PEACE RIVER REGIONAL DISTRICT

REPORT

To: Solid Waste Committee Report Number: ENV-SWC-166

From: Environmental Services Date: July 4, 2024

Subject: Solid Waste Management Best Practices: Pyrolysis Waste Management Study

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RECOMMENDATION:

That the Solid Waste Committee receive the reports prepared by Dominic Reiffarth from UNBC titled "Solid Waste Management Best Practices - Cost Effective Options to Sustainably Manage Solid Waste in the PRRD" (July 2022) and "Solid Waste Management Best Practices: Pyrolysis as a Waste Management Approach in the PRRD" (June 2024), which investigated solid waste best practices and the potential use of a pyrolysis unit within the PRRD to manage organic waste as an alternative to landfilling; further that the reports be shared with the Regional Board via the Consent Calendar.

BACKGROUND/RATIONALE:

On March 28, 2019 the Regional Board passed the following resolution:

> *MOVED, SECONDED, and CARRIED*
> That a meeting be arranged with the University of Northern BC – Science Department to determine if a PhD or Master's Degree student could be engaged to prepare a research paper on global leading best practices for solid waste management, focused on finding cost effective options to sustainably manage solid waste in the Regional District.

On January 7, 2020 the Solid Waste Committee passed the following resolution:

> *MOVED, SECONDED, and CARRIED*
> That the SWC recommends to the Regional Board that the draft proposal received from the University of British Columbia in response to the Regional District's request for a research project – focusing on solid waste management best practices: cost effective options for the sustainable management of solid waste be approved, and further that the project cost of $47,500 be included in the 2020 Solid Waste Management budget (Function 500).

The second draft of the 2020 Solid Waste Budget, inclusive of the increase of $47,000 to fund the project, was considered and approved by the Solid Waste Committee on February 6, 2020, and subsequently approved as presented by the Regional Board on February 26, 2020.

In 2020, PRRD commissioned a report through the University of Northern BC (UNBC) in conjunction with the Mitacs Accelerate program to investigate best management practices for cost effective options to sustainably manage solid waste in the Peace River Regional District (PRRD). Staff worked with UNBC post-doctoral researcher Dominic Reiffarth to look at on the initial study which focused on:

1. Increasing the recovery of waste generated in the PRRD,
2. Materials Recovery Facility – Plastics Processing, and
3. Anaerobic digesters – Organics Processing.

The first report was presented to the Regional Board during the Committee of the Whole Meeting held April 21, 2022, and completed shortly thereafter in 2022. The first report is available as Attachment 1 to this report.

In follow up to the first report, UNBC approached the PRRD about an opportunity to continue the study using grant funding available through the Mitacs Elevate program. On May 26, 2022 the Regional Board passed the following resolution:

> *MOVED, SECONDED and CARRIED*
> That the Regional Board authorize the submission of a grant application through the University of Northern BC (UNBC) to Mitacs Elevate, to secure funding for the continuance of the Solid Waste Management Best Practices Study, for a grant of up to \$160,000 over two years; further that \$40,000 be allocated in 2022 and 2023 totaling \$80,000 as the PRRD's contribution to the project.

This second phase for the study began in the summer of 2022 and focused on the use of a pyrolysis unit within the PRRD to manage organic waste as an alternative to landfilling. The report investigated a regional scale model looking at managing all organics generated in the region as well as a small-scale unit focused in the Chetwynd area. The report has been completed and Dominic Reiffarth presented his findings during the Solid Waste Committee Meeting held July 4, 2024. The completed report is available as Attachment 2 to this report.

ALTERNATIVE OPTIONS:

1. That the Solid Waste Committee provide further direction.

STRATEGIC PLAN RELEVANCE:

☒ Not Applicable to Strategic Plan

FINANCIAL CONSIDERATION(S):

The PRRD's contribution for the first study was \$47,500.

The PRRD's contribution for the second study was \$80,000.

COMMUNICATIONS CONSIDERATION(S):

None at this time.

OTHER CONSIDERATION(S):

None at this time.

Attachments:

1. Solid Waste Management Best Practices: Cost-effective options to sustainably manage solid waste in the Peace River Regional District.
2. Solid Waste Management Best Practices: Pyrolysis as a Waste Management Approach in the Peace River Regional District.

External Links:

1. March 3, 2022 Solid Waste Committee Meeting - See Item 9.1 "UNBC Solid Waste Management Study Presentation – ENV-SWC-081"
2. April 21, 2022 Committee of the Whole Meeting – See Item 4.1 "University of Northern BC – Solid Waste Management Best Practices Study"
3. May 13, 2022 Solid Waste Committee Meeting – See Item 8.1 "Email from H. Kasemian, UNBC (May 4, 2022) re: Possible Funding Opportunity (Mitacs Elevate)."
4. May 26, 2022 Regional Board Meeting – See Item 9.2 "May 13, 2022 Solid Waste Committee Recommendations, ENV-BRD-097"

Solid Waste Management Best Practices:
Cost-effective options to sustainably manage solid waste in the Peace River Regional District

FINAL REPORT

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List of abbreviations

General

AD	anaerobic digestion
capex	capital expenditures
CIF	Continuous Improvement Fund
GHG	greenhouse gas
MRF	materials recovery facility
MSW	municipal solid waste
OW	organic waste
PNG	Pacific Northern Gas
PRRD	Peace River Regional District
RNG	renewable natural gas
RSWMP	Regional Solid Waste Management Plan
SWM	solid waste management
WtE	waste to energy

Recycling streams and materials

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

Plastic types

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

Units of measure

GJ	Gigajoules
kW	kilowatt
kWh	kilowatt hour
MW	megawatt
MWh	megawatt hour
t	metric tonnes
tph	tonnes per hour

Executive summary

This report was commissioned by the Peace River Regional District (PRRD), in partnership with the University of Northern British Columbia (UNBC) and funding through Mitacs, to identify commercial, mainstream technologies that are currently available for the purpose of diverting solid waste from landfilling. As part of the review, high level feasibility studies were performed on the various technologies. The identified technologies include:

- Anaerobic digestion (AD) for the processing of food wastes, together with composting for green (e.g. woody) wastes. The primary focus is to divert food wastes from landfills and reduce methane (CH_4) emissions. Sales of upgraded CH_4 collected via the AD process may be used to offset capital expenses (capex) and variable costs.
- Fast pyrolysis for the processing of food, green and plastic wastes. Unlike AD, a variety of feedstocks may be used and feedstocks are not limited to specific organic wastes. Aside from waste diversion, energy recovery is the objective. The reduction of costs for plastics handling in the PRRD is possible, and the generation of energy products (e.g. bio-oil) is used to offset expenses. Costs tend to be much greater per tonne than AD.
- A materials recovery facility (MRF) to sort source-separated recyclables (glass, metals, paper and plastics) with further sorting of plastics into their respective categories (e.g. PET, HDPE, etc.) The objective is increase market value of source-separated recyclables through sorting. Further sorting of plastics into subcategories (e.g. PET clear, PET green) increases market values further. Washing and pelletizing of the sorted plastics leads to even higher economic returns.

A centralized facility was assumed for an AD facility located at the Bessborough landfill site due to available land, the potential to obtain lease income for a third party-operated facility, the convenience of residual waste disposal, and the proximity to a natural gas pipeline. Expenses related to biomass transport to the centralized facility were also examined. For pyrolysis, a centralized facility was investigated, as well as a scenario with individual facilities in Fort St. John and Dawson Creek.

Food waste collection costs for the single family residential (SFR) sector were estimated. Collection costs for the industrial, commercial and institutional (ICI) sector (organics, metals, glass, and paper) remain unknown, and it was assumed that commercial tipping fees, or some type of financial recovery mechanism, would lead to no net expenses for the PRRD for any wastes collected. Transport to centralized facilities (e.g. Fort St. John to Dawson Creek) was considered.

A centralized MRF for the PRRD was assumed, with the major contribution of materials from the ICI sector followed by the SFR sector. The primary objective of the MRF was to further sort source-separated recyclables into the categories of paper, glass, plastics and metals, as sorted materials tend to have much greater market value.

E.1. Summary of findings

All of the technologies (AD, pyrolysis, MRF) benefit from economies of scale. Anaerobic digestion, however, differs in that continual, homogeneous feedstock is required. A centralized AD facility, operating at the smallest scale of 25 000 t/year feedstock, is feasible in the PRRD if: a) ICI and SFR food waste (estimated 9 000 t/year) is reliably collected, stored, and transported; and b) 16 000 t/year of another feedstock (manure or fescue) is used to supplement the food waste. The quantities and type of feedstock need to be reliably accessible and homogenized, a key point for an AD facility. Under these conditions, a simple payback period as short as eight years is estimated through the sale of upgraded CH_4. Logistically, the challenge in collecting feedstock will need to be overcome.

Fast pyrolysis is the more convenient option to AD because there is much less concern with the homogeneity and consistency of feedstock. Pyrolysis is beneficial in that all organics may be processed, and inorganic impurities are not a major issue, unlike in AD. Moisture, however, is a major issue; food waste has high moisture content, thus requiring significant handling and drying. The labor costs were found to be quite high for pyrolysis and are a major barrier to implementation. Expected energy recovery from the energy-rich products produced via pyrolysis (biochar, bio-oil and synthesis gas) is estimated to be adequate to overcome energy consumption from the drying and pyrolysis of food and green wastes alone, but not for all energy needs. With the addition of plastics as feedstock, it was determined the process will result in significantly improved net energy production. However, plastic feedstock would still require pre-sorting from the ICI and SFR sectors.

A small, semi-automated, MRF in the PRRD would be feasible if plastics are sorted and pelletized, assuming efficient collection of materials from the ICI sector. Without pelletizing, the MRF would be revenue negative. If an MRF is implemented for the ~8 400 t/year estimated tonnes of recyclables primarily available via the SFR and ICI sectors, attempts should be made to increase available materials for recycling in order to maximize returns. An increase of MRF capacity to 13 000 t/year will incur minimal expenses compared to the initial investment for a 8 400 t/year operation, would not require a larger building, and will increase revenues. A 8 400 t/year operation is predicted to be revenue negative, whereas doubling of capacity leads to positive revenue.

E.2. Recommendations

The simplest implementation for some recyclable cost recovery is to manually sort CCR waste prior to baling for transport out of region. Sorting is expected to increase market value, reduce the unnecessary transportation of residuals that should be landfilled, and provide an employment opportunity. Such an implementation does not increase waste diversion.

Anaerobic digestion appears to be the most economically feasible, but also logistically challenging, technology that may be used in the PRRD for organic waste diversion. A centralized AD plant has been considered in the past, and still appears to be the most appropriate technology-based solution for food waste diversion from an environmental and economic perspective. A previous attempt at an AD implementation by a third party was unsuccessful in part due to feedstock insecurity. Proactively working toward securing feedstock for co-digestion with food waste (e.g. fescue, beef cattle manure) in particular may significantly improve interest by third parties. The other alternative is to continue with simple composting.

Pyrolysis of food and green waste does not appear to be economically favorable at this juncture based on waste quantities reviewed herein; however, much of the small scale, modular technology is proprietary, and there may be an implementation that will narrow the spread between expenses and cost recovery. If pyrolysis of food and green waste is coupled with plastics pyrolysis, the economics become considerably more favorable. Other sources of plastics (e.g. Recycle BC) may be added as feedstock sources to improve fuel production; a wide array of plastics may be used. Given the logistical challenges of an AD facility, pyrolysis implementation would be simpler, and would remove a larger quantity of materials from being landfilled. The quality of the economically valuable products produced from pyrolysis will depend on the quality of the feedstock. Some degree of sorting of materials will be necessary prior to pyrolyzing.

Implementation of a MRF appears feasible if enough tonnage is obtained. Discussion with an equipment manufacturer confirms that a scenario of initial implementation of 8 400 t/year facility (based on estimated PRRD waste available for sorting) with future expansion to 16 800 t/year may be performed without the need for additional facilities to be built and minimal equipment cost relative to the initial capex. The 25-year gap between income and expense was reasonably large, but could be overcome with increased capacity and minimal further investment.

There is high volatility of the recyclable plastics market on which cost recovery is primarily dependent. A MRF with pelletizing of plastics appears to be the best technological option, at present, for increasing landfill waste diversion of plastics and recovering costs with the potential for economic diversification. If pyrolysis is used as the end destination of sorted plastics, however, the economics of the MRF will need to be re-evaluated. The sorting system could be simplified.

E.3. Report organization

The report contains a main body which discusses the primary findings in a summarized manner, along with a short background on the technologies reviewed. The *Supplemental* section at the end of the report contains more details on each of the technologies and methods used to arrive at the findings presented in the main body, and acts as supporting information.

A white paper (PRRD_UNBC_MSW_WP_rev1.3c (MS Word document and pdf) accompanies this report that provides details on all the sources of data and calculations that were applied.

1. Introduction

Regional districts in British Columbia are required to have a Regional Solid Waste Management Plan (RSWMP), which sets out the direction of solid waste management (SWM) for the next ten years. After five years, an effectiveness review is completed with a plan renewal occurring every ten years. The PRRD has developed its own RSWMP plan that outlines waste reduction strategies and goals to achieve its Zero Waste[1] objectives. These strategies are based on the Government of BC waste diversion hierarchy principles of *Reduce*, *Reuse*, *Recycle*, *Recovery* and *Residuals Management* geared at creating a circular economy, and are part of the CleanBC Roadmap to 2030 net zero (carbon) emissions initiatives.[2] The focus herein is on aspects of *Recycle*, *Recovery* and *Residuals Management*.

Based on the amended 2016 RSWMP plan for the PRRD (inaugural version published 2008; updated 2021 version submitted for approval to the Ministry of Environment and Climate Change Strategy), the region is following a three-phase plan that aims at reducing waste disposal by 26% per capita at the end of Phase I, 41% cumulatively by the end of Phase II, and 42% cumulatively by the end of Phase III.[3] The amount of solid waste generated in the PRRD has decreased to 847 kg/capita (all values per annum) in 2017 from an estimated 1183 kg/capita in 2007;[4] a 28% reduction in solid waste has been achieved, but this is still above the provincial average of 506 kg/capita.

The purpose of this report is to identify available technologies that will improve waste diversion from landfilling in the PRRD. Two areas of SWM have been identified in the PRRD that will lead to environmental and potential economic benefits, bringing the PRRD closer to meeting Zero Waste objectives: The diversion of the organic waste (OW) portion of municipal solid waste (MSW) from landfills and the processing of recycled hard plastics. Diversion of OW from landfills, which does not currently occur to any great extent in the PRRD, would lead the district toward the CleanBC objective of 95% OW diversion by 2030.[5] Instituting a regional sorting facility with recovery of hard plastics will help close the recycling loop, and reduce the unnecessary transport of landfilled waste over long distances.

1.1. Diversion of organic wastes

Organic waste includes food waste, green waste (e.g. woody biomass), plastics and polymers (e.g. paint). Depending on the nature of the OW, it may be processed as follows: i) incineration; ii) waste to energy (WtE); iii) composting; and iv) anaerobic digestion (AD). Diversion of OW presents an opportunity to reduce OW destined for the landfill by as much as 30% by mass, and in the process reduce potent greenhouse gas (GHG) emissions of methane (CH_4) to the atmosphere.

Incineration, as a means of processing waste, is generally not considered a reasonable alternative to landfilling,[6] and was not further considered here. Incineration is associated with high energy costs, a lack of nutrient and energy recovery, and a high risk of pollution through the release of harmful chemicals such as dioxins, sulfur, nitrogen oxides, fly ash and other toxins.[7] Incineration is usually considered an option where landfilling is not possible.

Gasification and pyrolysis opportunities were reviewed, as both are means of energy recovery as part of a WtE strategy. Fast pyrolysis was determined to be the most suitable WtE technology based on a higher production potential of valuable bio-oil. Fast pyrolysis was examined with respect to biomass (food and green waste), and with the addition of plastics as feedstock. A high level feasibility study found that the gap between expenses and potential savings was considerable; the gap may be narrowed by securing additional plastic feedstock. Logistically, the technology would be the easiest to implement as a diverse range of feedstocks may be used; however, operating costs tend to be high when used on small scale. Labor costs were particularly high. The technology does provide a solution for biomass and the costs associated with plastic recycling and transport. The addition of plastics does require source-separated plastics from the single family residential (SFR) and industrial, commercial and institutional (ICI) sectors.

The other alternative for food and green wastes is AD coupled with composting. Implementing a centralized AD system in the PRRD suffers from an economy of scale issue. Feasibility of a centralized AD plant generally occurs at annual capacities of feedstocks greater than 25 000 t/year, with green waste not suitable for AD and requiring separate composting. Most of the food waste would need to be collected from the ICI and SFR sectors, be separated at source, stored and transported to a centralized location. Food waste from the SFR and ICI sectors would account for only 9 000 t/year, and the remaining required feedstock would need to be sourced as cattle manure. Logistically, obtaining feedstock, and especially manure, presents a challenge. However, economically, a payback period between 10-12 years may be achieved and an AD facility would be expected to be revenue positive over a 25-year lifespan.

1.2. Recyclable materials handling

A review of the various waste streams, according to 2020 data provided by the PRRD, was conducted. Historically, commingled curbside recyclable (CCR) material and hard plastics, collected via transfer station (TS) bins and through self-haul (SH), have resulted in the greatest processing expenses, including bringing materials to market. Materials, and in particular plastics, have a much higher economic value when sorted into their appropriate marketable categories. At a bare minimum, the PRRD should be manually sorting CCR material prior to baling for export from the region to reduce costs.

The potential for a material recoveries facility (MRF) was examined. A MRF increases the sorting speed of source-separated recyclables compared to manual sorting. The targeted recyclables are of glass, plastic, metals and paper. It was found that a basic MRF would be feasible in the PRRD at the right scale; however, the logistics of waste collection, and particular collection within the ICI sector, remain unknown. The ICI sector would be the main contributor of material. It was assumed in this report that the PRRD would not incur any costs from collecting source-separated materials from the ICI sector.

With an estimated 8 400 t of material available,[1] the minimum requirements for a semi-automated MRF would be met. However, doubling the feedstock quantities would significantly improve the economics; this would be possible by tapping into markets outside the PRRD, such as Grande Prairie or materials from Recycle BC. An increase in materials for the MRF would lead to minimal capital and labor cost increases, without the need for increased warehousing space.

The MRF was determined to be profitable only if plastic wastes were further sorted into their appropriate plastics categories (e.g. PET, HDPE), followed by even further sorting into color (e.g. PET color, PET green) and then pelletized. Pelletizing incurs greater capital expense, but increases the plastics value considerably. Furthermore, pelletizing would allow for economic diversification by reusing the plastics locally in recycled products. A market review of plastics prices revealed the volatility of the plastics recycling market, and thus any predictions of profitability need to be approached with caution.

1.3. MSW diversion strategy overview

The schematic in Figure 1 provides an overview of an idealized MSW diversion approach. Although implementation of the complete scheme may not currently be realistic, the scheme highlights the opportunities for diverting food waste, green waste and all plastic waste so as to minimize landfilling while maximizing nutrient and materials recovery.

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[1] This value is a conservative estimate based on 2020 commingled curbside collection in the PRRD and an estimated 10 211 t/year of ICI recyclables (glass, paper, plastics, metals) entering the regional landfills according to the 2018 Tetra Tech Four Season Waste Composition Study, of which approximately 7 000 t/year were assumed to be recoverable. The Supplemental section provides further details on materials quantities, as does the accompanying white paper.

