ECONOMIC ANALYSIS FOR THERMAL TREATMENT OF WASTEPAPER IN SASKATCHEWAN

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ABSTRACT

Changing recycling markets and fluctuating market prices for wastepaper are increasing the financial risks for Saskatchewan municipalities and their waste disposal practices. Landfilling is generally considered the lowest cost alternative while recycling, although considered to be the right thing to do environmentally, can be cost prohibitive. The increasing demand for non-fossil fuel-based energy sources may present an opportunity for municipalities to economically generate heat and in some cases, power, through thermal treatment of wastepaper utilizing incineration with heat recovery or combined heat and power units. Barriers to the adoption are the upfront financial cost and lack of consolidated information required to perform a feasibility analysis. This thesis consolidates the information required for municipalities to conduct a first-pass feasibility analysis.

Supporting information and data was collected to provide: a summary of technology, referenced values for the availability of wastepaper, capital costs for construction of thermal treatment plants, and expected values for heat and power production and sales. This data is intended for use by municipalities to evaluate thermal treatment of wastepaper. To assist with the evaluation, a Decision Support Tool (DST) was then developed to provide an automated economic evaluation of thermal treatment plants operating on wastepaper based on inputs from the user (municipality) and from available literature.

Saskatoon, Swift Current, Outlook, and La Loche in Saskatchewan, Canada, were used as case studies for the evaluation of wastepaper thermal treatment in Saskatchewan. Saskatoon is the largest city in Saskatchewan with a population of approximately 250,000. Swift Current is the mid-point of the ten largest Saskatchewan municipalities, approximately 17,000. Outlook is the tenth largest municipality, approximately 2,300. La Loche, approximate population of 2,300 was selected to evaluate a Northern community. The selected municipalities also serve to evaluate a large population range within Saskatchewan with approximately an order of magnitude difference between each municipality. Using the developed DST for the case studies indicated that thermal treatment of wastepaper in the four locations has the potential to provide a disposal cost lower than recycling. In all cases, capital cost was the main driver, with operating and

maintenance costs as the secondary driver, of the viability of thermal treatment of wastepaper compared to landfilling or recycling.

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I want to thank Dr. Terry Fonstad for your continual support and assistance in the completion of this thesis. Your help was invaluable and greatly appreciated. The extra practice on the links was also valued and I hope we'll continue.

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Finally, I would like to thank Darren Anweiler. Without your help I would not have started down the road to a Master's degree, and I am thankful for your guidance and assistance at the start of my career and continued education.

DEDICATION

I dedicate this thesis to my wife, Leann, and my son, Jake. Thank you for your patience, support, love, and joy.

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LIST OF ABBREVIATIONS

CEPCI – chemical engineering plant cost index

CHP – combined heat and power

DST – Decision Support Tool

GHG – greenhouse gas

GJ - gigajoule

HHV – higher heating value

IHR – incineration with heat recovery

IPCC -International Panel for Climate Change

kW – kilowatt

kWh – kilowatt-hour

LHV – lower heating value

MSW – municipal sorted waste

NPV – net present value

O&M – operating and maintenance

OAT – one-at-a-time

PBP – payback period

1. INTRODUCTION

1.1. Motivation

Waste disposal is an ongoing environmental and financial concern for municipalities due to increasing public pressure to divert materials from landfills and increasing operating costs. As such, waste diversion programs are increasingly utilized to reduce the amount of material deposited of in landfills. Wastepaper is a common target for diversion, typically through recycling. Recycling requires the collection and transport of wastepaper to a recycling facility that will convert the wastepaper into a recycled paper product. In the case of Saskatchewan, there are no wastepaper recycling plants in the province and all wastepaper must be shipped out of province. Given that wastepaper is a commodity for recycling it can be shipped within Canada, North America, or to another continent. There is no consistent location that wastepaper is shipped to. Utilizing a localized solution would reduce emissions related to transportation, create local jobs, and may lower costs. This thesis will evaluate the economic feasibility of thermal treatment of wastepaper as a localized option within Saskatchewan municipalities compared to landfilling and recycling.

Electricity and heating are also environmental concerns due to the current reliance on fossil fuels. Thermal treatment of wastepaper could be used to generate heat or heat and power to offset utility costs and reduce associated emissions. Utilizing heat from the thermal treatment plant in a residential context would likely require installation of a prohibitively expensive district heating system to service each house. Therefore, utilization of the heat would require an industrial partner(s) or utilization in larger municipal facilities where limited additional infrastructure is required.

Historically, waste disposal and energy (heat and power) generation are addressed individually and with little coordination between the two. The “waste department” typically focusses on construction and operation of landfills, waste diversion programs, etc. The “power department” typically focusses on construction and maintenance of the electrical grid, power production, etc. If both problems (waste disposal and energy production) are considered at once, alternatives that would be otherwise ignored, such as thermal treatment in the form of combined heat and power (CHP) or incineration with heat recovery (IHR) become viable.

A CHP or IHR, operating on waste products has the potential to address wastepaper disposal, a portion of heating demand, and lowering of greenhouse gas (GHG) emissions within Saskatchewan. One fraction of the waste material that goes to landfill is referred to as the “dry combustible” fraction, and in Saskatchewan this represents about one-third of landfilled material (Tartaniuk, 2007; Government of Canada, 2021a). This fraction includes paper, cardboard, tree trimmings, some plastics, and various other related materials. Simply put, it is the fraction of material that easily burns, has a lower moisture content, relatively high energy densities, and lower risk of toxic combustion by-products. Wastepaper products are the fraction of particular interest in this thesis as the material is relatively uniform in composition and could be used in a CHP or IHR. If thermal treatment was to be a viable solution it would need to be able to achieve disposal costs that are no higher than those paid by municipalities for the competing disposal methods recycling or landfilling.

1.2. Knowledge Gap

Despite CHP and IHR options existing, they are still not widely utilized compared to fossil fuels to provide municipalities with heat and/or electrical energy needs. This is potentially because they are comparatively new and not well understood. Municipalities and residents have a well-established history with conventional options for wastepaper management such as landfilling or recycling. However, increasing regulations for landfills, and the Saskatchewan government’s goal to reduce the number of landfill sites and waste per capita (Government of Saskatchewan, 2020), indicates that landfilling costs are likely to increase. Recycling is also becoming increasingly difficult and costly due to recent changes in China’s acceptance of foreign material for recycling (Shang, et al., 2020), creating instability in the market price of wastepaper. The market still exists for wastepaper but the reduction in market price can make recycling financially challenging and unstable. Given wastepaper is sold as a commodity, the freight is paid for by the buyer and the need to transport wastepaper long distances reduces the value. The nearest paper recycling plants to Saskatchewan in Canada, are in Vancouver or Toronto, at least 1,600 km away (ENF Recycling, 2022). This further increases price instability as increasing fuel costs directly increase the cost of transportation and the value of wastepaper.

Exploring alternative options such as thermal treatment may require that a municipality hire a technical consultant to perform a feasibility analysis if the technical capability does not already exist within the municipality. For municipalities to consider CHP and IHR as viable options, they need to perform evaluations and demonstrate a benefit to taxpayers while minimizing financial risk. The intent of this thesis is to provide a tool (Decision Support Tool (DST)) that a municipality can use, at minimal cost and effort, to determine if a feasibility study is indicate the economic viability of wastepaper thermal treatment.

The DST provides suggested values for critical parameters such as estimating the fraction of waste that is wastepaper, capital costs, and energy generation. The Decision Support Tool then calculates the net present value at the end of the project life, allowing for the total costs of a thermal treatment installation to be determined.

1.3. Scope

This study considered only thermal treatment of the wastepaper fraction of the waste stream utilizing either CHP or IHR technologies. The DST was created for use by municipalities to perform a basic feasibility analysis. Wood and plastic, although potential fuel sources, will not be discussed in depth. The primary reason for this is that both fractions have the potential to generate toxic compounds or by-products into a CHP or IHR project. Wood is often treated with paint or other preservatives and if combusted or gasified would need expensive scrubbing equipment to clean up the emissions. Plastics have a similar issue as some, like polyvinyl chloride, contain chlorine. Chlorine could cause the formation of toxic compounds, which would again require expensive treatment equipment to clean up emissions. Wastepaper represents the lowest capital cost requirement and therefore the most likely to be viable. Wood and plastic could be evaluated for incorporation in the future, but each would require special considerations and are therefore out of scope. The study was also limited to Saskatchewan communities.

1.4. Objectives

The objective of this thesis was to determine how and if thermal treatment of wastepaper can utilize a fraction of the wastepaper that is recycled or landfilled at a lower costs. This was determined through the following:

1. Determine if the use of an incinerator with heat recovery (IHR) or combined heat and power (CHP) unit operating on the dry combustible (wastepaper) fraction of municipal

sorted waste (MSW) have the potential to be economically viable when compare to the options of landfilling or recycling.

2. Determine baseline estimates for the key economic drivers (capital cost, operations and maintenance costs, waste generation rates, expected energy output).
3. Provide a Decision Support Tool (DST) to allow Saskatchewan municipalities to perform an initial feasibility evaluation for the thermal treatment of wastepaper.

2. BACKGROUND AND LITERATURE REVIEW

Municipalities in Saskatchewan trend towards two waste management strategies, landfilling and recycling (Government of Saskatchewan, 2020). Considering an alternative, such as thermal treatment, requires that municipalities have all the background information required to accurately evaluate it. Some municipalities, especially smaller ones, may not have the financial or personnel resources to effectively gather and evaluate alternatives and would therefore leave them out of consideration. This literature review will outline the necessary information as well as provide baseline values for each parameter listed below. The information required for an initial evaluation for a thermal treatment facility is:

- Technology overview of available thermal treatment options
- Capital cost estimation for available technologies and plant sizes
- Sizing determination based on wastepaper availability
- Wastepaper availability based on population and waste generation rates
- Utility rates based on conventional heat and power sources
- Energy generation estimation based on the heating value of mixed wastepaper

2.1. Locations

Four urban municipalities in Saskatchewan (Saskatoon, Swift Current, La Loche, and Outlook) were the focus of this study (Table 1). The largest cities are the most likely for a thermal treatment installation to be viable as they are the most likely to be able to afford the capital expenditure, provide a correspondingly larger volume of paper product waste, as well as likely uses for the heat in the form of large municipal buildings or complexes. Saskatoon has the highest population in Saskatchewan and Swift Current was selected as the median population of the ten largest cities. Outlook was selected to evaluate a smaller town in Saskatchewan. Northern communities face additional challenges when it comes to heating and electricity usage due to their isolated nature and cost of transporting fuel. Waste disposal is also an issue as transporting waste and recycling large distances creates an additional economic burden. As such, La Loche was included in the evaluation to determine if thermal treatment is a viable option for northern communities (Figure 1).

Table 1– List of the ten most populous cities in Saskatchewan with the cities of interest (Government of Saskatchewan, 2017).

City/Town	Population
Saskatoon	246,376
Regina	215,106
Prince Albert	35,926
Moose Jaw	33,890
Lloydminster	31,400
Swift Current	16,604
Yorkton	16,343
North Battleford	14,315
Estevan	11,483
Warman	11,020
La Loche	2,372
Outlook	2,279
TOTAL	617,479

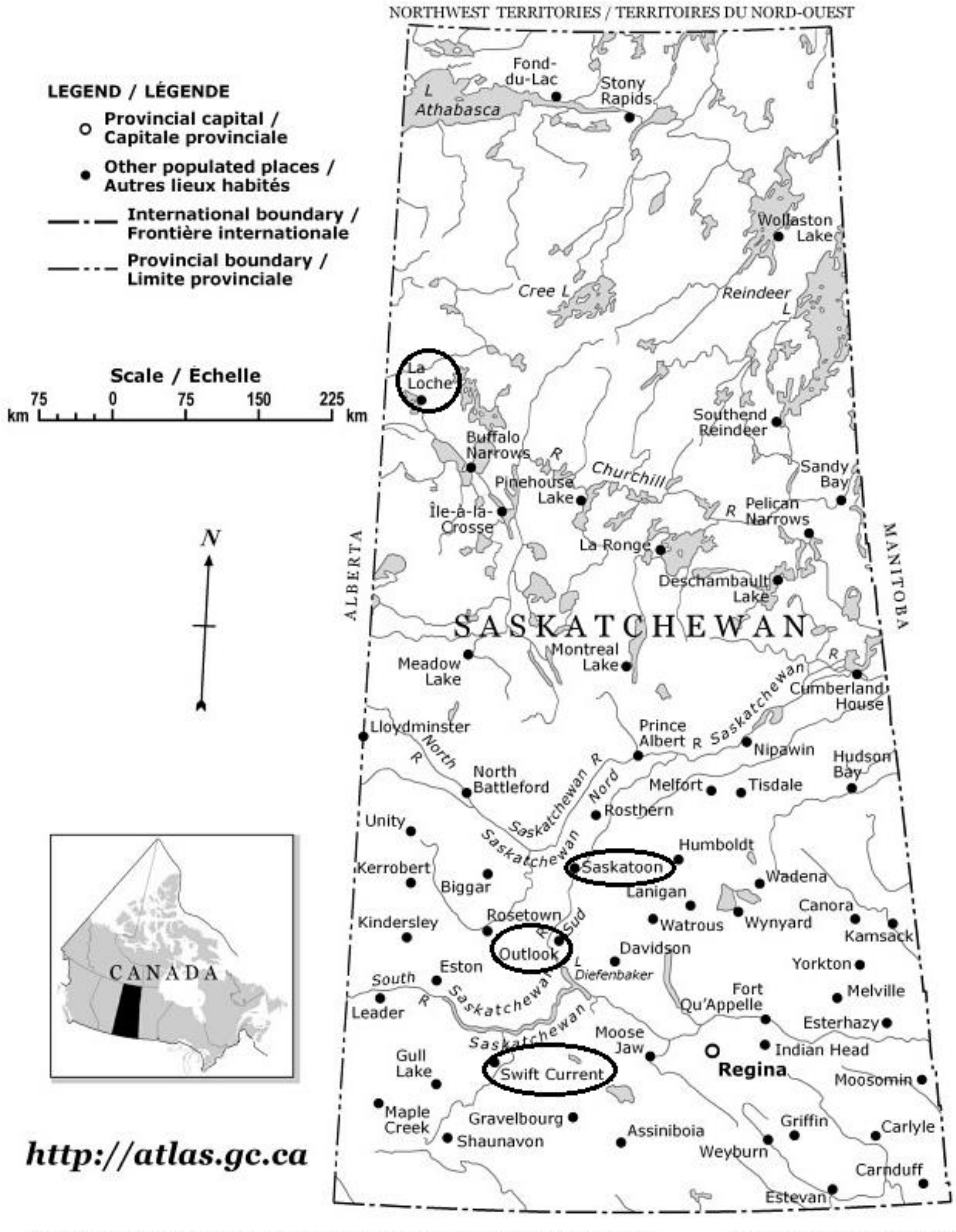

Figure 1 – map of Saskatchewan with the locations of interest highlighted (Government of Canada, 2002)
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2.2. Wastepaper Resource

Wastepaper is considered a resource for the purposes of a thermal treatment facility. A thermal treatment plant would convert the wastepaper to electrical and/or thermal energy that can be sold as a commodity. To determine the value of the resource, availability, competing market value (landfilling and recycling), and heating value must be understood. This information is used to estimate the size and financial viability of a thermal treatment facility.

2.2.1. Availability

Municipal solid waste (MSW) can be broadly separated into two categories: diverted material and landfilled material. Diverted material is anything that is not disposed of in a landfill and is instead sent for recycling or another alternative. Landfilled material is the remainder of waste that is transported to a landfill for disposal. Diverted material represents the most accessible material for thermal treatment as it has already been separated from general waste and possible contaminants. The Government of Saskatchewan lists waste diversion among the six main goals in Saskatchewan's Solid Waste Management Strategy (Government of Saskatchewan, 2021) indicating more material will be diverted from landfills in the future and could become accessible for thermal treatment.

Dry combustible material, primarily wastepaper and cardboard, is the portion of MSW that can be easily and safely combusted to generate energy. This makes it the waste fraction of interest for this study. Research has already been completed in quantifying the dry combustible fraction of waste and one study took place across in 12 landfills across Saskatchewan (Tartaniuk, 2007). Tartaniuk (2007) found that the dry combustible fraction in Saskatchewan represents approximately 33% of the waste located in landfills. Environment and Climate Change Canada (2020) indicated MSW landfilled in Saskatchewan was approximately 28% dry combustible material and diverted material was approximately 31% dry combustible material. This study, while more recent, was limited in scope as only two cities (Regina and Saskatoon) were considered. Another dataset (Government of Canada, 2021a) indicated that the proportion of paper fiber in diverted waste material is approximately 29%. This indicates an average wastepaper composition of 30% in MSW for Saskatchewan. Saskatchewan's total waste generated in 2018 (the most recent census data available at the time of writing) was 1,059,455 tonnes (Government of Canada, 2021a; Government of Canada, 2021c) from a population of 1,161,767 residents (Government of Canada, 2021b)

To utilize wastepaper in a thermal treatment plant it needs to be diverted from the general waste stream to prevent contamination. Diversion rate is the percentage of waste that is removed from the waste stream that would otherwise be deposited in landfills and would therefore be accessible for thermal treatment. The current diversion rate for Saskatchewan is 18% (Government of Canada, 2021a; Government of Canada, 2021c) and the province has a stated goal of 50% by 2040 (Government of Saskatchewan, 2020). The diversion rate is based on a percentage of total waste with no consideration given to the type of diverted materials but can serve as an indicator for reasonable capture rates to expect for wastepaper.

2.2.2. Wastepaper Products Reasoning

Wastepaper products were selected as they represent a common commodity and are well suited to thermal treatment methods such as gasification to power or incineration for heat. It is an excellent fuel source as it is relatively uniform in composition and does not contain plastics, paints, or other materials that may create toxic by-products during combustion (Xiu, et al., 2018). Because wastepaper represents the easiest waste fraction to gasify or incinerate, it also represents the "best case". If gasification/incineration of wastepaper is not economical, other waste fractions are also unlikely to be economical. Wastepaper can also represent a negative value commodity as municipalities need to pay for its disposal, either by transporting to another location for recycling or landfilling or placing it in a local landfill. From an economic perspective, gasification/incineration does not need to be profitable, it only needs to provide a disposal cost lower than recycling or landfilling.

2.2.3. Availability Forecasting

Changing trends to waste generation rates, waste composition, and capture rates should be considered as they directly impact the amount of wastepaper available for thermal treatment. The waste generation rates for 2010 to 2018 for the province were used to determine if there is a historical trend (Figure 2). A linear regression and resultant R^2 value of 0.28 on the provincial data indicates no discernable historical trend from 2010 to 2018 (data for waste generation in 2020 was not available at the time of writing) with respect to waste generation in the province.

