Solid Waste Management Best Practices: Pyrolysis as a Waste Management Approach in the Peace River Regional District

FINAL REPORT

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Abbreviations

General

AD	anaerobic digestion
CEAP	competitive electricity acquisition process
CH_4	methane
CHP	combined heat and power
CO_2	carbon dioxide
CO_2e	carbon dioxide equivalents
EWS	Emergent Waste Systems
FCI	fixed capital investment
FSWCS	Four Season Waste Composition Study
FW	food waste
GHG	greenhouse gas
GW	green waste
KOH	potassium hydroxide
LFG	landfill gas
MERC	mandatory employment related costs
MGI	Magnum Group International
MRF	materials recovery facility
N_2O	nitrous oxide
OC	operating costs
PRRD	Peace River Regional District
RFP	request for proposal
SWMBP	Solid Waste Management Best Practices

Plastic types

EPS	expanded polystyrene
HDPE	high-density polyethylene
LDPE	low-density polyethylene
PE	polyethylene
PET	polyethylene terephthalate
PP	polypropylene
PS	polystyrene
PVC	polyvinylchloride
XPS	extruded polystyrene

Waste

C&D	construction and demolition
CCR	commingled curbside recyclable
ICI	industrial, commercial, and institutional
MWP	mixed waste paper
OCC	old corrugated cardboard
SFR	single-family residential
SH	self-haul
TS	transfer station

Units of measure

atm	atmospheres
d	days
h	hours
kg	kilogram
kPa	kilopascals
KW	kilowatt
kWh	kilowatt hours
L	liter
m	meters
m^3	cubic meters
mm	millimeter
MWh	megawatt hours
s	seconds
t	metric tonnes

Regional landfills

BBLF	Bessborough landfill
CLF	Chetwynd landfill
NPLF	North Peace landfill

Executive summary

Food waste (FW) and green waste (GW) combine to form a major source of landfilled material in the Peace River Regional District (PRRD). The benefits of FW/GW diversion are two-fold: increased landfill lifespan; and a reduction in landfill gas (LFG) generation. Complete diversion of FW/GW significantly reduces LFG, which primarily consists of the greenhouse gases (GHGs) methane (CH_4) and carbon dioxide (CO_2). Methane is a particularly potent GHG; however, CH_4 is also energy rich. Treatment of FW/GW diverted from landfilling by technological means leads to a reduction in LFG emissions, capture of GHGs in a controlled environment, and has the potential for energy and/or materials recovery.

Background

This report examines the financial feasibility and environmental impact of processing landfill-diverted FW/GW using pyrolysis in the PRRD. The main document is based on a pilot scale pyrolysis implementation using a 500 kg/h rotary unit that processes locally landfilled (sub-regional) FW/GW with modeled expenses, income and global warming potential (GWP) in the form of carbon dioxide equivalents (CO_2e)[a]. The base or starting operating conditions assumed the pyrolysis unit operates 8 hours/day, 5 days/week, processing 1,043 t of 8% moisture feedstock annually, or ~3,200 t of wet FW. Additional financial scenarios are provided by expanding the base operating condition to 16 hours/day and to continuous operation (24 hours/day, 7 days/week), as the fixed capital investment (FCI) is similar in all cases. The three scenarios provide insight into the ideal operating conditions required for financial success. Regional scale pyrolysis scenarios are presented in the Appendix for consideration at a larger, regional scale.

Economic feasibility

The economic feasibility of implementing pyrolysis was modeled over a ten-year amortization period with 50% of profits used to pay down the principal in order to reduce the payback period. The marketable products are biochar or activated carbon (upgraded or modified biochar), and oils/waxes. The biochar is the more readily marketable product. All modeled scenarios resulted in heavy economic losses if the oils were considered to be of no value and the biochar was marketed at \$400/t. Profitably decreased if

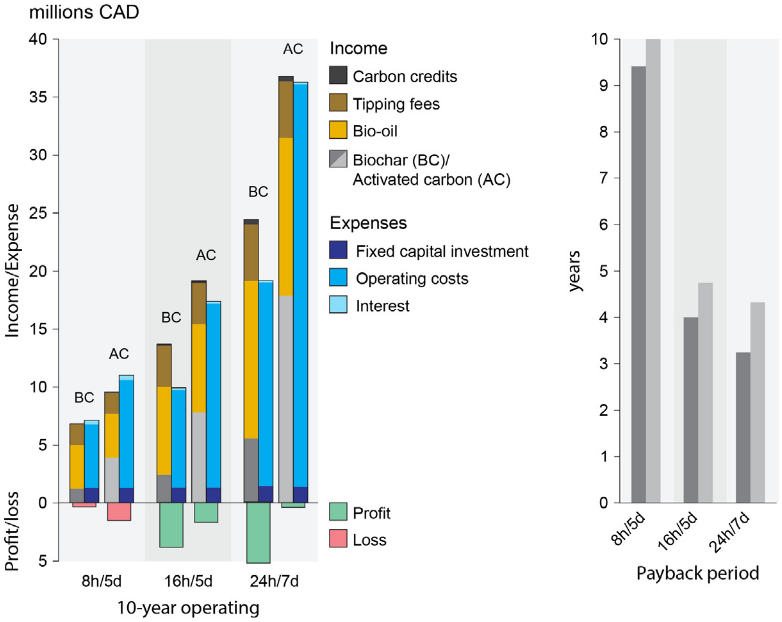

Figure E-1 Economic summary of a pilot scale pyrolysis unit implementation.
Scenario labeling is hours per day/days per week.
Left: Income and expenses (blue bar) for three operating conditions. Each scenario is split into biochar (BC) and activated carbon (AC) as possible products. Profit/loss is indicated at the bottom for each scenario.
Right: Payback periods for each scenario with BC (dark bar) and AC (light bar) as the possible products.

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[a] CO_2e: Carbon dioxide equivalents. The GWP of greenhouse gases is usually reported as CO_2e. Where available, N_2O and/or CH_4 have been converted to CO_2e and summed for a total CO_2 quantity. One molecule of N_2O is equivalent to 265 molecules of CO_2, and one molecule of CH_4 is equivalent to 28 molecules of CO_2 over a 100-year lifespan. Equivalents are according to the Government of BC.

upgrading from biochar to activated carbon was performed (Figure E-1). A minimum cost of $1,700/t for the biochar is required if only the biochar, and not the oil, is marketed in the base 8 hour/day scenario, with the cost decreasing to ~$1,000/t for the other two scenarios. The $1,000/t value may be obtainable in the current market, which would remove the pressure of marketing the bio-oil. Furthermore, the operating costs are based on two operators, a bookkeeper and an engineer; operating costs may be reduced by only employing the minimum two operators as required, according to the manufacturer.

Environmental impact

Landfill diversion of FW/GW was the major source of CO_2e reduction in the model, followed by carbon sequestration in the form of biochar (see Figure 7, page 18). The CO_2e generated by the pyrolysis process was minor in comparison to the achievable reduction in CO_2e for sub-regional and regional scale scenarios.

Conclusion

The base financial scenario of operating the unit 8 hours/day, 5 days/week incurs financial losses in the production of biochar (Figure E-1) when both the bio-oil and biochar are marketed. An increase in operating time has an impact on operating costs, but little impact on FCI; therefore, the target should be to operate the unit more than eight hours per day. Doubling the operating hours leads to profitability (Figure E-1). Adjustments may also be made for the operating costs in terms of number of employees, salaries and benefits paid.

The market value of biochar was assumed to be a low value of $400/t, and the bio-oil a mid-range value of $1.10/L. Non-upgraded bio-oil may be difficult to market. Consequently, the objective should be to establish a minimum market value for the biochar at $1,200/t, which is above break-even for production costs, when tipping fees and carbon credits are included, and will cover additional costs such as packaging, shipping, etc. Sale of the bio-oil should still be sought, even if a reduced market value is obtained. The priority lies with establishing an end market for the biochar. Once the end market is established, the model may be adjusted to reflect actual conditions. A solid business case exists for the treatment of diverted landfill waste using pyrolysis that has the potential for good financial returns, with some flexibility in the operating conditions and market value of the products to achieve a break-even scenario or better.

Environmentally, the removal of FW/GW from the landfill waste stream results in a relatively significant net reduction of CO_2e even when CO_2e production from pyrolysis is factored in. Furthermore, landfill diversion increases landfill lifespan; these cost savings were not taken into account in the modeling. An extension of a pyrolysis implementation to the regional scale will have benefits in reducing landfill CO_2e, transportation-related CO_2e for recyclables, and reduce the threat of micro- and nanoplastics in the environment.

1. Introduction

The diversion of waste from landfilling has economic and environmental benefits by extending landfill lifespans and reducing LFG emissions. In particular, FW and GW are major sources of CH_4 when decomposed in the anaerobic (oxygen-free) environment of landfills. The FW/GW component of landfill waste is suitable for energy recovery; other materials, such as paper, cardboard, plastics and textiles may be converted into energy or targeted for reuse as well.

A previous *Solid Waste Management Best Practices (SWMBP)*[b] report prepared for the PRRD reviewed waste diversion and recycling options using currently available technology. The options included: (i) pyrolysis, which could process all types of organic waste; and (ii) a materials recovery facility (MRF) for paper, cardboard, metal, glass, and plastics, combined with anaerobic digestion (AD) and composting for FW and GW recovery, respectively. Both options could provide a complete solution for the PRRD that addresses landfill diversion and recyclables handling.

Most technologies operate on economies of scale. The *SWMBP* report suggested that the only economically feasible means of implementing a MRF would be at a full regional scale with all sources of recyclables (e.g. Return-It, RecycleBC) accessible, and possible out-of-region materials, if technology were used in the sorting of recyclables. While achievable, initial capital investment would be high. The MRF may or may not address landfilled waste quantities.

Food and green waste is a major component of landfilled refuse, accounting for 30-45% of all materials entering PRRD landfills according to the *Four Season Waste Composition Study* (FSWCS, 2018)[1]. Strategies for reducing landfilling of common recyclables such as paper and plastics in the PRRD already exist through curbside programs and recycling depots; however, very limited opportunities for reducing FW/GW quantities from being landfilled are available, suggesting FW/GW should be prioritized as a landfill diversion strategy.

The Government of BC[c] has stated an objective of 95% organic waste diversion by 2030. For the purpose of this report, the main focus is on the diversion of FW/GW from landfilling, which will help meet Government of BC carbon emission reduction targets. The selected technology for diversion is pyrolysis, a thermal treatment of waste that produces marketable products, is scalable, and can process a variety of materials for energy and possible chemical recovery. The proposed pyrolysis unit size is limited to the sub-regional level using a pilot scale plant. A sub-regional implementation, for example, refers to a pyrolysis unit located at the North Peace landfill (NPLF) servicing the region in a similar fashion as the landfill does. The cases are similar for the Bessborough landfill (BBLF) and the Chetwynd landfill (CLF). The Appendix includes an examination of pyrolysis applied at a regional scale (PRRD) as partial or complete waste diversion solution using a centralized facility.

1.1. Selection of pyrolysis for waste treatment

The two most common methods of treating FW in a circular economy are composting and AD[3]. Composting is an aerobic (oxygen-based) process and produces CO_2, a less potent GHG than CH_4, with no energy recovery. An AD system captures energy-rich CH_4 for inclusion in natural gas distribution or for heat and power generation. The AD approach is considered one of the most energy efficient and environmentally-friendly methods for energy production[4]. Both composting and AD require source-separated organics. Anaerobic digestion is limited to non-woody compostable organic waste, and thus composting is often used as a complementary means of processing GW. In AD, 97-99% of the gases,

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[b] Solid Waste Management Best Practices: Cost-effective options to sustainably manage solid waste in the Peace River Regional District (2022)

[c] CleanBC Roadmap to 2030[2]

which are mostly composed of CH_4 and CO_2, are captured in a controlled environment[5]; in composting, CO_2 is released into the atmosphere.

A major drawback of AD is the need for continuous and homogenous feedstock. An AD facility cannot be readily shut down should feedstock supplies fail, and the feedstock must be pre-mixed and consistent. A sudden shutdown or change in feedstock could have adverse effects on the microbial population AD relies on for CH_4 production.

A centralized AD facility is sensitive to an economy of scale; approximately 25,000-30,000 t of feedstock (wet) would be required to justify an AD system in the PRRD as determined in the *SWMBP* report. However, FW in the PRRD is estimated to be around 9,000 t, thereby requiring supplemental feedstock. Woody waste, such as forest and lumber mill residues would not be ideal feedstock, and paper feedstock may be challenging to process due to required pre-treatments in order to ensure the material is broken down during the AD process. Feedstock would need to be supplemented by energy crops (e.g. alfalfa, hay, etc.), which are important animal feeds in the region, or cattle manure, which could be difficult to collect. In 2023, B.C. witnessed the most destructive and expensive wildfire season in its recorded history[6], coupled with unprecedented levels of drought in the PRRD[7]. The use of important crops to supplement an AD system at this time appears unfavorable.

Pyrolysis is a means of thermally treating biomass or waste. Thermal treatment of waste is often negatively perceived due to the use of elevated temperatures and the potential formation of toxic by-products such as dioxins in incineration[8,9]. Outright incineration occurs in an oxygen-rich environment at higher temperatures leading to the formation of toxic by-products, whereas pyrolysis occurs at lower temperatures in an oxygen-free environment and involves product recovery with minimal opportunity for toxic oxygenated products to form. One of the drawbacks of treating FW/GW using pyrolysis is the need to remove moisture from the feedstock, a process which may be energy intensive. Anaerobic digestion operates at high moisture levels.

A major appeal of pyrolysis is that units are scalable, operation may be interrupted without dire consequences, and a wide variety of organic feedstocks may be processed, such as FW, GW, paper, cardboard, textiles, plastics and tires. Although separation of feedstocks is generally still favorable to ensure consistent outcomes, pyrolysis does not suffer from the ill effects of impurities in the feedstock as does AD for FW/GW treatment or mechanical recycling for the treatment of plastics. Pyrolysis offers greater flexibility in waste processing in a single unit.

A rotating drum pyrolysis system was modeled at a pilot scale under three different operating conditions, leading to payback periods of less than ten years (Figure E-1, page E-1) if both the solid (biochar) and oil products are successfully marketed. The pilot scale project was assumed to operate on a sub-regional level, diverting up to 3,200 t of wet FW annually. Environmentally, sub-regional and regional scale pyrolysis scenarios indicated a significant net reduction in CO_2e, inclusive of the energy required for the pyrolysis process and feedstock drying, due to a considerable reduction in LFG (Figure 7). The implementation of a pilot scale pyrolysis unit has the potential to lead to both positive economic and environmental outcomes, allowing the PRRD to reduce landfilling while meeting CleanBC targets.

2. Pyrolysis overview

The three products of pyrolysis are gas (often referred to as synthesis gas (syngas), or pyrolysis gas), liquid (oils/waxes) and charcoal (Figure 1). The syngas is usually recycled and used as process heat, allowing the system to be self-sustaining after initial start-up; initial start-up requires diesel or natural gas.

The liquid products will vary in composition and value, depending on the feedstock. In some cases, the liquid products may form waxes as they age. Often, the water content of the liquid may be too high to use directly in equipment such as engines or turbines to generate electricity and heat, and therefore require drying and possible further refining, similar to how fossil fuels are refined. Some of the refined liquid products may be used as a diesel alternative.

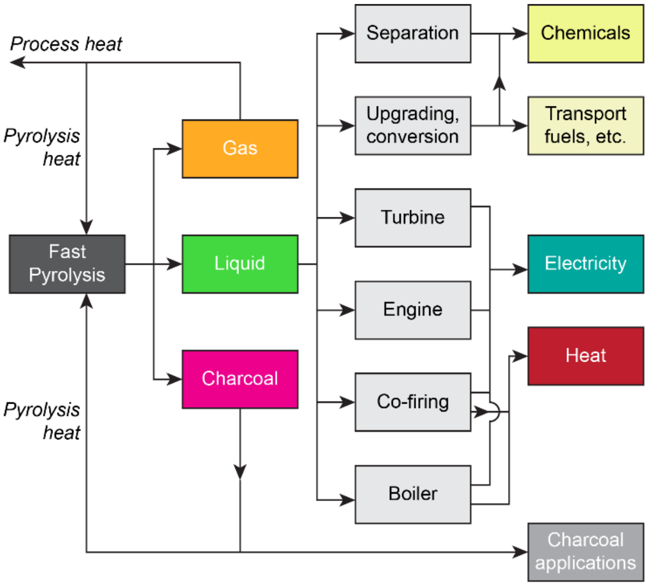

Figure 1. Products of pyrolysis and end uses[10].

