Plastics Recycling Market Development for Washington State and the Northwest Region

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EXECUTIVE SUMMARY

There is enormous potential to expand the plastics recycling value chain within Washington State. We have existing inventories of recycled plastics that can be increased and we have a recognized societal need and desire to reduce the plastic in our landfills and waterways. There are many technologies that are established and emerging that hold much promise, however we need to be educated customers and be smart in our decisions to support new operations and grow existing members of the recycling value chain.

The goal of this report is to provide the technical background of plastic recycling methods, evaluate their potential supply chain metrics and economic feasibility, and create a dynamic database of plastic recycling technologies. Much of the recent news related to plastic recycling is focused on alternative or chemical recycling as compared to a more traditional mechanical recycling method. This shift is due to the inabilities of mechanical recycling to provide an answer to efficiently convert all of our plastic waste. This is a heavy burden for one technology to answer and history will likely show hybrid recycling methods will create the most success. With that being said, currently most of our recycled plastics that are in products and goods are derived from mechanical recycling.

Fortunately, or unfortunately, Washington State and the neighboring regions have sufficient volumes of many of the common plastics we see in our everyday lives. These volumes were correlated with transportation logistics to estimate shipping costs. Results show the Puget Sound region with the lowest shipping costs and highest volumes, however Eastern WA also would have the needed feedstocks at a reasonable cost to maintain a viable recycling process, depending upon scale. Looking at the economics, the processes we evaluated (pyrolysis, gasification Fischer-Tropsch, and glycolysis), the potential cost of output products are higher than competing products. There are potential strategies to lower these costs, however this is a major hurdle in finding investment and developing a sustainable business case.

One thing to consider with the chemical and thermal recycling processes is what will be their end-product? With mechanical recycling, the output is often a pellet that can be sold, distributed and implemented very similarly as virgin plastic pellets. Even with limitations with feedstock purity, a secure and known end-product makes mechanical recycling a lower risk investment. Some chemical and thermal processes have identified viable end-markets, however more development in this area is needed to successfully implement these “alternative” recycling processes.

Next steps for Washington State – This report provides a significant amount of background on the technical, feedstock logistics, and economics of plastics recycling. Our Plastics Recycling Technology (PRT) database that was developed in conjunction with this report is a detailed list of commercial, academic, government and non-government entities associated with the plastics recycling supply chain. Using this report, the PRT database and the expertise of the Team which organized them both, WA State is backed with the ability to make educated and informed decisions on where to be in the new plastic recycling value chain.

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Introduction

There exist many options for plastic recycling and their technologies can vary tremendously, but their overall theme is to not consider recovered plastics as a waste, but instead as a resource or feedstock for another industry. WA State has the societal backing and support to position itself as a leader in the world of plastic recycling. It is poised to make a significant contribution to the plastics recycling world, however the actions and decisions on pathways and directions to head need to have sound technical, environmental, and economic judgements applied to this process. Recycling has its opponents and many attempts to create plastic recycling value chains have often failed for a variety of reasons. [11,12] This report chooses the mindset that finding the right opportunities with sound research and analysis can bring upon economical and environmentally sustainable growth to further developing the plastics recycling value chain in Washington State.

The work provided in this report outlines many of the emerging and existing technologies in the recycling plastics supply chain. Much of the data accumulated for this report can be found in the Plastics Recycling Technology (PRT) database, where a comprehensive list of commercial and start-up recycling technologies, equipment manufacturers and complementing additive suppliers are listed in a searchable database format. The report also considers a high-level analysis of potential inputs of a chemical/thermal (glycolysis, pyrolysis, gasification) recycling supply chain where generated volumes along with transportation costs are considered. A techno-economic analysis of the 3 recycling options is also presented.

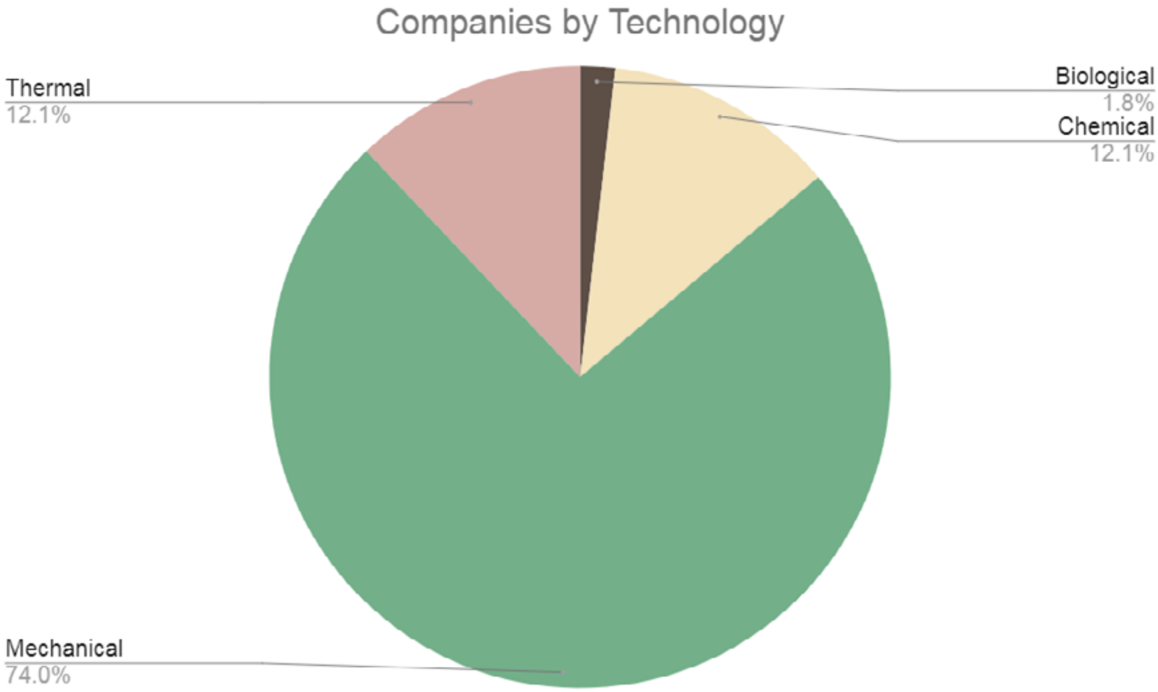
The Plastics Recycling Technology Database (PRT)

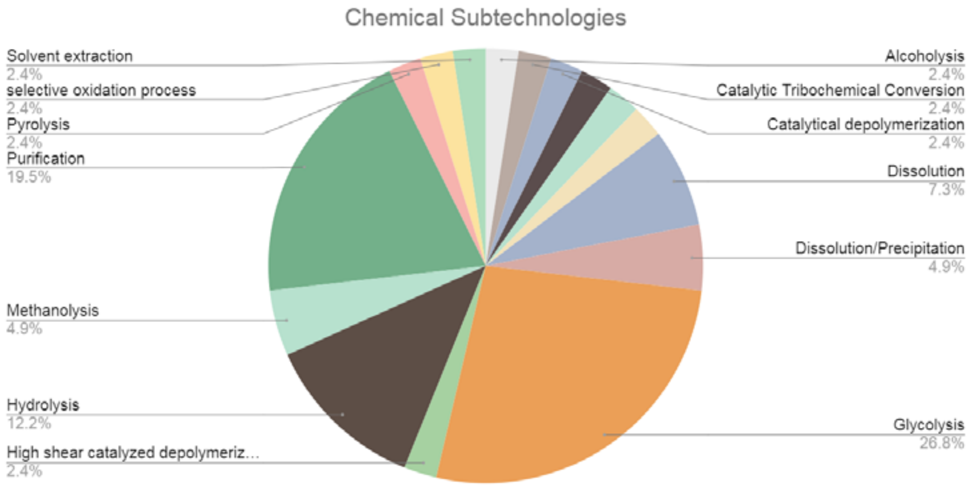
To supplement this report, a database of plastic recycling technologies is supplied in an Excel-based format. The PRT database is a compilation of companies and technologies that we collected that are related specifically to recycling methods for plastics. We did not include any sorting, washing, separation technologies in this database, however many of the companies listed either prepare their feedstock streams internally, team with other companies, and/or rely on the open market for inventory.

