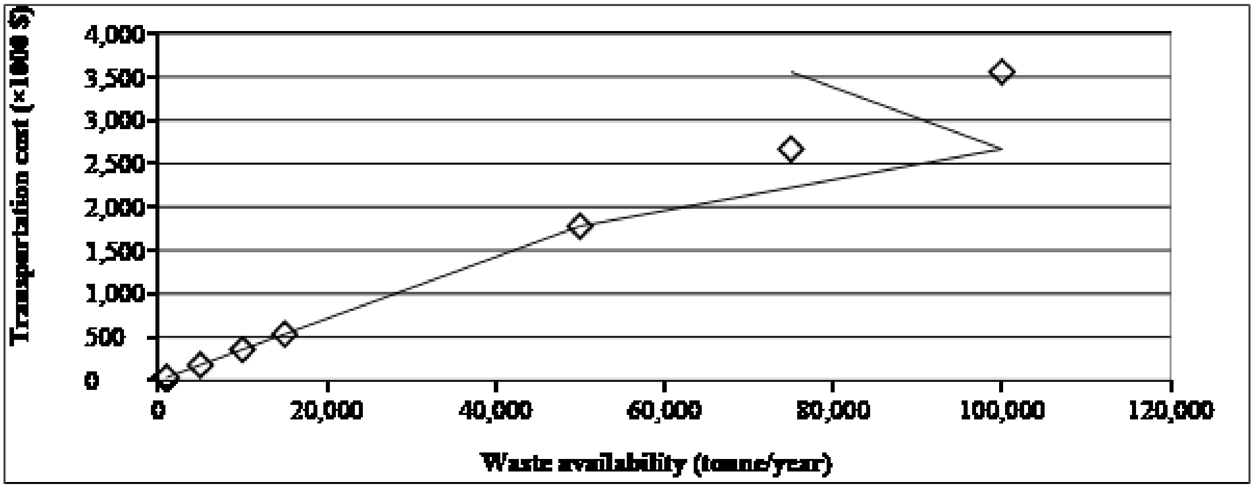


Figure 7: Correlation between ash and unsuitable waste transportation cost and waste availability