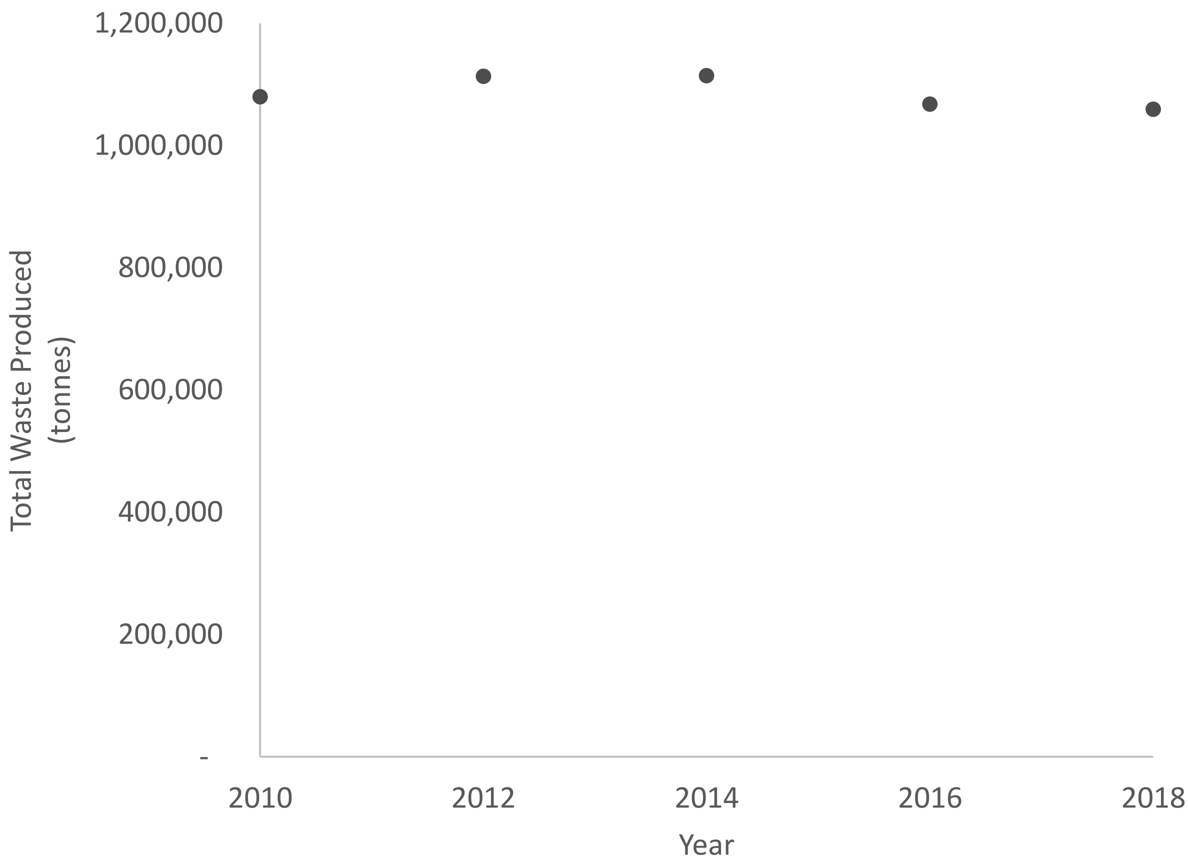


Figure 2 – Annual waste generation for Saskatchewan from 2010-2018 (Government of Canada, 2021a), (Government of Canada, 2021c)

Current events, such as the COVID-19 pandemic may drive change in waste generation and composition. The COVID-19 pandemic has created a surge in online purchasing which by extension, creates additional wastepaper products in the form of cardboard boxes and other shipping supplies (Baarsma & Groenewegen, 2021). A study of waste disposal in Regina, Saskatchewan showed an approximately 10% increase, by weight, in weekly curbside disposal for 2020 compared to 2019 (Richter, et al., 2021). Richter (2021) also noted that the weekly range of disposed waste differed greatly between 2019 (580 tonnes) and 2020 (1086 tonnes) which indicated the destabilizing nature that a pandemic can have on waste management. A study in Toronto, Ontario indicated similar increases for 2020 compared to 2019 with garbage increasing by 5%, organics by 8%, and recycling by 2% (Ikiz, et al., 2021). It is unclear if the trends observed during COVID-19 will continue but do indicate at least a short-term increase in waste generation.

The other consideration is the change of waste composition over time. Previously, studies on waste composition have been conducted on an ad hoc basis (Tartaniuk, 2007, Wang, et al., 2015, City of Saskatoon, 2016), making year over year comparisons difficult due to varying methodology and inconsistent time periods. At the time of writing, the Government of Canada has begun tracking disposed waste (Government of Canada, 2021c) and diverted waste (Government of Canada, 2021a) values every two years. Waste composition data began for the same studies in 2018 (Government of Canada, 2021a), so consistent historical data is not as available as it is for population or waste generation rates. Usage of disposable or single-use plastics such as bags, food containers, packaging materials, cutlery, etc. are declining due to their environmental impact and associated social pressure. In many cases (packaging, food containers, and bags) paper products or derivatives may begin to fill the gaps as paper is renewable and has a lower environmental impact (Wanatabe & Omori, 2020; Escursell, et al., 2021; Jensen, et al., 2021). Initiatives such as “Zero Plastic Waste” (CCME, 2018) are focused to shift from single-use plastics to renewable sources, such as paper. Diversion rate is also expected to increase due primarily to provincial government initiatives (Government of Saskatchewan, 2020). An increasing diversion rate will also produce a corresponding increase in the availability of wastepaper, even if the overall waste generation rate remains unchanged as more material is kept out of landfills.

2.2.4. Collection Cost

Given the distributed nature of household waste, it must be collected and transported to a central location for processing or disposal. Collection methods for recycling, landfilling, or material destined for a thermal treatment plant would all be fundamentally the same; trucks collect material and transport it to the appropriate location. A thermal treatment plant would require a dedicated collection stream as contamination of the wastepaper fraction with MSW will cause issues with plant operation. Plastics have the potential to generate toxic compounds, food waste may clog equipment, and harder materials such as metal may damage equipment only designed to handle wastepaper.

Saskatoon charged $7.47 per household for monthly recycling services in 2021 (City of Saskatoon, 2020). Saskatoon had 124,766 private dwellings, according to the most recent census in 2016 (Statisics Canada, 2016), for an annualized cost of approximately $932,000. In 2019, Loraas collected approximately 9,986 tonnes of recyclables in Saskatoon (City of Saskatoon, 2020a). This indicates an estimated household collection cost of $93/MT for household collection of a dedicated single stream.

2.2.5. Transportation

In some cases, a municipality may find it advantageous to transport and pay a levy to a separate municipality that has implemented a thermal treatment system, lower disposal cost option or increase their catchment area for a thermal treatment plant. Transportation costs outside of a municipality were assumed on a full truckload basis, meaning that the truck is filled and contracted solely for wastepaper. This represents the lowest cost per tonne option for truck shipments but may require the municipality stockpile material until there is enough to fill a truck.

Ko, et al. (2018) conducted a literature review focused on the transportation cost of biomass for energy. A major finding of the study was the variability of transportation costs for biomass products, and it is very much a situational price. As such, there is no single cost for the transportation of biomass (such as wastepaper). For Canada, Ko, et al (2018) suggest a range of $0.18 – $0.21 USD per dry ton-km for biomass. Han (2011) indicates similar pricing when performing an analysis of woody biomass transport in Oregon. Woody materials (hogfuel, chips, shavings, and sawdust) ranged in cost from $0.15 - $0.21 USD per green ton-mile, with shavings representing the highest cost due to the low density.

2.2.6. Historical Wastepaper Price

Wastepaper products are a commodity and can be sold on the open market to recyclers however, it is also quite volatile. According to the Continuous Improvement Fund (CIF), the peak price was $281 CDN/MT (May 2017) in the last five years and the low was $65 CDN/MT (Nov 2019) over the same period (CIF, 2020). This represents a 77% decrease in price in only three years. This historical variability represents a risk to municipalities as it directly relates to demand by recyclers. In the event of sustained lower prices, the revenue stream may become non-existent and leave the municipality without a disposal solution as recyclers are unable to sell collected material for a profit. For example, Winnipeg (a city of approximately 700,000 in Manitoba, Canada) made $2.4 million in 2017 with their recycling program but lost approximately $5.7 million in 2018 and $9 million in 2019 (Canadian Broadcast Coporation, 2019). This shift was primarily driven by the price of wastepaper rather than other recyclables such as plastic, glass, cans, etc. This highlights the risk involved for municipalities focused purely on recycling wastepaper as the only acceptable option.

2.2.7. Landfill and Recycling Rates

The most common competing disposal options for thermal treatment are landfilling and recycling. In the case of landfilling, the municipality pays for disposal at a private landfill or operates a municipal landfill. Landfill rates are set individually by the municipalities or private ownership and vary due with operating costs, types of waste accepted, etc. The cities and towns of interest have varying fees for disposal posted for their landfills (

Table 2). The average cost, excluding entry fees, across the ten most populous cities is $90/tonne.

When recycling wastepaper, the municipality pays a private company to take wastepaper and sell it to a recycler (or in some cases the private company is the recycler). Saskatoon for example, contracts Loraas Recycling (City of Saskatoon, 2020a) to provide removal services for all recyclable materials (cardboard, paper, glass, metal containers, etc.). The value of this contract started in 2019 and is worth approximately $46 million over eight years, for an average cost of $5.75 million per year. In 2019, Loraas collected approximately 9,986 tonnes of recyclables in Saskatoon (City of Saskatoon, 2020a) for an average cost of approximately $576 per tonne. In 2019 Regina paid approximately $1.9 million (City of Regina, 2020) to Emterra Environmental for collection of 6,891 tonnes of recyclables (City of Regina, 2019), approximately $275 per tonne. In both cases this is for collection of household single-stream recycling bins containing mixed recyclables, not just wastepaper.

Table 2 – Landfill fees in the ten most populous cities

City/Town	Disposal Fee	Entry Fee	Source
Saskatoon	$105/tonne	$15	(City of Saskatoon, 2020b)
Regina	$85/tonne	$10	(City of Regina, 2020)
Prince Albert	$73/tonne	N/A	(City of Prince Albert, 2020)
Moose Jaw	$89/tonne	N/A	(City of Moose Jaw, 2020)
Swift Current	$100/tonne	N/A	(City of Swift Current, 2020)
Yorkton	$70/tonne	$10	(City of Yorkton, 2020)
North Battleford	$125/tonne	$5	(City of North Battleford, 2020)
Lloydminster	$76/tonne	N/A	(City of Lloydminster, 2020)
Estevan	$75/tonne	N/A	(City of Estevan, 2020)
Warman	$105/tonne	$12	(City of Warman, 2020)

2.3. Thermal Conversion Technologies

There are three main categories for thermal treatment: incineration, gasification, and pyrolysis. Each treatment process also requires an energy utilization strategy that will convert the energy generated to a saleable form, typically through heat recovery (hot water or steam) or combined heat and power which produces both heat and electricity. This thesis will not evaluate individual offerings from technology providers as this requires a defined set of operational parameters that would only be applicable to a specific location or case. Instead, a broad overview of each approach and an outline of key information (Table 3) is provided. Incineration and gasification can both be used as energy production technologies and are therefore the focus of this thesis. Incineration typically a lower cost and complexity than gasification but as a result has a lower efficiency. Pyrolysis is an energy densification technology that reduces the volume of material for transportation.

Table 3 –Summary of thermal conversion technologies

Conversion Technology	Advantages	Disadvantages	Primary Use	Relative Cost
Incineration	• Simple design • Proven • Handles a variety of feedstock	• Lower efficiency than gasification	• Production of steam or hot water	Low
Gasification	• Can be easily paired with a combustion engine for power production • High conversion efficiency • Excess heat is easily captured	• Higher cost than incineration • Increased complexity	• Power and heat production	High
Pyrolysis	• Handles a variety of feedstock • Energy densification	• Variable quality of produced bio-oil • Requires specialized equipment to utilize bio-oil • Bio-oil is unstable in storage	• Energy densification	High

2.3.1. Incineration

Incineration is the traditional method of thermal treatment where fuel (wastepaper, natural gas, coal, etc.) is combusted with excess oxygen to produce heat, water vapour, and carbon dioxide. The goal is complete combustion of the fuel, which is the complete conversion to water vapour and carbon dioxide. The heat is then utilized directly, through industrial processes, district heating, building heat, etc. or indirectly, through power production with a turbine. Incineration is the simplest of the three categories and tends to represent the lowest cost for implementation.

A basic biomass incinerator has been shown previously (Figure 3) (Cheremisinoff & Rosenfeld, 2010; Matzing, et al., 2018; Islas, et al., 2019; Jiang, et al., 2019). Biomass is transferred from feed storage, typically a hopper, into the incinerator via screw conveyor or belt and feed mechanism. The feed mechanism is typically a rotary valve or similar mechanism that prevents material from catching fire in the conveyor. Air is co-fed to the incinerator in excess to ensure complete combustion of biomass. Ash removed from the bottom of the incinerator for disposal. The hot combustion gas is passed through a heat exchanger, such as a boiler, to capture heat in the form of steam or hot water. Finally, cooled combustion gasses are passed through a gas scrubber to remove products of incomplete combustion, particulates, and other pollutants.

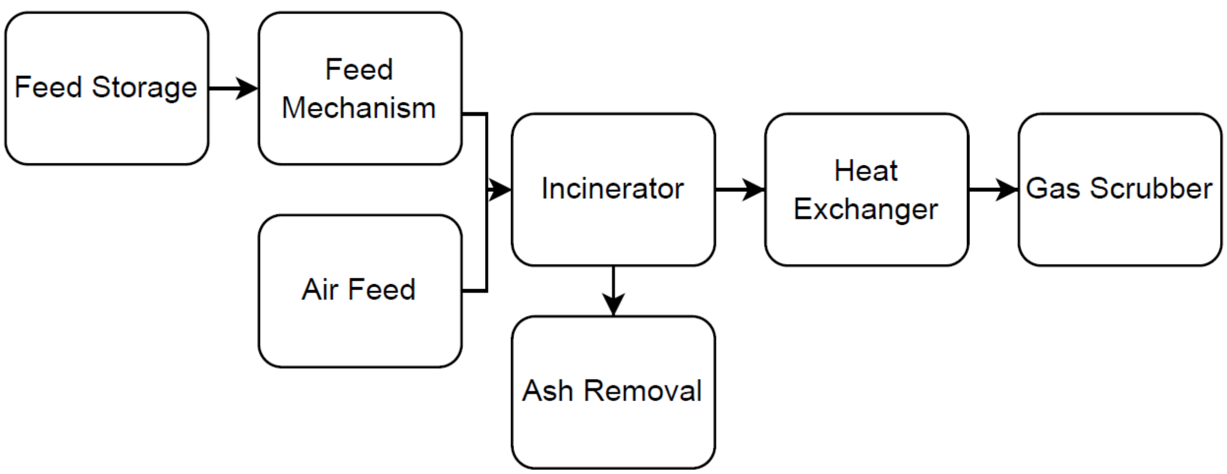


Figure 3 – Basic outline of a biomass incinerator
(Cheremisinoff & Rosenfeld, 2010; Matzing, et al., 2018; Islas, et al., 2019; Jiang, et al., 2019)

2.3.2. Gasification

Gasification is similar to incineration with the exception that the process is operated with limited oxygen rather than an excess. The limited oxygen supports a partial combustion of the material to provide heat for the reaction and prevents complete conversion to carbon dioxide and water vapour. Gasification takes place at temperatures above 700 ^{o}C (Basu, 2018) and produces primarily carbon monoxide and hydrogen gas, also known as syngas. Syngas can then be utilized in a boiler, combustion engine or turbine to produce heat or a combination of heat and power.

A basic gasifier has been shown previously (Figure 4) (Pfiefer, et al., 2011; Yan & Wang, 2018; Colantoni & Hamedani, 2021). Feed storage is typically hopper or vessel that biomass (feed) can be transferred from and into the gasifier, often by screw conveyor. As the biomass is transferred to the gasifier it goes through a feed mechanism, often a rotary valve, to prevent the gasifier products from back flowing through the feed system. The gasifier is where biomass is heated to the reaction temperature, at least 700 ^{o}C (Basu, 2018), and syngas is generated. Produced syngas is then passed through a scrubber to remove tars that could damage downstream combustion equipment. Ash and other particulates are then removed, typically using a cyclone, and sent for disposal. Syngas is then passed through a heat exchanger to recover heat and cool the gas before it is sent to a combustion genset, boiler, or alternative point of use. By-products of gasification are exhaust gas (primarily water vapour and carbon dioxide), biochar, and ash. Biochar is a carbon rich solid that can be utilized as a soil amendment (Zama, et al., 2018) and ash generated from biomass has the potential to be used in place of fly ash as a concrete additive (Roychard, et al., 2021).

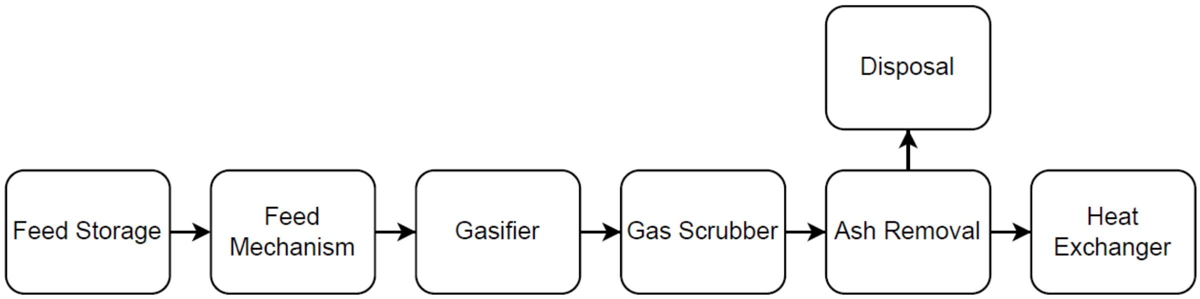


Figure 4 – Basic outline of a biomass gasifier
(Pfiefer, et al., 2011; Yan & Wang, 2018; Colantoni & Hamedani, 2021)

2.3.3. Pyrolysis

Pyrolysis differs from incineration and gasification due to the absence of oxygen and is typically an energy densification strategy rather than direct use (such as incineration). Organic matter is heated to around 500 ^{o}C (US Deparment of Agriculture, 2021) without oxygen and decomposes into bio-oil, a liquid containing hundreds of organic compounds. Pyrolysis also increases density, making transport over longer distances more economical as a smaller volume of material needs to be transported. This can allow for centralized facilities or shipment out of isolated locations.

Bio-oil is combusted in a boiler like conventional fossil fuels but does have some special considerations. Bio-oil is extremely variable as it is highly dependent on the method of pyrolysis and feedstock utilized. It is also difficult to store as it is relatively unstable and degrades rapidly compared to conventional fossil fuels (Vispute, 2011). For the purposes of this thesis, pyrolysis will not be considered as it requires a municipality to transport the bio-oil or utilize it locally, which would negate the value in energy densification and thereby pyrolysis itself.

2.4. Energy Utilization

Thermal conversion technologies (Section 2.3) would convert wastepaper either directly to heat (incineration) or syngas (gasification). These technologies don’t utilize the heat or syngas directly and require an energy utilization technology for conversion to transferable heat (such as a heat transfer fluid) or electricity which can then be sold as a commodity. The two primary technologies are heat recovery (saleable heat only) and combined heat and power (saleable heat and electricity).

2.4.1. Heat Recovery

With a heat recovery facility there is no power production, and all saleable energy generated is captured as heat in a heat carrier, typically steam or hot water. Steam or hot water is transported and utilized for an industrial process or heating buildings (typically large commercial or municipal buildings). Efficiency varies across heat recovery systems based on size and technologies but is reported between 77% and 86% (Thomas, 2018).

2.4.1.1. Capital Cost

The capital cost for incineration plants varies based on the country of construction, technology provider, and capacity. Siyuan Wu (2018) reported rates across 21 US facilities with a capital cost of \$544 - \$2,552 CAD_{2020} per metric tonne of annual capacity. Stantec (2011) reported costs across 14 European facilities with a capital cost of \$731 - \$1,920 CAD_{2020} per metric tonne of annual capacity . Both reports indicated the rated capacity (tonnes per year) did not strongly correlate with the overall size of the plant. For example, plant processing 80,000 tonnes per year would not necessarily have a higher cost per tonne than a plant that processes double that amount. It is dependent on the technology utilized and the location of construction. A range of \$544 - \$2,552 per metric tonne of annual capacity is suggested for a heat recovery-based installation.

2.4.2. Combined Heat and Power

Combined heat and power (CHP) is a power generation plant with the addition of capturing waste heat in a useable form, typically as hot water or steam. The thermal energy is typically used in an industrial process or for district/building heating similar to an incineration plant. Electrical production is the primary purpose of the unit with the waste heat captured as an added economic and efficiency opportunity. CHP plants for biomass are typically based on the use of a gasifier (Section 2.3.2) to generate syngas which is combusted in an internal combustion engine and used to drive a generator. Efficiency varies across CHP units based on size and design but is reported between 49% and 55% for the thermal fraction, and between 30% and 39% for electrical production (Colantoni & Hamedani, 2021). This provides a combined efficiency of between 79% and 94% depending on the technology selected.