The solid product is a charcoal, either referred to as char if it is from non-biomass sources (e.g. plastics) or biochar if from biomass (e.g. plant material, paper, etc.). The quality of the char will depend on the feedstock source and the production process. The characteristics of the char, such as surface area and porosity, will determine the application. Applications include use as a soil amender in agriculture, conversion (upgrading) to activated carbon (a char with higher surface area and porosity) to be used as a filter agent, energy production, or simple carbon sequestration. The upgrading of char to activated carbon leads to additional economic considerations and potential environmental costs (e.g. CO_2e emissions, water and energy use, wastewater treatment). Upgrading may result in better economic returns and/or produce a more desirable product. More information regarding char quality is provided in section 2.2 *Biochar quality* on page 6.

2.1. Process considerations

Key considerations when selecting pyrolysis equipment include: the rate at which the material is pyrolyzed; pyrolysis temperature control; the technology to move the feedstock through the equipment; pollution controls; biochar upgrading; and the quality of the final product. In order to target a specific product outcome, feedstock must be carefully selected and the pyrolysis rate and temperature controlled. The pyrolysis rate and temperature affect the distribution of gas, liquid and solid (Figure 2), as well as the quality of the products. Pyrolysis of biomass (e.g. wood, paper, FW/GW) favors solid (biochar) production, whereas oils/waxes are favored from synthetic materials (e.g. plastics, synthetic textiles).

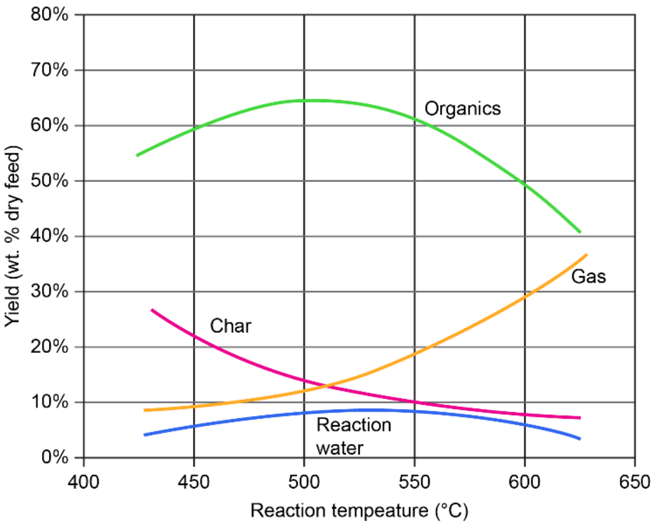

Figure 2. Pyrolysis product yields by temperature for aspen (poplar)[11].

2.1.1. Slow versus fast pyrolysis

The pyrolysis process may be divided into fast and slow pyrolysis. Fast pyrolysis involves the rapid heating of feedstocks (10-200°C/s) over a short period of time (e.g. 0.5-10s), whereas slow pyrolysis has much lower heating rates and longer residence times, sometimes on the order of minutes to days[12]. Fast pyrolysis is used to maximize the amount of oil produced; slower pyrolysis generally favors char formation with almost no oil but higher carbon sequestration[13]. Fast pyrolysis has been found to be more profitable than slow pyrolysis, despite an apparent higher investment cost[13], because the fuels and chars are of greater economic value. For FW, a medium rate (10-25 minutes) would be expected to produce an optimal biochar product, which is expected to produce some bio-oil as well.

2.1.2. Operating temperature

Pyrolysis systems conventionally operate in the 300-1,000°C range[14,15], with higher temperatures more typical of fast pyrolysis systems and lower temperatures for slow pyrolysis; operating temperatures for biomass pyrolysis vary depending on the desired product outcome. Pyrolysis technologies may use multiple programmable heating steps to increase the quality of the biochar. The objective in selecting a temperature is to minimize energy consumption, optimize distribution of products (char, liquid, oil) and maximize the quality of chars and oils. The predominant factor affecting biochar quality is the temperature at which the biochar is produced.

Higher temperatures favor syngas formation[11] (Figure 2), which is beneficial for ensuring the pyrolysis process is self-sustaining energy-wise (Figure 1). The most environmentally- and economically-friendly approach is to reduce start-up events through continuous operation. Most systems properly tuned for good biochar production should be self-sustaining using recirculated syngas, with excess syngas available for biomass drying or combined heat and power (CHP) applications.

2.2. Biochar quality

Not all biochar is created equally. The quality of the biochar will determine its economic value and future application. Two key features to consider are surface area and porosity[16], both of which are affected greatly by temperature.

Surface area is reflective of the ability of the biochar to retain moisture, nutrients or act as a filter[17,18]; high surface area indicates a cleaner product, free of ash and other volatile carbons. Porosity includes the number and type (size) of pores. Generally, surface area and porosity will increase with increasing temperature, and an increase in both is favorable[16,18,19]. An increase in surface area and porosity is usually accompanied by a loss in carbon, and possible functionality[16]. The formation of smaller pores, which usually occurs at higher temperatures, is not necessarily beneficial; for example, too small a pore size will not be effective in some agricultural applications[20].

A balance exists with increasing temperatures. The functionality of the biochar increases in terms of surface area and number of pores, which translates into potentially greater interactions with nutrients, pollutants, etc. However, the carbon structure of the biochar also changes with increased temperature; therefore, despite greater surface areas and more pores, changes in the physical structure may lead to an overall loss of functionality[19]. A biochar that is produced at a higher temperature may thus benefit from activation[16,18,19]. Activation improves the ability of the biochar to interact with other species while maintaining a high surface area and number of pores. Unmodified, or non-activated, biochar is not very desirable due to a lack of surface area and pores[19], with typical surface areas <20 m^2/g[21,22], feedstock- and operating condition-dependent. Activation may be through high temperature steam[18] or chemical means[18,19,23]. Activated biochar may have surface a surface area >3,000 m^2/g[16,19,24].

The exact effect temperature will have on biochar production is dependent on the feedstock. Temperatures <400°C cause the biochar to suffer from blocked pores due to lack of volatilization of material, with a dramatic increase in surface area and pore characteristics observed above 400°C[16]; maximum surface areas are obtained above 500°C. For example, a biochar produced at 500°C had a surface area of 70 m^2/g, but showed a dramatic increase in surface area to 375 m^2/g at 700°C[18]. If the desired application of the biochar is as a soil amender, increases in temperature result in increases in pH (more basic), cation exchange capacity (higher indicates greater soil fertility) and macronutrients such as potassium, calcium and magnesium[25], which are favorable characteristics.

2.2.1. Activation methods

For steam activation, the newly produced biochar is typically exposed to a high temperature steam (e.g. 800°C)[18]. The effect of steam treatment on surface area will vary depending on feedstock and the quality of the biochar used as activation feedstock. The steam activation process is usually part of the pyrolysis unit and thus availability will depend on the manufacturer. Typical chemical treatment (e.g. potassium hydroxide, or KOH) may involve mixing newly produced biochar in a specific ratio with the activation agent, followed by exposure of the mixture to elevated temperatures[16]. The industrial production of KOH leads to a large amount of CO_2e emissions, and the chemical upgrading process requires additional energy, water and wastewater treatment. The financial and environmental cost of chemical activation may be considerable; however, improved financial results may be realized due to the production of a higher quality and more desirable product. Alternative chemical methods are being actively researched to decrease the financial cost, obtain biochar with good characteristics, and lower environmental impacts. Upgrading using chemical means is usually independent of the pyrolysis unit and may be added at any time to the process.

2.2.2. Quality assurance

Equipment suppliers should be able to provide technical, certified data with information on surface area of chars, pore quantity and size, as well as heavy metal analyses according to feedstocks tested. Manufacturers of pyrolysis equipment, such as Magnum Group International (MGI), provide some indication on their website[26] as to their biochar quality. Before purchasing equipment, due diligence should be performed by requesting data on the biochar and also pyrolysis unit emissions.

Prior to biochar production, a market and application for the biochar needs to be identified to help guide decisions on process parameters and equipment suitability. The uncontrolled mixing of feedstocks is best avoided to ensure consistency in the product; for example, plastics should be separated into the various categories (PS, PET, PE, etc.) wherever possible. Food waste and GW will be highly variable and, due to its inhomogeneity, a wide range in the characteristics of the resulting biochar may be observed[10]. Co-pyrolysis, which involves the blending of two feedstocks (e.g. plastic and paper) is an option. Co-pyrolysis with a more consistent feedstock (e.g. forest residues) may decrease the uncertainty in quality associated with FW-derived biochars.

2.3. Bio-oils

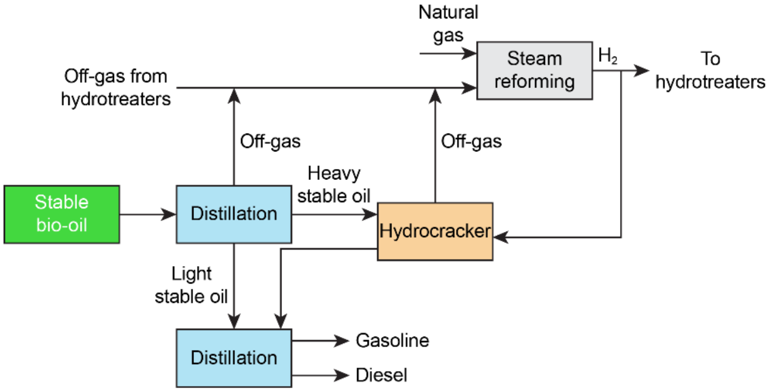

Figure 3. Possible bio-oil upgrading scheme[27].

Pyrolysis oils from biomass are often referred to as bio-oils and may be used in applications such as biodiesel production. Bio-oil comprises approximately 35-40% of FW pyrolysis products, and only decreases in percentage at temperature >600°C[28]. The types of chemical compounds in the oil differ from traditional mineral oils (fossil fuel-based). General pyrolysis oils have a low pH (~3), making the oil acidic and corrosive to industrial processes[29]. Direct use in a CHP or diesel engine is generally not possible without upgrading the oil. Moisture content is also high, and has been reported as 15-35% by weight[29]. Bio-oils from FW have shown lower moisture content of 12.1%, and a higher pH (~4.5)[30]. Food waste contains a wide distribution of food sources, so the actual values could show considerable fluctuations in properties.

During refinement, the bio-oil is treated to remove components lighter than butane[27]; the stabilized oil is then distilled into lighter and heavier fractions, with the heavier fraction sent for hydrocracking (Figure 3). The refining process bears some resemblance to traditional fossil fuel refining, although the wide variety of chemicals makes the process more challenging, involved and expensive[31].

The bio-oil may be refined and transformed into other chemicals (Figure 1) via distillation or solvent extraction[32]. The bio-oil may be used in asphalt applications as a binder. The pyrolysis of woody waste produces an aqueous fraction (wood vinegar), which contains a plethora of chemicals and is rich in acetic acid. The wood vinegar has been shown to have biocide (fungicide) properties[32], and has the potential to be commercialized[33].

2.4. Pyrolysis unit

A variety of pyrolysis technologies are commercially available (Table 1). Microwave technology has also been used, although scaling up may be challenging. Fluidized bed reactors have a strong market appeal (Figure 4) and may process large amounts of feedstock (up to 20,000 kg/h); however, the complexity of operating the system is high[34] (Table 1), with large amounts of inert gas (N_2) required to maintain pyrolytic conditions. Furthermore, sand is often used to enhance the transfer of heat to the biomass, leading to sand particles entrained in the biochar. Compared to an auger system, for example, it was estimated the fluidized bed reactor used 200 kWh energy/t of feedstock[35], whereas an auger system may use only 36 kWh/t. The target product of fluidized bed reactors is often the oil. Auger and rotating drum systems are readily available commercially, require little to no inert gas, and are scalable.

Pyrolysis units are typically listed according to processing capability in kg/h. The feedstock is assumed to be at pyrolysis-appropriate moisture levels of <15%. It was assumed that a pilot scale pyrolysis unit operates between 500 and 1,000 kg/h. Two systems were arbitrarily selected: the MJT-500 from Mingjie Environmental and the ATS-1000 from MGI. The MJT-500 is capable of processing ~500 kg/h, while the ATS-1000 processes between 1,000 and 1,500 kg/h. Mingjie Environmental offers larger units. MGI does offer a 500 kg/h unit, as well as a larger 2,000 kg/h unit. The two systems are believed to represent the lower (MJT-500) and higher (ATS-1000) ends of the pyrolysis market in terms

Table 1. Commercially available pyrolysis technologies.

Technology	Availability	Complexity	Inert gas requirements	Scale up	Description
Fluidized bed	Commercial	Medium	High	Easy	Filled with a fine solid (e.g. sand) for transfer of heat to materials. Uniform and even heating of feedstock.
Circulating fluidized bed	Commercial	High	High	Easy	Similar to fluidized bed with circulating function.
Auger	Pilot/Commercial	Medium	Low	Medium	Feedstock is fed through one or more temperature controlled compartments to break down feedstock.
Rotary drum	Pilot/Commercial	Medium	Low	Medium	Feedstock is fed into a rotating drum that is rotated within a heated cylinder.

Note: See the accompanying whitepaper for a more complete list of all technologies.

of cost and possibly features. The MJT-500 was assumed to be deployed at the sub-regional scale, and the ATS-1000 at the regional scale for modeling purposes.

The MJT-500 was selected as a pilot scale unit because of the minimal capital expense expected by directly purchasing the equipment from China. A quote was requested from Mingjie Environmental; it was estimated that the MJT-500 unit may be procured for ~$250,000 (listed for $78,550 USD for equipment) after shipping, duty and tax, incidentals and with installation. The MJT-500 is a basic rotary drum pyrolysis unit that does include a number of pollution controls, as per the manufacturer. One consideration is that the unit may need inspection by the Canadian Standards Association (CSA) before it can be deployed in Canada; this may be the case for any unit directly imported from abroad into Canada if the company does not have a presence in Canada. Similarly priced units from other manufacturers are available for purchase via online sites.

The MGI ATS-1000 unit was selected as a representative advanced, scalable, pyrolysis unit. The unit includes steam upgrading technology to produce activated carbon. The MGI units use a three temperature zone programmable setup allowing for customizability in feedstock processing. Feedstock is auger-fed. MGI offers a smaller 500 kg/h unit; however, it does not include the steam upgrading capability. The quote received for the ATS-1000 unit was for ~$9.3 million, which was assumed to include installation and any other incidentals. MGI has a business presence in Canada, and offers joint-venture opportunities for taking on financial risk; discussions with MGI also indicated an opportunity for either leasing or lease-to-own. A pilot scale 500 kg/h unit operated by Emergent Waste Systems (EWS) is processing wood waste in Ruby Creek, B.C. (near Hope). The unit was previously used in Alberta to process old tires, indicating the flexibility of the technology. A site visit was conducted, during which it was suggested that EWS may be willing to perform testing of various feedstocks for biochar production. Modeling results using the ATS-1000 are found in the Appendix.

Other providers, such as Klean Industries, may be considered for larger scale modular commercial units; however, obtaining a quote was not free of charge. MGI has proformas available online which include some of the energy and cost requirements of operating their system. The MGI systems were considered representative of similarly sized commercially available systems.

