Assessing the Feasibility of Landfill Mining in Whitehorse, Yukon

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Abstract

The relatively new concept of "enhanced landfill mining" has provided a way to shift the existence of landfills from a final site of waste disposal to being temporary storage locations for potentially valuable resources. Furthermore, the valorization potential of excavated municipal solid waste as an energy source for incineration and renewable resources for recycling processes broadens the landscape in discussions around alternative energy and resources in a time of concerns over scarcity. Landfills, as sites that are geographically dispersed and also close to most urban centers, have much potential to be the sites of valuable "mineable" materials in the near future. Whitehorse, the capital city of the Yukon Territory, is currently dealing with important questions and discussions about energy generation and waste management. The convergence of these issues makes this a particularly interesting time to investigate the potential for enhanced landfill mining to provide resources for material recycling and waste-to-energy incineration. Previous research about the city's current waste composition, landfill capacity, and the requirements for a waste-to-energy facility provide a foundation on which to base this research. This paper examines the materials present in the Whitehorse landfill and potential valorization paths for them, including recycling, waste-to-energy incineration, composting and plastic-to-oil conversion.

Table of Contents

Introduction

As global demand for non-renewable resources continues to grow, partly due to rising populations and income levels in the Global South, the need to identify new sources of these materials continues as well. However, this also comes at the same time as a growing desire among many industries and nations to implement practices of sustainable development, which has been defined by the Brundtland Commission as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (Brundtland Commission, 1987). Furthermore, concerns about the environmental and health implications of many resource extraction projects, as well as resistance to these projects from environmental organizations and local groups including indigenous communities, have brought increasing scrutiny to the methods of extracting those resources in the first place.

On the other side of the resource lifecycle are questions about how best to manage the waste that is generated by our resource consumption activities. Despite the commonality of the “3 Rs”, reduce, reuse and recycle, the success of these practices is greatly varied from place to place. Landfilling, due to the relative ease and low costs associated with this process, continues to be the fate of much of our solid waste. However, there is a growing interest within the waste management community in the practice of “landfill mining”. Landfill mining is the practice of excavating materials previously held in landfills or dumps, with a number of different goals including increasing landfill space, assessing the composition of the landfill, landfill site remediation and material reuse by way of incineration or recycling.

Recently, the notion of “enhanced landfill mining” has emerged, which has the specific goal of using previously landfilled materials as resources for energy generation or resource recovery. An enhanced landfill mining full-scale pilot project has begun in Belgium, much to the interest of people involved in waste management as researchers and industry employees alike (Jones et al., 2013).

Though the project in Belgium is taking place in the context of a densely populated region in which space for new landfills is scarce, it is possible that landfill mining projects could be a feasible option in many parts of the world. This paper will explore the feasibility of landfill mining in Whitehorse, Yukon. Whitehorse is a relatively remote community, but is very much dependent on its connection to southern Canada for most of its resources. It is also currently struggling with questions about appropriate energy sources to replace its back-up diesel generators. Furthermore, Whitehorse has a number of organizations active in issues of waste management, and has recently passed an updated Solid Waste Action Plan with the goal of 50% waste diversion by 2015. It is within this context that this paper will explore the potential of a landfill mining project at the Whitehorse Solid Waste Facility.

Whitehorse Context

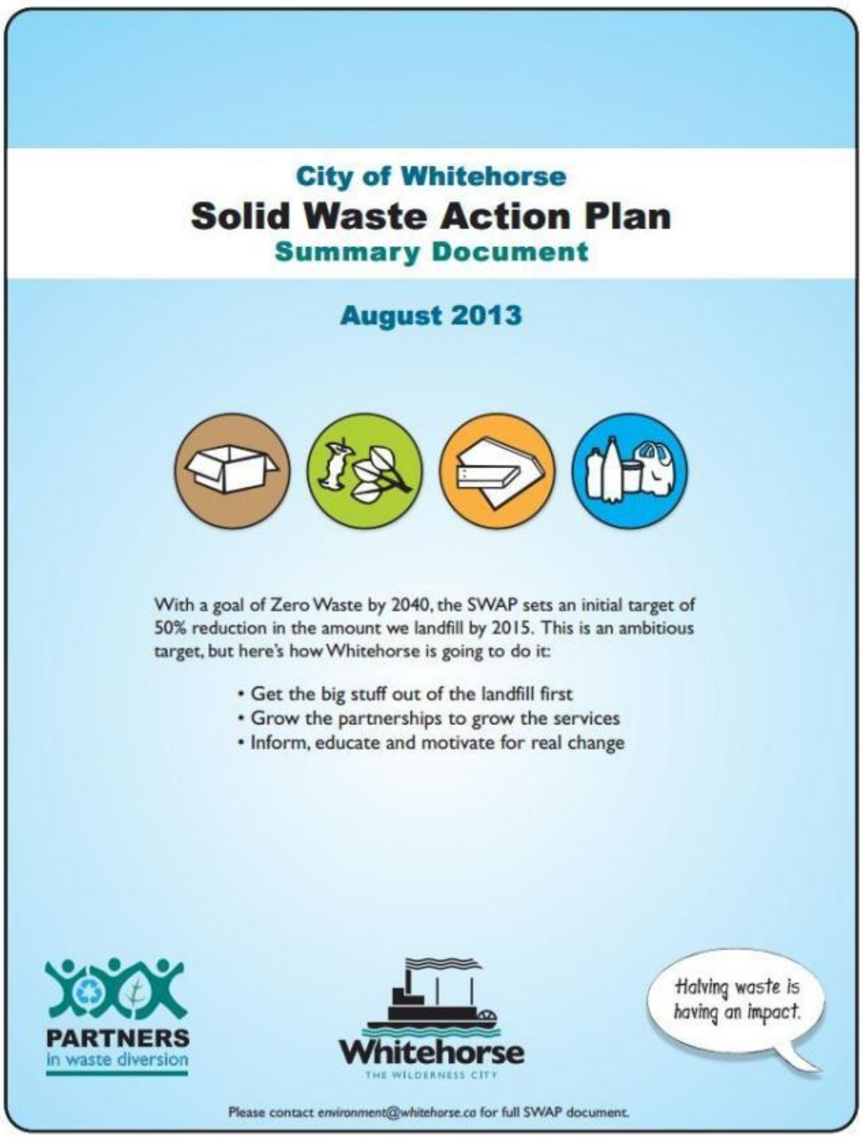
Over the past few years, a several separate-yet-related issues, reports and initiatives have converged around waste management and energy in Whitehorse to create an environment that is conducive to an examination of the feasibility of landfill mining. These include 1) the report in January 2013 that significantly reduced the estimated remaining lifespan of the local Son of War Eagle landfill; 2) the adoption of an updated Solid Waste Action Plan in August 2013 by Whitehorse City Council that includes the goal of 50% waste diversion by 2015; 3) a desire by the Yukon Energy Corporation beginning in 2011 to replace its back-up diesel generators with another fuel source (Yukon News, April 8, 2011); and 4) the purchase and operation of a "plastic-to-oil" machine since 2012 by a local entrepreneur in collaboration with one of the Whitehorse recycling centres (Yukon News, September 12, 2012).
This section will examine each of these issues in depth, as well as an explanation of how they connect with one another and the topic of landfill mining.

Landfill Capacity

In January 2013, the consulting company Morrison-Hershfield published a Landfill Cost Assessment report for the City of Whitehorse. The report examines the costs and estimated life expectancy of the Whitehorse Landfill under the following three scenarios: current waste diversion projections, enhanced waste diversion projections (elaborated in the section of this paper about the updated Solid Waste Action Plan), and a scenario in which waste-to-energy (WtE) incineration is being carried out.
According to the report, the landfill was constructed in 1987 with an estimated total capacity of 2,500,000 m^3; when allowing for a 750 mm final cover, this is reduced to 2,262,000 m^3. As of 2012, it was estimated that 24% of landfill air space capacity had been consumed.
Furthermore, the report points to the fact that waste production has been increasing at a rate above population increases in the city, particularly in recent years from the construction & demolition (C&D) sector. At the same time, waste diversion rates (recycling and composting) have remained around 20%.
With all this in mind, Morrison-Hershfield estimate that the lifespan of the landfill under current diversion rates to be another 34 years beginning in 2012, with enhanced diversion 45 years, and with a waste-to-energy facility in operation it could be upwards of 150 years. Previous work had set the estimated landfill lifespan to be 78 years, thus this update represents a 50% reduction under the current waste diversion framework. Landfill closure costs are currently set at $13.5 M, plus post-closure monitoring for 20 years at $50,000/year.

Updated Solid Waste Action Plan

In August 2013, Whitehorse City Council adopted a new Solid Waste Action Plan (SWAP). Similar to the research by Morrison-Hershfield and others, the SWAP acknowledges that waste generation in Whitehorse increased by 88% since 2000, which is partly attributed to an 18% population growth in that period but which also represents an increase in per capita waste generation of 34% over 12 years. Much of the SWAP is focused on the target of increasing waste diversion rates from ~20% to 50% by 2015. In order to do so, some items such as cardboard will be banned from the landfill, and the city collection of organics for composting will be expanded to commercial, institutional and multi-household buildings. However, as previously stated, the landfill's lifespan is only expected to be 45 year even with these diversion methods.



City of Whitehorse
Solid Waste Action Plan
Summary Document

August 2013

With a goal of Zero Waste by 2040, the SWAP sets an initial target of 50% reduction in the amount we landfill by 2015. This is an ambitious target, but here's how Whitehorse is going to do it:

- Get the big stuff out of the landfill first
- Grow the partnerships to grow the services
- Inform, educate and motivate for real change

PARTNERS in waste diversion

Whitehorse THE WILDERNESS CITY

Halving waste is having an impact.