2.4.2.1. Capital Cost

The capital cost of a CHP unit will vary depending on the capability, size, efficiency, etc. of the unit selected. Capital costs can be estimated based on values provided to evaluate feasibility of an installation. The cost of a CHP is typically determined by the electrical generation capacity as this is the primary driver of cost rather than heat capacity (ETSAP, 2010; IRENA, 2012). Estimates for a CHP unit will be more variable than an incineration unit due the complexity and variability of technology involved (Abdoulmoumine, et al., 2012). There are also numerous technology options available with varying degrees of automation, efficiency, feedstock capability, etc (Table 4).

Table 4 – CHP capital cost estimates

Technology	Adjusted Estimate to CAD_{2020}*	Source
Stoker CHP	\$5,155 - \$9,903 CAD_{2020}/kW	(IRENA, 2012)
Gasifier CHP	\$8,088 - \$9,504 CAD_{2020}/kW	(IRENA, 2012)
Biomass CHP	\$4,356 - \$8,712 CAD_{2020}/kW	(ETSAP, 2010)
Biomass CHP	\$7,239 CAD_{2020}/kW	(EIA, 2016)

*Capital estimates were updated to 2020 Canadian dollars using the method outlined in Section 3.1 and CEPCI values from the corresponding year.

2.4.2.2. Heat:Power Ratio

The heat to power ratio for a CHP describes the rate of heat production in relation to electricity production to meet market demand. This is typically reported as a unitless ratio as both production rates are reported in kW. The range varies widely across technologies as well as operational strategies. Typically, this would be to maximize electrical production while still maintaining the ability to sell the heat fraction. Mahkamov (2011) reported that the heat to power ratio nearly doubled by changing the operational strategy of a CHP. Rates reported range from 0.5 to 3.4 with the range of 0.5 to 1.5 being most common (Liso & Kaer, 2011; Wiranarinkorn & Arpornwichanop, 2019; Renau, et al., 2021).

2.4.3. Operations and Maintenance

Operations and maintenance (O&M) costs will vary across the range of units available, and the specific technology and provider employed. They include labour, maintenance, environmental testing, consumables, and utility costs. O&M costs are driven primarily by labour (van Driel, 2015). O&M costs are typically based on the capital cost of the facility and for biomass ranges from 2% to 10% of capital expense (IRENA, 2012; van Driel, 2015; GREBE, 2017).

2.4.4. Heating Value of Wastepaper

The heating value of a material can be expressed in two different forms, higher heating value (HHV) and lower heating value (LHV) (U.S. Environmental Protection Agency, 2007). The difference between the two terms is the end fate of water vapour produced during combustion. HHV includes both energy produced by combustion and energy recovered by condensing water vapour, rather than simply exhausting it. LHV is the energy produced by combustion without recovery of the water vapour and the energy of condensation is instead released to atmosphere (US Environmental Protection Agency: Office of Air and Radiation, 2007). Systems that collect water energy from the water vapour are typically more expensive and require more maintenance due to the increased complexity of the equipment. This difference is important to consider when evaluating different technologies and ensuring an apt comparison to their reported efficiencies.

The HHV of wastepaper has been reported in multiple studies: 6,477 btu/lb (15.1 GJ/tonne) (Ucuncu, 1993), 17.4 GJ/tonne (Shi, 2015), and 13.5 to 15.5 GJ/tonne (Malat'ak, et al., 2018). Variance in reported values exists due to the variable composition of wastepaper. The LHV of wastepaper can also be estimated based on the HHV using the formula (Equation 2.1 for btu/lb or Equation 2.2 for GJ/tonne) provided below (US Environmental Protection Agency: Office of Air and Radiation, 2007):

$$LHV = HHV - 10.55\ (W + 9H) \tag{2.1}$$

Where;

HHV = Higher Heating Value, Btu/lb

LHV = Lower Heating Value, Btu/lb

H = Weight % of hydrogen in fuel

W = Weight % of moisture in fuel

Converting the formula to allow for input as GJ/tonne for direct input of literature values:

$$LHV = HHV - 0.02454\ (W + 9H) \tag{2.2}$$

Where;

HHV = Higher Heating Value, GJ/tonne

LHV = Lower Heating Value, GJ/tonne

H = Weight % of hydrogen in fuel

W = Weight % of moisture in fuel

Moisture content of wastepaper will be highly variable based on the collection and storage processes. As indicated in **Error! Reference source not found.**.2, any moisture present in wastepaper reduces the available energy more energy is required for vapourizing water. A moisture content between 4% and 10% would be expected in most circumstances (Posada, et al., 2016; Krishna & Chaurasia, 2019; BMT Netherlands, 2020). Hydrogen content of wastepaper will be less variable than moisture content as it is an intrinsic property of the material. A value of 5% is common for paper and cellulose (Sorum, 2001; Muley, et al., 2019).

2.4.5. Sizing

Sizing of an IHR or CHP is critical to success and is based on three main facets, the availability of fuel, demand for produced heat and power (if applicable), and technology cost. Smaller units typically have a higher cost per tonne due to the economy of scale and therefore under sizing a unit reduces the economic viability. Sizing a unit too large demands excessive capital and operating costs as the unit may be required to idle or shut down until fuel is available. Fuel availability for a thermal treatment plant designed for wastepaper is based on wastepaper that can be diverted from the MSW stream and dedicated to the plant to limit contamination. This is a product of the waste generated and the diversion rate observed within the municipality (Section 2.2.1).

Demand for heat from a thermal treatment plant must be located directly adjacent to the plant or connected to a district heating system (Schmidt, et al., 2009). Hot water or steam are typically used for heat transfer through the system and increasing the distance from the plant lowers the overall efficiency. A plant designed to sell heat as a commodity must therefore do so locally. By contrast, power produced by the plant can be transferred through the electrical grid and utilized at any point in the grid. A plant located in one municipality could provide electricity to another location 100's of kilometers away, which is not possible for a heat-based plant.

2.5. Saskatchewan Utilities

A thermal treatment plant in Saskatchewan would compete with traditional sources of electricity and heating. The sale and distribution of electricity is performed by SaskPower and sale and distribution of natural gas is performed by SaskEnergy. If a CHP plant were installed, SaskPower would need to be at least partially involved as the grid would be required for the distribution of electricity. SaskPower electrical rates can be used as comparable prices for the sale of electricity from a CHP plant. SaskEnergy serves as the main competitor for heating sales for the thermal treatment plant and can be used as a basis for the price of saleable heat generated.

2.5.1. SaskPower

The success of a power production installation in Saskatchewan requires that SaskPower allows for connection to the grid to sell/distribute the power or that it provide locally utilized power at a comparable rate to the grid. SaskPower is seeking to reduce its environmental impact by increasing renewable energy production to 50% of capacity by 2030 and is expected to reduce greenhouse gases to 40% below 2005 levels (SaskPower, 2017b). Thermal treatment of wastepaper could fit well within SaskPower's plans as a renewable source of electricity.

2.5.1.1. Grid Capacity and Emission Intensity

The production capacity for the Saskatchewan grid is approximately 4,893 MW and is primarily from a mix of coal, hydro-electric, natural gas, and wind (SaskPower, 2020a). As of March 2020, 24.3 % of SaskPower's capacity came from renewable sources. For the 2019-20 fiscal year SaskPower sold approximately 23,000 GWh of electricity (SaskPower, 2020a) at a CO_2 intensity of 800 g CO_2eq/kWh. This is third highest in Canada behind only Alberta and Nunavut at 950 and 830 g CO_2eq/kWh respectively (Environment and Climate Change Canada, 2019), which further highlights the need for Saskatchewan to shift to less CO_2 intensive power production. Reducing the emission intensity of Saskatchewan's grid will require that SaskPower continue to move to renewable sources of energy generation (SaskPower, 2017b).

2.5.1.2. Electrical Rates

Electrical rates provided by SaskPower are in two main categories: residential and commercial. Residential rates only vary based on if the user is a rural or urban customer, which adjusts the monthly service charge. The rate paid kWh remains the same in both cases. Commercial rates and monthly charges vary based on peak demand, total volume purchased, whether the customer is providing their own transformer, time of use, and whether the customer is rural or urban. Commercial rates are therefore much more variable and based on a given circumstance. The rate for residential is $0.14228 per kWh and standard rate for urban businesses is $0.07674 per kWh (SaskPower Incorporated, 2021). If the power were distributed on SaskPower's grid, it would be done so under the "Power Generation Partner Program", which specifies a maximum price paid of $70.00 per MWh or $0.07 per kWh (SaskPower, 2020b).

2.5.2. SaskEnergy

SaskEnergy manages the distribution of natural gas throughout the province, serving approximately 93% of Saskatchewan communities (SaskEnergy Incorporated, 2021). Natural gas is distributed throughout the province for use in industrial processes and residential heating. Given the high rate of utilization of natural gas for heating, it would be represent a competing price for heat generated by a thermal treatment plant.

2.5.2.1. Capacity and Emission Intensity

In the 2019-2020 fiscal year, SaskEnergy sold 5.7 billion cubic meters of natural gas (SaskEnergy Incorporated, 2020) which translates to approximately 106 million GJ. The emission intensity of natural gas is different from electricity in that it is largely dependent on the point of use due to the variable combustion efficiency across different equipment. Lower combustion efficiency means that more natural gas (methane) escapes, increasing the greenhouse gas emission intensity. The IPCC (2006) provides an emission intensity of 56,100 kg CO_2/TJ (56.1 kg CO_2/GJ) for natural gas.

2.5.2.2. Natural Gas Rates

SaskEnergy also has rates split by residential and commercial/industrial users. Residential rates are $5.137/GJ (including delivery and commodity price) whereas commercial/industrial rates vary based on the monthly usage. The lowest posted rate is $3.558/GJ for industrial users with an annual consumption of 660,001 to 1,320,000 m^3 (SaskEnergy Incorporated, 2019). Natural gas has a heating value of 0.03875 GJ/m^3 (SaskEnergy Incorporated, 2019) and pricing includes a carbon tax cost of $0.0979/$m^3$ (SaskEnergy, 2021) at a carbon tax rate of $50/$\text{tonne}_{CO2}$.

2.6. Emissions

Coal and natural gas represent approximately 60% of power production capacity in Saskatchewan (SaskPower, 2017a). Electrical production represents 14.7 megatonnes CO_2 eq out of Saskatchewan's total emissions of 75.8 megatonnes CO_2 eq, or approximately 19% of annual emissions (Environment and Climate Change Canada, 2021). Building heating is a major contributor to Saskatchewan's greenhouse gas (GHG) emissions due to the primary reliance on natural gas (Environment and Climate Change Canada, 2019).

Emissions from an IHR or CHP plant could considered carbon neutral, as suggested by Canada Energy Regulator for biomass to energy systems (Canada Energy Regulator, 2020). Wastepaper products are composed of biomass which is already a part of the carbon cycle. Fossil fuels utilized to produce the original materials would be accounted for during their production and would therefore be out of scope for this thesis.

If carbon pricing were required for the plant, it could be estimated based on the carbon content of paper. The carbon content of wastepaper components has been previously reported: 37%

(Patcharee & Naruephat, 2015), 41% - 50% (Zhou, et al., 2014), and 47% (Biswal, et al., 2013). Given the variable nature of wastepaper a range of 37% to 50% carbon content is expected as it will change with wastepaper composition. Using the molecular weight of carbon and oxygen, the mass of carbon in wastepaper is converted to carbon dioxide at a ratio of 3.7 tonnes of carbon dioxide per tonne of carbon. The current carbon tax is $50 per tonne carbon dioxide, according to current Canadian law under the Greenhouse Gas Pollution Pricing Act (Government of Canada, 2018). The carbon tax is set to increase over time up to $170 per tonne carbon dioxide.

2.7. Economic Analysis

Economic analysis for the Decision Support Tool was completed using the profitability analysis outlined by G. Ulrich and P. Vasudevan (2004). The method is designed to evaluate the economic outcome of a plant over the course of its expected lifespan and can compare numerous scenarios (technologies, construction duration, cash flow, etc.). In doing so it estimates two important parameters, which are the payback period (PBP) and net present value (NPV).

2.7.1. Payback Period (PBP)

Payback period (PBP) is the amount of time, after construction, that it takes for cumulative net revenue to equal the cumulative expenses to date. Thermal treatment plants discussed may not have a PBP as they do not necessarily need to be profitable to be a viable option. The plants are evaluated on their ability to provide a wastepaper disposal option at a lower cost than recycling or landfilling rather than their ability to generate revenue.

2.7.2. Net Present Value (NPV)

Net present value (NPV) is the final cumulative discounted cash flow at the end of the project (Ulrich & Vasudevan, 2004) or the total cost/profit of a project. For a project that generates a profit, NPV is a positive number and for an installation that is not profitable, negative. The NPV is also reported in dollar value in the year of project initiation. In a profitable project, annual income will appear to decline each year due to inflation. In a non-profitable project, the loss observed each year would decline for the same reason. Using an undiscounted cashflow generates a linear trend over the life of the project as inflation is not considered and the profit/loss remains constant.

2.7.3. Discount Rate

A discount rate is used to account for inflation or the desired return for an investor. A discount rate of 0% does not account for inflation but can be compared to competing projects or alternative cases without additional financial factors (payments to investors, debt servicing, etc.) impacting the comparison. This means that if there is any profit, it remains within the operating budget of the installation and that there is no additional cost (interest) associated with the capital expense (Ulrich & Vasudevan, 2004). Any increase in the discount rate reflects additional cost to the project such as payments to investors, inflation, or debt servicing. Using a discount rate of 1.6% approximates annual inflation (Bank of Canada, 2021) during the life of the plant, assuming inflation stays relatively constant.

3. METHODOLOGY

Using the background information and values, a Decision Support Tool (DST) was developed in MS Excel to automate the evaluation of wastepaper thermal treatment. The DST was based on the method described by G. Ulrich and P. Vasudevan (2004) and Section 2.7. The DST was then used to evaluate the viability of thermal treatment plant installation at the locations of interest compared to recycling or landfilling.

3.1. Capital Cost Inflation Adjustment

Capital estimates were updated using Equation 3.1, the 2020 annual average Chemical Engineering Plant Cost Index (CEPCI) value, and CEPCI value from the corresponding year, (Chemical Engineering Online, 2021). USD to CAD conversion was competed using annual the average exchange rate (1.3415 USD per CAD) for 2020. (Bank of Canada, 2021)

$$CEPCI_{Ratio} = \frac{CEPCI_{Target\ Year}}{CEPCI_{Reference\ Year}} \tag{3.1}$$

Where;

$CEPCI_{Ratio}$ = final ratio used for inflation adjustment

$CEPCI_{Target\ Year}$ = CEPCI value for the year pricing will be updated to

$CEPCI_{Reference\ Year}$ = CEPCI value for the year pricing will be updated from

3.2. Decision Support Tool

The Decision Support Tool (DST) is designed such that a user enters values for each parameter and the DST then provides a summary of the total wastepaper utilization, heat and power generated (if applicable), and NPV at the end of the project. The data presented in the figures uses Saskatoon to demonstrate the DST. Figure 5 is a flowchart of the data input by the used and the calculations performed with inputs from the user on the left side of the chart and arrows indicating where the inputs are used in the calculation. The analysis begins with the calculation of available wastepaper based on waste generation rate, population, diversion rate, and waste composition to provide an annual wastepaper generation rate(tonnes/year) shown in Figure 6. Figure 7 is a screenshot of the DST and shows the capital investment, utility, and net present value summary. Initial capital investment for construction of the thermal treatment plant is determined based on the capital cost rate ($/tonne of annual capacity) and the calculated generation of wastepaper. Utility generation, heat or heat and power, is calculated based on the efficiency and throughput of the plant and heating value of wastepaper. Gross revenue is calculated each year from utility sales at the plant based on the utility rate specified for heat and power and, if applicable, revenue generated by accepting wastepaper. Operating expenses (wages, maintenance costs, and wastepaper cost) and capital repayment are then subtracted from the gross revenue to provide annual net revenue. Annual cashflow, accounting for the discount rate, is then summed across the 25-year life of the plant to provide the net present value of the plant at the end of its designed life (Figure 8). The net present value can then be used for comparison to other disposal methods as the indicates the total cost of the thermal treatment plant. If the thermal treatment plant indicates an NPV greater than landfilling and/or recycling, it provides disposal at a lower cost than that disposal method.

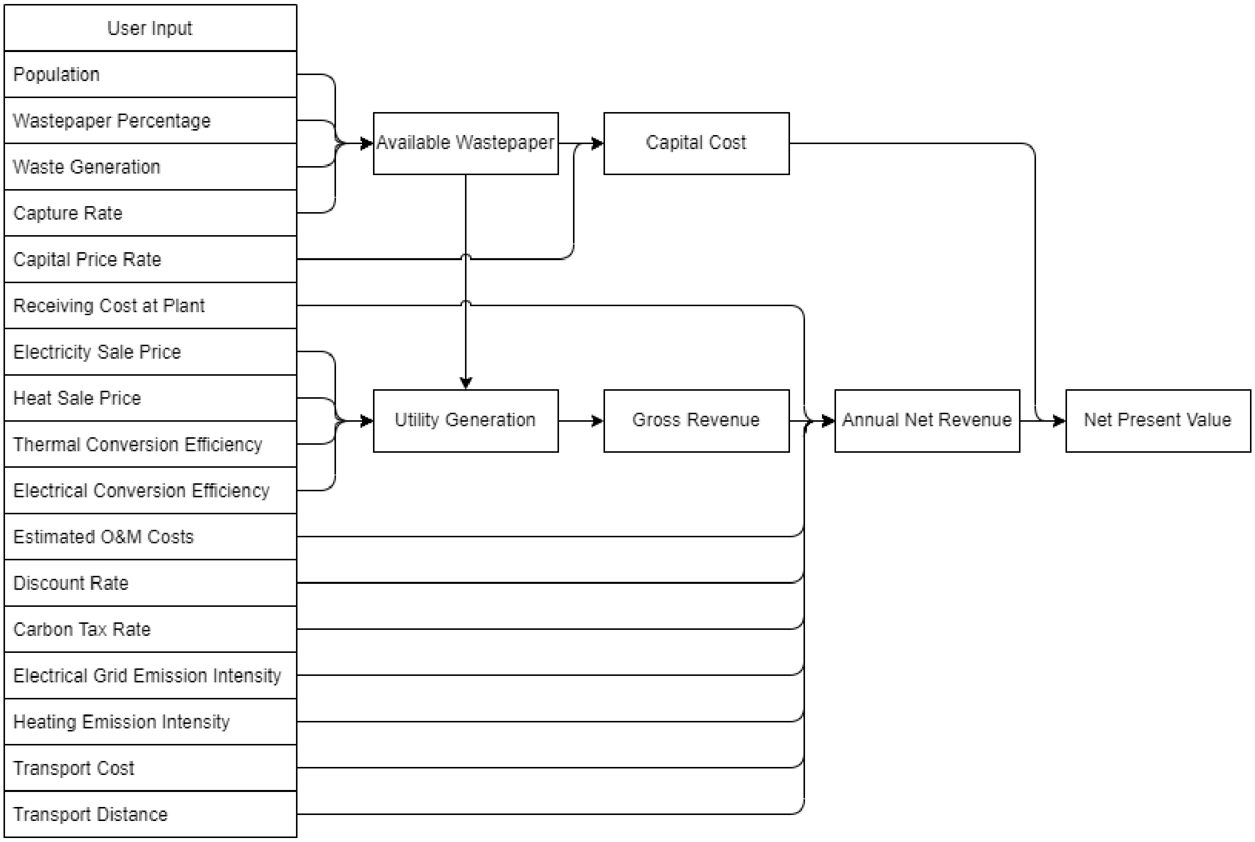


Figure 5 – Flowchart of the Decision Support Tool Calculation.