Figure 1 shows the distribution of technologies by type that are populated on the PRT database. As you can see from the pie chart, mechanical recyclers currently dominate the plastic recycling industry. When looking at the Figure 1 we separated out the chemical and thermal recyclers by technology. The PRT database is completely interactive and you can access at the following link (https://bit.ly/PRTDatabase). You can build your own graphs and charts within the database along with following links to find out more information on what different companies are doing to recycle.

What this report does not cover

The focus on this report is on the evaluation of current plastic recycling technologies. We do not cover the sorting and washing technologies to prepare plastics for recycling. There are numerous options and platforms to consider in this segment of the supply chain. The report does not look at potential end markets for recycled plastics. These options are vast and have similar attributes as virgin plastic applications. We do address some markets that directly consume bailed and flaked plastics such as the plastic and wood plastic lumber markets.





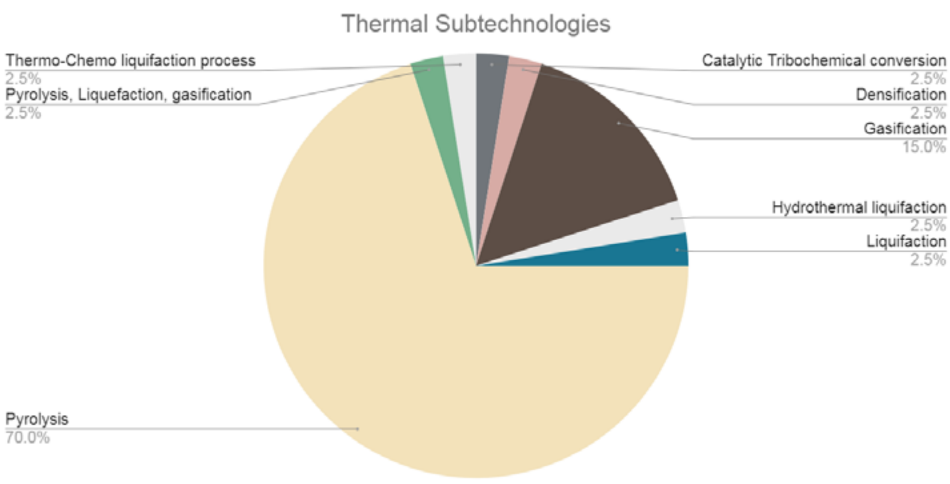


Figure 1: Recycling Technologies used by the companies included in the PRT Database.

How are plastics recycled?

The recycling process is directly tied to the plastic types that are being processed, how pure you want the final product to be and what the output product becomes. Mechanical, thermal, and chemical are three very basic categories for most recycling process, with many of them incorporating methods from each making them difficult to categorize. One way to view recycling methods is what they are doing to the polymer chains that make up the plastic. When a plastic melts or softens, the long chain molecules are not broken down but allowed to flow. In this melt phase, these plastics can be filtrated to remove contaminants, and reformed into a pellet, aggregate, or its final shape. This process is considered mechanical recycling. In thermal and chemical recycling, heat and chemicals, respectively, are primarily responsible for breaking down or depolymerizing the plastic into a variety of chemicals, oils, etc…

Recycling Methods: Thermal and chemical recycling, sometimes called "advanced" recycling, primarily are based upon a break of the polymer chain or bonds. Thermal recycling through pyrolysis, gasification (heating in the absence of or limited oxygen) or similar methods uses heat and often under anaerobic conditions to breakdown the polymer chains into oils and other chemical precursors. Chemical recycling uses many types of chemicals and solvents to reduce or break down the polymer chains down into a monomer form that can be used to refabricate a similar polymer or specialty chemical.

Theoretically, all thermoplastic resins can be mechanically recycled. Plastics are inherently thermo-responsive and melt* or soften upon heating to be reformed into a final part or intermediate pellet. In the case of polyethylenes (LLDPE, LDPE, HDPE) and similar plastics the process of heating and reforming can be done repeatedly with little or no reduction in performance. However, with plastics such as PET, the process of reheating the plastic causes a molecular weight (MW) reduction that impairs its use for many application, especially when considering gas permeance for food packaging. Much of the attention in the media and news is around chemical recycling or combinations of chemical and thermal processes. However, much of the recycled materials that are within the current supply chain are derived from a mechanical process, up to 99% of all recycled plastics.[17] These mechanical recycling methods often use a melt pelletization system that can have filtration options along with additives to improve properties and aid in processing.

End Products: The production of pellets from recycled plastics, especially mechanical recyclers, is often the final product for many recyclers. Pellets are the universal currency of the polymer processing world and is the preferred feedstock size for most manufacturers. By converting a bale of plastic into a pellet you are more able to market

* Melting is a crystalline behavior and not all plastics truly melt but often soften when heated. For brevity, the phrase "melt" will be used in this paper to describe all plastics' response to heating and reforming.

and distribute your product to a much broader audience and are not limited to selling only to clients that have a system to deal with loose plastic materials. Chemical and thermal recyclers can often generate a variety of specialty chemicals and oils that are sold on the market or used internally to further process into other products. The issue of what your end-product will be based upon many “advanced” recycling methods is often the most important aspect of making these technologies economically viable.

Additives

Additives in plastic recycling can be both part of the solution and part of the problem. Many additives can enhance the recyclability, build molecular weight, compatibilize between dissimilar polymers and contaminates, all to make the recycled plastic similar to its original properties. However additives that were put into the original plastic to impart some property or attribute, i.e. flame retardants, heat stabilizers, plasticizers, etc…, can have negative influences on the thermal breakdown of the plastic. Understanding their influence and identifying plastic products that obtain troublesome additives are key to a smooth running operation.

The thermal environment of pelletization, both melting and drying, can cause breakdown on virtually all polymers to varying degrees. This thermal environment causes thermal oxidation to occur and often other unwanted chemicals to be released. To minimize this decay process, antioxidants are often added to the process to prevent breakdown of the plastic. There are many suppliers of antioxidants, some of which are directly marketed to the recycled plastic industry and can be specific to plastic types. Avient, BASF, Hecoplast and many others are producers of anti-oxidant additives for the recycling industry. Other scavenger or removal additives are also available to minimize the influence of unwanted chemicals released in recycling, such as Avient’s ColorMatrix AAzure Acetaldehyde Control Additive removes acetyl aldehyde from the PET recycling process.

Building up the recycled plastic back to its virgin form (increasing molecular weight) and other additives to improve final properties are some of the most common additives for mechanical recycling of plastics. Sukano has a variety of additives that improve PET processing and final product performance, while Riverdale Global produces compounds to improve PE and PPs recycling properties. This area of additives is pretty extensive and crowded with competition, our PRT database provides some of the manufacturers that are supplying the mechanical recycling industry.

Recycling Methods Based Upon Polymer Type

Polyethylene Terephthalate (PET)

One of the most common plastics, PET is prolific in packaging, carpets, textiles, and numerous other applications in our daily lives. In WA State an estimated 91K tons of PET packaging waste was generated in 2017, which equates to about 43% of all rigid plastics packaging.[18] This number is increased when considering PET plastic film packaging and other non-packaging applications.