Please contact environment@whitehorse.ca for full SWAP document.

Whitehorse Solid Waste Action Plan. Source: City of Whitehorse

Yukon Energy Back-up Generator Replacement Needs

At the same time as these discussions and initiatives around waste management are taking place, the Yukon is currently debating the question of what types of energy generation are appropriate to the population's needs. The vast majority (99.9 percent) of the Yukon's energy needs are supplied by hydro electricity from 3 dams (Yukon Energy, 2014). However, increasing demand in recent years due to population growth and large projects such as new mine sites has meant that there is a strain on the current hydro capacity to meet all needs. Yukon Energy, the crown corporation in charge of energy generation infrastructure across the territory, currently uses 19 diesel generators with 39 megawatt capacity as a back-up source in times of hydro shut down or when demand exceeds hydro capacity, particularly in the winter.

However, two of the diesel generators located in Whitehorse are reaching the end of their useful life (*Ibid*). Additionally, the rising cost of diesel fuel means that it is becoming an increasingly expensive back-up fuel source. For this reason, over the last several years Yukon Energy has been in the process of examining other fuel types that could replace the diesel.

In 2011-2012 Yukon Energy began to examine the possibility of building a waste-to-energy (WtE) facility as the alternate back-up system. A series of meetings and consultation sessions were held, and two reports were published by Morrison-Hershfield to assess the feasibility of these facilities if they were to use freshly produced municipal solid waste (MSW). The first report had concluded that WtE would indeed be much less expensive than diesel at $0.16/kWh (Morrison-Hershfield, 2011). However, an updated version published in 2012 concluded that the cost per kWh would in fact be nearly double the original estimate, at around $0.31/kWh (Morrison Hershfield, 2012). One of the reasons for this was that due to the soon-to-be-completed SWAP with its enhanced diversion rates of 50% by 2015, the feedstock of MSW available for the facility would be lower than originally imagined, particularly in the winter months. The updated report included the estimated costs associated with using wood biomass in addition to MSW, as well as a slightly smaller WTE facility capacity.

For this reason, and in light of a number of concerns raised by community members about WTE's health and environmental impacts and its potential to compete with waste diversion efforts in the territory, Yukon Energy announced in April 2012 that it would not be proceeding with the WtE option in the near future (Yukon News, April 20, 2012).

Since then, Yukon Energy has been examining the possibility of building a liquid natural gas (LNG) facility as the new back-up generator. Reports it has commissioned on the matter suggest LNG would be cheaper than diesel, and would have lower emissions of some pollutants (Don McCallum, 2012). Currently, the LNG project is going through the Yukon Socio-Economic and Environmental Assessment Board for approval, with a ruling likely due out in the spring. However, many citizens are concerned about the environmental impacts of LNG as well, particularly due to concerns about the practice of shale gas fracking used to access previously untapped gas reserves. Furthermore, one of the First Nation governments in the territory that had previously agreed to partner on the project has backed out due to concerns from their members (YESAB, 2013; Yukon News, Dec 20, 2013; Yukon News, April 2, 2014).

Plastic-to-Oil Machine

In 2010, Blest, a Japanese company made international headlines when it announced that it had invented a machine that could convert certain types of plastics back into oil. According to the company website, the oil produced is a mix of "gasoline equivalent, kerosene equivalent, diesel equivalent and heavy oil 'mixed oil'" (Blest, n.d.), and one kg of plastic produces roughly one litre of oil.
In 2012, Andy Lera, a local entrepreneur, partnered with P&M Recycling to bring one of the machines to Whitehorse for a pilot project. The machine uses plastics #2,4,5 and 6 (polyethylene, polystyrene and polypropylene), which are sorted at P&M from the containers that customers bring them.
In a conversation with Lera in December 2012, he indicated that if the pilot project with the machine was successful, he would be interested in mining the Whitehorse landfill for plastics, in order to increase the amount of oil he would be able to produce (Andy Lera, personal communication, December 30 2012). The plastic-to-oil machine has thus recently become one more actor in waste management issues in Whitehorse, with a particular potential future interest in resources in the landfill. The next section will provide an overview of current waste management practices in the Yukon; this will allow for a discussion of how landfill mining would fit in with current practices and how the current actors could be involved in a landfill mining project.

Whitehorse: Current Waste Management Practices

Waste management in Whitehorse is made up of a number of different organizations that all work interdependently. These include the landfill, now known as the Whitehorse Waste Management Facility; two private recycling processing centres, as well as community bottle depots in nearby rural areas; compost, which includes composting services contracted by the City government as well as private composting facilities in backyards/neighbourhoods; and the plastic-to-oil machine, which is run in partnership with one of the recycling centres. Due to the concentration of the majority of the Yukon's population and waste management infrastructure in the capital, territory-wide processes will also be discussed to some extent.

Landfilling

The City of Whitehorse operates the Whitehorse Waste Management Facility, which includes the Son of War Eagle Landfill, as well as sites for composting and an area for dropping off recyclable materials.
The landfill accepts items such as household waste, construction and demolition waste, old furniture and old appliances (City of Whitehorse, 2014). Residential waste for some residents is picked up using a curbside cart system operated by the City on a biweekly basis, while larger items and household garbage from residents not on the collection route must be dropped off by the waste producers themselves. Several private, contracted waste collection services also operate around the City, and mostly haul waste generated by commercial and institutional buildings.
Most of the items dropped off at the landfill are subject to tipping fees, which range from $1-250 depending on the item and its size. Recyclable items do not have a charge provided they are sorted appropriately and disposed of in their designated bins.

The Whitehorse landfill. Source: Yukon News

The updated SWAP includes provisions to designate cardboard as a Controlled Waste as of May 2014, which means that all cardboard must be recycled (except waxed cardboard and food-soiled items such as pizza boxes, which can be composted) and any cardboard brought to the landfill with a load of garbage will automatically make the tipping fees of that load $250.

In addition to the Whitehorse Waste Management Facility, there exist a number of community dumps and transfer stations. These include 3 in close proximity to Whitehorse (Marsh Lake, Mount Lorne and Deep Creek), as well as others in communities throughout the territory. The transfer stations tend to accept both recyclable and non-recyclable solid waste material, and currently do not have tipping fees, which can make them a more popular dumping location than the Whitehorse landfill for nearby residents (Cable, interview, December 19 2014). However, the domestic waste that the community transfer stations accept is later transported to the Whitehorse landfill, paid for by the territorial government. As such, much of the waste generated across the territory eventually ends up at the Whitehorse site.

Recycling

Recycling in Whitehorse is carried out by two recycling processers, Raven Recycling and P&M Recycling. Items accepted for recycling include plastics, paper/cardboard, beverage containers such as aluminum cans and waxed cartons, glass and tin. Additionally, Raven Recycling accepts styrofoam, electronic waste such as batteries and computers, and certain types of scrap metal such as copper and stainless steel (Raven Recycling, 2012).

The two facilities receive, sort and bale the different commodities, which are then shipped elsewhere for further processing.

Cardboard being baled at Raven Recycling. Source: Yukon News

Recyclable materials are also accepted at transfer stations and bottle depots in the communities throughout the territory. Raven and P&M act as processing centres for those recyclable commodities as well.

Recycling is funded through a combination of measures. Most beverage containers, with the exception of milk and milk substitutes, have a recycling deposit included in the price that customers pay. Part of that deposit is returned to the customer when they bring it to the bottle depot, but a small amount goes to the bottle depot itself, and an even smaller amount goes to the recycling processor. Raven and P&M both act as both a depot and a processor, but when bottles are returned to bottle depots elsewhere in the territory, those two facilities only receive the processing fee (Joy Snyder, phone conversation, February 2014).

The funding for processing other recyclable materials partly comes from the price per tonne that each commodity receives when it is shipped down south to be turned into 'new' materials and products. However, those prices are all determined based on the worldwide recycling industry demand, and some items do not receive prices that cover the costs associated with processing them in Whitehorse. The loss on these items is cross-subsidized by the profit made by Raven and P&M on other, more valuable commodities. Additionally, the City of Whitehorse pays $50/tonne in "diversion credits," in return for the reduction in materials going to the landfill. As part of the SWAP, these diversion credits will increase to $75/tonne in order to cover rising costs for processing (City of Whitehorse, 2013).

Composting

Composting in Whitehorse happens in two ways: either by the City's contracted composting company located at the Whitehorse Waste Management Facility, or by households on their own property.

Residents who are on the municipal collection route for garbage also have their organic waste picked up from separate bins on a bi-weekly basis. Additionally, residents who do not have their organic materials collected by the City may drop it off at the Waste Management Facility, where it is subject to a $5 tipping fee for small loads. These are then taken to the compost operation run by Boreal Composting, on contract for the City of Whitehorse. Their method used is hot aerobic composting, and the process lasts for a year before the material is ready to be screened and used. The final product is then made available as both compost and topsoil for sale to local residents.

Organics are one of the key items identified in the SWAP as an important part of the 50% diversion goal, since although the facilities exist to divert them, they have been found to be a large percent of the volume within the landfill (Maura Walker & Associates, 2011). For this reason, the City has begun an "organics pilot" to encourage commercial, institutional buildings and multi-family residential buildings that have not previously had an organics pick-up service to do so. This pilot project will include the City providing collection carts free of charge to buildings that sign up; these can be picked up by the City or by a private hauler. Additionally, the charge at the landfill for loads containing organics will increase to $250 as of 2015 (City of Whitehorse, 2014).

Compost piles at the Whitehorse Waste Management Facility. Source: Boreal Compost

Plastic-to-oil Machine

The Blest B-240 plastic-to-oil machine operated by Andy Lera in collaboration with P&M Recycling, Cold Climate Innovation and the Yukon Research Centre began operating in 2013.