Location Inputs		
Population	246,746	people
Wastepaper Waste Percentage	30%	wastepaper
Waste Generation	912	kg/person/year
Capture Rate	18%	
Plant Inputs		
A typical plant will range from $487 - $2281 per metric tonne of annual capacity		
Capital Price Rate	$ 3,834	CAD/metric tonne/yr
Receiving Cost at Plant	$ 103.00	per metric tonne
Electricity Sale Price	$0.07000	per kWh
Heat Sale Price	$ 3.558	per GJ
Thermal Conversion Efficiency	55%	
Electrical Conversion Efficiency	35%	
Estimated O&M Costs	10%	of capital expense
Discount Rate		
Discount values adjust the cash flow to account for inflation or allow for comparison to another investment.		
Discount Rate 1	1.6%	
Discount Rate 2	0.0%	
Plant Cost		
If a known plant cost is to be evaluated, enter the capital cost below. Otherwise, leave it blank for the tool to estimate the cost.		
Known Plant Cost	$ -	million CAD
Carbon Tax		
Use the inputs below to determine the impact of a carbon tax. It will calculate the amount that would otherwise go towards the carbon tax or, in the event of a cap and trade, the potential value of offsets.		
Carbon Tax Rate	$ 50.00	per tonne CO_2
Electrical Grid Emission Intensity	800	g CO_2/kWh
Heating Emission Intensity	50	kg CO_2/GJ
Transportation and Collection		
Use the inputs below to determine the cost of transporting wastepaper to a centralized location.		
Transport Cost	$ 0.37	$/tonne-km
Single Trip Distance		km

Figure 6 – "Screen Shot" of the "Input" tab for the DST

Estimated Plant Values			
Estimated Capital Price Rate	$	3,834	CAD/metric tonne/yr
Annual Waste Throughput		12,152	Metric Tonnes
Capital Cost	$	46.59	million CAD
Estimated Annual Gross Revenue	$	1.45	million CAD
Estimated Annual O&M Costs	$	4.66	million CAD
Annual Heat Generation		91,231	GJ
Electricity Generation		16126864.4	kWh
Net Present Value (Undiscounted)	$	(153.56)	Million CAD
Net Present Value (Discount 1)	$	(134.84)	Million CAD
Net Present Value (Discount 2)	$	(153.56)	Million CAD

Figure 7 – Capital investment summary from the DST

	Completion of Year (millions CAD)												
	Construction	Operation											
Quantity	1	2	3	4	5	6	7	8	9	10	11	12	13
Annual Capital Investment	$(47)	-	-	-	-	-	-	-	-	-	-	-	-
Utility Income (Heat and Power)	-	$1.5	$1.5	$1.5	$1.5	$1.5	$1.5	$1.5	$1.5	$1.5	$1.5	$1.5	$1.5
Wastepaper Cost	-	$(1.3)	$(1.3)	$(1.3)	$(1.3)	$(1.3)	$(1.3)	$(1.3)	$(1.3)	$(1.3)	$(1.3)	$(1.3)	$(1.3)
O&M	-	$(4.7)	$(4.7)	$(4.7)	$(4.7)	$(4.7)	$(4.7)	$(4.7)	$(4.7)	$(4.7)	$(4.7)	$(4.7)	$(4.7)
Transportation	-	-	-	-	-	-	-	-	-	-	-	-	-
Net Profit Before Tax	-	$(4.5)	$(4.5)	$(4.5)	$(4.5)	$(4.5)	$(4.5)	$(4.5)	$(4.5)	$(4.5)	$(4.5)	$(4.5)	$(4.5)
Net Cash Income	$(46.6)	$(4.46)	$(4.46)	$(4.46)	$(4.46)	$(4.46)	$(4.46)	$(4.46)	$(4.46)	$(4.46)	$(4.46)	$(4.46)	$(4.46)

	Completion of Year (millions CAD)												
	Operation												
Quantity	14	15	16	17	18	19	20	21	22	23	24	25	26
Annual Capital Investment	-	-	-	-	-	-	-	-	-	-	-	-	-
Utility Income (Heat and Power)	$1.5	$1.5	$1.5	$1.5	$1.5	$1.5	$1.5	$1.5	$1.5	$1.5	$1.5	$1.5	$1.5
Wastepaper Cost	$(1.3)	$(1.3)	$(1.3)	$(1.3)	$(1.3)	$(1.3)	$(1.3)	$(1.3)	$(1.3)	$(1.3)	$(1.3)	$(1.3)	$(1.3)
O&M	$(4.7)	$(4.7)	$(4.7)	$(4.7)	$(4.7)	$(4.7)	$(4.7)	$(4.7)	$(4.7)	$(4.7)	$(4.7)	$(4.7)	$(4.7)
Transportation	-	-	-	-	-	-	-	-	-	-	-	-	-
Net Profit Before Tax	$(4.5)	$(4.5)	$(4.5)	$(4.5)	$(4.5)	$(4.5)	$(4.5)	$(4.5)	$(4.5)	$(4.5)	$(4.5)	$(4.5)	$(4.5)
Net Cash Income	$(4.46)	$(4.46)	$(4.46)	$(4.46)	$(4.46)	$(4.46)	$(4.46)	$(4.46)	$(4.46)	$(4.46)	$(4.46)	$(4.46)	$(4.46)

	Undiscounted Cash Flow	
	Undiscounted	
	Annual	Cumulative
End of Year		
0	-$ 46.6	-$ 46.6
1	-$ 4.5	-$ 51.0
2	-$ 4.5	-$ 55.5
3	-$ 4.5	-$ 60.0
4	-$ 4.5	-$ 64.4
5	-$ 4.5	-$ 68.9
6	-$ 4.5	-$ 73.3
7	-$ 4.5	-$ 77.8
8	-$ 4.5	-$ 82.2
9	-$ 4.5	-$ 86.7
10	-$ 4.5	-$ 91.2
11	-$ 4.5	-$ 95.6
12	-$ 4.5	-$ 100.1
13	-$ 4.5	-$ 104.5
14	-$ 4.5	-$ 109.0
15	-$ 4.5	-$ 113.4
16	-$ 4.5	-$ 117.9
17	-$ 4.5	-$ 122.4
18	-$ 4.5	-$ 126.8
19	-$ 4.5	-$ 131.3
20	-$ 4.5	-$ 135.7
21	-$ 4.5	-$ 140.2
22	-$ 4.5	-$ 144.6
23	-$ 4.5	-$ 149.1
24	-$ 4.5	-$ 153.6
	NPV =	-$ 153.6

Figure 8 – Annual cashflow summary and NPV

The DST was utilized with inputs for population, wastepaper percentage, waste generation, capture rate, capital cost, utility sale price, and conversion efficiency (Section 2) to evaluate thermal treatment for four cities in Saskatchewan (Saskatoon, Swift Current, La Loche and Outlook). An additional analysis was performed using a population of 500,000 to simulate a larger city and provide a forecasting opportunity for Saskatoon. For the analysis in this thesis the cost for landfilling and recycling all wastepaper (Section 2.2.7) for 25 years was calculated for use as a comparison. Using the baseline values (Section 2) a capital cost for the plant was calculated that would provide an NPV equivalent to the combined landfilling and recycling cost. The capital cost was then compared to those found in literature (Section 2.4) to determine if the plant was within the reported range.

A one-at-a-time (OAT) sensitivity analysis using linear regression to evaluate change in NPV is built into the DST. This evaluates the degree to which individual parameters (capital cost, utility price, receiving cost, and O&M cost) change the NPV and therefore the viability of the project. The user inputs the points as a percent of the baseline value (i.e. 50%, 75%, 150%, and 200%) for each parameter. The DST then calculates individual NPVs for each parameter and point. A scatterplot of each parameter is then generated and a trendline fit between the points. The slope of the trendline indicates the degree of change that the parameter has on the NPV (in millions CAD) for every 100% change in the parameter. For example, a slope of -30 for feedstock cost would indicate that for every 100% increase in feedstock cost, the NPV would decrease by $30 million. This allows for the prioritization the parameters that have the largest effect on NPV and the viability of the thermal treatment plant.

3.3. Baseline Information

The information collected was used as the basis for an initial evaluation in this thesis, as well as to give municipalities a starting point to begin a feasibility analysis or critically evaluate a project presented to them. The literature review (Section 2) therefore provides properly sourced values for comparison and baseline inputs for the following variables in a wastepaper to energy project:

- Capital cost estimation
- Wastepaper generation and capture rate
- Utility rates
- Energy generation estimates
- Transportation costs
- Carbon Tax

3.3.1. Capital Cost Estimation

In addition to literature values (Section 2.4.1.1), vendors in Canada were also contacted to determine the cost of smaller IHR units. Three vendors responded with estimates based on the available units and feedstock characteristics discussed in this study (Table 5). Both vendors indicated that wastepaper would likely require some type of pre-processing, including pelletization. Pelletization and pre-treatment costs would add to the prices provided and the cost would be dependent on the requirements of the specific unit. Pricing from Säätötuli is on the lower end of the range of pricing found in literature ($544 - $2,552 per metric tonne of annual capacity, Section 2.4.1.1). The pricing from Krann is much lower than literature would suggest but given the high-level nature of the estimate this could be due to variance in technology, a variety of construction factors, or the lack of required pre-treatment processes. An additional vendor (Fröling) was contacted and provided estimates for a much smaller unit that could be suitable for use in smaller cities or installations (Biothermic Wood Energy Systems, 2021), and provided a capacity cost similar to Säätötuli units. Estimates from Canadian vendors indicate a range of $73 - $533 per metric tonne of annual capacity, below that found in literature of $544 - $2,552 per metric tonne of annual capacity (Section 2.4.1.1). Canadian estimates only included the cost of the equipment and not a turn-key operation as found in literature. Due to the limited scope of the pricing from Canadian vendors the value they were not used for analysis but are provided for reference.

Table 5 – IHR estimates from Canadian vendors

Vendor	Estimated Cost CAD	Estimated Cost per Annual MT Capacity*
Säätötuli Canada Enterprises Inc.	$1,300,000	$533
	$1,700,000	$465
Krann Energy Systems	$ 825,000	$169
	$1,075,000	$110
	$2,035,000	$ 83
	$2,675,000	$ 73
Fröling	$ 20,000	$410

*Estimated cost per metric tonne was calculated based on MW capacity and assumed LHV of 13.7 GJ/MT, facility uptime of 90% and a conversion efficiency of 85%

The $544 - $2,552 per metric tonne of annual capacity (Section 2.4.1.1) found in literature was used. These costs are based on a complete installation whereas those provided by Canadian vendors indicated the need for additional processes. Capital cost rates ($4,356 - $9,903 per kW_e) used for CHP case studies were those found in literature (Section 2.4.2.1). Capital cost rates were converted to dollars per metric tonne of annual capacity to align with incineration plant rates assuming 13.7 GJ/tonne and 90% facility uptime for a range of $2,101 - $4,777 per tonne of annual capacity for wastepaper.

3.3.2. Wastepaper Generation and Diversion Rate

The expected wastepaper available per city was determined using the values found in literature (approximately 273 kg/person/yr, Section 2.2.1). The total amount of wastepaper was estimated by multiplying the municipality population by the average waste generation rate for the province and the proportion of wastepaper. The total wastepaper was then multiplied by the current diversion rate (18%, Section 2.2.1) as well as the government's diversion rate target (50%, Section 2.2.1). The estimated availability of wastepaper is shown in

Table 6.

Table 6– Estimated annual availability of dry combustible material at indicated diversion rates in the selected cities

City/Town	Population	100% Diversion (tonnes)	50% Diversion (tonnes)	18% Diversion (tonnes)
Saskatoon	246,376	73,900	37,000	12,100
Swift Current	16,604	5,000	2,500	820
La Loche	2,372	700	350	120
Outlook	2,279	680	340	110

Historical waste generation rates for neighbouring provinces and Canada were also calculated (Table 7) using the same data sets (Government of Canada, 2021a; Government of Canada, 2021b; Government of Canada, 2021c) for comparison. Saskatchewan has historically remained below Alberta but typically above both Manitoba and the Canadian average. Since 2010 the Canadian average has declined slightly by approximately 2.5%. Saskatchewan had a larger reduction of annual waste generation by about 8.5%, bringing Saskatchewan slightly below the Canadian average.

Table 7 – Historical waste generation (kg/per person) for neighbouring provinces and Canada based on population and waste generated

	2010	2012	2014	2016	2018
Saskatchewan	1,027	1,028	1,001	940	912
Alberta	1,243	1,206	1,200	1,201	1,175
Manitoba	982	962	918	898	876
Canada	972	955	955	948	959

3.3.3. Energy Generation Estimates

Energy generation estimates are based on a LHV calculated assuming an HHV of 15 GJ/tonne and a moisture content of between 4% and 10% (Section 2.4.4) using Equation 2.2, for an energy content of 13.7 GJ/tonne. This provides the overall energy generation of the plant prior to accounting for plant efficiency.

For a heat recovery plant, this is multiplied by the median plant efficiency of 85% (Section 2.4.1) to determine the amount of heat the plant could provide. For a CHP unit, a median thermal conversion efficient of 52% and electrical conversion efficiency of 34% (providing a combined plant efficiency of 86% (Section 2.4.2) is used to determine the heat and electrical production of the plant.

3.3.4. Utility Rates

Utility rates for heat based on the equivalent cost for heating with natural gas, approximately $3.558/GJ for large consumers (Section 2.5.2.2) due to the heat generated. This represent the cost that a municipality would offset from typical natural gas use. Electricity sale price was based the rate specified under the Power Generation Partner Program of $0.07 per kWh (Section 2.5.1.2) as this is the rate that SaskPower would pay the municipality for electricity sold into the grid.

3.3.5. Transportation Costs

Transportation costs for biomass were first adjusted to 2020 Canadian dollars and metric tonnes. Ko, et al (2018) suggested a range of $0.18 – $0.21 per dry ton-km for straw and woodchips. Adjusting to metric tonnes and 2019 Canadian dollars (assuming a 2014 exchange rate of 1.1045 CAD per USD (Bank of Canada, 2017) and annual inflation of 1.62% (Bank of Canada, 2021) the range is approximately $0.24 - $0.28 CAD per dry tonne-km. Applying a similar conversion to the range given by Han (2011) and using an exchange rate of 0.9891 CAD per USD (Bank of Canada, 2021) and inflation of 1.62% (Bank of Canada, 2021) the range is approximately $0.27 - $0.37 CAD per green tonne-km.

As a localized comparison, a trucking company operating in Saskatchewan was contacted to estimate the cost of full truckload shipping. In 2020, the company was transporting wastepaper bales within the province for recycling and provided some estimates and insight into the logistics. Currently the company can fill a 12m tractor trailer unit with baled wastepaper. The estimated cost for shipping using a 40-foot tractor trailer unit was approximately $0.35 per tonne-km and a full load of cardboard was approximately 40,000 lbs or 18,144 kg for a one-way haul. If the trucking company does not have a back-haul (the return direction of the truck), the municipality could be charged for the round trip to pay for the truck to return to the point of origin. This could nearly double the cost of transportation depending on the rate charge for the empty return trip. It would therefore be crucial for the municipality to find a back-haul route where the cost of shipping is offset by goods moving in the other direction. If a trucking company can be found that has an empty backhaul route already available in the desired direction, the trucking company indicated rates could drop by approximately 20% depending on the circumstance. Changes in fuel prices, logistics (such as the availability of a back-haul), availability of shipping companies in the area, loading requirements, viability of a long-term contract etc. will impact the price a municipality will pay. Both literature and localized pricing suggest a trucking cost of $0.24 - $0.37 per tonne-km would be expected for long haul shipments.

3.3.6. Landfill and Recycling Rates for Cost Comparison

The costs for landfilling or recycling wastepaper were used as a reference point for a thermal treatment plant. When available, the local landfill cost was used (

Table 2) for the portion estimated to go to landfill otherwise the average of $90/MT was used. Recycling costs were based on either the available cost (such as for Saskatoon) or the range of available costs of $275 to $576 per tonne (Section 2.2.7). Recycling was used as the base case for disposal cost where recycling was available. If no recycling known to be available, landfill costs were used.

3.3.7. Carbon Tax

Emissions from a thermal treatment plant utilizing wastepaper may be considered carbon neutral (Section 2.6). If the plant was not considered carbon neutral and was required to pay a carbon tax on emissions, the carbon tax cost was also determined. The carbon composition of wastepaper ranges from 37% to 50% carbon by weight (Section 2.6). When converted to carbon dioxide, each tonne of carbon generates approximately 3.7 tonnes of carbon dioxide. The thermal treatment of wastepaper would therefore be expected to generate between 1.4 and 1.9 tonnes of carbon dioxide. At a carbon tax rate of $50 per tonne carbon dioxide, this represents a cost of approximately $70 - $95 per tonne of wastepaper for the carbon tax.

3.3.8. Sensitivity Analysis

A one-at-a-time (OAT) sensitivity analysis was then completed for each parameter to determine the main drivers of plant economics. The sensitivity analysis generates a trendline that can be used to determine the rate of change each parameter has on the NPV indicated by the slope. The slope of the trendline indicates the resulting change in NPV that is estimated for each 100% change in the parameter. A negative slope indicates that there is an inverse relationship and that as the parameter increases in value, the NPV decreases. If the slope were positive this would indicate a direct relationship (such as with utility price) and an increase in the parameter would increase the NPV. An increase in NPV indicates that the financial feasibility of the proposed facility/operation has increased and a decrease in NPV indicates that the facility/operation becomes less financially viable.

4. RESULTS AND DISCUSSION

Using the data discussed, the Decision Support Tool was created to assist municipalities in performing a high-level analysis on the feasibility of thermal conversion for wastepaper disposal. The four cities selected (Saskatoon, Swift Current, La Loche, and Outlook) and a forecasted population center of 500,000 were used to demonstrate the tool as well as provide a preliminary analysis for the cities. A population of 500,000 was selected to represent a forecasting opportunity for larger cities, such as Saskatoon, and it represents Saskatoon's population approximately doubling.

4.1. Evaluation Outline

Inputs used for the best-case and worst-case scenarios are shown in Table 8. These inputs were used to calculate the comparative NPV of a thermal treatment system compared to landfilling or recycling. The resulting NPV represents the potential savings, if positive, or loss, if negative, compared to either landfilling or recycling. Receiving cost in the DST (the cost paid by the plant to purchase wastepaper) was used to account for the offset cost of landfilling or recycling. Either the cost to landfill ($90/tonne, Section 2.2.7) or the cost of recycling ($576/tonne) was subtracted from the baseline receiving cost ($93/tonne for collection and $10 for purchasing the wastepaper, Section 2.2.4 and Section 2.2.6) to represent the offset. For landfilling this represents $13/tonne and for recycling $(470)/tonne. The negative receiving cost in the recycling scenario indicates that the plant would save the municipality $470 for every tonne of wastepaper that was received at the plant due to the high cost of recycling. The positive price for the landfilling comparison indicates that it costs the plant $13 for each tonne received at the plant rather than landfilled.

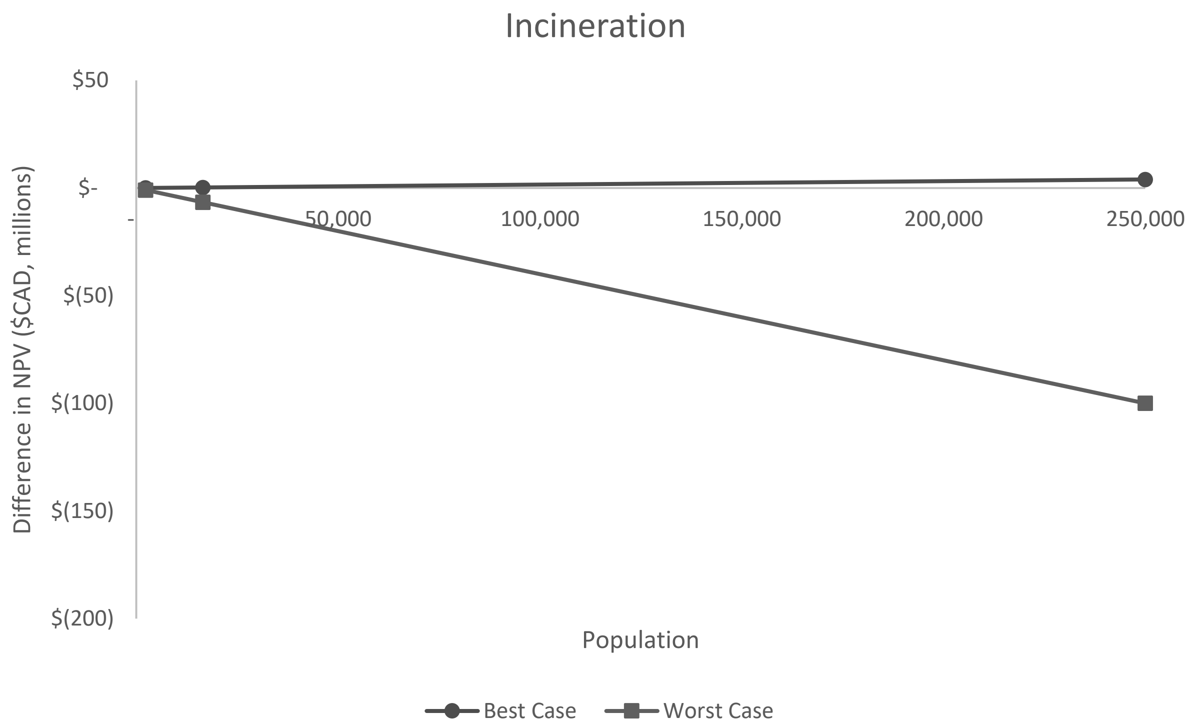
Table 8 – Inputs used for best-case and worst-case scenarios for thermal treatment comparison to recycling and landfilling

Input Variable for the Decision Support Tool	**Incineration**		**CHP**	
	Best-Case	Worst-Case	Best-Case	Worst-Case
Capital Price Rate ($/metric tonne annual capacity)	$544	$2,552	$2101	$4,777
Electricity Price ($/kWh)	N/A	N/A	$0.14	$0.07
Heat Sale Price $/GJ	$5.14	$3.56	$5.14	$3.56
Thermal Conversion Efficiency (%)	86%	77%	55%	49%
Electrical Conversion Efficiency (%)	N/A	N/A	39%	30%
Estimated O&M Costs (% of capital expense per annum)	2%	10%	2%	10%

The comparison of thermal treatment was then performed for the range of 2,300 to 250,000 to cover the identified cities (La Loche, Outlook, Swift Current, and Saskatoon) and is shown for landfilling (Figure 9) and recycling (Figure 10). The area between the lines represents the expected cost (negative NPV) or savings (positive NPV) for the implementation of a thermal treatment plant compared to recycling or landfilling.

