Potential Northwest Regional Feedstock and Production of Sustainable Aviation Fuel

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WASHINGTON STATE UNIVERSITY

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Executive Summary

In 2011, the Sustainable Aviation Fuels Northwest (SAFN) collaborative completed the nation's first regional stakeholder effort, examining the feasibility, challenges, and opportunities for creating a commercially viable, sustainable aviation fuel (SAF) industry in the Northwest. This report builds upon the original SAFN effort with an updated review of SAF supply chain and economic scenarios for the Northwestern (NW) U.S., defined as Washington, Oregon, Idaho and Montana. Information for British Columbia feedstock was also included where readily available.

This work supports the Port of Seattle's efforts to meet their goal to have a 10 percent SAF jet fuel blend available at Seattle-Tacoma International Airport by 2028. In addition, it provides valuable techno-economic analyses for SAF production pathways to producers, airlines, and policymakers. This review quantifies available regional feedstock suitable for ASTM-approved pathways for producing SAF. In addition, the potential quantities converted to SAF were modeled, as well as the minimum selling prices (MSP) for the fuel products for each of the feedstock types.

The feedstocks evaluated in this report include lipids from oilseeds and fats/oils/grease (FOGs), forest residuals, and municipal solid wastes. The conversion pathways evaluated for these feedstocks included hydro-processed esters and fatty acids (HEFA), alcohol-to-jet (ATJ), and gasification Fischer-Tropsch (GFT). These modeled pathways are generic in nature and do not represent any specific proprietary process.

The minimum selling prices (MSPs) for SAF provided are at the production facility and do not include transportation to airports unless specifically stated. A range of MSPs at the biorefinery was determined for each pathway and feedstock combination. The low value of the MSP range assumes a production facility with mature technology, and the high value represents a pioneer, or first of a kind facility/technology.

A summary of the benefits and challenges of each conversion pathway are discussed below.

Lipids/HEFA

SAF produced using lipids via the HEFA process is the lowest cost option, approaching cost parity with conventional fuels. However, waste fats, oils, and greases (FOGs) are necessary to achieve these lower fuel prices. This requirement presents a challenge because most of the regional FOGs feedstock is under long-term contract and the amount available for potential SAF production is estimated to be at or near zero. The alternative to FOGs , for this study, is regionally grown oilseed crops processed into canola oil which is then converted to SAF.

Producing the volumes of oilseeds needed for fuels production in the NW would require a significant change in regional agricultural practices as the current production of canola is low. Because the HEFA process requires a low capital investment and results in a high fuel yield, it can counteract the elevated feedstock costs when compared to other options. The HEFA model used for this project assumes a total liquid fuel or total distillate slate including jet, diesel, naphtha, and propane. The two largest categories are jet (55%) and diesel (26%) followed by propane (11%) and naphtha (8%). This pathway will only be viable in the near term by importing feedstock from other regions of the U.S. or overseas.

Forest Residuals/GFT or ATJ

Forest residuals are material remaining after traditional forest harvest practices are complete. This feedstock is plentiful in the region and currently has little commercial value. While it is necessary to leave some of this material on the site for forest health and environmental purposes, the excess is typically burned to facilitate replanting and forest fire protection. Our models assume utilizing 47% of the total amount of forest residuals produced from 2019 harvests, leaving ample material for environmental services. Commercial competition for this material is low, which translates to low feedstock cost. However, costs of collection and transportation to a conversion site can be high when the forest density is low and conversion plant sizes are large.

It is technically feasible to convert forest residuals into SAF using either the ATJ or the GFT process. The modeled MSP values from the ATJ process include the economic benefit of producing two co-products to utilize the wood components that are not converted into fuel. For ATJ, the total distillate is a combination of 70% jet fuel and 30% iso-octane gasoline. For GFT, the total distillate includes jet fuel (40%), diesel (40%) and naphtha (20%). Because the primary driver for forest residual costs is transportation, a logistics optimization model was used to select the lowest cost locations for SAF facilities and the optimized capacities for these facilities within the region.

The total fuel production using forest residuals was 170-210 million gallons/year split between three plants located near Northwest Oregon, the Western Columbia River region, and Northwest Idaho. The Idaho facility is 60% of the size of the other two facilities. This is an aspirational goal that would utilize 94% of accessible feedstock, or 47% of the total available in the region. The markets for the co-products created in this model would need to be better assessed to verify if this production scale can be supported. Northwest Oregon and the Western Columbia River region were determined to be the lowest cost locations if only a single ATJ facility is built. In this scenario only 36% of the regional feedstock is utilized. Of the feedstock/conversion combinations surveyed, forest residuals converted with either GFT or ATJ are consistently more expensive than petroleum jet fuel. In both cases, incentive programs will be needed to achieve economic viability.

Municipal Solid Waste/GFT

Municipal solid waste (MSW) is plentiful, currently aggregated by an existing disposal system, and not well utilized for secondary products. The viability of using MSW for producing fuels via GFT was assessed. In this scenario, an automated sorting facility is added to the modeled facility to produce a suitable feedstock stream. The assumed GFT feedstock is primarily composed of waste paper and wood contaminated with 16% plastics. It is important to note that this feedstock stream is separated from the MSW after all potential recyclables are removed. The marketable recycle streams are considered in the total revenues for the facility. With this additional sorting facility, the capital cost of this process is the highest of any pathway/feedstock combination. However, in this scenario, the high capital cost is balanced by a zero-feedstock cost when the SAF is produced at a landfill. The zero feedstock costs for MSW is justified by the avoidance of tipping fees and substantial savings from landfilling. The largest regional landfill is the Columbia Ridge Landfill in Arlington, OR. The model used to depict SAF made from MSW divides the total distillate into 40% jet, 40% diesel and 20% naphtha. The addition of incentives is required for this pathway to be achieve price parity with petroleum aviation fuel. MSW can be converted to SAF using other technologies, including ATJ, however sufficient public knowledge was not available at the time of this report.

Key Findings

• There is sufficient volume of available feedstocks in the Pacific Northwest to produce up to 220-290 million gallons of sustainable aviation fuel per year (80-130 from forest residuals and 140-160 from MSW), or about one-third of the fuel dispensed at Seattle-Tacoma International Airport. However, economic models predict the minimum selling prices using these feedstocks in early generation/pioneer plants to be 3-5x higher than cost of conventional jet fuel.

• There is insufficient regional supply of lipids for SAF production. Conversion of waste fats, oils and grease using the HEFA process is currently the lowest-cost scenario for producing sustainable aviation fuel. It is currently believed that this feedstock is fully utilized in the Northwest U.S.by other industries.

• Utilizing purpose-grown oilseeds in the HEFA process will substantially increase the fuel cost and require considerable change in practice by the agricultural community. Even though the region has potential for oilseed production, there is not adequate availability to supply sustainable aviation fuel production. Any lipid feedstock would need to be imported into the region to support this pathway.

• MSW and forest residuals-based fuel production facilities will require large capital investments, and the technology has not been proven at scale.

• Models indicate the best logistical costs for MSW and forest residual conversion in the region are realized when biofuel facilities are located are Oregon.

• When evaluated from a purely logistical standpoint, the lowest-cost delivery market for fuels produced from either MSW or forest residuals is Portland, OR.

• Financial incentives will be necessary to bring sustainable aviation fuel to price parity with petroleum jet fuels. These incentives will likely be a combination of policies such as low carbon fuel standards (LCFS), the federal Renewable Fuel Standard renewable identification numbers (RINs), blender tax credits and green bonds to help incent business investments.

• Given existing incentive programs, the most likely location for the fuel to be sold is California as a result of the Low Carbon Fuel Standard (LCFS) incentive. In addition, Oregon will be a potential market as this state's LCFS is implemented.

1.0 Introduction

In 2017, the Port of Seattle set a goal to power every flight fueled at Seattle-Tacoma International Airport (SEA) with at least a 10% blend of sustainable aviation fuel (SAF) by 2028. This is equivalent to a volume of approximately 75 million gallons per year, assuming SEA's fuel demand will grow to 750 million from the current 650 million gallons per year. The goal delineated increasing SAF use for 2028, 2035, and 2050. An important principle of the goal is that the fuels be "produced locally from sustainable sources" (Port of Seattle, 2017). To help achieve these goals, airlines operating at SEA, signed an MOU with the Port of Seattle (Port of Seattle, 2018).

The Washington legislature and Governor Inslee have established regulations, programs and initiatives to address the State's greenhouse gas emissions (State of Washington Department of Ecology, 2019a). Jet fuel and aviation gasoline contribute 7.8% of Washington's total greenhouse gas emissions, which is nearly three times the national average of 2.7% (State of Washington Department of Ecology, 2019b, ICAO, 2019a). Achieving the Port's SAF goal will make an important contribution toward the State of Washington reaching its climate goals.

In 2009, the global aviation industry adopted three ambitious targets to reduce carbon dioxide emissions: an average 1.5% improvement in fuel efficiency from 2009-2020; a cap on net CO2 emissions from 2020 (i.e., carbon neutral growth); a net 50% reduction in CO2 emissions by 2050, relative to a 2005 baseline (IATA, 2015). SAF contributes to the industry's goals in two ways. First, the International Civil Aviation Organization (ICAO) established the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) which requires airlines to offset international growth emissions either through the purchase of carbon offsets or using CORSIA eligible fuels (i.e., SAF). Second, the introduction of a commercial supply of SAF into the global aviation fuel supply chain, plus technology and operational improvements, is essential for the industry to meet its 50% emission reduction target. The Port's SAF goal will also move the industry forward in achieving its goals.

This study was conducted to inform the decision making for the Port of Seattle SAF goals. The objectives are to:

1. Estimate the commercially available feedstock quantities for fats, oils and greases (FOGs), oil-seeds, forest residuals and municipal solid waste (MSW) for use in manufacturing SAF, and

2. Estimate SAF volume and minimum selling price (MSP) via certified conversion pathways from those regional feedstock quantities.

1.1 Sustainability of Feedstocks and Fuel Production

In the 2011 Sustainable Aviation Fuel Northwest (SAFN) report, the stakeholders recognized the need to evaluate and demonstrate the long-term sustainability of SAF production. SAFN did not want to "reinvent the wheel" by developing its own sustainability criteria and identified the Roundtable on Sustainable Biomaterials (RSB) principles as the most appropriate screening tool for sustainability issues.

Since that time, there has been significant work done worldwide to define the parameters of SAF sustainability. This includes work through the International Civil Aviation Organization (ICAO) Committee on Aviation Environmental Protection (CAEP). Members of a CAEP subcommittee have been working to develop a Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), which includes methods for sustainability certification of CORSIA-eligible fuels. It is expected that final CORSIA standards will soon be adopted.

The shared principles among most sustainability certification programs for alternative fuels include the following:

- Sustainable Production. Raw materials may not come from land that has been converted from primary forests, protected areas, highly biodiverse grasslands, areas with high stocks of carbon or peatlands.

- Other environmental impacts. The production, conversion and logistics may not lead to negative impacts on soil, water and air quality.

- Efficient energy conversion. Bioenergy chains should strive for maximum energy efficiency in feedstock production and conversion and logistics.

- Protection of biodiversity. The production of biomass may not negatively affect biodiversity.

- Contribute to local prosperity and welfare. Bioenergy chains should contribute towards social well-being for employees and local population.

The Port of Seattle anticipates that tenant airlines will require their suppliers to provide verification that the SAF meets accepted sustainability criteria. The feedstocks and conversion technologies explored in this report will be evaluated through this sustainability lens as more specific fuel projects are defined.

1.2 Existing Fuel Production Facilities

Waste FOGs are typically used to manufacture biodiesel in the Pacific Northwest. Locally grown vegetable oil can be used to supplement FOGs as a feedstock when the feedstock supply is low. There are three existing biodiesel plants: Sequential in Salem, OR, General Biodiesel in Seattle, WA and REG in Grays Harbor, WA. Their respective production capacities are 17, 5 and 100 million gal/year, with expected feedstock demands of approximately 62,000, 18,300 and 381,000 tons/year when operating at full capacity (EIA, 2019). Used cooking oil (UCO) is the preferred feedstock for Sequential and General Biodiesel. UCO storage, collection and transportation are vertically integrated from these two companies operating throughout the NW. Sequential collects UCO throughout all of Oregon and Washington and into California as far south as San Francisco and Sacramento (Sequential, 2019). REG Grays Harbor has a stated feedstock of "low free fatty acid feedstocks" (REG, 2020).

NEXT Renewables plans to build a HEFA biodiesel refinery near Clatskanie, OR. The finished capacity of this facility is projected to be nearly 600 million gal/year and would require 2.2 million tons of lipid feedstocks per year (NEXT Renewables, 2019). In addition, BP is conducting co-processing trials with animal fats and crude petroleum in one of its diesel units at its Cherry Point refinery near Blaine, WA (Gallagher, 2018, Kessel, 2019).

World Energy manufactures a full slate of biofuels, including SAF. SAF is made at the Paramount, CA facility using agricultural waste fats and oils. World Energy and Shell Aviation are working together to create more impactful scale of SAF that will be delivered to the San Francisco International Airport and utilized by Lufthansa (Biofuels International, 2020).

Red Rock Biofuels is building a GFT forest residuals-to-biofuels production facility in Lakeview, OR. It will process 136,000 tons/year of feedstock to produce 15.1 million gallons/year of biofuels. The announced facility cost is $320 million (Kennedy, 2018; Red Rock Biofuels, 2019). The fuel from the facility is expected to be used by FedEx and Southwest Airlines planes flying out of the Oakland International Airport in California (Greene, 2016, Southwest Airlines, 2014).

Northwest Advanced Bio-Fuels (NWABF) announced an offtake agreement with Delta Airlines for a sustainable biofuel refinery in Hoquiam, Washington using forest residuals (Delta, 2020). These two projects illustrate the potential for using forest residuals for SAF.

GEVO has a functioning alcohol-to-hydrocarbon demonstration facility in Silsbee, Texas. The technical feasibility of converting forest residuals to jet fuel using the GEVO process was demonstrated as part of the Northwest Advanced Renewables Alliance (NARA) (Wooley, 2016).

LanzaTech currently uses the ATJ process to upgrade ethanol to jet fuel. LanzaTech is in negotiations with the U.S. government for a large investment in a pilot-scale ATJ facility in Georgia using proprietary processes (Sherrard, 2019). LanzaTech also practices a unique gas fermentation process that allows various waste feedstock to be fermented into ethanol. While this process requires carbon monoxide (CO) as the fermentation feedstock, the CO can be derived from a variety of sources including industrial process gases or gasification of a variety of biomass resources including forest residuals and MSW (LanzaTech, 2020).

Fulcrum Bioenergy is planning to use sorted MSW to manufacture biofuels at a plant that is under construction in Storey County, Nevada (Fulcrum, 2019). It has built and is operating a feedstock processing facility (FPF) to sort incoming MSW. The biofuels plant is expected to begin production in 2020. The biofuels plant will convert 175 million tons of feedstock per year into 11 million gallons of synthetic crude oil, also known as syncrude. The syncrude will be shipped to and upgraded at Marathon Petroleum.

2.0 Methodologies

The following descriptions of used throughout the analyses cover the methods used to quantify and locate feedstock, the feedstock to fuel conversion pathways, the economic methodologies and assumptions and the models used for siting biorefineries.

2.1 Feedstock Availability Assessment

Lipids, forest residuals and municipal solid waste (MSW) were evaluated for availability as feedstocks to manufacture SAF in the NW U.S. The potential quantity and location of each feedstock was determined, and the total amount was reduced to an available amount based on existing industry demand and physical accessibility.

Lipids, as a regional feedstock, can be divided into three categories: waste fats, oils and grease (FOGs), vegetable oils from purpose-grown oilseed crops such as canola, mustard, rapeseed, soybean or corn oil and tall oil from pulp production. Used cooking oil (UCO) is a specific type of FOG. The quantity of UCO estimated in this study is based on population and population density. Waste fats and greases are collected at slaughterhouses and the amount produced is based on the type and count of animals that are processed at each location. The quantity of tall oil is a rough estimate based on the kraft paper production in the NW.

Forest residuals is the material that remains after timber harvest and the merchantable logs have been collected and sold. These residuals are typically burned in slash piles. Forest residuals are tracked by the U.S. Forest Service. The total amount available is contingent on the harvest method which determines the realistic amount that can be affordably removed.