The machine uses a process called thermal depolymerization, which involves plastics going through pyrolysis in order to be reduced to a petroleum product that can be used for heat or transport (Rising Sun Innovation, 2014). The plastics used in the process include #2 (high-density polyethylene), 3 (polyvinyl chloride), 4 (low-density polyethylene), 5 (polypropylene) & 6 (polystyrene).

According to a report published by Rising Sun Innovations earlier this year, the machine has been more successful than previously expected in terms of both financial and environmental considerations.

In terms of financial costs associated with operating the machine, a trial of 12 different processing runs showed an average cost of $0.51/L of final product. Much of this cost comes from the labour required to granulate the plastic before the conversion process. Rising Sun estimates that costs could be as low as $0.31/L if they installed a shredder (ibid).

Blest plastic-to-oil machine. Source: Rising Sun Innovations

In terms of environmental effects, Rising Sun's report argues that the plastic-to-oil conversion process in fact has a smaller environmental impact than recycling, at least for the plastic types listed above. Their argument is based particularly on the low CO_2 emissions associated with plastic-to-oil conversion process 186g/kg of plastic, compared to 3500 g/kg emitted during conventional recycling (ibid); these emissions do not include the final burning of the fuel itself. Testing for methane, total volatile organic compounds, NO_x and SO_x showed low levels for all of those emissions as well. Furthermore, Rising Sun argues that because of China's recent Green Fence Initiative, which restricts the types of commodities China will accept for recycling, it makes more environmental sense to convert lower-grade types of plastic into oil as those plastics may end up being discarded rather than recycled in any case (ibid).

The next section will discuss the idea of landfill mining in general, including literature reviews. Following that, the Whitehorse context and ideas around landfill mining will be drawn together to determine what are the potential paths of mined materials in the Whitehorse landfill.

Landfill Mining

The following section will provide an introduction to the concepts and processes associated with landfill mining. Most of the referenced material is from the academic literature on the topic. Although this includes some case studies of landfill mining projects, there are likely other operations in existence that have not been the subject of academic research and thus will not be examined in depth by this paper. For that reason, the scope of the research related to the specific technical processes used may not include all of the techniques that have been used in the field, if those processes themselves have not be documented in the existing literature. Furthermore, considerations related to things like the climate – which is an important consideration due to the relatively long winter in Whitehorse given its northern location – on landfill mining operations have not been covered by previous research and thus can only be speculated upon here.

The first section is a broad literature review related to landfill mining generally. This includes research up until 2012 or thereabouts, with categories of research such as landfill composition case studies, economic considerations, environmental impact and technology that could be used.

The next section will specifically discuss literature related to the relatively new concept of "enhanced landfill mining". This concept has emerged only in the last few years, and has important implications for the future of landfill mining. The section will include an overview of the meaning of the term, where it is being applied currently and the findings in terms of its effectiveness.

Literature Review: Landfill Mining in General

Landfilling remains one of the most common ways of dealing with solid waste worldwide, since it is a relatively cheap and technically simple method. Landfills themselves vary in terms of size, composition and level of engineering sophistication to deal with things like landfill gas and liquid escape. However, the general idea of putting solid waste into a compartment in the earth and then covering it once it is full remains more or less the same.

Over the last several decades, the simplicity and effectiveness of landfilling has come into question. Waste diversion initiatives such as "the 3 Rs" and composting have aimed to change the way that people think about the materials that they are purchasing, using and disposing of in an effort to place fewer items in the landfills and instead extend the lifespan of those materials. However, there is also an interest in landfills themselves. A combination of diminishing raw resource quantities and a shortage of space for new landfill sites in densely populated areas has meant that growing numbers of academics and companies in the waste management sector are looking at the potential of "mining" already-existing landfills[1].

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[1] Note: this literature review is focused on landfill mining in the Euro-North American context. There is much documentation of "urban mining" or "landfill

The first documented landfill mining project took place in 1953 in Tel Aviv, Israel (Savage et al, 1993) where a company excavated fine materials from the landfill site for use as a soil amendment in nearby citrus groves. Following that, it was not until the 1980s that much academic work was done on the subject.
In the 1980s and 90s, there was renewed interest in the potentials of landfill mining. This was partly due to the passing of stricter environmental legislation in the United States related to landfill operations, closure and post-closure monitoring (Krook et al, 2012). The relatively high cost of landfill closure and monitoring, and the difficulty in finding new landfill sites around densely populated areas meant that there was new incentive to find out whether still-operating landfills could be mined so as to reduce the volume of material in them and thus extend their lifetimes.
In the early 2000s, interest in landfill mining dropped significantly, possibly due to a combination of economic downturns and increased diversion efforts that reduced the pressure on existing landfill capacity (*ibid*).
The review by Krook et al (2012) provides a comprehensive overview of the literature up until 2008. Much of the literature drawn on for this paper was published after that, and will be the focus of the following sections. The papers reviewed are grouped into the following categories: landfill composition assessments; economic considerations; environmental impact, processes and technology; and recycling potential.

Escambia landfill mining project. Source: Waste360

pickers" in parts of the Global South, and in many of these cases this activity is a major source of income for some urban poor populations. However, because the focus of this research has to do with the potential for a large-scale, mechanized operation in a North American context, only research about similar projects will be covered here.

Composition Assessments

As mentioned by Krook et al, landfill composition assessments are the most common category of research related to landfill mining. Though numerous studies in different landfill sites have been done, their review noted a pattern in terms of the results. This includes fine, soil-like materials making up 50-60% of the total weight of samples, combustibles – including paper, plastic and wood – making up 20-30% of the weight, inorganics making up ~10%, and a relatively small percentage of metals (*Ibid*). Generally this assessment is made through a process of excavating, drying and screening the materials and then manually sorting the larger material into different categories. The sorting process allows for an assessment of both the type of materials contained as well as their energy potential for incineration. Recycling potential has generally only been considered for the various metals found. A more recent paper by Kaartinen et al (2013) aimed to more thoroughly examine the treatability and material recovery potential of landfilled materials. Their study included a comparison between manual sorting processes and a full mechanical pre-treatment. In the sample that was manually sorted, they found that plastic, paper/cardboard, textiles and wood amounted to 40-45% of the mass and metals were 3.4-4.4%, following a screening out of materials of less than 20 mm. For the sample that was subject to the mechanical pre-treatment, ~30% was potential fuel, and 1% was magnetic metals. One important finding of their study was that there was a higher quantity of chlorine found in this sample compared to previous assessments, likely due to the landfilling of PVC. Their paper explains that chlorine amounts in solid recovered fuels have been limited in Europe due to chlorine's corrosive impact and tendency to convert to hydrochloric acid in the flue gas in incineration processes, which can also mobilize metals such as lead and zinc. The paper's final assessment found that the calorific fractions had a relatively high value of 20-25MJ/kg, but the presence of the chlorine could be a hindrance to their incineration potential. However, they note that older landfills with a lower fraction of plastics would likely have less chlorine.

Economics

The most commonly cited economic assessment of landfill mining is by Van der Zee et al (2004). Their method includes a step-wise approach to categorize various landfill sites according to profitability potential of a mining project. With this methodology, only the sites with the highest profitability potential are then subject to a full on-site investigation. One important element of note is that their method is based on the needs of a private company, Essent, and thus the expectations of what "profitability" implies are different than what they might be for a project initiated by a public body such as a local government.

The only other paper found in the literature discussing the economics of landfill mining has to do with 'enhanced landfill mining' and will be discussed in the section dealing with that approach specifically.

Environmental Impact

The first paper that discusses the environmental effects of landfill mining is Tesfai & Dresher (2009), which discusses the use of landfill materials as fertilizer by small farmers in Eritrea. They note that the use of landfill materials was of growing interest to farmers due to their desire to increase productivity, and that access to other fertilizers is limited because other organic fertilizers are used for other purposes while commercial fertilizer use is not economically possible. The study analyzes the soil on the property of farmers who have used landfill materials as fertilizer in order to test for the presence of heavy metals. They find that the landfill materials have a lower amount of nitrogen and phosphorous than fresh compost. They also found that heavy metal levels for the materials directly from the landfill are higher than the standard for compost for every metal tested for, with the exception of mercury. Lead, copper, chromium and zinc were found to have particularly high levels. The concentrations of metals found in the farmer's fields themselves were relatively low, likely due to a low application rate at the time of study. However, the potential toxic impacts of lead, zinc and copper on humans and animals was motivation for the authors to strongly suggest a transition to other sources of fertilizer, such as fresh compost.

Frandegard et al (2013a) develop an environmental evaluation method for landfill mining, using a combination of the principles of Life Cycle Assessment (LCA) and Monte Carlo Simulation (MCS). They use this method to examine three potential scenarios for a closed landfill that requires remediation of some kind. The scenarios are the following: remediation only, landfill mining using a mobile plant and landfill mining using a stationary plant with state-of-the-art technologies. The analysis includes considerations around the energy use of the processes, the efficiency of material and energy recovery, and the net emissions (and avoided emissions). Four environmental impact factors are chosen: global warming potential, acidification, eutrophication and photochemical exudation. Although their own assessment used a hypothetical landfill site, they conclude that it is an approach that could be used to help decision-making with respect to existing sites as potential landfill mining projects.