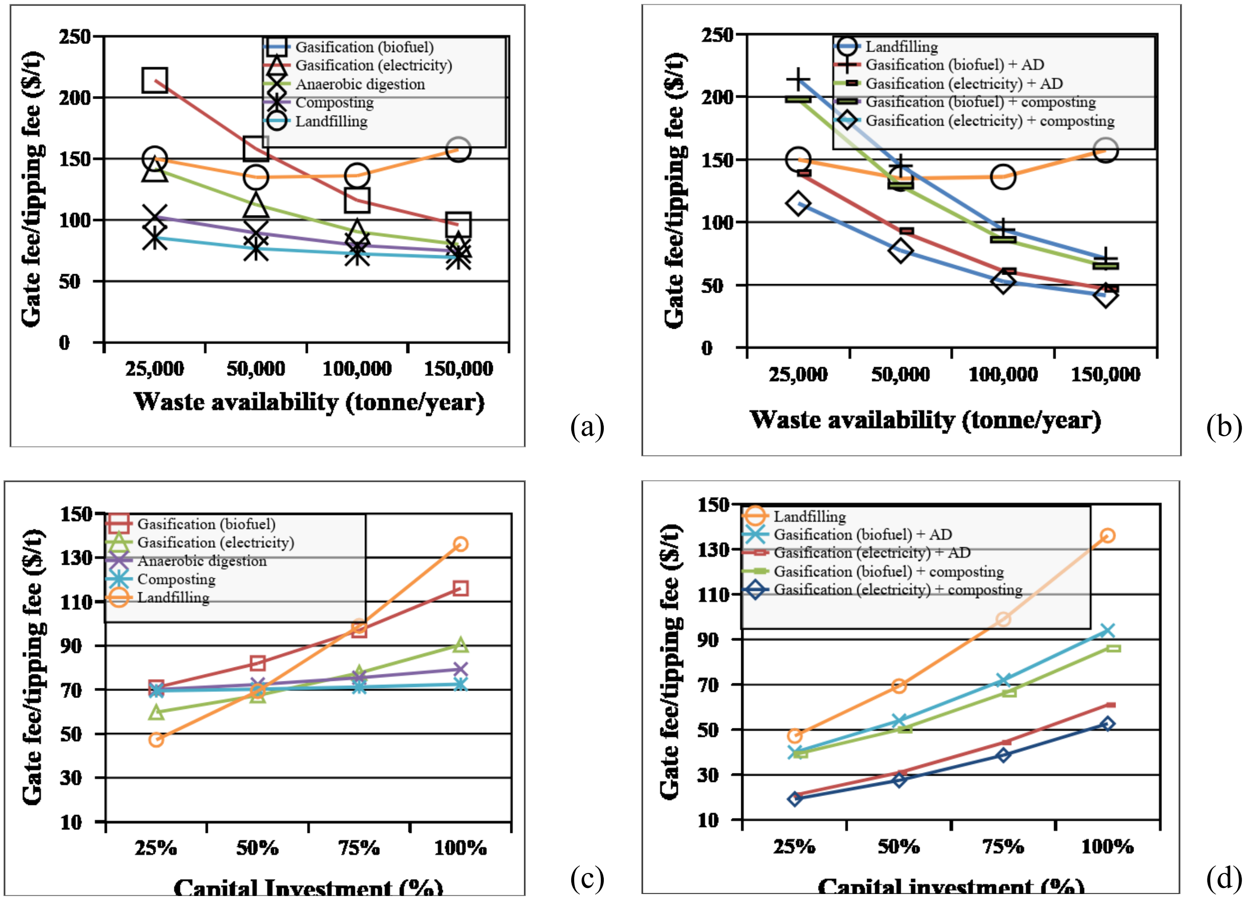


Figure 8: Comparison of gate fees for (a) standalone waste conversion scenarios with landfilling for different waste availability, (b) integrated waste conversion scenarios with landfilling for different waste availability, (c) standalone waste conversion scenarios with landfilling for different capital investment, and (d) integrated waste conversion scenarios with landfilling for different capital investment