Both incineration and CHP are unlikely to provide disposal at a lower cost than the evaluated landfill rate of $90 per tonne (Figure 9). For landfilling, only approximately 4% of the range is at a total cost equal to or less than landfilling. A CHP based plant is also unlikely to produce a disposal cost equal to or less than landfilling this is only approximately 15% of the range. In both cases, only the best-case scenario indicates a disposal cost lower than landfilling at a rate of $90 per tonne. Thermal treatment is therefore unlikely to be able to provide a lower cost than landfilling at current prices of $90/tonne.

A thermal treatment plant has a high likelihood of providing disposal at a lower cost than recycling (Figure 10). For an incineration plant the entire range is positive, indicating that even in the worst-case scenario incineration would be expected to provide a disposal route at a lower cost than recycling. Combined heat and power indicates most outcomes provide a lower cost of disposal with only 15% of the range indicating a higher cost than recycling. Thermal treatment is therefore likely to provide disposal at a lower cost than recycling.



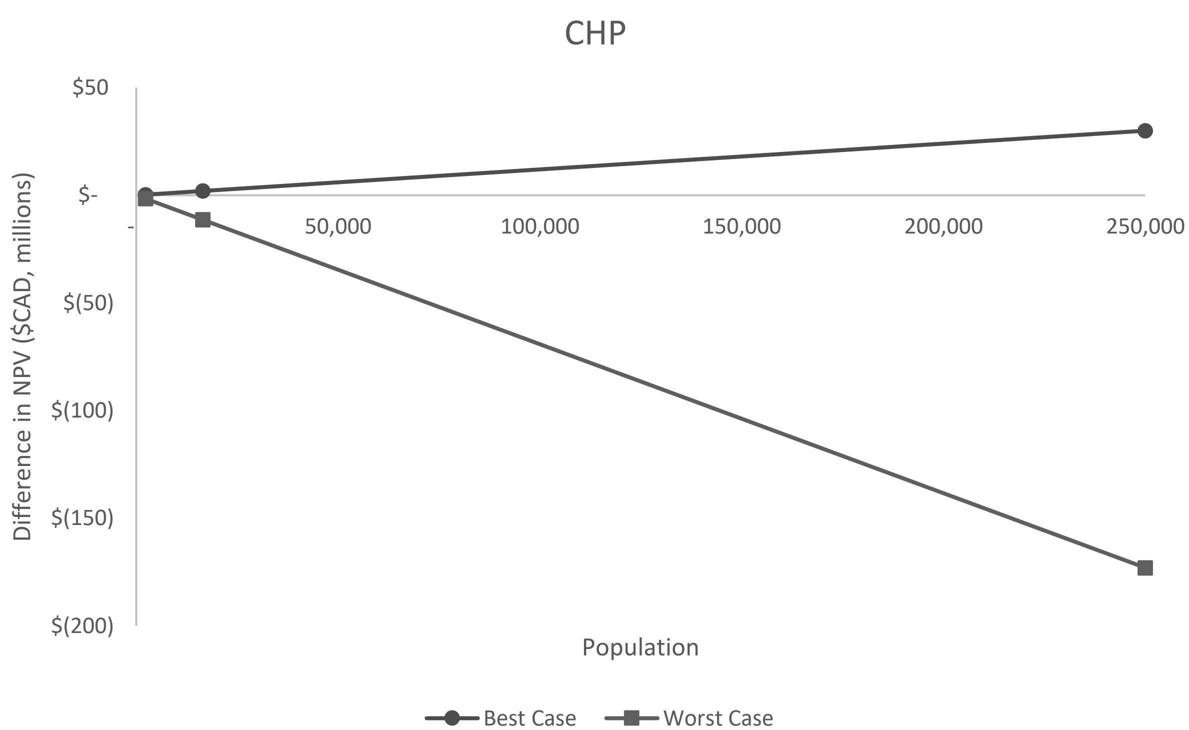


Figure 9 - Net Present Value (NPV) of an incineration based thermal treatment plant (top) and combined heat and power (bottom) compared to landfilling in Saskatchewan

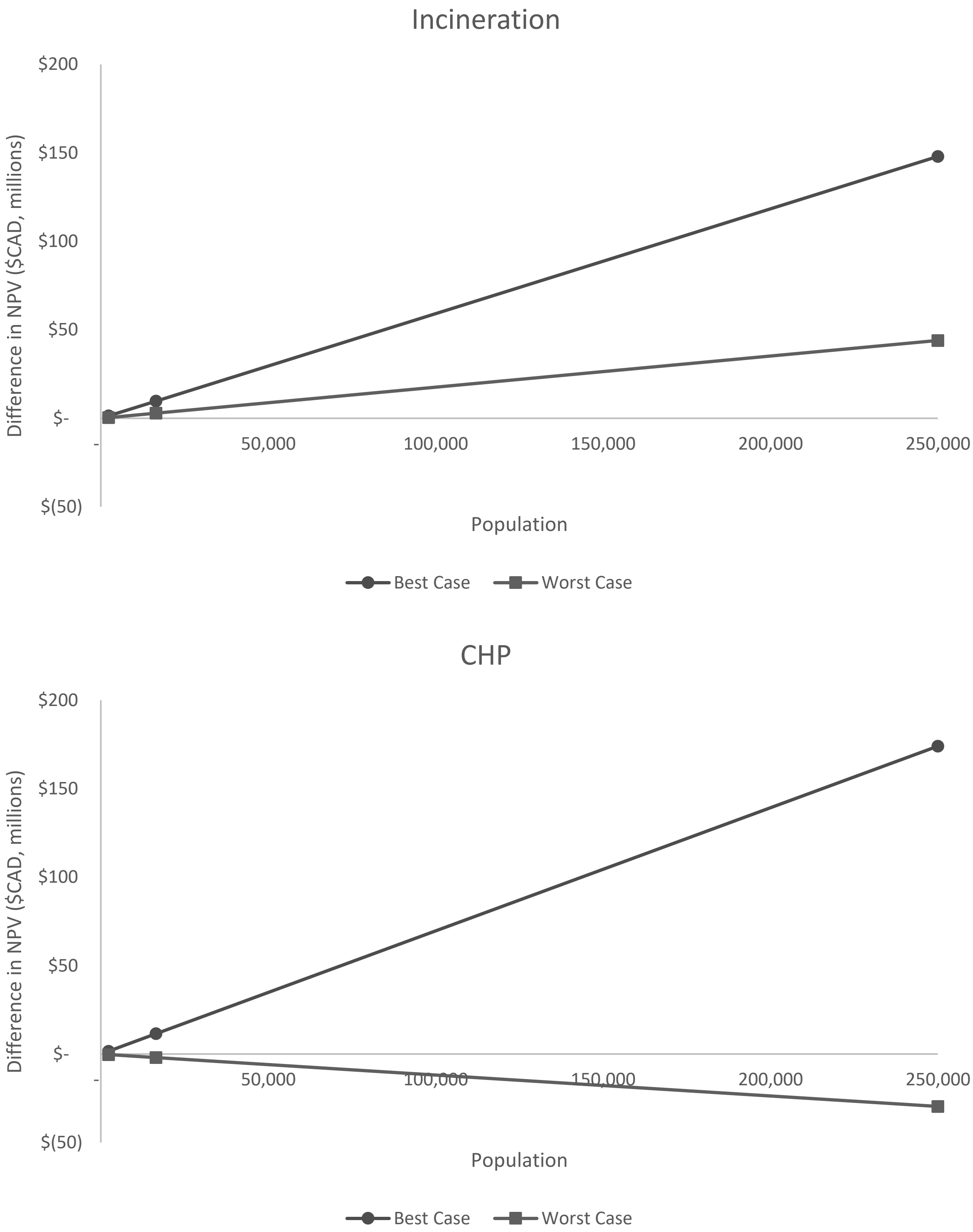


Figure 10 – Net Present Value (NPV) of an incineration based thermal treatment plant (top) and combined heat and power (bottom) compared to recycling in Saskatchewan

4.1.1. Decision Support Tool Inputs and Calculated Values

Inputs are based on literature values provided in this thesis or provided by the municipality itself. Inputs can be changed to determine the sensitivity of the project or assist the municipality in forecasting the impact to project viability based on changing inputs.

For individual locations, the large range and inconsistent nature of the critical parameters can make an initial evaluation challenging. To evaluate the viability of a thermal treatment plant in each location, baseline values were utilized for plant inputs to determine the capacity price that delivers an NPV equal to either recycling or landfilling at each of the identified locations. This defines a maximum capacity that was compared to the discussed pricing. A sensitivity analysis was used to indicate the economic impact of the plant inputs and identify the most impactful parameters that can be used to increase the profitability of a thermal treatment plant. Using the cost of landfilling and/or recycling over 25 years, the capital cost rate of the thermal treatment plant is adjusted until the NPV matches the competing methods cost. This provides a maximum cost that the technology provider would need to provide a thermal treatment plant for. The inputs defined in the DST are as follows:

- Population – number of people in the area of interest
- Wastepaper Waste Percentage – percentage of waste that is wastepaper
- Waste Generation Rate – average waste generation of the population
- Wastepaper Capture Rate – percent of wastepaper that is captured (i.e., not landfilled)
- Capital Cost – estimated capital cost based on an annual capacity
- Receiving Cost at Plant – cost paid by the plant to a wastepaper supplier
- Heat Sale Price – sale price of generated heat
- Thermal Conversion Efficiency – how efficiently the plant can generate heat
- Electrical Conversion Efficiency – how efficiently the plant can generate electricity
- Estimated O&M Costs – operation and maintenance costs based on percent of capital
- Discount Rate – accounts for inflation or a desired profit rate
- Transportation Cost – cost of bringing in material from the surrounding area

Calculated values are the basis for the financial decision. They are calculated based on the input values to the DST and used to generate the NPV of the thermal treatment plant.

- Annual Waste Throughput – amount of wastepaper utilized by the plant each year
- Capital Cost – total cost of construction
- Estimated Annual Gross Revenue – gross revenue generated by the plant annually
- Estimated Annual O&M Costs – annual cost of operations and maintenance
- Annual Heat Generation – amount of heat generated annually
- Electricity Generation – amount of electricity generated annually
- Net Present Value – value of the plant (in current year dollars) at the end of its designed life
- Sensitivity Summary – indicates the sensitivity of net present value to changes on the inputs of capital cost, utility income, receiving cost at plant and O&M costs.

The inputs, except for population, remain the same for each municipality for the initial evaluation. Two diversion rates were selected to reflect the current waste diversion rate (18%) as well as the opportunity if the provincial diversion target is met (50%).For each of the evaluations the following parameters were used:

- Wastepaper Waste Percentage – 30%
- Waste Generation Rate – 912 kg/person/yr
- Wastepaper Capture Rate – 18% and 50%
- Receiving Cost at Plant – $103/tonne (includes $93/tonne collection cost)
- Heat Sale Price – $3.558/GJ
- Electricity Sale Price – $0.07 per kWh
- Thermal Conversion Efficiency – 85%
- Estimated O&M Costs – 10% of capital cost per annum
- Thermal Conversion Efficiency
    - Incineration – 85%
    - Combined Heat and Power – 52%
- Combined Heat and Power Electrical Conversion Efficiency – 34%

4.2. Saskatoon Incineration with Heat Recovery

A population of 246,746 was used to evaluate the viability of IHR plant in Saskatoon in comparison to landfilling and recycling. Current estimates for recycling ($576 per tonne, Section 2.2.7) were used to evaluate the feasibility of an IHR plant in Saskatoon. Based on the population (246,746) , wastepaper waste percentage (30%), and waste generation rate (912 kg/person/yr) from Section 4.1.1, Saskatoon would have approximately 1,700,000 tonnes of wastepaper for disposal and recycling over 25 years. Table 9 shows the expected costs and volumes of wastepaper based on diversion rates of 18% and 50% (Section 2.2.1).

Table 9– Estimated annual wastepaper amounts and cost for disposal based on diversion

	18% Diversion (tonnes)	**Cost**	**50% Diversion (tonnes)**	**Cost**
Landfilled	1,394,000	$146,370,000	850,000	$89,250,000
Recycled	306,000	$176,256,000	850,000	$489,600,000
Total	1,700,000	$322,626,000	1,700,000	$578,850,000

4.2.1. Capital Expenditure and Net Present Value Baseline

Using the inputs specified in Section 4.2, the Decision Support Tool was used to estimate the capital cost that would result in a net present values (NPV) of $(176) million and $(490) million (Table 10) to represent the 18% and 50% diversion cases respectively. Using the undiscounted rate allows for a direct comparison to be made to the extrapolated landfilling and recycling costs as inflation is not considered. Based on these estimates, a capital cost upper limit of $3,834 per tonne of annual capacity using baseline assumptions, would equal current recycling costs over 25 years.

Table 10 – Base Case Estimated Plant Values for Saskatoon

	%18 Diversion	%50 Diversion	
Estimated Capital Price Rate	$3,834	$3,834	CAD/metric tonne/yr
Annual Waste Throughput	12,152	33,755	Metric Tonnes
Capital Cost	$47	$129	million CAD
Estimated Annual Revenue	$0.5	$1.4	million CAD
Estimated Annual O&M Costs	$4.7	$13	million CAD
Annual Heat Generation	140,994	391,649	GJ
Net Present Value (Undiscounted)	$(176)	$(490)	million CAD

4.2.2. Sensitivity Analysis of the Baseline

A sensitivity analysis was used to determine the degree to which individual parameters change the NPV. Each parameter will have a varying impact on the success of a project and that impact was estimated by varying each parameter individually across a range. The resulting change to NPV was then graphed and a trendline fit to the points. The slope of the trendline indicates the degree to which the target parameter changes the NPV. The slope of each sensitivity analysis was then compared to determine the parameters that have the largest impact on NPV can be identified.

4.2.2.1. Wastepaper Price

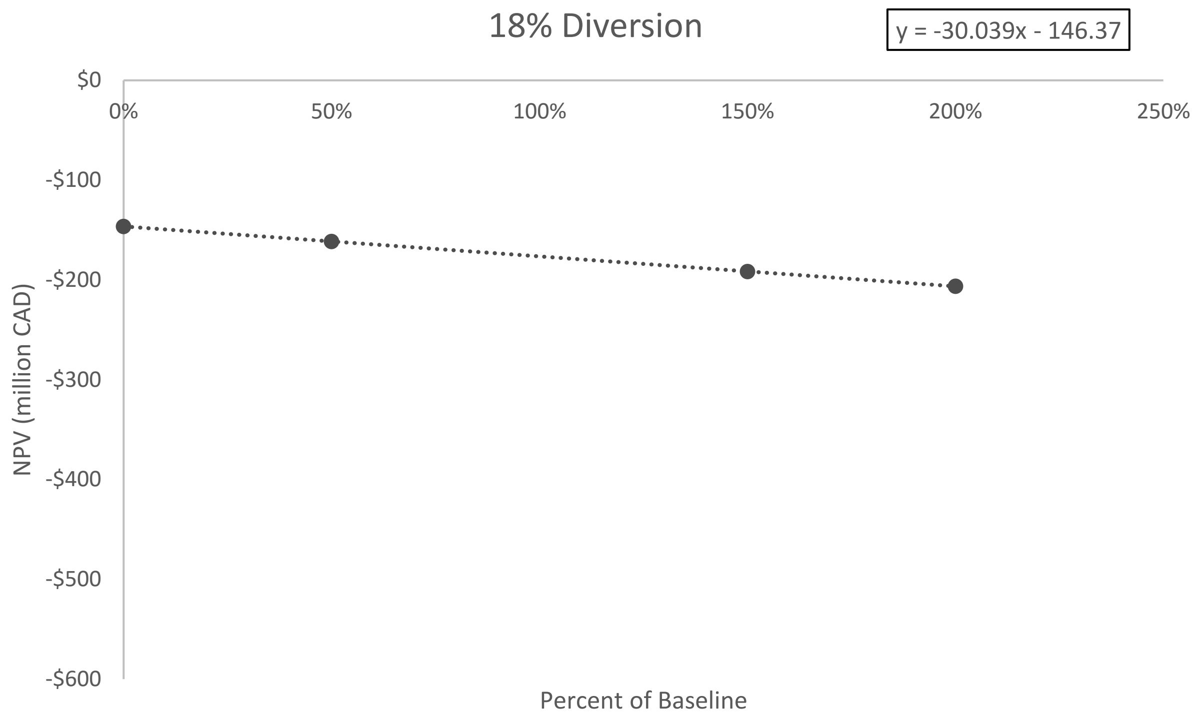
The base model assumes that feedstock is available at a cost of $103/MT to the City which includes a $93/MT collection fee and a receiving price of $10/MT (Section 2.2.6). The sensitivity analysis is shown in Table 11 with the impact of a changing feedstock cost with a discount rate of 0%. Percent of assumed value indicates the change to the cost of wastepaper and establishes the range that was evaluated.

Table 11 – Sensitivity of feedstock cost with a discount rate of 0%

Percent of Assumed Value	Wastepaper Price (per Tonne)	NPV 18% Diversion (million CAD)	NPV 50% Diversion (million CAD)
200%	$206	$(206)	$(573)
150%	$155	$(191)	$(532)
100%	$103	$(176)	$(490)
50%	$52	$(161)	$(448)
0%	$0	$(146)	$(407)

The results from Table 11 were then graphed for both the 18% and 50% diversion rates with a linear trendline fit to both data sets to determine the slope (Figure 11). The slope of the trendlines indicate the degree of change that delivered wastepaper price has on the NPV of the IHR plant. The slopes indicates that for every 100% increase to wastepaper cost, there is a $30 million decrease in NPV for the 18% diversion case and a $83 million decrease for the 50% diversion case.

The equations can also be used to estimate any change to wastepaper cost with respect to the baseline. The x in the trendline equation represents the target multiplier for evaluation and the y represents the corresponding NPV. For example, if the delivered wastepaper price for the 50% diversion case were to increase by five times (500% of the baseline value) then x is five. The resultant NPV would be approximately $(824) million. This can be verified by using the DST to calculate the NPV of the plant using the increased wastepaper cost of $515 per metric tonne, which also returns an NPV of $(824) million.