Another paper by Frandegard et al (2013b) aims to evaluate the resource and climate implications of landfill mining in Sweden, building off the approach developed in the previous paper. Their paper determines that 25% of the plastics separated in a stationary plant would be potentially recyclable, and that the remaining 75% could be incinerated. Furthermore, they estimate that 70% of the nonferrous and 50% of the ferrous metals could be separated out into potentially marketable materials. Additionally, they determine that about 80 million tonnes of combustible material is available as a resource for waste to energy incineration. In light of all this, they calculate that, depending on the scenario, up to 75 million t of GHGs could be avoided using a stationary plant, and up to 45 million t could be avoided using a mobile plant. They recommend that for landfills that are already in need of remediation, landfill mining be a part of the process; furthermore, landfill mining could lead to significant amounts of avoided GHGs.

Processes and Technology

A paper by Jain et al (2013) documents the results of a reclamation project on a MSW landfill in Excambia County, Florida. Though landfill reclamation projects have happened elsewhere, few of them have been a topic of academic research, and as such the paper provided an important documentation of the process. The process included a preliminary site evaluation and excavation, a pilot project to evaluate operational issues, and finally the full-scale project itself. In this project, the recovery of fine material for use as cover was one of the main objectives, so the techniques used aimed to maximize that supply. The pilot project involved putting the material through a shredder and initially shaker screen to separate the fines, as well as a magnet to separate the ferrous metals; however, it was found that the ferrous metals were not of marketable quality so the use of the magnet was discontinued. As well, the shaker screen was later replaced with a trammel screen that was found to be more effective. The full-scale project used an excavator to remove the waste and screened through a trammel screen. An off-road truck was used to transport the waste from the excavation site to the screen. Later, following equipment breakdowns, the trommel screen was replaced with a punch-plate screen drum mounted on a track so that it could move along with the excavator.

Landfill excavation and screening. Source: Geosynthetics Magazine

Other work on the topic shows a trend in terms of the processes used. In Kaartinen et al (2013), the full-scale mechanical process included the use of a shredder, magnet and a drum sieve with openings of 30 and 70 mm. A wind sieve is also used to separate the lighter materials. Two other papers discussing landfill contents sampling processes in Thailand (Prechthai et al, 2008) and India (Kurian et al, 2003), both involved the use of excavators and screens.

Recycling Potential

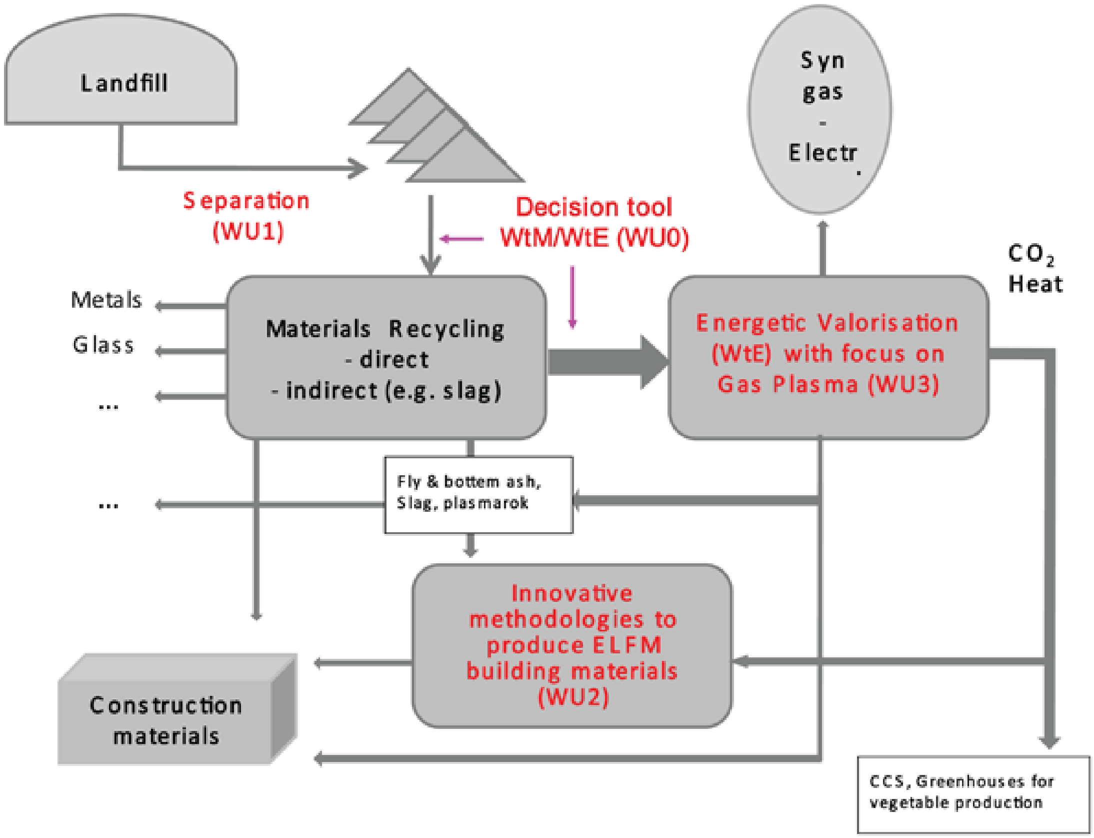
Two papers explicitly discuss the recycling potential of mined landfill material. The first is Prechthai et al (2008), which assesses the recycling potential of plastics in a landfill in Thailand. The size of the plastics as well as the presence of heavy metals were taken into consideration, and use as fuel in a waste incinerator was also proposed as a path for the recovered materials. The team found that the metal concentrations were at an acceptable level for incineration. Furthermore, it was suggested that the larger (>50 mm) pieces could be used in the production of materials such as benches, tables and other items.

A second paper by Zhao et al (2007) discusses the potential use of aged refuse in a landfill outside Shanghai, China. Their research studied the breakdown process of the landfill's contents, and measured indicators like organic carbon, bacteria population and quantity of heavy metals. Their work concludes that some of the remaining materials such as plastics could potentially be cleaned and recycled once separated from other material, though they do not explain the process through which that should happen.

Enhanced Landfill Mining

In the last few years, a new concept has emerged among academics and industry-members working on questions about landfill mining. This concept is referred to as "enhanced landfill mining" or ELFM, and it has been defined as "the combined and integrated valorization of distinct landfilled urban waste streams as both materials and energy while meeting the most stringent ecological and social criteria" (Jones et al, 2013). This concept thus gives a more clear focus to certain landfill mining activities, in terms of having a goal of maximum resource recovery as a result of a landfill mining project. Indeed, Jones et al (2013) state that ELFM is one of many tools in creating "circular economy material loops" in which the process of landfilling eventually becomes unnecessary.

In the context of this research into the feasibility of landfill mining in Whitehorse, enhanced landfill mining is the most appropriate approach. For one, the goal of circular economy material loops is similar to the idea of Zero Waste, which is the driving concept behind the City's updated SWAP. Having this as the overall goal of a project means that questions of feasibility go beyond the immediate economic or technical considerations involved, and instead may broaden the approach to include larger societal motivations such as that of sustainable development, and assessments such as lifecycle analyses.



Intended paths for materials from the Closing the Circle Project. Source: Waste Management World

On a more practical level, enhanced landfill mining makes sense for this project because it is unlikely that landfill mining in Whitehorse would be economically justified based solely on its potential to increase landfill capacity and lifespan. While the shorter lifetime of the landfill and related closure costs are not insignificant, the addition of potentially recyclable materials and feedstock for a waste-to-energy facility might go a long way in terms of increasing interest in this type of operation.

As such, the literature related to enhanced landfill mining can offer even more insights and tools for analysis than the previous section.

In 2013 the Journal of Cleaner Production dedicated an issue to the topic of landfill mining. This issue brought together a number of articles related to enhanced landfill mining. Many of them focus on the REMO landfill in Houthalen, Belgium, where the first large-scale enhanced landfill mining project to date is currently underway after a number of studies were done in order to assess its potential (Quaghebeur et al, 2013).

Composition and Energy Value Assessment

According to Quaghebeur et al (2013), who carried out a characterization study and assessment of the valorization potential of the waste stored in the REMO site, the landfill contains roughly 13 million tons of household waste, and the rest is industrial waste. They find that a fine soil-type material is the largest fraction in both the household waste and industrial waste sections, but that it is considerably larger in the industrial waste. They also note that the amount of plastic in the waste increased in more recent years, while metal and glass/ceramics decreased in newer waste samples compared to older. Furthermore, the proportions of each type of waste are similar to when they were originally landfilled; this includes organic materials that have since degraded into soil-like fraction.

In terms of valorization potential of the waste, they note that the calorific value and total organic carbon (TOC) decreases over time, likely due to the decomposition of the carbon-rich waste into landfill gas. That being said, they also find that the plastic components do not lost calorific value over time.

Their recommendations for valorization options involve grouping the waste into three categories: fine soil-type; metals, glass/ceramics and stone; and paper/cardboard, textiles, wood and plastic. These groupings are similar to those used in previous studies of a similar nature. For the fine fraction, they point to three potential uses: waste-to-energy, due to the large amount of organics present; filler or construction material, if the organic matter is removed; and metal recovery using a magnet that could likely remove more than 50% of the metals. For metals, glass/ceramic and stone they recommend further research into valorization options, but note that the metals are mostly composed of ferrous metals and aluminum. For the plastics, paper/cardboard, textiles and wood, they argue that waste-to-energy is likely the best use. This is because although recycling for paper/cardboard and plastics could be an option, the contamination of the materials is likely to make this process too complicated to be worthwhile. Finally, they note that in the MSW category, combustibles make up a large share of the contents (38%), and increases in more recent waste due to higher amounts of plastic.

Technology

Following from this, Bosmans et al (2013) discuss the importance of waste-to-energy technologies for landfill mining. First, they point to the necessity of the process of transforming MSW in landfills into refuse derived fuel (RDF), which involves shredding, screening, sorting, drying and/or pelletization. This process can produce fuel with a higher calorific value, lower pollutant emissions and lower ash content, as well as being easier to handle and transport.