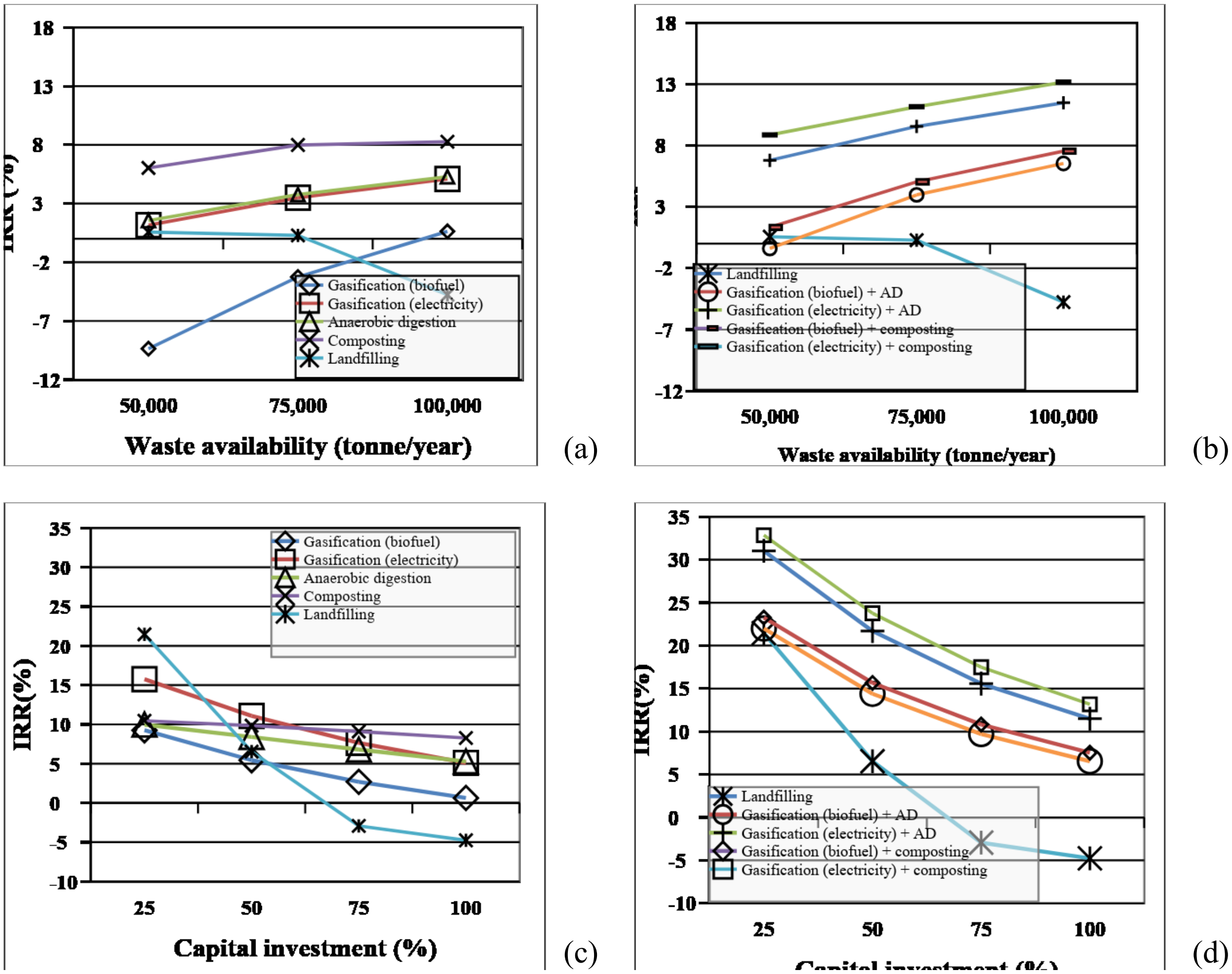
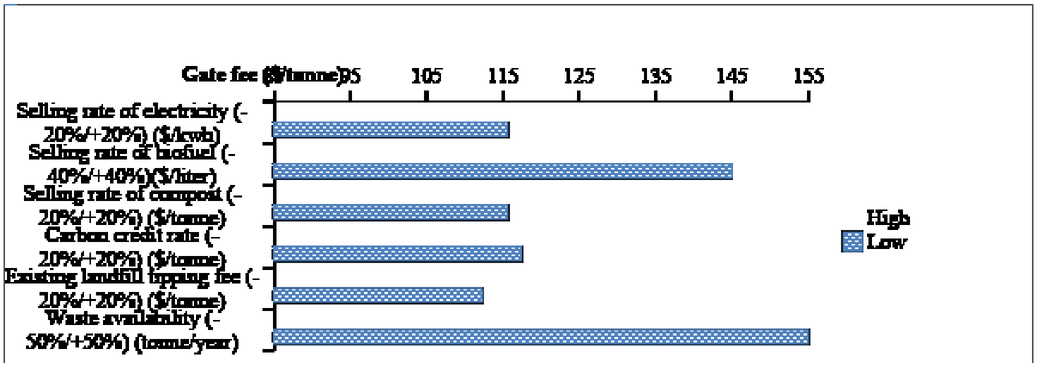
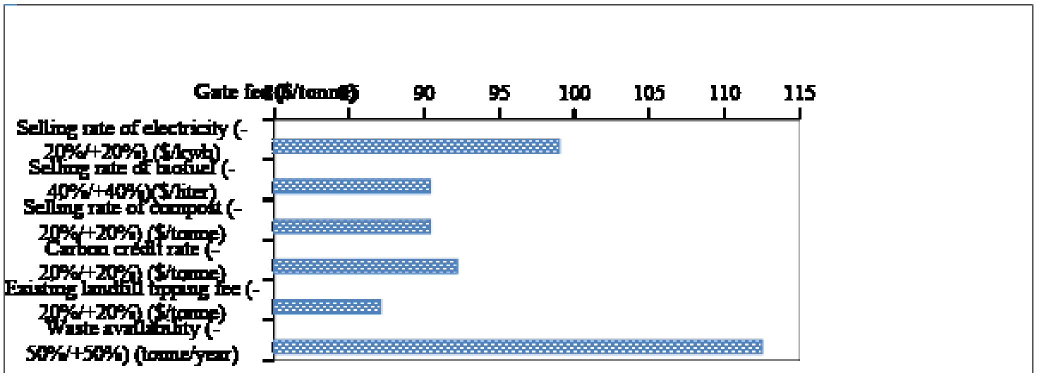


Figure 9: Comparison in terms of IRRs for (a) standalone waste conversion scenarios with landfilling, (b) integrated waste conversion scenarios with landfilling for different waste availability scenarios, (c) standalone waste conversion scenarios with landfilling and (d) integrated waste conversion scenarios with landfilling for different capital investment scenarios