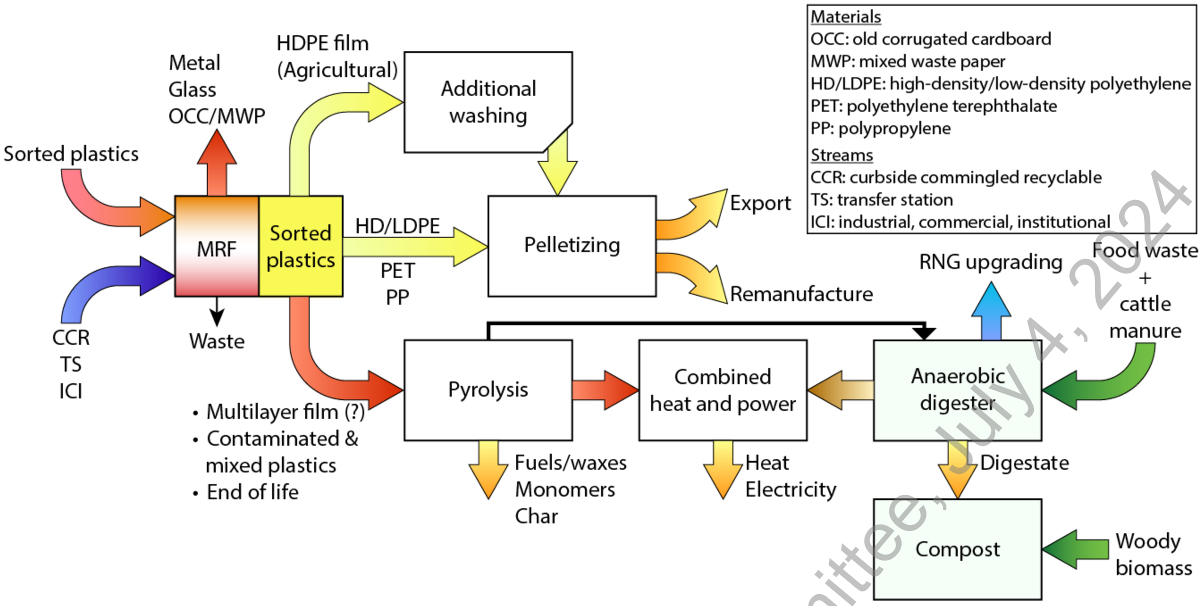


Figure 1. Idealized materials recovery scheme proposed for the PRRD.

2. Organic wastes

Each tonne of food waste landfilled is estimated to produce the equivalent of four tonnes of carbon dioxide (CO_2) to the atmosphere.[8] The landfill gas generated from the decomposition of food waste is primarily CH_4 and CO_2; the CH_4 is often reported as CO_2 equivalents (CO_{2eq}) when discussing global warming impacts. Methane is at least twenty-five times more effective as a GHG than CO_2; therefore, there is a desire to decrease CH_4 emissions. Diversion of food waste from landfills has the added benefit of extending landfill lifespans.

Methane is generated naturally in oxygen-free (anaerobic) conditions. Landfills, with the continual compaction of material added to the surface, create suitable conditions for microbes that generate CH_4 to thrive. A reduction in CH_4 emissions may be achieved by ensuring aerobic (oxygen-rich) conditions, such as those used in aerobic composting, which will generate CO_2 but not CH_4. Capturing landfill gas is a possibility; such systems are considered to be 68% efficient.[9]

Methane is the primary component of natural gas; when the CH_4 source is from microbial processes, it is referred to as renewable natural gas, or RNG. Generated CH_4 may by burned (flared) and converted to CO_2; however, CH_4 is of economic value as a fuel.

2.4. Landfilling alternatives for food waste

Brief overviews of compositing, WtE and AD are provided below. The WtE and AD options were evaluated in greater depth thereafter. Composting and AD are currently the two most common methods for treating food waste.[9] Additional information on WtE technologies may be found in the *Supplemental* section *WtE technologies* on page S-13.

2.4.1. Composting

Composting is a low technology and relatively low cost method of processing organics. The process is generally aerobic (requiring oxygen), although anaerobic conditions may also be possible. It is assumed here that aerobic composting is desired to reduce CH_4 emissions; CO_2 emissions still occur. Composting may be performed on many types of biomass, including wood and forestry waste, kitchen and food scraps, yard waste, etc., and is readily scalable. The only economically beneficial product is the finished compost, which is regulated for resale in British Columbia. Processing times may be anywhere form 3-9 months using windrowing to 1-2 years for a static pile. The process is suitable for food and green waste.

The British Columbia Organic Matter Recycling Regulation (OMRR)[10] distinguishes between types of compost. One of the primary considerations is pathogen level. Higher pathogen levels make the compost unsuitable for use as a fertilizer. Pathogens are reduced by being selective of the organic sources; biosolids (e.g. sewage sludge) carry higher risks of pathogens. Pathogen reduction is often achieved by using thermophilic temperatures (>50°C). In a colder climate such as the PRRD, it may be necessary to perform the composting indoors to retain or add heat, adding to costs. Vermicomposting, which requires temperatures around 20°C, has been tried as a pilot project in the PRRD.

The type of feedstock will affect the quality of the compost. Considerations are the carbon to nitrogen (C/N) ratio. The OMRR requires C/N ratios >15:1 and <35:1, so optimization to achieve the appropriate ratios is necessary. Food waste is also high in moisture content, so dewatering and drying of feedstock may be necessary, and leachate will be a concern. Analysis for heavy metal and pathogen content is required, and a leachate management system must be in place.

The size of the facility will depend on the type of technology employed, pre- and post-treatments and the type and quantity of feedstock targeted. Very simple composting, such as windrowing where the compost piles are processed in batches, are highly scalable, with most of the cost associated with the compost pad, especially if it is paved. Using reactors, for example, to increase throughput will be dependent on the amount of feedstock, will increase costs, but also improve turnover times, kill pathogens, and decrease nitrogen losses.

2.4.2. Anaerobic digestion

The AD process has been in use for several decades; Europe is the global leader in AD technology due to strict environmental policies.[11] The technology is less common in North America. According to the Canadian Biogas Association, there are currently only five facilities operating in BC.[12] Consequently, most available information for centralized AD plants is in a European context. The AD processing time depends on conditions, but has a window of 15-40 days. Higher temperatures (thermophilic) lead to faster processing times and a better reduction in pathogens. The drawback is that the microbial community that produces the CH_4 becomes more vulnerable.

The objective of AD is to produce as much CH_4 as possible using microbes that break down the organics in an oxygen-free (anaerobic) environment. The major advantage of AD over composting is the recovery of CH_4 as RNG, or alternatively the generation of heat and power. The biogas that is initially produced is a mixture of 40-70% CH_4 and the balance mostly CO_2 with small amounts of hydrogen (H_2) and hydrogen sulfide (H_2S).[13] Fugitive emissions of CH_4 are estimated at only 1-3% of the total amount of CH_4 produced in an AD facility.

In Europe, biogas is most commonly used for heat and electricity generation. Electricity is generated using a combined heat and power (CHP) plant, which is essentially a turbine. The other option is to upgrade the CH_4 by removing gaseous impurities, with purified CH_4 fed into existing natural gas pipelines. The CO_2 portion may be released as a GHG; direct applications (e.g. greenhouse growing, carbonation) are another possibility.

An AD facility is sized according to available feedstock and is subject to many of the concerns associated with composting for efficiency: operating temperature, presence of pathogens, and C/N ratios. The digester needs to be conditioned and a continuous, homogenized feedstock provided in order to ensure maximum CH_4 generation. This means feedstock needs to be continuously available in the correct mixture and quantities. Holding and mixing facilities are required. The “leftovers” (digestate) from the AD process may be used in direct fertilizer application, or added to existing compost treatments in order to maximize organic breakdown.

2.4.3. Waste to energy (WtE)

The different types of WtE options are too numerous to review here, much of the technology is proprietary, and finding information in the public domain with installed costs has proven difficult. The two most common approaches are gasification and pyrolysis. The two processes differ from combustion (incineration) in the amount of oxygen used and the products produced. Processing of feedstock is fast and often measured in tonnes per hour (tph). Pre-treatment (e.g. drying, grinding) is much slower.

Gasification, usually performed at higher temperatures (800-1000°C), leads to the production of synthesis gas (syngas; mostly carbon monoxide (CO) and H_2) and possibly fuels. The syngas is usually used in heating and power generation, and to offset the energy expenses for the facility. Ash and tar are unwanted by-products that are usually landfilled. Gasification may be performed on any scale; pyrolysis is generally restricted to smaller scale applications.

Pyrolysis spans a range of temperatures from slow pyrolysis (low temperature, 200-300°C)[14] to fast and flash pyrolysis (>600°C).[15] The process is low-oxygen and nitrogen gas is often used to ensure low oxygen conditions prevail. With fast and flash pyrolysis, the target is usually the production of fuels, and yields between 70-80% have been achieved.[15] The main products are syngas, biochar (solid carbon used for heating) and bio-oils. The quantities obtained depend on feedstock and operating conditions. The products are usually used in part to offset energy inputs in the process.

WtE technology is scalable and even modular, and may be tuned according to desired outcomes. For food wastes, the major drawback is moisture content, which is between 60-90%, making pre-drying of feedstock necessary, and thus preventing gasification and pyrolysis from having a net positive energy balance.[16] Gasification should have a moisture content <20-25%.[17] Lower moisture content in the feedstock leads to a better bio-oil, with less moisture in the bio-oil.[18] The natural drying process for wet wood, for example, to obtain moisture levels that are not usually <35% takes 3-4 months.[19]

A major benefit of WtE technologies is the indiscriminate use of organic feedstocks, including contaminated hospital plastic wastes, which are not allowed under conventional Canadian recycling regulations due to worker safety concerns. The actual feedstock mix and quality will affect the consistency and predictability of bio-oil, biochar and syngas distributions, ash and moisture content, and composition.[20] Plastics, which are organics, are suitable for pyrolysis, and co-pyrolysis of plastics and MSW has been shown to provide better bio-oils with higher hydrocarbon content, lower moisture and improved energy yield than for MSW alone.[21]

Not all plastics may be indiscriminately added. Polyvinyl chloride (PVC), for example, contains chloride that will produce corrosive hydrochloric acid,[22] which will decrease system performance and life expectancy unless appropriate measures are taken. Feedstock should be adequately separated prior to pyrolyzing, and some level of sorting is still required. However, plastics that are generally difficult to recycle using mechanical recycling techniques, such as mixed plastics, agricultural films, and food wrappers, may be used as feedstock. Food wrappers, which contain multiple layers of material laminated together, including an aluminum (non-organic) layer,[23] are problematic to mechanically recycle. Non-pyrolyzable material will end up in the bottom ash. Textiles, which often contain polyesters and/or other synthetic polymers, often blended with cotton, also do not present an issue.

A more recently developed, but not yet commercially available, technology is hydrothermal liquefaction.[15,16] The advantage of this method is that it is relatively low temperature (250-450°C) and is suitable for food wastes because no pre-drying is required. The result is a crude bio-oil that has characteristics similar to diesel, although yields are lower than for pyrolysis at 20-30%.

Pyrolysis does not lead to nutrient recovery, unlike AD and composting. The labor cost per tonne of feedstock is also generally high. Pyrolysis is generally the most expensive food waste treatment method per tonne of feedstock.

2.5. The PRRD situation

Composting, AD and WtE operate on economies of scale. The challenge is obtaining adequate feedstock to offset expenses for more advanced technologies such as AD and WtE, or even advanced composting. The majority of food waste is from the ICI sector, followed by the SFR sector (Figure 2a; Four Season Waste Composition Study (2018)[24]). A centralized AD or WtE installation will require transport of waste. There is also no program for collecting source-separated organics curbside for the SFR sector. Cost estimation of a curbside program has been performed.

Composting is the least expensive, scalable, option, and may be performed with less waste hauling, especially if a low-tech system is used. An AD system is estimated to cost 1.2-1.5 times that of a composting system.[25] Composting is effective for diversion, some nutrient recovery, GHG reduction compared to landfilling, but no energy recovery. Simple outdoor windrowing of compost may not be a suitable solution to meet BC government OMRR requirements and make the compost commercially viable for resale unless measures are taken to increase internal temperatures to reduce

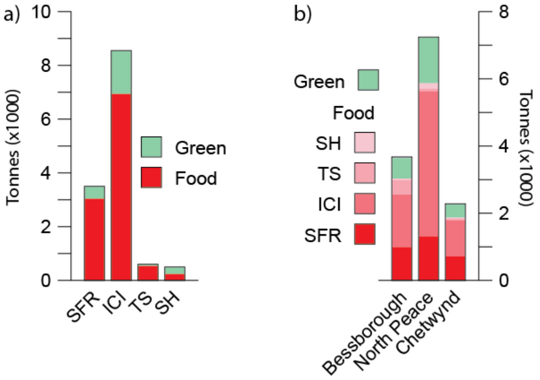


Figure 2. Sources of food and green waste in the PRRD. a) Sources by sector for all landfills (10 801 t food waste; 2 359 t green waste). b) Sources by landfill with food waste shown by sector.[24] Sources only account for material brought to the landfills.

pathogens, and appropriate sampling for heavy metals is performed. A reactor-type system or indoor composting may be necessary. Composting has not been explored further herein.

The two technologies investigated here are AD and fast pyrolysis. Anaerobic digestion is considered the most environmentally friendly option, but can only address food waste, whereas pyrolysis is suitable for the PRRD's green and plastics waste streams. After review of both technologies, AD is the most suitable option for food waste, but also the most challenging logistically due to feedstock supply.

A centralized AD facility becomes economically feasible with either a CHP plant or CH_4 upgrading, with a minimum feedstock of 25 000 t/year. Cattle manure was selected as a suitable feedstock to supplement the 9 000 t of annual food waste. Manure is plentiful in the PRRD, although logistical challenges exist in its collection and transport to a centralized facility. The addition of 16 000 t/year dry manure will lower the high C/N ratio and moisture content of food waste to within ideal operating parameters of an AD.

A high level economic evaluation of AD in the PRRD indicated a payback period as short as 10-12 years. The assumptions are discussed in more detail in *Anaerobic digestion* on page 12. Fast pyrolysis of food waste, and the possible addition of plastic for co-pyrolysis, was also examined. The findings suggest this option would result in negative cost recovery at the scales investigated. A summary of the findings are presented.

For AD, the greatest factor affecting AD profitability has been identified as the transportation cost.[26] However, SFR sector curbside collection costs are present for any type of centralized facility. For this reason, collection costs were examined separately and the estimated costs are presented in the next section (*Curbside collection of organics*). Additionally, a centralized facility requires hauling between municipalities. Waste hauling costs were estimated for food wastes and manure to an AD facility assumed to be located at the Bessorough landfill (*Waste hauling costs*, page 8)

2.6. Curbside collection of organics

Collection costs are included because AD in particular relies on continuous feedstocks. Two collection possibilities were evaluated: i) weekly collection using dedicated trucks for OW; and ii) weekly collection using a 60/40 MSW/OW collection truck. Costs were based on a 2011 feasibility study produced for the City of Prince George[27] with adjustments for collection truck type and inflation to 2022 dollars. A 25-year period was used with 2% inflation applied. The trucks and cart quantities were calculated based on the number of households (11 245) that use carts for MSW collection in the Fort St. John/Taylor and Dawson Creek/Pouce Coupe areas.

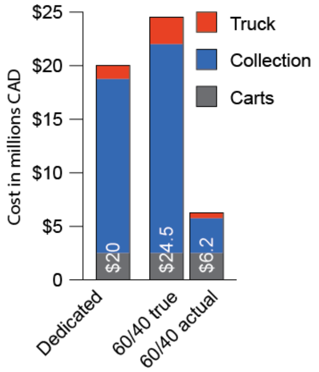


Figure 3. 25-year source-separated organic collection costs. "Dedicated" assumes a dedicated truck. "60/40" assumes a single truck is used for MSW and organics concurrently. See text for details.

Dedicated carts for OW collection are assumed (no differentiation between green and food waste). For an AD facility, green waste would need to be kept separate from food waste or not collected; for pyrolysis, mixed green and food waste is fine. Initial expenditure and replacement costs for carts over a 25-year period are identical for both scenarios (Figure 3). The collection costs include collection labor and fleet maintenance. The cost for dedicated OW trucks is lower than regular MSW trucks, whereas the costs for a 60/40 collection truck are higher

The *Dedicated* scenario uses dedicated OW collection trucks added to the existing MSW fleet (Figure 3). The *60/40* scenario assumes 20% higher collection costs than standard MSW collection due to the increased time collecting for each household and increased fuel usage. The 60/40 scenario was divided into *60/40 true* and *60/40* actual. The

60/40 true values reflect the cost of co-collecting MSW with organics and the purchase of the needed trucks. The *60/40 actual* assumes only the increased costs of using 60/40 trucks over standard MSW trucks, and the associated collection times and costs for using a split collection. This *60/40 actual* values were used going forward for any discussion on 60/40 collection costs.

No collection costs were calculated for Chetwynd, Hudson Hope, or Tumbler Ridge. A refined cost analysis will need to include the added expenses associated with an OW collection strategy for these municipalities. Hauling of food waste (next section) from Chetwynd to the Bessborough landfill was included, however.

Table 1. Cost of hauling feedstock to the Bessborough landfill site.
Percentages under manure are estimates of number of tonnes of total manure obtained at the specified travel distance.

	Distance (km)	t/year	25-year cost
Food waste			
Fort St. John	64	5 888	$3 400 000
Chetwynd	97	1 867	1 400 000
	Total:	7 755	$4 800 00
Manure			
Collection point	20	6 400 (40%)	$1 900 000
	40	3 200 (20%)	$1 800 000
	60	3 200 (20%)	$1 500 000
Fort St. John	64	3 200 (20%)	$2 400 000
	Total:	16 000 (100%)	$7 600 000
		Total:	$12 400 000

2.7. Waste hauling costs

Centralized facilities in the PRRD will require waste to be hauled between locales. An AD facility will further require the hauling of cattle manure. The assumption here is hauling of OW to a centralized Bessborough site, and the hauling of cattle manure. The purpose is to include the costs as part of the expenses of operating an AD facility at the Bessborough site. A summary of the hauling costs is provided in Table 1, with costs calculated based on a 40-tonne tandem trailer operating at 85% capacity.

A major unknown is the cost associated with manure collection and hauling distances. An assumption was made that 40% of the required manure for an AD facility could be collected within a 20 km radius of the Bessborough landfill (Table 1, *Manure*), 20% within 40 km, and so forth. The amount of manure available in the region was determined based on the reported number of cattle, and in theory well exceeds the minimum required amount (16 000 t/year) for AD (Table 2). It should be noted that the consistency (moisture) may vary greatly, which will affect quantities required, shipping and collection. As many of the cattle may be free roaming, collection may be an issue, and it may be necessary to identify larger feedlot operators who are willing to participate in a collection program. Manure may need to be purchased, which has not been considered here. If purchasing is required, costs may be offset by sale or exchange of the post-AD digestate, which is rich in nutrients and generally a better soil amender than inorganic ammonium fertilizers and manure,[30] and in many cases even compost.[31]

Silage, grass or hay may be an alternative to using manure, and would be a suitable feedstock for AD. Grasses generally have low lignocellulosic content, which make them suitable for AD. Collection of feedstock may be simpler than for manure in the PRRD.

Table 2. Estimated annual tonnage of beef cattle manure.
Electoral districts in parentheses.

Area	Manure (t)	District km^2
Dawson Creek (D)	193 862	11 707
PRRD north (B)	303 108	86 103
Fort St. John (C)	28 421	577
Total:	525 391	

Number of head of beef cattle estimated from Statistics Canada census[28] and an estimated 13 444 kg/year manure production per head.[29]

Storage costs for food waste and manure at collection points have not been considered. A general loss in nutrients occurs, especially with uncovered storage,[32] which will affect biogas productivity, and hence CHP production or CH_4 upgrading, and profitability.[26] Optimal AD locations are usually those that can provide 100 kW of energy equivalent from feedstock with 10 km of the plant.[33] With a total estimated AD plant size of 384 kW for Bessborough, more than a third of material should be within 10 km. However, it is important to note that these assumptions are usually based on urban areas of European cities, and factors such as traffic congestion that affect transport times differ.

2.8. Landfill cost savings and methane reduction

Organic waste diverted from landfills was considered as offsets for costs. The initial landfilling rate was set to $58.25/t. The rate is a hybrid between the 2022 residential ($55/t) and the commercial ($60/t) landfilling rates. Commercial sources accounted for 64.3% of food waste, and 65.1% of food and green waste combined; for simplicity, 65.1% was used for food and green wastes. Inflation was set at 2% and the costs estimated over 25 years.