The media often promotes the "bottle-to-bottle" or "bottle-to-fiber" recycling concept for PET. PET bottles are easy to separate, high in volume, and can be cleaned and contaminates removed pretty easily.[19] However, the recycling process of PET often lowers the oxygen barrier properties, causes hazing or yellowing of the plastic and can cause environmental stress cracking failures[20,21], requiring the use of additives or increasing the molecular weight (MW) in mechanical recycling or chemical recycling where a food-grade specification can be met. "Bottle to fiber" strategies are another option to recycle PET bottle scrap into fibers for textiles, carpets, and other applications with a bit more flexibility of incoming PET quality.

Mechanical recycling is the most common method for PET plastics. A critical concern with mechanically recycling PET is the degradation that is inflicted on its physical, mechanical and rheological properties[22]. Degradation results from thermal and oxidative mechanisms that are initiated by high temperatures, mechanical shearing and ambient oxygen concentrations, which are all characteristic of melt processing. PVC, water, and other contaminates are known to either catalyze degradation or directly depolymerize the PET plastic when exposed to elevated temperatures[23]. Notable foreign materials include poly(vinyl chloride), adhesive and water. At elevated temperatures, another concern is the concentration of oxygen. While oxidation is less of a concern compared to the influence of foreign materials, it is still known to alter the physical and rheological properties of PET.[24,25]

Mechanical recycling of PET is often performed on varying levels of contaminated streams. Extrusion systems with exhausts and melt filtration mechanisms are commonly used to clean and pelletize. The reduction in MW due to thermal oxidation or breakdown of polymer chains can be mitigated and fixed with various methods. Additives that rebuild or promote chain development such as stabilizers and chain extenders can be added to the mix to obtain virgin properties[26]. Solid state polymerization (SSP) is another technique that is commonly used to create food grade PET from both a virgin based and recycled process[27,28] Commercial entities such as Gneuss, Erema, Coperion and others provide mechanical equipment technologies to recycle PET and build MW.

Another innovative mechanical solution to PET carpet fibers is the Rise Building Products process process to make siding and other exterior products. In this process the PET (also Polyamide or nylon) fibers from carpets and fabrics are harvested, cleaned and pressed into a final product of siding and trim for residential markets. This innovative process minimizes many of the other issues associated with traditional mechanical and advanced recycling technologies.

Chemical recycling of PET has gained quite a bit of interest in the last couple of years and is the focus of much attention, both in academic and commercial sectors. Often chemical recycling is seen as the fix for materials that cannot be mechanically recycled without significant damage or down-grading of the end product. Using a solvent, or solvolysis, is the predominate chemical recycling technology that is seeing the most commercial attention in this area. Eastman, Dupont/Teijin and Sabic are just a few of the numerous companies looking at a glycolysis (ethylene glycol) or methanolysis (methanol) to breakdown the PET into re-buildable elements. Further discussion on glycolysis methods is found in the TEA section of this document.

Carbios and Bioxyle have taken a slightly different approach to PET recycling through biological/chemical methods. Using biological enzymes, the PET is broken down to its fundamental components, thus allowing to fabricate a new PET resin. The biological approach to degrading polymers is still in its infancy, however there is quite a bit of interest and motivation behind these processes.

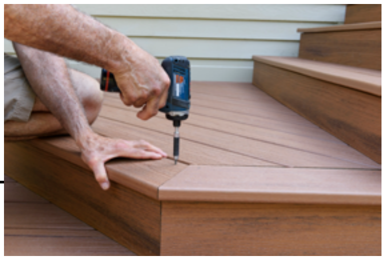
Polyolefins (PO)

Polyolefins are a family of linear chained carbon plastics that primarily include polyethylenes (LLDPE, LDPE, HDPE, etc..) and polypropylenes (PP). In Washington State, we generated 76K tons of polyolefin rigid packaging in 2017.[18] When you consider that PE's make up the majority of the close to 200K tons of film and flexible packaging in the State, POs footprint in our plastic waste stream is quite large.

Although many recycled POs are susceptible to degradation during repeated melting cycles, the damage to their properties is less severe than PET or other polymers.[29] However, to minimize thermal oxidation degradation, antioxidants or similar additives are used to stabilize the polymer.[30] The same process of adding stabilizers is also done in the manufacture of virgin plastics.

Since the melt degradation of POs are more easily controlled, mechanical recycling is often used. To create a clean recycled polyolefin pellet, the input stream needs to be source separated, washed and cleaned. Often melt filtration techniques are used to create a more purified product. The type of filtration set-up is based upon your input material contaminant level and desired output quality.

Chemical recycling of POs is also becoming more prevalent in the plastics world, often in combination with mechanical recycling. Borealis has a both a mechanical process (Borocycle M) to capture PO plastics that can be sorted and cleaned efficiently followed by a chemical process (Borocycle C) that converts the remaining PO material to a crude oil through pyrolysis where it is then converted into olefins through steam cracking techniques.



Other Polyolefin Recycling Options - Plastic and Wood Plastic Composites

Tangent Technologies, Miura Board, Greentree Plastics and others produce a plastic lumber and similar products using recycled feedstocks. Trex, AERT, Fiberon, Avon Plastics, Timbertech (Azek), and others also use recycled plastics with wood or natural fibers as fillers and reinforcement. The railroad and landscape tie industry is also heavily involved with making replacement wooden ties such as Integrico, Evertrak, and TieTek to name a few. Many of these entities can receive plastics in a variety of forms; baled, flakes and pellets and use them to produce predominately composite lumber for decking and exterior residential products. The baled and flaked material can come directly from MRFs or material brokers. Many of these manufacturers use PE based plastics (films and/or rigid), PP and PVC in some cases.

Other Plastics and Mixed Stream Technologies

The quantities of other plastic types, such as polystyrene (PS), acrylonitrile butadiene styrene (ABS), polyvinyl chloride (PVC), polycarbonate (PC) and nylons (PA), are smaller than that of POs and PET but still pose a significant amount of material when agglomerated. Many options for mixed plastic recycling streams rely upon thermal methods such as pyrolysis and gasification to convert them into a gas or oil that can be converted into a variety of chemicals including plastics, similar to the virgin oil refinery process. One of the issues with thermal treatments of mixed plastics are the chlorine derivatives from PVC.[31] Hydrochloric acid gas is the predominate concern not only to human health but also corrosion to equipment and catalyst disruptions when further processing the resulting oil.[32] Methods to manage the chlorine in process or remove any PVC prior to processing are crucial to a successful operation.

Pyrolysis and gasification are two similar but uniquely different thermal-chemical processes for managing plastic waste streams. Both processes utilize anaerobic conditions along with heat and catalysts to produce oils (pyrolysis) and gases (gasification). These end-products can then be converted into a variety of chemicals and eventually plastics. Pyrolysis temperatures generally range between 500-650°C and result in condensed oils and waxes.[33] Gasification is similar but processing temperatures are a bit higher, between 800-1000°C, and the end-product is a gas or syngas that is often converted to a liquid via Fischer-Tropsch techniques.[34]

Companies such as Agilyx, Brightmark, New Hope Energy, and many others utilize pyrolysis methods to create a variety of products that stem from a condensed oils and waxes. Fulcrum Bio-energy and Eastman Chemicals are two major players converting mixed waste plastics to a gas via gasification methods. Many of these companies will take mixed stream plastics or concentrate on one or a select number of plastics. Mura (HydroPRS™) and Renew ELP present an alternative thermal treatment via hydro-thermal liquefaction process that uses pressured water at high temperatures to break down mixed plastics to a naptha product similar to pyrolysis. Polyamides (PA) or nylons have had limited commercial interest in recycling, however Aquafil is recycling these materials back into fibers for carpets and textiles.