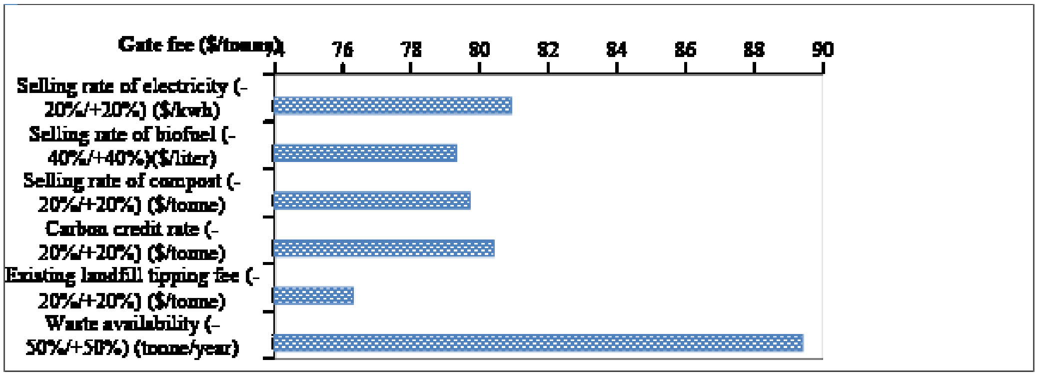
Gate fee ($/tonne)
95
105
115
125
135
145
155
Selling rate of electricity (-20%/+20%) ($/kwh)
Selling rate of biofuel (-40%/+40%)($/liter)
Selling rate of compost (-20%/+20%) ($/tonne)
Carbon credit rate (-20%/+20%) ($/tonne)
Existing landfill tipping fee (-20%/+20%) ($/tonne)
Waste availability (-50%/+50%) (tonne/year)
High
▨ Low

(a)



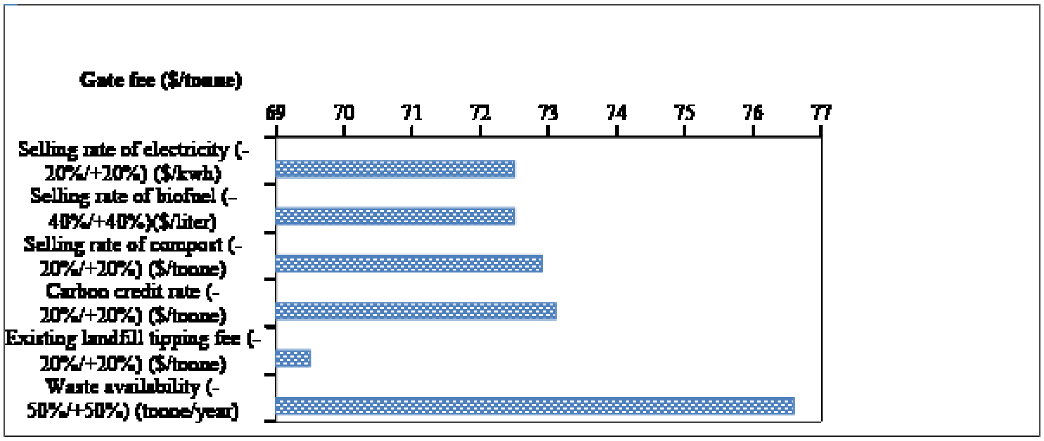
Gate fee ($/tonne)
85
90
95
100
105
110
115
Selling rate of electricity (-20%/+20%) ($/kwh)
Selling rate of biofuel (-40%/+40%)($/liter)
Selling rate of compost (-20%/+20%) ($/tonne)
Carbon credit rate (-20%/+20%) ($/tonne)
Existing landfill tipping fee (-20%/+20%) ($/tonne)
Waste availability (-50%/+50%) (tonne/year)

(b)