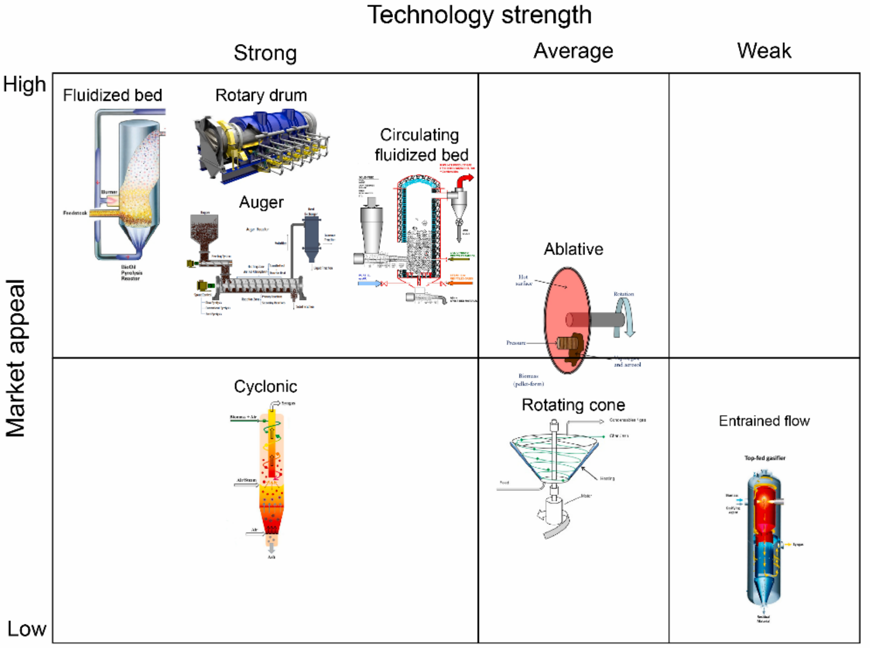

Figure 4. Common pyrolysis technologies in use[34].

2.4.1. Ancillary equipment

Pyrolysis specifications require moisture levels <15% and small particle sizes (<20 mm), thereby necessitating some pre-processing (Figure 5). For a 3,200 t per year FW diversion scenario, dewatering, drying and hammer milling will be required with the possible need of a wood chipper if feedstocks need to be supplemented with large woody waste.

Upgrading of the biochar following production may be desirable. Additional equipment is required for such upgrading, which has not been included here.

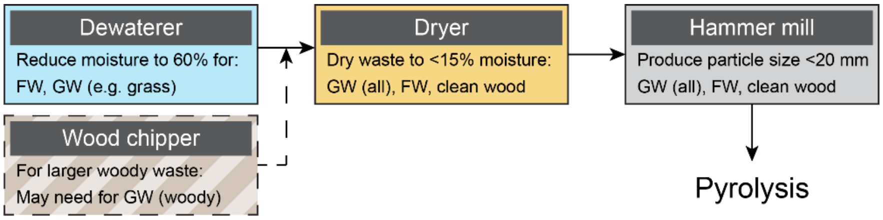

Figure 5. Pre-pyrolysis processing of food and woody waste.

2.5. Feedstock

Feedstock was assumed to be local to the siting of the pyrolysis unit e.g. all feedstock for a unit located in Chetwynd was sourced from the nearby community as landfill-diverted material. Feedstock processed by pyrolysis needs to have a moisture content of <15%; a moisture content of 8% was assumed.

The MJT-500 unit is capable of processing ~500 kg/h of waste. If the pyrolysis unit is operated 5 days/week, 8 hours per day with a 90% uptime, approximately 936 t/year of FW may be processed at 8% moisture, or 3,153 t wet if the moisture is assumed to be 70% in the FW; FW moisture varies greatly from 70% to >90%. The FW quantity was rounded up to 3,200 t wet per year, which equates to 1,043 t/year at 8% moisture. According to the FSWCS[1], only the Fort St. John area produces enough FW to completely satisfy the annual processing requirements of 1,043 t/year for the MJT-500 under the 8 hours/day, 5 days a week, operating conditions. The Dawson Creek and Chetwynd regions do not produce enough FW to achieve the 1,043 t/year target 8% moisture target according to the FSWCS[1]; therefore, FW is expected to be supplemented with GW (Table 2). From a practical perspective, other sources of FW or GW may be found more locally that do not require transport. For modeling purposes, FW was prioritized, followed by GW, to reduce landfilling and associated CO$_2$e generation.

For reference and perspective, other diversion scenarios have been referenced in this document (Table 2). The scenarios have been expanded upon in the Appendix and are intended for future, larger scale regional waste diversion solutions. Additional information on available feedstocks in the PRRD may be found in the Appendix (section A1 *Feedstock availability* on page A-1) and in the accompanying whitepaper.

The best and most consistent results are found when biochar and bio-oil come from a homogenous feedstock. The system may be “switched over” from biomass to plastics, for example, but the initial product produced after the switch may be inferior. There is also the opportunity to co-pyrolyze feedstocks (e.g. biomass and plastics). In other words, in the absence of FW/GW feedstocks, the pyrolysis unit may still be run to maximize profitability.

Table 2. Scenario descriptions.

Scenario	Scale	Feedstocks
Full	Regional	All identified feedstocks suitable for diversion. Feedstocks: FW/GW, paper/cardboard, plastics textiles (natural, synthetic). Sectors: Landfill (SFR, ICI, TS, SH), CCR and TS recyclables, recycling depots, agricultural plastics, ICI recycled paper and plastics. Excluded: Return-It plastics.
Decomposable	Regional	Feedstocks: Highly decomposable FW/GW and moderately decomposable cardboard/paper. Sectors: Landfill, CCR and TS, ICI paper.
FW/GW	Regional	Highly decomposable FW/GW. Sector: Landfill.
1,043 t	Sub-regional	Tonnage of material diverted on an 8% moisture basis for pyrolysis. Wet tonnages vary for each landfill. On a wet basis: NPLF 3,200 t FW; BBLF ~2,400 t FW and 340 t GW; CLF 2,330 t FW and 420 t GW. Sector: Landfill.

3. Financial

The base financial scenario assumes an operator shift of 8 hours/day, 5 days/week. Two additional scenarios include: (i) doubling the workday to 16 h/day; and (ii) operating the pyrolysis on a continuous 24 h/day, 7 days/week schedule (Figure 6). The selected pyrolysis unit is the MJT-500, capable of processing ~500 kg/h of feedstock. The FCI of the pyrolysis unit is the same in all scenarios; there are slightly increased FCIs for ancillary equipment (e.g. dewaterer, dryer) to accommodate scaled up feedstock quantities. Operating costs (OCs) increase with an increase in operational hours due to labor and utilities expenses. Some transport within the region is necessary for the Local-2t and Local-5t scenarios in order to maximize regional FW/GW diversion and the capacity of the pyrolysis unit.

Scenario	Hours (per day)	Days (per week)	Tonnes* (annual)
Local-1t	8	5	1,043
Local-2t	16	5	2,087
Local-5t	24	7	4,915

* Based on 8% moisture of pre-dried feedstock, 90% operating uptime.

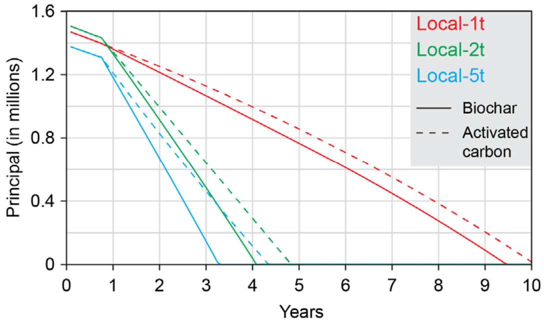

Figure 6. Payback period for a pilot scale 500 kg/h pyrolysis unit. All scenarios assume a 10-year amortization period with 50% of profits from the sale of biochar/activated carbon + bio-oil paid toward the principal.

The two marketable products from pyrolysis are biochar and oil (bio-oil). Chemical upgrading of biochar to activated carbon incurs significant costs and leads to longer amortization periods (Figure 6); however, upgrading may produce a more marketable product. The degree of upgrading, based on the product's intended end use, needs to be considered. The modeled scenarios assume the sale of both the biochar and the bio-oil using a medium rate of feedstock processing (~15-25 min). The sale of the bio-oil may present a challenge without further upgrading and refining. Additional details are discussed in the following sections; proformas (FCIs, income, OCs) for each scenario are found in the Appendix (section A2.1, *MJT-500*, page A-2). A full breakdown of all income and expenses is provided in the whitepaper.

Operating the pyrolysis unit on a continuous basis (Local-5t) gives the most favorable payback period (Figure 6), although the payback period for the sixteen hour day (Local-2t) is similar. Implementation of the Local-2t scenario may be simpler than the Local-5t one as there is a lower requirement for feedstock transport and fewer potential challenges of operating a night shift.

If the assumption is made that the bio-oil is of zero value, the minimum selling price of the biochar is $1,000/t in the Local-2t scenario if an annual increase in 2.5% in tipping fee income is applied (Table 3) over the amortization period; if no increase in tipping fees occurs, the biochar selling price increases by $75/t. These selling values reflect a minimum cost that will allow for no net loss over the ten year period. The minimum assumed selling values are used to arrive at a no loss balance over

Table 3. Minimum price of biochar required to break-even without bio-oil. The two prices reflect an annual increase (monthly basis) of 2.5% in tipping fee income, and no increase.

Scenario	CAD/t*	
	2.5%	0%
Local-1t	$1,700	$1,775
Local-2t	$1,000	$1,075
Local-5t	$980	$1,025

* Note: Minimum price assumes income from tipping fees and carbon credits, 50% of any profits paid toward principal.

the ten year period. The selling price of the biochar was modeled without an increase in tipping fees, unless otherwise specified.

Relying only on the selling price of biochar (no tipping fees or carbon credits as income), the minimum required selling price for the Local-1t scenario balloons to $2,375/t and $1,675 for the Local-2t scenario. The Local-2t scenario appears to be the most favorable scenario to implement when tipping fees and carbon credits are considered.

3.1. Amortization period

An amortization period of ten years was selected to repay FCIs (Table 4) for all scenarios. The annual amortization interest (6%) and inflation (2.5%) rates were fixed. The model was set so that 50% of all profits (if applicable) were paid back to the principal each month in order to reduce the amortization time and interest payments. It was assumed that the initial six months accrued OCs and payments to the principal were made without any income, resulting in an initial start-up cost. The source of the initial start-up funds were not considered. The start-up costs, without interest, were subtracted from the profits, if any, that were realized over the ten year period. In some modeled scenarios, income was negative due to fixed payments and inflationary increased in OCs without a matching inflationary increase in income, resulting in diminishing returns. However, once the principal was paid off, profit was realized, resulting in a net positive revenue flow.

Table 4. Sub-regional amortization rates. The rate and inflation is annual.

	Conditions		
Time	120 months (10 years)		
Rate	6%		
Inflation	2.5%		
% profit to principal	50%		
Monthly payment	Local-1t	Local-2t	Local-5t
	$14,273	$14,606	$15,272

3.2. Expenses

The expenses are divided into the FCIs and OCs, the details of which may be found in the proforma in Table A-1 on page A-2 of the Appendix. A summary is provided in the following sections.

3.2.1. Fixed capital investment

The FCI of the base pyrolysis unit is fixed for each scenario; however, a slight increase in FCI occurs with increased feedstock processing due to a need for larger ancillary equipment with greater capacity (Table 5). The FCIs do not include the cost of land; however, the cost of site preparation ($512,550) is included in the building cost. Costs of the pyrolysis system (includes ancillary equipment) were padded to cover incidentals. The building was assumed to be enclosed, insulated, and constructed with a concrete pad. Cruder examples of pyrolysis implementations exist; however, given the winter climate in the PRRD, a mostly indoor installation was assumed.

Table 5. Sub-regional fixed capital investments.

	Local-1t	Local-2t	Local-5t
Pyrolysis system	$300,000	$330,000	$390,000
Building (6,030 ft^2)	$723,600		
Misc. office equipment	$12,000		
Rolling stock	$250,000		
CHP	n/a		
Total	$1,285,600	$1,315,600	$1,375,600

3.2.2. Operating costs

Operating costs were estimated separately for the production of biochar and activated carbon (Table 6). All OCs were subject to a fixed annual inflation (Table 4), and thus the OCs shown represent the first month of the first year of operation. The OCs increase due to an increase in utility demand (electricity, heat, water) and employee costs as feedstock quantities increase. Differing gas and electricity usage rates were assumed depending on whether the facility is in operating or standby mode. Furthermore, scaling up of the ancillary equipment results in more electricity usage.

Table 6. Sub-regional operating costs (year 1).

	Local-1t	Local-2t	Local-5t
Feedstock transportation	$0	$65,232	$162,347
Employee (number)	$290,827 (3.5)	$482,725 (6)	$1,226,364 (14)
Utilities	$81,189	$129,585	$190,824
Other (biochar)	$69,600	$76,900	$65,300
Other (activated carbon)	$398,400	$734,500	$1,570,000
Insurance	$12,286	$15,470	$27,417
Testing	$5,000	$12,600	$12,600
Fees & licenses	$8,000	$8,000	$8,000
Taxes	$15,461	$16,061	$17,261
Total (biochar)	$484,787	$741,341	$1,547,766
Total (activated carbon)	$821,187	$1,398,941	$3,052,466

The manufacturer of the MJT-500 indicates a minimum of two employees per shift to operate the equipment. A site visit to a MGI pyrolysis plant indicated two employees operating the system with routine maintenance and cleaning performed by the operators, as well as general troubleshooting. All sub-regional scenarios assume at least two employees per shift with a plant manager/engineer. The Local-1t assumes a part-time bookkeeper, and the other two scenarios a full-time bookkeeper, with paid benefits for all employees. Operators in the Local-5t (continuous) scenarios are assumed to be paid weekend and night premiums. Assumed wages for each position are listed in the Appendix in section A2.4.2 *Employees* on page A-9 with a full breakdown in the accompanying whitepaper.

The Local-1t scenario assumes the pyrolysis unit is situated at the CLF; however, the Local-2t and Local-5t scenarios assume the unit to be located at the BBLF because of a lack of feedstock in the CLF region to attain full operating capacity. All the scenarios assume that FW/GW is prioritized as a waste diversion strategy in the PRRD. In order to maximize the amount of FW/GW processed in the Local-2t and Local-5t scenarios, some FW and GW feedstock needs to be transported from other parts in the region, increasing OCs. Transport OCs are decreased by moving the pyrolysis unit to the BBLF from the CLF, and reduced even further if the unit is located at the NPLF.

The cost of chemical upgrading results in a significant difference in OCs between biochar and activated carbon production. It was assumed that the chemical upgrading agent (KOH) used to produce activated carbon costs ~$1,040/t and is utilized in a 1:1 ratio with the biochar produced. Despite the increased OC, the amortization period is not much greater because of higher market returns (Figure 6) for the upgraded product.

3.3. Income

Table 7. Income potential of biochar and activated carbon (year 1). Values are not intended to reflect accuracy and are only estimates.

Scenario	Increase*	Local-1t	Local-2t	Local-5t
Biochar	0%	$126,720	$253,440	$579,935
Activated carbon	0%	$411,840	$823,680	$1,884,790
Bio-oil	0%	$399,332	$798,663	$1,429,802
Carbon credits	0%	$10,238	$20,477	$46,730
Tipping fees	0%	$182,400	$364,800	$497,380
Total biochar		$718,690	$1,437,380	$1,553,652
Total activated carbon		$1,003,810	$2,007,620	$3,058,352

* Annual increase in income source.

Four sources of income were considered: biochar/activated carbon; bio-oil; carbon credits; and tipping fees (Table 7). The crude bio-oil may be difficult to market without refining. The bio-oil may qualify for carbon credits if sequestered, although a B.C. precedent could not be found. No increase in the biochar value was assumed due to fluctuations in the market which could send values upwards or downwards. No increase in tipping fees was also assumed, although it is expected that over a ten year period increases would be applied as costs rise.

3.3.1. Biochar/activated carbon

The value of the biochar will depend on the quality and application of the product. A wholesale price range of $899-$2,778 USD ($1,244-$3,844 CAD/t) has been reported (2018)[36], which is assumed to include unmodified biochar on the lower end and activated carbon on the higher end. Another source estimated wholesale prices of biochar from $250/t to $1,170/t CAD for retail[37]. Canadian AgriChar (2024) charges approximately $1,200/t, without an indication of quality. A conservative estimate of $400/t was used for biochar. Another source indicated activated carbon has a market value of $2,600-$3,100 CAD[38]; a conservative estimate of $2,000 CAD/t was used.