MSW production is estimated using per capita state values and census information. The total MSW is reduced to include only the disposed (i.e., landfilled) portion. The landfilled portion is then sorted into material that is suited for conversion into liquid fuels for a given process. Oregon and Washington have data on the disposed fraction that is used to further reduce the mass of MSW to only include the material that aligns with the chosen conversion pathway.

2.2 Conversion Pathways

The conversion pathways modeled to estimate minimum selling price (MSP) were chosen based on the feedstock type, ASTM approval and publicly available data (Lane, 2019). **These models represent generic processes for producing SAF and are not intended to replicate commercial entities who employ proprietary technologies to improve competitiveness.** Hydro-processed esters and fatty acids (HEFA) is the pathway for the lipid feedstocks. Alcohol-to-jet (ATJ) and gasification Fischer-Tropsch (GFT) are both options for forest residuals and GFT was chosen for converting MSW. Terse process descriptions are included, however more process details can be found in the cited literature.

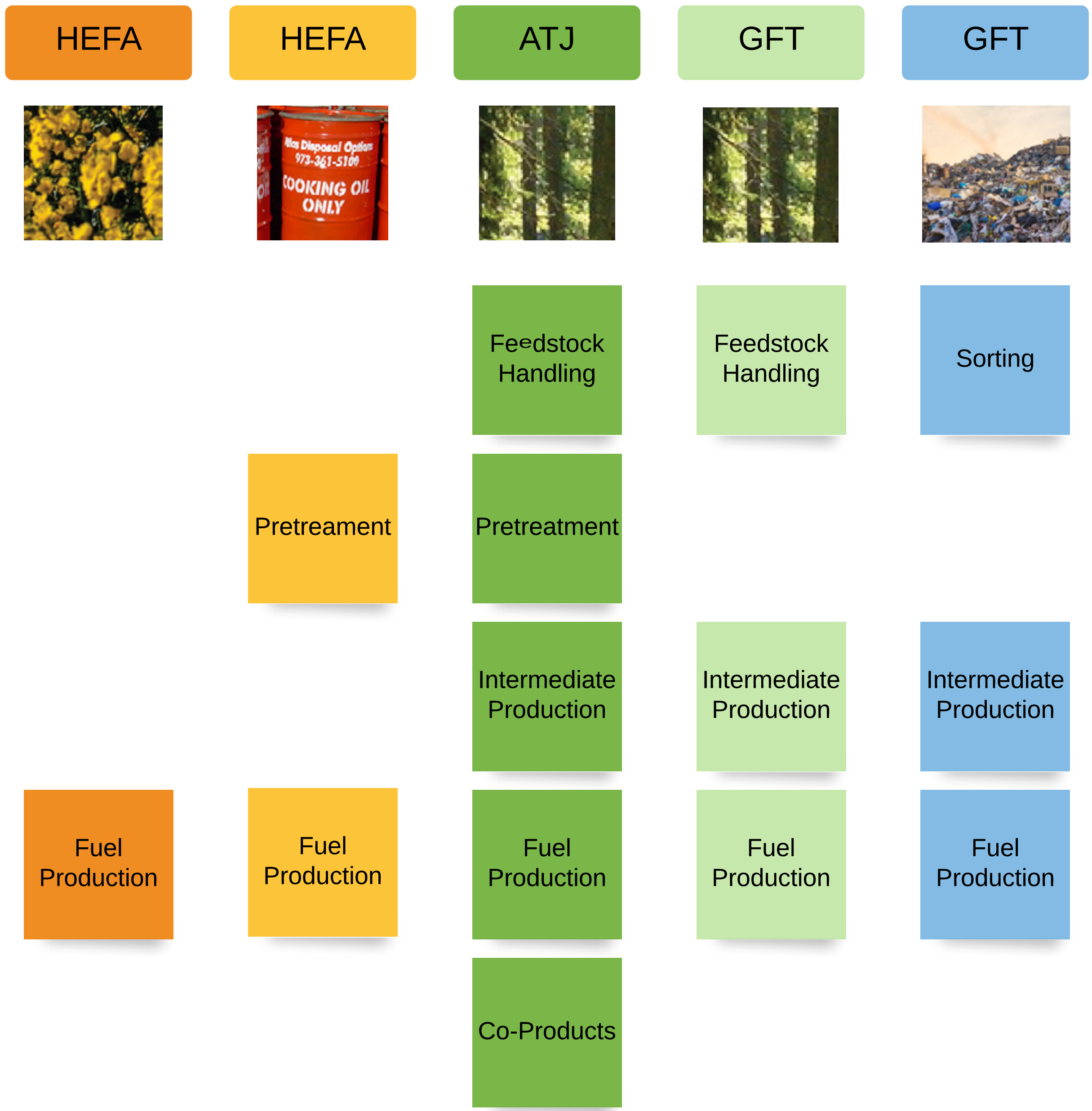
HEFA conversion has three basic steps: hydrogenation, cleaving propane, and removal of oxygen. Hydrogenation uses hydrogen to saturate free fatty acids in the presence of catalysts. The propane backbone is then removed, leaving three oxygenated fatty acids. The oxygen attached to the fatty acids is then removed and released as carbon dioxide, carbon monoxide or water (CO2, CO or H2O, respectively) (Tao et al., 2017).

The integrated ATJ biorefinery process model converts forest residuals into simple sugars which are fermented into isobutanol before upgrading to liquid fuels (Chen et al., 2017, Geleynse et al., 2018). The capital costs provided reflect the additional processes to fully utilize the collected biomass. ATJ economics are impacted by feedstock type and cost, intermediate alcohol produced, the process used to manufacture the intermediate alcohol and other proprietary processes. The model included is just one pathway that utilizes information that is available in the public domain.

Finally, GFT is a thermochemical pathway used to produce biofuel. Feedstock is partially oxidized using a combination of air, steam and/or oxygen. The result is a mixture of gases that are often called synthesis gas or syngas. The syngas is then cleaned before catalytic conversion into liquid fuels (Swanson et al., 2010).

The capital costs and equipment requirements vary among the pathway and feedstock combinations. These differences partially result from differences in initial feedstock chemistries which dictate the number of steps required to convert the material into a hydrocarbon. In short, all biological feedstocks contain oxygen. Those with the greatest amount of oxygen and the most diverse set of constituent compounds tend to require more operations resulting in higher capital costs to convert. Figure 1 demonstrates that HEFA has fewer manufacturing steps to convert lipids into liquid fuels compared to both GFT and ATJ.

Figure 1: Manufacturing area summary for the conversion pathway and feedstock combinations.



The models are built from public information and as such the yields are based on similar information. The separation process is similar for all of the pathways; however, the resulting liquid fuel quantities vary. The total liquid fuel is termed “total distillate” and is the sum of all liquid fuels produced. For each pathway and feedstock combination, the total distillate is divided based on the method and infrastructure in the literature models (Table 1). It is important to note the infrastructure and processing choices will impact these values.

Table 1: Total mass percent distillate breakdown for pathway/feedstock combinations.

Pathway	HEFA	HEFA	ATJ	GFT	GFT
Feedstock	Vegetable oil	FOGs	FR	FR	MSW
Jet	55%	55%	70%	40%	40%
Iso-octane gasoline			30%		
Diesel	26%	26%		40%	40%
Naphtha	8%	8%		20%	20%
Propane	11%	11%			

2.3 Economic Methodology

Techno-economic analyses for each feedstock and pathway combination were used to estimate ranges for the minimum selling price (MSP) of SAF. The expressed range is established using a set of common assumptions (Table 3) for technology scenarios denoting high, mature and low costs (Table 2).

The financial analysis was completed using the method outlined by Petter and Tyner for an assumed mature technology (i.e., a facility that is deploying technology that has been used successfully in previous facilities) (2014). A range of MSP values were calculated for each feedstock, technology and facility scale combination. The capital costs for the mature technology scenarios were increased using the RAND method to determine cost growth factors and are identified as pioneer CAPEX. These factors are used to increase the estimated capital investment for new, unproven technologies. Unless specifically stated, all MSP values presented as a single value are for "high" costs, which include increased CAPEX for pioneer facilities. Pioneer facilities are ones that use early generation, or unproven technology.

The cost growth factors applied were calculated based using the information in Merrow et al. (1981) and de Jong et al. (2015) and are 0.93, 0.58 and 0.50 for HEFA, ATJ and GFT, respectively. These cost growth factors were applied to each process. However, the cost growth factor of 0.50 for GFT was not applied to the sorting manufacturing area for the MSW model because this manufacturing area is an established process that can be a separate business and applying the cost growth factor would falsely inflate the capital investment. In addition to cost growth factors, Merrow et al. (1981) defines plant performance as a percent of the nameplate production and it incorporates both the novelty of the process and the type of process. Plant performance was calculated for each process and the percent of the total nameplate production volume was assumed to grow by 20% per year until 90% was reached (de Jong et al. 2015). The performance factors used are 85.8%,40.2% and 41.7% for HEFA, ATJ, and GFT, respectively. The performance factor for HEFA was not applied as it is less conservative than the assumed start up schedule for nth plants.

The increased capital costs combined with increased feedstock cost and lower yields represent at the high cost end of the ranges discussed. Facility capital requirements and minimum selling prices are expected to decrease as the technology matures, these estimates are labeled "mature". The lowest numbers in each range provided represent a reduction in capital costs of

10% from mature as well as a drop in feedstock costs. Yield improvements for pathways other than HEFA were also included. This set of data is labeled “low” and is meant to show a possible minimum selling price goal with continued technology improvement.

Table 2: Scenarios used to create MSP ranges at multiple facility scales.

	High	Mature	Low
HEFA	pioneer CAPEX, +10% feedstock cost	mature CAPEX, no change to OPEX or yield	mature -10% CAPEX, -10% feedstock cost
ATJ	pioneer CAPEX, +10% feedstock cost, -5% yield	mature CAPEX, no change to OPEX or yield	mature -10% CAPEX, -10% feedstock cost, +5% yield
GFT-forest residuals	pioneer CAPEX, +10% feedstock cost, -5% yield	mature CAPEX, no change to OPEX or yield	mature -10% CAPEX, -10% feedstock cost, +5% yield
GFT-MSW	pioneer CAPEX, +$20/ton feedstock cost, - 5% yield	mature CAPEX, no change to OPEX or yield	mature -10% CAPEX, -$20/ton feedstock cost, + 5% yield

A baseline real discount rate of 10% and an inflation rate of 2% were used which combine for a nominal financial discount rate of 12.2%. The return that will incent investors to build these facilities is debatable and as such, this value is included in sensitivity analyses. Using this discount rate and a net present value (NPV) of zero we calculated the MSP. These analyses start with the cost of delivered feedstock to the conversion facility and end with stored product. No outgoing fuel transportation to the fueling point (e.g. airport) is included in the calculated MSP unless specifically stated. The impact of incentives is discussed in this work, but none of the calculated MSP values include incentives.

Table 3: Financial parameters used in all economic calculations

Economic Parameter	Assumed Value
Cost Year	2017
Plant Financing	30% equity
Plant Life	20 years + 3 years for construction
Real Discount Rate	10%
Income Tax Rate	17.2%[a]
Inflation	2%
Working Capital	20% annual operation costs
Depreciation Schedule	7 years, double declining balance to straight line
Construction Schedule	3 years (8% first year, 60% second year, 32% third year)[b]
Maintenance	6% TDEC

[a] OECD, 2019 [b] percent of FCI spent during each year of construction

The financial analysis uses capital costs that are a combination of quotes, literature values and costs from the Aspen Plus process engineering software for inside battery limit (ISBL) equipment (i.e., equipment that is integral to the process of manufacturing SAF). The outside battery limit (OSBL) equipment costs were estimated using ratio factors for solid-liquid processing plants that are applied to the total delivered equipment cost (TDEC) of the ISBL equipment to estimate fixed capital investment (FCI) (Peters et al. 2003). OSBL costs cover items that are common to most manufacturing facilities such as service facilities, yard improvements, and buildings. The expected accuracy of the estimated FCI using ratio factors is ±20-30% and depends on the completeness and precision of the ISBL TDEC values (Peters et al. 2003). The accuracy of this method is appropriate for a strategic study to guide decisions about more in-depth process, economic, and site-specific research. Total capital investment (TCI) is the sum of FCI and working capital.

National average values for industrial electricity and natural gas, averaged over 5 years from 2013 through 2017, were used for the initial analyses. Analyses with specific locations identified utilize county-level data. Pioneer, or early generation, equipment costs and FCI values are listed in Table 4 for facilities that manufacture 90 million gallons of distillates (liquid fuels) per year. This facility scale was chosen based on the decreasing change in MSP for additional distillate capacity, i.e., decreasing return on economies of scale.

Table 4: Equipment costs by manufacturing area summary for each conversion pathway and feedstock combination rounded to the nearest million dollars. Fixed capital investment (FCI) is for the high scenario (pioneer technology).

Manufacturing Area	HEFA	HEFA	ATJ	GFT	GFT
Feedstock	Vegetable oil	FOGs	FR	FR	MSW
Feedstock Preparation			98	43	128
Pretreatment		3	209		
Intermediate Production			100	401	272
Fuel Production	32	32	73	227	203
Other			168		
Total Equipment Cost	32	35	648	671	603
FCI	171	186	2896	2993	2757
Total Distillate (million gal/yr)	90	90	90	90	90
FCI/annual gal distillate ($/gal)	1.9	2.1	32.2	33.3	30.6

2.4 Siting Methodology

A full siting analysis was completed for forest residuals but was not necessary for lipids or MSW because these feedstocks are minimally available or already aggregated. This section provides a brief description of the analysis with a full description in Appendix A. The siting methodology chosen for forest residuals-based facilities was previously used for canola in the NW U.S. (Camenzind, 2018). There is a significant supply of forest residuals in the NW and if most of the available material were utilized, it could supply several biorefineries in the region. A multi-step procedure was performed which generated initial candidate locations for refineries followed by supply chain optimization. Supply chain optimization determines both the capacity and locations of potential facilities based on available feedstock and transportation infrastructure.

The model selects the best candidate locations that have an optimized set of incoming transportation costs, geospatially specific factors such as industrial electricity and natural gas rates, population centers, availability of truck and rail at each location, as well as outgoing transportation costs. This full supply-chain level siting analysis determines the lowest cost location. However, locations that are not selected in the analysis may be more suitable based on community acceptance, permitting and other factors. Exact sites were not determined, and locations are provided in general terms.

A siting analysis was not conducted for a HEFA-based facility in the NW due to the lack of available local feedstock. It is assumed that any new HEFA facilities will be sited near existing hydrogen-dependent industries and near marine or rail facility which will allow access to imported feedstocks.

3.0 Feedstock Analysis

The analyses to determine the amount of available feedstock and the possible resultant SAF quantity and MSP are detailed in the following sections. The total regional feedstock is reduced to the amount that is reasonable to aggregate for processing, which was used to estimate the gallons of SAF from each feedstock. Techno-economic analyses and siting analyses where appropriate were used to determine a range of MSP values for each feedstock/process combination.

3.1 Lipids

Lipids are a combination of fats, oils and greases (FOGs) and vegetable oils from oilseed crops. These feedstocks are molecularly closest to liquid hydrocarbon fuels and thus require the least amount of processing, which in turn translates into the lowest capital cost option and the best estimated MSPs. The low capital costs and high yields have also made this same feedstock appealing to the biodiesel industry. The result is that this feedstock has already been fully utilized in the region and additional volumes are currently being imported to meet existing demand.