Current Plastic Recyclers in the Region

The report to WA DOE from Cascadia Consulting identified 11 reprocessing facilities for plastics, with only 4 from WA[13] (Figure 2). Of these reprocessors Denton Plastics, Fraser Plastics, Merlin Plastics, Northwest Polymers, Rainier Plastics, and Westcoast Plastics are mechanical recyclers that can generate a melted pellet product. Most of these recyclers can take a wide variety of plastic types as feedstock, however much of the focus in their supply is on PE and PPs. Agilyx in OR is the only thermal or pyrolysis recycler in the area. They have focused on PS recycling (up to 10 tons/day) with their Regenyx technology (partnership with AmSty), but they are also incorporating other plastics (PMMA, PET, PE and PP) into intermediates and fuels. There are currently no other chemical/thermal recyclers in the region.

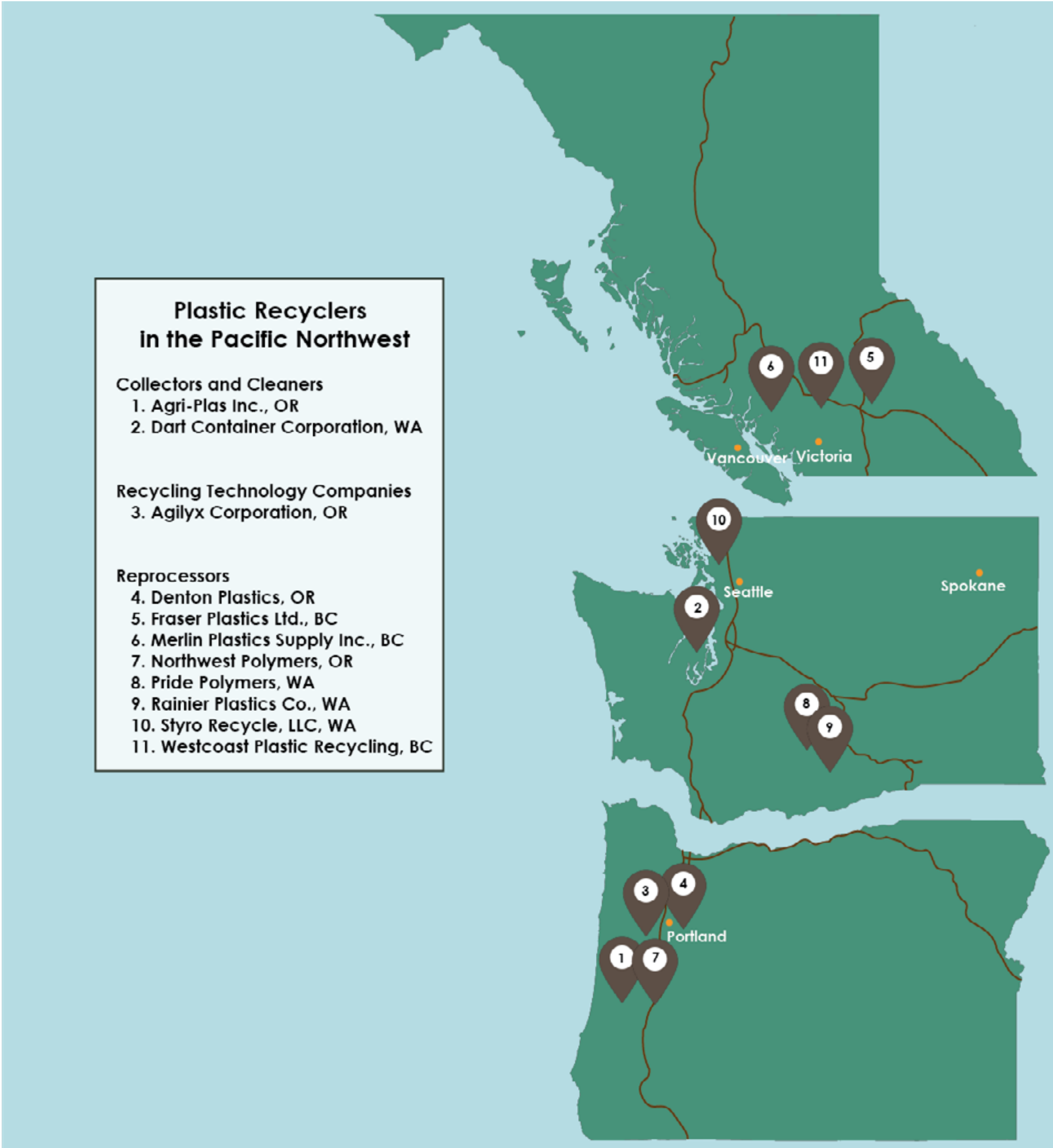


Figure 2: Map of Recycling companies in the Pacific Northwest.

The other reprocessors in the region, Agri-Plas, Dart Container Corporation, and Styro Recycle LLC are collectors, sorters, and cleaners of different plastics; agricultural plastics, PS and other containers, and PS foams, respectively, that are then sold to another party for further recycling. In the case with PS, much of this material is part of the Agilyx feedstock chain.

Enhancing the WA State Supply Chain for Recycled Plastics

To investigate the potential recycling options for WA State to consider, we looked at 3 chemical/thermal methods for further evaluation of supply chain logistics and economic analysis. A solvolysis process (glycolysis) which accepts only PET plastics, a gasification Fischer-Tropsh and pyrolysis to oil processes that both accept mixed plastic waste. We also considered two potential locations for a new recycling operation, the Puget Sound and Eastern Washington areas.

We did not evaluate a mechanical recycling process since these are numerous entities both globally and locally (Denton, Merlin, Rainier Plastics, etc…) and data for these operations can be acquired through commercial channels. However, much of the supply chain work on plastics availability and transportation costs can be used to refine any type of recycling process.

In order to develop a comprehensive supply chain model for recycling plastics, we need to evaluate where the materials are and how much it will cost to have them delivered to a processing site. Since population has a direct correlation with the amount of post-consumer resin (PCR) material present, an evaluation of population and information on plastic volumes for WA State and outlying regions were utilized to determine some initial supply chain logistics.

Supply Chain Overview

The information provided in the report commissioned by the Washington State Department of Ecology provided detailed information about the locations and amounts of generated and recycled plastics within the state of Washington and according to the study, both plastic generation and recycling vary significantly by region.[13] Figure 3 shows the amount of PCR plastics located by regions. The amount of PET found in each region was also estimated, since we are considering a solvolysis process. According to the study[13], annual plastic production varies between 80 kg/capita in the west region to 190 kg/capita in the east region. The State average is approximately 91 kg/capita. In addition to variable waste plastic production rates, the total recycling rate also varies significantly. In the northwest region, the combined plastic recycling rate is nearly 12%, while the east region has a rate below 4%. Across the entire State, the average recycling rate is approximately 8.3%. Two sorts of plastic are needed for the processes analyzed: mixed waste and PET only. For glycolysis facilities, only PET plastic can be used and the average per capita production of PET in Washington is only 12 kg per year. However, the recycling rate of PET is much higher than the overall state average of 8.3%, at 27.8%. The lowest rate of PET recycling is 6%, in the central region, while the highest rate is 46%in the northwest region.[13]

Supply Chain Methods

Populated places, defined using data from the Census Bureau and provided by Esri,[1] were used to determine the locations of potential sources of plastic in Washington, Oregon and Idaho. These values were adjusted from 2012 to 2019 values using county population growth from US Census Bureau.[10] Locations with a population of less than 500 were excluded.