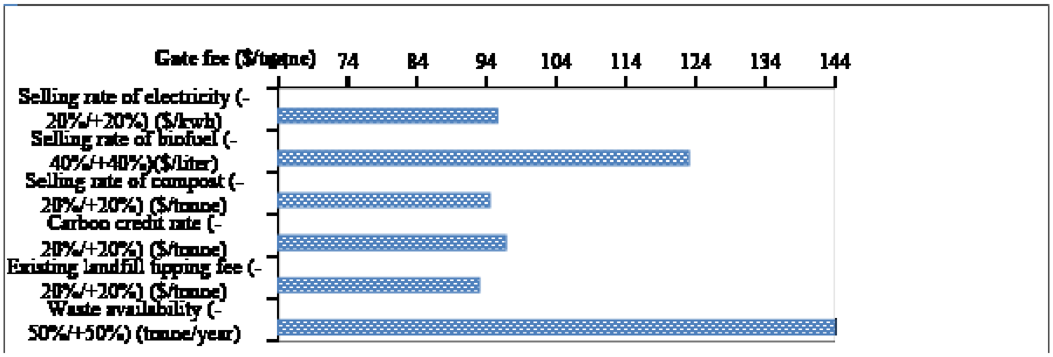
Gate fee ($/tonne)
74
76
78
80
82
84
86
88
90
Selling rate of electricity (-20%/+20%) ($/kwh)
Selling rate of biofuel (-40%/+40%)($/liter)
Selling rate of compost (-20%/+20%) ($/tonne)
Carbon credit rate (-20%/+20%) ($/tonne)
Existing landfill tipping fee (-20%/+20%) ($/tonne)
Waste availability (-50%/+50%) (tonne/year)

(c)

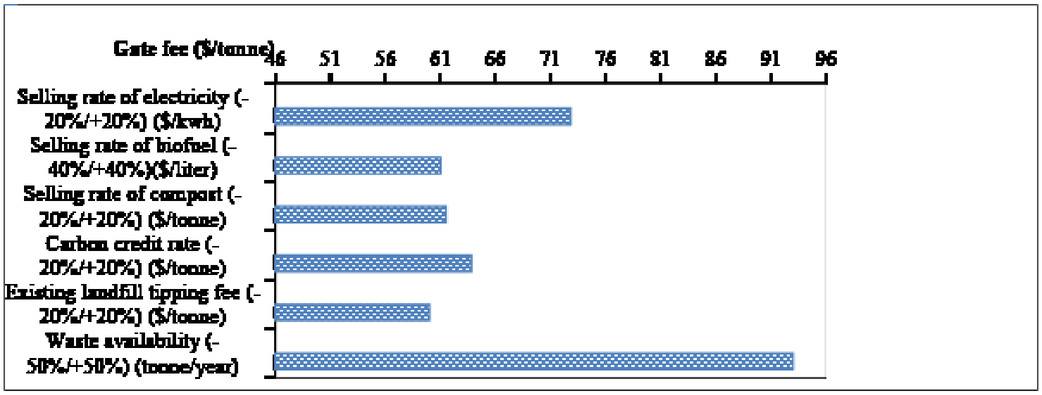


Gate fee ($/tonne)
69
70
71
72
73
74
75
76
77
Selling rate of electricity (-20%/+20%) ($/kwh)
Selling rate of biofuel (-40%/+40%)($/liter)
Selling rate of compost (-20%/+20%) ($/tonne)
Carbon credit rate (-20%/+20%) ($/tonne)
Existing landfill tipping fee (-20%/+20%) ($/tonne)
Waste availability (-50%/+50%) (tonne/year)

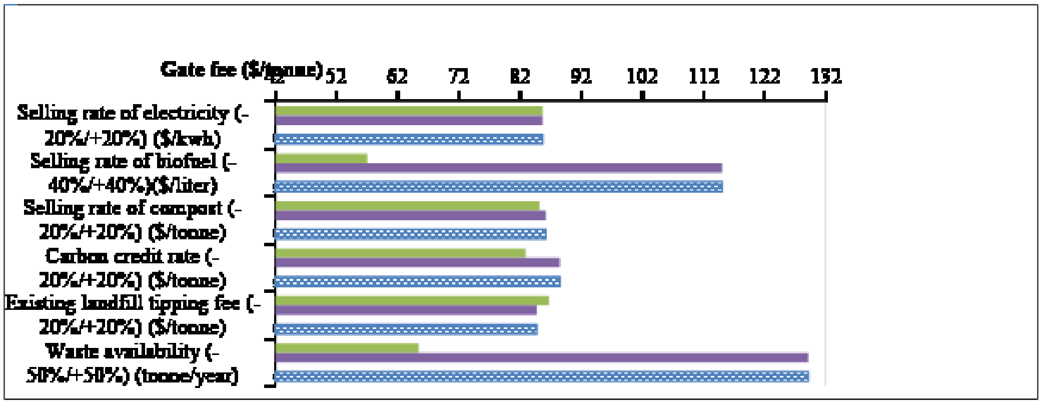
(d)