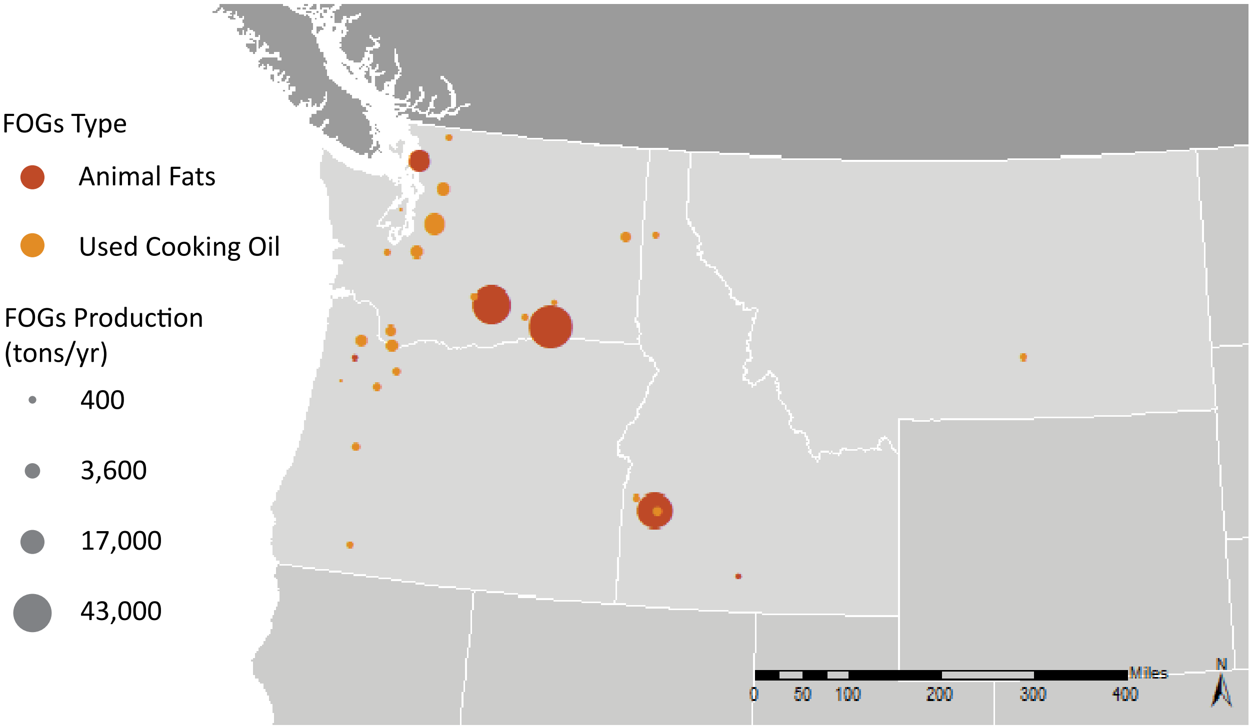
3.1.1 Fats, Oils, and Greases

FOGs are split into two waste streams for estimating volumes: used cooking oil and animal fats. The method to estimate used cooking oil production applies a per capita use factor to population centers with at least 100,000 residents, details are provided in Appendix B. The amount of animal fats produced is a compilation of waste fats from a variety of slaughter operations in the NW U.S. (Appendix B). The total combined FOGs production for the NW U.S. is estimated to be nearly 160,000 tons per year (Table 5 and Figure 2). Despite labeling FOGs as “wastes”, these materials are used in a variety of chemical and biofuels industries. It is especially challenging to quantify and value available animal fats because slaughter companies release very limited information and typically consider offtake agreements and partnerships with potential buyers as confidential. For analysis, it can be assumed that the animal fats produced in the NW are sold at a competitive rate.

Table 5: Annual production of FOGs (tons) in the NW United States.

	Used Cooking Oil	Tallow	Lard/White Grease	Total Production
Idaho	2,800	31,400	1,100	35,300
Montana	600	-	-	600
Oregon	9,700	-	1,100	10,800
Washington	22,800	88,900	-	111,700
Total	35,900	120,300	2,200	158,400
British Columbia	15.100			

Figure 2: Annual regional FOGs production for NW U.S.



3.1.2 Vegetable Oil

Current production of vegetable oil from oilseeds in the NW U.S. is not reflective of the region's potential to grow oilseeds. Over time, production may increase as the regional supply chain develops, farmers gain the necessary knowledge to grow the crops competitively and the infrastructure to grow, store and crush oilseeds becomes available. The 2018 oilseed production and estimated canola oil production for the region and British Columbia, are summarized in Table 6 (USDA 2019c, Statistics Canada, 2019). Canola oil is the only currently cultivated, large scale oilseed in the study region. Details on possible future canola production are included in Appendix B.

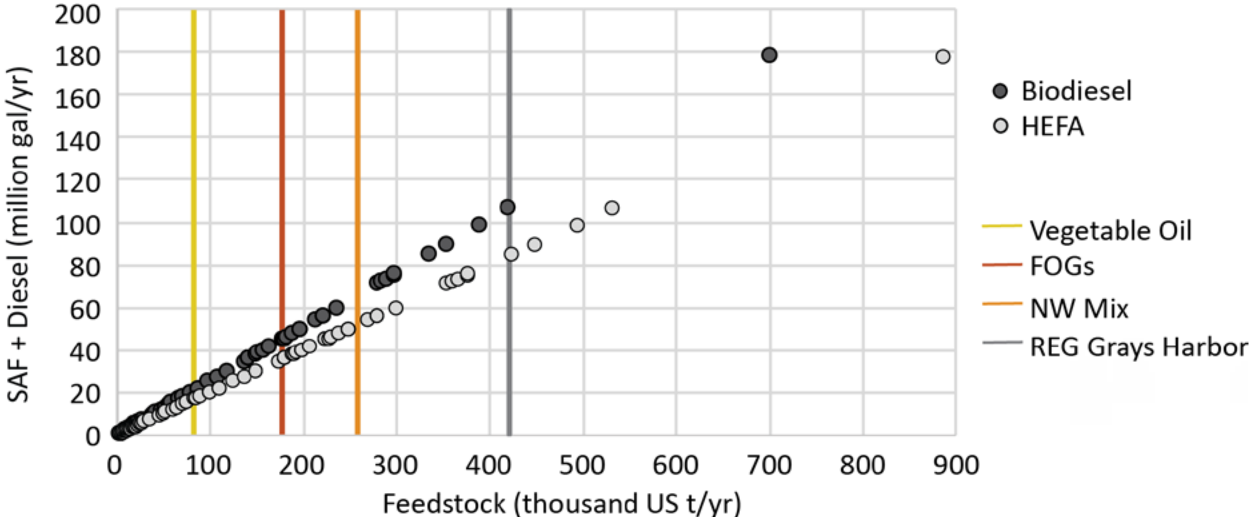
Table 6: 2018 annual production (tons) of oilseeds and estimated canola oil in the NW United States.

	2018 Oilseed Production	Estimated Canola Oil Production
Idaho	44,100	18,500
Montana	65,500	27,500
Oregon	3,800	1,600
Washington	60,000	25,200
NW Total	173,400	72,800
British Columbia	136,300	57,200

Vegetable oil, from NW oilseed crops, is not a viable feedstock in the near term. Oilseed crops for fuel production are purpose-grown crops with minimal current production and demand in the region. The NW does have potential to expand oilseed crops but in the best-case scenario, it would take many years of continual progression for oilseed production to approach the theoretical maximum. Several developments would need to occur to result in greater production. Most importantly, the economics of growing oilseeds must be beneficial for each individual farmer. Economic concerns pertaining to risk-taking can be abated as the collective knowledge of farmers and extension agents within the NW is further developed (Ghadim et al., 2005). The return on growing oilseeds must also exceed the returns of the alternatives, keeping in mind that the NW is currently a globally significant producer of several varieties of specialty wheat and high-value legumes (Schillinger et al., 2006). Oilseeds do offer agronomic benefits that can help improve the overall health of multiple years (Pan et al., 2016). Regional vegetable oil is not a large enough volume to be a viable feedstock option in the near term.

Biodiesel production is one of the major consumers of lipids in the U.S. according to annual reports published by the U.S. Energy Information Administration (EIA 2019b). This information informs us about the range of scales and the locations of one classification of existing lipid feedstock users. Figure 3 is a plot of the existing biodiesel facilities by capacity and the corresponding annual feedstock consumption. These facilities use either biodiesel technology or HEFA to produce renewable diesel and/or SAF. Superimposed on this chart is the amount of regional FOGs, oilseed and the total NW feedstock mix produced. Also included is the feedstock demand of the REG Grays Harbor facility, which is greater than the entire NW feedstock supply. Figure 3 is capped at 180 million gallons/yr, the largest sized U.S. biodiesel facility.

Figure 3: Existing U.S. biodiesel facility capacity with NW feedstock scenarios, including the REG biodiesel location in Grays Harbor, WA.



3.1.3 Lipid Financial Analysis

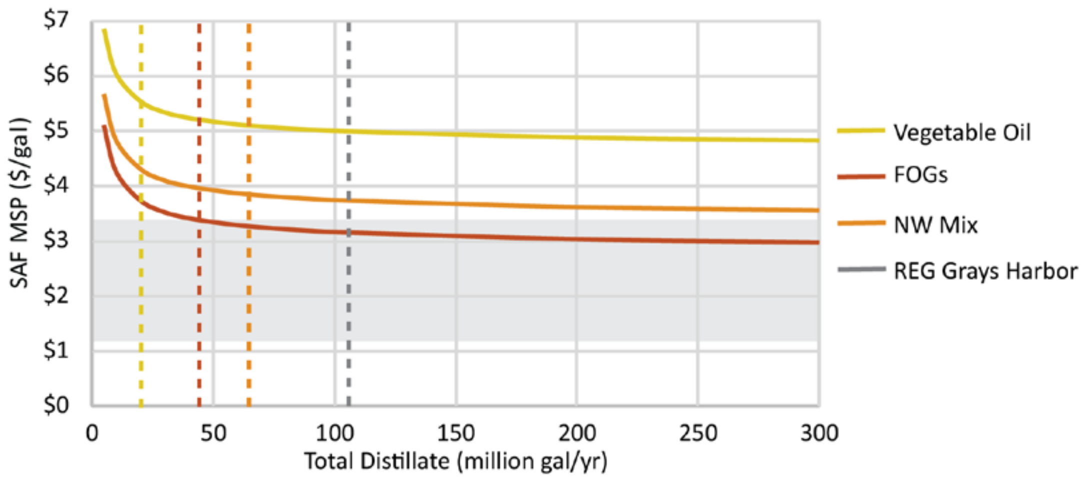
Techno-economic analyses were developed for vegetable oil, FOGs and a combination of the two using the HEFA process to manufacture SAF. Estimated values of FCI, annual operating costs and MSP ranges for each cost scenario and a total distillate output of 90 million gal/yr are listed in Table 7. These costs are estimates and will increase or decrease based on the chosen facility scale. Given the limited availability of this feedstock in the region, a detailed siting analysis was not completed. The MSP ranges are based on a generalized set of geospatial cost parameters.

Table 7: HEFA scenario FCI (million $), OPEX (million $/yr) and MSP ($/gal) values for 90 million gal/yr of distillate. FCI and OPEX values are rounded to the nearest $10 million.

Feedstock	Variable	High	Mature	Low
NW Mix	FCI	180	170	150
	OPEX	270	250	230
Vegetable Oil	FCI	170	160	140
	OPEX	360	330	300
FOGs	FCI	190	170	160
	OPEX	230	210	200
All	MSP		2.7 – 5.0	

The purpose of this report is to evaluate regional feedstock availability in the near-term. The total amount of both FOGs and oilseeds available for SAF production is much lower than what is required to supply an economically viable facility. The MSP values modeled for the different biorefineries discussed throughout this report all have economies of scale. Economies of scale means that larger facilities can produce SAF with a lower MSP than smaller facilities. The impact of increasing scale, or capacity is a non-linear relationship. This non-linearity translates into very high MSP for small facilities and an eventual decline in MSP reduction for size increases. Economies of scale explains the MSP curves in Figure 4. If the total of all produced and currently-utilized lipids in the entire four state region are used for SAF production, the SAF MSP would be down the steepest part of the curve, but not at the lowest cost section (Figure 4). Realistically the available volume of these feedstocks sourced in the region is zero and costs would be based on purchase of imported vegetable oils. It should be noted that more than the regional available feedstock is required for the single biodiesel facility in Grays Harbor, WA (Figure 4). In addition, the facilities in the top 10% of production volume each produce 330 million gallons or more each year and require more feedstock than the region can provide (Figure 3). The estimated MSP of SAF for the high scenario was run at multiple facility scales for three feedstock categories: FOGs, vegetable oil and a mix of FOGs and canola oil that matches the NW production rates (Figure 4).

Figure 4: SAF price curves for SAF manufactured using HEFA for three feedstocks (solid line) versus annual feedstock demand (vertical dashed lines).



The largest regional demand centers for lipids are described in section 1.2. Given these existing facilities, as well as the expected future demand, FOGs are not a feedstock that will be available in commercially viable quantities within the NW U.S. without reliance on imported feedstock.

3.2 Forest Residuals

In the NW U.S., it is estimated that nearly seven million bone dry tons of forest residuals are produced annually, with the majority of the material beinglocated in Western Oregon and Washington. The estimated total quantity available for collection decreases with the type of logging, the slope of the forest and other factors. The material that can be logistically and economically collected is called harvestable. Details on the methodology to quantify harvestable forest residuals are in Appendix B. These residuals are from all non-federal land, which includes private, state and tribal lands. Estimates of the harvestable forest residual quantity in the NW United States are listed in Table 8.

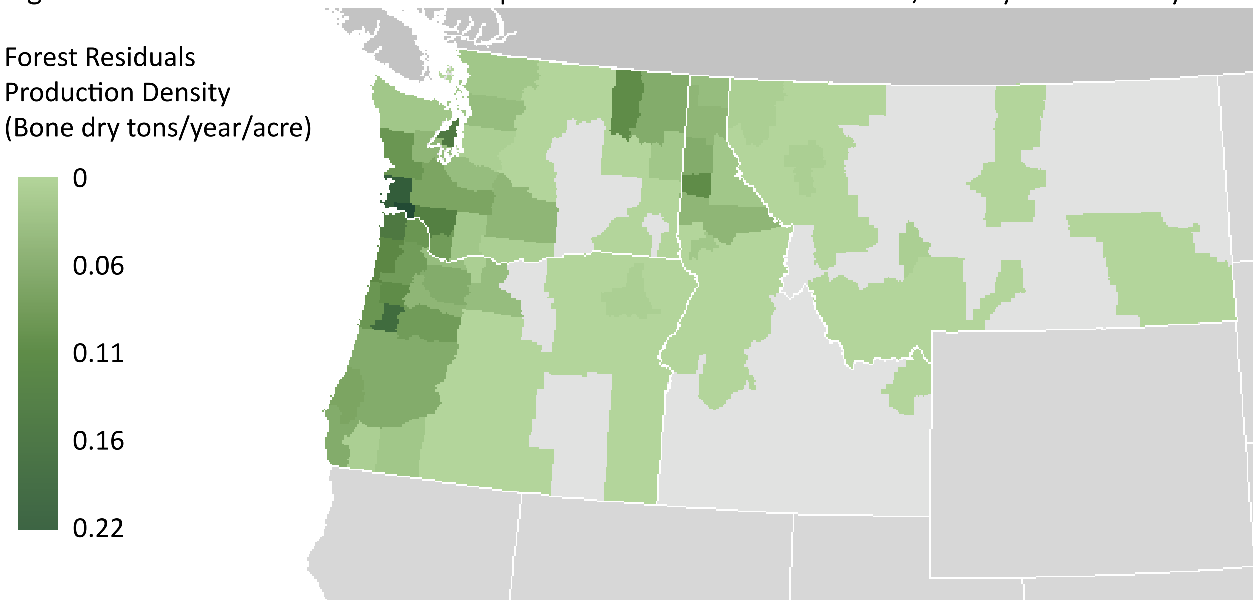
Table 8: Annual harvestable forest residuals (bone dry tons) in the NW United States from non-federal land.

	Softwood	Hardwood	Total Harvestable	% of Total Residuals
Idaho	375,029	7,568	382,598	45
Montana	149,391	1,232	150,623	33
Oregon	1,164,658	289,271	1,453,929	49
Washington	1,230,108	190,477	1,420,585	55
Regional	2,919,186	488,549	3,407,735	50

3.3 Forest Residuals Financial and Siting Analysis

Forest residual biomass in the NW is plentiful, especially in Western Oregon and Washington. The geographic density of forest residuals, the amount available close to a potential facility, influences facility scale and transport cost, both of which will impact the final cost of fuel. Figure 5 shows the non-federal forested land within the region and topographic cost curves for the weighted average delivery costs for 1 million bone dry tons annually.

Figure 5: Annual LURA forest residuals production on non-federal lands, county-level density.