Combing the WA DOE data [13] with the census bureau county population data allowed for calculation of factors for production and recycling rate per capita in each region. These factors were combined with the geospatial population data and road networks to develop feedstock collection cost curves for each siting location. Curves relate the estimated transportation costs for the average incoming ton of material versus the total tons supplied. The curves are used to determine transportation costs for one metric ton of material between each populated place (collection location) and the two potential processing regions: Puget Sound and Eastern WA. The delivery per ton price was applied to the total plastic available in a given populated place. Beginning with the nearest locations and iteratively adding each successive location, the summed feedstock supplied, and the summed transportation costs were calculated. The average transportation costs from each location were calculated by dividing the total costs by the total feedstock.

Facility candidate locations were selected to include: relatively high population density in the surrounding area, easy access to additional high density locations, existing industrial activity, and potential for future growth of industrial activities. The extended study focused on two of these locations: Puget Sound and Eastern Washington to compare two, disperse locations.

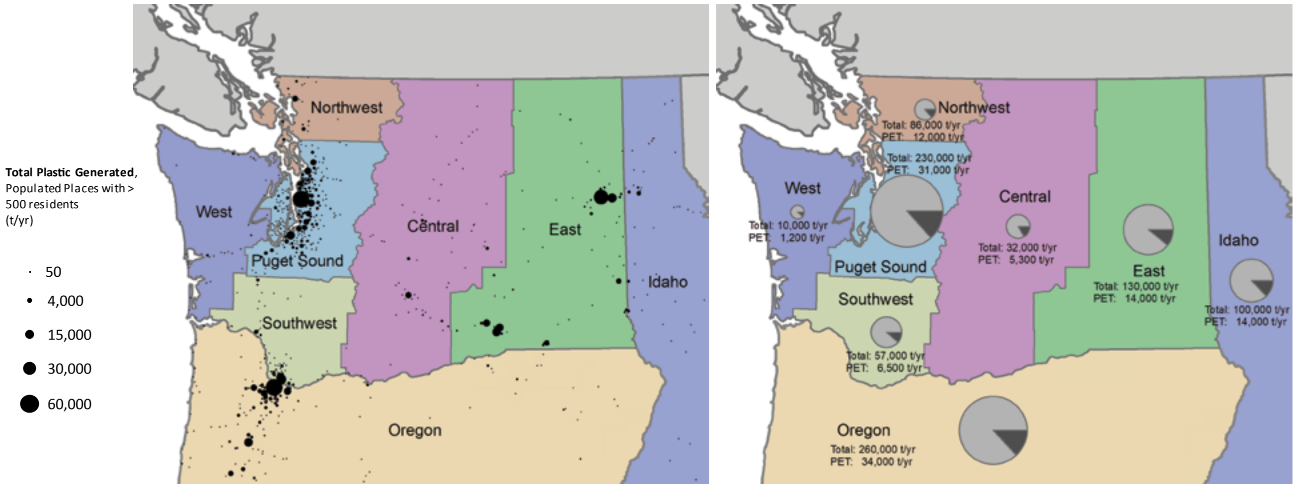


Figure 3: Plastic volumes by regions within WA State and neighboring states.

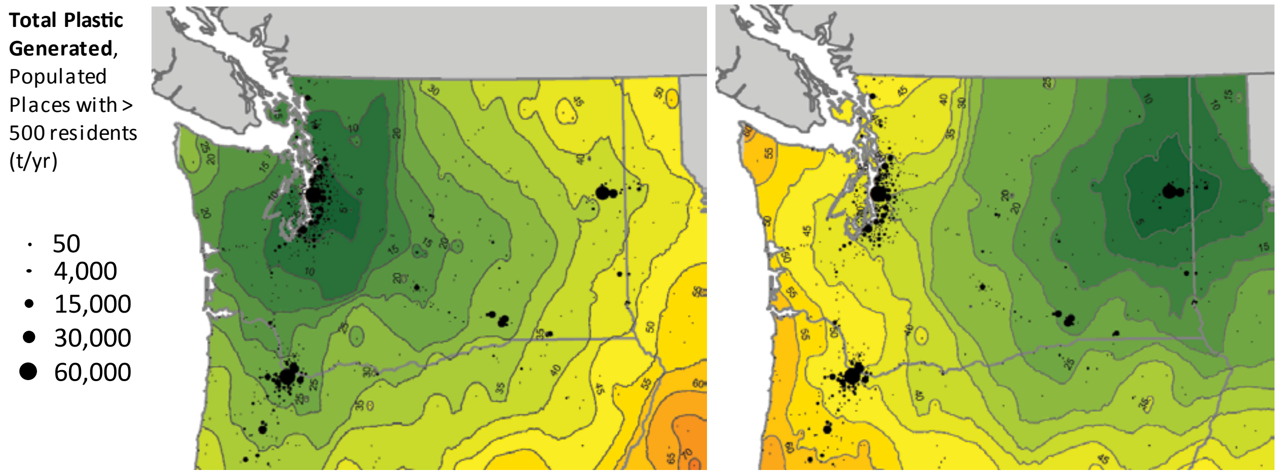


Figure 4: Transportation Costs for 2 locations, Puget Sound and Eastern Washington. Does not include any material costs.

In this study we assumed that plastic collection was only available from residents living in populated places of 500 or more residents. In Washington, 6.2 million of the 7.6 million residents lived in a location with greater than 500 people as of 2019. An additional 4.4 million residents were considered in the study from Oregon and Idaho. We assumed that the plastic production and recycling rates in Oregon and Washington are equal to the average rates in Washington.

Both a perspective location and the chosen scale of a potential facility impacts estimated transportation costs. Figure 4 graphically illustrates this relationship for two facilities, one located in the Puget Sound region and on sited in eastern Washington. Siting a facility near a population hub can result in low costs for collecting the plastic localized to that area, but additional costs related to scale may make that location less than ideal. In the state of Washington, siting a facility in the Puget Sound region results in the lowest transportation costs. Eastern WA is a bit more isolated and produces similar transportation costs at smaller scales, but have much larger costs once feedstock within the metro area of Spokane is exhausted. Siting a facility between two population hubs may produce competitive costs at large scales, but a lack of immediate nearby feedstock produces poor performance at small scales.

Figure 5 shows what can happen to feedstock volume and transportation costs if recycling rates are increased. The “base” curve is where we stand right now for recycling rate for all plastics. Estimations for specific polymers available can be extrapolated from plastic composition percentages. The assumption can be made that if there is a viable recycling process in a region, there will be more effort for communities to recycle and an industry focus on acquiring feedstock. With this in mind, we estimated higher recoveries of plastic of up to 50% recycling rate making some dramatic shifts in the volume of material available. In the Puget Sound region this shift is associated with maintaining low transportation costs as feedstock quantities increase as shown by the flatter curves.