3.3.2. Bio-oil and wood vinegar

Assessing the value of the bio-oil is difficult because the quality and re-sale opportunities are unknown. The possibility exists to refine the oil into biodiesel or sell it for such purpose; another possibility is to use an appropriately outfitted CHP that is corrosion resistant to the expected low pH of raw bio-oil, or to treat the bio-oil prior to use. A bio-oil value of $1.10/L was used. Bio-oil, which was assumed to be unrefined, has been reported to have a value of $0.40 USD/kg (~$0.55 CAD/L assuming a density of ~1 kg/L). The average retail price in the U.S. of B99-B100 (almost pure biodiesel) in January of 2024 was $4.69/gal ($1.70 CAD/L)[39]. The value of the bio-oil was held constant over the ten year amortization period. Wood vinegar (the aqueous fraction) was not included in the income calculation; however, the product is marketable.

3.3.3. Carbon credits

Carbon credits are a relatively minor income component. The rate, which aligns with similar purpose driven projects in B.C to reduce CO_2e, was assumed to be $10/t CO_2 and was evaluated for the biochar only. Carbon credits would not apply if the biochar were used for fuel (charcoal). The carbon credit was based on the amount of carbon content of the biochar (e.g. 88.2% for FW biochar[40]) and the tonnes of biochar expected. The carbon credits were held constant over the ten year amortization period. With the assumption that one of the objectives is to decrease GHG emissions, it was assumed the biochar was sequestered, even though sale as a fuel source may be more profitable.

3.3.4. Tipping fees

Tipping fees were estimated using current rates ($55/t residential, $60/t commercial) in the PRRD and weighted according to the residential and commercial contribution of waste to each landfill, which varied by landfill. A rate of $57/t was used without any increases over the ten year amortization period. Most probably, some type of increase would be applied at least once during the time period. An informal survey of tipping fees in B.C. indicates the rates in the PRRD are very low compared to other regional districts.

3.3.5. Combined heat and power (CHP) and electricity

Excess pyrolysis gases were assumed to be used for drying and heating the building before CHP consideration. No CHP for electricity generation was assumed. Only the Local-5t scenario uses enough feedstock to justify a possible CHP installation with a potential for 366 MWh of electricity. A CHP of appropriate size is estimated to be $200,000. In 2016, BC Hydro had purchasing agreements for the Peace region that paid $102/MWh, which at that rate could produce an annual income of $37,000. BC Hydro has (April 3, 2024) posted a request for proposals (RFPs) to purchase power; RFPs are due September 16, 2024. Projects need to become online as early as the fall of 2028[41]. BC Hydro also has another program in place to purchase from independent power producers, referred to as a competitive electricity acquisition process (CEAP)[42].

3.4. Additional comments

Table 8. Projected profits (losses) for pyrolysis over ten years.

	Local-1t	Local-2t	Local-5t
Biochar + bio-oil	-$331,000	$3,728,000	$5,129,000
Activated carbon + bio-oil	-$1,486,000	$1,642,000	$378,000
Biochar only	-$4,163,000	-$4,114,000	-$8,754,000
Activated carbon only	-$5,280,000	-$6,175,000	-$13,468,000
Start-up biochar	-$328,000	-$461,000	-$871,000
Start-up activated carbon	-$498,000	-$792,000	-$1,629,000

The original scenarios that assumed biochar at $400/t and activated carbon at $2,000/t would not be profitable without the sale of the bio-oil (Table 8). The minimum price in the Local-1t scenario of $1,700/t (Table 3) may not be attainable without upgrading; however, the Local-2t and Local-5t scenario value of $1,000/t is, and a realistic price of $1,200-$1,400 could be expected. This price falls slightly below a published minimum selling price (Table 9) and is considerably above the break-even price. However, these values depend on the production costs and the scale of the operation.

The production costs of biochar in the Local-1t scenario (Table 10) are higher than the industry-reported maximum (Table 9), while the Local-2t and Local 5t costs fall within the range. Labor is a major contributor. Note that a shortened amortization period will reduce production costs slightly as interest payments are reduced. In the scenarios, 50% of profits were put toward paying down the principal; increasing the payment amount will reduce the payback period and the production costs.

Table 9. Reported biochar prices.

Biochar price per t	Description
$1,445	Minimum selling price of biochar
$304-$387	Break-even prices
$2,214	Most commonly cited sale prices
$1,244-$3,844	Reported industry wholesale price
$790-$2,013	Production costs

As reported in Nematian et al.[36]

Table 10. Biochar production costs.

Scenario	Cost per t*
Local-1t	$2,272 / $2,137
Local-2t	$1,567 / $1,538
Local-5t	$1,320 / $1,309

* Cost with/without interest

Modified scenarios

Modifications to the original Local-1t scenario were made to determine the type of scenario that would be profitable over ten years (Table 11). The original scenarios incurred losses after ten years even with the sale of bio-oil. No increases in income (tipping fees, carbon credits, biochar or oil) were assumed in the original scenarios (Table 7).

Two modified scenarios were considered (Option 1 and Option2, Table 11). For both scenarios, it was assumed the value of the biochar increased annually by 2% (applied monthly), below the rate of inflation (2.5%), with an initial value of $1,200/t. The original tipping fee was set at $57/t. In both modified scenarios, a $7/t increase in tipping fees was applied at 37 months and another $7/t increase at 73 months, for rates of $65/t and $72/t, respectively. Option 1 assumes the sale of unrefined bio-oil at $0.55/L (see section 3.3.2 *Bio-oil* on page 15), while Option 2 assumes no sale of bio-oil. The start-up periods were reduced from six months to three.

Adjustments were made to the salaries of workers from the original scenario (Table 11). Option 2 removes the plant manager/engineer salary. The salaries still include benefit costs. The payback period for Option 1 is six years nine months and eight years ten months for Option 2.

Table 11. Modified Local-1t scenarios.

Scenario	Start-up time	Products			Operating costs			Ten year projected profit
		Biochar per t	Biochar rate increase	Bio-oil	Operator	Plant manager	Bookkeeper (part-time)	
Original 1	6 mo	$400	0%	$1.10/L	$30/h	$40/h	$28/h	-$324,000
Original 2	6 mo	$400	0%	$0/L	$30/h	$40/h	$28/h	-$4,157,000
Option 1	3 mo	$1,200	2%	$0.55/L	$27/h	$35/h	$28/h	$1,312,000
Option 2	3 mo	$1,200	2%	$0/L	$30/h	$0/h	$28/h	$287,000

4. CO_2e reduction

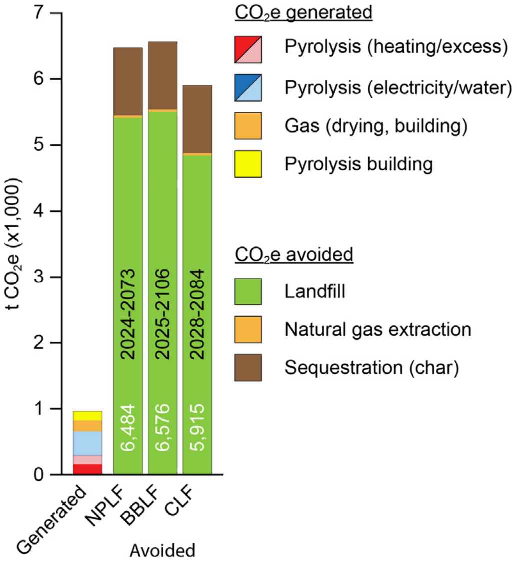

Figure 7. *Annual CO_2e balance in the pyrolysis of 3,200 t of FW in the PRRD. White text indicates total CO_2e avoided, black the years of landfill operation*[d]*.*

The GWP of GHGs is reported in CO_2 equivalents (CO_2e; see footnote *a* on page E-1), which includes CO_2. Carbon dioxide is the other major gas, asides from CH_4, emitted from landfills; CO_2 is also generated during any carbon-based combustion process. For the scenarios, the sources of CO_2e include transportation (CO_2, CH_4, N_2O), LFG (CH_4, CO_2), pyrolysis gases (CO_2 and other hydrocarbons), natural gas, electricity generation, building construction and water supply[e].

The CO_2e balance from diverting ~3,200 t annually of FW/GW results in a net avoidance of CO_2e emissions (Figure 7). The CO_2e for transport was not considered for the 1,043 t scenario because it was assumed all feedstocks were local to the landfill where the pyrolysis unit was located. The scenarios that involve larger quantities of feedstocks do have an intraregional CO_2e transport component. Compared to the benefit of landfill diversion, the CO_2e impact is relatively minor.

The pyrolysis-related CO_2e sources include: pyrolysis of feedstock (red); excess syngas (pink); gas for building heat and pre-drying of feedstock (orange) and the impact of the building (yellow). The CO_2e associated with equipment manufacturing, transport and installation has not been evaluated at this time but will be a factor in any technology used in processing recyclables. Electricity usage was factored in; the CO_2e values are extremely small because a hydroelectric source was assumed, which is of low environmental impact.

The CO_2e avoided includes a reduction in LFG, the assumed recirculation of syngas for heating (natural gas extraction avoidance), and sequestration of biochar. Sequestration assumes the biochar is not used for energy production and is either landfilled, used as a soil amender, etc.

An average CO_2e value was used to compare CO_2e generated and avoided as a simplified comparison. Averages for the BBLF and NPLF are similar as only FW quantities are diverted for the NPLF scenarios and some GW for the BBLF scenario; the CLF includes more GW, which has a lower CO_2e emissions impact. Modeling of LFG is discussed in subsequent section 4.1 *Landfill diversion and landfill gases* on page 19. Additional scenarios are discussed in the Appendix (section A3, page A-9).

For generated CO_2e, a quantity of 3,200 t wet FW was used, which applied only to the NPLF. The quantities of waste diverted for the BBLF and CLF were slightly less on a wet basis (see Table 2 on page 11). The CH_4 generation rates were identical in all scenarios; however, the overall waste decomposition rates and CH_4 generation potential varied due to differences in waste composition

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[d] CO_2e avoided for each landfill is an annual average based on the CO_2e produced during landfill operation years (black writing) plus twenty years after closure. Figure 8 illustrates the year to year changes in CO_2e.

[e] CO_2e determinations: transportation GHGs from the GREET model[43] Sept. 2023 update; LFG composition assumed 50% CH_4, 50% CO_2 using the LandGEM algorithm[44] modeled in Python; pyrolysis gas compositions taken from various academic journal sources and include CO_2-producing gases (CO, CH_4, C_2H_4, C_2H_6, C_3H_6, C_3H_8, n-C_4H_{10}) where applicable; natural gas composition from FortisBC[45]; hydroelectric assumed with values from the International Panel on Climate Change (IPCC)[46]; building construction modeled in Athena[47] using Calgary as an equivalent location; industrial water supply CO_2 costs[48]. Detailed calculations presented in the whitepaper.

between landfills, as estimated using the FSWCS[1]. More details are provided in section 4.1 *Landfill diversion and landfill gases* on page 19, with a complete breakdown in the accompanying whitepaper.

The CO_2e for upgrading (activating) biochar via chemical means has not been included here. The CO_2e cost using KOH, for example, is 1.77 kg CO_2e/kg of KOH used[43]. A common ratio of pyrolysis feedstock to activating agent is 1:1 or even lower on a mass basis. For the 1,043 t of waste, ~317 t of char is expected as the pyrolysis product, requiring at least the same mass of KOH and treatment at high temperature[49]. The financial cost of KOH treatment is quite high. Alternative chemical treatments exist[16,49–51], but have not been explored. The ATS-1000 pyrolysis system presented in the Appendix, for example, uses a physical means (steam) for activation which should improve the biochar properties; however, steam treatment does not necessarily preclude some form of chemical treatment.

4.1. Landfill diversion and landfill gases

Waste, listed in order of increasing CH_4 generation potential, is divided into inert, moderately decomposable and decomposable. The designations reflect the potential to decompose and generate LFG, a combination of mostly CH_4 and CO_2. The decomposition rate is reflected by the *k* value in LFG modeling, and the CH_4 generation potential by the L_o value[f]. Food and some yard and garden waste (non-woody) fall into the decomposable category and are the largest sources of CO_2e, with woody waste moderately decomposable.

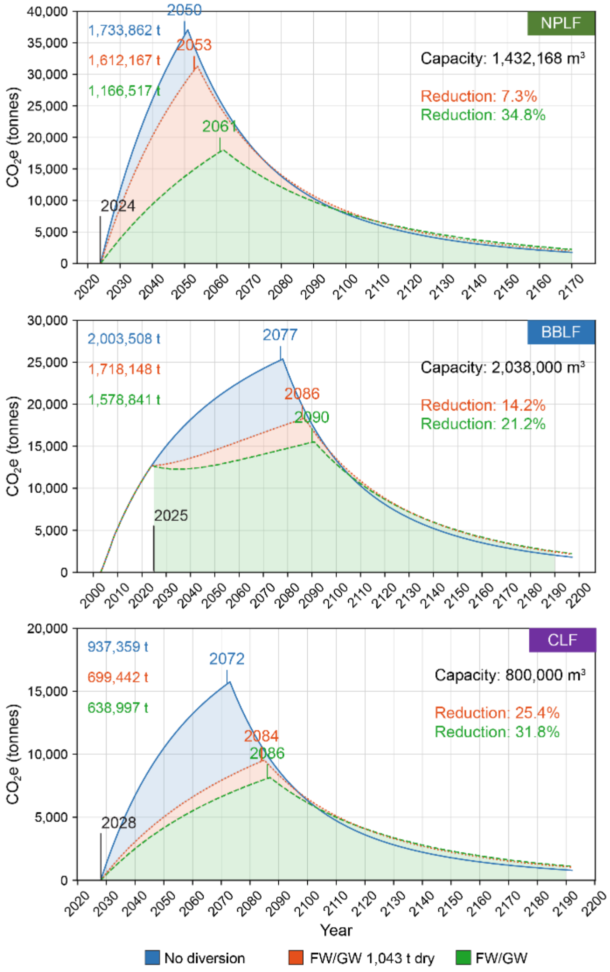

Figure 8. Effect of diverting 1,043 t FW/GW from landfilling in the PRRD on CO_2e emissions. Shaded areas represent expected cumulative CO_2e t for the indicated time periods. Landfill closing dates are indicated above each line with diversion dates in black.

Landfill CO_2e is not only dependent on waste type; CO_2e is also dependent on factors such as moisture (precipitation), temperature, landfill management (e.g. compaction) and water infiltration. The decomposition rate (*k*) was applied according to the composition of the waste as estimated by the FSWCS[1], taking into account annual precipitation and assuming normal infiltration of water. Large swings in landfill temperature could affect these rates, but were not accounted for[g].

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[f] Waste categories, *k* and L_o values modeled according to Government of BC guidelines[52].

[g] The *Operational Specifications* document[53] prepared for the PRRD uses default values of 0.045 $year^{-1}$ for *k* and 150 m^3/t for L_o. These values are likely high for the region considering a value for k of 0.05 and a L_o of 160 is for decomposable material. Details for the model parameters are given in the whitepaper.

4.1.1. Scenario background

Three scenarios are presented: *No diversion* ("business as usual"), *FW/GW 1,043 t dry*, and *FW/GW*. The *No diversion* scenario (blue in Figure 8) is the base case, representing current practices. The *FW/GW 1,043 t dry* scenario (red in Figure 8) assumes 1,043 t of FW and/or GW at 8% moisture is diverted. The equivalent wet quantities removed vary by landfill (Table 2, page 11). The *FW/GW* scenario (green in Figure 8) assumes that 90% of SFR, ICI, TS and SH FW/GW landfill-bound waste is diverted, representing the ideal scenario for removing the most highly decomposable material and is used as a reference. Diversion begins from the year the landfill is opened for the CLF and NPLF; for the BBLF, diversion is assumed to begin in 2025.