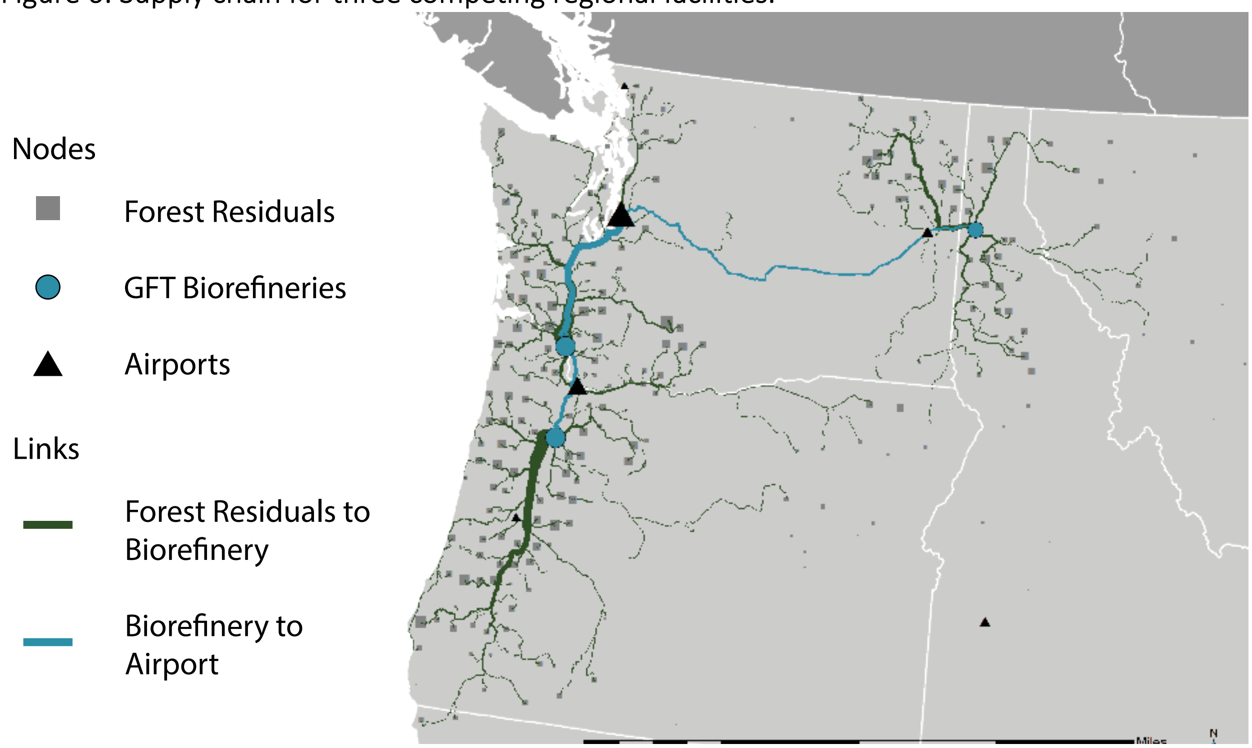
The size of a production facility has a strong influence on fuel costs. As the facility size increases, production costs per volume decreases as a result of economies of scale. However, the feedstock costs increase because larger quantities must be transported over longer distances. These factors must be evaluated together to best optimize MSP. To assess potential production schemes, two scenarios were assessed: build a single facility at the lowest cost location or build several facilities that are economical based on the siting analyses.

Using the siting analysis detailed in Appendix A, two locations, one in Northwest OR and one in the Western Columbia River region, demonstrated the lowest combination of geospatially controlled costs at large facility capacities for SAF manufactured using either GFT or ATJ. The

MSP for the ATJ production includes the impact of non-fuel co-products. If these co-products are changed or eliminated, the MSP will change as well. If the SAF manufactured in Northwest OR is sent to the Portland International Airport (PDX) or the Seattle-Tacoma International Airport (SEA), the delivery cost will add $0.03/gal or $0.10/gal, respectively to the MSP. The transport costs for the Western Columbia River region to PDX is the same at $0.03/gal, but drops to $0.07/gal to SEA.

A second scenario enabled the model to select three facilities to be built simultaneously, and the model selected locations in Northwest OR, Western Columbia River and Northwest ID for SAF delivered to SEA (Figure 6). It should be noted that adding the Western Columbia River location increased the delivered feedstock costs to Northwest OR.

Figure 6: Supply chain for three competing regional facilities.

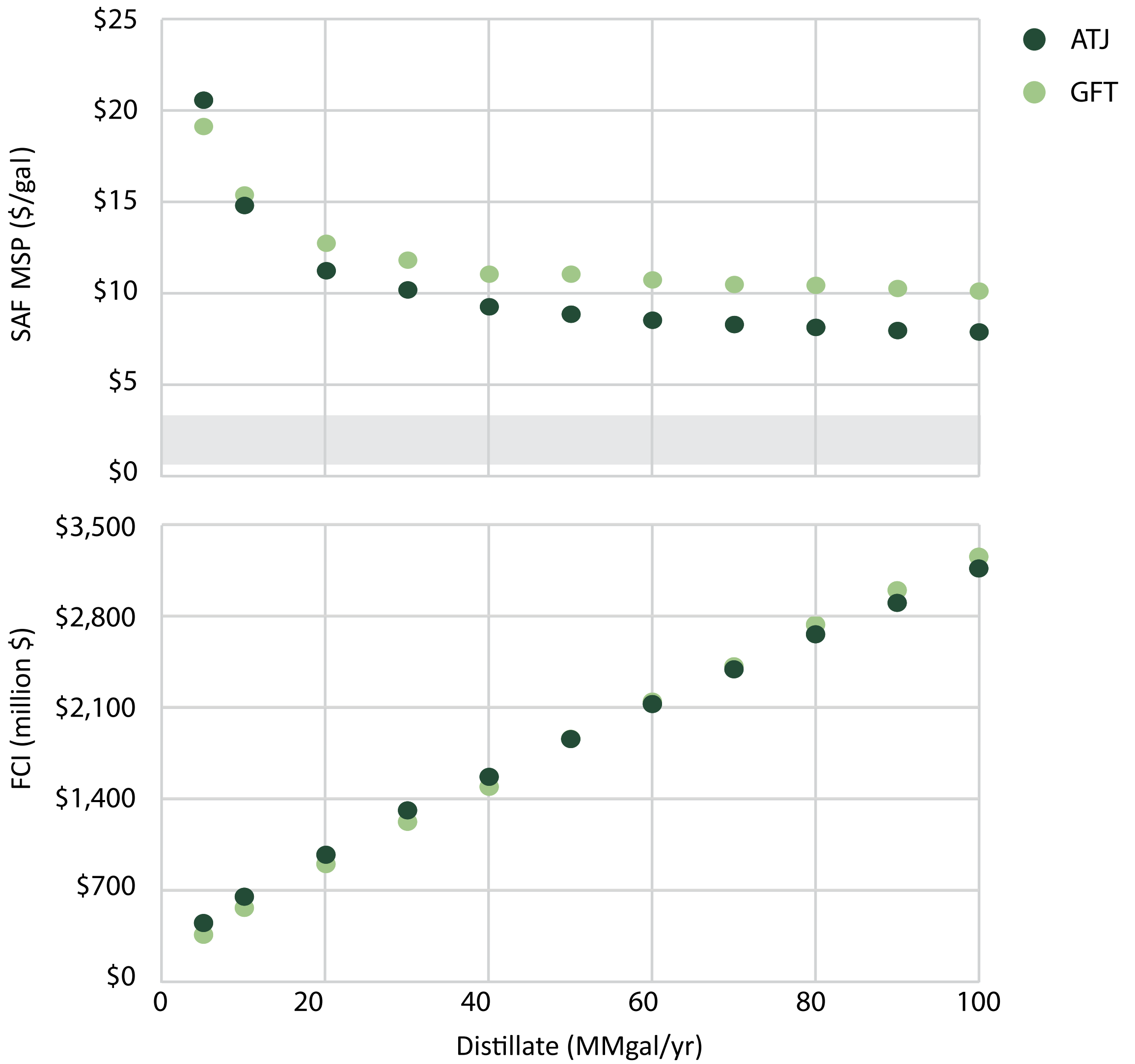


SAF can be produced from forest residuals using multiple pathways, two of which are ASTM approved: GFT and ATJ. These two pathways can use a variety of processes and technologies and the work in this report does not model any specific company's process or technology. Techno-economic analyses were completed for the low, mature and high cost scenarios with FCI, operating and MSP values listed for a 90 million gal/yr total distillate facility which are shown in Table 9 and shown for multiple capacities in Figure 7. The feedstock costs used to calculate the data in Table 9 are for the lowest cost scenario determined in the siting analysis.

Table 9: Forest residual scenario FCI (million $), OPEX (million $/yr) and MSP ($/gal) values for 90 million gal/yr of distillate. FCI and OPEX values are rounded to the nearest $10 million.

Pathway	Variable	High	Mature	Low
ATJ	FCI (million $)	2900	1610	1410
	OPEX (million $/yr)	650	510	460
GFT	FCI (million $)	2990	1470	1280
	OPEX (million $/yr)	480	320	290
Both	MSP ($/gal)		3.7-10.3	

Figure 7: Minimum selling price (MSP) and fixed capital investment (FCI) for "high scenario" SAF facilities sited in Northwest OR for various versus total distillate. The grey shaded region is the EIA, FOB jet fuel price range for 2012-2019 (EIA, 2019a)



The MSP ranges for each location discussed in the siting analysis are listed in Table 10 for a 40 million gal/yr of total distillate capacity. The total distillate was reduced from the 90 million gal/yr value because the cost to aggregate the required feedstock to operate a facility that large increases costs beyond the benefits economies of scale. The best economics for these candidates is making SAF in Northwest OR or in the Western Columbia River region and sending the fuel to PDX. It should be noted that the Western Columbia River costs increase to a less competitive level if the facility is sited in WA based on increased energy costs. When transport of fuel is included, the Western Columbia River region facility is the lowest cost facility. The NW ID location is the least competitive based on both production and shipping costs, even if the fuel supplies first to GEG first, the excess supply would then be sent to SEA. The facility is sited in Idaho, instead of across the border into Washington and closer to GEG, primarily because the energy costs are higher on the Washington side of the state line.

Table 10: MSP range and delivery costs for SAF manufactured at optimized siting locations with a scale of 40 million gallons of total distillate each year.

Location	MSP range ($/gal)	Delivery Cost: SEA ($/gal)	Low Cost Airport	Low Cost Delivery ($/gal)
NW OR: 1 facility	4.7-11.1	0.10	PDX	0.03
NW OR: 3 facilities	4.7-11.1	0.10	PDX	0.03
W Columbia River: 3 facilities	4.7-11.1	0.07	SEA	0.03
NW ID: 3 facilities	5.0-11.3	0.14	GEG/SEA	0.04/0.14

3.4 Municipal Solid Waste

The amount, type, and availability of MSW currently produced in the NW was estimated using population data for each state/province obtained from the Census Bureau or Statistics Canada (U.S. Census Bureau, 2018, Statistics Canada, 2018). The MSW that is suitable as an SAF feedstock is the portion of the disposed or landfilled MSW that can be simply converted into liquid fuels. Approximately 47% of the MSW disposed is potential feedstock for liquid fuels using the assumptions used in this specific GFT model (Cascadia Consulting Group, 2018, Oregon Department of Environmental Quality, 2019, Oregon Department of Environmental Quality, 2017, Washington State Department of Ecology, 2017). We acknowledge that there are additional categories that are possible feedstocks, some are better suited than others. For instance, categories such as yard and food waste are potential feedstock, but they were eliminated in this study because their moisture content and degradation make them difficult to process. The MSW feedstock evaluated in this study includes paper and paperboard, rubber, leather and textiles, plastics and wood (Table 11). The detailed process for this feedstock is included in Appendix B.

The composition of the MSW feedstock used in the GFT process influences both the yield and the environmental benefits of the fuel. Most MSW contains a certain percentage of plastics. A feedstock with a higher plastic content increases yield but also has negative environmental impacts. Pressley et al. states that although gasification of plastics increases syngas yield, the increased emissions that contribute to global warming potential outpace the fuel yield increase (2014). Therefore, the environmental benefits of SAF fuel decrease with increased plastic content. This relationship between yield and environmental benefits will have to be balanced by potential manufacturers.

The amount of convertible MSW listed in Table 11 includes 16% plastic. This level is similar to the amount used in the baseline yield number, which has a plastic content of 19% (Pressley et al. 2014). The yield trends from plastic levels in the feedstock are understood, but exact numbers vary in the literature (Pressley et al. 2014, Niziolek et al. 2015, Onel et al. 2014). Two yield values were chosen that surround the baseline yield and correspond to more and less plastic addition. The low plastic yield is representative of what might be expected with less plastic addition. It is important to note that not only will a low plastic content reduce the yield, it will also increase the sorting costs and there is a practical limit to how much plastic can be removed. The high plastic yield value is above the baseline yield and can be achieved by additional plastic addition but would need to be balanced with the environmental costs.

The range of SAF volume numbers reported in Table 11 assume that all disposed feedstock MSW is collected, sorted and converted to SAF. The incoming feedstock is at an unknown moisture content and the range of SAF volume reflects the possible moisture content values. The two scenarios discussed in detail are for facilities located at Columbia Ridge or a location in Western WA, assumed to be located south of Seattle.

Table 11: MSW (million tons/yr) that can be converted to SAF in the NW U.S. and British Columbia, Canada and the corresponding range of SAF (million gal/yr). Columbia Ridge and Western WA are two scenarios discussed in detail.

	Convertible MSW	SAF from Disposed MSW (million gal/yr)		
		Low Plastic	Baseline Plastic	High Plastic
Idaho	0.9	19-23	21-25	22-27
Montana	0.5	10-13	11-14	12-15
Oregon	1.4	27-34	30-37	32-39
Washington	2.4	47-58	52-64	54-66
NW Total	5.2	105-128	115-141	121-147
British Columbia	1.6	32-39	35-43	37-45
Columbia Ridge	1.3	26-32	28-35	30-36
Western WA	0.3	6-7	7-8	7-8

3.4.1 MSW Financial Analysis

The financial data included in this report is based on converting MSW to SAF using the GFT conversion process and does not include any proprietary data (Table 12). The authors acknowledge that other pathways are possible but information in the public domain limits the ability to model the costs. These comparable MSP values could drop with the addition of federal and state government incentives depending on feedstock choices.

Table 12: MSW scenario FCI (million \$), OPEX (million \$/yr) and MSP (\$/gal) values for 90 million gal/yr of distillate. FCI and OPEX values are rounded to the nearest \$10 million.

Pathway	Variable	High	Mature	Low
GFT	FCI (million $)	2690	1570	1420
	OPEX (million $/yr)	330	230	210
	MSP ($/gal)		3.6-7.1	

The supply chain logistics for MSW appears to be simple because this feedstock is already collected and delivered to a single location, and landfills are paid a tipping fee to dispose of the material. This collection process does assist the aggregation of feedstock, but it should be noted that final destination of MSW is often remote and the resulting fuel will need to be transported back to a population center where liquid fuel is used in large quantities.

In the NW Region, the largest landfill is the Columbia Ridge Landfill located in Arlington, Oregon and operated by Waste Management. This landfill processed 2.74 million tons of MSW in 2017, primarily from Oregon and Washington, including both Portland and Seattle. Columbia Ridge collects 35% of the regional MSW and has an expected life of 143 years, which makes it an ideal location for an SAF facility utilizing MSW (Columbia Ridge, 2019).