They follow this with an overview of existing thermochemical conversion technologies. Direct combustion or incineration are noted as being the most conventional approach, while other more advanced technologies such as pyrolysis, gasification and plasma-based technologies are continuing to be developed. That

being said, they make the point that pyrolysis, gasification and combustion are usually used in combination to recover the energy of the feedstock materials.
Products of the incineration process include flue gases such as CO_2, H_2O, O_2 and N_2, as well as other gases and compounds including heavy metals. They note that the impacts of WtE can be managed with proper emissions controls and disposal of final waste products. Furthermore, the bottom ash that is produced in the process can potentially be used in concrete aggregates and other construction materials.
Next, they describe the process of gasification, which involves the partial oxidation of organic substances to product synthesis gas, or syngas. Syngas can then be used as a fuel to product electricity or heat. However, gasification may require more work in terms of pre-treatment of the MSW, including granulation.
Pyrolysis is a technology described by the authors as thermal degradation either in complete absence of an oxidizing agent or with limited supply. The products of the process include pyrolysis gas, pyrolysis liquid and solid coke; the gas and coke can then be incinerated. This process also requires pre-treatment including grinding and drying of the materials.
Finally, they describe various plasma-based technologies, which include plasma pyrolysis, plasma gasification, plasma compaction and vitrification of solid wastes. Plasma processes are found to be a good option for wastes with high concentrations of organic materials that have high calorific values.
They end the piece with a comparison of the different technologies. Incineration, they find, can offer a large source of heat and electricity, with electrical efficiency rates of up to 26%. However, the process does produce both bottom ash and flue gas that must be disposed of (and in the case of flue gas, must be immobilized before doing so). Pyrolysis, with an end result of three products that can be further used for energy generation, does require significant treatment both before and after the process to make that possible. Because of this, the authors note that some specific items such as tires have been found to be very suitable for pyrolysis, but not all MSW is attractive feedstock. Gasification is found to be an attractive option in that the emissions produced are less than traditional combustion methods. However, very few examples exist of facilities designed to take full advantage of its potential. Plasma systems are also seen as being an attractive option that is growing in acceptance within the waste management field. That being said, it is a more expensive technology in the process of being simplified.

Economics

Van Passel et al (2013) assess the economics of enhanced landfill mining. They begin by noting the important roles that technology, regulation and markets all play in driving potential ELFM projects. Furthermore, they observe that the social and environmental benefits of landfill mining are not likely to translate directly into financial profits, and particularly if the projects are being carried out by a private entity there should be government intervention to incentivize the process. Their research methodology itself includes assessments of Payback time, Internal Rate of Return (IRR), Net Present Value (NPV) and a Monte Carlo simulation to assess financial risk. Furthermore, they use the methodology developed by van der Zee et al (2004) to assess various potential sites for a project. Regarding the more technical aspects of the process, they note that in projects in which the goal was to produce cover material for landfills, the 'fine' fraction has been sifted out using screens of up to 75 mm. In the context of ELFM, in which resource recovery for other uses is prioritized, they recommend that the screens be at 5 mm.

In terms of methods to deal with the various costs and benefits associated with a project, they recommend the use of a Cost Benefit Analysis (CBA) that would include external benefits and costs in order to truly assess the societal implications of the project. External costs and benefits include a carbon footprint analysis (for CO_2, CH_4 and N_2O) as well as things like the benefits of a restored and usable parcel of land. They go on to apply their methodology to the Closing the Circle project at the REMO landfill site in Belgium. They note that according to the Monte Carlo simulations, there are a number of parameters that impact the economic performance measures IRR and NPV, including WtE efficiency; electricity price; CO_2 price; investment costs of the WtE installation and operational costs of energy production. 34% of the variation in IRR can be explained due to WtE efficiency, and cost of Co_2 emissions account for 29% of the variation.

When applying van der Zee et al (2004)'s methodology, they narrow down the initial number of landfill sites in Flanders from 1618 to 58 medium sized ones. In doing that, they do note that once ELFM technology has matured somewhat, smaller sites may be more attractive for projects. That being said, the overall conclusion from their calculations is that the projects could have a positive economic impact in Flanders, largely due to the use of WtE. Furthermore, they conclude that compared to business as usual, ELFM would have a positive environmental impact in terms of a reduced carbon footprint, with a reduction in greenhouse gas emissions of 15%.

Enhanced Landfill Mining: A Critical Review

Finally, a paper by Jones et al (2013) provides a critical review of ELFM. They begin by reviewing some of the concepts related to landfill mining. This includes the distinction between *in situ* and *ex situ* landfill mining; *in situ* being the recovery of resources that do not involve the excavation of waste (so includes things like methane extraction and the management of contaminants in surrounding soil and water), while *ex situ* landfill mining involves partial or full excavation of materials. They note that the process of *in situ* extraction can help to stabilize the site so that it becomes a temporary storage site awaiting future *ex situ* projects. Furthermore, in discussing the technical process of ELFM, they caution that while WtE incineration is a commonly discussed path for many of the extracted materials, it does eliminate any future use of those materials via recycling processes, and so the idea of a 'temporary storage' site may be useful in terms of waiting for more sophisticated recycling technology if resource lifespan-extension is an overall goal.

The rest of their paper's aim is to gather the literature related to ELFM in order to show how the Closing the Circle project in Belgium is feasible. They do so by characterizing the materials in the landfill, including the assumption that 50% of the materials degraded during the storage time. This is followed by an on-site sampling of the landfill's contents (the same one described in Quaghebeur et al (2013)), which concludes that slightly more than 50% of the material has degraded, and thus the fines fraction is higher than originally stated. Solid recoverable fuels (SRF) make up 38% (by weight) of the contents, and metals make up 6%. In terms of energy recuperation, they find that the average gross calorific value of the MSW portion of the site's contents are between 6.6 MJ kg^{-1} to 11 MJ kg^{-1}; once separated manually, the gross calorific value for plastics is 19-28 MJ kg^{-1}, for wood is 18 MJ kg^{-1}, paper/cardboard is 11 MJ kg^{-1}. The average ash content for combustibles is found to be 29% (weight). Their assessment continues with an overview of the environmental impacts and carbon footprint of the project, including the positive benefits arising from the project due to the installation of greenhouses on site that will be heated by the WtE facility. Their report also includes a description of the non-technical barriers to the project; these include the existing legislation and regulations around landfills in the EU, the potential reactions of nearby communities, and the need to incorporate external costs and benefits in order for projects to be seen as economically viable. They conclude by scaling up the measurements applied to the REMO site regarding greenhouse gas emission reduction and estimate that if ELFM were to be put into practice across Europe it would result in a savings of 15-75 million metric tons of CO_2 equivalent emissions/year for 20-30 years.

Estimated Material Quantities and their Potential Paths

The following section will discuss the potential paths for extracted materials if the Whitehorse landfill were to be part of an ELFM project. This will draw on the existing literature about ELFM while situating the process in the Whitehorse-specific context. As such, it will draw on already-existing estimates of landfill contents at the Whitehorse Waste Management Facility, and discuss the current waste-management infrastructure already found in the city. Furthermore, it will make use of the work done by Morrison-Hershfield regarding the potential for the installation of a WtE facility by Yukon Energy, since WtE is a potential end point for many of the mined materials.

The Whitehorse waste composition report carried out by Maura Walker & Associates in 2011 provided important insights regarding the types of materials found in the Whitehorse landfill and will provide a base for the following assessments, as shown in Table 1. That being said, some of the reviewed literature pertaining to landfill mining makes the important point that waste composition has changed over time, particularly in terms of the amount of plastics which have risen in use in more recent years (17% in 1993 compared to 24% in 2001, as found in Quaghebeur et al (2013)), whereas glass/ceramics have been found to decrease in more recent years. Since the Whitehorse landfill was built in 1987 (Morrison-Hershfield, 2012), it is likely that it has seen a similar trend, so I will attempt to take that into account rather than assuming that the numbers in the waste composition report are directly applicable to the older contents of the site.

The next sections will discuss the following paths: recycling, plastic-to-oil, composting, waste-to-energy and fine materials, summarized in Table 2. Each section will discuss the full potential for use of these technologies, as though that path was the priority of the project. This approach is obviously not entirely realistic since in a real situation, more than one of these technologies would be deployed and some of them have overlapping resource needs/uses. However, if further work is to be done in terms of an actual cost-benefit analysis of this process, these numbers may be useful to determine what is the appropriate balance of each process.

Material	July %	November %	Annual %
Paper/cardboard	8.6	17.2	13.6
Wood	22.6	9.8	15.1
Plastic	8.1	9.8	9.1
Textiles	3.2	2.5	2.8
Composite	9.7	9.0	9.3
Organics	11.1	21.6	17.3
Total Combustibles (including organics)	52.2 (63.3)	48.3 (69.9)	49.9 (67.2)
Metals	8.6	5.4	6.7

Table 1: Estimated annual waste composition, Whitehorse. Modified from Table 6, Maura Walker & Associates, 2011.

Material	Est. Annual %	Valorization Options to Explore	Est. Net Calorific Value (MJ/kg^{-1})	Est Ash Content
Paper/ cardboard	13.6	WtE, compost	11	41 wt%
Wood	15.1	WtE	18	14.2 wt%
Plastic	9.1	Recycling, plastic-to-oil, WtE	19-28	29 wt%
Textiles	2.8	WtE	18.8	
Composite	9.3	WtE, recycling (depending on material), plastic to oil (?)	Unclear	Unclear
Organics	17.3	WtE, composting, cover/filler (if fine)	Unclear	Unclear
Metals	6.7	Recycling	N/A	N/A

Table 2: Estimated proportions and potential paths for waste categories in the Whitehorse landfill

Estimated Total Material Volumes

In order to fully appreciate the potential uses for the materials buried in the Whitehorse landfill, we require some estimation of the total amount available of each material.