Waste quantities

The *No Diversion* scenario uses waste quantities as determined by the FSWCS[1] from all sectors (SFR, ICI, C&D, TS, SH); all other scenario quantities are based on the composition of the *No Diversion* scenario. All scenarios assume an annual population growth of 0.14% and a disposal rate of 0.97 t per capita. The amount of waste disposed each year increases with population growth for all scenarios. It was assumed that the diversion rate (percentage) for all scenarios remained the same, other than for the fixed quantity used in the *FW/GW 1,043 t dry* scenario; thus, the pyrolysis capacity to process diverted waste increased accordingly.

The *FW/GW 1,043 t dry* scenario prioritizes diverting FW and then GW non-woody, followed by GW woody. Wet quantities of waste varied (Table 2, page 11) as moisture in FW, GW (woody) and GW (non-woody) also vary. The quantities selected for diversion from each landfill equated to 1,043 t at 8% moisture after drying. Waste quantities added to each landfill annually differ due to differing base populations. The waste quantities diverted each year were fixed due to limited processing capacity by the pyrolysis unit.

Waste composition

The base *No diversion* scenario used the same waste composition (Table 12), as determined by the FSWCS[1], for all years the landfill was accepting waste. The *FW/GW* scenario composition was based on removing 90% of selected FW and GW from the quantities of waste used in the *No diversion* scenario, resulting in a new percentage composition for the waste types (Table 12). The new composition (percentage) was applied to subsequent years of waste disposal.

Table 12. Composition (percentage) of waste by scenario.
Semi.: moderately decomposable; Decom.: decomposable

Landfill	No diversion			FW/GW			1,043 t dry*		
	Inert	Semi.	Decom.	Inert	Semi.	Decom.	Inert	Semi.	Decom.
NPLF	40.2	35.4	24.4	57.3	39.2	3.5	44.0	38.8	17.1
BBLF	47.7	35.0	17.2	60.0	37.8	2.2	56.1	39.0	4.9
CLF	43.6	31.4	25.1	58.3	38.3	3.4	56.5	36.2	7.3

* First year of diversion reflected in the composition.

The composition of the waste varied from year to year for the *1,043 t dry* scenario (first year of diversion composition indicated in Table 12) because the amount of FW/GW that was disposed of was fixed. Therefore, the percentage of FW/GW entering the landfill increased slightly each year as the population increased. The amount of FW available each year theoretically increased with an increase in population; however, fixed quantities were used for moderately decomposable and decomposable diverted mixed waste. This approach affects the results for the BBLF and CLF scenarios, as a mixture of FW and GW was used in these scenarios to compensate for a lack of FW. In practice, FW should be prioritized, and thus the amount of GW treated would decrease, resulting in a greater CO_2e reduction.

Landfill capacities

The capacity of the BBLF, including initial waste quantities, was estimated according to information contained in the *Operational Specifications* report prepared for the PRRD[53]. The landfill opened in 2003; diversion was assumed to begin in 2025 in the scenario. All modeled scenarios assumed an annual settling rate of 5% by volume with an in situ waste density of 0.85 t/m^3 and a waste-to-cover ratio of 3.5 to 1. Adding cover reduces the available volume for waste disposal.

For the NPLF, it was assumed a new phase opened in 2024 for modeling purposes that was similar in nature to the Phase 4 design referenced in the *Operational Specifications* report[53], using the phase's approximate dimensions and capacity. The use of the Phase 4 parameters is simply to assess the effect diversion would have on a similar landfill operation given the composition and quantity of waste disposed of in the region served by the NPLF. The model may be adapted in future to better reflect any newly proposed landfill operations.

An online search revealed a public tender for a new Chetwynd landfill, which indicated an expected opening date of 2028 with an annual disposal rate of 12,000 t. An assumed capacity of 800,000 m^3 was used.

The models presented here are for illustrative purposes and not intended to be used as a substitute for the technical planning and expertise provided by a landfill engineer. The LFG modeling results are necessary to estimate the CO_2e produced from landfilling without diversion versus using pyrolysis to treat diverted landfill waste.

Landfill gas generation

The major components of LFG, by volume, are CH_4 (40-60%) and CO_2. The CH_4 generated has been converted to CO_2e and combined with landfill CO_2 for total CO_2e in the model. The model calculates the amount of waste that is added to the landfill each year. The decomposition rate (k) and the CH_4 generation potential (L_o) are determined for each waste type (inert, moderately decomposable and decomposable), calculated on a fractional year basis. The CH_4 generated by newly added waste is then added to previously added waste. For example, if 2,000 t of highly decomposable waste is added to the landfill in January, the amount of CH_4 generated by that waste in February will decrease as it decomposes. The decreased amount of CH_4 from the January addition will be added to the newly added CH_4 generated in February. The cover material used in the model was assumed to be completely inert and non-contributing to CO_2e quantities.

4.1.2. Scenario results

The scenario results are intended to be used as a guideline to illustrate the positive impact that diverting waste from landfilling will have on landfill lifespan and CO_2e reduction. All of these models may be modified to reflect the true state of each landfill as required.

Landfill capacity

An expected increase in landfill lifespan was determined with the diversion of waste (Table 13). The lifespan of the NPLF resulted in a very small extension of three years for the *1,043 t dry* scenario as the total quantity of waste entering the NPLF is quite large compared to the other landfills.

Table 13. Expected landfill close dates after diversion.

Landfill	Original	FW/GW		1,043 t	
	Close	Close	Extend*	Close	Extend
NPLF	2050	2061	+11	2053	+3
BBLF	2077	2090	+13	2086	+9
CLF	2072	2086	+14	2084	+12

* Number of years the lifespan of the landfill is expected to be extended under the relevant diversion scenario.

Of note is that the waste density in the landfill diversion was set to 0.85 t/m^3 for all waste types. The density of waste varies with depth in the landfill and waste type[54]. The density in the NLPF between 2013-17 was found to be only 0.60[53]. Food waste has been found to have a density of 1.06 t/m^3 at 15m depth and 1.30 t/m^3 at 45m; cardboard has a density of 0.3 t/m^3 at 15m depth and 0.61 t/m^3 at 45m.

Thus, removing lower density waste and improving the compaction of landfilled waste should increase each landfill's lifespan further.

CO_2e generation

The removal of FW/GW in the CLF and BBLF 1,043 t scenarios led to near removal of all FW/GW (Figure 8), resulting in a noticeable decrease in CO_2e compared to the *No diversion* scenario. Although the impact appears to be minimal for the NPLF, the CH_4 generation rate is strictly dependent on the decomposition rate k of the material, the CH_4 potential L_o, and the quantity of waste. Therefore, the same type and quantity of waste, with the same k and L_o values, as is the case here, will result in the same amount of CH_4 generation avoided if landfill characteristics are assumed to be the same for all locations. The diverted FW and FW/GW compositions differ slightly between landfills (Table 2) due to feedstock availability, and thus slight differences in CO_2e reduction are observed. A greater factor is the quantity of waste disposed of in each landfill (base and subsequent population growth) and the initial composition of waste (Table 12).

Two additional scenarios at the regional scale are presented in the Appendix section A3.3 *Landfill diversion and CH_4 (CO_2e)* page A-10), and include the SFR, ICI, TS, and SH sectors: (i) diversion of 90% of all FW/GW in the PRRD including paper/cardboard; and (ii) diversion of all FW/GW, paper/cardboard and plastics, less Return-It materials, and textiles.

Landfill gas capture

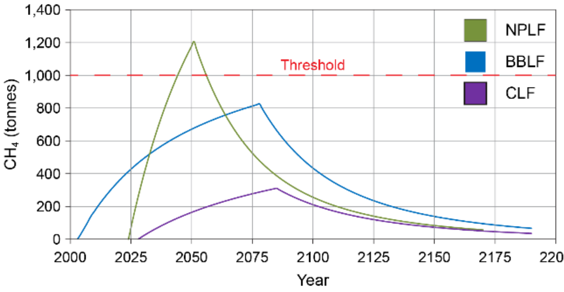

Figure 9. Annual CH_4 landfill emissions without diversion.

Landfill gas capture systems are expensive to install and require a post-operation service life of >30 years, with an efficiency rate of only 68%[3], with CH_4 either being flared (converted to the less potent GHG CO_2) or captured and used for energy. Even if a system is already in place, expanding the system may be costly. For the NPLF, the modeled Phase 4 of the landfill encompasses ~37 acres, and is estimated to cost between \$2.4 and \$4.3 million, depending on existing infrastructure. According to Government of BC regulations, a system is required to capture LFG once emissions exceed 1,000 t of CH_4 annually, which is predicted to occur in 2045-2056 in the *No Diversion* scenario (Figure 9) for the NPLF only. The model predicts that, with the diversion of 1,043 t, the 1,000 t threshold would only be exceeded in the year 2054, indicating that no LFG system would be required. However, these predictions are based on an assumed capacity of 1.4 million m^3 for the landfill phase.

One point to note is that past values of k and L_o used in modeling LFG in the *Operational Specifications* report[53] were default values for the model, which may result in much higher CH_4 emissions estimates for the PRRD than what are observed. This is because the PRRD has relatively low precipitation and extended cold periods. Furthermore, any value of k is dependent on the temperature of the waste undergoing decay, nutrient availability and pH. The model predicts volumes of LFG, which are then converted to tonnages. The volume depends on the temperature and atmospheric pressure at which the gas is measured. Default calculations used in the model are 20°C and 1 atm (101.3 kPa) of atmospheric pressure. The best approach is to use actual LFG data and estimate the values of k and L_o that are representative for the region. With measured data, the need for an LFG system can more accurately be predicted and strategies can be implemented to initiate diversion that replace the need for a LFG capture system with possible better efficiency and energy recovery.

5. Conclusions and recommendations

A pilot scale pyrolysis unit capable of processing 500 kg/h of dried (8% moisture) feedstock was modeled, with priority placed on FW and then GW in order to reduce LFG. The processing rate translated to ~3,200 of wet FW diverted from landfilling. A base scenario was assumed with the unit operating 40 h/week (8 hours/day, 5 days/week). The two products from FW processing are biochar and bio-oil. A low value for the biochar of $400/t was used for unmodified char, and $2,000/t for modified char (activated carbon); a moderate value for the bio-oil of $1.10/L was assumed. The base scenario was further expanded to doubling the daily operating hours of the unit to 16 h/day, 5 days/week, and to operating the unit continuously (24 h/day, 7 days/week), resulting in three modeled financial scenarios. The pilot scale unit was modeled to serve the same region as the landfill from which diversion was occurring at a sub-regional level.

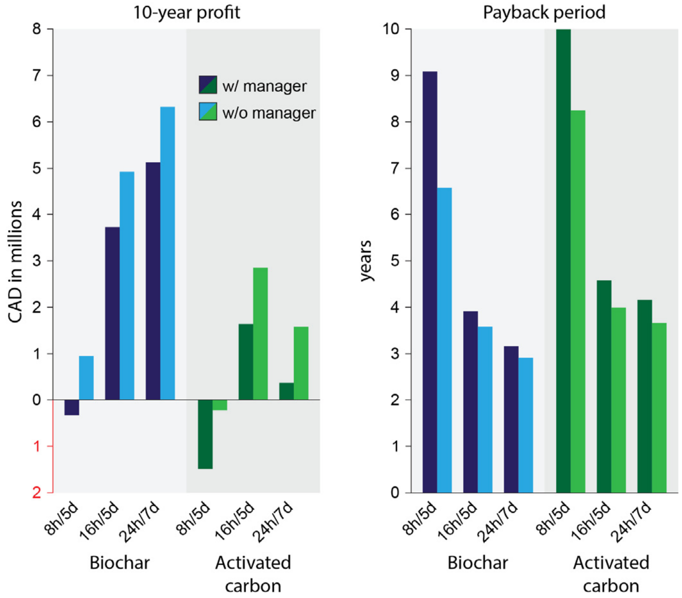

Figure 10. Expected ten-year profit and payback period for sub-regional scenarios. Scenario labeling is hours per day/days per week. See text for comments.

Financial outcomes

The FCIs for the three sub-regional scenarios were all similar, with minimal cost increases due to upscaling of the pre-processing equipment (e.g. dryer, dewaterer). The greatest gains in profitability and a reduction in amortization time were realized when the operating time was doubled from 8 h/day to 16 h/day; the impact of moving to continuous operation was much less due to increased labor costs (Figure 10) and may also present challenges with night shifts. Increasing the operating time of the pyrolysis unit increases profits and helps to absorb increased labor costs.

The manufacturer of the modeled pyrolysis unit suggests a minimum of two operators. The original scenarios assumed a bookkeeper, a plant manager/engineer and two operators per shift on payroll. Removal of the plant manager/engineer salary improves profitability by reducing operating costs and amortization times (Figure 10). Such a scenario could be explored further.

Upgrading the biochar to activated carbon is very expensive, but should result in a more profitable product. The need to upgrade will depend on quality of the biochar that is produced by the unit. Chemical upgrading (KOH) was assumed here; alternative forms of upgrading, such as steam, are a possibility, but not an option for the modeled pyrolysis unit. Upgrading results in a decrease in biochar quantity with an increase in value; however, all scenarios with chemically upgraded biochar resulted in reduced profits or heavier losses (Figure 10).

Diversion of landfill waste increased landfill lifespans, as expected, albeit moderately due to the relatively small quantity of waste diverted. Tipping fees and carbon credits were assumed as income for pyrolysis, and are part of the profitability estimate. Neither tipping fees nor carbon credits were increased during the ten year modeling period. The financial benefit of the increased lifespan of the landfill was not taken into consideration.

Environmental outcomes

Thermal treatment of waste often raises concerns of increased energy use and GHG emissions compared to treatments such as AD. The degree of GHG emissions is dependent on the type and quantity of feedstock, as well as the operating temperatures. All modeled scenarios indicated a substantial net reduction in CO_2e using pyrolysis when compared to landfilling of FW and FW/GW combinations. In particular, FW is highly decomposable in anaerobic conditions. Furthermore, the pyrolysis gases may be captured in a controlled environment with greater efficiency than capturing LFG in situ.

Feedstock challenges

The 8 h/day, 5 days/week base scenario assumed 3,200 t of wet FW were diverted from landfilling annually and processed using pyrolysis. Only the NPLF is estimated to receive adequate FW-only waste quantities for this scenario (~5,042 t). The BBLF is expected to receive enough FW/GW feedstock combined, and the CLF is only expected to meet about half the required quantities. Extending the operating hours beyond forty hours per week, in order to ensure profitability, will require importing feedstocks from other landfills, if the pyrolysis unit is not located at the NPLF, finding other feedstock sources (e.g. forestry slash), or processing other types of feedstocks (e.g. paper).

Recommendations

The profitability of using pyrolysis for waste diversion is greatly dependent on the market value of the biochar and bio-oil. Profitability increases dramatically between 8 h/day, 5 days/week and 16 h/day, 5 days per week compared to moving from 16 h/day, 5 days/week to a continuous operation. It is therefore recommended that the operating hours are maximized each day without necessarily moving to a fully continuous operation. If only landfill diversion is considered, locating the unit at the BBLF or NPLF will increase access to feedstock and reduce transportation costs. Furthermore, to ensure greater profitability, using only two operators who are trained in routine maintenance should be the objective for a pilot scale implementation. The manufacturers of some equipment provide training as part of the purchase; the manufacturer of the pilot scale unit modeled here will be onsite as part of the setup, which is included in the cost of the unit.

An end market for the biochar needs to be established. The difficulty lies in the unknown quality of the biochar, which is dependent on feedstock, the pyrolysis unit and operating conditions. Carbon credits provided by the B.C. government constitute a very small portion of the projected profits; the major value lies in the biochar and bio-oil. Because of the considerable effort in upgrading the bio-oil, the biochar value should be established with the assumption the bio-oil is of no value. For the 16 h/day, 5 day/week scenario, the minimum market price of the biochar should be $1,200/t; the price appears to be a fair market rate and achievable. Unrefined bio-oil may sell for $0.55/L and could be considered “bonus” income.

In addition to determining the end market, a next step is to consider funding. Larger scale projects may be eligible for green bonds. Companies such as MGI may be able to provide joint venture partnerships as well as training and involvement in day-to-day operations; it was suggested a type of lease-to-own agreement may be possible. Additionally, funding through collaboration with research institutions is a possibility. Pyrolysis operates on an economy of scale, and thus a more regional solution presents less risk for financial loss with a larger buffer for fluctuations in the market.