Landfill savings amounted to $16.7 million when only food waste (9 000 t/year) was considered for the AD facility. When food and green wastes were considered (11 000 t/year), the savings were $20.5 million.

Food waste diversion for the Bessborough landfill was modelled, assuming food waste accounted for 25% of waste. The landfill lifespan would increase by 20 years. Information for the Bessborough landfill was obtained from *Operational Specifications: Bessborough Landfill, Chetwynd Landfill, North Peace Regional Landfill* (January 2020). Information for the North Peace and Chetwynd landfills was not located.

Methane emissions were estimated using the LandGem[34] model parameters provided in the *Operational Specifications* report. The amount of CH_4 emitted from landfill waste is determined by a variety of parameters. One major factor is the type of waste and how biodegradable the waste is; the more biodegradable, the higher the CH_4 generation. Assuming food waste diversion (9 000 t) from 2022 onward, a 19.7% reduction in CH_4 emissions over twenty-five years was found to be possible.

2.9. Pyrolysis of organic wastes

The rate of pyrolysis affects the distribution of the liquid (bio-oil) and solid (biochar) energy-rich products produced. Slow pyrolysis favors more biochar (lower energy fuel) and fast pyrolysis bio-oil (higher energy fuel).[15,21,35] Fast pyrolysis is performed at higher temperatures, so moisture is less of an issue in the resulting bio-oil, but more energy input is required; adequate drying of feedstock improves pyrolytic outcomes.[17] A fast-pyrolysis system was assumed here.

2.9.1. Facility costs

Most information available in the public domain for WtE is based on large installations, such as the Enerkem facility in Edmonton, Alberta, which is designed to handle 100 000 t/year of non-recyclable MSW at a price of $75 million (2013 dollars). The 2019 Environment and Climate Change Canada report puts the capital cost for chemical recycling (production of fuels, and other chemicals) at $1 000-$1 300/t and an average plant capacity of 30 000 t/year, with general WtE costs at $1 400-2 000/t and an average plant capacity of 106 000 t/year.[36] The rates are not specific to food waste, which has a much higher moisture content than woody biomass and general MSW.

An estimate for a small, continuous, fast pyrolysis installation of 10 t/day for $1.7 million USD[37] was used and costs were scaled based on tonnage. The costs were based on 7 200 hours of operation per year, which equates to continual operation for 300 days, 24 hours per day.

Three scenarios were evaluated (Figure 4a): i) Separate pyrolysis facilities that serve Fort St. John (*FSJ*) and Dawson Creek/Chetwynd (*DC + Chet*) and only process food and green waste; ii) a single, combined facility for food and green waste processing (*Combined*); iv) a single facility that processes food, green and plastic wastes (*+ plastics*).

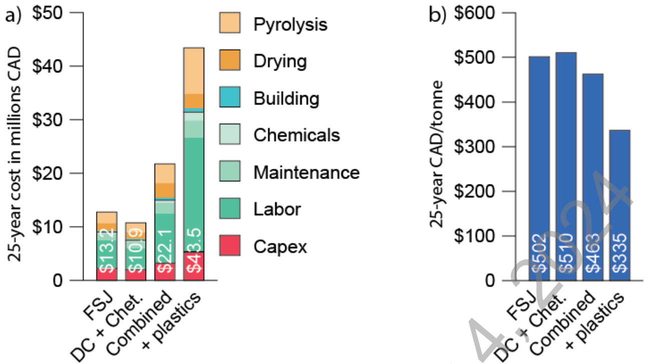


Figure 4. Pyrolysis in the PRRD.
a) 25-year cost for a Fort St. John (FSJ), Dawson Creek + Chetwynd (DC + Chet.) food/green waste pyrolysis plant, a single plant (Combined), and adding plastics to the Combined plant (+plastics).
b) Cost of energy to process feedstock (Input) and recoverable energy (Output). See text for details.

Feedstock was assumed to be from a waste collection program that included SFR, TS and ICI waste (Figure 2). Figure 4a summarizes the 25-year cost for operating a fast pyrolysis plant and does not include collection or transportation costs. Included in the costs are: building, machinery, civil work, storage facility, feedstock dryer, dewatering machine and pyrolysis equipment costs as fixed costs. Variable costs include electricity for the building and processes, chemicals (and nitrogen gas), maintenance and labor costs. Pyrolysis and drying costs reflect the cost of energy required for the respective processes. Dewatering costs were very small and not included as a variable cost in Figure 4a. The economy of scale and the positive effect of including plastic waste as feedstock is evident in Figure 4b. Increasing the plastic to OW ratio further will decrease the cost per tonne, and improve the quality of the bio-oil.

Capital expenditures fell within the expected range, with the lowest cost at $1 100/t for the facility combined facility processing plastics, and the highest for the smallest plant, which would be the Dawson Creek/Chetwynd processing plant at $2 300/t. The costs per tonne are based on dry (8% moisture) feedstock. It was assumed the pyrolysis equipment would last 25 years, although this is a generous assumption.

Labor is the greatest cost over 25 years, and is based on a 24-hour operating schedule. The labor rate used is a modest $20/hour. Compared to AD, for example, more labor is required for pyrolysis to continually dry and load feedstock into the pyrolyzer. Labor was increased at an annual inflation rate of 2%. Proprietary technologies may include solutions for significant labor reduction.

2.9.2. Energy balance and pyrolysis products

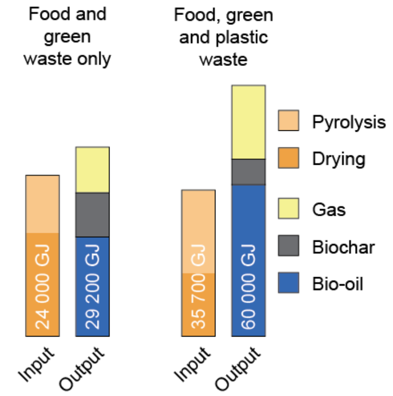


Figure 5. *Energy balance for the co-pyrolysis of food, green and plastic wastes in the PRRD. See text for details.*

The three main products of pyrolysis are syngas, biochar and bio-oil. Revenue generally comes from biochar and bio-oil sales. The syngas is used for processes such as providing heat and electricity via CHP and to offset facility operating costs. The bio-oil and biochar is usually used to do the same, with any excess sold.

The first processing step is dewatering, which reduces the food waste moisture content to ~60% and does not require a large amount of energy. The second step involves drying; in this scenario, moisture was reduced from 60% to 8% (Figure 4a, *Drying*), resulting in similar costs to the final pyrolysis step for food and green waste only (Figure 4a, *Pyrolysis*). The energy balance of using only food and green wastes results in an almost net zero energy balance for drying and pyrolysis only (Figure 5). Plastic waste does not require drying, so the energy balance becomes much more favorable when a co-pyrolysis process of food/green waste and plastics is carried out. The energy value of the bio-oil also increases considerably, from 17.5 MJ/kg to

43 MJ/kg.[21] The takeaway is that processing food waste, due to its very high moisture content, is energy inefficient; the addition of plastics will help to overcome these inefficiencies.

One way to unload drying costs and energy consumption would be to require ICI waste be pre-dried by major food waste contributors, such as the restaurant industry and grocery stores. Commercial scale dehydrators are available, and transport costs would be reduced; this may also encourage producers to reduce their waste, which is the ideal means of diverting food waste from landfilling.

Table 3. Summary of pyrolysis income and expenses. Expenses and income for a single pyrolysis plant processing food/green and plastics wastes from the SFR, ICI, and TS sectors in the PRRD.

	25-year
Expenses	
Facility and operating	$43 500 000
Sorting of CCR for plastics (labor)	$2 400 000
Organics collection	$6 200 000
Expenses total:	$52 100 000
Income	
Landfill offsets: Food and green waste	$20 500 000
CCR plastics	$500 000
ICI plastics (2 522t/year)	$4 800 000
Bio-oil sales	$17 500 000
Income total:	$43 800 000
Net	-$8 300 000

2.9.3. Income and expenses summary

The summary in Table 3 identifies some additional costs and sources of income with respect to a single pyrolysis plant that processes plastics from the SFR, ICI, and TS sectors. Manual sorting (two sorters) was assumed for the CCR stream, and it was assumed that ICI plastics did not incur any sorting costs i.e. plastics were separated at the source prior to collection. The *Organics collection* cost was based on using a 60/40 truck for CCR collection (see *Curbside collection of organics*, page 7). Additional transport expenses for food/green waste and plastics to a single facility have not been included.

The landfill offsets for food and green waste were included based on previous calculations (*Landfill cost savings*, page 9). It was assumed that CCR plastics (hard and flexible) would no longer be sent to market which would save the region money (*CCR plastics*). For ICI plastics, it was assumed that 2 522 t/year would not be landfilled.

The *Energy offset value* assumes that the syngas and biochar (Figure 5) produced from the biomass/plastics pyrolysis would be adequate to offset biomass drying and pyrolysis energy costs. The bio-oil sales assumes that excess bio-oil could be brought to market. It should be noted that, although not included here, mixed waste paper (MWP) may also be pyrolyzed.

2.9.4. Pyrolysis conclusions

Logistically, pyrolysis provides a simpler solution for OW than AD, but suffers from an energy imbalance that hurts the process environmentally and economically in the scenarios reviewed herein, particularly if only food and green wastes are considered. Even with the addition of plastics as feedstock, which overcomes the energy imbalance, the cost of labor is high and the major contributor to the 25-year expense (Figure 4a). Overcoming the high cost of labor may be achieved by scaling up the facilities or possibly finding automated solutions. Based on the analysis herein, the expense and income gap (Table 3) is considerable and it would appear a pyrolysis solution would not be suitable under the conditions reviewed. However, consideration should be given to increasing high energy and low moisture feedstocks such as plastics to lessen the gap.

2.10. Anaerobic digestion

Simple payback periods for a 25 000 t/year AD facility at the Bessborough site were estimated over a 25-year period using 9 000 t/year of food waste and 16 000 t/year of cattle manure. The cattle manure may be substituted with an energy stock, such as fescue. Energy content of grasses varies widely, and fescue has to potential to increase biogas yield;[38,39] time of harvest will also impact yield, with first cuts providing higher yields.[40] Further considerations will be the moisture content, which is high and will depend on harvesting and storage factors. Lignocellulosic content, which cannot be readily digested, also becomes an issue, and pre-treatment, which will add expense and handling costs, may be necessary.[41] The use of fescue is assumed to produce at least as much biogas as manure, with higher production potential expected based on reported biogas yields from grasses.[38]

The sources of income and expenses included in the calculation of the payback period are listed in Table 4.

2.10.1. Expenses

An AD plant is either geared toward heat and power production (CHP) or upgrading of CH_4 for injection into existing natural gas lines. There are currently no BC Hydro electricity purchasing agreements in place, as the program was discontinued in 2016.[42] All heat and electricity would be for local (facility and process) use only. Methane upgrading is currently the most lucrative route for shortening the payback period. The white paper includes estimated electricity and heat costs for the AD process and buildings to provide an estimate of savings in these areas if a CHP were considered.

The cost of connecting to an existing natural gas pipeline has not been included. According to Energy BC, the closest natural gas pipeline is the Spectra/Westcoast line that runs approximately 2.5-3 km east of the proposed Bessborough landfill site.

A major unknown potential expense is the cost of non-food waste feedstock collection; only transport of feedstock (see *Waste hauling costs*, page 8) has been included, and it was assumed manure and fescue would incur similar hauling charges. Food waste transport was assumed to be from Fort St. John and Chetwynd to the Bessborough landfill.

There are multiple methods of estimating operating costs for an AD facility, and expenses will vary depending on local taxation schemes, credits, insurance, wages, etc. Few reported costs for North American facilities exist; costs are typically higher for straight MSW due to sorting and residue

Table 4. List of expenses and income for the construction of an AD facility. The cost of land is not included; neither is the cost of connecting to a NG pipeline. The expenses and income are based on a 25-year operating timeline.

Expense		Income	
Plant capital cost	$7 550 000	Landfilling offset	$16 700 000
Technology		CH_4 sales (manure + food)	$18 800 000
CHP cost	$1 600 000	CH_4 sales (fescue + food)	$39 500 000
CH_4 upgrading (manure)	$1 500 000	Carbon offsets	$2 800 000
CH_4 upgrading (fescue)	$2 470 000	Digestate	$0 ($341 700)[1]
Operating costs			
$26/t	$20 900 000		
$30/t	$24 100 000		
$40/t	$32 100 000		
Feedstock transport			
Food waste	$4 800 000		
Manure/fescue	$7 600 000		

[1]market value undetermined; CHP: Combined heat and power.

production versus agricultural feedstock. A review of European operating costs, when converted to CAD and 2022 dollars, estimated the range at \$40-\$110/t[43], whereas a review that included some Canadian facilities placed the range at \$65-\$168 CAD/t.[11] A life cycle assessment for a proposed plant in Iowa to process the manure from 2 400 head of cattle (~30 000 t/year) used economic modeling of industrial facilities to predict operating costs of \$344 000 USD/year, with labor and maintenance comprising \$232 000 USD/year (assumed 2018 dollars). This translates into \$500 000 CAD/year, or \$17/t (CAD 2022). The GrowTec facility located in Chin, AB,[44] upon which the capital costs were loosely modeled herein, reported operating costs of \$26/t. It is assumed that the operating costs for a Bessborough AD facility would fall between \$26-\$40/t. The operating costs listed in Table 4 reflect this range and some of the modeling of payback periods are shown in Table 5.

The CH_4 upgrading cost estimate in Table 4 is slightly higher for fescue than for manure. The difference is due to the increase in expected biogas generation (Table S-14). The increased cost of upgrading is minimal compared to the anticipated income from greater CH_4 sales.

2.10.2. Income

The *Landfilling offsets* (Table 4) reflect the diversion of food waste (9 000 t/year) from the SFR, TS, SH and ICI sectors. The calculation is based on the tipping fee rate as discussed in *Landfill cost savings* on page 9. A 2% inflation rate was applied over 25 years to the tipping fee rate.

The *CH_4 sales* reflect the market value of CH_4 based on a rate of \$25/GJ. FortisBC, for example, has a purchasing program that pays up to \$30/GJ for high quality RNG.[45] Pacific Northern Gas (PNG) has had discussions with the PRRD regarding RNG purchasing for the North Peace landfill. The interest by PNG indicates a purchasing agreement may be achievable between PNG and the PRRD.

The amount of biogas generated and CH_4 content of the biogas is dependent on the type of feedstock (Table S-14). The average biogas potential (32.5 m^3/t) was used for cattle manure, whereas the low biogas potential was used for food waste at 143 m^3/t;[46] food waste may produce as much as 214 m^3/t.[47] The CH_4 content of biogas varies; a mid-range value of 53% CH_4 content was used. Of the yearly estimated amount, it was assumed only 80% could be recovered due to nutrient losses from transport and storage.

For fescue, the average values from a published review on CH_4 yields was used.[39] Values were reported on a dry basis (volatile solids), which were then converted to a wet basis (CH_4 85.9 m^3/t). For comparison, if CH_4 content was assumed to be 56% in the biogas generated from fescue, the biogas potential is 153 m^3/t.

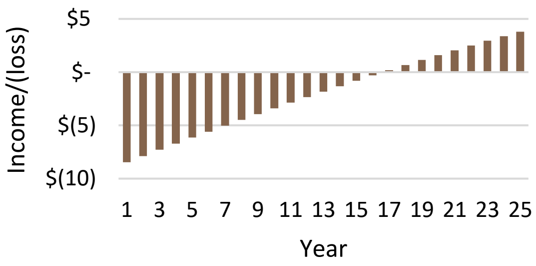
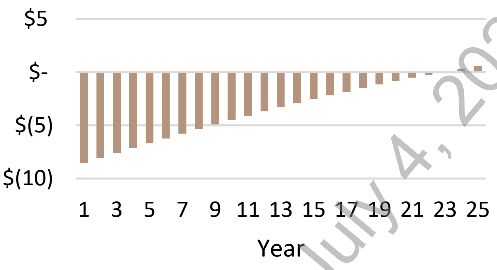
Carbon credits were calculated solely on CH_4 reduction from food waste diversion and the amount of CH_4 that could be generated by AD. It was assumed that only 80% of the maximum calculated CH_4 yield could be recovered and would receive credits. A rate of \$12/t CO_2 was used to calculate the credit, which is in line with rates paid by the Government of BC for similar types of projects.[48]

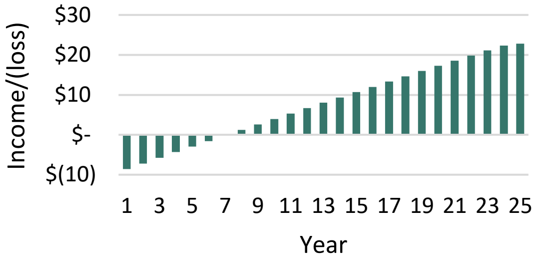
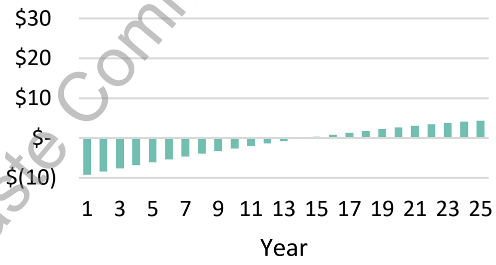
The value of digestate is highly variable and dependent on its properties (e.g. carbon/nitrogen, heavy metal and pathogen content). It was estimated that 87% of the original feedstock would remain after AD, and a low monetary value of \$0.63/t was assigned.[49] In terms of income, a zero value was assumed as part of the payback scenario, although it would be valuable as a fertilizer and could potentially be used to offset manure collection costs.

2.10.3. AD payback periods

The length of the payback period and feasibility of the project is dependent on the amount of CH_4 generated and operating costs. All the scenarios shown here (Table 5) assume carbon credits. The payback period using manure as a co-digestion feedstock would be seventeen years assuming a low operating cost of \$26/t. Fescue is the desirable feedstock to use; even at \$50/t operating cost, the payback period would be 15 years. The upper operating cost limit is ~\$55/t. Assuming an operating cost

Table 5. Payback periods for a centralized AD facility.
Four scenarios illustrating the expected payback period based on varying operating costs ($/tonne)

Manure with carbon offsets	
$26/tonne	$30/tonne
	
17-year payback period	23-year payback period

Fescue with carbon offsets	
$26/tonne	$50/tonne
	
8-year payback period	12- to 14-year payback period

of $30/t, payback would be possible in 8-10 years. Payback may be even shorter considering the lower limit for biogas potential from food waste was assumed.

2.10.4. Anaerobic digestion conclusions

Anaerobic digestion is sensitive to the availability of consistent, homogeneous feedstock. Operating costs and methane production potential will determine the facility's feasibility. Operating costs of $26/tonne, which is similar to a facility processing cattle manure in Alberta, would lead to a feedback period of seventeen years. Not considered here is that the use of cattle manure may lead to additional carbon credits.

Fescue, with 4.5 times the biogas potential of manure, would be an excellent feedstock for AD. Additional costs, which have not been assessed here, may arise for the pre-treatment of lignin content in the grass. The PRRD has indicated that a suitable arrangement for an AD facility would be for a third party operator to be responsible for the facility, with the facility located at the Bessborough site and a leasing agreement used. This would put the onus on the operator to reduce the operating costs.

A previous call for proposals resulted in two responses, one of which indicated a concern regarding feedstock availability. A pro-active approach to securing feedstock by approaching suppliers in proximity to the site and obtaining letters of intent may be obvious, but would likely improve third party interest by creating the necessary network connections for an outside entity. Environmentally, AD is remains the best solution for food waste.

3. Materials recycling

For materials recovery, MSW needs to be sorted. Typical categories for ICI and SFR waste sorting include paper, metals, glass and hard plastics. The paper category is further divided into MWP, old corrugated cardboard (OCC), and possibly newsprint. The plastics category is divided into hard (rigid) and film plastics. Hard plastics include all categories (Table 6), mixtures thereof, and other materials. Single-polymer films are usually LDPE.