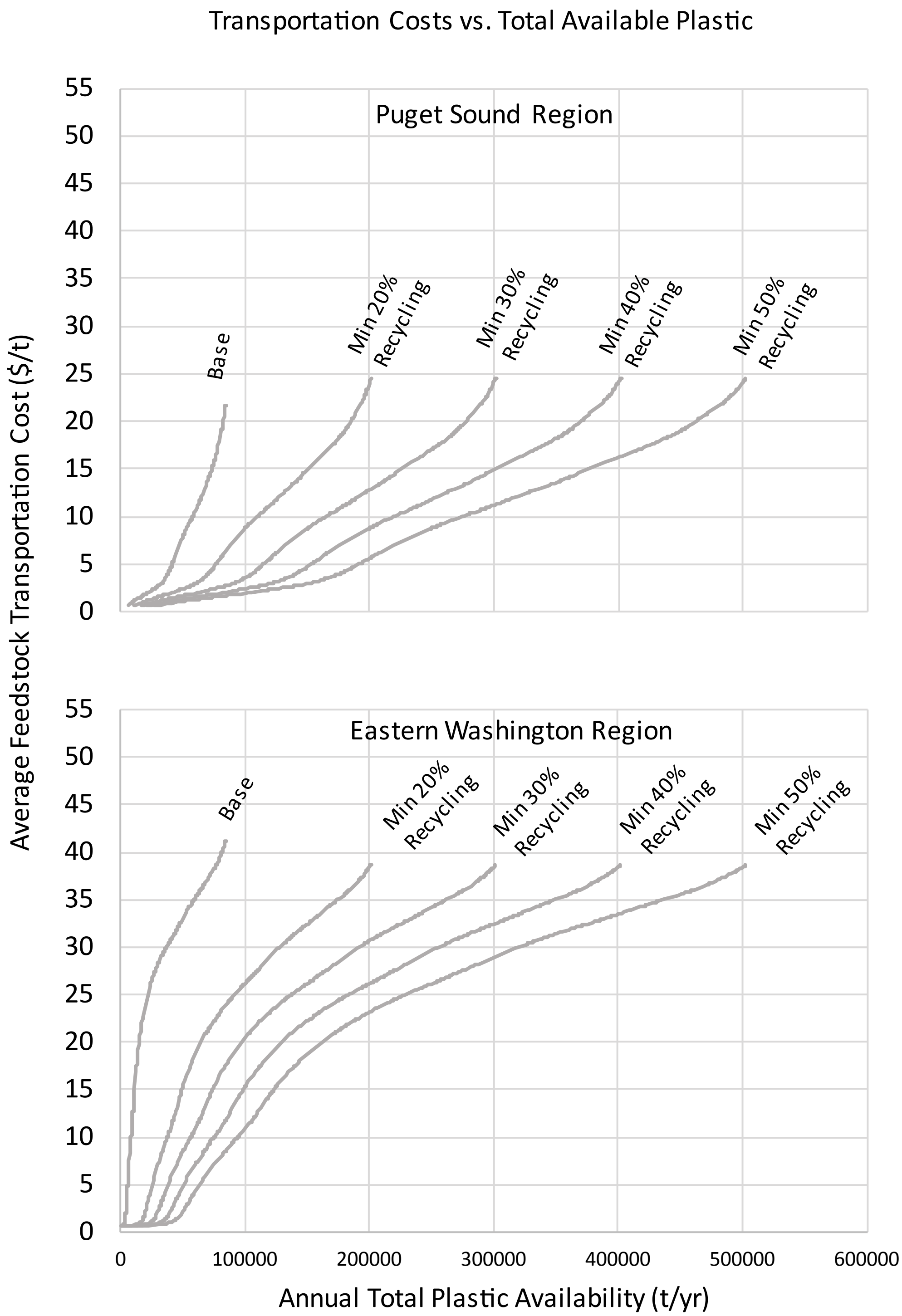


Figure 5: Transportation costs and available plastic for the two regions with varying recycling rates.

Preliminary Techno-economic Analysis (TEA) for Chemical and Thermal Recycling Methods

A financial analysis was used to assess the economic feasibility and to identify the most influential variables of three processes of converting plastic waste: gasification Fischer-Tropsch, pyrolysis, and glycolysis. Although the same framework was used to build each TEA, the level of detail varies based on the quantity and quality of public information. The assumptions and costs for each process were unified as possible. One underlying assumption is that the modeled plants are mature technology, with no additional capital or operating costs are incurred that will be needed in early iterations of commercializing new technology.

Economic Analysis Methods

The fixed capital investment (FCI) was estimated by applying ratio factors to delivered inside battery limit (ISBL) equipment costs. ISBL equipment is equipment that is part of the primary process, while outside battery limit (OSBL) costs are for supporting equipment that is common to most manufacturing processes, for example electrical distribution, buildings, and yard improvements and indirect costs such as legal and engineering fees.[2] The ratio factor method aligns with preliminary, or study estimates with an accuracy range of ±20-30% for analyses with detailed equipment information and has been widely utilized.[3-9] Ratio factors simplify the comparative analysis of greenfield, co-located and repurposed facilities, which can improve financial performance.[5,7] Capital costs were combined with operating costs and product yields to calculate a product minimum selling price for a variety of scenarios using each process techno-economic analysis (TEA). The TEAs are adaptations of those described in detail in Tanzil et al.[14] for pyrolysis and gasification Fischer-Tropsch. Adaptations related to scale, feedstock, and the removal of all capital and operating costs after the production of bio-oil or syngas. Glycolysis of PET into polyester was modeled using adaptations to Drah et al.[15] for scale, location, and cost year. Yield was chosen from the range presented in Ügdüler et al.16 The basic economic parameters utilized are listed in Table 1, further methodology details are provided in Tanzil et al.[14]

Table 1. Economic parameter assumptions.

Economic Parameter	Assumed Value
Cost Year	2017
Plant Financing	30% equity, 70% loan
Loan Rate, Term	8%, 10 years
Plant Life	20 years + 3 years construction
Income Tax Rate (OECD, 2019)	17.3%
Working Capital	20% yearly operating cost
Nominal Financial Discount Rate	12.2%
Inflation	2%

For all three processes, the incoming feedstock is assumed to be waste plastic that is then shredded before entering the process. If further processing is needed for a specific process, i.e. melting and processing through an auger, additional costs will be incurred. Our assumption is that the feedstock is 100% plastic, however literature sources discuss increased yield when co-processing for gasification, which may require additional capital and operating costs.[35] The pyrolysis TEA output is bio-oil that can be further processed with varying expected technical and financial success into biofuels, chemicals, hydrogen, plastics.[36] Gasification of plastic, in our models, ends with clean syngas, which has a wide variety of applications including fuels, energy and chemicals.[37] The glycolysis process has the least publicly available information. The TEA is based on Drah et al. and Ügdüler et al.[15,16] and should be interpreted with caution as additional information is needed to verify the costs are complete and realistic.

For the purposes of discussion, a baseline case for each process was selected. All of the baseline values listed in Table 2 are for facilities located in the generalized Puget Sound region of Western Washington. This location was chosen because it has the lowest cost feedstock resulting from the shorter transportation distances required to meet facility demand. However, Eastern Washington was also analyzed and although the cost increased, the practical impact was low as the minimum selling price is driven by costs outside of feedstock transportation. The analyses for the two locations shown: Puget Sound and Eastern WA were completed with geospatially adapted variables. The labor cost for Eastern WA was reduced by 6% (BLS 2019), the electricity was increased from 0.05/kWh to 0.06/kWh38 and the feedstock transportation costs follow the supply chain analysis, varying with both location and required quantity.

The glycolysis TEA is dominated by operating costs, including the higher feedstock transportation costs associated with the more restricted feedstock stream. As a result, while larger scale facilities preform better financially for a given total feedstock price, the impact of scale is overshadowed by higher transportation costs (Figure 6). The scale of the baseline pyrolysis and gasification facilities is 50,000 t/yr of mixed plastic feedstock. The selected feedstock scale drops significantly for glycolysis to 10,000 t/yr. These scales were chosen to match the available, regional feedstock quantities while minimizing the required MSP. Costs will change if recycling rates are altered and more volume becomes available.

Table 2: FCI and MSP for three facility scales located in the Puget Sound region. The baseline numbers for each process are designated with bold text.