In order to do this, information from the Whitehorse Waste Composition Report and the Whitehorse Landfill Full-Cost Accounting Study was used as they discuss the proportions of various materials, as well as the mass (in kilograms) per m3 of landfill space (Maura Walker & Associates, 2011; Morrison-Hershfield, 2012). Furthermore, information about degradation over time of various materials was taken from some of the literature on landfill composition (Quaghebeur et al., 2013; Jones et al., 2013).

That being said, many assumptions were made in the calculations. For example, it was assumed that 50% of both the paper/cardboard and wood would have degraded over time, and that 90% of the organic materials would have degraded. Given the Whitehorse's relatively cold, dry climate (Environment Canada), it is possible that degradation rates would be slower than expected and that more of the material would remain intact. Additionally, though the mass/m3 for MSW (750kg/m3) is different than that of construction & demolition waste (500 kg/m3) (Morrison-Hershfield, 2012), in order to make the calculations simpler, most of the materials were assumed to have the same mass/volume ratio as MSW, with the exception of the wood waste. Furthermore, the proportions used were the same as those presented in the waste composition report, despite the fact that diversion rates have not always been as high as they are now, in which case there could be more recyclable materials present. Finally, in order to make the numbers slightly easier to understand, they have been converted from kg into tonnes.

Table 3 presents the full estimated volumes and masses of all of the materials discussed in the rest of the study. This means that some items that were present in the waste composition report, such as gypsum wallboard and electronic waste, are

not included. For that reason, the total percentages of each material do not add up to 100%. Additionally, Table 3 shows the likely total amount of fine material, if this includes everything that has degraded over time.
In all, the Whitehorse landfill likely contains over 250,000 tonnes of landfilled material.

Material	Estimated original amount			Degraded	Estimated current amount		
	%	Volume (m3)	Mass (kg)		%	Volume (m3)	Mass (t)
Total contents		600,117				600,117	
Cover material	17.5	105,020				105,020	
Waste material	82.5	495,096	340,378,500				
Est. MSW	75	371,322	278,491,500				
Est. C&D	25	123,774	61,887,000				
Paper/Cardboard	13.6	67,333	50,499,792	~ 50%	6.8	33,667	25,250
Wood	15.1	74,759	37,379,748	~ 50%	7.6	37,380	18,690
Plastic	9.1	45,054	33,790,302	< 1%	9.0	44,603	33,452
Textiles	2.8	13,863	10,397,016	< 5%	2.7	13,170	9,877
Organics	17.3	85,652	64,238,706	> 90%	1.7	8,565	6,424
Composite	9.3	46,044	34,532,946	< 5%	8.8	43,742	32,806
Metal	6.7	33,171	23,220,002	< 1%	6.6	32,840	22,988
Fines	0.3	1,485	1,113,966	N/A	31.0	153,396	105,685
	74.2						
Total (waste)		367,361	255,172,478			367,361	255,172

Table 3: Estimated total amounts of materials in the Whitehorse Landfill

Recycling

According to Maura Walker & Associates (2011), a number of potentially recyclable materials are found in the Whitehorse landfill. These include paper, glass, metals and plastics with estimated annual proportions of 13.6%, 1.3%, 6.7% and 9.1%, respectively.
That being said, their composition report was based on recently generated waste, which they collected as it came fresh to the landfill. Based on sampling and characterization work done by others in which material was excavated from different depths of landfill sites and their findings related to material decomposition, it is likely that much of the paper in the Whitehorse landfill will have degraded significantly over time. For this reason, and due to the level of contamination which would be experienced, it also feels safe to assume that what paper remains intact would not be of sufficient quality for recycling.
This leaves glass, metals, plastics and electronic waste. Glass is indeed accepted at the recycling centres in Whitehorse for processing, but much of it is then returned to

the landfill for use as cover material. Furthermore, it is likely that glass found in the landfill would be broken into small pieces, so it would probably be mixed with any fine fraction that would result from screening the materials.

Plastics were found to be 9% of the estimated annual waste composition (Maura Walker & Associates, 2011). Based on findings related to the change in waste composition of other landfills over time, it is possible that older sections of the landfill would have less plastic in them. That being said, recycling in the Yukon is only 25 years old (Raven Recycling, 2014) and the items being accepted for recycling have increased over the years since then, so it is possible that materials which are currently commonly diverted would have a much larger presence in the older sections of the landfill.
However, the recycling potential of plastics extracted from the landfill is uncertain. Recycling takes place in the context of global markets and commodity prices, and much of the plastic recycling takes place in China. Last year, China enacted its "Green Fence Initiative" in response to the high levels of contamination found in some of the commodities it was receiving from places such as Canada and the United States. This includes a limit of 1.5% contamination in all commodities, an explicit list of items it would reject, much closer inspection of incoming materials, and the disposal of rejected items either as waste, as energy, or back to their country of origin (Alberta Plastics Recyclers Association, 2014). Though the overall implications of this policy are beyond the scope of this paper, the point is that while plastics that have sat in a landfill for a number of years may not have degraded in the same way as paper products, they are likely contaminated by their interaction with other materials and potentially not fit for recycling. This is supported by answers received over email from Dave Rotherty of Bluewater Project Inc, a recycling broker based in British Columbia, who says that "it's currently hard enough to sell plastic/have it clean enough let alone pulling it out of a landfill," (Dave Rotherty, personal communication, December 2013).

This leaves metals. According to the waste composition report, of the 6.7% of all waste that was metal, and 2/3 of this was steel products. Non-ferrous materials were 21%, and food and beverage containers were 12%. Currently, non-ferrous metals such as aluminum, brass, copper are also accepted in scrap metal processers such as Raven Recycling, along with beverage containers such as aluminum and tin cans (Raven Recycling, 2014). Stainless steel is the only ferrous metal that is explicitly accepted, although "breakage" items that include a number of different metals including steel parts are bought as well. With that in mind, it is possible that 2/3 of the metals found in the landfill would not be easily recycled. The beverage containers and other non-ferrous metals, however, could likely be recycled fairly easily, depending on the contamination levels. Like plastics, it is also possible that earlier in the landfill's history the same diversion methods were not in place for metals, and so the overall percentage of metal in the landfill as a whole may be higher.
However, using the assumption that ~30% of metals in the landfill are non-ferrous, this gives us a total of 6,895 tonnes of recyclable metals with Whitehorse's current

metal recycling capacity. This is out of a total of close to 23,000 tonnes of metals sitting in the landfill, as seen in Table 4.

Metal	
Total mass (t)	22,988
Est. % non-ferrous	30
Total t non-ferrous	6,896

Table 4: Estimated total mass of metals in Whitehorse landfill.

Plastic-to-Oil

The plastic-to-oil machine being operated by Rising Sun Innovations in Whitehorse accepts plastic types #2, 3, 4, 5 & 6. According to the waste composition report, 42% of the plastics found were soft plastics such as grocery bags and plastic wrap, rigid plastics such as lawn furniture and toys comprised 39%, rigid non-beverage containers accounted for 9% and beverage containers were the remaining 4% (Maura Walker & Associates, 2011).

The plastics that the plastic-to-oil machine will accept potentially cover much of what is found in the landfill. Many beverage containers are #1 PET plastic that is not suitable for plastic-to-oil processing, but because they are by and large recycled for deposit they are less likely to be found in the landfill, as the composition report has found. "Soft plastics" are likely low-density polyethylene or #4 plastic, so they could be good potential candidates to be turned into oil. Furniture and toys are less clear, since these items may be composed of a number of different plastic types or may not have a number associated with them at all. In the latter case, they may not be suitable for conversion into oil; that being said, they could also be made of high-density polyethylene, or #2 plastic, in which case they would be suitable. "Rigid non-beverage containers" as a category could include a range of plastic types, including #1, so further investigation would be required to determine whether they could be used.

Plastic	
Total mass(kg)	33,452,399
Est. % for plastic-to-oil	50
Est kg for plastic-to-oil	16,726,200
Est volume of oil (L)	16,726,200
Resulting barrels of oil	105,196

Table 5: Estimated amount of plastic and oil that could be generated.

To estimate the amount of plastic in the landfill that could be used in the plastic-to-oil machine, it is important to take into account the fact that soft plastics such as plastic bags have a considerably smaller volume and mass than hard plastics. As such, the proportion of potential materials for the plastic-to-oil machine has been estimated to be at 50% of the landfill's total plastic contents. From these calculations, more than 16 million kg of plastic could be available. The mass of plastics was measured in kg in order to easily convert this amount to the number of liters of oil that would be generated, as the ratio is roughly 1:1. This number was then used to estimate the number of barrels of oil that could be produced. This is summarized in Table 5.

Composting

Considering that the first-ever landfill mining project in Tel Aviv had the goal of extracting a fertilizer for nearby citrus groves (Savage et al, 1999), and since then there have been other projects with a similar goal (Tesfai & Dresher, 2009), compost should be considered as a potential path for excavated materials from the Whitehorse landfill.
The Whitehorse waste composition report found organics to be the largest fraction by weight (17.3%) in freshly collected municipal solid waste for the yearly average, with food waste making up the most significant portion (Maura Walker and Associates, 2011). As has been stated before, it is likely that organic material within the landfill would have degraded considerably over time, resulting in a fine soil-like material. The question is then: would it be possible to use that material as compost, or add it to other organic material undergoing the composting process? Previous research on the Closing the Circle project in Belgium found that when a magnet was used to separate out some of the metals from the soil-like fraction, it resulted in metal quantities below the local limit for compost (Quaghebeur et al, 2013). However, inquiries to Garret Gillespie, who operates Boreal Composting at the Whitehorse Waste Management Facility, regarding the composting potential of degraded materials were answered with a clear negative. He believes that the level of contamination in those materials is likely far too high (Gillespie, personal communication, March 5, 2014). For this reason, the amount of potential compost was not calculated.