The diversion of plastics should be of particular concern because breakdown of plastics into microplastics (<5 mm) leads to negative health impacts and amplification through the food chain.[50–52] Landfilling should be considered as the last option because of their higher environmental impact than other MSW disposal routes, including incineration and gasification.[52]

Table 6. Plastic types by category.

Cat.	Type	Abb.
1	Polyethylene terephthalate	PET
2	High-density polyethylene	HDPE
3	Polyvinyl chloride	PVC
4	Low-density polyethylene	LDPE
5	Polypropylene	PP
6	Polystyrene (Styrofoam)	PS
7	Other	

Cat.: Category; Abb.: Abbreviation

Single polymer films include agricultural bale wrap or greenhouse films. Multi-layer plastics are typically found in the food industry (e.g. potato chip bags). Multiple types of plastics may be used in food wraps and may include a metal (aluminum) layer, all of which are laminated together using a variety of adhesives.[53] Food packaging is complex and often destined for the landfill.

The objective was to determine the feasibility of a materials recovery facility (MRF) that will primarily divert SFR and ICI waste from landfilling. A further objective, from both an environmental and economic perspective, was to determine the economic opportunity for processing hard plastics in the PPRD.

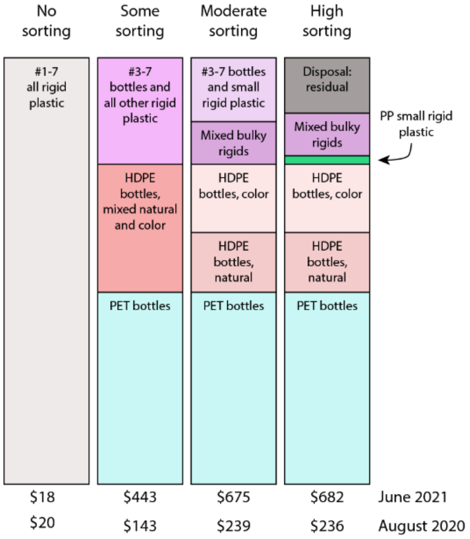
3.4. Plastics recovery

Two processes may be used for recycling of plastics: WtE or mechanical recycling. The WtE route has already been discussed (*Pyrolysis of organic wastes*, page 9), and has the benefit of handling all film plastics and mixed hard plastics of all categories, if provisions are in place for PVC. The other, more common route used in Canada, is mechanical recycling.[36]

The objective of mechanical recycling is to reuse the plastic in similar or new applications. The plastics are separated into their respective categories (Table 6), washed, ground into flakes and extruded into pellets. Their end use will depend on the purity and quality of the pellets. Mechanical recycling leads to *downcycling*, meaning the quality of the plastic decreases with each round of processing, unless chemical additives are used (*upcycling*).

Sorting of plastics into their respective categories (Table 6) is required due to incompatibilities between polymer types.[54] Typically, the focus is on the thermoplastics PET, PE, and PP because they may be melted and reshaped. These plastics may be further divided into PET clear, PET colored or green, HDPE natural color (NC; white), and HDPE mixed color (MC).

The value of sorting plastics is shown in Figure 6. Of note is that minimal sorting into categories has a significant impact on bale prices. The other point of note is



Prices in USD per US ton based on material prices per pound.
Source: plasticsrecycling.org (Association of Plastic Recyclers)

Figure 6. Sorted plastic bale prices. Bale values in USD per US ton based on the amount of sorting performed prior to baling. Values from August 2020 (left) and June 2021 (right) are shown.

that the plastics market fluctuates considerably, as is evident in the difference between August 2020 and June 2021 prices. Furthermore, market values are highly dependent on regional and local market conditions, and loosely associated with crude oil prices, and affected by policy.

3.5. The PRRD situation

The success of a MRF is dependent on the ICI sector. The ICI sector is expected to provide the majority of recyclables (Figure 7), quantities of which were estimated based on the Four Season Waste Composition Study.[24] The study only took into account waste entering landfills, so other recycling activities by the ICI sector are unaccounted for.

For the CCR stream, the current practice in the PRRD is to bale residential recyclables and ship the bales out of region (e.g. Vancouver, Calgary) for sorting and further processing. The process is contracted to a third party (R3 Residential Recycling). Market and shipping costs are highly variable, and thus difficult to project, as the market is, in part, policy-driven. A summary of residential recycling costs is shown in Figure 8. The CCR and hard plastics streams are the most revenue negative per tonne of material. The unsorted CCR stream cost the PRRD $200 000 in 2020; hard plastics cost $30 000. Transfer station (TS) quantities were also included herein along with the CCR stream and the ICI sector.

Whether mechanical recycling or WtE is selected as a processing method for plastic waste, a pre-sort is required. A MRF allows for sorting at 0.75 tph per sorter, which is higher than manual sorting without a MRF (~0.4 tph). The economic feasibility of a MRF was examined. As plastic waste is one of the most promising streams to generate revenue (OCC is the other), a more in-depth analysis of plastic was performed than other recyclable materials. The plastics stream is also more complex than other streams (glass, paper, metals), due to the wide range of polymers used.

Little is known about the composition of the CCR stream, and limited information was available on the nature of the plastics in the ICI sector waste. A more detailed accounting of assumptions regarding composition and quantities is provided in the *Supplemental* section *Recyclables in the PRRD* on page S-9.

3.6. MRF capital and operating costs

A cost estimate for a 8 400 t/year MRF was performed (Table 7). The estimate is for a basic semi-automated sorting line. Most of the sorting is performed manually using a conveyor belt system; however, some automation is used to remove paper (eddy currents) and magnets to remove ferromagnetic metals. The assumption was that the sorting line operates 7 hours/day, 5 days/week and 48 weeks/year, which results in a processing rate of 5 tph. A 5 tph MRF is considered very small and at the lower limit of technology that exceeds using a simple conveyor belt. Cost of land was not included.

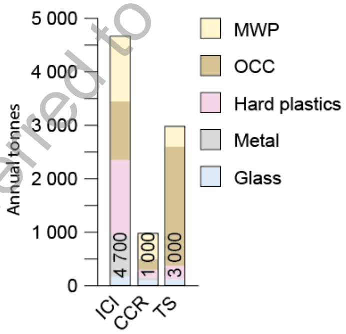


Figure 7. Recyclable quantities in the PRRD.

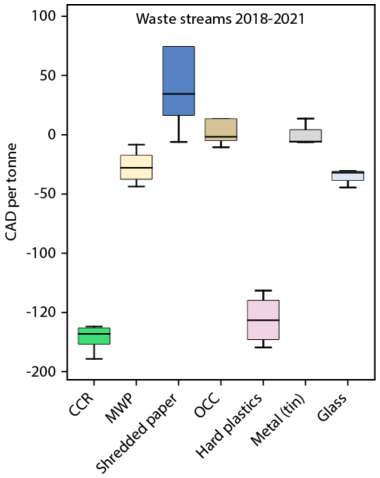


Figure 8. Summary of PRRD recycling stream revenues (2018-Feb. 2021).

Table 7. Capital and operating expenses of a 8 400 t/year MRF.

Employees		
Employee[56]		Cost
Type	Qty	Year 1
Sorter	6	$248 000
Equip. operator	1	$125 000
Maintenance	1	$63 000
Management	1	$73 000
Plastics processor	2	$71 000
Total	9	$580 000
25-year total		$18 600 000
Rolling stock		
Small loader	1	$125 000
Forklift	1	$43 000
Skidsteer	1	$65 000
Total		$233 000
Capital cost		
Building (50 000 ft^2)		$7 500 000
Sorting equipment		$6 500 000
Pelletizing equipment		$2 000 000
Total		$16 000 000
Energy		
Heating		$72,000
Electricity		$200,000
Total		$272 000
25-year total		$41 633 000

The required floor space was estimated at 50 000 ft^2, which includes an indoor tipping floor. The space is large enough to allow for expansion of the sorting line to more than 10 tph under the same operating hours. The cost of expansion would be minimal compared to the initial capex, involving some added labor and insertion of additional equipment into the single sorting line. Discussions with one of the equipment providers (Machinex, a Quebec company) confirmed this to be the case. As the facility operates on an economy of scale, there should be a drive to increase the amount of material processed. Additional material may be handled through expansion of equipment and/or operating hours.

Labor is a major expense and is based on only operating 7 hours/day and 5 days/week. Expansion of processing ability is possible by increasing the number of sorters. Larger sorting lines (e.g. >10 tph) usually include further automation, such as near-infrared sensors that sort plastic, which would reduce labor costs per tonne of material.

Labor rates were estimated from as low as $17/hour for sorters to $35/hour for management, and 2% inflation was added annually. A feasibility study performed by the City of Lethbridge,[55] which began its MRF under similar processing quantity conditions, indicated the best operating scenario was for the city to put up the capital for the facilities and hire a third party with experience in the industry to keep labor costs lower than by employing city workers. Additional information on fixed and variable MRF costs is provided in the *Supplemental* section *Materials recovery facility* on page on page S-8.

3.7. Sorted materials revenue

The amount of CCR available for sorting was based on data provided by the PRRD for 2020. The distribution of recyclable materials (paper, glass, metals, plastics) in the CCR stream was estimated using the 2020 Recycle BC Annual Report.[57] The Recycle BC report categorizes recyclables into paper and plastics, but does not further subcategorize paper into OCC and MWP, nor plastics into HDPE, PET, etc. An Alberta study[58] on the composition of CCR was used to estimate the paper stream composition; a US study was used to estimate the composition of plastics.[59] The Four Season Waste Composition Study[24] was not used to identify SFR material suitable for recycling being landfilled. The assumption was that residents already have easy access to curbside programs in Dawson Creek and Fort St. John and material found in the SFR landfill stream was due either to the material not being suitable for recycling or a lack of recycling effort.

Transfer station data were used as provided by the PRRD for the year 2020. The 2020 rates paid by the PRRD for bringing TS recyclables to market and shipping were used for materials from the ICI sector and the CCR stream. The rates vary on a monthly basis, so rates had to be approximated (*Supplemental*, *CCR and TS streams*, page S-9).

Table 8. Estimated MRF revenue for recyclables from CCR, TS and ICI sectors.

	Tonnes	Revenue[d]
Paper[a]		
MWP	*2 069*	*-$85 000*
OCC	*3 525*	*$69 000*
Total	5 594	-$16 000

Rigid plastic[b]		Baled		Pellets[e]
		Mixed	Sorted	
PET (incl. non bottle) clear[c]	*186.2*	*-$35,000*	*$97 000*	*$277 000*
PET (incl. non bottle) green	*242.5*			*$125 000*
HDPE NC	*94.4*		*$156 000*	*$323 000*
HDPE MC	*109.1*			*$253 000*
PP	*268.2*		*$88 000*	*$252 000*
Other plastics 3-7	*89.0*		*-$3 000*	
Bulky rigid plastics	*807.5*		*-$15 000*	
Total	1797	-$35 000	$323 000	$1 212 000

Metal	808	$74 000
Glass	389	-$12 000
Residue	174	-$13 000

Annual total	8 762	-$2 000	$356 000	$1 245 000
25-year total	219 057	-$50 000	$8 900 000	$31 125 000

For the ICI sector, The Four Season Waste Composition Study[24] was relied upon to provide information on the distribution of paper types (MWP, OCC), metals and glass. For plastics, a Vancouver study on ICI waste was used to determine distribution of plastics categories.[60] Disposal of residues were not considered for the ICI stream as these would be passed on as tipping fees potentially.

Using studies non-specific to the PRRD may not be representative of actual distributions. For residential waste, the distribution of plastic is highly influenced by deposit programs. For the ICI sector, the types of businesses operating in the region will heavily influence the plastics distribution. A cross-sector average reported in the Vancouver ICI waste study was used; however, the study may, for example, contain a disproportionate amount of restaurant waste compared to industrial waste, which will affect the distribution of HDPE, PP, and PET. Further analysis of the ICI sector recyclables available in the PRRD, as well as the composition of CCR, would provide a more precise estimate.

A summary of estimated revenue from sorted materials is provided in Table 8. The degree of sorting heavily influences the value of plastics, with the value further increased by sorting into color categories. Clear PET and HDPE NC (white) usually have a higher return than colored pellets. It should also be noted that recent changes to milk jug recycling will influence the quantities of HDPE NC available; the deposit system now in place in BC would be expected to decrease quantities. Pelletizing will require dedicated washing and extrusion equipment for each plastic type. For this reason, a more detailed breakdown of various plastic types would be beneficial to determine which plastics could be pelletized.

3.8. Materials recycling conclusions

At a scale of 8 400 t/year, there is a shortfall of revenue (Table 9) compared to expenses. While variable expenses have been estimated at the higher end of the range, a scaling up of the sorting process would be beneficial. For example, a 13 000 t/year facility would be expected to have a cost of ~$50 million over 25 years. At 13 000 t/year, the facility closer to breaking even with increased plastics revenue from pelletizing as is projected to be profitable with 16 800 t/year.

Opportunities exist to obtain more source-separated recyclables. These include receiving material from Grande Prairie (population 63 166 (2016)) and Prince George (74 003 (2016)), which could effectively double to triple processing capacity for the region, with the caveat that residuals will require landfilling. Recyclables brought to regional Return-It (Encorp Pacific) may also be available for purchase and pelletizing; an estimated 221 t of plastic was collected in the region in 2020.[61]

Table 9. Estimated MRF revenue for recyclables from CCR, TS and ICI sectors by scale. Economies of scale: Doubling of capacity from 8 400 t/year to 16 8000 t/year over 25 years is expected to revenue positive. Expenses are over 25 years, revenue has been indicated as annual and 25-year based on Table 8 pellet values.

	8 400 t/yr		13 000 t/yr		16 800 t/yr	
	Expenses	Revenue	Expenses	Revenue	Expenses	Revenue
Annual	$41 633 000	$1 245 000	$50 516 000	$1 926 000	$57 100 000	$2 490 000
25-year		$31 125 000		$48 100 000		$62 200 000
Net	-$10 508 000		-$2 416 000		$5 100 000	

See Supplemental (page S-12) and white paper for more information on assumptions. Expenses are over 25 years and include capital costs and labor (2% inflation/year). Revenue was assumed flat over 25 years and was based on the 8 400 t/year (pellets) in Table 8.

4. Summary

Scale remains an issue for the PRRD, which is not easily overcome. AD remains the best and most environmentally-friendly option for food waste if feedstock issues can be addressed, but would be need to be coupled with composting to address green waste. The issue of obtaining additional feedstock such as cattle manure will be challenging. The economics for the AD facility showed the greatest promise of cost recovery and was the only waste diversion option that indicated postive revenue over 25 years.

Pyrolysis is convenient, fast and may generate bio-fuels, but is not very well suited to food waste due to energy-intensive drying processes. Pyrolysis does, however, address the issue of recycling mixed plastic waste, food packaging and contaminated wastes, which makes the process very convenient and the most effective method for diverting waste from landfilling. If the ratio of a high energy feedstock such as plastic to food waste can be increased, the biofuel production potential will lead to more favorable economic outcomes. Success would hinge on primarily non-food waste as feedstock and obtaining additional plastics than quantities calculated here for the SFR, TS and ICI sectors. Some degree of materials separation may still be necessary, but the primary source of feedstock would be from the ICI sector, upon which the burden could fall.

The MRF at a scale of 8 400 t/year would be revenue negative, but could become postive by doubling processing capacity, which will have a minimal effect on capex and labor costs versus increased income.

4.4. A way forward

It is the opinion of this review that pro-actively ensuring the availability of organic feedstocks for AD there is a reasonably good possibility the PRRD will be successful in finding a third party interested in operating a centralized AD facility. Without the assurance of feedstock, investment may appear too risky considering the requirement for consistent, homogenous quantities of organics. Manure was initially proposed at a co-digestion feedstock with food waste, after discussion with the PRRD Board of Directors, the availability of fescue as a co-digestion feedstock should be examined further. Fescue has a higher CH_4 yield than manure and may prove to be easier to collect.

Pyrolysis is an option that should be further explored. A better estimate of scale quality/quantity of fuel output could be made if more precise plastics quantities are known. This would include surveying the ICI sector on current practices. Recycle BC should also be consulted to see what arrangements could be made for pyrolyzing PRRD plastics, as well as plastics from outside the region that are currently being shipped long distances to major centers. The approval of a pyrolysis project may hinge on illustrating to the Government of British Columbia a positive environmental carbon and energy balance.

4.5. Additional options

The simplest option would be to compost green and food waste. Basic sorting of the CCR stream could be performed for cost recovery, and would be assumed to improve market value of recyclables and reducing overall costs for the PRRD. A sorting system for ICI waste could be implemented that would allow for segregated landfilling of materials for future processing when the economics are more favorable.

There is also the possibility of establishing a pilot project with either an industrial partner and/or post-secondary institution (college/university). A pilot scale pyrolysis or similar technology will be able to address some of the PRRD's diversion needs while opening the door to funding through research grants and providing insight into the effectiveness of such facilities.

Supplemental

The supplemental section provides additional supporting information for the respective sections in the main document. This includes more information on assumptions, information sources and how some of the values were determined. For a complete breakdown of calculations, please see the accompanying white paper.

S1. Scaling of facilities and costs

A commonly applied equation for scaling fixed costs was used in this report:[32]

$$E_2 = E_1 \cdot \left({}^{C_2}/_{C_1}\right)^{\propto}$$

The α is the scaling factor (usually 0.6 or 0.7; set to 0.6 here), C_1 and C_2 are conditions 1 & 2, respectively, E_1 is the outcome for condition 1, and E_2 the new outcome.

The general approach was to establish the capex for a specific sized facility and then scale according to needs (e.g. tonnage). For example, if the cost of an AD facility was determined to be $5 000 000 ($E_1$) with a capacity of 20 000 t/year (C_1), the cost (E_2) of a 30 000 t/year (C_2) could be estimated. The approach was loosely applied to variable costs as well, but not in all cases. For example, only one scale attendant may be needed at a landfill at any given time regardless of 2 000 t or 4 000 t of waste.

S2. Pyrolysis

The calculations for the cost of pyrolysis were based on a recent small-scale pyrolysis processing facility operating 24 hours/day, processing 10 t/day of feedstock with 8% moisture content. The three options considered in this section were separate buildings for Fort St. John ("FSJ") and Dawson Creek ("DC"); a single, combined plant processing the same tonnage as Fort St. John and Dawson Creek ("Combined"); and a combined plant with plastic waste available from the SFR, ICI, TS and SH sectors added ("w/ plastics").

S2.1. Fixed costs

Pyrolysis costs were estimated based on published values for an outdoor 10 t/day setup using biomass already dried to 8% moisture (Table S-1).[37] The cost of dewatering and drying equipment, and building costs were added.

Table S-1. Estimated capital costs for fast pyrolysis.
Building size requirements and equipment costs for a pyrolysis facility.

	Tonnage		Building		Other*	Pyrolysis	Total
	per day	per year	Size (ft^2)	Cost			
Fort St. John (FSJ)	4	1 184	4 300	$660 000	$230 000	$1 302 000	$2 200 000
Dawson Creek (DC)	4	962	3 900	$585 000	$203 000	$1 150 000	$2 000 000
Combined	8	2 146	6 300	$945 000	$328 000	$1 860 000	$3 200 000
w/ plastics	17	5 051	10 400	$1 560 000	$549 000	$3 109 000	$5 300 000

* Includes: Shredder, storage tanks, dewatering, dryer, civil work and miscellaneous items.

It was assumed pyrolysis equipment would be used indoors in the PRRD due to the climate. A warehouse-type structure was assumed. An 8-10 t/day unit may require about 5 000-6 000 ft^2 of space with room for operation and possible indoor tipping. The dimensions of a 10 t/day commercially available unit was used to estimate floor space, to which 30% additional square footage was added. An additional 100 ft^2 was added for a drying unit. Building sizes reflect scaling according to estimated tonnes per day for each facility. Buildings were assumed to be square for the purpose of calculating heat, and having 15-ft ceilings. The construction cost was set to $150/ft^2. The actual dimensions and costs may vary considerably.