Appendix

A1. Feedstock availability

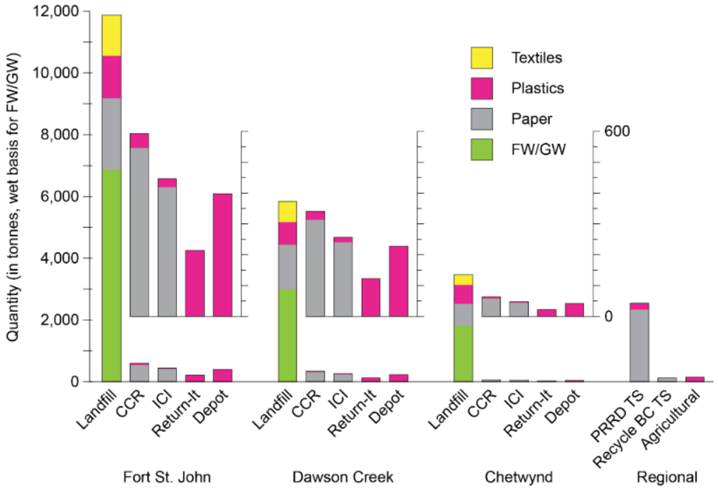

Figure A-1. Waste quantities by type and municipality/region in the PRRD.

Waste diverted from landfilling is expected to provide the bulk of the feedstock for pyrolysis (Figure A-1). A complete breakdown of feedstock estimates may be found in the accompanying whitepaper. Estimates of landfill waste include all sectors (SFR, ICI, TS, SH and C&D) as determined in the FSWCS[1]. C&D sources were excluded for diversion scenarios. The CCR and PRRD TS estimate was based on data provided by the PRRD in 2020. The ICI category includes paper and plastic recyclables as estimated in a report prepared for the Government of BC in 2023[55]. *Return-It* refers to mostly drink container quantities returned via the provincial deposit system, and *Depot* to the estimated materials processed by private recycling depots in each municipality. Note that city names were used in the estimates because of the location of depots and to reflect the major population centers generating the waste for potential waste collection purposes.

A1.1. Ancillary equipment

Pre-processing of feedstock is required prior to pyrolysis (Figure A-2); the type and scale of equipment needed is dependent on the feedstock and its quantity. A complete regional solution would include all ancillary equipment.

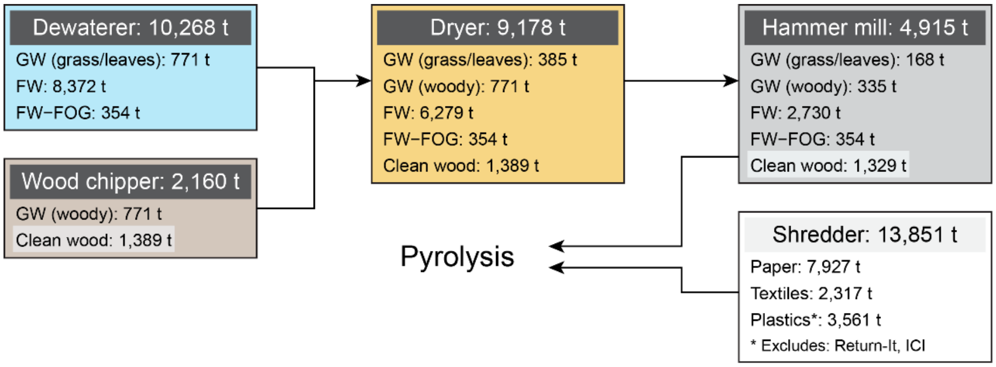

Figure A-2. Accessible tonnages of pyrolysis feedstock in the PRRD and pre-pyrolysis processing. The tonnages and process summarize the suggested approach to equipment usage for processing wastes prior to pyrolyzing.

A2. Financial

The following sections contain the proformas for the MJT-500 pyrolysis unit presented in the main paper as a sub-regional scale waste diversion strategy and for the regional scale ATS-1000 implementation. The ATS-1000 proforma section (page A-4) includes unit-specific information that was presented in the main document for the MJT-500. Information regarding pyrolysis-related income and expenses is also presented. A full, detailed breakdown of all calculations and sources of information may be found in the accompanying whitepaper.

A2.1. MJT-500 proforma

The proforma (Table A-1) is in support of the discussion in section 3 *Financial* on page 12, providing an estimate of FCIs, OCs, and income for the three sub-regional scenarios that were presented. The proforma includes estimated OCs for biochar and activated carbon as products.

Income estimates, FCIs and most OCs have already been discussed. Income and OCs include biochar and activated carbon as the products. Employee salaries are an estimate based on the position, and include benefits (10% premium on salaries); more information is provided in section A2.4.2 *Employees* on page A-9. Some intraregional transport is required to maximize FW/GW processing in the Local-2t and Local-5t scenarios; it was assumed the pyrolysis unit was located at the BBLF to reduce transportation costs for these two scenarios.

Table A-1. Proforma for pyrolysis in the PRRD with the MJT-500 (sub-regional scale).

	1,043 t (Local-1t)	2,087 t (Local-2t)	4,915 t (Local 5-t)	Comments
Hours per day	8	16	24	
Days per week	5	5	7	
kg/h	502	502	563	
Equipment	MJT-500	MJT-500	MJT-500	
No. of units	1	1	1	
Income				
Biochar ($400/t)	$126,720	$253,440	$579,935	$400-$1,000/t market value
Activated carbon ($2,000/t)	$411,840	$823,680	$1,884,790	$2,300-$3,500/t market value
Oil/waxes ($1.10/dried L)	$399,332	$798,663	$1,429,802	$1.10/L, dried
Electricity ($102/MWh)	-	-	-	BC Hydro (2016 rates)
Carbon credits (char)	$10,238	$20,477	$46,730	$10/t CO_2e
Tipping fees ($57/t landfill)	$182,400	$364,800	$497,380	Landfill diverted waste; year 1
Total biochar	$718,690	$1,437,380	$2,553,847	
Total activated carbon	$1,003,810	$2,007,620	$3,858,701	
Expenses: Capital				
Pyrolysis equipment	$300,000	$330,000	$390,000	Padded values
Pyrolysis unit	*$199,000*	*$199,000*	*$199,000*	
Wood chipper	*n/a*	*n/a*	*$28,400*	*May be required for GW*
Hammer mill	*$15,200*	*$33,000*	*$33,000*	*Produce particles (<20 mm)*
Dewatering	*$9,400*	*$37,400*	*$29,300*	*Remove moisture to ~60%*
Dryer	*$28,100*	*$38,200*	*$34,700*	*Drying of FW/GW to 8% moisture*
Shredder	*n/a*	*n/a*	*n/a*	*For paper/OCC and plastics*
Sorting	*n/a*	*n/a*	*n/a*	*Conveyor for plastics*
Building	$723,600	$723,600	$723,600	
Structure ($35/$ft^2$)	*$211,050*	*$211,050*	*$211,050*	*6,030 ft^2*
Site prep ($85/$ft^2$)	*$512,550*	*$512,550*	*$512,550*	*Site preparation/construction*
Land	*$0*	*$0*	*$0*	*Use available PRRD land*
Misc. office equipment	$12,000	$12,000	$12,000	Computers, desks, etc.
Rolling stock	$250,000	$250,000	$250,000	Skid steer, fork lift

CHP	n/a	n/a	n/a	Electricity/heat generation
Total capital	$1,285,600	$1,315,600	$1,375,600	

Expenses: Operating							
Feedstock transportation		$0		$65,232 ($125,613 to CLF)		$162,347 ($269,564 to CLF)	Local-2t and Local-5t scenarios pyrolysis located at BBLF.
Employee		$290,827		$482,725		$1,226,364	
Foreman/asst. plant manager	*0*		*0*		*0*		*$35/h*
Equipment operators	*2*	*$154,814*	*4*	*$309,628*	*12*	*$1,053,267*	*$30/h; required minimums*
Engineer/plant manager	*1*	*$101,327*	*1*	*$101,327*	*1*	*$101,327*	*$40/h*
Technical consultant	*0*		*0*		*0*		*$40/h*
Bookkeeper	*.5*	*$34,687*	*1*	*$71,770*	*1*	*$71,770*	*$28/h*
Sorter	*0*		*0*		*0*		*$22/h*
Utilities		$81,189		$129,585		$190,824	
Electricity		*$26,641*		*$46,345*		*$75,084*	
Gas		*$25,387*		*$50,422*		*$86,941*	
Water/sewage		*$29,161*		*$32,818*		*$28,799*	
Other char:		$69,600		$76,900		$65,300	
Other activated carbon:		$398,400		$734,500		$1,570,000	Incl. chemicals for activation
Diesel		*$22,230*		*$22,230*		*$2,280*	*Pyrolysis plant start up*
Equipment maintenance		*$25,712*		*$22,230*		*$27,512*	*2% of FCI less site development*
Water treatment[1]		*$2,850*		*$5,700*		*$2,570*	*Pyrolysis water neutralization*
Landfill waste disposal		*$912*		*$1,824*		*$2,487*	*0.5% residual ($57/t tipping fee)*
Chemical catalyst		*$328,779*		*$657,558*		*$1,504,660*	*Only if char is upgraded to AC*
Cleaning		*$3,618*		*$3,618*		*$3,618*	*\$0.60/ft^2, office space (30% of ft^2)*
Misc. office employee		*$4,200*		*$7,200*		*$16,800*	*$100/month per employee*
Phones, website, tech		*$6,000*		*$6,000*		*$6,000*	
Mailing (not product)		*$4,000*		*$4,000*		*$4,000*	*Office admin., not product sales*
Yard maintenance		*$0*		*$0*		*$0*	*Assume PRRD maintaining*
Insurance:		$12,286		$15,470		$27,417	
Facilities		*$4,778*		*$5,748*		*$5,408*	*0.4% building, 0.7% contents*
Vehicle		*$3,000*		*$3,000*		*$3,000*	*Equipment insurance*
WCB		*$4,508*		*$7,482*		*$19,009*	*1.55% of employment expenses*
Testing		$5,000		$12,600		$12,600	Initial may be higher during setup and lower thereafter
Fees and licenses		$8,000		$8,000		$8,000	Business licenses, affiliations
Taxes		$16,515		$16,061		$17,261	2% of FCI less site development
Total OCs biochar:		$482,364		$741,341		$1,547,766	Year 1; subject to inflation
Total OCs activated carbon:		$811,164		$1,398,941		$3,052,466	Year 1; subject to inflation

[1] Does not include treatment of pyrolysis oil containing aqueous layers.

A2.2. ATS-1000 proforma

The ATS-1000 was modeled as a regional scale solution. The ATS-1000 scenarios use a variety of feedstocks (see section A1 *Feedstock availability* on page A-1). The *FW/GW* scenario using the ATS-1000 is similar to the Local-5t scenario that focuses only on *FW/GW*; however, the *FW/GW* scenario does not include a capacity limit on processing *FW/GW* in the region as the population grows and is modeled as operating 5 days/week, 16 hours/day. The *Decomposable* and *Full* scenarios are modeled as continuously running and able to process annual increases in feedstock with population increases. The *Decomposable* scenario expands biomass processing to include paper products, and the *Full* scenario to include paper products, textiles and plastics. Plastics and synthetic textiles are targeted for the oil.

The ATS-1000 system is equipped with the ability to upgrade biochar to activated carbon using steam, resulting in a higher water demand than for the MJT-500. It is assumed that all biochar was upgraded. The information is therefore presented as biochar of "low" value ($400/t) and "high" value ($2000/t). No chemical upgrading costs are assumed. Upgrading via steam does not necessarily preclude chemical upgrading in a practical implementation. Selection of the ATS-1000 is discussed in section 2.4 *Pyrolysis unit* on page 8. Note that upgrading through chemical means assumes a conversion efficiency from biochar to activated carbon of 65%[22], meaning a loss of mass. The conversion rate of FW feedstock to biochar was assumed to be 33%, which is approximately the same as the rate reported by MGI using the ATS-1000 for modified biochar. Lower profits may thus be realized, depending on the actual upgrading efficiency experienced once the unit is implemented.

Table A-2. Financial summary for a regional scale solution using the ATS-1000.

	Full		Decomposable		FW/GW	
Expense						
FCI	$23,564,952		$11,381,416		$11,397,914	
Payment (monthly)	*$261,619*		*$126,357*		*$126,540*	
OC (year 1)	$3,440,882		$2,476,911		$1,685,404	
OC start-up cost	$3,302,745		$2,005,660		$1,608,109	
Income (year 1)						
	Solid	Oil/wax	Solid	Oil/wax	Solid	Oil/wax
Biochar ($400/t)	$1,725,486	$5,742,367	$1,629,483	$2,340,037	$579,935	$1,429,802
Biochar ($2,000/t)	$8,627,428		$8,147,415		$2,899,677	
Electricity (CHP)	$456,388		$104,917		$55,024	
Carbon credits	$120,932		$114,798		$46,730	
Tipping fees	$1,361,380		$1,039,679		$585,255	
Summary						
	Solid only	Solid + oil	Solid only	Solid + oil	Solid only	Solid + oil
Payback ($400/t)	10y 12m	6y 10m	10y 12m	7y 2m	10y 12m	10y 12m
10-year profit	-$35,711,000	$21,405,000	-$15,884,000	$7,461,000	-$22,314,000	-$8,730,000
Payback ($2,000/t)	5y 11m	3y 10m	3y 6m	2y 10m	9y 4m	6y 1m
10-year profit	$33,042,000	$89,113,000	$48,404,000	$70,860,000	$61,000	$14,792,000

The ATS-1000 scenarios assume the pyrolysis unit is located at the BBLF to reduce transportation costs and CO_2e. For the *Full* scenario, within-region transport would increase to $482,000 from $281,000 if the unit were located at the CLF. Locating the unit at the NPLF would reduce the cost to $197,000.

For the *Full* and *Decomposable* scenarios, a full complement of employees was assumed; equipment operators were assumed to receive night and weekend premiums. Two systems are needed for the *Full* scenario (biomass and plastics/synthetics) and one system in the other two scenarios. The *Full* scenario requires double the amount of floor space, which increases OCs and the FCI. All three scenarios use a CHP plant to utilize excess syngas. Some of the syngas was assumed to be diverted, prior to use in a CHP plant, for drying.

The terms for amortization are identical to those used in the sub-regional scenarios (Table 4, page 13). As with the sub-regional scenarios, 2.5% inflation was applied to all OCs. No increase in any sources of income (biochar, bio-oil/oil, tipping fees, carbon credits) was assumed.

When biochar is assumed to be the only marketable product, heavy losses are incurred (Table A-2) for most scenarios. For the *Full* scenario, heavy losses occur because plastics are assumed to produce no char and only oil; therefore, running the system in this scenario for only solid products would not be financially beneficial. Generally, the pyrolysis of plastics targets the oil. Only the *Decomposable* scenario indicates that if the solid alone is marketed, a profit may be realized if the biochar selling price is greater than $800/t; the minimum selling price drops to $750/t if the employees are scaled back to include only the operators, a plant manager/engineer and bookkeeper. If a modest annual 2% increase is then applied to the selling price of the biochar, the break-even drops even further to $675/t. The *Decomposable* scenario is an enticing regional solution that minimizes the risk of return value for the biochar and removes the pressure of marketing the bio-oil.

The large profits predicted by the model (Table A-2) in the *Full* and *Decomposable* scenarios are dependent on a very good diversion of all feedstocks from landfilling, while sourcing materials from other sectors (e.g. ICI). The actual realized returns may be much less. However, the results suggest there is a lot of leeway in the collection of feedstocks and the market value of the pyrolysis products that the opportunity for good returns is quite promising. The full proforma for each of the three scenarios is provided in Table A-3.

Table A-3. Proforma for pyrolysis in the PRRD with the ATS-1000 (regional scale).