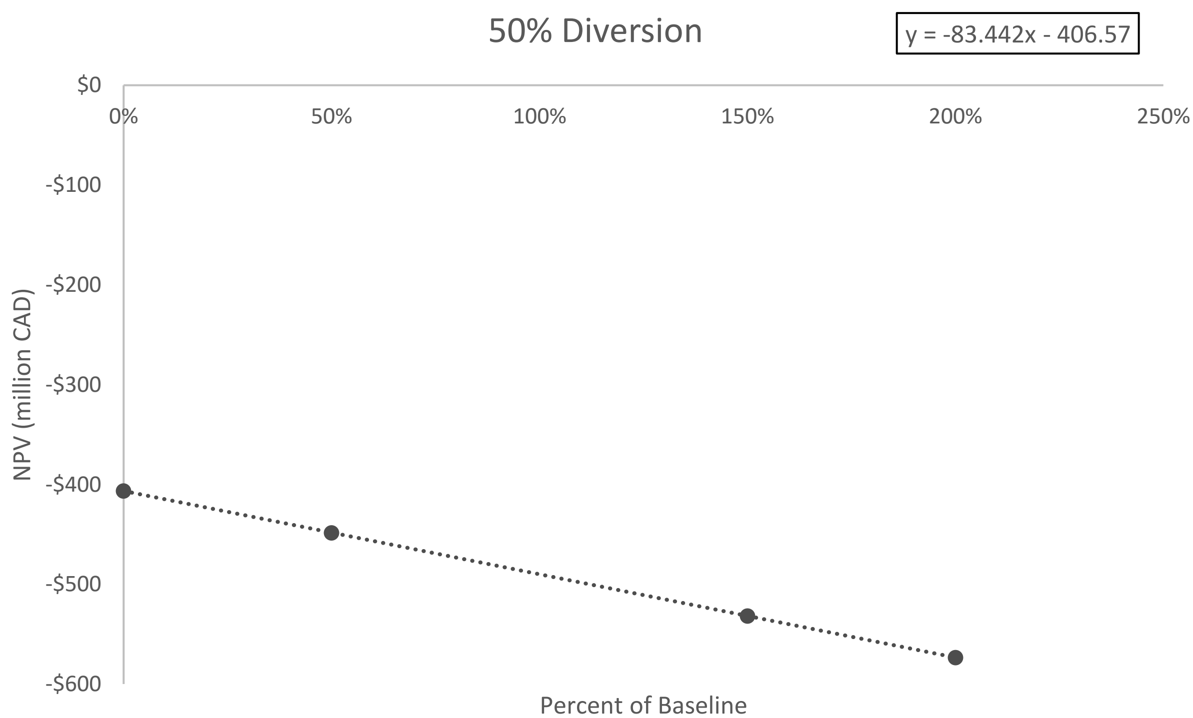


Figure 11 – Change in net present value (NPV) with respect to wastepaper cost for 18% diversion rate (top) and 50% diversion rate (bottom) for an incineration with heat recovery plant in Saskatoon.

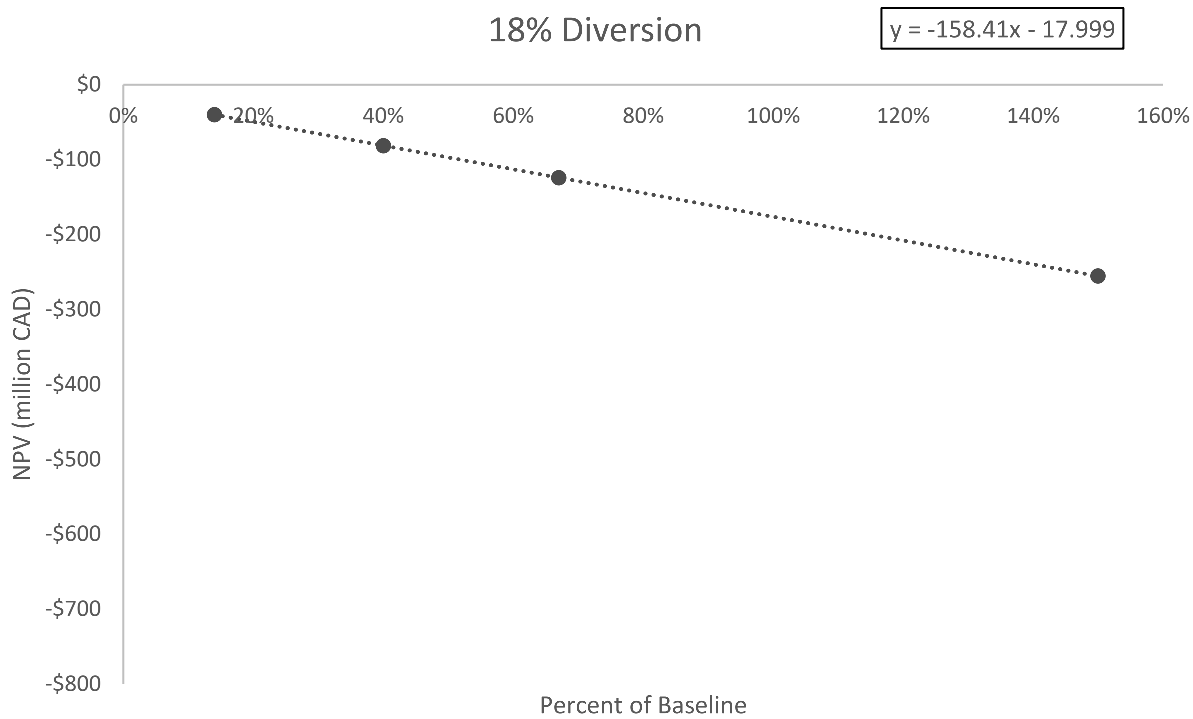
4.2.2.2. Capital Cost

The case for Saskatoon assumes a capital cost upper limit of $3,834 per tonne of annual capacity and this is above the range found in literature of $544 - $2,552 per tonne of annual capacity and the range of $73 – $533 per tonne of annual capacity provided by Canadian vendors (Section 3.3.1). This indicates that the selection of a unit with a capital cost less than $3,834 is feasible. As such the sensitivity analysis focused on the upper, median, and lower points of the range reported in literature (67%, 40%, and 14% of assumed respectively) and one point to evaluate a higher capital cost (150%) shown in Table 12

Table 12 – Sensitivity of capital cost with a discount rate of 0%

Percent of Assumed Value	Capital Cost ($/tonne annual capacity)	NPV 18% Diversion (million CAD)	NPV 50% Diversion (million CAD)
150%	$5,751	$(256)	$(710)
100%	$3,834	$(176)	$(490)
67%	$2,569	$(124)	$(345)
40%	$1,534	$(81)	$(226)
14%	$ 537	$(40)	$(112)

The results from Table 12 were then graphed for both the 18% and 50% diversion rates with a linear trendline fit to both data sets (Figure 12). The slope of the trendlines indicate the degree of change that capital cost has on the NPV of the IHR plant. The slopes indicates that for every 100% increase to capital cost, there is a $158 million dollar decrease in NPV for the 18% diversion case and an $440 million dollar decrease for the 50% diversion case.



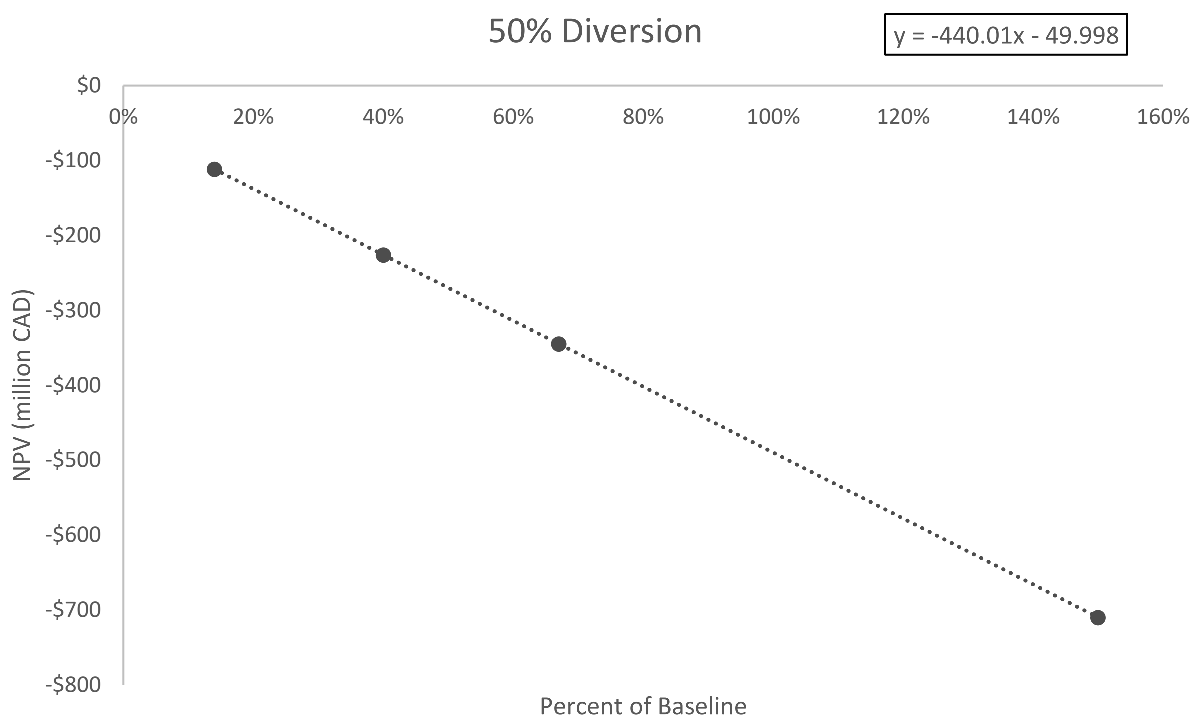


Figure 12 - Impact of capital cost on net present value (NPV) for 18% diversion rate (top) and 50% diversion rate (bottom) for an incineration with heat recovery plant in Saskatoon.

The equations can also be used to estimate any change to wastepaper cost with respect to the baseline. The *x* in the trendline equation represents the target multiplier for evaluation and the *y* represents the corresponding NPV. For example, if the capital cost for the 18% diversion case were to decrease by 25% (75% of the baseline value) then *x* is 0.75. The resultant NPV would be approximately $(137) million. This can be verified by using the DST to calculate the NPV of the plant using the lower capital cost of $2876 per metric tonne of annual capacity, which also returns an NPV of $(137) million.

4.2.2.3. Utility Sale Price

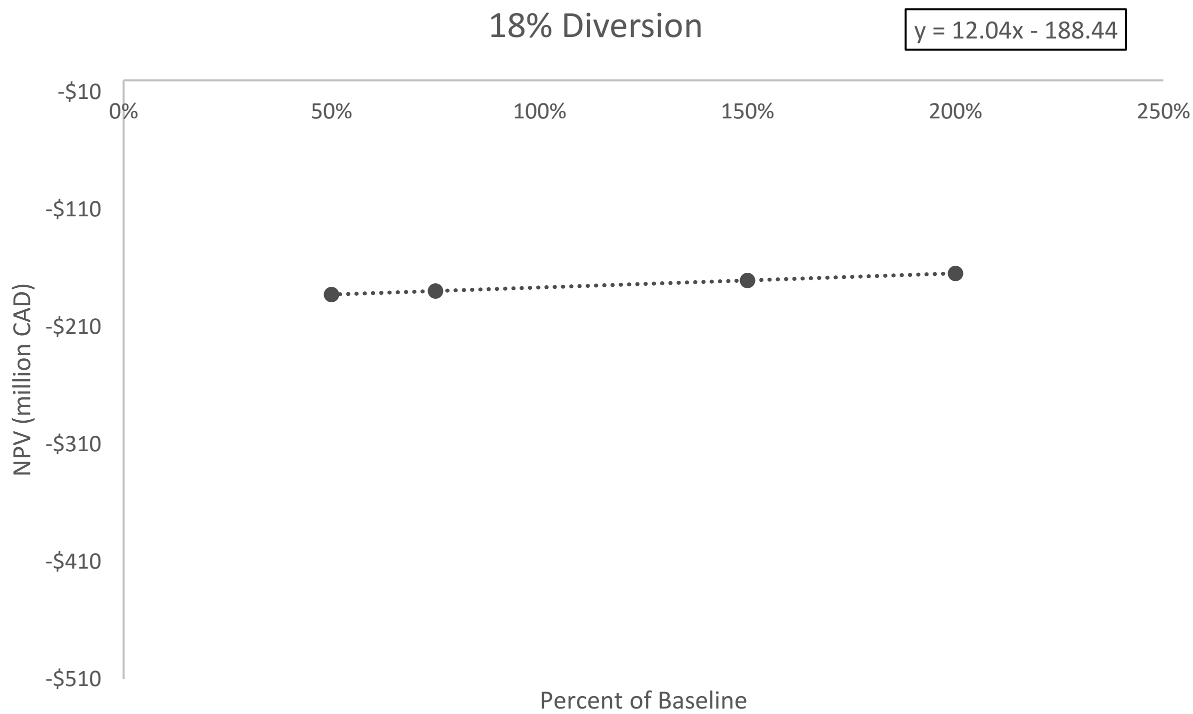
For the base case it was assumed that Saskatoon would be able to sell the generated heat at $3.558 per GJ (Section 2.5.2.2). This utility price includes the carbon tax of $50/tonne$_{CO2}$ that would be charged on natural gas at a rate of $0.0979/m^3 of natural gas (Section 2.5.2.2). As the carbon tax increases, and thereby the cost of natural gas, an increased utility price could be demanded to match the price of natural gas. An increasing carbon tax positively impacts the viability of the IHR plant as it will directly increase the competing cost of natural gas and therefore the sensitivity is weighted towards increasing prices with 144% of baseline approximating the current residential rate of $5.137/GJ. Table 13 shows the changes in heating price with a discount rate of 0%. The results from Table 13 were then graphed for both the 18% and 50% diversion rates with a linear trendline fit to both data sets to determine the slope (Figure 13).

The slope of the trendlines indicate the degree of change that utility price has on the NPV of the IHR plant. For utility prices, the slope indicates that for every 100% increase to wastepaper cost, there is a $12 million decrease to the NPV for the 18% diversion case and a $33 million dollar decrease for the 50% diversion case. Utility price is the only parameter that has a positive slope as increasing utility price increases revenue generated by the plant.

The equations can also be used to estimate any change to utility price with respect to the baseline. The *x* in the trendline equation represents the target multiplier for evaluation and the *y* represents the corresponding NPV. For example, if the utility price for the 50% diversion case were to increase by 10% (110% of the baseline value) then *x* is 1.1. The resultant NPV would be approximately $(487) million. This can be verified by using the DST to calculate the NPV of the plant using the increased utility price of $3.914/GJ, which also returns an NPV of $(487) million.

Table 13 – Sensitivity of utility price with a discount rate of 0%

Percent of Assumed Value	Utility Price ($/GJ)	NPV 18% Diversion (million CAD)	NPV 50% Diversion (million CAD)
200%	$7.116	$(164)	$(457)
144%	$5.124	$(171)	$(475)
120%	$4.570	$(174)	$(483)
100%	$3.558	$(176)	$(490)
50%	$1.779	$(182)	$(507)



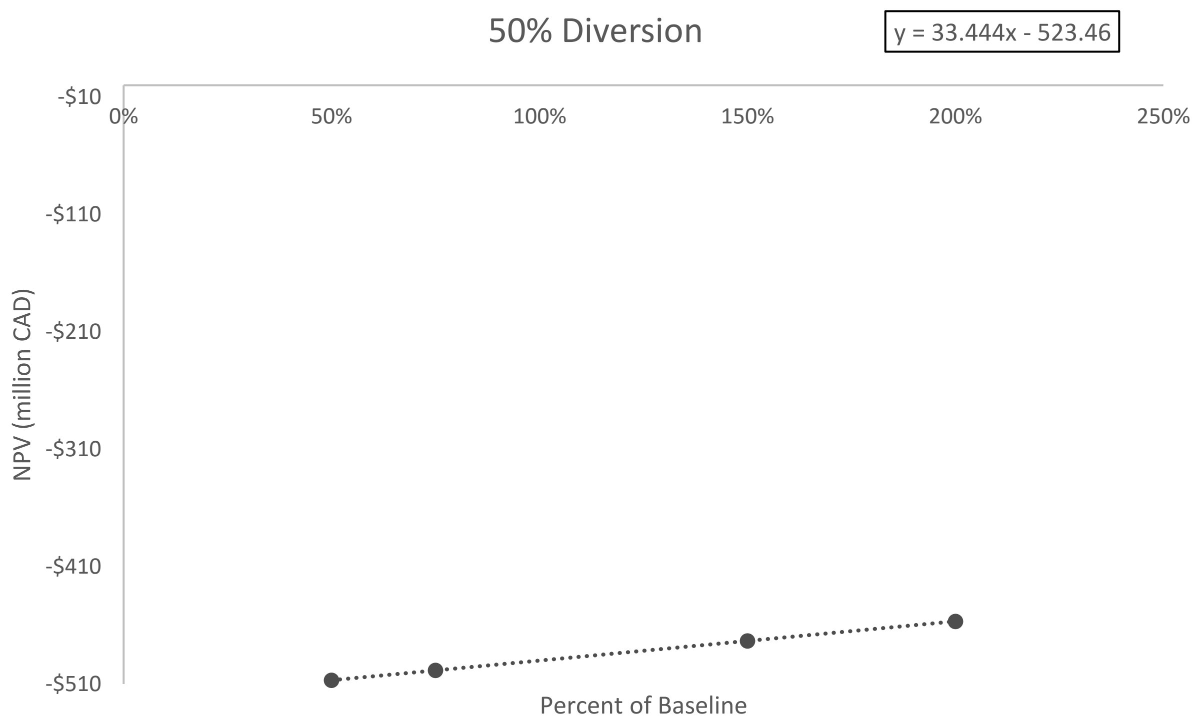


Figure 13 – Impact of utility price on net present value (NPV) for 18% diversion rate (top) and 50% diversion rate (bottom) for an incineration with heat recovery plant in Saskatoon.

4.2.2.4. Operating and Maintenance Costs

The base case for Saskatoon assumed an annual O&M cost of 10% of capital expense. O&M costs will vary based on the technology provider selected, level of automation, and available workers and literature suggests a range of 4% - 10% (Section 2.4.3). Table 14 shows the impact of changing O&M costs using a discount rate of 0%.

The results from Table 14 were then graphed for both the 18% and 50% diversion rates with a linear trendline fit to both data sets to determine the slope (Figure 11). The slope of the trendlines indicate the degree of change that O&M costs have on the NPV of the IHR plant. For O&M, the slope indicates that for every 100% increase there is a $112 million decrease in NPV for the 18% diversion case and a $311 million decrease for the 50% diversion case.

The equations can also be used to estimate any change to O&M cost with respect to the baseline. The *x* in the trendline equation represents the target multiplier for evaluation and the *y* represents the corresponding NPV. For example, if the O&M costs for the 50% diversion case were 6% of capital (60% of the baseline value) then *x* is 0.5. The resultant NPV would be approximately $(366) million. This can be verified by using the DST to calculate the NPV of the plant using the increased wastepaper cost of $515 per metric tonne, which also returns an NPV of $(366) million.