S2.2. Variable costs

Variable costs were divided into process costs (dewatering, drying and pyrolysis), labor, maintenance and chemicals (e.g. nitrogen), and building (electricity and heat). Labor was based on a $20/hour wage without additional associated employment costs (annual salary of $41 600). The number of workers was estimated as 3 workers/1000 t for dry processing (8% moisture) and plastics , and 3.5 workers/1000 t for wet processing (e.g. food waste, biomass). Yearly maintenance was based on 2% of capex.[37] Chemical and nitrogen costs were based on $16 000 and $12 000 per 3 000 annual tonnes, and scaled according to the facility tonnage (Table S-1). A cost summary is provided in Table S-2.

Table S-2. Non-electricity and heating pyrolysis variable costs.
Estimated year-1 costs for a pyrolysis plant. 25-year costs were subjected to 2% annual inflation.

	Workers						
	Dry	Wet	Cost	Maintenance	Chemicals	Nitrogen	Total
Fort St. John (FSJ)	0	4	$166 400	$42 000	$300 000	$5 700	$218 400
Dawson Creek (DC)	0	3	$124 800	$38 000	$275 000	$4 600	$170 900
Combined	0	7	$291 200	$60 000	$429 000	$10 200	$369 100
w/ plastics	9	16	$665 600	$102 000	$656 000	$25 700	$812 600

Variable process costs are dependent on energy usage of the equipment and energy type. Rates were calculated according to the rate list in the *Appendix* (*Electricity and natural gas rates*, page A-1). Dewatering was not required for plastics, nor was drying. Dewatering assumed a moisture reduction to 60% from 85%. For the FSJ and DC separate plants, smaller dewatering (7.5 kW, 40 t/day) equipment was assumed than for the combined plant (11 kW, 70 t/day). The estimated annual costs are summarized in Table S-3.

Table S-3. Annual electricity costs for dewatering of food and green waste.

	t/day	kW	kWh/year	Cost*
Fort St. John (FSJ)	24.2	4.54	32 668	$2 000
Dawson Creek (DC)	19.7	3.69	26 553	$1 600
Combined	43.9	6.89	49 633	$4 800
w/ plastics	43.9	6.89	49 633	$4 800

* Annual kWh hours only, no demand charge, large business rate.

The drying process was based on a rotating dryer that uses natural gas for drying; no electricity cost was added (Table S-4). A variety of dryer types are available, and are based on the daily tonnage to be dried. No explicit value for food waste drying could be found; however, the energy required (3.1 GJ/t wet) to dry wood chips (~50-60% moisture) was used,[19] although the post-drying moisture content was not specified. The drying process was assumed to reduce moisture content from 60% to 8%.

Table S-4. Annual natural gas costs for drying biomass.

	Tonnage			
	Wet	Dry	GJ	Cost
Fort St. John (FSJ)	2 722	1 184	8 439	$55 100
Dawson Creek (DC)	2 216	962	6 870	$44 900
Combined	4 938	2 146	15 309	$100 000
w/ plastics	4 938	2 146	15 309	$100 000

The final pyrolysis step cost was based on biomass with a moisture content of 8% and contains both an electrical component and a thermal component (Table S-5). The electrical component was based on usage of 240 kWh/t, and the thermal component on 873 kWh/t.[37] These numbers may vary considerably depending on the system, and features such as recirculating heat or natural gas used for drying. Commonly, the syngas is recirculated to offset thermal energy costs.

Table S-5. Annual electricity costs for pyrolysis of waste.

	Tonnes	kWh/year	Cost*
Fort St. John (FSJ)	1 184	1 317 381	$79 400
Dawson Creek (DC)	962	1 070 766	$64 500
Combined	2 146	2 388 147	$143 800
w/ plastics	5 051	5 621 301	$338 500

* Annual kWh hours only, no demand charge, large business rate.

The building variable costs included estimates for electricity and heating. Electricity estimates included lighting and miscellaneous electricity usage, and heating was based on cubic feet of space for each facility. See *Estimation of building heating costs* on page A-1 in the *Appendix* for more information on how heating costs were estimated. Heating cost estimates are provided in Table S-6.

Table S-6. Annual pyrolysis facility heating costs.

	ft^2	BTU/°C	GJ/year	Cost
Fort St. John (FSJ)	4 400	5 713	896	$5 900
Dawson Creek (DC)	3 900	5 314	852	$5 600
Combined	6 300	7 595	1 191	$7 800
w/ plastics	10 400	11 613	1 820	$11 900

It was assumed that building lighting and power usage remained constant 24 hours/day. The estimated power usage is summarized in Table S-7.

Table S-7. Annual pyrolysis facility electricity usage.

		kWh		
	ft^2	Lighting	Other	Total
Fort St. John (FSJ)	4 400	10 519	43 830	54 349
Dawson Creek (DC)	3 900	9 204	43 830	53 034
Combined	6 300	14 464	65 745	80 209
w/ plastics	10 400	22 353	87 660	110 013

A summary of electricity charges is provided in Table S-8 and assumed power draw (kW).

Table S-8. Summary of annual pyrolysis facility electricity costs. Costs based on large business rate due to high kWh/year and demand (kW).

			Cost		
	kWh	kW	kWh	Demand*	Total
Fort St. John (FSJ)	1 225 781	31	$78 900	$5 900	$84 000
Dawson Creek (DC)	1 004 928	30	$65 600	$5 600	$70 700
Combined	2 204 849	42	$139 500	$7 800	$146 300
w/ plastics	3 189 177	54	$200 100	$11 900	$208 200

* Includes the BC Hydro daily rate.

A summary of natural gas charges is provided in Table S-9.

Table S-9. Summary of annual pyrolysis facility natural gas costs.

		Cost		
	GJ	GJ	Monthly*	Total
Fort St. John (FSJ)	9 335	$61 000	$4 920	$84 000
Dawson Creek (DC)	7 722	$50 500		$70 700
Combined	17 129	$111 900		$146 300
w/ plastics	17 129	$111 900		$208 200

* Monthly basic charge of $410 x 12 months by PNG.

S2.3. Energy balance

The energy yield of bio-oil, biochar and syngas varies depending on feedstock and operating conditions for pyrolysis equipment. Published values for specific processes were used as an estimation (Table S-10); however, for biomass, for example, energy recovery may be as high as 30 GJ/t. Syngas from plastics may have an energy value as high as 50 GJ/t.[21] For reference, natural gas has a value of 52 GJ/t.

Table S-10. Energy values for pyrolysis products. Values listed under "Average" were used. Co-pyrolysis refers to a mixture of biomass with plastics.

	Energy value (GJ/t)		
	Low	High	Average
Bio-oil[21]			
Biomass	15	20	17.5
Plastic			36.6
Co-pyrolysis	41.3	46.4	43.9
Biochar[62]			13.25
Syngas[37]			11.9

Table S-11. Feedstock-dependent distribution of pyrolysis products.

	Food waste	Plastics
Gas	29%	34%
Bio-oil	46%	65%
Biochar	25%	1%

The distribution of bio-oil, char and syngas varies according to pyrolysis techniques and equipment. Estimates were based on reported values[21] (Table S-10). The ratio of plastics to biomass will affect the distribution; generally, the higher the plastic content, the more liquid is produced.[63]

The energy recovery was based on the distribution in Table S-11 and was calculated according to the number of dry tonnes of available food waste as listed in Table S-5, less the 8% moisture content. The plastics content was based on the tonnage of estimated plastics (2 905 t) from the CCR, TS, SH and ICI sectors. A summary is provided in Table S-12.

Table S-12. Energy recovery of food and plastics waste via pyrolysis.

	Total tonnes	Syngas		Bio-oil		Biochar	
		tonnes	GJ	tonnes	GJ	tonnes	GJ
Food/green	1 974	572	6 807	908	15 891	494	6 539
Plastics	2 905	988	11 743	1 894	22 520	23	276
Total		1 560	18 550	2 802	38 411	517	6 815

S2.4. Bio-oil value

Biofuels that are produced via pyrolysis will vary in moisture content, energy value, density and absolute composition. It was assumed that 63 700 GJ of energy were produced from pyrolysis of food waste and plastics combined. About 28 100 GJ of energy were assumed to remain in the form of biofuel with the remainder (syngas and biochar) having been used for the drying and pyrolysis processes.

The energy value of the biofuel was considered to be 40 GJ/t, and it was assumed the biofuel had a density of 1 g/mL; petroleum diesel has a typical density of 0.85 g/mL, and biofuels may be up to 1.3 g/mL or more. This resulted in 702.5 t of biofuel. The assumption was made that 80% could be recovered after drying and distillation, resulting in 562 000 L with a value of $1.25/L, resulting in a net value of $17.5 million over 25 years.

S3. Anaerobic digestion

The following sections include additional information on the AD process.

S3.1. Fixed costs

The costs of AD facilities vary widely. The general approach, exclusive of land but inclusive of CHP technology, is to estimate the cost per tonne processed annually. A 25 000 t/year plant built by GrowTEC in Chin, AB, in 2014 for $7.2 million with a CHP was used as a point of reference after reviewing the costs of several other facilities in Canada. In 2021 dollars, the cost to build the plant would be $331/t of feedstock, or ~$8.3 million, inclusive of the CHP. The estimate used for the PRRD was based on $350/t with a CHP ($8.75 million total). The capital cost of the plant provided in Table 4 is the predicted cost here less the cost of a CHP unit ($1.2 million). Other considerations not included here are additional storage and mixing facilities for feedstock, and rolling stock.

S3.2. Variable costs

Numerous methods may be used for estimating variable costs. The GrowTec plant in Chin, Alberta, reported operating costs of $555 000/year (2016) for a 25 000 t/year facility processing cattle manure.[44] Reported operating costs vary; the lowest reported costs was $40 CAD/t (2022 dollars) from a European study.[43]

Electricity and heating costs for the AD process and facility are provided in the next section. Although the preferred route is CH_4 upgrading and resale, the electricity and heating costs indicate the cost offsets if a CHP plant were used to heat and power the process and facility.

S3.2.1. Heating and electricity costs

The heating and electricity requirements were divided into the AD process and facility. Natural gas (heating) cost was based on PNG rates and electricity costs on BC Hydro small business rates (*Electricity and natural gas rates*, page A-1). For the AD process, electricity requirements have been estimated at 2% of total electricity generated by CHP, or 61 438 kWh. The annual cost was estimated at $7 831 for the kWh consumed using the BC Hydro small business rate (*Electricity and natural gas rates*, page A-1). The 25-year cost is $196 000.

Table S-13. AD facility variable costs.

	Annual	25-year
Labor[1]	$82 941	$2 657 000
AD process[2]		
Electricity	$7 831	$196 000
Heating	$32 169	$825 000
Facility		
Electricity	$3 638	$91 000
Heating	$12 500	$313 000
Total	$140 000	$4 100 000

[1] Year 1 value; 2% annual inflation added in subsequent years.
[2] Daily charges for BC Hydro and monthly fees for PNG included.

The heat requirements for AD have been estimated at 25% of the total heat output from a CHP.[64] The total output was estimated to be 13 914 GJ/year. The percent was increased to 30% to account for the cold climate, with 4 174 GJ/year required. The total annual cost was estimated to be $32 169 for natural gas (*Electricity and natural gas rates*, page A-1), with the 25-year total of $825 000.

Building operating time was assumed to be 10 hours/day, 5 days/week. Electricity usage was assumed to be 25% of operating usage during standby times. For heating, it was assumed that operating conditions indoors were 20°C and standby 15°C.

Building electricity requirements were divided into lighting and ‘other’. Lighting requirements were assumed to be 150 W/630 ft^2 for a total of 3.1 kW. ‘Other’ was assumed to include operating use such as computers, and was assigned a value of 3 kW. Total usage was 6.1 kW, rounded to 7 kW. The annual cost was estimated to be $3 638, and the 25-year total rounded to $91 000.

Building heating costs were based on a structure measuring about 131 ft by 98 ft and a ceiling height of 15 ft, with the building located in Dawson Creek. Calculations were performed as described in *Estimation of building heating costs* on page A-1. Annual heating costs were estimated to be $12 500 with the 25-year total $313 000.

The small business rate from BC Hydro does not include a demand charge. However, a daily charge is added, which was $133.10 per year. PNG also has a flat rate charge for natural gas, which was $4 920 annually. The additional service charges were combined with the respective costs for the AD process. A summary of variable expenses is provided in Table S-13. Note that not all variable costs have been included, such as maintenance and insurance.

S3.3. Biogas and methane production

The amount of biogas and CH_4 content of the biogas for a variety of feedstocks is summarized in Table S-14. It was assumed that beef cattle manure produced 32.5 m^3/t of biogas with 53% CH_4 content. Household waste (food waste) was assumed to produce 143 m^3/t with 56% CH_4 content. Note that the 143 m^3/t is on the low end of the spectrum. The total biogas produced from 9 000 t/year of food waste and 16 000 t/year of beef cattle manure was estimated at 1 807 000 m^3/year. The methane content was estimated to be 999 320 m^3/year.

S3.4. Energy and heat production

One of the options for AD is to generate heat and power directly from the syngas, which consists mostly of CH_4 and CO_2, but also contains small amounts of hydrogen (H_2) and hydrogen sulfide (H_2S). The syngas may be used directly in a CHP application, but the H_2S will shorten the CHP life expectancy. The heat generated is typically used to heat the immediate facilities, provide heat for the AD process, with the remainder possibly used in a district heating application. Electricity is similarly used for immediate facilities and processes, while the balance is sold to the grid.

The estimated amount of annual electricity produced was calculated as 280 kW based on 8 000 hours of operation (91% uptime), typical of AD plants. A conservative estimate was used and it was assumed that only 80% of the biogas predicted in section S3.3 was available for both heat and electricity generation. The last listed base price for electricity purchase by BC Hydro for the Peace Region was $102.06/MWh in 2016 when a program was still available.[42] The value of the electricity (2 458 MWh) is thus estimated at

Table S-14. Biogas and methane yield of feedstocks. Yields are dependent on feedstock composition and reactor conditions.[46]

Feedstock	Biogas yield m^3/tonne	CH_4 content (%)
Beef cattle manure	19-46	53
Hog manure-grower to finisher	28-46	58
Dairy manure	25-32	54
Poultry manure	69-96	60
Animal fat	801-837	N/A
Animal carcass (bovine, homogenized)	348-413	N/A
Municipal wastewater sludge	17-140	65
Household waste[i]	143-214	56[47]
Grass silage (wet)	186[38]/153[ii]	N/A

[i] CH_4 content was N/A for the Government of Alberta pamphlet from which the above values were sourced. Value for full-scale AD reactor with source separated fraction. [ii]Value used for estimate of CH_4 from fescue in this report based on data reported by Zhang et al. (2021).[39]

$250 000/year with a 25-year total of $6.25 million assuming a flat rate.

The generated heat could only offset heating requirements of infrastructure located at the Bessborough site. Assuming a PNG rate of $6.528/GJ (Apr. 2022 rate) applied to 11 131 GJ/year of heat produced, the total savings would be ~$72 600/year with a 25-year total of $1.81 million. The combined heat and electricity savings would be $8.06 million over 25 years.

Details for estimating the cost of the CHP plant may be found in the white paper. The cost is based on the amount of biogas produced. The amount of biogas predicted in section S3.3 was used, for a CHP estimate of $1.2 million. A 30% increase in the cost was added to account for potential higher CH_4 production as a low value for biogas from food waste and an average value for biogas from manure was used. The resulting CHP cost was $1.6 million.

S3.5. Methane upgrading

The potential CH_4 sales listed in Table 4 were based on upgrading 80% of the biogas predicted in section S3.3. The energy predicted form the CH_4 was 30 129 GJ/year. At a modest flat rate of $25/GJ, the value of upgraded CH_4 was predicted to be $18.8 million over 25 years.

The cost of CH_4 upgrading was based on reported values from a European study, with prices varying depending on the technology employed. The upgrading costs are based on the amount of biogas produced. The amount of biogas predicted in section S3.3 was used, for an estimate of $1.1 million. A 30% increase in the cost was added to account for potential higher CH_4 production as a low value for biogas from food waste and an average value for biogas from manure was used. The resulting value was $1.5 million.

S3.6. Carbon offsets

The Government of BC offers a carbon offset purchasing program for approved projects.[48] The development of an AD facility would fall into the scope of projects listed in the Government of BC offset portfolio and would meet the sought after requirements. The offset price paid per tonne of CO_2 equivalents (CO_{2eq}) varies; however, a typical example of the amount paid includes landfill CH_4 capture for the Columbia Shuswap Regional district at $13/tonne and for the Fraser Fort George Regional District at $12.50/tonne.

Only the CH_4 produced from food waste was used to calculate the carbon offset value (section S3.3). Potential losses from the facility were subtracted, and the amount of CH_4 was further reduced to 80% to account for losses from transport and storage. The CH_4 volume was converted to $CO_{2(eq)}$ which resulted in a carbon credit estimate of $113 831 annually based on a rate of $12/t, giving the value shown in Table 4. A complete calculation is provided in the white paper.

S3.7. Digestate

The post-AD digestate is a value-added product that has been shown to be an excellent fertilizer for agricultural applications due to its highly available nutrient content (N, P, K) with the potential to replace inorganic fertilizers, producing similar or higher crop yields.[11,31,65] In Europe, 80-97% of the digestate is reused in agriculture.[66] The use of digestates in crop fertilization has seen enhanced crop productivity compared to the use of mineral fertilizers, with improved yields as high as 30%.[65] Overall, the digestate is considered of higher value than manure, because it generally has higher levels of plant-accessible nitrogen (ammonium, NH_4^+), and it may increase soil organic matter contents, leading to beneficial maintenance or improvement of soil quality.[30] The digestate generally has a high concentration of organic nitrogen, similar to that in ammonium fertilizers.[31] Additionally, other important micronutrients for agricultural applications, such as potash (potassium dioxide, K_2O) and phosphorus (phosphorus pentoxide, P_2O_5) are in high concentrations.[31] Nitrogen levels are often higher for the digestate than for composted organics; phosphorus and potassium levels are also comparable or higher than for compost,[31] and the digestate is possibly more hygienic than compost as the anaerobic process will destroy most pathogens.[64]

The digestate may be optimized according to crop type and to reduce nutrient run-off and leaching.[67] There are some drawbacks for the digestate, such as high levels of ammoniacal nitrogen (NH_4^+/NH_3) which increases the nutrient content but leads to NH_3 emissions when spreading, possible toxicity to plants,[68] and can release nitrates into the water, leading to eutrophication.[9] A reduction in NH_3 emissions is possible through the use of natural zeolites.[69]

Pathogens and heavy metal concentrations are a concern for both AD digestate and compost, with feedstock a factor in determining levels,[68,70] but co-digestion during AD can help in limiting the concentrations through dilution.[71] Pathogens may be reduced through appropriate temperature regimes (thermophilic[70]), and the toxicity of AD digestate may be balanced by adding the digestate to compost with a dried bulking agent[68] (e.g. wood fibers). Post-AD processing of digestate may also be performed to reduce the amount of liquid and obtain a desirable nutrient balance according to desired application.[67]

While the digestate has been assigned a value of zero for income purposes, the digestate and its nutrient value could be used as a bargaining implement when obtaining cattle manure.

S4. Materials recovery facility

A summary of the fixed and variable costs presented in Table 7 is provided in the following subsections.

S4.1. Fixed costs

Cost estimates were in part based on a feasibility study conducted for the City of Lethbridge (population 93 000) in 2015, with equipment supplied by Machinex, a Quebec company. The initial setup was to process 4-5 tph with an objective of 10 tph with a service area of 150 km. The projected facility cost was between \$11.4 and \$12.6 million, and ultimately cost \$7 million when completed in 2019.[72] It is not clear if cost included land, but approximately three acres were required. The 46 000 ft^2 facility is capable of sorting plastics into HDPE MC, HDPE NC and plastic #3-#7.