Gate fee ($/tonne)
74
84
94
104
114
124
134
144
Selling rate of electricity (-20%/+20%) ($/kwh)
Selling rate of biofuel (-40%/+40%)($/liter)
Selling rate of compost (-20%/+20%) ($/tonne)
Carbon credit rate (-20%/+20%) ($/tonne)
Existing landfill tipping fee (-20%/+20%) ($/tonne)
Waste availability (-50%/+50%) (tonne/year)

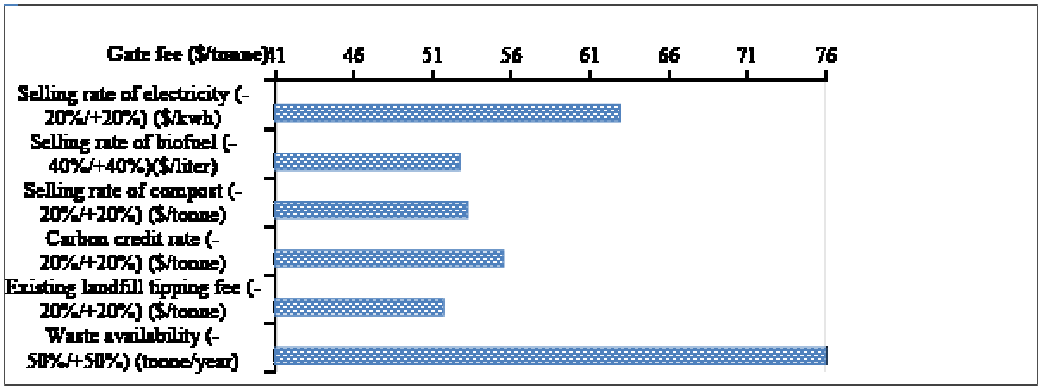
(e)


Gate fee ($/tonne)
46
51
56
61
66
71
76
81
86
91
96
Selling rate of electricity (-20%/+20%) ($/kwh)
Selling rate of biofuel (-40%/+40%)($/liter)
Selling rate of compost (-20%/+20%) ($/tonne)
Carbon credit rate (-20%/+20%) ($/tonne)
Existing landfill tipping fee (-20%/+20%) ($/tonne)
Waste availability (-50%/+50%) (tonne/year)

(f)


Gate fee ($/tonne)
42
52
62
72
82
92
102
112
122
132
Selling rate of electricity (-20%/+20%) ($/kwh)
Selling rate of biofuel (-40%/+40%)($/liter)
Selling rate of compost (-20%/+20%) ($/tonne)
Carbon credit rate (-20%/+20%) ($/tonne)
Existing landfill tipping fee (-20%/+20%) ($/tonne)
Waste availability (-50%/+50%) (tonne/year)

(g)


Gate fee ($/tonne)
41
46
51
56
61
66
71
76
Selling rate of electricity (-20%/+20%) ($/kwh)
Selling rate of biofuel (-40%/+40%)($/liter)
Selling rate of compost (-20%/+20%) ($/tonne)
Carbon credit rate (-20%/+20%) ($/tonne)
Existing landfill tipping fee (-20%/+20%) ($/tonne)
Waste availability (-50%/+50%) (tonne/year)

(h)

Figure 10: Sensitivity analysis using 10% IRR and using the base values of the key parameters shown in Table 7, for (a) gasification (producing biofuel), (b) gasification (producing electricity), (c) anaerobic digestion, (d) composting, (e) gasification (producing biofuel) integrated with anaerobic digestion, (f) gasification (producing electricity) integrated with anaerobic digestion, (g) gasification (producing biofuel) integrated with composting, and (h) gasification (producing electricity) integrated with composting

Table 1: Identified constraints and corresponding buffer zones

Criteria	Specifications	Source/ Reference
Rivers, lakes, and other water bodies	More than 300 m from water bodies	(Government of Alberta, 2010)
Rural and urban areas	More than 1 km from residential and urban areas	(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 from industrial and mining zones	(Sultana and Kumar, 2012)
Environmentally sensitive areas (ESA) (flood plains, conservation areas, habitat sites)	More than 1 km from ESAs	(Eskandari et al., 2012)
Natural gas pipelines	More than 100 m from natural gas pipelines	(Sultana and Kumar, 2012; Ma et al., 2005),
Park and recreational areas	More than 500 m from these sites	(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)