Process	Variable	Facility Scale (t/yr)		
		10,000	25,000	50,000
Pyrolysis	FCI (million $)	36	55	**81**
Gasification	FCI (million $)	27	51	**83**
Glycolysis	FCI (million $)	**8**	13	
Pyrolysis	MSP (bio-oil $/t)	1451	834	**599**
Gasification	MSP (syngas $/t)	1219	826	**654**
Glycolysis	MSP (polyester $/t)	**3298**	3999	

Figure 6 shows the impact of facility scale on MSP for each process and their assumed products. The value of bio oil, the pyrolysis product, is difficult to quantify. However, Tanzil et al.[14] compared pyrolysis fuel values to petroleum fuels with bio oil as the intermediary, which allows us to estimate a value of bio oil if it is used for petroleum fuels and this range is the grey band in Figure 6. Syngas, the product from the gasification process, has a defined value, which is illustrated by the grey bar in Figure 6. The range shown covers values for syngas using either coal or natural gas a feedstock.[39] The range of values for polyester is shown in Figure 6 by the grey band.[40-42]

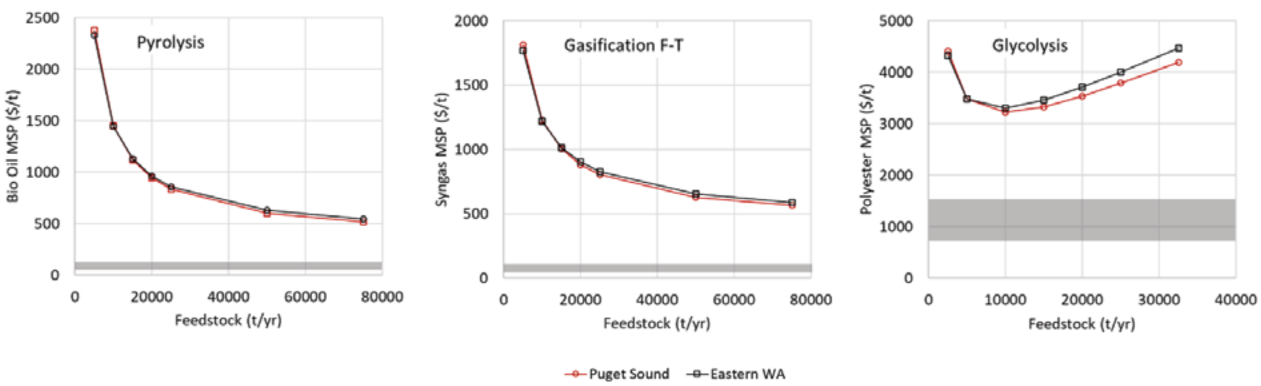


Figure 6: Impact of facility scale on MSP for pyrolysis, gasification and glycolysis recycling operations.

*increasing and decreasing scale for glycolysis increases MSP as a result of high feedstock transport costs.

Feedstock price has a predictably significant influence on product MSP. The value of mixed plastic waste used for pyrolysis and gasification is not well documented and the values are volatile. Published costs are often for a single type of plastic which includes sorting costs that are not needed in the modeled processes. Plastic Markets lists the price for waste plastics without sorting at $22/t, but with low-high sorting the price increases to over $150/t.43 We assumed a mixed plastic waste value of $50/t, which allows for some processing, but does not include significant sorting. Figure 7 illustrates the impact of feedstock price on two facility scales as well as both locations in Washington State.

The predicted MSP values for polyester made from PET using the glycolysis process are shown in Figure 7. The same baseline feedstock price of $50/t was assumed. Although this is below the price of PET bottles, recycling centers charge $110-550/t to recycle PET carpet.[44] Our assumed price was validated as reasonable in discussions with Eastman, but will change based on actual processes. The trend of increasing MSP with increasing feedstock price follows the other processes. However, the difference in the two locations at a scale of 10,000 t/yr clearly demonstrates the impact of the increased transportation costs.

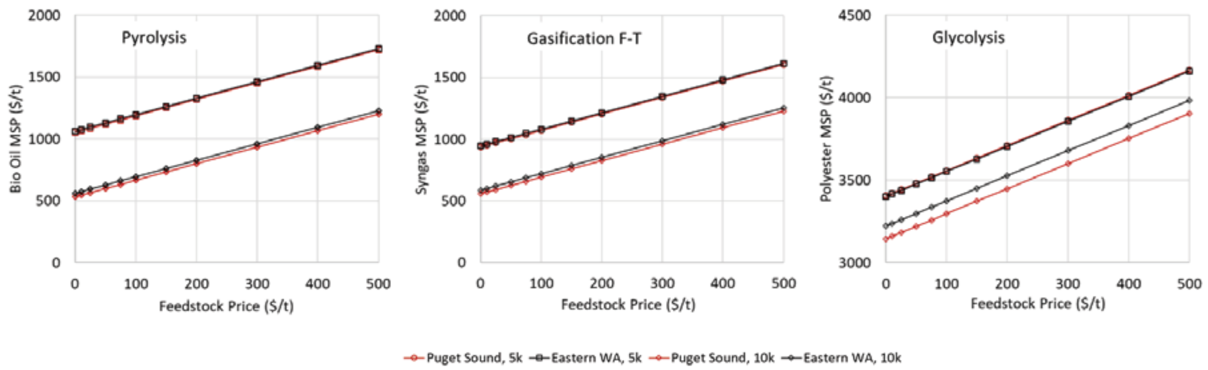


Figure 7: Impact of feedstock price on MSP for baseline scale pyrolysis, gasification and glycolysis facilities at two locations and facility scales.

Yield is another value that will change with specific process parameters and affects product MSP. For each of the three processes, a range of yield values were evaluated for a subset of feedstock prices (Figure 8). The same yield of wt/wt 0.8 was assumed for pyrolysis and gasification.[45-47] The wide band shown for glycolysis demonstrates the high impact of the wt/wt 0.7±0.15 on MSP.

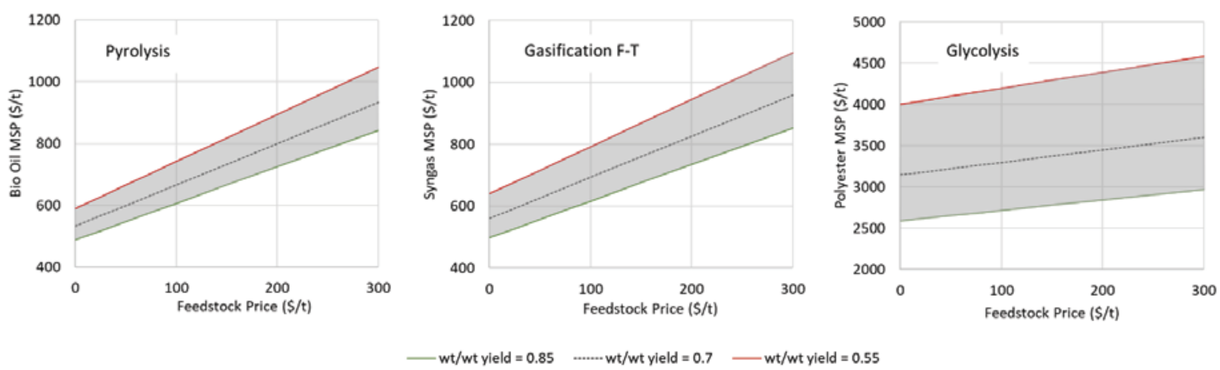


Figure 8: Impact of assumed product yield on the MSP for: pyrolysis, gasification and glycolysis.

The gap between the grey bands of estimated, current product value and predicted MSP values shown Figure 6 demonstrates that the MSP values calculated are not cost competitive in the baseline scenario. To help determine the most influential variables, a single factor sensitivity analysis was completed (Figure 9). Scale, feedstock price, capital investment and yield are the four most influential variables for both pyrolysis and gasification. Glycolysis has the same variables in the top five, but electricity is also influential as it is a large part of the non-feedstock operating costs. It should be noted that both increasing and decreasing the scale of a glycolysis facility is predicted to increase the MSP resulting from the large feedstock transportation costs.