A similar size building was estimated for the PRRD with 45 000 ft^2 assumed for sorting and 5 000 ft^2 for pelletizing with a construction rate of \$150/ ft^2 for a warehouse-type structure. Discussions with a Machinex representative confirmed the assumed cost for a single semi-automated line. It was also confirmed expansion to 10 tph could be readily achieved within the space. Rolling stock needs were based on a cost modelling report (2012) prepared for Waste Diversion Ontario through the Continuous Improvement Fund that examined several types of MRF configurations.[56]

S4.2. Variable costs

The variable costs reported here are not exhaustive and may be as high as \$150/t[56] annually, putting the operating cost of a 8 400 t/year facility at \$1.26 million/year. Other variable costs that need to be considered are taxes, insurance and waste disposal. Some of these costs would be expected to be covered through the ICI stream in lieu of tipping fees, although it would be expected that MRF processing fees are higher than landfilling. Disposal costs would be minimal if the MRF is located at the Bessborough landfill site compared to facilities located in urban centers.

The rates used for labor are indicated in Table S-15. A scale operator was not included because siting at the Bessborough landfill assumed the use of current facilities and labor.

Heating costs were estimated based on a facility measuring 280 ft x 180 ft (50 400 ft^2). Heating costs depend on the insulating factor of the building, outside temperatures and the desired indoor temperature. Outdoor temperatures used according to monthly average temperatures for Dawson Creek, and indoor temperatures set to 20°C under operating conditions and 15°C for standby conditions. Operating times of 10

Table S-15. MRF labor rates.

	Hourly	Annual
Sorter (0.75 tph)	\$17	\$36 000
Equipment operator	\$30	\$63 000
Maintenance	\$30	\$63 000
Management	\$35	\$73 000
Plastics processing	\$17	\$36 000

hours/day, 5 days/week were assumed. Heating requirements were calculated using an online calculator (*Estimation of building heating costs*, page A-1) with an average value for *Poor* and *Normal* insulation conditions used.

Table S-16. MRF electricity usage.

	Max. kW	kWh/year
Building	22	49 778
Sorting equipment	188.8	515 815
Plastic washing	240	888 473
Plastic extruding	300	
Totals	750.8	1 486 312

Poor was used as part of the heat calculation because of the tipping floor and large door openings for delivery of materials. In some cases, tipping floors may be designated cold zones and separated from processing areas to reduce heat loss. Due to the cold climate, it was assumed that no cold zone existed. There may be alternatives available for building design to reduce heat loss further. It was also assumed that equipment and personnel did not contribute to heat generated in the building. A detailed analysis would consider these factors but is beyond the scope of this report.

A summary of electricity usage estimates is provided in Table S-16. Building power usage is for lighting and other (e.g. computers and office equipment, etc.). Sorting equipment power is based on a typical single-stream sorting line at 50% load.[73] Plastic washing and extruding is energy intensive, and was calculated according to specs for two washing lines and three extruders. The energy demand for washing and extrusion reflects maximum load; however, maximum load is unlikely. The final energy rates were calculated according to the annual kWh/year power usage (~$110 000) and the maximum kW draw ($89 000 per year) for a large commercial operation (*Electricity and natural gas rates*, page A-1).

S5. Recyclables in the PRRD

The three streams considered were CCR (commingled curbside recyclable), transfer station (TS) and ICI (industrial, commercial and institutional) waste. The following subsections provide information on material quantities and costs for each stream (CCR/TS and ICI) and plastic quantity estimates.

S5.1. CCR and TS streams

CCR and TS quantities were based on data provided by the PRRD for a range of years. Data for the year 2020 was used as representative for estimating tonnages, marketing and freight costs. As marketing and freight costs vary by shipment, assumptions were made regarding actual costs per tonne. A summary of 2020 values is provided in Table S-17.

Table S-17. Summary of 2020 PRRD tonnages and approximated costs. Freight and Market rates are on a per tonne basis.

	Stream	Tonnes	Freight	Market	Freight + market	Revenue
1.	CCR	1 162.2	$44	-$130	$-172	-$200 132
2.	MWP	379.1	$44	$3.25	-$40.75	-$15 449
3.	OCC	2221.4	$44	$47	$28.15	$31 913
4.	Hard plastic	237.9	$68	-$61	-$129	-$30 601
5.	Glass	117.8	$33	$13	-$30.56	-$3 600
6.	Metal	6.06	n/a	n/a	$92.70	-

Stream abbreviations. 1. CCR: Commingled curbside recycling; 2. MWP: Mixed waste paper; 3. OCC: Old corrugated cardboard.

A residue rate of 15% was assumed for the CCR stream, thereby reducing tonnage to 988 t/year (Table S-18). Composition of the CCR stream is not known, so the composition as reported by Recycle BC for CCR waste (2020) was used.[57] The Recycle BC report did not include a breakdown of paper and plastics into subcategories. An Alberta report on CCR waste estimated paper to consist of 32.9% newsprint, 29.5% OCC and 37.6% MWP. These values were used for the 663 t/year shown in Table S-18.

Table S-18. Composition of CCR according to Recycle BC (2020).

Category	%	Tonnes*
Paper	67.1	663
Rigid Plastic	14.7	145
Flexible Plastic	2.5	25
Metal	5.6	56
Glass	10.0	99
Total	100	988

* The PRRD tonnes were based on 2020 values for CCR of 1162.2 less 15% residue.

The newsprint and MWP categories were combined (467 t), although newsprint typically carries a higher market value than MWP.[74]

Table S-21. Plastics and paper composition in the CCR and TS streams in the PRRD.

	%	Tonnes	
		CCR	TS
Plastics[59]			
PET (incl. non bottle)	42	61.1	100.2
HDPE NC	7	10.4	17.1
HDPE MC	11	16.0	26.2
PP	12	16.8	28.1
Other plastics 3-7	12	17.2	27.6
Bulky rigid plastics	16	23.6	38.7
Total:	100	145.2	237.9
Paper[58]			
Newsprint	29.4	*218*	*187*
Mixed paper	30.3	*249*	*192*
MWP total	59.7	*467*	*379*
Cardboard/boxboard (OCC)	40.3	196	2 221
Total:	100	663	2 600

HDPE NC: High-density polyethylene natural color;
HDPE MC: High-density polyethylene mixed color

Plastic estimates were based on a 2020 evaluation of the CCR stream in the United States.[59] It was assumed that PET from drinking containers was not a large part of the material due to the deposit system in British Columbia, and thus was only from non-bottle sources. Polypropylene (PP) was not distinguished from hard plastics #3-#7 mentioned in the report. Hard plastics #3-#7 accounted for 24% of all plastics; it was assumed 12% was PP.

The TS stream was mostly assumed sorted with no residue. Hard plastic (Table S-17) was assumed to have the same distribution as for CCR, although this may be inaccurate. A summary of the tonnages for the CCR plastic and paper streams is provided in Table S-21.

Table S-19. ICI waste composition in the PRRD.

	Category	%	Tonnage
1	Paper	18.7	5 217
2	Plastic	13.1	3 655
3	Compostable org.	30.7	8 565
4	Non-compostable org.	6.5	1 814
5	Textiles	5.7	1 590
6	Metals	3.9	1 088
7	Glass	0.9	251
8	Building Mat.	6.2	1730
9	Elec. Waste	2.2	614
10	Household hazard	1.2	335
11	Household hygiene	2.6	725
12	Bulky objects	3.3	921
13	Agricultural waste	0	0
14	Unidentified	4.9	1 367
	Totals	100	27 872
		To sort:	10 211

org.: organic

Table S-20. Annual recyclable tonnes by category in the ICI sector (PRRD).
Numbers in italics represent subcategory values.

Material	%	Tonnes
Paper	51.1	3 576
MWP	*34.2*	*1 224*
OCC	*31.0*	*1 109*
Other	*34.8*	*1 243*
Plastic	35.8	2 506
Recyclable 1-7	*26.5*	664
Styrofoam	*4.5*	*115*
Film: recyclable	*7.6*	*191*
Film: other	*31.8*	*803*
Other rigid	*29.5*	*745*
Metals	10.7	746
Glass	2.5	172
Total	100	7 000

Table S-22. *Hard plastics by category in the ICI sector.*

Category[60]	% of total	Used %	Tonnes
PET: bottles and jars	6.7	20	133
PET: other packaging	13.3		
HDPE: bottles and jugs	26.7	40	266
HDPE: tubs and lids	13.3		
PVC	0.0		0
LDPE	0.0		0
PP	33.3	33.3	221
#7 mixed	6.7	6.7	44
Total	100	100	664

Table S-23. *Tonnage of plastics available from the ICI sector (PRRD) for pelletizing.*

		Tonnes	
Category	%	Total	Each
PET clear	50 clear	133	66.5
PET green			66.5
HDPE MC	38.9 NC	266	103.5
HDPE NC			162.5
PP	100	221	221
Total		664	664

S5.2. ICI stream

The ICI recyclable quantities available for sorting were strictly based on the Four Season Waste Composition Study[24] issued for the PRRD. The targeted materials for recycling were paper, plastics, metals and glass. The percentages for each category were provided in the waste study. A summary of the tonnages is provided in Table S-19 with the materials of interest highlighted in green. The materials comprised 10 211 t/year. It was assumed that 7 000 t/year (~68.5%) could be diverted to a MRF for sorting. Of the 7 000 t, however, a certain amount would be expected as residue.

The composition study further subcategorized paper and plastic. The details of how the tonnages were estimated for paper and plastic may be found in the accompanying white paper. A summary of the tonnages is provided in Table S-20. The green highlighted materials, and metals and glass, were assumed to be processed further, whereas those shown in red were assumed to be either landfilled or disposed of in some other way.

The plastics PP, HDPE and PET were of greatest interest for further processing. The *Recyclables 1-7* category in Table S-20 did not differentiate these plastics from other hard plastics, other than PS (Styrofoam). A Vancouver study on ICI waste was used to estimate the distribution of each plastic.[60] The assumed distributions are provided in Table S-22 and the results of subcategorizing the *Recyclables 1-7* in Table S-20 are provided in Table S-23.

S5.3. Market value of recyclables

The rates used for OCC, MWP, metal, and glass were those listed in Table S-17 and include freight and market costs. The rate for plastics varied depending on the degree of sorting. Sorting levels included mixed bales, sorted and then pellets. Bale values were based on the CIF reported averages for 2010-19 (Table S-24); 2021 and 2021 was not used because of exceptional market conditions due to the Covid-19 pandemic (see Figure S-5, page S-16). No value was provided for PP, so the value for PET was used.

An assumption that was made was that once PET, HDPE and PP were removed from the mixed plastics, the remaining tonnage was assigned a market value of $48.40 (Table S-24) and a freight value of -$67.77 (Table S-17) for a combined value of -$19.37/t. The remaining plastics may need to be landfilled rather than brought to market.

Accessing data for pellet prices was challenging without subscription to a market service. Pellet prices were obtained from Vecoplan AG (a recycling technology provider) via plasticsnews.com. The applied rates are listed in Table S-25. The trends in the prices are shown in the *Appendix* (*Plastics market outlook*, page A-1).

Table S-24. CIF value of bales. Values are for average returns from 2010-19.

Category	CAD/tonne
PET (mixed)	$397.40
HDPE (mixed)	$530.80
Mixed plastics	$48.40

Table S-25. Plastic pellet prices.

Category	CAD/kg
PET (clear)	$1.88
PET (color)	$0.85
HDPE NC	$2.43
HDPE MC	$1.24
PP	$0.94

S5.4. Scalability of MRF

The following contains additional notes on Table 9 values for the 13 000 t/year and 16 800 t/year MRF sizes. Table 7 and Table 8 list the breakdown of expenses and revenue, respectively, for the 8 400 t/year facility. The annual and 25-year labor costs for each scale, based on the employee rates listed in Table S-15, are provided in Table S-26.

Table S-26. MRF labor costs at various scales. Annual cost reflects the first year of operation according to rates listed in Table S-15. The 25-year totals are the annual rates over 25 years with 2% inflation added annually. 25-year totals have been rounded up.

	8 400 t/year		13 000 t/year		16 800 t/year	
	Employees	Annual	Employees	Annual	Employees	Annual
Sorter (0.75 tph)	7	$247 520	11	$388 960	14	$495 040
Equipment operator	2	$124 800	2	$124 800	3	$187 200
Maintenance	1	$62 400	1	$62 400	1	$62 400
Management	1	$72 800	2	$145 600	2	$145 600
Plastics processing	2	$70 720	3	$106 080	3	$106 080
Total	13	$578 240	19	$827 840	23	$1 031 680
25-year	$18 600 000		$26 600 000		$33 100 000	

The capital costs for the 8 400 t/year facility were listed in Table 7 on page 17. The cost of rolling stock was doubled ($466 000) for the 13 000 t/year and 16 800 t/year facilities. Heating and electricity costs remained the same for all facility sizes because the costs were estimated on the high end for the 8 400 t/year facility. The other major cost difference is for the capex of the equipment. Scaling up from 8 400 t/year to 13 000 t/year included a 10% increase in the capex from $6.5 million to $7.15 million to account for additional automation. No reduction in the number of sorters was included due to increased automation. The capex for the 16 800 t/year facility was the same as for the 13 000 t/year.

Revenue was simply scaled according to annual revenue shown in Table 8 for pellets ($1 245 000) and multiplied by the number of tonnes the facility will process and the number of years (25). The potential for better returns exists as it is assumed additional tonnage would be source-separated and thus fewer residues.

Table S-27. MRF expenses summary at various scales.

	8 400 t/year	13 000 t/year	16 800 t/year
Labor	$18 600 000	$26 600 000	$33 100 000
Rolling stock	$233 000	$466 000	$466 000
Capital			
Building	$7 500 000	$7 500 000	$7 500 000
Sorting equipment	$6 500 000	$7 150 000	$7 150 000
Pelletizing	$2 000 000	$2 000 000	$2 000 000
Energy	$6 800 000	$6 800 000	$6 800 000
Total	$41 633 000	$50 516 000	$57 100 000

S6. Further reading

This section includes further information on the topics researched. WtE technologies that are currently being researched are discussed; however, most were not commercially available at the time of writing. Additional information about plastics processing is included which highlights some of the challenges with diverting plastic waste via mechanical recycling.

S6.1. WtE technologies

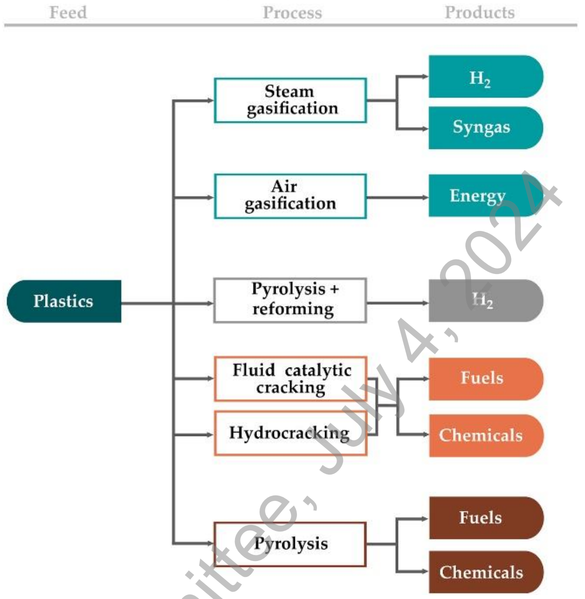


Figure S-1. Current chemical recycling WtE processes. Methods used to break down plastic feedstock and potential end products.[75]

The WtE pathway includes the generation of syngas to be used in a CHP plant as well as chemical recycling. Whereas the production of syngas results in the evolution of H_2, CO_2, CO, CH_4 and N_2, chemical recycling focuses on recovering monomers of the constituent plastic and/or producing liquid fuels/lubricants. Note that the production of syngas and chemical recycling are not necessarily mutually exclusive.[76] The nature of the final mixture of products, whether syngas or fuels or chemicals, will depend on the precise methods used (e.g. catalysts, temperature) and the nature of the feedstock (e.g. PP, PE, etc.).[75,77] The resulting value-added products may then be incorporated into other processes. Some of the more commonly applied gasification methods are shown in Figure S-1.

The steam and air gasification methods shown in Figure S-1 are mostly experimental in nature; pyrolysis followed by steam reforming to produce H_2 is as well,[75,77] but this may be changing soon. The steam reforming process, when applied to mostly pure feedstock such as PP and PE, has provided yields of H_2 as high as 70%, with little to no formation of the unwanted tar by-products that form in other WtE processes.[75] Many industrial scale examples exist of steam methane reforming using feedstocks such as naphtha; however, commercial implementations using plastics as a feedstock are difficult to locate. Considering the renewed global interest in H_2 as a fuel, this type of technology may be of interest to.[78] A H_2-producing facility may also be of value to natural gas providers, such as FortisBC, which has, for example, interest in the Chetwynd H_2 electrolyzer plant being proposed by Renewable Hydrogen Canada.[79]

An example of a pyrolysis WtE scheme is shown in Figure S-2. The actual products and distributions (e.g. light oil, kerosene and diesel) are dependent on feedstock and the precise technology selected; generally, purer feedstock (one type of polymer) leads to a more controlled environment and expected

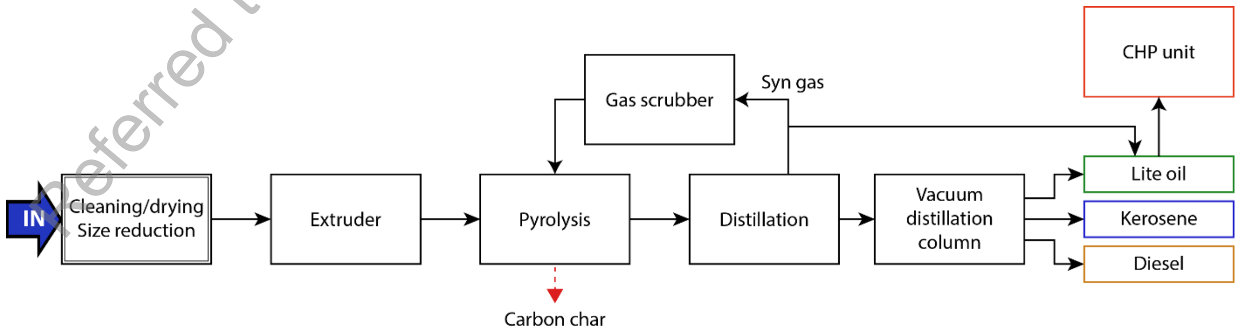


Figure S-2. Example of a pyrolysis method for processing plastics. Adapted from Ragaert et al.[77]

chemical outcomes. Figure S-2 indicates that part of the syngas produced may be repurposed (burned) to reduce the amount of external energy required in the pyrolysis step.

The market for biofuels is heavily dependent on the cost of raw materials and the price of crude, and will also depend on the targeted molecules. For example, one analysis of naphtha and slack wax prices, two products that result from the processing of plastic feedstock, was based on the assumption that slack wax had a constant cost 68% higher than that of crude, and a naphtha cost that was 10% lower than crude as feedstock. Depending on the process that was applied to refine the plastic, the minimum cost for a barrel of crude had to be between 50 and 75 euros ($80-$115 CAD) to break even.[80]

S6.2. Plastics

S6.2.1. Pelletizing of plastics

The pelletizing process is shown in Figure S-3 for hard and soft plastics. A typical method for separating PET, PE and PP includes washing the combined plastics in a caustic solution, where PET is removed based on its higher density (sinks) and PE and PP on its lower density (floats).[82] Optical sorters are then able to sort the flakes into their various plastic types, remove contaminants, and remove colored flakes from clear polymer samples to ensure high quality, uniform material. The flakes are then melted and extruded.

Due to the differing nature of plastics (e.g. viscosity, melt temperature), machinery for producing pellets is set up to the specifications of each polymer type, and thus a decision needs to be made as to the type of plastics that will be targeted for extrusion and pelletizing.[83]

S6.2.2. Plastics processing facilities

According to the Canadian Plastics Recyclers Directory (June 2020) posted by Plastic Action Center,[84] two operators are currently recycling in the Lower Mainland of BC: Fraser Plastics in Maple Ridge, and Merlin Plastics in Delta and New Westminster. Merlin Plastics also has a facility in Calgary and one in Bassano, AB. Fraser Plastics recycles HDPE,[85] whereas Merlin offers LDPE, HDPE, PP and PET products. There appear to be no larger scale pellet producers north of the Lower Mainland, nor in Edmonton, AB.