Table 14 – Sensitivity of O&M costs with a 0% discount rate

Percent of Assumed Value	O&M Cost (% of capital)	NPV 18% Diversion (million CAD)	NPV 50% Diversion (million CAD)
150%	15%	$(232)	$(645)
100%	10%	$(176)	$(490)
70%	7%	$(143)	$(397)
40%	4%	$(109)	$(304)
20%	3%	$(87)	$(242)

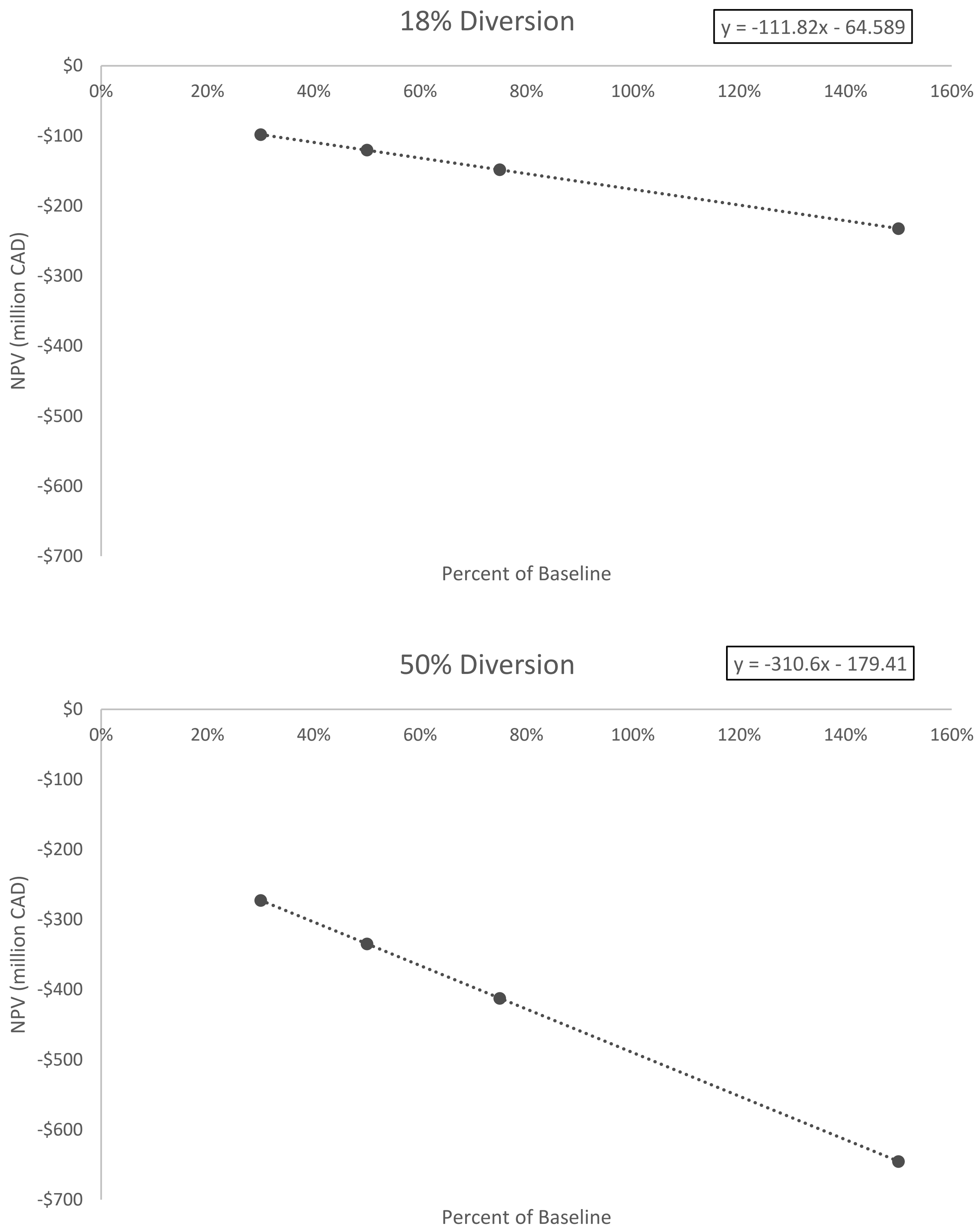


Figure 14 – Impact of O&M costs on net present value (NPV) for 18% diversion rate (top) and 50% diversion rate (bottom) for an incineration with heat recovery plant in Saskatoon.

4.2.2.5. Sensitivity Summary

Using the trendline slopes from Sections 4.2.2.1 to 4.2.2.4 a hierarchy can be established based on the parameter impact on NPV (Table 15). For Saskatoon, the critical parameters are the capital cost rate and O&M costs as they are three to four times higher than utility price or receiving costs. If Saskatoon were to go ahead with construction of a plant, capital cost and O&M costs would need to be the focus of cost control and savings. A cost savings of as little as 5% on capital cost or O&M would translate to between $8 million and $22 million over the life of the project. Utility pricing would be difficult for the City to increase as it is a market commodity and the benefit of such an increase to the overall finances is minimal compared to the other parameters. This case study indicated that doubling the sale price of heat over the lifetime of the plant would only generate an additional $12 million for the 18% diversion case and $33 million in the 50% diversion case. The cost of wastepaper transported to the plant has a slightly higher impact than the utility price but still only has one-quarter of the impact of capital cost or O&M.

Table 15 – Saskatoon IHR sensitivity summary

Parameter	Impact on NPV (Trendline Slope) 18% Diversion	Impact on NPV (Trendline Slope) 50% Diversion
Capital Cost	-158	-440
Operating and Maintenance Costs	-111	-310
Wastepaper Price	-30	-83
Utility Sale Price	12	33

4.2.3. Recommendation

For the extrapolated costs of $176 million (18% diversion) and $490 million (50% diversion) for wastepaper recycling, a thermal treatment plant for Saskatoon appears to be viable based on the parameters outlined (Section 4.2). The comparative cost used for the baseline analysis ($3,834 per metric tonne of annual capacity, Section 4.2.1) was above the range in literature ($544 - $2,552 per metric tonne of annual capacity, Section 2.4.1.1) and provided by Canadian vendors ($73 - $533, Table 5). Therefore, selecting a technology below the $3,834 per metric tonne of annual capacity would be reasonable and provide a disposal route to recycling at a lower cost.

Sizing the plant for the current diversion rate (~18%), or lower, would be recommended as the first step. Saskatoon has targeted a diversion rate of 70% (City of Saskatoon, 2020a) but constructing a plant sized for a 70% diversion rate would oversize the plant by approximately 3.5 times. This would substantially increase capital expense and reduce the NPV as the plant would be running at 25% of capacity until Saskatoon achieves 70% diversion. Given that capital expense is the largest indicator of project economics, oversizing the plant in this way would be unlikely to provide disposal at a competitive cost. Sizing the plant near the current diversion rate allows the plant to run at capacity and provide the City an opportunity to optimize the process and gather operational data. It also represents a lower capital expenditure and thereby reduces financial risk. New plants could then be constructed as Saskatoon reaches diversion milestones such as 36%, 54%, and 70% to accommodate the increase in available wastepaper.

If the plant were constructed based on an 18% diversion rate, it would utilize approximately 12,000 metric tonnes of wastepaper annually and approximately 300,000 metric tonnes over the 25-year life. At the capital rate evaluated ($3,834 per metric tonne of annual capacity, Section 4.2.1) this would represent a capital expense of approximately $46 million, generate approximately 141,000 GJ of heat and replace approximately 3.6 million cubic meters of natural gas (Section 2.5.2.2). The thermal treatment plant in Saskatoon would then need a suitable outlet for the heat. The University of Saskatchewan used approximately 30 million cubic meters of natural gas in 2020 to generate steam and distribute it for building heat (University of Saskatchewan, 2020). This aligns with a thermal treatment facility as it could potentially be constructed to utilize this infrastructure, reducing capital cost. The University may also be interested due to the potential for research into thermal treatment facilities as well as reducing reliance on fossil fuels. Other potential partners could be nearby potash facilities or other high heat demand facilities.

Saskatoon appears to be a viable option for a wastepaper thermal treatment plant with potential outlets for the heat. The precise savings are dependent on the technology selected but if an incineration plant were selected at $2,552 per metric tonne of annual capacity (top of the range identified in literature, Section 2.4.1.1) the NPV would be approximately $(124) million. Based on the current disposal cost $(176) million (Section 4.2.1) this would be a savings of $52 million over 25 years. The City is constantly working towards a higher diversion rate (City of Saskatoon, 2021) and a smaller facility designed for a diversion rate of 18% - 25% could be constructed as part of a pilot trial and provide a disposal route below current recycling costs and assist in achieving diversion targets.

4.3. Saskatoon Combined Heat and Power Summary and Recommendation

The following section is a brief analysis following a similar methodology as outlined in Section 4.1 and demonstrated in Section 4.2 using the same population of 246,746. Using the same assumptions from Section 4.2.1, total wastepaper recycling cost would be approximately $176 million and $490 million for the 18% and 50% diversion cases over 25 years for Saskatoon. For a CHP in Saskatoon to be competitive with recycling the DST indicates that capital cost must be no more than of $4,358 per tonne of annual capacity for the baseline case, which would provide an NPV of $(176) million and $(490) million.

Table 16 – Saskatoon CHP Sensitivity Summary

Parameter	Impact on NPV (Trendline Slope) 18% Diversion	Impact on NPV (Trendline Slope) 50% Diversion
Capital Cost	-180	-500
Operating and Maintenance Costs	-127	-353
Utility Sale Price	34	94
Wastepaper Price	-30	-83

For the CHP in Saskatoon, capital costs and O&M costs are the largest driver of project economics. The maximum capacity cost ($4,358 per tonne per year) for CHP is in the upper end of prices suggested ($2,101 - $4,777, Section 3.3.1) indicating that a CHP could be viable alternative to recycling. Utility sale price has a larger influence than the IHR case (Section 4.2.2.5) as the electricity can be sold at a higher rate than heat. Given the influence of utility rates, residential pricing ($0.14228/ kWh, Section 3.3.4) for electricity should also be considered. This could be applicable if Saskatoon were able to utilize the power directly and therefore offset electricity previously purchased at that rate from SaskPower. Using the DST to evaluate indicates an NPV of $(149) million for the 18% diversion and $(415) million for 50% diversion, a savings of approximately 15% compared to selling electricity at the industrial rate.

While the required capital cost is on the upper end of the range found in literature it is still within the range. However, with IHR (Section 4.2) the maximum capital cost allowable was above the range found in literature indicating that the technology available for CHP will be more limited than IHR and it is recommended for Saskatoon to pursue an IHR plant instead of a CHP plant. The CHP also represents a higher capital cost compared to IHR and indicates a maximum capacity cost that is more restrictive. An IHR plant completed for the 18% diversion case would most likely be able to provide a disposal route at a lower cost than recycling, lower capital expense and would allow for baseline studies to be completed. As increasing capacity is required due to increasing diversion, Saskatoon could revisit the viability of a CHP or construct additional IHR plants to meet the increasing demand.

4.4. Swift Current

The following section is a brief analysis of both incineration with heat recovery and combined heat and power following the same methodology as outlined in Section 4.1 and demonstrated in Section 4.2.

4.4.1. Incineration with Heat Recovery

A population of 16,604 people was used for the evaluation of and IHR plant in Swift Current. Swift Current does have recycling services (City of Swift Current, 2021) but did not have a published cost for recycling so the average cost for recycling was used ($426 per tonne, Section 3.3.6). Over 25 years, Swift Current would be expected to generate and dispose of approximately 20,500 tonnes of wastepaper at an 18% diversion rate and 56,800 tonnes at a 50% diversion rate at a cost of $8.7 million and $24 million. An IHR plant with a maximum capacity cost of $2,694 per tonne of annual capacity would result in an equivalent disposal cost to recycling. This is above the range found in literature ($544 - $2,552) and provided by Canadian vendors ($73 - $533) for IHR installations (Section 3.3.1) and therefore could be viable with the appropriate technology provider.

Table 17 – Swift Current IHR Sensitivity Summary

Parameter	Impact on NPV (Trendline Slope) 18% Diversion	Impact on NPV (Trendline Slope) 50% Diversion
Capital Cost	-7.5	-21
Operating and Maintenance Costs	-5.3	-15
Wastepaper Price	-2.0	-5.6
Utility Sale Price	0.8	2.3

For Swift Current, capital cost and O&M costs are the largest drivers of overall project cost, with an effect on the NPV at least 2.5 times greater that wastepaper price or utility price. Given that the estimated maximum capital cost is above both values reported in literature and by Canadian vendors, an IHR plant in Swift Current could be a viable option for wastepaper. A smaller plant sized for 18% diversion would be recommended initially to meet current demand and assist in the refinement of capital and O&M costs. If Swift Current were to select a technology near the midpoint ($1,550 per annual tonne capacity) of those reported ($544 - $2,552) this would represent a 43% reduction in capital cost. Based on the sensitivity analysis, the NPV would increase by approximately $3.2 million. Indicating that a thermal treatment facility would provide a lower disposal cost than recycling by approximately $3.2 million over 25 years.

4.4.2. Combined Heat and Power

A CHP analysis for Swift Current was completed using the same assumed values from Section 4.4.1 except for a thermal conversion efficiency of 52%, electrical conversion efficiency of 34%, and the addition of an electricity sale price of $0.07 per kWh. A CHP plant with a maximum capacity cost of $3,217 per tonne of annual capacity would result in an equivalent disposal cost to recycling. This is just below the mid-point of the range indicated of $2,101 - $4,777 (Section 3.3.1) and potentially viable.

Table 18 – Swift Current CHP Sensitivity Summary

Parameter	Impact on NPV (Trendline Slope) 18% Diversion	Impact on NPV (Trendline Slope) 50% Diversion
Capital Cost	-8.9	-25
Operating and Maintenance Costs	-6.3	-18
Utility Sale Price	2.3	6.3
Wastepaper Price	-2.0	-5.6

A CHP in Swift Current again has capital cost and O&M costs as the main drivers of project cost. With the maximum capacity cost near the mid-point of the range indicated in literature, and capacity cost being the main driver, a CHP may be viable but at an increased risk compared to IHR. Increasing the sale price of electricity to the residential rate of $0.14228 (Section 3.3.4), approximately a 100% increase, would increase the NPV by approximately $2.3 million for the 18% diversion case and $6.3 million for the 50% diversion case. However, an increase in capacity cost of only 25% to $4,000 per tonne of annual capacity, still within the values indicated of $2,101 - $4,777 (Section 3.3.1), would offset the increase in price.

A CHP may be able to provide a disposal cost equal to or less than recycling but based on the analysis of an IHR (Section 4.4.1), Swift Current would be recommended to pursue an IHR instead. The IHR has a much larger capacity cost range and represents a lower overall capital cost.

4.5. Outlook

The following section is a brief analysis of both incineration with heat recovery and combined heat and power following the same methodology as outlined in Section 4.1 and demonstrated in Section 4.2.

4.5.1. Incineration with Heat Recovery

A population of 2,279 people was used to evaluate the viability of IHR plant in Outlook. Outlook does have recycling services (Town of Outlook, 2021) but did not have a published cost. Outlook uses Loraas and so the recycling rate for Saskatoon ($576 per tonne, Section 2.2.7), whose recycling service is also provided by Loraas, was used. Outlook would be expected to generate and dispose of approximately 2,750 tonnes of wastepaper at 18% diversion and 8,500 tonnes at 50% diversion (Section 3.3.2) over 25 years at a cost of $1.6 million and $4.9 million respectively. An IHR plant with a capacity cost of $3,722 per tonne per year would have an equivalent NPV to the cost of recycling. This is above the range of $544 - $2,552 discussed and the range of $73 - $533 provided by Canadian vendors (Section 3.3.1) and therefore is likely to be viable.

For Outlook, capital cost and O&M costs are again the largest drivers of overall project cost. If Outlook were able to select a technology near the midpoint ($1,550 per annual tonne capacity) of those reported in literature ($544 - $2,552) this would represent a 41% reduction in capital cost and based on the sensitivity analysis this would increase the NPV by approximately $0.6 million. An IHR plant would then provide a disposal route cheaper than the estimated recycling cost or at the same cost under the baseline evaluation. If Outlook were to pursue a thermal treatment system, and IHR facility appears to be able to provide a wastepaper disposal route at the same cost, or lower, than the estimated recycling cost.

Table 19 – Outlook IHR Sensitivity Summary

Parameter	Impact on NPV (Trendline Slope) 18% Diversion	Impact on NPV (Trendline Slope) 50% Diversion
Capital Cost	-1.4	-3.9
Operating and Maintenance Costs	-1.0	-2.8
Wastepaper Price	-0.3	-0.8
Utility Sale Price	0.1	0.3

4.5.2. Combined Heat and Power

A CHP analysis for Outlook was completed using the same assumed values from Section 4.5.1, except for a thermal conversion efficiency of 52%, electrical conversion efficiency of 34%, and the addition of an electricity sale price of $0.07 per kWh. A CHP plant with a maximum capacity cost of $4,281 per tonne of annual capacity would result in an equivalent disposal cost to recycling. This is near the upper limit of the range indicated ($2,101 - $4,777; Section 3.3.1) and is potentially viable.

Table 20 – Outlook CHP Sensitivity Summary

Parameter	Impact on NPV (Trendline Slope) 18% Diversion	Impact on NPV (Trendline Slope) 50% Diversion
Capital Cost	-1.6	-4.5
Operating and Maintenance Costs	-1.2	-3.2
Utility Sale Price	0.31	0.86
Wastepaper Price	-0.28	-0.77

A CHP in Outlook again has capital cost and O&M costs as the main drivers of project cost. The allowable cost for a CHP is near the upper limit suggested, indicated that a thermal treatment plant is likely to be viabile. A CHP may be viable for Outlook but does carry more risk than an IHR (Section 4.5.1) due to the increased capital cost and that an IHR plant should be available at a much lower capacity cost than the indicated maximum (Section 4.5.1). A CHP would provide a unique opportunity for Outlook to power a portion of the town on its own wastepaper, but an IHR would have a lower risk. An IHR would be recommended due to the lower risk but if Outlook were willing to accept the increased risk, a CHP could be viable.

4.6. La Loche

The following section is a brief analysis of both incineration with heat recovery and combined heat and power following the same methodology as outlined in Section 4.1 and demonstrated in Section 4.2.

4.6.1. Incineration with Heat Recovery

A population of 2,372 people was used to evaluate the viability of IHR plant in La Loche. La Loche did not have a published cost for recycling, landfilling, or indicate the availability of household recycling. The thermal treatment facility will be compared to the average cost of landfilling in the province ($90/tonne) as it is a closer comparison in the absence of a recycling program. La Loche would be expected to generate and dispose of approximately 3,000 tonnes of wastepaper at 18% diversion and 8,500 tonnes at 50% diversion (Section 3.3.2) over 25 years at a cost of $0.27 million and $0.77 million respectively. An IHR plant with a capacity cost of $262 per tonne per year would have an equivalent NPV to the cost of landfilling. This is below the range of $544 - $2,552 discussed but within the range of $73 - $533 provided by Canadian vendors (Section 3.3.1). It is possible that an IHR could be utilized in La Loche using a Canadian vendor, but additional costs would be required for pelletizing or densification (Section 3.3.1)

Table 21 – La Loche IHR Sensitivity Summary

Parameter	Impact on NPV (Trendline Slope) 18% Diversion	Impact on NPV (Trendline Slope) 50% Diversion
Capital Cost	-0.10	-0.29
Operating and Maintenance Costs	-0.07	-0.20
Wastepaper Price	-0.29	-0.80
Utility Sale Price	0.12	0.32

For La Loche, capital cost and O&M are again the largest drivers of overall project costs. The maximum capital cost rate of $1,576 per tonne of annual capacity is at the midpoint ($1,550) of the range of $544 - $2,552 (Section 3.3.1) so the opportunity for cost savings is more limited compared to other cases. Given that the competing cost of landfilling is lower than the other cases discussed this is to be expected. Despite the lower competing cost of landfilling, an IHR still appears to be viable in La Loche and could be expected to provide a disposal cost similar to landfilling.

4.6.2. Combined Heat and Power

A CHP analysis for La Loche was completed using the same assumed values from Section 4.6.1 except for a thermal conversion efficiency of 52%, electrical conversion efficiency of 34%, and the addition of an electricity sale price of $0.07 per kWh. A CHP plant with a maximum capacity cost of $786 per tonne of annual capacity would result in an equivalent disposal cost to recycling. This is well below the range indicated of $2,101 - $4,777 (Section 3.3.1) and is unlikely to be viable.

Table 22 – La Loche CHP Sensitivity Summary

Parameter	Impact on NPV (Trendline Slope) 18% Diversion	Impact on NPV (Trendline Slope) 50% Diversion
Utility Sale Price	0.32	0.90
Capital Cost	-0.31	-0.87
Wastepaper Price	-0.29	-0.80
Operating and Maintenance Costs	0.22	-0.61

A CHP in La Loche, with an NPV comparable to landfilling, has utility price and capital cost as the main drivers. This is due to the capacity cost ($786) being approximately 40% of the bottom of the range indicated in literature of $2,101 - $4,777. Utility sale price is independent of capacity cost and the lower required capacity cost increases the financial impact of utility income. Given the maximum indicated capacity cost ($786) is well below the range indicated ($2,101 - $4,777), it is strongly recommended that La Ronge not pursue a CHP unit as it is likely to greatly increase wastepaper disposal costs compared to landfilling. A more viable alternative to landfilling would be to pursue an IHR plant.