Table 2: MSW conversion technology-based scenarios

Scenario label	**Scenario name**	**Description of scenarios**
Scenario 1	Gasification (producing biofuel)	Production of biofuel (methanol) through MSW gasification
Scenario 2	Gasification (generating electricity)	Generation of electricity from syngas by MSW gasification
Scenario 3	Anaerobic digestion	Anaerobic digestion of MSW to produce electricity from biogas
Scenario 4	Composting	Production of compost from MSW
Scenario 5	Landfilling	Disposal of MSW to a landfill
Scenario 6	Gasification (producing biofuel) integrated with anaerobic digestion	Production of biofuel and electricity through MSW gasification and anaerobic digestion, respectively
Scenario 7	Gasification (producing electricity) integrated with anaerobic digestion	Production of electricity through MSW gasification and anaerobic digestion
Scenario 8	Gasification (producing biofuel) integrated with composting	Production of biofuel and compost through MSW gasification and composting, respectively
Scenario 9	Gasification (producing electricity) integrated with composting	Production of electricity and compost through MSW gasification and composting, respectively

Table 3: Revenue components available for the nine scenarios

Scenario	Biofuel sale	Electricity sale	Compost	Gate fee/ Tipping fee	Carbon credit	Incentives
Scenario 1	√			√	√	√
Scenario 2		√		√	√	√
Scenario 3		√	√	√	√	√
Scenario 4			√	√	√	√
Scenario 5				√		√
Scenario 6	√	√	√	√	√	√
Scenario 7		√	√	√	√	√
Scenario 8	√		√	√	√	√
Scenario 9		√	√	√	√	√

Table 4: Economic parameters of various facilities

	Capacity (base case)	Capital Cost	Operating Expenditure	Scale Factor	Reference
Sorting facility	53,571 (MSW/year)	$8 million	25 ($/t)	0.6	Sultana and Li (2014); Kumar et al. (2003); Yassin et al. (2009)
Gasification to produce biofuel	500,000 BDT/year	$263 million	0.35 ($/liter of biofuel produced)	0.6	Arena et al. (2015); Jacobs Consultancy (2013); Sultana and Li (2014)
Gasification to produce electricity	18,214 BDT/year	$25.5 million	1.525 million ($/year)	0.6	Sultana and Li (2014); Yassin et al. (2009)
Anaerobic digestion	15,000 BDT/year	$9.45 million	810,000 ($/year)	0.6	Murphy and McKeogh (2004); Sultana and Li (2014)

Table 5: Waste availability in Parkland and surrounding counties (Sultana and Li, 2014)

County name	Waste availability (tonne/year)
Parkland	15,098
Spruce Grove	14,750
Stony Plain	9,750
Leduc and Beaumont	21,172
St. Albert	27,524
Strathcona	45,694

Table 6: Pairwise comparison matrix and weights of preference factors

Preference factors	WA[1]	Urban	Water	Roads	Transmission	Substation	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	0.50	1.00	2.00	3	3	4	5	0.15
Roads	0.25	0.33	0.50	1.00	2	2	3	3	0.09
Transmission	0.20	0.25	0.33	0.50	1	1	2	2	0.06
Substation	0.14	0.25	0.33	0.50	1	1	2	2	0.06
Land cover	0.13	0.20	0.25	0.33	0.5	0.5	1	1	0.03
Slope	0.11	0.17	0.20	0.33	0.5	0.5	1	1	0.03

[1] WA= Waste availability

Table 7: Input data considered for economic comparison of various scenarios for the case study

Input variables	Values	References
Selling rate of biofuel ($/liter)	0.67	Nasdaq (2015)
Selling rate of electricity ($/kWh)	0.08	Alberta Government (2015)
Selling rate of compost ($/t)	30	Amyot (2005); Antler (2012); Government of Alberta (2012)
Carbon credit/offset rate ($/t of CO_2)	13	Partington (2013); Preferred Carbon Group (2011)
Existing landfill's tipping fee ($/t)	25	Sultana and Li (2014)
Subsidies available for scenarios ($)	-	User-defined
IRR (%)	10	User-defined

Supplementary materials

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 A1.

Table SP1: 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 $n \times n$ 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:

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

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.