Waste-to-Energy

As has been seen previously, waste-to-energy is the most commonly proposed use for previously landfilled materials, particularly when levels of contamination are too high to realistically attempt to recycle them. Combustible materials include plastic, paper/cardboard, textiles, wood and other organics.
In Whitehorse, these combustible materials are some of the largest fractions of the waste going to the landfill: paper, 13.6%; plastic 9.1%; organics 17.3%; wood 15.1%; textiles 2.8% (Maura Walker and Associates, 2011). The waste composition report also included a category of 'composites', which include items like furniture, binders, suitcases and composite packaging, and made up 9.3% of what was found (*Ibid*). It is likely that much of this material would also be suitable for incineration. In total, up to 57.9% of what was found in this waste composition assessment could be combustible fuels.
Previous work has also found that more than 50% of the degradable waste (such as

paper, cardboard and other organic materials) did break down over the course of its time in the landfill (Jones et al, 2013). In the context of the REMO landfill site, 20% by weight of all landfilled material had decomposed (Quaghebeur et al, 2013). It is not clear whether these percentages would make sense in the Whitehorse context, since the climate of Whitehorse is drier and colder than in Belgium, such that degradation may occur more slowly than at the REMO site.
For use in WtE, the calorific values of each commodity must be found. Previous work has found overall net calorific values of between 20 and 25 MJ/kg of dry matter for all combustible materials together (Kaartinen et al, 2013). More specific studies have found calorific values to be between 18 and 27 MJ/kg^{-1} (dry weight) for plastics, between 6.7 and 12 MJ/kg^{-1} for paper/cardboard, between 1.3 and 4.8 MJ/kg^{-1} for fines and 18 MJ/kg^{-1} for wood (Jones et al, 2013; Quaghebeur et al, 2013). An additional consideration related to WtE incineration is the ash content of each commodity. In the REMO site, the average ash content was found to be 29% (by weight) for plastics, 14.2% for wood and 41% for paper/cardboard (Jones et al, 2012). While the specific numbers for the contents of the Whitehorse landfill may be somewhat different, they provide a base from which estimations can be made. The estimated calorific values of each commodity are summarized in Table 6. The total mass of combustible materials is summarized in Table 7.

Material	**Estimated current amount**			**Calorific Value**	**Est Ash Content**	**Est Total Energy Content**	
	%	Volume (m3)	Mass (kg)	(MJ kg-1)	% (weight)	(MJ) total min	max
Total contents		600,117					
Cover material		105,020					
Waste material							
Estimated MSW							
Estimated C&D							
Paper/Cardboard	6.8	33,667	25,249,896	11	41	277,748,856	
Wood	7.6	37,380	18,689,874	18	14.2	336,417,732	
Plastic	9	44,603	33,452,399	19-28	29	635,595,581	936,667,172
Textiles	2.7	13,170	9,877,165	18.8	Unclear	185,690,702	
Organics	1.7	8,565	6,423,871	Unclear	Unclear		
Composite	8.8	43,742	32,806,299	Unclear	Unclear		
Metal	6.6	32,840	22,987,802	N/A	N/A		
Fines	31	153,396	105,685,173	2.2-4.8	80	232,507,381	507,288,830
Total (waste)		367,361	255,172,478				

Table 6: Estimated calorific value of materials in the Whitehorse landfill

As the results in Table 7 show, there are over 100,000 tonnes of combustible materials available in the Whitehorse landfill. The WtE facility projected by Morrison-Hershfield (2012) has a capacity of 25,000 t/year. As such, the landfill likely contains enough materials to run a facility for at least 4 years. That being said, if a combination of freshly produced waste and landfilled materials were used, the fuel source would be spread out over many more years. That being said, the use of fresh MSW for the WtE facility has been the cause of concern for many already involved in the waste management industry in Whitehorse. This will be explained further in the “Implications” section, but in general doing so would require proper management of this operation in conjunction with current efforts to enhance waste diversion rates.

Combustibles	
Total mass (t)	103,349
Original WtE facility capacity(t/yr)	25,000

Table 7: Estimated total combustible materials in the Whitehorse landfill

The business case analysis of a potential waste-to-energy facility for use by Yukon Energy does not include any specific findings related to the calorific potential of the waste currently being generated in Whitehorse, nor does it include specific numbers related to the energy efficiency of the various WtE facilities being considered. However, literature on the subject alludes to an efficiency range of 22-26% for incinerators currently being used, with a potential of >30% as technology continues to develop (Bosmans et al, 2013).

Spittelau waste-to-energy incinerator. Source: Be Waste Wise

Fine Materials

Previous research involving landfill excavation and materials characterization has found that the fraction of "fine" or "soil-like" material can be around 45% of the landfill's contents (Jones et al, 2013; Quaghebeur et al 2013; Kaartinen et al 2013). Since it is likely that the results will be somewhat similar in the Whitehorse context, it is useful to consider what could be done with that material once it has been recovered.

In previous research about landfill mining, before the emergence of the concept of enhanced landfill mining, there has been much discussion about the use of the fine fraction as an additional cover material, or as some type of filler material to be used off-site (Krook et al, 2012). This particular use was often in the context of research about what should be done in terms of remediating closed landfills that have problems or pollution, or in the case of desiring to create more space in current landfills in locations where free land for future landfill sites is in short supply. However, in the context of enhanced landfill mining, more options for fine material valorization have been presented: WtE generation and metal recovery (Quaghebeur et al, 2013). WtE is seen as an option due to the large amount of organic materials present in the fine fraction, and it is proposed that the organics could be separated for this use while the rest be used as construction or filler material. However, there is no clear explanation as to how to separate the organics from the non-organics. Metal recovery by use of a magnet is also proposed, in conjunction with the desire to reduce the heavy metal load if the fines are to be used as a soil or compost (*Ibid*). With these options in mind, further research could be done to assess potential local uses for the fine material were a landfill-mining project to go forward.

Project Implications

The following section will outline some of the economic, environmental & health, political and operational implications of an enhanced landfill mining project in Whitehorse. This section will include the following assumptions: 1) That landfill mining would only be done in conjunction with the construction of a waste-to-energy facility which would be operated by Yukon Energy as a replacement for aging diesel back-up generators; 2) That this project would be done in collaboration with existing waste haulers and processors.

Economic Implications

When Yukon Energy chose to end its research into using a Waste-to-Energy facility to replace its aging diesel generators, it did so because the costs would be too high to justify the project. Yukon Energy's plan had involved using only freshly produced solid waste, and because of the increased waste diversion stemming from the SWAP starting in 2015, the waste quantities would not be sufficient and it would need to supplement those (especially during the winter) with locally-sourced biomass. The cost of biomass was estimated at $104 per tonne, and it was assumed that 7500 tonnes of biomass would be needed in the first year, to a total of $780,000, with decreasing amounts in following years as the amount of MSW continued to grow despite increased diversion (Morrison Hershfield, 2012).

Were there to be an enhanced landfill mining project begun in Whitehorse with most of the combustible excavated materials going to WtE generation, the costs associated with using biomass could be eliminated. According to the updated WtE business case analysis for Yukon Energy, the costs of purchasing, storing, handling and chipping the wood add up to more than $1.8 million. With landfill mining, it is possible that these costs could be eliminated entirely.

Furthermore, the $13.5 million needed for landfill closure, and additional $1 million for post-closure monitoring ($50,000/year X 20 years) would likely be reduced to some extent, were the landfill to change from a final storage location for waste into a temporary one waiting to be mined.

That being said, landfill mining would also bring with it other costs. For example, the equipment needed for the process would include some kind of mobile excavator and a screen. To sort the material further, tools such as a magnet and a blower of some kind would likely be needed. This would also require a facility in which to operate. In addition to that, operational costs such as labour and energy to run the equipment would also have to be factored in. The scale and speed of the project would determine those costs, so there will be no attempt to estimate them here.

Environmental and Health Implications

In order to more clearly understand the potential environmental and health implications of an enhanced landfill mining project in Whitehorse, this section will cover two broad categories: the more localized impacts associated with the process

of mining the landfill and incinerating the waste and the more general impacts, such as diverted greenhouse gas emissions.
The process of mining a landfill is certainly not without environmental impact. In addition to the potential impacts such as noise and its effects on surrounding wildlife, there could be methane emissions produced as degrading waste is exposed. Leaching of contaminants such as heavy metals is also a possibility, particularly if more of the waste is exposed to precipitation as it is being excavated. Many of the studies on the topic have found the health and safety hazards associated with those project to be low, but there remains a need for further research into the long-term impacts of these projects (Krook et al, 2012).
The construction and operation of a waste-to-energy incinerator would also have impacts on the surrounding environment. During operation, incinerators to produce some emissions, including small amounts of CO, HCl, HF, HBr, HI, NO_X, SO_2, and volatile organic compounds (VOCs) (Bosmans et al, 2013). In addition, the process also produces bottom ash and fly ash, both of which can be hazardous to human health and must be property stabilized and disposed of. Furthermore, many concerns have been raised about the production of dioxins by waste incinerators in the past, and they are indeed produced in small quantities. In order responsibly carry out waste-to-energy incineration, there would have to be great care in terms of selecting a facility with sufficient efficiency and pollution control mechanisms to minimize the production of all of these harmful substances (Vehlow et al., 2006; Rabl & Spadaro, 2002).