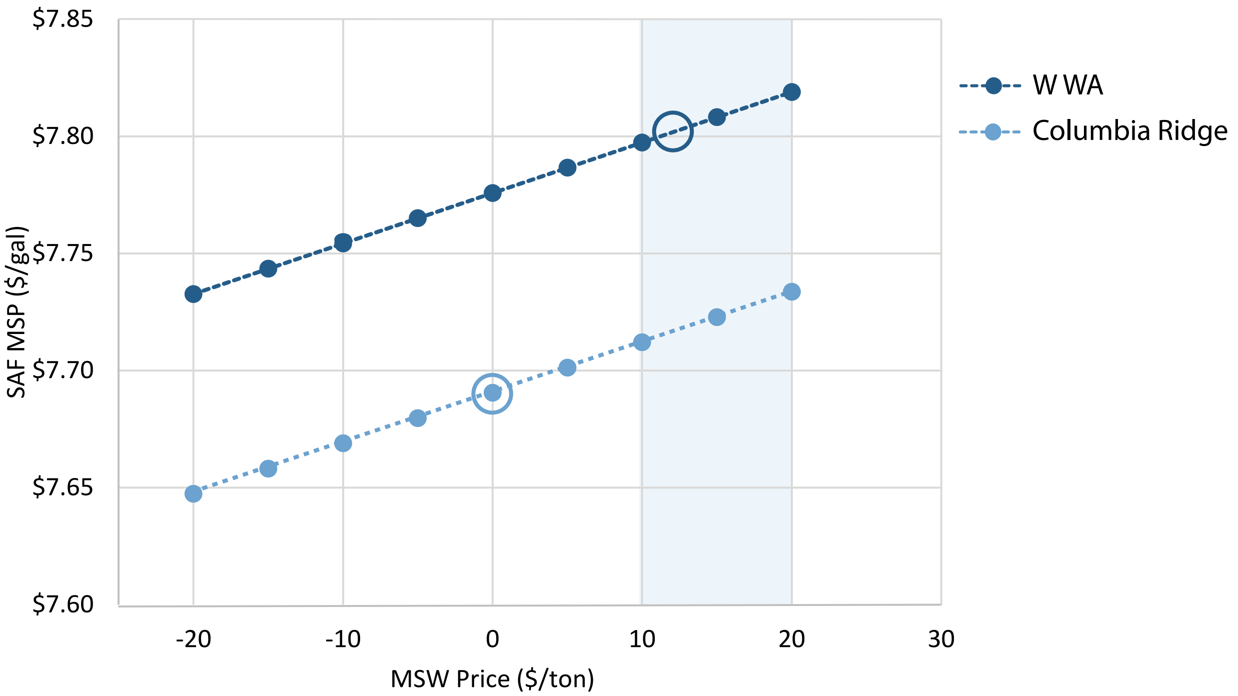
A second scenario is to have the SAF facility, with MSW sorting, located near the greater Seattle area, the largest population center, and then transport only the material not suitable for SAF production to the Columbia Ridge Landfill. For the purposes of this analysis the SAF facility is assumed to be located in Western WA, south of Seattle. In theory, this will save the cost to transport MSW to a remote landfill and save transport costs of the finished SAF to SEA. The amount of MSW available is uncertain, but MSW from the city of Seattle and a few surrounding counties are sent to Columbia Ridge Landfill through the Argo Yard in Seattle. The quantity of MSW passing through this location in 2002 was reported by the King County Solid Division. In this analysis, the King County number was scaled for the increased population of Seattle using the per capita waste numbers for Washington and the reported relative quantities from the surrounding areas (2006). This method approximates 775,000 tons of MSW annually could be processed at this location. The authors acknowledge that this estimate is rough and that if a facility that processes MSW is built, additional municipalities may want to send MSW to this location.

For a scenario that assumes MSW is sorted and processed in Western WA, the shipping and handling costs are assumed to be $28/ton (King County Solid Waste Division, 2006). This value may be low as this cost is over a decade old and the impact described below may be magnified. The total cost of $28/ton is the sum of approximately $10/ton to ship the MSW via rail to Columbia Ridge and $18/ton for handling costs to load, unload, store, bundle and transport the MSW to and from the rail station. We assume that the $10/ton of rail costs that are potentially saved by locating a facility in Western WA are split between the current waste company and the potential SAF facility. This means that if all of the waste is kept at the Western WA facility, the SAF facility would be paid $5/ton. However, because only 47% of the MSW is acceptable feedstock, the facility portion would drop from $5/ton to $2.5/ton.

This revenue stream is more than offset by the additional handling costs associated with moving and reloading the MSW. Handling costs are estimated to be $18/ton before the material is sent via rail out of Argo Yard. A reasonable estimate of the handling costs at the Western WA biorefinery is $13.5/ton, which is roughly three quarters of the $18/ton. Although all of the material will be unloaded, unbundled and processed at the biorefinery, just over half of it will be rebundled and shipped to Columbia Ridge. It may be less expensive to truck the MSW to the Western WA location, but this would require a major shift in the current MSW management system, and such analysis is beyond the scope of this work.

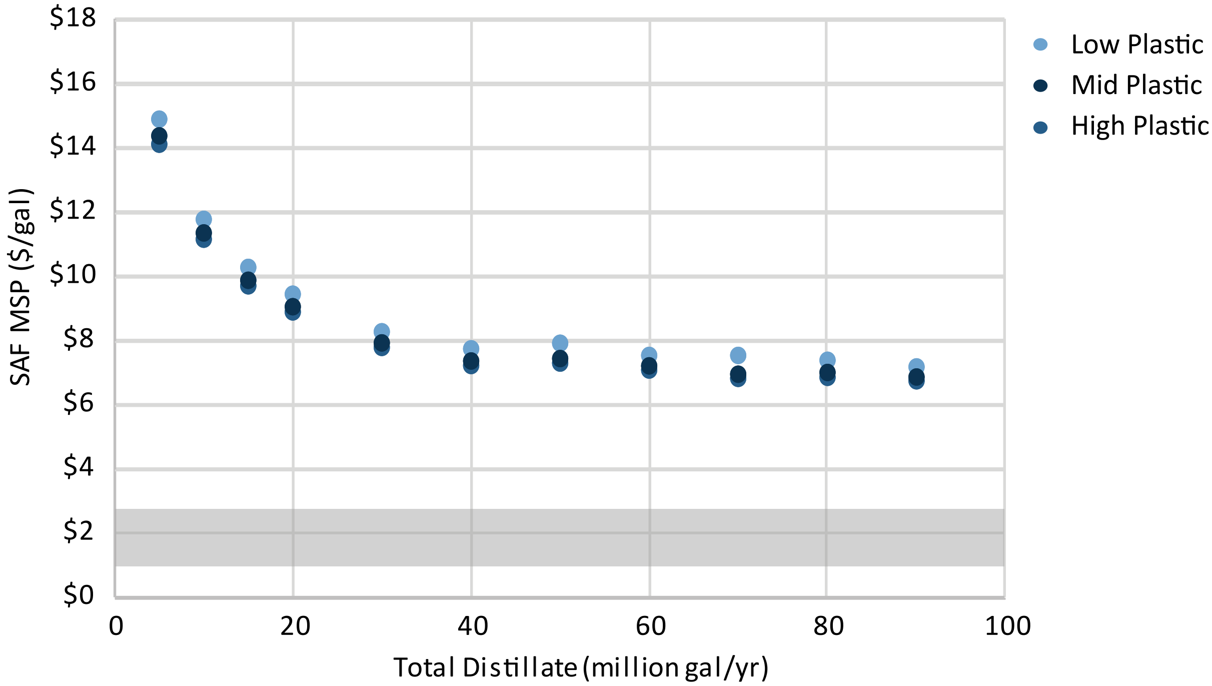
The SAF MSPs for both the Western WA and the Columbia Ridge scenarios are shown in Figure 8 for pioneer capital costs. The blue shaded region is the most likely cost for handling MSW in Western WA. The circles on each facility's line are the assumed most realistic combination of MSW cost and SAF MSP. The difference between these two SAF MSPs is approximately $0.08 / gal. The information in Figure 8 is for a facility that sorts and processes 0.775 million tons/yr. The Columbia Ridge point at $0/ton is estimated to drop $1.03/gal if all of the MSW at the landfill is used.

Figure 8: SAF MSP for the high scenario versus MSW purchase price facilities at Columbia Ridge or W WA for assumed bone dry feedstock both scaled to the W WA available feedstock. The blue shaded area is the most likely MSW price range at the W WA. The larger circles are the estimated MSW price and SAF MSP combination at each location.



Although MSW is a feedstock with a negative value, meaning landfills are paid to take this material, it is unlikely that a SAF facility would operate under the same economic model. In this report, it is assumed that the MSW will be transferred to the SAF facility, located at the landfill, at a zero cost (Niziolek et al., 2015, Suresh et al., 2018). The material is then sorted and the portion that is not viable SAF feedstock will be transferred back to the landfill. Any recyclables, sorted out during the process, can be sold for an additional revenue stream at the SAF facility (Suresh et al., 2018). Both feedstock price and revenue from recyclables will be included in sensitivity analyses. When recyclables are included as a revenue stream, only metals are included, and both the quantity and price are from the King County waste-to-energy and waste export by rail feasibility study (2019). There may be additional revenue possible from high value plastics but quantifying and monetizing that stream is beyond the scope of this project.

Figure 9: Estimated SAF "pioneer plant" MSP at Columbia Ridge for low, baseline and high plastic levels with revenue from metal recycling for a feedstock price of $0/ton using pioneer capital costs. The grey range is the 2012-2019 petroleum jet fuel price range.

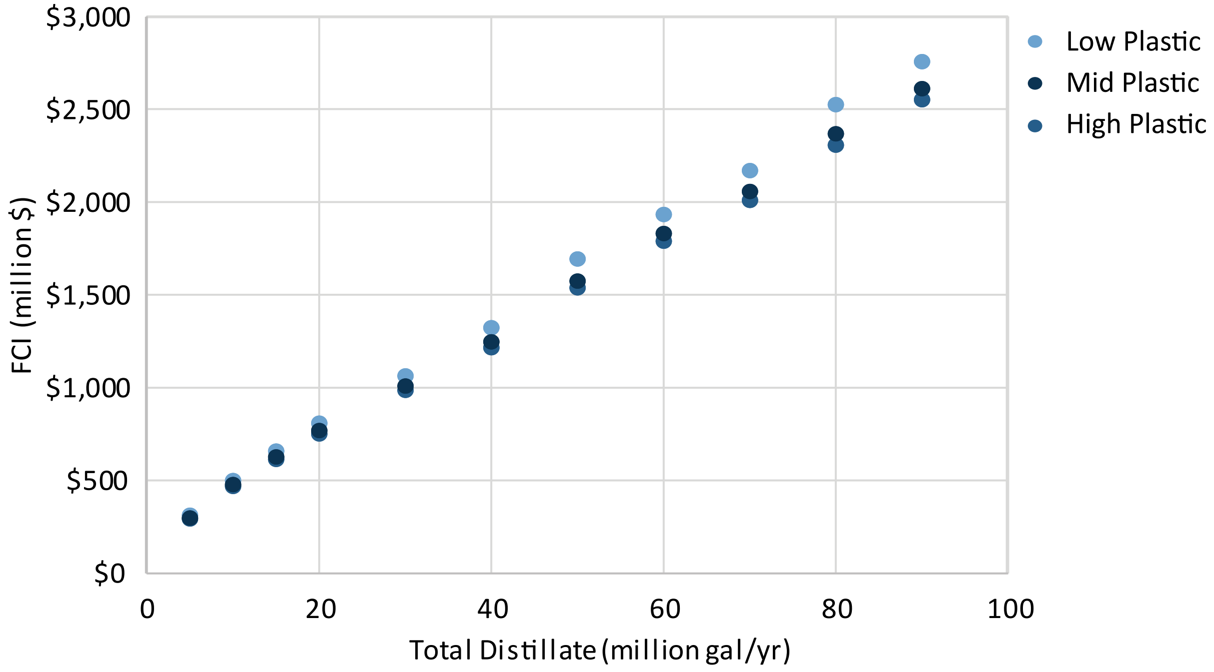


A range of MSP values for SAF manufactured at the Columbia Ridge Landfill location are shown in Figure 9. These MSP values assume pioneer capital costs for all of the facility capacities and the three levels of plastic utilization, which impact fuel yield. The Columbia Ridge Landfill has the lowest feedstock cost and a large supply of feedstock, but the closest natural gas line is 15-20 miles away and this will likely increase costs. This is not an insurmountable obstacle but the cost of SAF will likely increase no matter the solution chosen. In addition, the cost to transport SAF to PDX and SEA from the Columbia Ridge Landfill is $0.12/gal and $0.22/gal, respectively. This cost will be added to the MSP prices that are located at the facility.

Feedstock cost is an item that is not publicly reported for MSW. It is not surprising that MSP follows both negative and positive feedstock cost changes. Unless the SAF facility receives a large portion of the tipping fees that currently go to the landfill, it will take additional measures to reach MSP to price parity with petroleum jet fuel. A change in feedstock price of of $20/ton impacts SAF MSP by $0.04/gal. This change is for a pioneer capital scenario and will change as the capital costs drop. It is important to note that landfill tipping fees are contracted and that it may be challenging to change or influence these economic models.

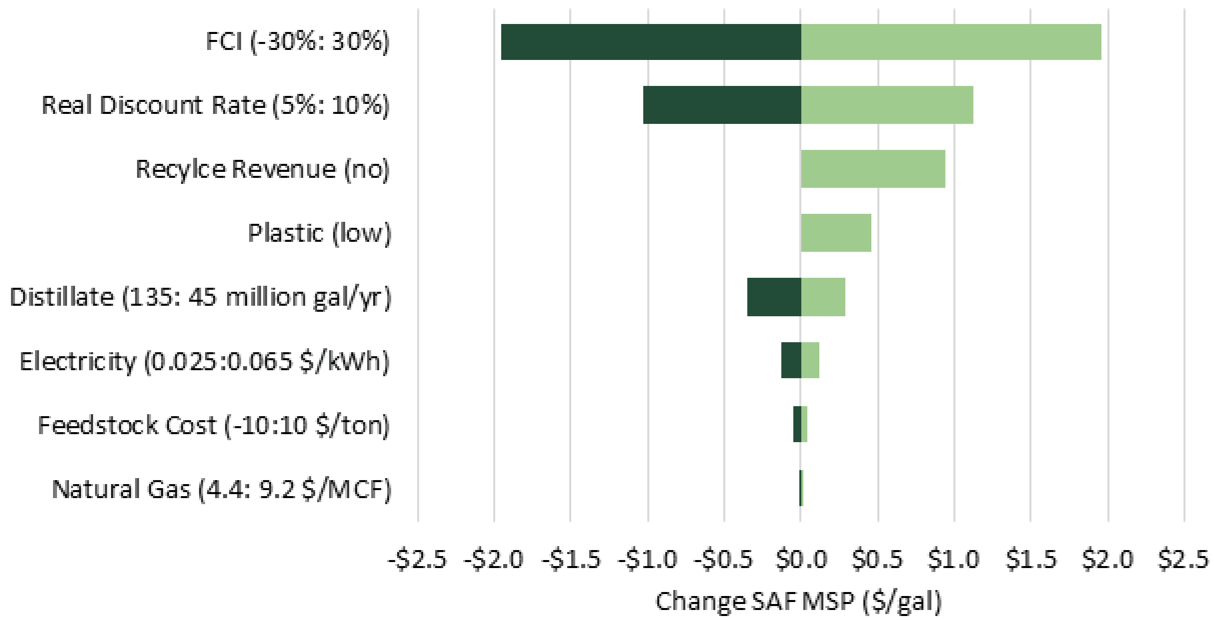
The economies of scale are apparent in Figure 9 and Figure 10, even with the more linear scaling of the sorting operation that is included in this SAF facility (Caputo and Pelagagge, 2002). The sorting portion of the facility is the second most expensive operation, with only gasification being more expensive.

Figure 10: Pioneer FCI versus total distillate facility scales for low and baseline plastic addition rate yields and MSW = $0/ton.



The capital costs for processing MSW into SAF are substantial and influence the final MSP. The ability to recover and sell metals for recycling and including plastic in the feedstock at baseline rates are more influential than any other process variables (Figure 11). It should be noted that the scales included in Figure 11 are all in the optimal range and that the impact on MSP would be significant for a much smaller facility.

Figure 11: Impact of process and economic parameters on SAF MSP manufactured from MSW using the GFT process.



Converting MSW to SAF is a compelling scenario as the processing technology matures, especially if government incentives are included in the MSP values. The economies of scale for the GFT process mean that a large facility is the best solution. A facility that handles more than 700,000 tons of MSW annually, before sorting, is a reasonable minimum size. The Columbia Ridge Landfill has approximately 1.3 million tons annually of feedstock that can be converted to SAF, or 2.7 million tons before sorting. The size of the facility will more likely be controlled by available capital than by available feedstock. In addition, this remote location is estimated to have more than 100 years of remaining capacity which means the feedstock will likely continue to be available (Columbia Ridge 2019).