S6.2.3. Plastic films

Film plastics are estimated to account for 40% of MSW plastic waste;[23] they also tend to be more heavily contaminated. Part of the difficulty in dealing with film plastics is the multilayer nature of the material that is used in the food industry. Figure S-4 shows an example of the multilayer structure of modern food packaging. Several layers of polymers are laminated together to ensure strength and

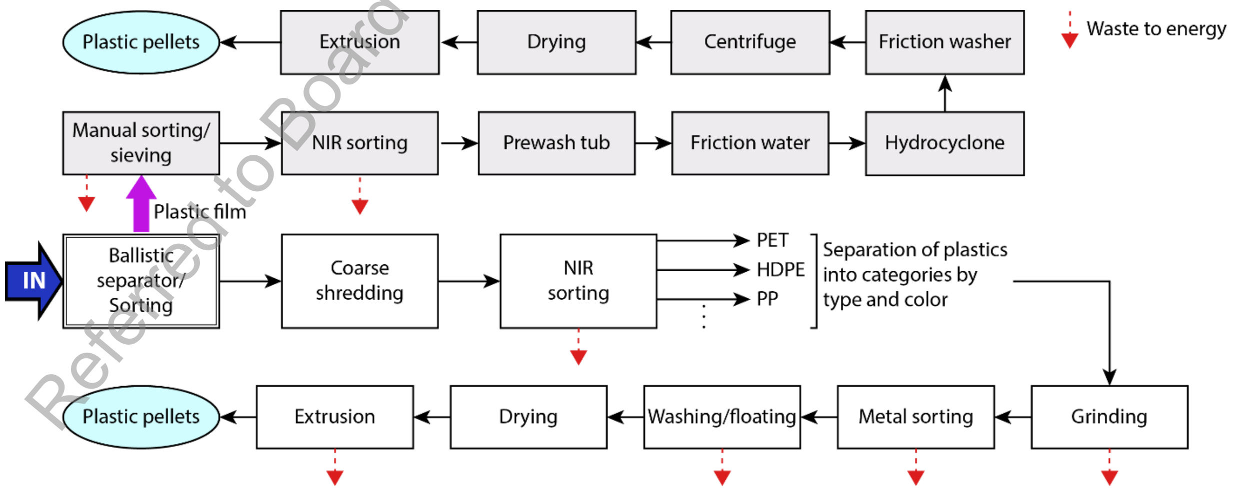
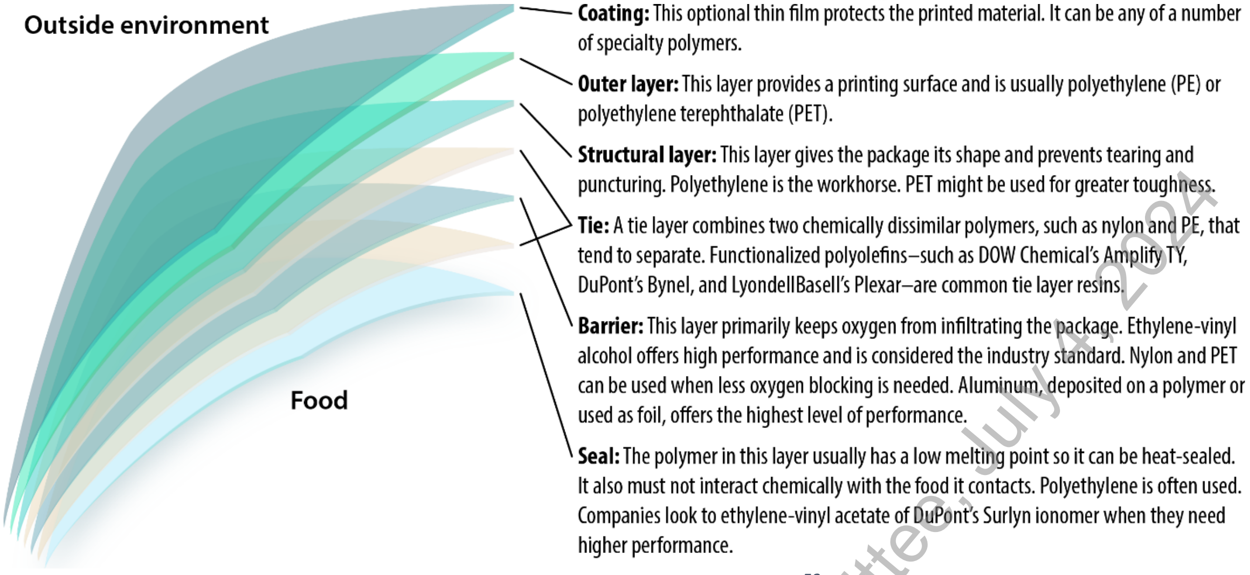


Figure S-3. Mechanical recycling processing of plastics in pellet production. The scheme was adapted from Faraca and Astrup[81] for non-film plastics; for film plastics, the scheme was primarily adapted from Soto et al.[23] NIR: near-infrared.



Coating: This optional thin film protects the printed material. It can be any of a number of specialty polymers.

Outer layer: This layer provides a printing surface and is usually polyethylene (PE) or polyethylene terephthalate (PET).

Structural layer: This layer gives the package its shape and prevents tearing and puncturing. Polyethylene is the workhorse. PET might be used for greater toughness.

Tie: A tie layer combines two chemically dissimilar polymers, such as nylon and PE, that tend to separate. Functionalized polyolefins–such as DOW Chemical's Amplify TY, DuPont's Bynel, and LyondellBasell's Plexar–are common tie layer resins.

Barrier: This layer primarily keeps oxygen from infiltrating the package. Ethylene-vinyl alcohol offers high performance and is considered the industry standard. Nylon and PET can be used when less oxygen blocking is needed. Aluminum, deposited on a polymer or used as foil, offers the highest level of performance.

Seal: The polymer in this layer usually has a low melting point so it can be heat-sealed. It also must not interact chemically with the food it contacts. Polyethylene is often used. Companies look to ethylene-vinyl acetate of DuPont's Surlyn ionomer when they need higher performance.

Figure S-4. Architecture of modern plastic films used in the food industry.[53]

freshness of the food contents. As is shown for the barrier layer, aluminum is often incorporated into the packaging. The complexity of the packaging leads to challenges in the recycling process, which require steps such as delamination to separate the layers,[23] as well as removal of non-plastic material. The various binders also produce challenges.

Films made of single types of plastic may be more simply processed, such as those common in agricultural plastic wraps. The plastic PE pellets obtained using the process for single layer film waste as illustrated in Figure S-3 were of good quality, with properties close to that of virgin PE.[23] Due to the increased complexity (and cost) of processing multilayer films and a lack of commercially available technology, multilayer films are currently best suited for energy recovery.[86]

S6.2.4. Market outlook

A large factor driving North American recycled plastics (e.g. rPET, rHDPE, rPP) prices is policy. China's National sword policy has eliminated a large market for Canada's recycled plastics by having reduced import by 99%,[87] resulting in a significant shortage in global capacity. Countries such as Malaysia have taken over as the leading waste plastic importers, but with concerns that Southeast Asia is becoming a dumping ground for the West's trash.[88] Most recently, the European Union (EU) has placed a ban on the export of unsorted plastics to poor countries to address concerns of dumping.[89]

In the United States, California has recently enacted a law that requires the use of at least 15% recycled plastics in containers[90]; by 2030, the content is required to be 50%.[91] Such laws raise some concern because of the lack of recycled materials that may be available. Companies such as Pepsi Co. and Coca-Cola have made commitments to include certain amounts of recycled plastics in their products;[92,93] it is estimated that the amount of rPET currently available on the market would have to be tripled to meet the intentions of brand owners.[94] Part of the supply shortage is due to processing capacity, as well as rPET market value. Recently, the City of Calgary, for example, landfilled 2 000 t of PET clamshell containers because they could not be processed and the cost of storage was high.[95]

The Canadian government recently announced a ban on some single use plastics, such as plastic grocery bags, six pack rings and hard to recycle takeout containers.[96] At a regional scale, the Province of BC has instituted a deposit system for milk cartons which is expected to affect the amount of natural color HDPE being landfilled. The City of Vancouver has also has attempted to implement a single-use plastics fee for the restaurant industry.[97]

The cost of plastics in the past were loosely tied to the cost of crude oil, but in North America, the demand for recyclables is very much policy-driven.[99] The recent Covid-19 pandemic also put downward pressure on rPET prices,[94] although recycled plastic prices have reached some all-time highs recently. The trend of selected mixed bale plastics is shown in Figure S-5, indicating the spike in HDPE values. The trends in the pellet prices are shown in the *Appendix* (Plastics market outlook, page A-1)

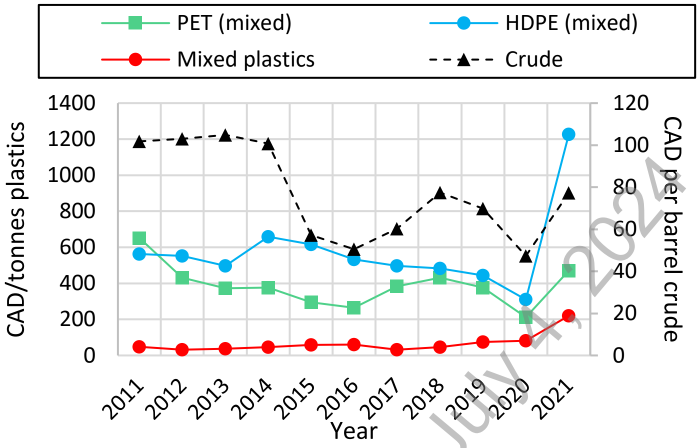


Figure S-5. Baled plastic and oil market trends. Cost of recycled plastic bales as estimated by the Continuous Improvement Fund (CIF) in Ontario.[98] The data are presented for information purposes only. Crude prices were taken from Index Mundi for West Texas and Brent.

Appendix

A1. Electricity and natural gas rates

The rates used throughout this document were based on those listed in Table A-1 for natural gas (heating) and electricity estimates. Demand charges are based on the highest peak power draw (kW) averaged over a 15-minute period in any given billing period (month) according to BC Hydro.

Table A-1. Natural gas and electricity rates.
Rates are based on April 2022 values posted to the respective provider's website at the time. The small rate is based on <35kW peak demand. The medium rate for BC Hydro is based on <550 000 kWh/year and a peak demand charge between 35 and 150 kW according to the BC Hydro website.

Pacific Northern Gas	
Basic monthly charge	$410
/GJ total	$6.528

BC Hydro			
	Small	Medium	Large
Admin fee (daily)	$0.3644	$0.2672	
CAD/kWh	$0.1253	$0.0968	$0.0606
Demand (per kW)		$5.41	$12.34

A1.1. Estimation of building heating costs

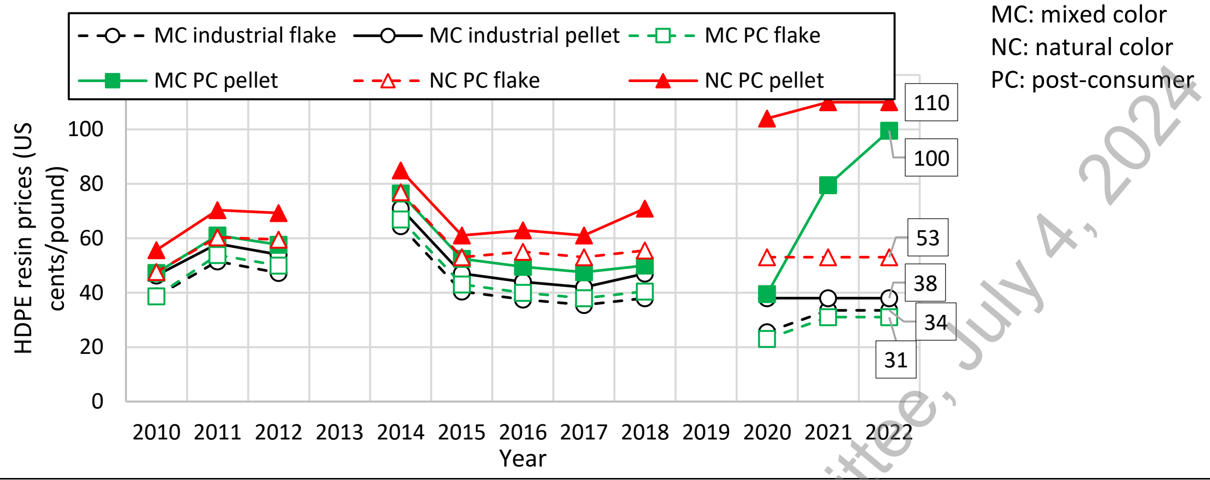
Heating is dependent on insulating factors, outside temperature and desired inside temperature, building shape, contents, personnel and other factors. A simple online calculator (https://www.calculator.net/btu-calculator.html) was used to estimate BTU usage per 1°C, and it was assumed all buildings were square for floor space dimensions with "normal" insulation. The average outdoor temperatures were used for each month in Fort St. John and Dawson Creek and it was assumed the standby temperature was 15°C (unoccupied building) and the operating temperature was 20°C. The operating of machinery and presence of personnel would be expected to reduce natural gas requirements, so usage estimated herein is an overestimate. All BTUs were converted to GJ for cost estimation. Detailed calculations may be found in the accompanying white paper.

A2. Plastics market outlook

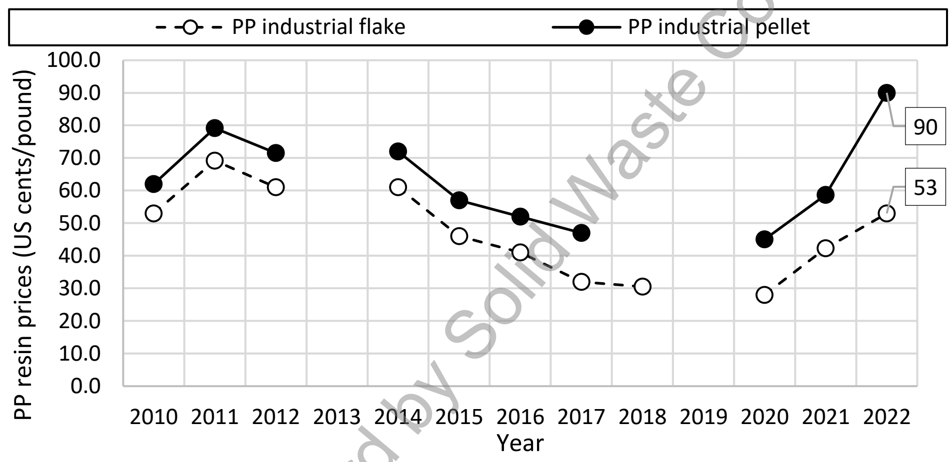
The following section contains information on resin prices in US cents per pound for selected plastics. The data were obtained from Plastic News (plasticnews.com), with data provided courtesy of Vecoplan AG according to the website. "Vecoplan AG develops, produces and markets machinery and plants for shredding, conveying and processing primary and secondary raw materials gained in recycling processes." Some years had multiple data points, which were averaged; data were unavailable for other years. The data are provided for information purposes only.

Figure A-1. Plastic pellet and flake market trends.

High-density polyethylene (HDPE)

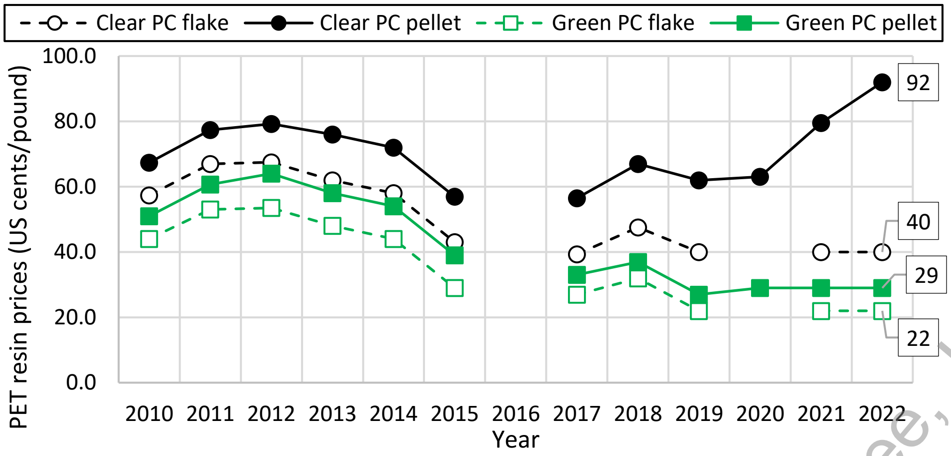


Polypropylene (PP)



Polyethylene terephthalate (PET)

PC: post-consumer



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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.

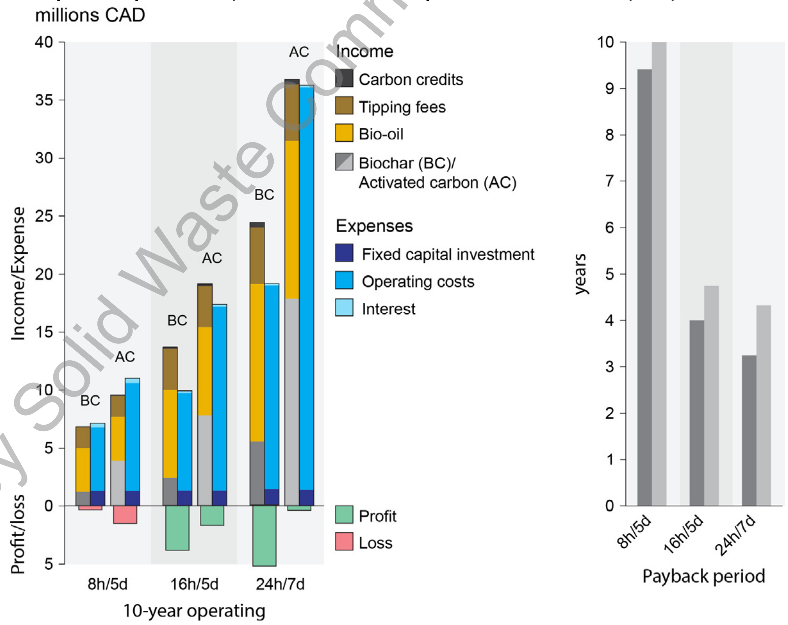

Figure E-1 Economic summary of a pilot scale pyrolysis unit implementation.
Scenario labeling is hours per day/days per week.
Left: Income and expenses (blue bar) for three operating conditions. Each scenario is split into biochar (BC) and activated carbon (AC) as possible products. Profit/loss is indicated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

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

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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.

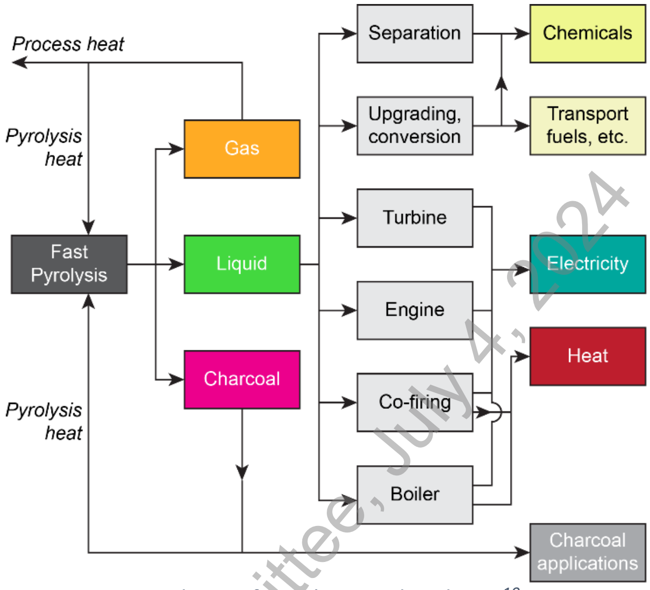

Figure 1. Products of pyrolysis and end uses[10].

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).