	Full	Decomp.	FW/GW	Comments
Hours per day	24	24	16	
Days per week	7	7	5	
kg/hr	1,061	1,475	1,182	Capable up to 1,500 kg/h
Equipment	ATS-1000	ATS-1000	ATS-1000	
No. of units	2	1	1	

Income				
Biochar-low ($400/t)	$1,725,486	$1,629,483	$579,935	$400-$1,000/t market value
Biochar-high ($2,000/t)	$8,627,428	$8,147,415	$1,884,790	$2,300-$3,500/t market value
Oil/waxes ($1.10/ dried L)	$5,742,367	$2,340,037	$1,429,802	$1.10/L, dried
Electricity ($102/MWh)	$456,388	$104,917	$55,024	Apply to BC Hydro (2016 rates)
Carbon credits (char)	$120,932	$114,798	$46,730	$10/t CO_2e
Tipping fees ($57/t landfill)	$1,361,380	$1,039,679	$585,255	Landfill diverted waste (year 1)
Total biochar-low	$8,950,165	$5,123,997	$2,696,745	BC as main solid product (year 1)
Total biochar-high	$15,852,108	$11,641,929	$4,001,600	AC as main solid product (year 1)

Expenses: Capital				
Pyrolysis equipment	$19,609,600	$9,877,800	$9,841,800	
Pyrolysis unit	*$19,234,200*	*$9,617,100*	*$9,617,100*	
Wood chipper	*$65,900*	*$65,900*	*$65,900*	*May be required for GW*
Hammer mill	*$50,700*	*$50,700*	*$50,700*	*Produce particles (<20 mm)*
Dewatering	*$37,400*	*$37,400*	*$37,400*	*Remove moisture to ~60%*
Dryer	*$70,700*	*$70,700*	*$70,700*	*Drying of FW/GW to 8% moisture*
Shredder	*$36,000*	*$36,000*	*n/a*	*For paper/OCC and plastics*
Sorting	*$114,700*	*n/a*	*n/a*	*Conveyor for plastics*
Building	$1,440,000	$723,600	$723,600	
Structure ($35/ft^2)	*$420,000*	*$211,050*	*$211,050*	*6,030 ft^2; 12,000 ft^2 for Full 2 units*
Site prep ($85/ft^2)	*$1,020,000*	*$512,550*	*$512,550*	*Site preparation/construction*
Land	*$0*	*$0*	*$0*	*Use available PRRD land*
Misc. office equipment	$12,000	$12,000	$12,000	Computers, desks, etc.
Rolling stock	$250,000	$250,000	$250,000	Skid steer, fork lift
CHP	$2,253,352	$518,016	$570,514	Electricity/heat generation
Total FCIs	$23,564,952	$11,381,416	$11,397,914	

Expenses: Operating							
Feedstock transportation		$281,145		$217,670		$162,347	Diversion of waste to BBLF
Employee		$1,533,568		$1,417,026		$792,353	
Foreman/asst. plant manager	*1*	*$89,335*	*1*	*$89,335*	*0*		*$35/h*
Equipment operators	*12*	*$1,053,267*	*12*	*$1,053,267*	*8*	*$619,255*	*$30/h; required minimums number*
Engineer/plant manager	*1*	*$101,327*	*1*	*$101,327*	*1*	*$101,327*	*$40/h*
Technical consultant	*1*	*$101,327*	*1*	*$101,327*	*0*		*$40/h*
Bookkeeper	*1*	*$71,770*	*1*	*$71,770*	*1*	*$71,770*	*$28/h*
Sorter	*2*	*$116,542*	*0*		*0*		*$22/h*
Utilities		$633,890		$389,195		$260,998	
Electricity		*$343,205*		*$163,722*		*$102,216*	
Gas		*$116,595*		*$86,941*		*$70,479*	
Water/sewage		*$174,091*		*$138,532*		*$88,303*	
Other:		$611,200		$332,300		$302,900	
Diesel		*$3,420*		*$3,420*		*$22,230*	*Pyrolysis plant start up*
Equipment maintenance		*$471,299*		*$227,628*		*$227,958*	*2% of FCI less site development*
Water treatment[1]		*$90,870*		*$63,200*		*$24,110*	*Pyrolysis water neutralization*
Landfill waste disposal		*$6,807*		*$5,198*		*$2,926*	*0.5% residual ($65/t tipping fee)*
Chemical catalyst		*$0*		*$0*		*$0*	*Steam upgrading*
Cleaning		*$7,200*		*$3,618*		*$3,618*	*$0.60/ft^2, office space (30% of ft^2)*
Misc. office employee		*$21,600*		*$19,200*		*$12,000*	*$100/month per employee*
Phones, website, tech		*$6,000*		*$6,000*		*$6,000*	
Mailing (not product)		*$4,000*		*$4,000*		*$4,000*	*Office admin., not product sales*
Yard maintenance		*$0*		*$0*		*$0*	*Assume PRRD maintaining*

Insurance:	$183,325	$100,413	$90,846	
Facilities	*$156,555*	*$75,449*	*$75,564*	*0.4% building, 0.7% contents*
Vehicle	*$3,000*	*$3,000*	*$3,000*	*Equipment insurance*
WCB	*$23,770*	*$21,964*	*$12,281*	*1.55% of employment expenses*
Testing	$20,000	$12,600	$12,600	Initial may be higher during setup and lower thereafter
Fees and licenses	$8,000	$8,000	$8,000	Business licenses, affiliations
Taxes	$450,899	$217,377	$217,707	2% of FCI less site development
Total OCs:	$3,440,882	$2,476,911	$1,685,404	Year 1; subject to inflation

[1.] Does not include treatment of pyrolysis oil containing aqueous layers.

The original *FW/GW*, *Decomposable* and *Full* scenarios were modified to test the break-even price of the biochar if the oil has a low market value of $0.55/L. All other parameters in the scenario were kept the same as the original. The *Decomposable* scenario (FW/GW and paper) produces the lowest minimum selling value, thereby minimizing the risk of fluctuations and/or low value for the biochar (Table A-4).

Table A-4. Break-even price of biochar regional scenario. Assumes value of oil is $0.55/L

Scenario	Price
Full	$600
Decomposable	$525
FW/GW	$1,525

A2.3. Income potential

A2.3.1. Char and activated carbon

Biochar, produced from FW and GW, tends to have the highest percentage of fixed carbon (non-volatile) compared to other sources, including paper and cardboard[40,56–59]. Depending on the application, the fixed carbon importance varies. If the biochar is upgraded to activated carbon and used for filtration or remediation, high carbon content with minimal impurities (ash content) may be desirable. Activated carbon used in food-grade applications will require further treatment to remove the ash. If the biochar is used as a soil amendment, the presence of non-carbon species (e.g. macro- and micronutrients) is beneficial[60]. Thus, it is necessary to know the end market prior to production. More information about char/biochar characteristics is available in the accompanying whitepaper under Pyrolysis→Feedstocks→Characteristics.

Forest residues may be a good source of material to substitute for MWP/OCC, as MWP/OCC does have a good market value, and Canada is a major exporter of MWP/OCC. Furthermore, it may be argued that waste paper is an important commodity globally as a source for plant-based fibers[61], especially in countries that do not have access to large swaths of forests for raw materials. The carbon content of forest residue biochar is similar to that of paper and cardboard[59,62], but lower than FW/GW[40,57].

A2.3.2. Oils/waxes

The oils and waxes produced from biomass and plastics range widely in composition and application. Some oils have a high water content, dependent on feedstock[57,63], and thus require drying prior to use; additional drying and upgrading expenses have not been included here.

Plastic pyrolysis often targets the production of oils and pyrolytic gas. The oils from plastics pyrolysis tend to be higher in energy[64] than, for example, paper-derived oils[63,65]. For the wetter oil products, drying may allow for use in a CHP plant directly. Upgraded and refined oils may be used as a substitute in internal combustion engines[66]. Generally, the oils are a mixture of many types of organics[67] that make them difficult to use as building blocks for bio-plastics (if from biomass) at this juncture, but they may be sequestered for longer term storage as an asphalt or concrete additive[66].

Oils are often considered as a diesel substitute and compared to diesel as such[64,68]. Although PP, styrene, LDPE and HDPE have been successfully used in diesel engine trials, the use of the oil without further refining or treatment may limit its application. For example, LDPE and HDPE form waxes upon storage[64]. For this reason, a moderately low value of $1.10/L has been assigned to the oil although removal of moisture on site may improve the value. Further refining into light and heavy fractions may be necessary to further improve the value.

A2.3.3. Electricity

The pyrolysis process produces a significant amount of pyrolytic gas of relatively high energetic value that may be harnessed through a combined CHP plant. Generally, it is recommended that the pyrolysis plant is connected to the electrical grid to ensure stability and to have electricity available during maintenance and down times. A large amount of heat is also produced, which was not considered here economically, but is of value. The cited CHP unit costs are based on a scaling formula, and are not reflective of what an individual unit costs. Units are typically sold by their potential to produce electricity (kWh, MWh) and are manufactured in pre-determined generating capacities. Currently available programs through BC Hydro are discussed in section 3.3.5 *Combined heat and power (CHP) and electricity* on page 15.

A2.3.4. Carbon credits

The value of the carbon credits was solely based on the mass of char produced and its fixed carbon content, with an assigned value of $10/t of fixed carbon in the form of CO_2. It is not known what value the Government of BC would assign; the value was assumed according to other projects listed by the Government of BC that provided credits for CO_2 reduction. Discussions with a representative from Emergent Waste Systems, which operates a pyrolysis plant in Ruby Creek, B.C., indicated the company had received carbon credits for biochar production. However, if the char were to be used as fuel, the credits would be rescinded. The heating value (energy) of the char depends on the feedstock, with low values for cardboard[65] and paper[63], and higher values for biomass[57] and food waste[69]. From a financial perspective, the economic value of the char may exceed the economic value of receiving carbon credits.

A2.3.5. Tipping fees

A weighted average of $57/t was used for the tipping fee, which falls between the $55/t for residential and $60/t commercial tipping fee. Commercial diverted waste (no C&D) accounted for 55-60% of the waste for the BBLF and CLF, whereas commercial waste accounted for ~70% of waste in the NPLF. These fees are assumed conservative and are considered low by British Columbia standards (e.g. Kelowna $104/t; Columbia Shuswap $80/t; Prince George $98/t).

A2.4. Expenses

A detailed accounting of all costs is not provided here; please see the accompanying whitepaper for a complete breakdown of major expense items and amortization of FCIs.

A2.4.1. Pyrolysis unit

A basic overview of the types of pyrolysis units available has been presented in section 2.4 *Pyrolysis unit* on page 8, with a focus on the MingJie Environmental Equipment MJT-500. Additional information regarding the technical specifications of the MJT-500 and ATS-1000 systems may be found in section A5 *Pyrolysis/carbonization plant* on page A-14. These units have been selected as representative of technology currently available and suitable for the PRRD's requirements; their use herein is not an endorsement. Other manufacturers and suppliers exist which the PRRD may be interested in.

Considerations when selecting a unit include, but are not limited to: the ability to customize the heating zones; recirculation and cleaning of syngas; environmental controls; electricity and water usage; methods and cost of upgrading from biochar to activated carbon; ability to meet Canadian certification standards.

A2.4.2. Employees

The employee salaries used in the various scenarios is provided in Table A-5. Benefits include items such as extended medical and are calculated as 10% of the base salary. The mandatory employment related costs (MERCs) include CPP/CPP2 and EI costs for the employer (2024 rates), as well as paid vacation at 5% (minimum 4% must be paid). Shift premiums have been added for equipment operators working night and weekend shifts where applicable. The hourly rates are estimates and may be adjusted to better reflect the PRRD's employment environment.

Table A-5. Pyrolysis employee costs.

Position	No.	Hourly	Salary	MERCs*	Benefits	Total
Foreman/asst. plant manager	1	$35	$72,800	$9,255	$7,280	$88,991
Equip. operators	1	$30	$62,400	$8,236	$6,240	$76,876
Engineer/plant manager	1	$40	$83,200	$5,366	$8,320	$100,951
Technical consultant	1	$40	$83,200	$5,366	$8,320	$100,951
Bookkeeper	1	$28	$58,240	$4,794	$5,824	$71,770
Sorter	1	$22	$45,760	$10,732	$4,576	$56,391

* Mandatory employment related costs

A3. Regional scale CO_2e reduction

The *Full*, *Decomposable* and *FW/GW* scenarios offer regional scale solutions (Table 2) for landfill waste diversion, and assume the ATS-1000 unit is used for processing. A net overall reduction in regional CO_2e emissions is expected (Figure A-3), with the greatest impact due to FW/GW diversion. The 1,043 t scenario is discussed in the main document (*CO_2e reduction*, page 18, section 4).

A comparison of the *Full* and *Decomposable* scenarios shows there is a net loss in CO_2e avoidance as plastics are not considered decomposable. Despite the loss, a major intangible is the avoidance of microplastics in the environment. Microplastics have been found distributed throughout the environment, leading to human consumption with ill-understood health consequences[70–72].

Zooplankton have been found to ingest the microplastics, with each microplastic particle forming hundreds of thousands of nanoparticles[73]; these smaller particles are even more difficult to remove from the environment. Even if plastics are mechanically recycled into pellets for reuse, eventually the plastics reach their end of life. Pyrolysis is a controlled method for removing the micro- and nanoplastic threat.

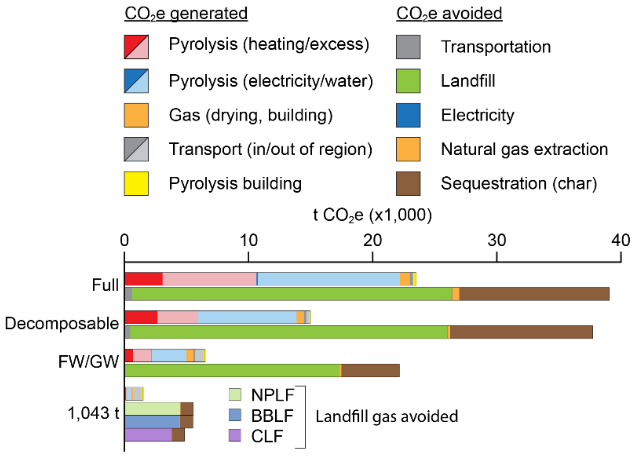

Figure A-3. Annual tonnes of CO_2e generated and avoided using pyrolysis.
The upper bar for each scenario is the amount of CO_2e produced and the lower bar the amount avoided for each scenario.

A3.1. CO_2e generated

The major sources of CO_2e generated (Figure A-3) are from processing feedstocks (red), the pyrolysis gases produced (pink) and water consumption. The CO_2e from the pyrolysis process–the actual conversion of feedstocks to char and oil/wax–is unavoidable. The CO_2e produced from the heating of the feedstocks will depend on the final temperature and the efficiency of the pyrolysis unit, so opportunities exist to reduce CO_2e

when purchasing equipment and developing the process. The pyrolysis gases produced in the regional scale scenarios are assumed to be converted to heat and electricity using a CHP. Conversion will still produce CO_2e; however, useable energy will be produced, and the potential exists to capture emissions in a controlled environment.

The ATS-1000 as a regional scale solution increases the anticipated water consumption over the sub-regional scale MJT-500 unit because of the steam system used to upgrade biochar to activated carbon. The CO_2e from using steam, however, is anticipated to be much lower than using KOH as a chemical upgrading method. It may be possible to combine chemical treatment with steam to produce a very high quality product.

Gas usage for heating of the facilities and drying of feedstock is a minor contributor to CO_2e. The added processing of plastics in the *Full* scenario assumes two ATS-1000 units, and expands the required square footage of the building from 6,030 ft^2 to 12,000 ft^2, which also affects heating and electricity usage, although to a small extent only.

Transport was divided into within-region and out-of-region transport. Within-region estimates are for transporting landfill-bound material from the Fort St. John and Chetwynd areas to the BBLF for processing. The BBLF was selected because it reduces the transport and CO_2e costs due to its more centralized location in the PRRD compared to the CLF. Out-of-region transport estimates were made for moving recyclable materials to market in the Lower Mainland, or in the case of agricultural plastics, to Bashaw, AB. In the *Full* scenario, it was assumed all recyclable materials, with the exception of Return-It plastics, were retained in the PRRD for processing. For the *Decomposable* scenario, it was assumed only plastics were transported out of region. For the *FW/GW* scenario, it was assumed plastics and paper/cardboard were sent out of region. Additional information on transportation costs and CO_2e is provided separately in section A4 *Transportation of feedstocks* on page A-11.