4.0 Conclusions

The amount of SAF that can be manufactured from available regional feedstock of lipids, forest residuals and MSW is summarized in Table 13. The total potential is sufficient to meet the volume requirements of the Port of Seattle's 2028 goal, though the price per gallon for pioneer facilities start at nearly 3x the cost of conventional jet fuel. The proportion of SAF to total distillate used in the models is included. However, these proportions can change significantly with process and equipment changes. The total distillate number is a more consistent measure by which to compare the process and feedstock combinations. The data in this report was reduced based on known supply constraints to provide values that are realistically available for regional SAF production. This feedstock quantity was combined with cost values, SAF techno-economic analyses and supply chain analyses to provide estimated costs to produce SAF. The amount of fuel assumes all of the available feedstock is utilized.

Table 13: Summary data of the constrained regional SAF potential by feedstock for 90 million gal/yr of total distillate. Capital costs are rounded to the nearest million dollars and maximum regional volumes are rounded to the nearest ten million gallons/yr.

	Lipids	Forest Residuals	MSW
Conversion Pathway	HEFA	ATJ/GFT	GFT
Estimated yield (ton distillate/ton feedstock)	0.83	0.16-0.19	0.29-0.32
Maximum regional distillate (million gal/yr)	0	170-210	330-370
Maximum regional SAF (million gal/yr)	**0**	**80-130**	**140-160**
Total Distillate (million gal/yr)	90	90	90
SAF (million gal/yr)	49	38-63	38
FCI range 90 mgy facility (million $)	140-190	1280-2990	1420-2690
OPEX range 90 mgy facility (million $/yr)	200-360	210-650	210-330
SAF MSP range 90 mgy facility ($/gal)	2.7-5.0	3.6-10.3	3.6-7.1

Table 13 and Figure 12 illustrate that the capital requirements for HEFA are much lower than for

GFT or ATJ, regardless of feedstock type. This reduced capital value, combined with a tight band on SAF MSP, demonstrates a lower risk technology compared to the others studied. However, the required lipid feedstock is not available in the region. SAF MSP ranges for forest residuals and MSW overlap. Regardless of the chosen feedstock/pathway combination, incentives are required to achieve price parity with petroleum fuels (Figure 13).

Figure 12: FCI for four pathway/feedstock combinations at multiple total distillate production values.

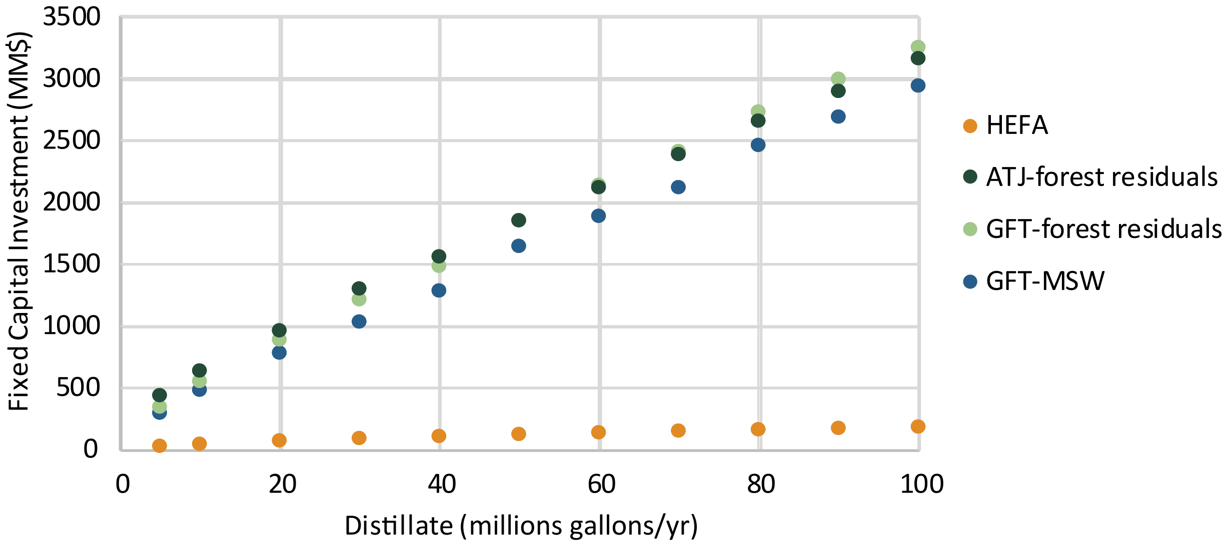
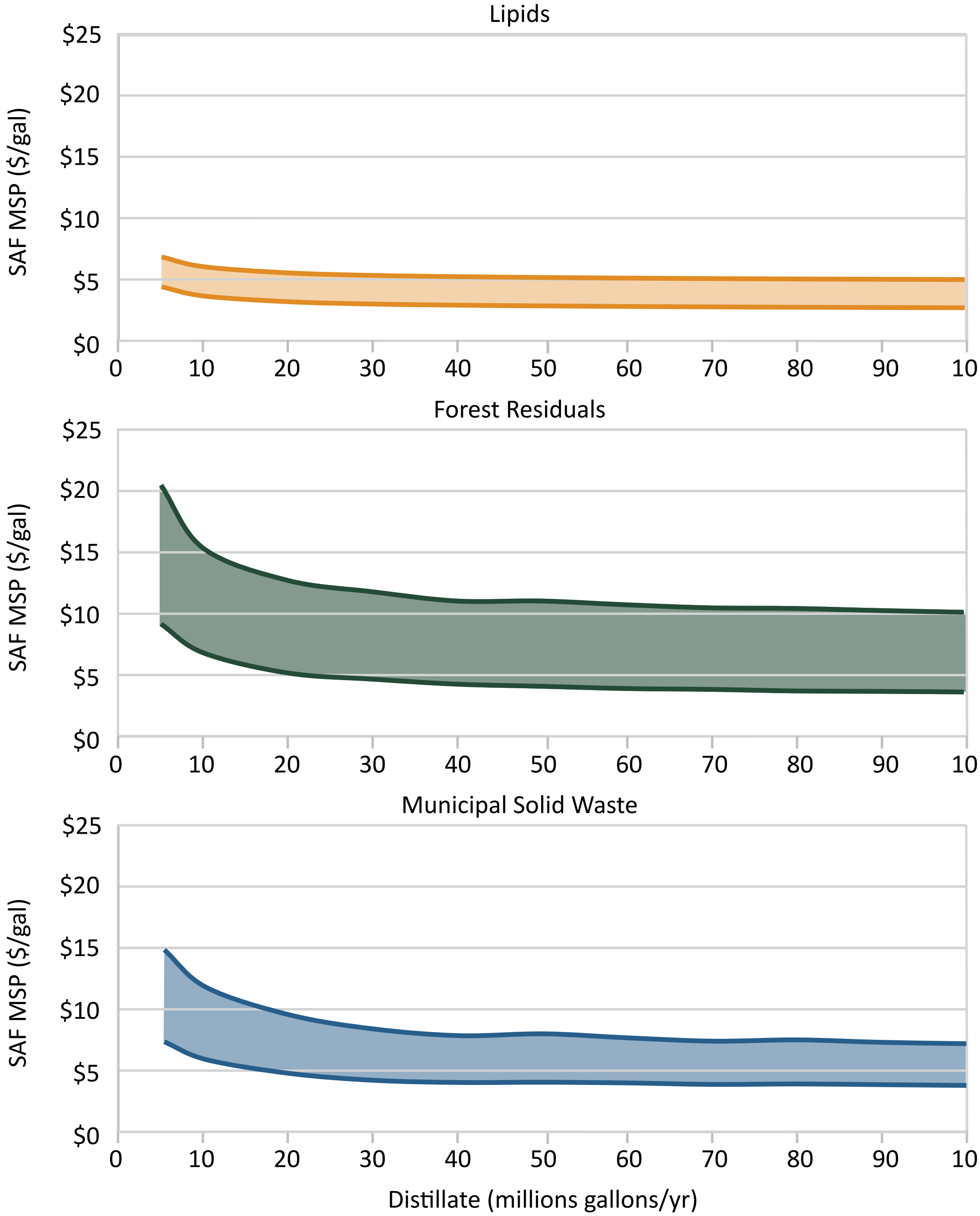


Figure 13 shows bands of SAF MSP values versus the amount of total distillate produced. Wider MSP bands are partially a result of technology uncertainty, quantified using cost growth factors. The MSP values, regardless of technology are influenced by economies of scale, which will have to be balanced with total capital available to invest to optimize risk.

Figure 13: MSP range for each of the three feedstocks selected. The top of the range represents

current technology and the bottom is mature technology with optimistic yields and feedstock prices.



5.0 Challenges and Opportunities

SAF manufactured in the NW U.S., using regional feedstock will likely need significant incentives to be cost competitive with conventional jet fuel, at least in the near term. The HEFA technology is the most mature and fuel can be made at a lower price than with the other two feedstocks. However, there is no available supply of lipid feedstocks in the region to support this technology. Both forest residuals and MSW are available in large quantities but the capital costs modeled are prohibitive (over $1 billion). Specific industrial processes from individual companies were not modeled and costs using proprietary processes may alleviate this issue.

6.0 Summary

This project evaluated the NW regional feedstock for use in SAF. The amount of feedstock that is not currently utilized was used to estimate possible SAF volumes. Techno-economic analyses were used to determine a range of expected MSPs. This information was used to establish the following key findings:

- There is adequate volume available of MSW and forest residuals to meet the SEA goal of 10% SAF, however the MSPs for early generation/pioneer plants are estimated to be 3-5x higher than cost of petroleum jet fuel.

- The regional supply of lipids is inadequate to support SAF production. The region has potential for oilseed production; however, the current supply isn't enough to support SAF production. Use of lipids as a feedstock would require them to be imported.

- MSW and forest residuals-based fuel production facilities will require large capital investments, and the technology has not been proven at scale.

- Price parity between petroleum jet fuel and SAF from NW feedstocks will require financial support and will be sold to locations with the best incentives.

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References

Arcadis U.S., Inc. (2019). King County waste-to-energy and waste export by rail feasibility study. Ref. 30015954 (WTE42955.0001). Accessed 12/18/2019. https://mkcclegisearch.kingcounty.gov/LegislationDetail.aspx?ID=4157155&GUID=B6B5D3D6-894F-4452-80EA-17607DB2E69A&Options=Advanced&Search

Aspen Plus (2016). Aspentech. https://www.aspentech.com/en/products/engineering/aspen-plus.

Biofuels International (2020). Shell Aviation, World Energy to increase supply of sustainable aviation fuel. Accessed 2/6/2020. https://biofuels-news.com/news/shell-aviation-world-energy-to-increase-supply-of-sustainable-aviation-fuel/

Camenzind, D. "Supply Chain Analysis for Alternative Jet Fuel Production from Fatty Acid Feedstocks in the U.S. Pacific Northwest," Washington State University, Master of Science in Civil Engineering, Pullman, WA, 2018.

Caputo, A.C., Pelagagge, P.M. (2002) "RDF production plants: II. Economics and profitability," Applied Thermal Engineering, vol. 22, pp. 439-448, 2002. DOI: 10.1016/S1359-4311(01)00101-6

Cascadia Consulting Group, "Waste Characterization Study: 2015-2016 Washington Statewide," State of Washington Department of Ecology, 2018.

Chen, S., Spink, T., Gao, A. 2016. Aspen modeling of the NARA conversion process. http://hdl.handle.net/2376/6470. Accessed 3 February 2017.

Columbia Ridge Landfill, 2019. Landfill Group: Columbia Ridge Recycling and Landfill http://www.wmnorthwest.com/landfill/columbiaridge.htm. Accessed 16 December 2019.

de Jong, S., Faaij, A., Slade, R., Mawhood, R., and Junginger, M. (2015). The feasibility of short-term production strategies for renewable jet fuels – a comprehensive techno-economic comparison. Biofuels, Bioprod. Bioref. DOI: 10.1002/bbb.

Delta (2020). Delta partners with Northwest Advanced Bio-Fuels among actions toward more sustainable future. Accessed 2/6/2020 https://news.delta.com/delta-partners-northwest-advanced-bio-fuels-among-actions-toward-more-sustainable-future

EIA 2019a. Petroleum & Other Liquids: U.S. Kerosene-Type Jet Fuel Wholesale/Resale Price by Refiners. Accessed 12/10/2019. https://www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=PET&s=EMA_EPJK_PWG_NU.S._DPG&f=M

EIA, 2019b. Petroleum & Other Liquids: U.S. Biodiesel Plant Production Capacity. Release Date: 9/13/2019. Accessed 11/14/2019. https://www.eia.gov/biofuels/biodiesel/capacity/

Fulcrum Bioenergy 2019. Fulcrum Bioenergy: Our Process https://fulcrum-bioenergy.com/technology/our-process/ Accessed 12/23/2019.

Gallagher, Dave, "BP Cherry Point takes a step toward cleaner diesel with new major fuel unit," Bellingham Herald, 10/29/2018. Accessed 10/26/2019.

Geleynse, S., Brandt, K., Manuel Garcia-Perez, M., Wolcott, M., Zhang, X. 2018. The Alcohol-to-Jet conversion pathway for drop-in biofuels: Techno-economic evaluation. ChemSusChem, Vol. 11, 3728 – 3741. DOI:10.1002/cssc.201801690.

Georgia Tech: Center for Paper Business and Industry Studies. "Mills Online." Dataset: Directory of Pulp and Paper Mills. Parameters: all states, 2013 q4. Downloaded: 4/13/15. http://www.cpbis.gatech.edu/data/mills-online-new

Ghadim, A. K. A., Pannell, D. J., Burton, M. P. (2005). Risk, uncertainty, and learning in adoption of a crop innovation. Agricultural Economics Volume 33(1),1-9. DOI: 10.1111/j.1574-0862.2005.00433.x

Greene, John (2016). FedEx Commits to Biofuels Derived from Healthy Western Forests. Forest2Market. Accessed 2/6/2020. https://www.forest2market.com/blog/fedex-commits-to-biofuels-derived-from-healthy-western-forests

IATA (International Air Transport Association) 2015. IATA Sustainable Aviation Fuel Roadmap. Accessed 1/29/2020. https://www.iata.org/contentassets/d13875e9ed784f75bac90f000760e998/safr-1-2015.pdf

ICAO. 2019a. U.S. Efforts to Address Aviation's Climate Impacts. Working Paper A40-WP/531. 40th ICAO Assembly. Accessed 16 October 2019. https://www.icao.int/ Meetings/a40/Documents/WP/wp_531_en.pdf

ICAO. 2019b. Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA). https://www.icao.int/environmental-protection/CORSIA/Pages/default.aspx

Kennedy, HT (2018). Red Rock Biofuels facility breaks ground in Lakeview. Biofuels Digest, July 29, 2018. Accessed 12/5/2019. https://www.biofuelsdigest.com/bdigest/2018/07/29/red-rock-biofuels-facility-breaks-ground-in-lakeview/

Kessel, Candace, Personal Communication, BP. 10/18/2019.

King County Solid Waste Division (2006). Preliminary Transfer & Waste Export Facility Recommendations and Estimated System Costs, Rate Impacts & Financial Policy Assumptions: Fourth Milestone Report. Accessed 12/18/2019. https://kingcounty.gov/~/media/depts/dnrp/solid-waste/about/planning/documents/Milestone_report-4.ashx?la=en.

LanzaTech, 2020. Accessed 1/23/2020. https://www.lanzatech.com/.

Lane, J. , 2019. “The Compelling Case for Biojet Fuel”. Biofuels Digest. https://www.biofuelsdigest.com/bdigest/2019/04/01/the-compelling-case-for-biojet-fuel/ Accessed 12/29/2019.

Lee, S.Y., Hubbe, M.A., Saka, S., 2006. Prospects for biodiesel as a byproduct of wood pulping – a review. BioResources 1 (1): 150-171.

McGarvey, E., Tyner, W. (2017). A stochastic techno-economic analysis of the catalytic hydrothermolysis aviation biofuel technology. Biofuels, Bioprod. Bioref. DOI: 10.1002/bbb.1863.

Merrow ,W., Phillips, K., Myers, C. (1981). Understanding Cost Growth and Performance Shortfalls in Pioneer Process Plants. RAND Corporation, Santa Monica, US.

Neibergs, J., Galinato, S., Tozer, P., Brady, M. “2014 Economic Contribution Analysis of the Washington Beef Industry,” Washington State University School of Economics, Pullman, WA, 2014.