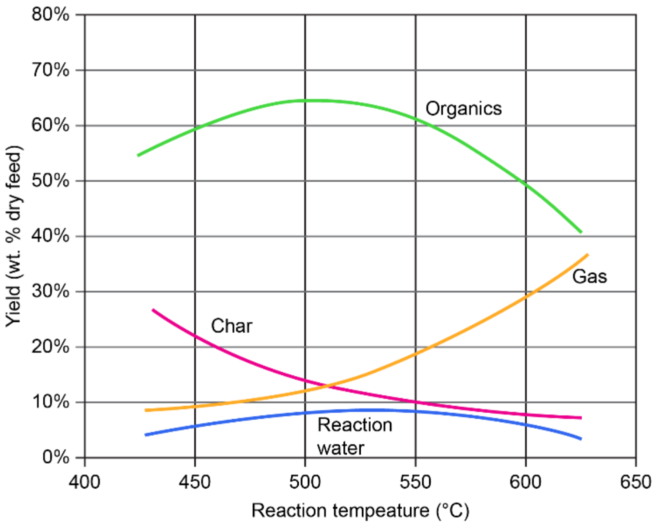

Figure 2. Pyrolysis product yields by temperature for aspen (poplar)[11].

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

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

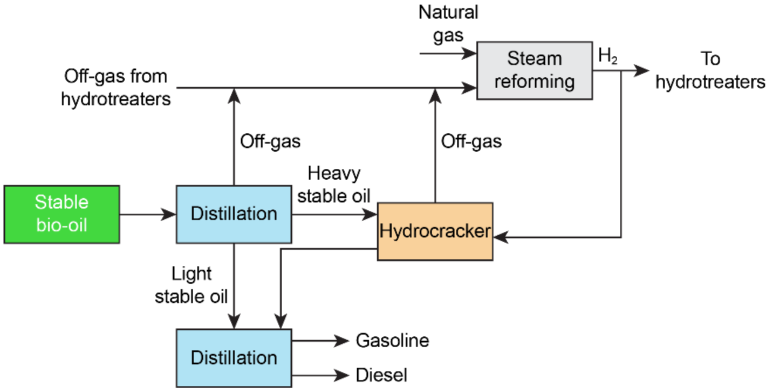

Figure 3. Possible bio-oil upgrading scheme[27].

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.

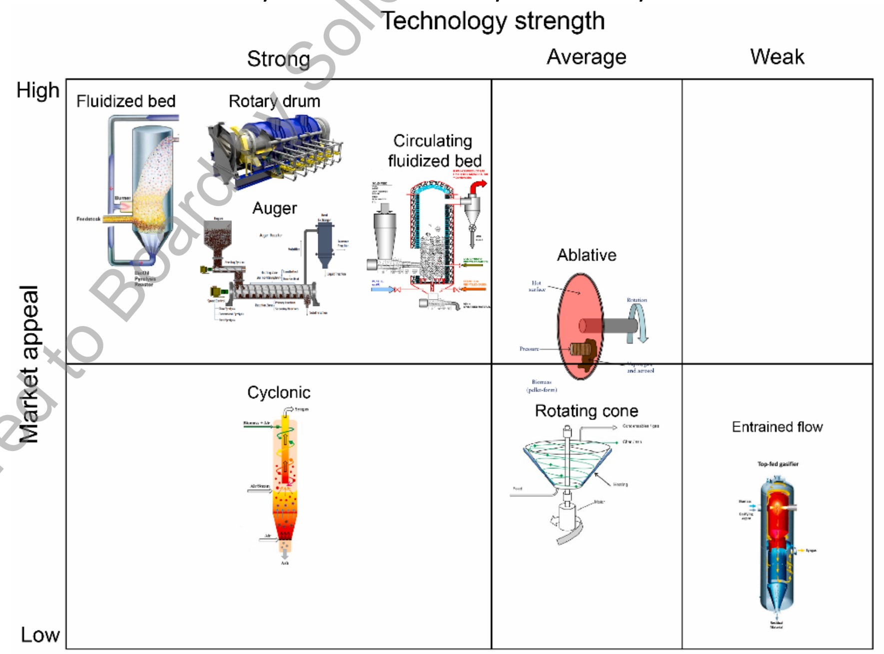

Figure 4. Common pyrolysis technologies in use[34].

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.

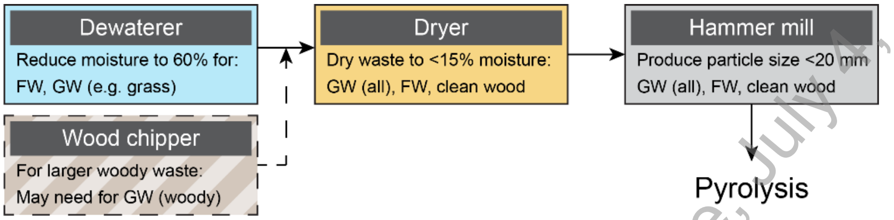

Figure 5. Pre-pyrolysis processing of food and woody waste.

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_2e 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.

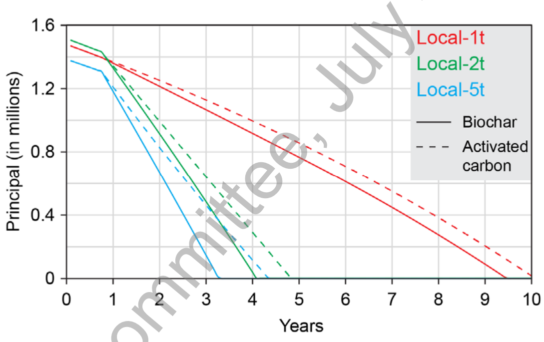

Figure 6. Payback period for a pilot scale 500 kg/h pyrolysis unit. All scenarios assume a 10-year amortization period with 50% of profits from the sale of biochar/activated carbon + bio-oil paid toward the principal.

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

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.

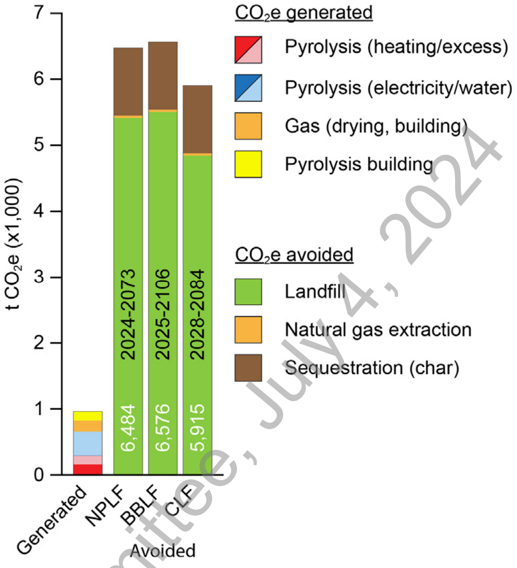

Figure 7. Annual CO_2e balance in the pyrolysis of 3,200 t of FW in the PRRD. White text indicates total CO_2e avoided, black the years of landfill operation[d].

The 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.

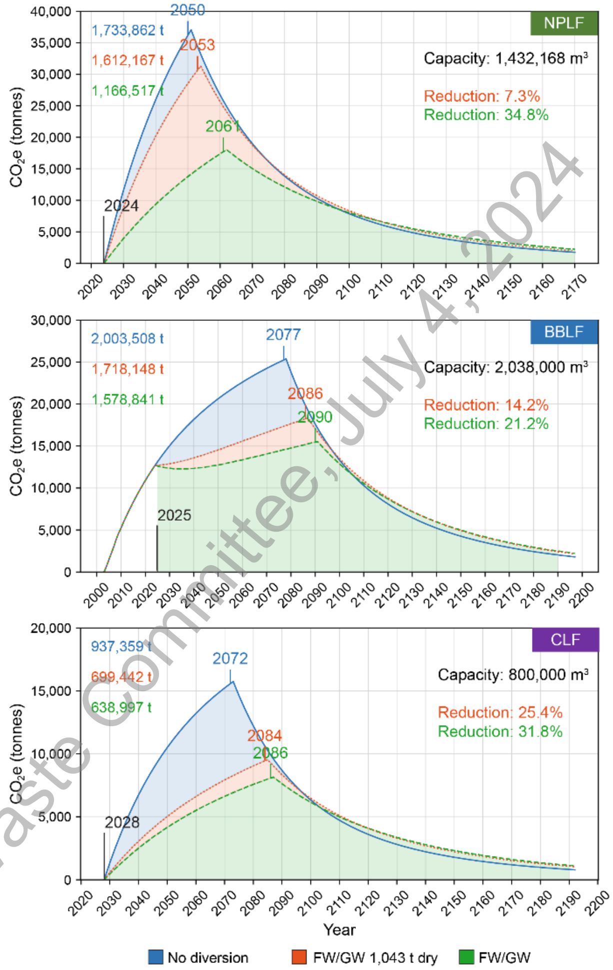

Figure 8. *Effect of diverting 1,043 t FW/GW from landfilling in the PRRD on CO_2e emissions. Shaded areas represent expected cumulative CO_2e t for the indicated time periods. Landfill closing dates are indicated above each line with diversion dates in black.*

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

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.

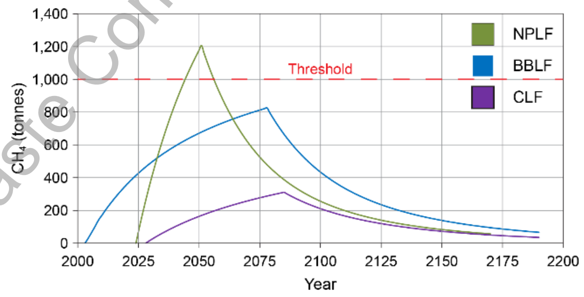

Figure 9. Annual CH_4 landfill emissions without diversion.

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.

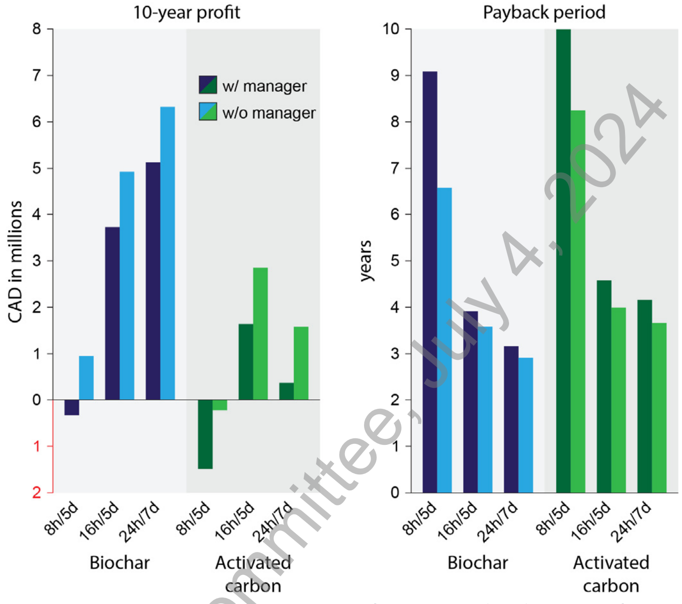

Figure 10. Expected ten-year profit and payback period for sub-regional scenarios. Scenario labeling is hours per day/days per week. See text for comments.

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

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.

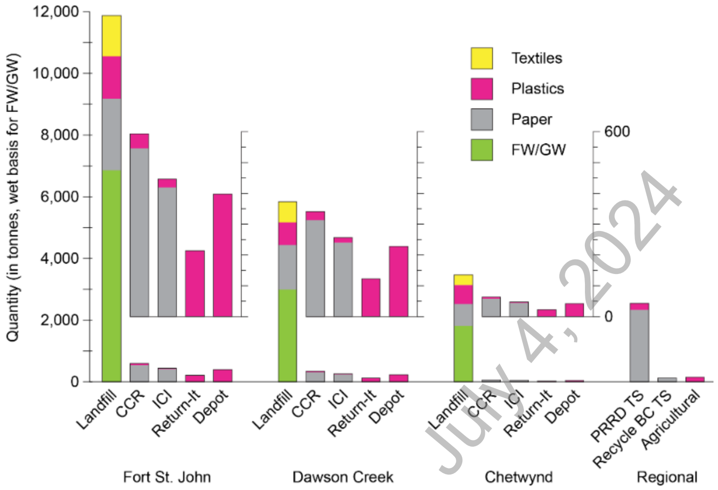

Figure A-1. Waste quantities by type and municipality/region in the PRRD.

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.

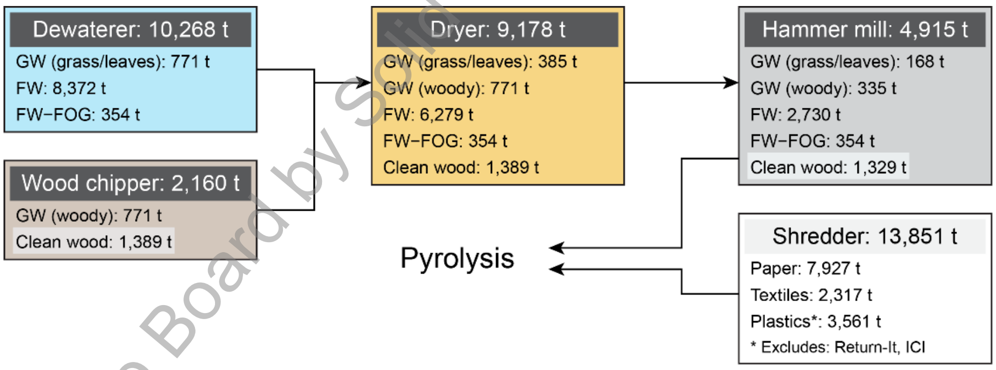

Figure A-2. Accessible tonnages of pyrolysis feedstock in the PRRD and pre-pyrolysis processing. The tonnages and process summarize the suggested approach to equipment usage for processing wastes prior to pyrolyzing.

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*	$\$0.60/\text{ft}^2$, *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/\text{ft}^2$)	*$420,000*	*$211,050*	*$211,050*	*6,030 ft^2; 12,000 ft^2 for Full 2 units*
Site prep ($\$85/\text{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/\text{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.

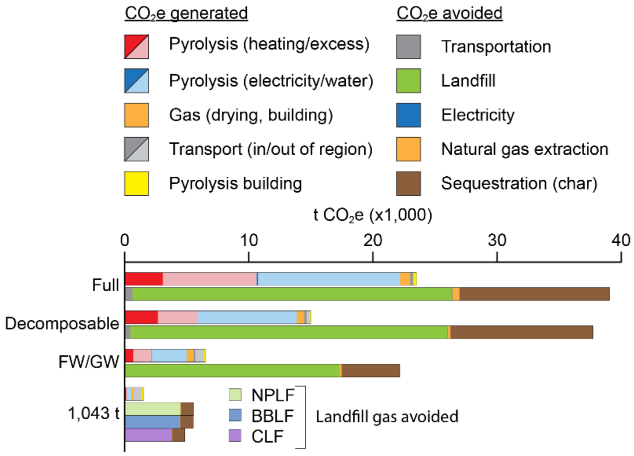

Figure A-3. Annual tonnes of CO_2e generated and avoided using pyrolysis.
The upper bar for each scenario is the amount of CO_2e produced and the lower bar the amount avoided for each scenario.

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.

<u>Landfill capacity</u>

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.

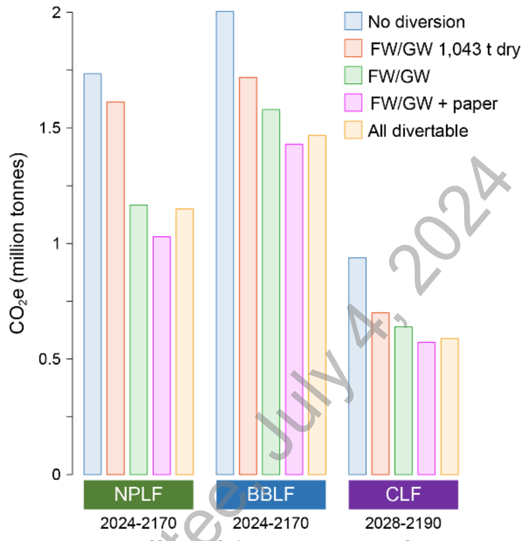

Figure A-4. Effect of diverting waste from landfilling on CO_2e emissions for all landfills.

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.

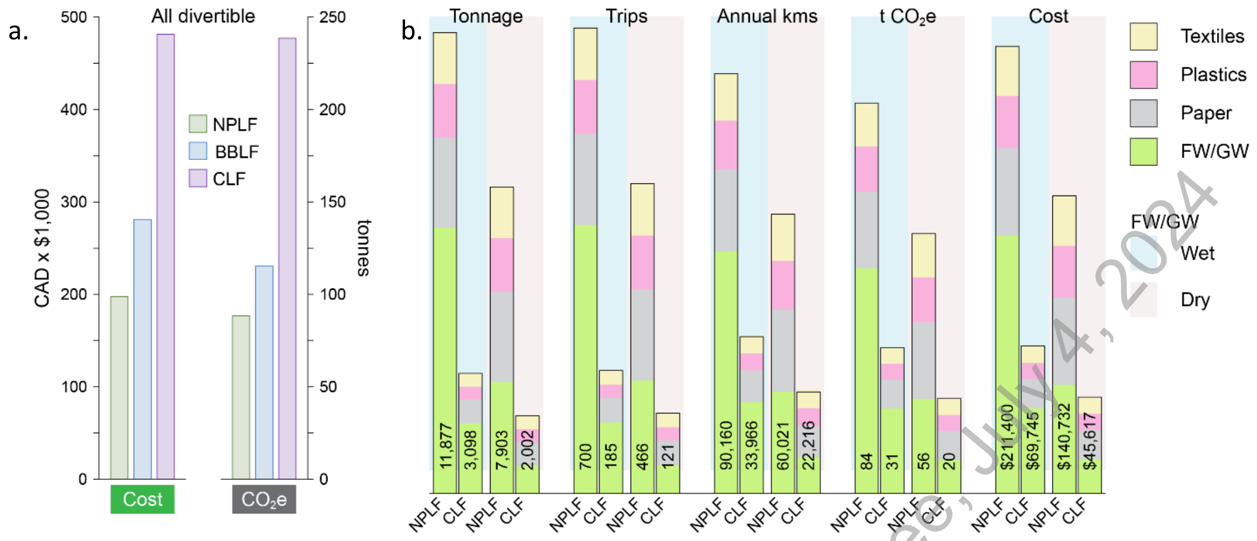

Figure A-5. Annual within-region transportation costs of diverted landfill waste.
a. Cost of transporting all divertable landfill waste to a centralized processing facility located at either the NPLF, BBLF, or CLF. b. Breakdown of tonnages, trips, kilometers, CO_2e generated and associated costs for 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).

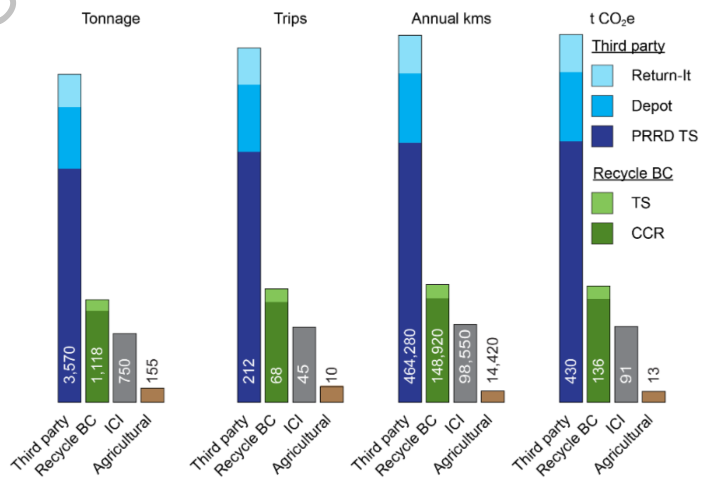

Figure A-6. Out-of-region transport of recyclables and CO_2e emissions. Transport is from Chetwynd to Richmond, B.C. (third party, Recycle BC, ICI) and Bashaw, AB (agricultural).
Notes: Tonnages (not volumes) were used; t CO_2e assumes no payload on return trips. Total quantities are indicated for each 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 m³ 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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