That being said, waste incineration would involve the diversion of some greenhouse gas emissions, including both those that are currently being produced by the diesel generators it would replace, as well as methane gas being emitted from the landfill as it currently stands. Frandegard et al (2013) used a Monte Carlo Simulation to assess the GHG implications of landfill mining for WtE, using either a stationary plant or a mobile one. Their results found a close to 100% probability of avoided GHGs using either scenario.

Political Implications

The political implications of a landfill mining project in Whitehorse are difficult to determine, as it has not been publicly discussed up until now. However, Yukon Energy's past and current proposals regarding replacement options for their aging diesel generators have generated much controversy and these may provide some kind of basis for potential discussions around landfill mining.
In 2011-2012 when Yukon Energy originally proposed the idea of a waste-to-energy facility, the topic was much discussed in local media, as well as in public consultation sessions that was part of the process. Some members of the public seemed to favour the idea, particularly due to the fact that the fuel would be locally sourced and could create jobs in the facility's operations, both of which are important considerations in a relatively isolated community. However, not everyone shared this view. Recycling processors in the territory, namely Raven Recycling and P&M Recycling, both opposed the idea on the grounds that a WtE facility could

directly compete with the work of their facilities to divert waste from the landfill. Though Yukon Energy did their best in their proposal to address those concerns, the two organizations maintained their doubts that the City would be able to achieve their goals of 50% waste diversion, and eventually Zero Waste, if a WtE created a competing incentive to simply dispose of things in the garbage (Letter to the Editor, Yukon News, March 25, 2011).

In addition to these issues, there were also concerns raised about the health and economic impacts of waste incineration. Waste incineration facilities elsewhere in North America have faced resistance from their communities due to toxic emissions from the technology at the time. A well-publicized case of a community in Pennsylvania whose incinerator eventually drove the municipal government to insolvency is also an example of the imperfections of WtE facilities (Bloomberg, Nov 25, 2013).

That being said, Yukon Energy's current proposal to construct a liquid natural gas (LNG) facility as their new back-up power supply is also facing considerable community resistance. Concerns about the greenhouse gas implications of LNG, as well as the potential for the gas itself to come from wells using hydraulic fracking, recently led to presentations at public consultations on the topic almost entirely from opponents of the project (Yukon News, April 2, 2013). Furthermore, one of the Yukon First Nation governments that had originally planned to be a partner on the project has since backed down, citing concerns from their members about the source of the LNG.

It is possible that an enhanced landfill mining project could avoid some of these concerns, at least those related to competition with recycling, and provide an alternative back-up fuel that would not have the same environmental impacts as the use of LNG. However, the concerns about the health and environmental impacts of an incinerator discussed above are not without merit, and more research should be done about the effects of WtE facilities elsewhere and the reliability of current pollution-management technology to control the emission of toxic substances. Furthermore, while the Yukon has a long history of mining activity, the close proximity of a landfill excavation project to residents of Whitehorse may lead to a range of concerns about impacts such as noise and odour, as well as potential pollution from the excavation on things like fresh water sources.

Energy and resource extraction are a hot political topic globally, and it is unlikely that it will become less so any time soon. As such, it almost feels inevitable that these issues will spark discussion and a range of points of view. Since enhanced landfill mining projects are still in their early stages, if being carried out at all, it is hard to say how it will fit into the current debates around these issues. One way or another, it may be a possibility to widen the discussion and increase the potential for creative and innovative ideas.

Operational Implications

This section will cover the ways in which enhanced landfill mining could affect current waste management operations in Whitehorse. These include both the construction and establishment of a WtE facility, as well as the operational

requirements of the landfill mining process itself.
The report by Morrison-Hershfield about a WtE facility included information about potential sites for a facility. They noted that a 25,000 tonne facility would require a relatively flat site that is approximately 2 hectares in size, and would likely have a stack of 20-30 m high. Furthermore, the site would require full electrical, water and sewage connections; this would include a water demand of 14,500,000 L annually and 4,500,000 L of wastewater produced. Their report identified two potential sites close to downtown Whitehorse (Morrison-Hershfield, 2012).

In addition to this, the landfill mining project would require a facility in which the excavated waste could be dried, screened and sorted. Literature on the topic has referred to both mobile and stationary plants as potential processing sites. A mobile site, as described by Frandegard et al (2013) would involve the excavated material first being passed through a coarse screen to separate out bulk materials. The rest would pass through a star screen which would separate out the fines, and then an air classifier would separate the paper, plastics and textiles while a magnet and eddy current separation would sort out the ferrous and non-ferrous metals. The stationary plant would involve similar separation mechanisms, though the coarse and star screening processes would remain on site. Other researchers have found that although both types of plant can be effective for material separation, the general consensus seems to be that a stationary plant yields a higher quantity of sorted materials (Frandegard, 2013). Furthermore, whatever metals are sorted out would need to be cleaned before they can be recycled, so a stationary plant may provide more space for that process to occur.
This facility would also require a site on which to operate. Determining the exact requirements for that site are beyond the scope of this paper, but considerations in terms of where that facility should be located in relation to the landfill itself as well as other waste management operations in Whitehorse would have an impact on how the entire system would fit together. For example, does it make more sense for the facility to be located near the landfill itself so that fine materials can be returned to the landfill, or should it be nearer to where the waste incineration plant might be located? This location of the site would also affect how the transportation of excavated and sorted materials would occur.
In terms of transportation itself, there are already waste haulers in Whitehorse who transport materials between various locations such as waste sources, the landfill and recycling processors. It is likely that these companies could provide the transportation needed for the enhanced landfill mining, and requirements in terms of increasing transport capacity would depend on the amount of materials being transported on a daily or weekly basis.

Questions of Ownership

Another question to consider, as was mentioned previously, is how an enhanced landfill mining project would impact the management of freshly generated waste. The concerns that have been raised about the potential for a WtE facility to compete

with existing waste diversion efforts in Whitehorse are extremely important and valid, and great care would have to be taken in order to ensure that diversion remains the main goal of current residents. The existence of a sorting facility for excavated waste could potentially also serve to sort freshly produced waste in order to divert it to composting, recycling and plastic-to-oil processing facilities, but maintaining or increasing diversion methods before it even gets to that point would reduce the potential logistical complications of such a process.
Despite the relatively small population in Whitehorse, the waste management landscape includes quite a few different organizational actors. Some of them are in direct competition for resources, while others have long-established business partnerships. Some are privately owned and receive no core funding from the government, while others are contracted directly by the municipal or territorial governments. The addition of an enhanced landfill mining project, while it could provide useful energy and recyclable resources, would certainly add to the complicated nature of the overall waste management system.

Finally, one question that has not been touched on so far is who exactly would be in control of a landfill mining project? Would it be run by Yukon Energy, which in itself has no experience with waste management? Should it be carried out mostly by private organizations, perhaps local companies that do have the technical experience required? Once we begin to think about waste as a resource, rather than just a problem that needs to be dealt with, how does that affect our ideas around ownership of that resource? Since the waste itself has been communally generated, should whatever benefits come from it be held in common, including any financial benefits? Is it possible that this be a project that would bring together the multiple partners and stakeholders in waste management and energy production in Whitehorse, along with the general public, so as to attempt to meet all of the needs which have been identified over the course of previous conversations about these issues? Could Whitehorse be an example of effective inclusive project design and management, which could serve as a model for other communities considering similar questions? It would indeed be an interesting challenge to put forward.

Conclusions and Recommendations for Further Research

The relatively new concept of "enhanced landfill mining" has provided a way to shift the existence of landfills from a final site of waste disposal to being temporary storage locations for potentially valuable resources. Furthermore, the valorization potential of excavated municipal solid waste as an energy source for incineration and renewable resources for recycling processes broadens the landscape in discussions around alternative energy and resources in a time of concerns over scarcity. Landfills, as sites that are geographically dispersed and also close to most urban centers, have much potential to be the sites of valuable "mineable" materials in the near future.

Whitehorse, the capital city of the Yukon Territory, is currently dealing with important questions and discussions about energy generation and waste management. The convergence of these issues makes this a particularly interesting time to investigate the potential for enhanced landfill mining to provide resources for material recycling and waste-to-energy incineration. Previous research about the city's current waste composition, landfill capacity, and the requirements for a waste-to-energy facility provide a solid foundation on which to base this research. Furthermore, the recently adopted Solid Waste Action Plan has reinvigorated the discussion about waste management in the territory in the context of a long-term goal of Zero Waste.

This paper is only the first step in answering the questions about the feasibility of an enhanced landfill mining project in Whitehorse. Its overall achievement has been to provide what is hopefully a relatively holistic examination of current waste management practices, as well as an overview of the ongoing debate over new sources of back-up energy. This has been combined with an examination of the emerging literature about enhanced landfill mining, including the case studies of the REMO landfill site in Belgium.

As such, there is a great deal of space for further work on the topic, if this were to become an attractive subject for other researcher. For example, an assessment of the costs of such a project would be needed, depending on the scale of such a project. This should also be combined with an evaluation of the savings and benefits, including the larger societal benefits such as avoided greenhouse gas emissions. Furthermore, there would need to be much more work in terms of engaging all relevant stakeholders, in order to design a system which would not compete with existing waste management efforts and instead could enhance them. Of course, a waste composition assessment of the inner contents of the landfill would provide considerably more information about its contents and the level to which things have degraded. Additionally, more work could be done into the long-term environmental impacts of enhanced landfill mining generally, though some modeling research has already been carried out.

Enhanced landfill mining is only just beginning to be talked about in the literature about waste management. The next several years, particularly as the Closing the

Circle project at the REMO site goes forward, could be an important time to explore the potential of landfill mining in other communities. This assessment is hopefully one more component in this ongoing conversation.

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