4.7. Forecasted Population of 500,000

The following section is a brief analysis of both incineration with heat recovery and combined heat and power following the same methodology as outlined in Section 4.1 and demonstrated in Section 4.2.

4.7.1. Incineration with Heat Recovery

A city with a population of 500,000 was evaluated and was assumed that the forecasted city is due to the growth of either Saskatoon or Regina and recycling plan would be in place. The average cost of recycling for Saskatoon and Regina provides an estimated cost of $426 per tonne (Section 3.3.6). The City would recycle approximately 616,000 tonnes of wastepaper at 18% diversion and 1,710,000 tonnes at 50% diversion over 25 years at a cost of $262 million and $728 million respectively. An IHR plant with a capacity cost of $2,695 per tonne per year would have an equivalent NPV to the cost of recycling. This is above the range of $544 - $2,552 discussed in literature and the range of $73 - $533 provided by Canadian vendors (Section 3.3.1) and therefore is likely viable.

Table 23 – Forecasted City IHR Sensitivity Summary

Parameter	Impact on NPV (Trendline Slope) 18% Diversion	Impact on NPV (Trendline Slope) 50% Diversion
Capital Cost	-225	-627
Operating and Maintenance Costs	-159	-442
Wastepaper Price	-61	-169
Utility Sale Price	24	68

For the forecasted city, capital cost and O&M costs are again the largest drivers of overall project cost. An IHR plant if constructed in the forecasted city would be expected to provide a disposal route comparative to expected recycling cost. Given that the analysis of Saskatoon's current population (Section 4.2) it would be advantageous for the forecasted city (likely Regina or Saskatoon) to construct a thermal treatment plan prior to expansion, and once the population grew to the forecasted size, construct another thermal treatment plant to handle wastepaper from the additional population.

4.7.2. Combined Heat and Power

A CHP analysis for the forecasted city was completed using the same assumed values from Section 4.5.1 except for a thermal conversion efficiency of 52%, electrical conversion efficiency of 34%, and the addition of an electricity sale price of $0.07 per kWh. A CHP plant with a maximum capacity cost of $3,218 per tonne of annual capacity would result in an equivalent disposal cost to recycling. This is within the range indicated in literature of $2,101 - $4,777 (Section 3.3.1), indicating that CHP may be viable.

Table 24 – Forecasted City CHP Sensitivity Summary

Parameter	Impact on NPV (Trendline Slope) 18% Diversion	Impact on NPV (Trendline Slope) 50% Diversion
Capital Cost	-269	-748
Operating and Maintenance Costs	-190	-528
Utility Sale Price	68	190
Wastepaper Price	-61	-169

A CHP in the forecasted city again has capital cost and O&M costs as the main drivers of project cost. As the maximum estimated capital cost is near the mid-point of the range, it is possible that a CHP be viable in the forecasted city. Similar to the Saskatoon case study (Sections 4.2 and 4.3) the forecasted city would have a higher likelihood of success utilizing an IHR over a CHP due to the forecasted capital costs and the ranges found in literature.

4.8. Greenhouse Gas Emissions

As discussed in Section 2.6, the carbon tax was not included in the financial analysis as biomass-based systems are typically considered carbon neutral. However, if emissions from the plant were covered by the carbon tax, the cost can be estimated based on the carbon content of wastepaper, which is approximately 37% - 50% (Section 2.6). Using the molecular weight of carbon and oxygen, the mass of carbon in wastepaper is converted to carbon dioxide at a ratio of 3.7 tonnes of carbon dioxide per tonne of carbon.

One tonne of paper is therefore 0.37 – 0.50 tonnes of carbon or 1.4 – 1.85 tonnes of carbon dioxide. At a carbon tax rate of $50/tonne carbon dioxide (Section 2.6) this would represent an additional cost of $70 - $93 per tonne of wastepaper utilized at the thermal treatment plant and could be accounted for in the receiving cost of wastepaper. In each case study evaluated (Sections 4.2 - 4.7) the receiving cost of wastepaper played a minimal role in economic viability.

For example, the Saskatoon incineration case (Section 4.2) utilizes 12,152 tonnes of wastepaper per year at 18% diversion. The carbon tax would represent an annual receiving cost increase between $0.85 million and $1.1 million per year or $21.3 million to $27.5 million over 25 years. This would also represent an approximate increase of 100% in the wastepaper receiving cost which was originally estimated to be $103 per tonne. By contrast, based on Table 15 an increase in capital cost of only 13% to 17% would have the same effect on NPV.

5. CONCLUSION

Many municipalities have made the decision to collect wastepaper rather than dispose of the material in their landfill. The combination of the cost of wastepaper collection, handling and storage, current low values for wastepaper, and relatively high costs of transporting the wastepaper to recycling plants, has created a situation where the recycling of wastepaper is significantly higher than the cost of landfilling the material. The objective of this thesis was to provide Saskatchewan municipalities with a decision support tool to perform a high-level feasibility analysis for the potential utilization of wastepaper as fuel for a local waste to energy facility as an alternative to recycling and landfilling.

Thermal treatment options evaluated were incineration with heat recovery (IHR) and combined heat and power (CHP). IHR would combust the wastepaper to generate heat and serve as a replacement for natural gas heating. CHP would gasify the wastepaper and convert it to heat and electricity and serve as a replacement for natural gas heating and conventional electrical production. IHR represents a lower capital cost but lower utility potential due to only producing heat. A CHP would produce less heat as a utility but has the added benefit of more easily distributed electricity. Both plant types were evaluated to determine if they could provide a disposal cost lower than recycling or landfilling. The analysis showed that both IHR and CHP have the potential for economical utilization of wastepaper for energy generation compared to disposal via recycling but not for disposal via landfilling.

Compared to recycling in Saskatoon, the installation of an IHR plant with a capital cost rate at the upper limit of the range discussed ($544 - $2,552 per metric tonne) for a total capital expense of approximately $31 million, could represent a savings of approximately $52 million over a plant life of 25 years. This would replace approximately 3.6 million cubic meters of natural gas with heat generated by the thermal treatment plant. In cities with existing recycling programs, incineration with heat recovery consistently indicated that it could provide disposal at a cost equal to or below current recycling costs ($275 - $576 per tonne). Combined heat and power evaluations indicated that it could provide wastepaper disposal at rates below recycling but carried higher capital costs ($2,101 - $4,777 per metric tonne) than incineration and similar cost reductions from recycling. For Saskatchewan, thermal treatment of wastepaper appears to be a viable option when compared to recycling with IHR representing the lower capital cost option.

When compared to landfilling, thermal treatment appears to be unlikely to offer disposal at a lower cost and only indicates a similar disposal costs under a best-case conditions for the thermal treatment plant. The inability of thermal treatment to provide a lower disposal cost is due to the low cost of landfilling ($90 per tonne) compared to the cost of recycling ($275 - $576 per tonne). Currently in Saskatchewan, landfilling of material is priced too low for thermal treatment to be economical. If wastepaper is to be diverted from the landfill, as the provincial and municipal governments have indicated, the cost of landfilling would either need to be increased close to the current cost of recycling or wastepaper banned from landfills with the expectation that disposal costs would increase as it is diverted for recycling or thermal treatment. Under current financial conditions thermal treatment will be unable to provide disposal costs similar to landfilling.

Key economic drivers were identified as: capacity cost (capital cost), wastepaper availability, energy available in the wastepaper, collection costs, competing utility rates (electricity and natural gas for heating), operating and maintenance costs, and costs for competing disposal methods (landfilling and recycling). Baseline values for these economic drivers were collected and catalogued from the literature, government statistics, and publicly available sources. The capital cost rate for heat recovery units was found to be between $544 - $2,552 per metric tonne of annual capacity and for combined heat and power units it was between $2,101 - $4,777 per tonne of annual capacity. Wastepaper availability was estimated to be approximately 49 kg per person per year based on a waste generation rate of 912 kg/year, of which 30% was wastepaper and 18% was diverted from landfill. Collection costs for a dedicated collection stream were estimated to be $93/tonne Competing utility costs were based on those available from local utilities (SaskPower and SaskEnergy) and were estimated to be $3.558/GJ for heat and $0.07 per kWh for electricity. Operating and maintenance cost were estimated in relation to the capital cost of the facility and were between 2% - 10% of capital expense annually. Finally, the cost of landfilling ($90/tonne) and recycling ($275 - $576/tonne) were based on current actual cost for Saskatchewan obtained from municipalities. This provides a previously unavailable, centralized source for the critical parameters of a wastepaper thermal treatment plant in Saskatchewan.

The utility of the identified key economic drivers was then demonstrated through the completion of five case studies for locations within Saskatchewan: Saskatoon, Swift Current, Outlook, La Loche, and a projected population of 500,000. The four selected cities represented, in respective order: the largest population (approximately 250,000 people), median of the ten most populous (approximately 17,000 people), a smaller community (approximately 2,000 people), and a northern community (approximately 2,000 people). To facilitate this analysis, an MS Excel spreadsheet-based Decision Support Tool (DST) was developed to provide an automated method for performing a simple financial sensitivity analysis for wastepaper thermal treatment and rank the key parameters based the their effect on the net present value of the thermal treatment plant. The DST was demonstrated in this thesis through the five case studies and evaluated the feasibility of incineration with heat recovery and combined heat and power installations at the identified cities.

The key economic drivers (capital cost, operating and maintenance costs, utility sale price and wastepaper price) were evaluated using linear regression and determining their effect on the NPV of a thermal treatment plant. Capital cost showed the largest effect in all the evaluated cases. Using Saskatoon as an example, an IHR thermal treatment plant with an NPV of ($176) million would provide a disposal cost equal to recycling over 25 years and decreasing the capital cost by 10% would increase the NPV by $16 million. A municipality considering the installation of a thermal treatment plant should focus on reducing capital cost should with any cost saving initiative to maximize cost reduction. Operating and maintenance costs are the second largest driver of NPV. For Saskatoon, decreasing the operating and maintenance cost by 10% would increase the NPV by $11 million for IHR. This provides a benefit similar to reducing capital expense and operating and maintenance costs should be given similar consideration for cost savings.

Price paid for wastepaper and the utility price charged by the thermal treatment plant were consistently lower indicators of NPV than capital cost or operating and maintenance costs. For Saskatoon, decreasing the price paid for wastepaper, such as the cost for collection or pre-processing costs, by 10% would increase the NPV by $3 million over 25 years for IHR. Given the comparatively minimal influence that wastepaper and utility price have on NPV they should be of minimal focus for cost savings. Wastepaper price in most case could be increased substantially, such as may be required for additional pre-processing, if it allows for a reduction in capital cost. Saskatoon for instance could increase the price paid for wastepaper collection and processing by 50% from $93 to $140 per tonne if it would reduce capital cost by 10% and achieve a savings of $3 million over the life of a an IHR plant. Given the volatile nature of the price of wastepaper this is another benefit to thermal treatment of recycling. Price has a minimal influence on thermal treatment economics but directly influences the cost for a city to recycle wastepaper. Thermal treatment could assist municipalities in stabilizing the cost of disposal and minimizing volatility in disposal costs.

Utility prices result in a similarly minimal change to NPV of the thermal treatment plant. Increasing the utility price (heat) by 10% would increase the NPV by $1 million over 25 years for IHR. Utility price would still need to be considered by the municipality but would not be the main driver of viability. The results of the sensitivity analysis in all cases indicate that capital cost and operating and maintenance costs should be the focus of a thermal treatment plant installation and that increases in wastepaper price or decreases in utility prices can be tolerated even if they only provide a minimal decrease in capital cost of maintenance and operating costs.

The scope of this thesis was limited to the use of wastepaper in thermal treatment plants in Saskatchewan using values available in literature and was intended as a baseline study. Further research is recommended to focus on additional clean sources of dry combustible material such as tree trimmings, agricultural residue, or other forms of clean wood waste that could be added at minimal cost to increase the output of the thermal treatment plant. There may also be an opportunity to co-fire wastepaper with coal. Given the prevalence of coal-based power production in Saskatchewan this could represent a lower capital cost opportunity and would still offset coal combustion. Emissions by-products were not fully considered in this thesis and further work should be completed to evaluate their potential generation. Operational strategies (combustion temperature, air:fuel ratio, etc.) or additional treatment, such as scrubbers, may be required to limit their generation and release.

A life-cycle analysis of wastepaper thermal treatment compared to recycling would also be of value. While this thesis evaluated the economics of thermal treatment the effect it would have on the paper industry by reducing the availability of paper for recycling was not considered. Given that paper cannot be recycled indefinitely thermal treatment can likely still be utilized in the context of wastepaper disposal but the optimum utilization within wastepaper disposal and production was not evaluated.

A hub-city could also be explored wherein multiple municipalities ship wastepaper to a central thermal treatment facility. This greatly increase the logistical and political complexity of an installation but may prove viable. It would require a more through evaluation of the logistical parameters (location of construction, shipping costs/emissions, etc.) than were within the scope of this thesis. It would also require that multiple municipalities agree to the entirety of the project, which is likely to have disparate costs and benefits to each of the municipalities.

Additionally, the case studies completed in this thesis were based on values found in literature. Given the financial evaluations provided in this thesis, pilot-scale trials are recommended to evaluate the potential to evaluate the replacement of recycling or landfilling with thermal treatment. Pilot scale studies would provide real-world evaluation of operational costs, energy generation, and capital costs to provide a more refined evaluation of wastepaper thermal treatment in Saskatchewan.

The key finding of this thesis is that thermal treatment appears to be able to provide disposal of wastepaper at a lower cost than current recycling costs of approximately $575 per tonne. Saskatoon for example could realize a savings of approximately $52 million over 25 years, or a cost reduction of approximately 30%. These savings also assume that Saskatoon selects at thermal treatment plant with a cost at the upper end of the range ($544 - $2,552 per tonne annual capacity) identified. The savings are likely to be even higher as it’s likely Saskatoon would be able utilize a plant closer to the midpoint of the range (cost of $1,548 per tonne annual capacity). This would increase savings to approximately $140 million over 25 years. This exercise also demonstrates the value of the DST. These calculation can be quickly carried out and compared to other scenarios to determine the sensitivity of the thermal treatment plant economics to changes to the key economic drivers of capital cost, operating and maintenance costs, utility sale price and wastepaper price. Each driver can be manipulated individually to determine its effect on the NPV. This allows for a municipality to focus effort on reducing costs in areas that will result in the greatest increase to NPV.

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7. APPENDICES

Appendix 1 - Decision Support Tool (DST)

The DST is an Excel based spreadsheet that calculates the net present value of a wastepaper to energy thermal treatment plant. The use inputs the required information (Appendix 2), and the sheet performs the calculation. The DST is included with this thesis as an Excel file.

Appendix 2 - Decision Support Tool Instructions

Input Tab

This is where the user enters baseline data for the selected location. To prevent errors, this tab is the only location that date should be entered. If the value for a parameter is unknown the referenced values may be used.

Location Inputs

Location inputs are based on the specific location to be evaluated. They will vary from location to location and can also be used to forecast viability in the future

Population – number of people for the area being evaluated

Wastepaper Waste Percentage – percentage of waste that is wastepaper. For Saskatchewan this is approximately 33% (Tartaniuk, 2007, Government of Canada, 2021a)

Waste Generation – rate that each person in the area generates waste in kg/person/year. For Saskatchewan this is approximately 912 kg/person/year (Government of Canada, 2021a, Government of Canada, 2021b, Government of Canada, 2021c)

Capture Rate – percent of waste captured for collection. For Saskatchewan this is approximately 18% (Government of Canada, 2021a, Government of Canada, 2021c)

Plant Inputs

Plant inputs are based on expected parameters for the plant itself.

Capital Price Rate – capital cost of an installation based on the per metric tonne annual capacity. Units can range from $70 to $2000 per metric tonne of annual capacity (Stantec, 2011, Siyuan Wu, 2018, Biothermic Wood Energy Systems, 2021).

Thermal Conversion Efficiency – amount of the energy that is converted for use in heating. For a heating only plant this is set to between 77% and 86% (Thomas, 2018). For CHP it is set to the efficiency of the heating portion of the plant, typically between 49% and 55% (Colantoni, 2021).

Electrical Conversion Efficiency – amount of energy that is converted to electrical production. For a heating plant this is zero and a CHP plant is typically between 30% and 39% (Colantoni, 2021).

Receiving Cost at Plant – price paid by the plant for wastepaper. If the plant is paid to take wastepaper this would be a negative number.

Electricity Sale Price – expected sale price of electricity for the plant.

Heat Sale Price – expected sale price of the heat for the plant.

Plant Conversion Efficiency – efficiency of the plant for converting the potential energy into useable heat or electricity. This typically ranges from 77% to 86% (Thomas, 2018).

Estimated O&M Costs – estimated annual costs for operations and maintenance expressed as a percent of capital expense. This cost depends on the technology but typically ranges from 2% to 10% (IRENA, 2012, van Driel, 2015, GREBE, 2017).

Discount Rate

Discount rate is used to evaluate the long-term financial viability of a project. They can be set to the rate of inflation, loan interest, or a payment rate to shareholders. Both rates are treated the same and will be calculated and displayed separately.

Plant Cost

If the capital cost of a proposed plant is already known, it can be input here. If the cost is not known, this space must be left blank and will calculate the plant cost based on the inputs above.

Carbon Tax

This determines the economic impact of a carbon tax. It will calculate the amount that would be paid to carbon tax based on the intensity of competing sources.

Carbon Tax Rate – rate charged per tonne of CO_2.

Electrical Grid Emission Intensity – CO_2 intensity of competing electrical production. For Saskatchewan this is 800 g CO_2eq/kWh (Environment and Climate Change Canada, 2019).

Heating Emission Intensity – CO_2 intensity of competing heating production. For natural gas this is approximately 56.1 kg/GJ (IPCC, 2006).

Transportation

If material must be transported from another location (such as a nearby city) the cost of transportation can be calculated here.

Transport Cost – cost to haul material, this is typically $0.25 to $0.40 per tonne per km.

Single Trip Distance – distance of a one-way haul, if there is no back-haul available this distance may need to be increased.

Sensitivity Analysis

The above inputs will all be based on assumptions or estimates. The sensitivity analysis is used to determine what effect a variation in these values would have. Enter four “percent of estimate” values to evaluate for each parameter. For example, a capital cost value of 200% would evaluate the effect of the capital cost being 2x the estimated value.

Results Tab

This is the final results based on the inputs of the user.

Estimated Plant Value

Estimated Capital Price Rate – from the input tab

Annual Waste Throughput – amount of wastepaper ran through the plant annually

Capital Cost – expected capital cost of the plant

Estimated Annual Gross Revenue – expected gross revenue per year

Estimated Annual O&M Costs – expected O&M costs per year

Annual Heat Generation – amount of saleable heat generated by the plant

Electricity Generation – amount of saleable electricity generated by the plant

Net Present Value (Undiscounted) – undiscounted net present value of the plant after 25 years of operation

Net Present Value (Discount 1) - discounted net present value of the plant after 25 years of operation using the rate from the input tab

Net Present Value (Discount 2) - discounted net present value of the plant after 25 years of operation using the rate from the input tab

User Input Summary

This is a summary of the user inputs from the Input tab.

Sensitivity Summary

Calculated based on the values given for sensitivity analysis on the input tab. The net present value for each given sensitivity range. The equation for the line is also displayed on each graph.

The slope of each graph can be compared to determine the driving factor for a given installation. The further the slope is from zero (either positive or negative), the greater effect it has on the final net present value. Note that the slope is based on a "percent of estimate" rate and not a "dollar to dollar" value.

Carbon Tax

This summarizes the potential impact of a carbon tax on the plant. This value is not included in the cash flow analysis. If carbon credits are an option, it could be considered a potential income stream or could. Otherwise, it represents an avoided cost.

Net Present Value Graph

This graph shows the net present value of the plant at the end of each year for the undiscounted case and both discounted cases for 25 years.

Int Calcs

These are the interim calculations used by the decision support tool. They are not necessary to review as part of an evaluation but can provide additional detail if needed.

"CS" Tabs

These tabs are used to perform the sensitivity analysis for the respective parameter. A summary of each tab is provided in the Results tab.