NEXT Renewable Fuels, Inc., “NEXT Fact Sheet.” Accessed 12/26/2019. https://nextrenewables.com/wp-content/uploads/2019/07/NEXT-FactSheet_070219.pdf

Niziolek, A.M, Onel, O., Faruque Hasan, M.M., Flouda, C.A. (2015) Municipal solid waste to liquid transportation fuels – Part II: Process synthesis and global optimization strategies. Computers and Chemical Engineering. 74 (2015) 184–203. DOI:10.1016/j.compchemeng.2014.10.007.

Onel, O., Niziolek, A.M., Hasan, M.M.F, Floudas, C.A. (2014). Municipal solid waste to liquid transportation fuels – Part I: Mathematical modeling of a municipal solid waste gasifier. Computers and Chemical Engineering 71 (2014) 636–647. DOI: 10.1016/j.compchemeng.2014.03.0

Oregon Department of Environmental Quality, “Oregon Solid Waste Characterization and Composition Study,” 2017.

Oregon Department of Environmental Quality, “2017 Oregon Material Recovery and Waste Generation Rates Report,” 2019.

Organization for Economic Co-Operation and Development. Composite Effective Marginal Tax Rate. https://stats.oecd.org/Index.aspx?DataSetCode=CTS_CIT. Accessed 30 October 2019.

Pan, W.L., Young, F.L., Maaz, T.M., Huggins, D.R. (2016). Canola integration into semi-arid wheat cropping system of the inland Pacific Northwestern U.S.A. Crop & Pasture Science 67, 253-265. DOI: 10.1071/CP15217

Peters, M.S., Timmerhaus, K.D. and West, R.E. (2003). “Analysis of Cost Estimatio” in Plant Design and Economics for Chemical Engineers, 5th edition. (New York, NY: McGraw-Hill), 226-278.

Peters, D., Stojcheva, V. (2017). “Crude tall oil low ILUC risk assessment Comparing global supply and demand. Project number: SISNL17494. Accessed 1/30/2020. https://www.upmbiofuels.com/siteassets/documents/other-publications/ecofys-crude-tall-oil-low-iluc-risk-assessment-report.pdf

Petter, R., and Tyner, W.E. (2014). Technoeconomic and Policy Analysis for Corn Stover Biofuels. ISRN Economics. Volume 2014, Article ID 515898. http://dx.doi.org/10.1155/2014/515898.

Port of Settle Commission. 2017. Motion of the Port of Seattle Commission to Develop a Comprehensive Port of Seattle Sustainable Aviation Fuels Strategy. https://www.portseattle.org/sites/default/files/2018-03/SAFS%20Motion.pdf. Accessed, December 27, 2019

Port of Seattle. 2018. Sustainable Aviation Fuels Memorandum of Understanding. https://www.portseattle.org/sites/default/files/2018-05/SAF_MOU.pdf Accessed December 27, 2019.

Pressley P.N., Aziz T.N., DeCarolis J.F., Barlaz M.A., Heb F., Li F., Damgaard A.
Skog, K., Rummer, R., Barbour, J., Nelson, R. (2014). Municipal solid waste conversion to transportation fuels: a life-cycle estimation. Journal of Cleaner Production. DOI: 10.1016/j.jclepro.2014.02.041.

Red Rock Biofuels (2019). Accessed 12/5/2019 https://www.redrockbio.com/lakeview-site.html

REG (2020). Grays Harbor Biorefinery. Accessed 2/6/2020. https://www.regi.com/find-fuel/production-facilities/grays-harbor

Schillinger, W. F., Papendick, R. I., Guy S. O., Rasmussen, P. E., Van Kessel, C. (2006). Dryland Cropping in the Western United States (2nd ed.), Dryland Agriculture (365-394). Madison, WI: American Society of Agronomy, Inc., Crop Science Society of America, Inc., Soil Science Society of America, Inc.

Sequential, “Free, Reliable Used Cooking Oil Recycling.” Accessed 12/26/2019 https://choosesq.com/used-cooking-oil-recycling/

Sherrard, A., 2019. “LanzaTech advances on alcohol-to-jet scale-ups in the United States and Japan”, Bioenergy International. https://bioenergyinternational.com/opinion-commentary/lanzatech-advances-on-alcohol-to-jet-scale-ups-in-the-united-states-and-japan Accessed 12/29/2019.

Southwest Airlines, 2014. Southwest Airlines Announces Purchase Agreement with Red Rock Biofuels: Company Intends to Purchase Low Carbon Renewable Jet Fuel. https://www.swamedia.com/releases/release-f28fd231382f4e768dbb5130f5782020-southwest-airlines-announces-purchase-agreement-with-red-rock-biofuels?query=red+rock Accessed February 28, 2020.

State of Washington Department of Ecology, 2019a. Reducing Greenhouse Gases. https://ecology.wa.gov/Air-Climate/Climate-change/Greenhouse-gases/Reducing-greenhouse-gases Accessed December 27, 2019.

State of Washington Department of Ecology, 2019b. Washington State Greenhouse Gas Emissions Inventory: 1990-2015. https://fortress.wa.gov/ecy/publications/documents/1802043.pdf Accessed December 27, 2019.

Statistics Canada, 2018 “Population estimates on July 1st, by age and sex,” 2018.

Statistics Canada, 2019 “Table 32-10-0359-01, Estimated areas, yield, production, average farm price and total farm value of principal field crops, in metric and imperial units”.

Suresh, P., Malina, R., Staples, M.D., Lizin, S., Olcay, H., Blazy, D., Pearlson, M.N. Barrett, S.R.H. (2018). Life Cycle Greenhouse Gas Emissions and Costs of Production of Diesel and Jet Fuel from Municipal Solid Waste. Environ. Sci. Technol. 2018, 52, 12055−12065. DOI: 10.1021/acs.est.7b04277.

Swanson, R.M.; Satrio, J.A.; Brown, R.C.; Platon, A.; Hsu, D.D. (2010). Techno-Economic Analysis of Biofuels Production Based on Gasification. NREL/TP-6A20-46587. https://www.nrel.gov/docs/fy11osti/46587.pdf

Tao, L., Milbrandt, A., Zhang, Y., Wang, W.-C. (2017). Techno-economic and resource analysis of hydroprocessed renewable jet fuel. Biotechnology for Biofuels volume 10, Article number: 261 (2017). DOI: 10.1186/s13068-017-0945-3

United States Census Bureau, “State Population Totals and Components of Change: 2010-2018”.

United States Department of Agriculture, 2019c “Crop Production: 2018 Summary,” 2019.

U.S. Energy Information Administration, “U.S. Biodiesel Plant Production Capacity,” 2019. Accessed 12/26/2019 https://www.eia.gov/biofuels/biodiesel/capacity/

Washington State Department of Ecology, “Material Recovery and Disposal Data in Washington,” 2017.

Wooley, R., Zhu, J.Y., Gleisner, R., Hawkins, A., Starkey, P., Gao, J., Spink, T., Ley, J., Evans, K., Wolcott, M., Marrs, G., Sessions, J. (2016). Production of 1,000 Gallons of Biojet in the NARA Consortium, NARA report. http://hdl.handle.net/2376/11865

Image Attributions

Appendix A

Potential Northwest Regional Feedstock and Production of Sustainable Aviation Fuel

2019 Report from the Port of Seattle and Washington State University

Prepared February 2020

WASHINGTON STATE UNIVERSITY

Port of Seattle

This research was funded by the Port of Seattle Sustainable Aviation Fuel Production Potential in the Pacific Northwest Service Agreement p-00319928

Siting Methodology

The methodology for siting fuel production facilities requires data on feedstock location, transportation networks with associated costs, geospatially distinct energy costs and final destinations of the product. In addition, population centers are necessary to ensure a labor force. The following description details the process used to generate candidate locations for integrated biorefineries using forest residuals as a feedstock.

The geospatial siting pre-selection tool (GSP), developed at WSU was used to identify several possible facility locations and then GSP selects a limited number of the most likely locations. The GSP Python script automates geospatial line, point, and polygon datasets and uses this information to generate a group of geospatially dispersed candidate locations that are suitable for new industrial facilities. Within the program, layers are created and used either as buffer layers or cost layers. Buffer layers force candidate locations to be placed within a defined distance of a type of infrastructure, for example within a set distance to a railroad. Cost layers help select candidate locations based on geospatially controlled economic factors, such as industrial electricity price.

For the forest residual supply chain, seven Geographic Information System (GIS) layers were used in candidate generation. The first layer is an incoming forest residual transportation cost estimate. This estimate relates forest residual density within a given radius to the modeled transportation costs required to supply a specified quantity of forest residuals, and was determined using a calibration procedure developed at WSU. The destination of the fuel was not pre-selected for all model runs, thus the outgoing transportation was not modeled with costs. Two buffer layers were used to ensure that all candidates are within two miles of freight roadways and railroads (ORNL, 2019, USBTS, 2019).

The National Renewable Energy Laboratory's (NREL) HyDRA database was used to supply county-level, industrial natural gas and electricity costs and verified as needed with data from the U.S. Energy Information Administration (EIA) (NREL, 2019, EIA 2020). Natural gas is not available via pipeline in all locations, thus the EIA natural gas pipeline dataset was also used to place candidates within five miles of the pipeline (EIA, 2019). To ensure a local workforce, the final layer is a buffer layer that forces candidates to be placed within 10 miles of locations with a minimum population of 300 people (ESRI, 2019). Candidates were not allowed to be placed within 25 miles of each other. The selected candidates represented the location with the lowest estimated costs within each cell. For the study region, the number of candidates was further reduced to include only the 35 best candidates which were then used in the optimization analysis.

Supply chain optimization is completed using the Many-Step Transshipment Solver (MASTRS), a tool developed at WSU. MASTRS links all entities or groups of similar nodes, such as feedstock location and candidate facilities, together through equations that represent both costs and the physical flow of material. These equations are used to find the minimum total cost that can be achieved for the supply chain with the defined constraints.

The results of the model describe how and where material is moved in the supply chain and which combination of candidate facilities result in the lowest cost supply chain. Four types of entities were used for the forest residuals supply chain. The first entity used to enter material into the supply chain is a ¼ decimal degree by ¼ decimal degree grid with the forest residuals at LURA points summed to the center of the cell in which they are located (Latta et al., 2018). A collection cost of $42.8/bone dry ton was assigned to each harvested bone dry ton of residuals (Martinkus et al., 2017). The second entity is the list of candidate biorefinery locations generated by the GSP. Each candidate location is given four capacity settings with corresponding fixed costs that must be paid to activate the node. The model calculates the optimal locations and capacities for new biorefineries. Not all candidate biorefinery locations will be activated within the model based on costs and feedstock availability. For cost purposes, it is assumed that all forest residuals are transported between the feedstock nodes and candidate biorefineries using chip trucks. Biorefineries also have variable costs for natural gas and electricity use are a function of facility capacity and if the capacity is fully utilized.

The final two entities represent end users of the fuel and co-products, and are modeled in an outgoing supply chain. The entities that purchase SAF are located at airport within the region. Urban areas with populations greater than 100,000 people are modeled as the markets for the non-SAF fuel products coproduced at the biorefinery. An opportunity cost that represents potential revenue for fuel sold was assigned to each exit node. Fuel was transported to the exit entities by tanker trucks and tanker rail cars, whichever is more economical.

References

EIA, 2019., "Natural Gas Interstate and Intrastate Pipelines." Accessed 12/26/2019, https://www.eia.gov/maps/layer_info-m.php.

EIA, 2020. "Electricity: Form EIA-861-M (formerly EIA-826) detailed data". Accessed 6/12/2020, https://www.eia.gov/electricity/data/eia861m/.

ESRI, "USA Census Populated Places," June 18, 2019. Accessed 12/26/2019, https://www.arcgis.com/home/item.html?id=9e25e210684c4acfbab785b9c4e3ed2d

Latta, G., Baker, J., Ohrel, S. "A Land Use and Resource Allocation (LURA) modeling system for projecting localized forest CO2 effects of alternative macroeconomic futures," Forest Policy and Economics, vol. 87, pp. 35-48, 2018.

Martinkus, N., Latta, G., Morgan, T., and Wolcott, M. (2017). A comparison of methodologies for estimating delivered forest residue volume and cost to a wood-based biorefinery. Biomass and Bioenergy Vol. 106, 83-94. https://doi.org/10.1016/j.biombioe.2017.08.023.

NREL, 2019. National Demand and Resource Analysis. Map accessed January 2019. https://maps.nrel.gov/hydra/?aL=xZMS-8%255Bv%255D%3Dt&bL=clight&cE=0&lR=0&mC=40.21244%2C-91.625976&zL=4

ORNL, 2019. Oak Ridge National Laboratory, "Freight Analysis Framework Version 4." Accessed 12/26/2019, https://faf.ornl.gov/fafweb/

USBTS, 2019. United States Department of Transportation Bureau of Transportation Statistics, "North American Rail Lines," 9/13/2019. Accessed 12/26/2019, http://osav-usdot.opendata.arcgis.com/datasets/f15d9e40cd1d4170a36bf31d4e6a3c28_0

Appendix B

Potential Northwest Regional Feedstock and Production of Sustainable Aviation Fuel

2019 Report from the Port of Seattle and Washington State University

Prepared February 2020

WASHINGTON STATE UNIVERSITY

Port of Seattle

This research was funded by the Port of Seattle Sustainable Aviation Fuel Production Potential in the Pacific Northwest Service Agreement p-00319928

Detailed Feedstock Methodologies

The quantity and availability of each of the three feedstocks: lipids, forest residuals and municipal solid waste, were developed using publicly available data and models/methodologies. Lipids in the Northwest (NW) U.S. were separated into FOGs and vegetable oil. These two categories differ in content, handling in a facility and classification as a waste. Forest residuals are a waste product that is dependent on existing timber harvest. It is not viable for use in production of lumber or paper. It is important to note that at the assumed stumpage fee of $4/ bone dry ton, harvesting will not occur unless the timber is needed for another product. This means that forest residuals are only available when harvest is occurring for another purpose. The total amount of MSW had to be quantified and the total was divided into material that is recovered/recycled versus material that is landfilled. Only the landfilled portion is included in the potential feedstock numbers and this portion was further subdivided based on applicability for conversion to SAF.

FOGs

The method to quantify the amount of used cooking oil was originally implemented by the Western Governors Association (Skog et al., 2008). It was assumed that nine pounds of used cooking oil was produced per capita for each urban area, defined as a city with a population greater than 100,000 by the U.S. Census Bureau (Wiltsee, 1998). In 2017, an estimated 88 million people lived in the urban areas of ID, MT, OR, and WA. This population information combined with the per capital used cooking oil factor was used to estimate 35,900 tons of used cooking oil was produced. Statistics Canada provides "census metropolitan areas" that are similarly defined as urban areas in the United States. It is estimated that an additional 15,100 tons of used cooking oil were produced in British Columbia in 2018. This value is calculated using the method developed for the U.S. and the British Columbia metropolitan areas population (Statistics Canada, 2019a). It is important to note that this value is an estimate of the total waste grease produced which is likely much higher than the amount of available waste grease available as an SAF feedstock.

The production of FOGs from animal fats includes tallow produced from beef in ID and WA and lard/white grease from ID and OR. No significant animal fat production occurs in MT, so a zero value is assumed. Although there are many facilities in the region that have some slaughter capacity, almost all slaughter activities occur at a only few packing plants. Neibergs et al. identified four major beef processing facilities in the NW U.S. including: Tyson Fresh Meats, Washington Beef, CS Beef, and Schenk Packing (2014). For each animal processed at a packing plant specializing in steers and heifers, an average liveweight of 1425 pounds was used. For each animal processed at a packing plant specializing in cull cows, an average liveweight of 1250 pounds was used (USDA, 2016). A liveweight/tallow production factor of 12% was applied to all cattle (Centrec Consulting Group, 2014). In 2018, Tyson Fresh Meats Pasco and Washington Beef processed 907,000 head of steers and heifers, likely near 400,000 and 500,000 head respectively based on past rates (Agri Beef, 2016). Using these assumptions, it was calculated that these two facilities produce a combined 77,500 tons of tallow annually. Based on annual slaughter reports and known slaughter capacities (Neibergs et al. 2014, USDA 2019a), Schenk Packing and CS Beef processed an estimated 151,000 and 419,000 cull cows, respectively, producing 42,800 tons of tallow annually. This is a total regional production of 120,300 tons of tallow. OR and ID each have one federally approved facility specializing in swine slaughter, Carlton Packing in OR and Independent Meat in ID (USDA 2019b). It is assumed that each state's swine slaughter is conducted at these facilities. In 2018, Idaho slaughtered 164,000 hogs and Oregon slaughtered 166,000 hogs at an average live weight of 283 pounds (USDA 2019a). A liveweight/fat production rate of 4.8% was applied to all swine (Centrec Consulting Group, 2014). An estimated total 2,200 tons of pig fat (edible lard and inedible white grease) was produced in the NW U.S. during 2018.