A3.2. CO_2e avoided

The major reduction in CO_2e is due to the diversion of highly decomposable FW/GW from landfilling. The CO_2e reduction from landfilling was estimated using the average CO_2e produced until the year 2100 for all scenarios. Although an average was used, CO_2e LFG production is non-linear and will vary by year (see Figure 8). The *Full* and *Decomposable* landfill LFG scenarios are discussed in the subsequent section of the Appendix; the FW/GW and 1,043 t scenarios are discussed on page 19 (section 4.1 *Landfill diversion and landfill gases*, page 19).

The other major form of CO_2e reduction was through carbon sequestration as char, with FW/GW containing the highest amount of fixed carbon of all feedstocks, followed by paper and cardboard. Plastics (*Full* scenario) were not considered to produce char, and the oil was not considered for sequestration.

A3.3. Landfill diversion and CH_4 (CO_2e)

The approach to modeling regional landfill lifespans and CO_2e emissions follows the methodology already discussed for the sub-regional scenarios (section 4.1 *Landfill diversion and landfill gases*, page 19). The two additional scenarios include the diversion of (i) FW/GW + paper (OCC, MWP, cardboard); and (ii) all FW/GW + all suitable recyclable materials, less Return-It plastics.

Table A-6. Expected landfill lifespan due to diversion.

Landfill	Original	FW/GW + paper		All divertible	
	Close	Close	Extend*	Close	Extend
NPLF	2050	2065	+15	2075	+25
BBLF	2077	2098	+21	2109	+32
CLF	2072	2093	+21	2102	+30

* Number of years the lifespan of the landfill is expected to be extended by under the relevant diversion scenario.

Landfill capacity

It was assumed 90% of FW/GW and 80% of paper products were diverted from landfilling in both scenarios. The *All divertible* scenario adds plastic (80% recovery), textiles (synthetic and natural, 90% recovery) and household hazardous (paint, pesticides, medications, 90% recovery) to the total quantities. Textiles add a significant quantity to the overall diversion (2,300 t/yr), as do plastics (2,400 t/yr); household hazardous does not (18 t). The diversion of household hazardous materials removes an important health threat from landfilling. Considerable gains in landfill lifespan are achieved in the diversion scenarios (Table A-6).

CO_2e generation

Very few gains in landfill CO_2e reduction are realized once most FW/GW is removed (Figure A-4). The *All divertible* scenario showed slightly increased CO_2e emissions over the *FW/GW + paper* scenarios for all landfills because the landfill closing dates were pushed back, allowing for greater waste disposal quantities. Plastic is not considered decomposable relative to FW/GW and paper; the removal of plastic has very little impact on overall CO_2e emissions in the short term.

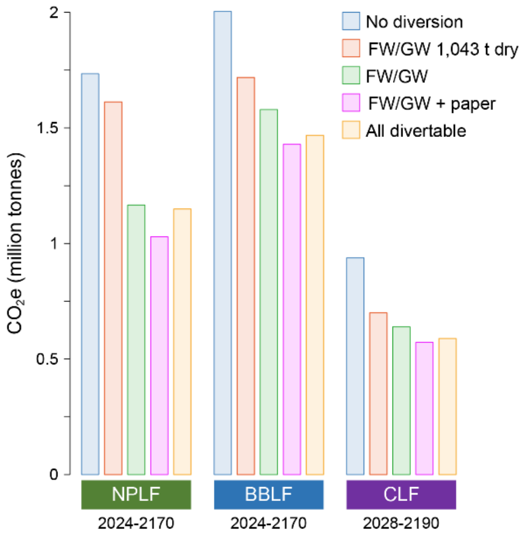

Figure A-4. Effect of diverting waste from landfilling on CO_2e emissions for all landfills.
CO_2e emissions date ranges are indicated underneath each graph.

A4. Transportation of feedstocks

Ground transportation was considered for (i) the within-region transport of landfill-diverted materials to a centralized processing location; and (ii) the out-of-region transport from Chetwynd to the Greater Vancouver area for all recyclables other than for agricultural plastics. Agricultural plastics are collected by the CleanFarms stewardship program in the PRRD and transported to Bashaw, AB, for processing.

Oceanic transport has been included to determine how much CO_2e is generated when transporting recyclables by container ship overseas and importing the re-manufactured products. Only plastics and transport by container ship transport were modeled. More information may be found in section A4.3 *Oceanic transport* on page A-12.

For FW/GW, transport was also determined on wet and dry (8% moisture) quantities to evaluate monetary and CO_2e savings. No collection costs were included, although further exploration into the collection of source-separated wastes versus mixed wastes could be explored.

A4.1. Within-region transportation

Using the *All divertible* scenario as a basis, the cost of within-region transport and the corresponding CO_2e generated was evaluated (Figure A-5a), with costs dependent on the location (NPLF, BBLF, CLF) of a centralized waste processing facility. The two best options financially and environmentally would be to locate the facility at either the NPLF or the BBLF as a regional solution. The NPLF location is slightly favored due to the larger quantity of waste that the NPLF handles, thereby reducing the need for transport.

The *All divertible* scenario was also examined assuming pre-drying of FW/GW to 8% moisture prior to transportation to determine the fiscal and environmental impacts. The assumption was a central processing facility located at the BBLF. Considerable cost and CO_2e savings could be realized by a reduction in mass with the removal of water prior to transport (Figure A-5b). Section A4.4 *Reduction of CO_2e by pre-drying FW/GW* on page A-13 presents some pre-drying strategies that may be of interest in a future implementation.

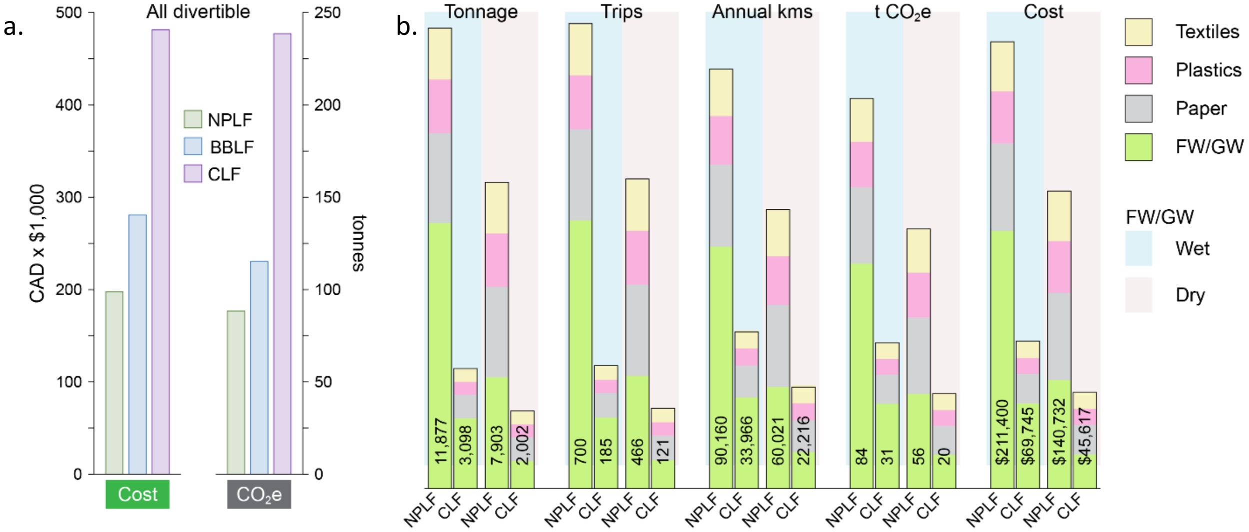

Figure A-5. Annual within-region transportation costs of diverted landfill waste.
a. Cost of transporting all divertable landfill waste to a centralized processing facility located at either the NPLF, BBLF, or CLF. b. Breakdown of tonnages, trips, kilometers, CO_2e generated and associated costs for transporting waste from the NPLF and CLF to the BBLF on a wet and dry basis for FW/GW. Single direction transport with load, empty deadheading. Numbers in bars are total quantities.

A4.2. Out-of-region transport

Out-of-region ground transportation was applied to all non-landfill bound recyclables (section A1, *Feedstock availability*, page A-1). It was assumed that four groups were responsible for organizing the collection and transport of materials: Recycle BC (CCR and Recycle BC TS); a third party contractor (Return-It, depots and PRRD TS); ICI paper and plastics; and an agricultural contractor (e.g. CleanFarms). Transport was assumed between Chetwynd and Richmond, B.C. (1,095 km one-way) for all material other than CleanFarms, which was sent to Bashaw, AB, with the origin point assumed to be Dawson Creek and a travel distance of 721 km. Only CO_2e estimates were made (Figure A-6) as the financial costs were assumed borne by the entities transporting the materials. The out-of-region transport CO_2e quantities generated are relatively small compared to LFG CO_2e (Figure A-3).

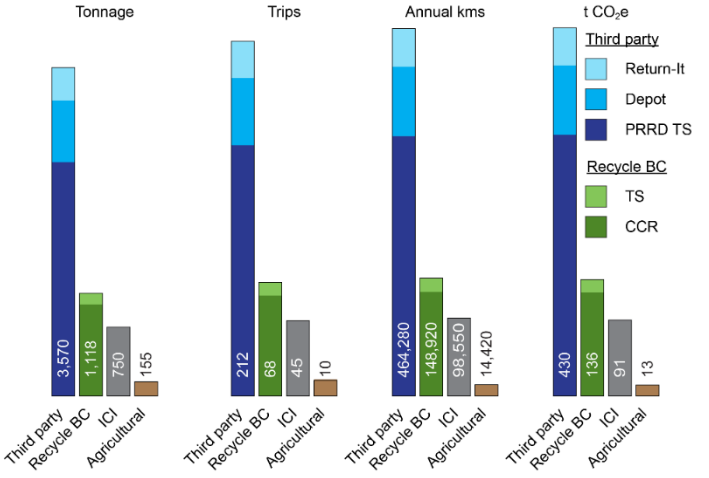

Figure A-6. Out-of-region transport of recyclables and CO_2e emissions. Transport is from Chetwynd to Richmond, B.C. (third party, Recycle BC, ICI) and Bashaw, AB (agricultural).
Notes: Tonnages (not volumes) were used; t CO_2e assumes no payload on return trips. Total quantities are indicated for each bar.

A4.3. Oceanic transport

According to RecycleBC, plastic foam packaging (expanded polystyrene, or EPS) is recycled into picture frames, construction trim, park benches and fence posts[74,75]. Although not officially verified, the EPS is likely processed in the Greater Vancouver area and sent by container ship for remanufacturing in Asia, with items then returned by container ship. Based on this possible export/import scenario, the CO_2e impact was estimated to better understand the environmental costs of such a business model.

It was assumed that 80% of recycled EPS is sent to China via container ship, processed into higher density PS (extruded PS, or XPS), and returned to Vancouver. Only the shipping-related CO_2e emissions were estimated. Common practice is to compress low density EPS prior to shipping to improve its density. A compression ratio of 40:1 was assumed.

Other plastic materials were also considered. Recycled plastics such as PE, PET, and PP are ground and extruded into pellets in the Greater Vancouver area. It was assumed that 50% (by mass) of the PE, PET and PP recycled in B.C. was transported to Asia. Shipping of EPS quantities found in the PRRD accounted for 4.8 t of CO_2e; EPS, with other resins (PE, PET, PP), totaled 20.8 t CO_2e. Return shipping of EPS products to Vancouver totaled 34.0 t CO_2e. The impact on overall CO_2e was found to be relatively small compared to LFG CO_2e (Figure A-3).

A4.4. Reduction of CO_2e by pre-drying FW/GW

Pre-drying of FW/GW prior to transport would reduce costs and CO_2e directly associated with within-region transportation of diverted landfill materials (Figure A-6). The onus of pre-drying FW/GW could be partially or completely placed on those producing the waste. For example, restaurants could be held responsible for pre-drying FW prior to disposal. A pre-drying requirement could ultimately result in financial savings for the restaurant by reducing pickup/transport costs and encouraging less waste to be produced.

According to the FSWCS[1], the ICI sector accounted for 66% (8,800 t) of all compostable organic waste entering the regional landfills, compared to 26% (3,400 t) for the SFR sector. Restaurant and grocery store food waste that is destined for the landfill could be dehydrated on-site or at a centrally located area prior to collection using commercial dehydration technology. One company, Hungry Giant, provides such technology with claims of reducing waste volume by 70-90%[76]; the Yorkdale Shopping Centre in Toronto is an example of where such technology has helped in greatly reducing the volume of waste[77].

Household-sized waste food dehydrators have been evaluated, resulting in a reduction of organic mass of 58-78% simply by removing moisture[78]. The cost of operating the domestic dryer was estimated to be approximately one-third of the cost of waste management per tonne of waste. Furthermore, by dehydrating the waste at the source, GHG emissions are decreased because microbial activity is inhibited when moisture is removed, indicative of a reduction in unwanted fugitive emissions during transport and storage.

The District of Mackenzie recently concluded a pilot program where one hundred countertop dehydration units were deployed, with an estimated 247.7 kg of FW per household diverted from landfilling annually. A reduction in CO_2e, landfilling and transportation costs may also be realized. A similar program in the PRRD would benefit pyrolysis tremendously by reducing labor and energy costs associated with pre-drying of FW. Note that the deployment of such units will require recycling at some point, which will comes with a CO_2e and economic cost.

An additional solution could be to use excess heat from the oil and gas industry. In a past discussion with the PRRD, it was indicated that excess heat up to 150°C may be available in the Fort St. John region.

A5. Pyrolysis/carbonization plant

This section contains some of the technical information regarding the two pyrolysis units used in the modeling exercise: the MJT-500 and the ATS-1000. Information is included for reference purposes only.

500 kg/h carbonization plant from MingJie Environmental Equipment (China)

A carbonization plant produced by MingJie Environmental Equipment (China) was arbitrarily selected (https://www.mingjiegroup.com/products/Woody_Waste_Carbonization_Plant.html; visited Feb. 13, 2024). The 300-500 kg/h processing capability was selected. The specifications, as provided by the company are shown below and in Table A-7:

Table A-7. 500 kg/h carbonization plant specifications

Specification	MJT-500
Reactor structure	Dual cylinders
Reactor material	304 stainless steel
Input capacity	300-500 kg/h
Feedstock size	<20 mm
Feedstock moisture	<15%
Charcoal output ratio	28-35%
Working method	Fully continuous
Fuel consumption	35-50 m^3 natural gas for initial heating
Power consumption	4 KW
Temperature range	300-800°C
Land required	L35 x W12 x H6m
Operators per shift	2

Costs listed in USD:
Unit cost: $78,550
Shipping: $15,710 (quoted by manufacturer as $14,000 USD to Vancouver, four containers)

Duty at 15%: $11,783
GST at 18%: $14,139
Ancillary: $23,565 (30% of unit cost)
Installation:
Tech quoted at $100 USD/day, 30-45 days + accommodation, flight.
Not determined but estimated ~$25,000
Total cost estimate used: $199,000 CAD; used $250,000

1000 kg/h pyrolysis plant from Magnum International (ATS-1000)

Estimate received: ~$9.3 million

Working parameters are similar to those listed for the 500 kg/h equipment from MingJie Environmental for feedstock and moisture size. Initial heating is performed with diesel. Electricity usage is estimated at 36 kWh/t. The equipment has a similar temperature range to the MJT-500.

The ATS-1000 (https://www.magnumgroup.net/ats-technology; accessed Feb. 13, 2024) technology uses a three temperature stage auger fed system with advanced pollution controls. The company claims no quantifiable emissions of organic pollutants. Biochar may be upgraded (increased surface area and pores) via a steam system. The technology is marketed as an advanced modular pyrolysis unit.

The estimated number of equipment operators would be 2-4 per shift depending on workload.

For the ATS-1000 system, approximately one day is required for a feedstock switch from biomass, for example, to plastics processing.

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