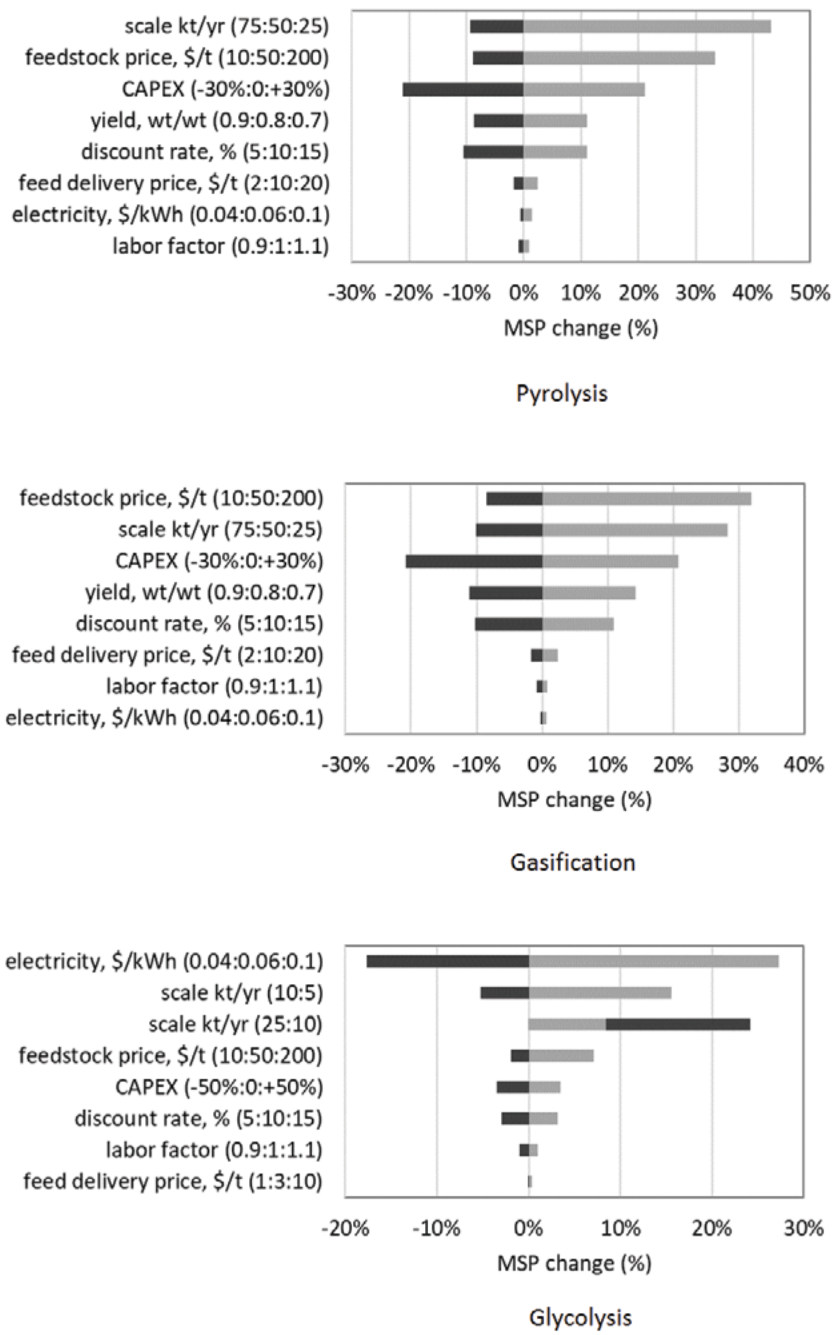


Figure 9: Impact of assumed product yield on the MSP for: (a) pyrolysis, (b) gasification and (c) glycolysis.

Even with a combination of optimistic variable values, the MSPs required make the scenarios financially viable are high. However, there are options to reduce costs. If an existing industrial facility is repurposed, a portion of the OSBL costs can be avoided, which will reduce the capital costs and thus the resulting MSP. For this discussion, the costs related to yard improvements were removed and building costs were reduced. The general category of service facilities had some minor reductions with the removal of sanitary waste disposal and raw material storage. Specific locations will need to be analyzed to calculate more precise reductions, which could vary positively or negatively from the assumptions made. The resulting FCI dropped 12% for both pyrolysis and gasification, which results in a 9% drop in MSP (Table 3).

TABLE 3: Repurposed FCI and MSP for facility scale of 25,000 t/yr located in the Puget Sound region.

Process	Variable	Repurposed Value	Reduction
Pyrolysis	FCI (million $)	71	12%
Gasification	FCI (million $)	73	12%
Pyrolysis	MSP (bio-oil $/t)	547	9%
Gasification	MSP (syngas $/t)	573	9%

Investment Needs

The report by the Recycling Partnership indicated a $17B investment is needed over the next 5 years to boost the existing US recycling framework with returns on investment over $30B in the next 10 years.[48] Circulate Capital declares a $5B/yr investment is needed to keep plastics from entering our waterways. Much of the plastics in our water originates from Asia, so higher investment in collecting and diverting in these regions is required.[49] However, the US and many European nations also contribute a significant amount of plastics to our oceans, where an estimated 2% of all plastics generated can enter our waterways.[50]

These numbers can be daunting and be looked at as an obstacle or an opportunity to expand job base, taxes and most importantly the generation of a raw material stream. Investment groups such as Closed Loop Partners focus the funding strategy around circular economies related to recycled plastics within their Closed Loop Circular Plastics Fund. This Investment fund was established by Dow, LyondellBassell and Nova Chemicals.[51] These big-name players provide additional security to other investors to pursue similar investment paths in the plastic recycling market.

There is a definite need to secure investment dollars to make any recycling process a success. The high capital costs make it difficult to facilitate a start-up operation along with uncertainty in the supply chain from feedstock costs and consistency to the final market acceptance of the recycled product. Having investors that are educated and informed about the recycling supply chain is a must for them to be comfortable to invest in what can be a somewhat risky venture. Without sufficient investment management, smaller companies and start-ups will have a difficult time securing investments and mitigating risks.

Next Steps for WA State

The information provided in this report details the existing and emerging technologies in the plastics recycling world. If Washington State wants to position itself to create an innovative and sustaining plastic recycling manufacturing sector, understanding the options available and the pros and cons of each is imperative.

The intent of this effort is for stakeholders within or looking to be within the plastic recycling value chain have sufficient resources and validation to assist in the decision making process. Whether a new start-up is looking to locate in the State or an existing industry is looking to expand their recycling operations, the information provided in this report, the PRT database and the expertise of the Team to compiled this report should be utilized to aid in the assessment of plastic recycling technology.

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Links

RTP Database: https://docs.google.com/spreadsheets/d/1IghF9MfYDyfHZY4hU5F1_CQEQ4vfwzZXUI0wOWwb4ww/edit?usp=sharing

AERT: https://www.moistureshield.com/
Agilyx: https://www.agilyx.com/
Agri-Plas: https://agriplasinc.com/
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Rainier Plastics: https://www.westcoastplasticrecycling.com/
Renew ELP: https://renewelp.co.uk/
Rise Building Products: https://www.risebuildingproducts.com/
Riverdale Global: http://www.riverdaleglobal.com/regrind-100-percent-use
Sabic: https://sfs.sabic.eu/
Styro Recycle LLC: https://www.closedlooppartners.com/
Sukano: https://www.sukano.com/en/applications/rpet
Tangent Technologies: https://tangentmaterials.com/
TieTek: http://www.tietek.net/
Timbertech (Azek): https://www.timbertech.com/
Trex: http://www.trex.com/
Westcoast Plastics: https://www.westcoastplasticrecycling.com/

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