It should be noted that poultry also produces useful fat, but it was not included in the FOG analysis because the production in this region is negligible.

Vegetable Oils

Plant-based sources of lipids may become more available for renewable fuel production in the NW U.S. in the medium and long-term future, though they are very limited in the near term. Within this region, extensive research has been conducted on opportunities to expand production of brassica crops such as canola and rapeseed (Camenzind, 2018). Camenzind developed several production scenarios for dryland spring and winter canola in Washington, Oregon, and Idaho (2018). The method used to build these scenarios considered how oilseeds could be added into existing crop rotations using agro-ecological classes developed by Washington State University and the U.S. Department of Agriculture.

Potential yields that could be achieved were determined using CROPSYST model runs from WSU and oilseed field trial data. CROPSYST is a modeling tool that uses climate and soil data to predict crop production. The results from Camenzind, shown in Table B1, gives an optimistic scenario for canola production that assumes 100% adoption by farmers in the region. Depending on the agro-ecological zone, farmers would plant canola once every three or four years. The amounts listed in Table B1 are not expected to be produced in the 3-5 year time horizon requested by the Port of Seattle.

Table B1: Maximum annual potential oilseed production scenario (tons) that could be produced in the NW U.S. dryland cropping zones.

	Maximum Oilseed Production	Estimated Canola Oil Production
Idaho	254,000	107,000
Oregon	286,000	120,000
Washington	961,000	404,000
NW Total	1,501,000	630,000

Forest Residuals

The amount of forest residuals produced in the region was predicted using the Land Use and Resource Allocation (LURA) model (Latta et al., 2018). Each LURA model run conducts an analysis of the entire forest products industry across the United States over a specific time horizon. The model uses detailed inputs about existing forests from: the U.S. Forest Service's Forest Inventory Analysis (FIA) points; macroeconomic indicators to build demand scenarios from the Energy Information Administration's Energy Outlook; capacities and products from sawmills and paper mills across the United States; gasoline prices to estimate transportation costs. The availability of forest residuals is expected to remain relatively stable over time if the production of primary forest products is stable. The LURA model runs are designed to reflect average production over a fifteen-year period. The LURA dataset used for this study was produced based on 2019 information.

The total annual production of forest residuals is significantly higher than the amount of forest residuals that can be practically removed from forests, defined here as the harvestable portion. The slope of the harvest area and the type of harvest system impact the fraction of material that can be readily removed from the forest using both economic and site sustainability considerations. Following work by Martinkus et al., it was assumed that 46.5% of the forest residuals can be harvested on lands with slopes greater than 30 degrees and 67.2% harvested on lands with slopes less than/equal to 30 degrees (2017).

All forest residuals from federal lands were omitted from the estimates because biofuels manufactured using feedstock from federal land are not currently eligible for incentives based on the Renewable Fuels Standard (RFS), including renewable identification numbers (RINs) and cellulosic waiver credits (CWCs). Although these programs are currently available for materials harvested on non-federal lands, the congressional mandate for RINs expires in 2022 and then the EPA will set volumes (McGarvey & Tyner, 2016). It should be noted that fuels from forest residuals are approved for California's Low Carbon Fuel Standard (LCFS) and these different federal and state incentives can be stacked. LCFS is the major factor that currently drives much of the biofuel produced in the U.S. to the California market.

Municipal Solid Waste (MSW)

Availability of MSW as a SAF feedstock is challenging to quantify. This is a result of the need to categorize the heterogeneous material collected into fractions that can be converted to SAF. For this report, MSW is characterized by both destination and material type. Waste destinations can be separated in two general groups, disposed and recovered. Disposed waste is any waste directed to a landfill and is the ideal portion of the waste stream to divert to biofuels production. Recovered waste includes recycled, composted, and burned waste (waste-to-energy).

The average reported waste generation by individuals varies between states from about 1.0 to 1.5 tons/person/year. These variations are at least partially due to non-standard data collection and accounting techniques. Recovery rates between states vary considerably. WA and OR have high recycling and composting rates, while both MT and ID have relatively high disposal rates. MSW combustion does not occur in any significant quantity in this region. Recovery and generation rates should be viewed differently. Generation is accomplished by many individuals, households, and commercial businesses and includes both disposed and recovered MSW. Recovery is accomplished by a few companies in each state or region, so the presence, absence, or specialties of one company can significantly impact the amount and types of materials recovered.

Many studies addressing the composition of MSW use original methodologies that result in unique material categories. For this study, MSW is separated in nine generalized categories that are standard in EPA studies (U.S. EPA, 2015): paper and paperboard; glass; metals; plastics; rubber, leather, and textiles; wood; yard trimmings; food; other. Not all waste categories are compatible with producing SAF from MSW. Glass and metals can be ignored completely, and other categories may not be feasible based on high moisture content and the need to remove water from feedstock as a pretreatment step before conversion. In addition, some waste types are more desirable for composters and recyclers than others, which also impacts recovery rates. For example, yard trimmings are the most likely material to be composted, and paper is recycled at a higher rate than plastic.

This study seeks to quantify each type of waste and how it is currently recovered or disposed in each state. Sufficient data is not available from all states or on a national level to quantify waste completely. Thus, per capita values were developed for waste generation. Recovery rates are based on state data, when available, with national scale sources used when state data is nonexistent or insufficient.

The region included in this assessment is comprised of WA, OR, ID, and MT. General numbers from British Columbia, Canada are also included in the results. The methodology for estimating MSW production are primarily based on data from WA and OR, as these states maintain annual recycling databases, and have intermittently launched studies to characterize disposed waste. Data is incomplete or not available in ID and MT. The method has four steps:

1. Determine a total quantity of waste generated per person.
2. Determine the overall breakdown of waste into destination categories.
3. Determine the breakdown of waste into material categories for each destination category.
4. Determine how recovery trends in different states impact the recovery rates of specific materials.

Table B2 lists the per capita waste generated as the average value for Washington and Oregon between 2012-2016 (Washington State Department of Ecology, 2017, Oregon Department of Environmental Quality 2019). The average per capita value was applied to 2018 population data for the entire region (Oregon Department of Environmental Quality 2019, van Haaren et al., 2010). This waste data was selected because it is based on several years of consistent, detailed, public data. Other resources available provide only a single value with limited context (van Haaren et al., 2010, U.S. EPA, 2015)

Table B2: Total and destination specific per capita waste estimates (ton/capita/yr)

	Disposed Waste	Recovered Waste	Generated Waste
Washington	0.61	0.70	1.31
Oregon	0.69	0.57	1.26
Average	-	-	1.29

Recycling and recovery rates were calculated by combining the detailed categories into a single waste-generated per capita value for Washington and Oregon. For Idaho and Montana, general recycling and recovery rates were obtained from communications with state agencies or other resources. Table B3 shows available rates for each state and the source of the information.

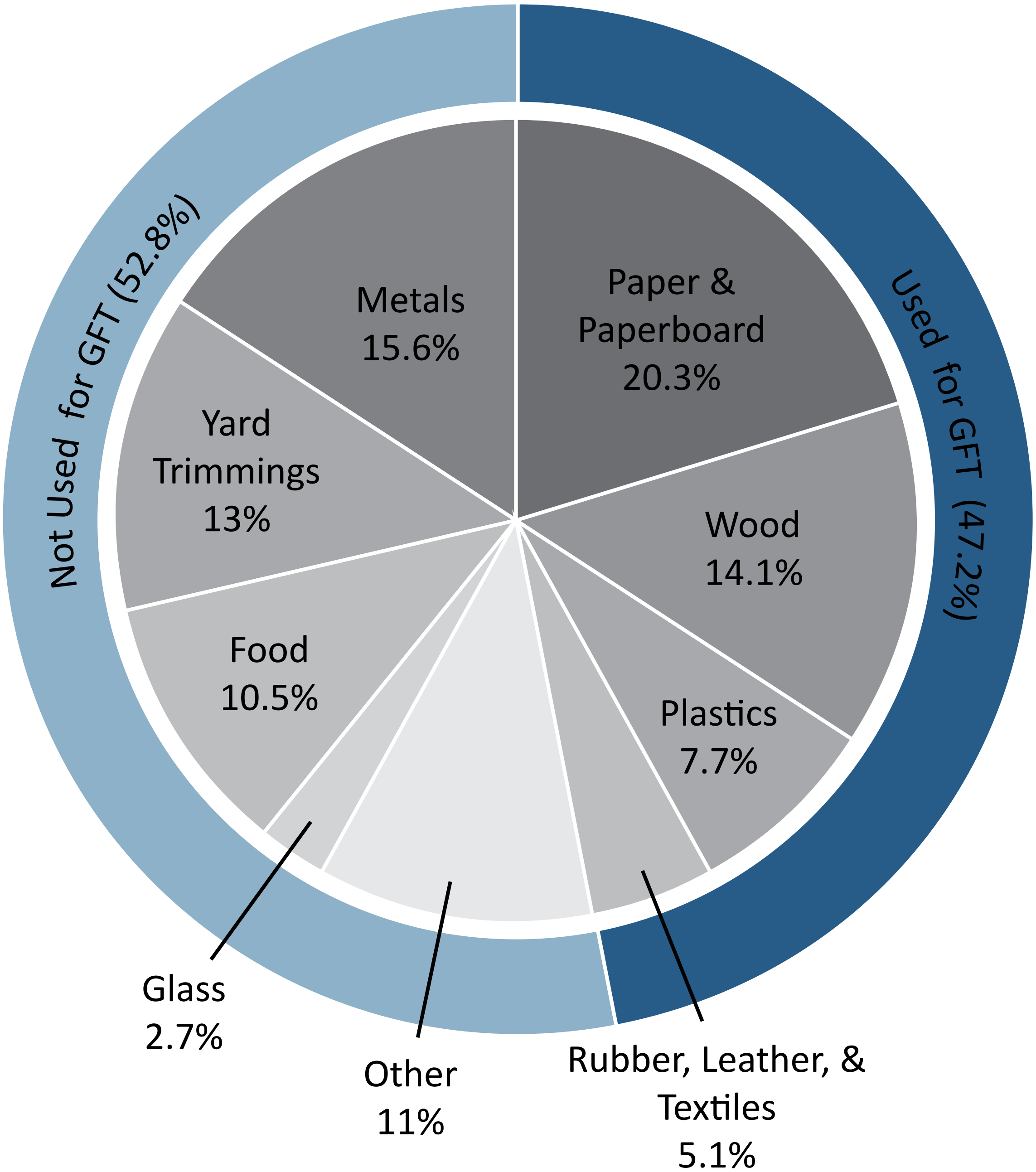
Table B3: State specific recycling and recovery rates

	Recycling Rate	Total Recovery Rate	Source
Washington	46.2%	53.6%	State Database[a]
Oregon	-	45.1%	State Database[b]
Idaho	9.0%	-	Biocycle/EEC Report[c]
Montana	14.7%	-	Communication with MDEQ[d]

[a]Washington State Department of Ecology, 2017, [b]Oregon Department of Environmental Quality, 2019, [c]van Haaren et al., 2010, [d]Johnson, 2019, [e]Statistics Canada, 2019b, [f]Statistics Canada, 2019c

The breakdown of waste by category uses annual MSW recovery reports from Washington and Oregon and reports on MSW disposal (Cascadia Consulting Group, 2018, Oregon Department of Environmental Quality, 2019, Oregon Department of Environmental Quality, 2017, Washington State Department of Ecology, 2017). The Washington and Oregon annual reports have detailed breakdowns for the material recovered and total values for material disposed. The total material disposed were compared between the reports to ensure that each considered the same materials. The result is that WA and OR MSW per capita generation values are nearly identical. To determine the fraction of MSW generated in each category, disposed materials are combined with recovered materials. The categories in each report are combined into one of the nine primary categories. The results from WA and OR were averaged using population weighting (Figure B1). The average category-specific generation rates, reported as the percent of total waste, were applied to the regional MSW generation rate.

Figure B1: MSW generation rates for nine generalized categories shown as an average of OR and WA.



The final step is to determine the fraction recovered of each material category. Detailed data on recovered material is available for Washington and Oregon, but the same resources do not exist for Idaho and Montana. A method was developed to quantify how overall recycling rates are related to recycling rates of specific material categories using data from a joint Columbia University and Biocycle report (van Haaren et al., 2010). The report summarizes data from the

29 U.S. states that responded to the survey. Overall recycling rates were related to available rates for specific material types. These relationships were used to determine the amount of material in each category for the MSW disposed in the NW U.S. region.

References

Agri Beef Homepage, "Washington Beef". Accessed 14 July 2016. https://www.agribeef.com/.

Camenzind, D. "Supply Chain Analysis for Alternative Jet Fuel Production from Fatty Acid Feedstocks in the U.S. Pacific Northwest," Washington State University, Master of Science in Civil Engineering, Pullman, WA, 2018.

Cascadia Consulting Group, "Waste Characterization Study: 2015-2016 Washington Statewide," State of Washington Department of Ecology, 2018.

Centrec Consulting Group, "Biodiesel Demand for Animal Fats and Tallow Generates an Additional Revenue Stream for the Livestock Industry," National Biodiesel Board, 2014.

Johnson, D., 2019 "2018 [MSW Disposal and Recycling] Numbers," Montana Department of Environmental Quality, Personal Communication, August 2019.

Latta, G., Baker, J., Ohrel, S. "A Land Use and Resource Allocation (LURA) modeling system for projecting localized forest CO2 effects of alternative macroeconomic futures," Forest Policy and Economics, vol. 87, pp. 35-48, 2018.

Martinkus, N., Latta, G., Morgan, T., and Wolcott, M. (2017). A comparison of methodologies for estimating delivered forest residue volume and cost to a wood-based biorefinery. Biomass and Bioenergy Vol. 106, 83-94. https://doi.org/10.1016/j.biombioe.2017.08.023.

McGarvey, E., Tyner, W. (2017). A stochastic techno-economic analysis of the catalytic hydrothermolysis aviation biofuel technology. Biofuels, Bioprod. Bioref. DOI: 10.1002/bbb.1863.

Neibergs, J., Galinato, S., Tozer, P., Brady, M. "2014 Economic Contribution Analysis of the Washington Beef Industry," Washington State University School of Economics, Pullman, WA, 2014.

Oregon Department of Environmental Quality, "Oregon Solid Waste Characterization and Composition Study," 2017.

Oregon Department of Environmental Quality, "2017 Oregon Material Recovery and Waste Generation Rates Report," 2019.

Skog, K., Rummer, R., Barbour, J., Nelson, R. "Biomass Resource Assessment and Supply Chain

Analysis for the WGA Region: Strategic Assessment of Bioenergy in the Western United States," Western Governors Association, Denver, CO, 2008.

Statistics Canada, 2019a. "Annual population estimates by census metropolitan area, July 1, 2018".

Statistics Canada, 2019b. "Table 38-10-0032-01 Disposal of Waste, by Source," 2016.

Statistics Canada, 2019c. "Table 38-10-0033-01 Materials diverted, by source," 2016.

U.S. EPA, 2015. United States Environmental Protection Agency, "National Overview: Facts and Figures on Materials, Wastes and Recycling," 2015.

USDA, 2016. United States Department of Agriculture, "Livestock Slaughter: 2015 Summary".

USDA, 2019a. United States Department of Agriculture. "Livestock Slaughter: 2018 Summary," 2019.

USDA, 2019b. United States Department of Agriculture. "List of Plant Approved to Receive Immediate Slaughter Animals," 2019.

van Haaren, R., Themelis, N., Goldstein, N. "The State if Garbage in America: 17th Nationwide Survey of MSW Management in the U.S.," October 2010.

Washington State Department of Ecology, "Material Recovery and Disposal Data in Washington," 2017.

Wiltsee, G. "Urban Waste Grease Resource Assessment," National Renewable Energy Laboratory, Golden, CO, 1998.