Waste to Fuels Technology: Evaluating Three Technology Options and the Economics for Converting Biomass to Fuels

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FINAL REPORT

Waste to Fuels Technology: Evaluating Three Technology Options and the Economics for Converting Biomass to Fuels

Submitted by
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Beyond Waste Objectives

Turning organic wastes into resources, such as compost, bioenergy, biofuels, recovery of stable carbon and nutrients and other products promotes economic vitality in growing industries, and protects the environment. This creates robust markets and sustainable jobs in all sectors of the economy, and facilitates closed-loop materials management where by-products from one process become feedstocks for another with no waste generated.

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Executive Summary

Introduction

Washington is well positioned to be a major player in the future bioeconomy in terms of biomass as potential feedstocks for producing biofuels and chemicals. A 2005 study funded by the Washington State Department of Ecology (Ecology) revealed that Washington State produces about 17 million dry tons of biomass annually (http://www.ecy.wa.gov/biblio/0507047.html). This biomass included under-utilized field residues, animal wastes, forestry residues, food packing/processing wastes, and municipal wastes. Subsequent utilization of the biomass requires additional information on technical options and economics, each considering type of feedstocks geographical distribution of the biomass, and the available road infrastructure for transportation of the biomass and the products. To address these needs, Ecology and Washington State University (WSU) entered into an interagency agreement in 2007 to conduct a techno-economical assessment of biomass utilization building upon the results of the earlier effort. This 2007 study expands upon the previous work by: spatially investigating specific types of the inventoried biomass, comparing three conversion technologies (dilute acid pretreatment with simultaneous saccharification and co-fermentation (SSCF) for producing bioethanol, biomass gasification for synthesizing mix-alcohols, and anaerobic digestion (AD) for producing biogas), and determining feedstock transportation, processing and total delivered costs for the produced biofuels. To assess the final delivered costs of biofuel, the study integrated all the major cost factors including, biomass availability, feedstock prices, transportation costs, processing costs, and geographic distribution into a comprehensive model framework using geographical information system (GIS) and MATLAB-SIMULINK platforms. To evaluate the feasible scale of biofuel plants, proximity of the processing plants to both feedstocks and market locations in the state was also considered. Based on the model framework and process data from National Renewable Energy Laboratory (NREL), the models were run using data compiled in the 2005 study (Frear et al. 2005) and the results provided information that can be used as reference for decision making in planning for future utilization of the major types of biomass.

In this report, literature sources are cited to estimate the cost and efficacy of conversion processes such as fermentation, gasification and anaerobic digestion. However, the suggested optimal facility scale may be shifted by factors that are beyond the scope of this project. For example, Washington dairy farms have begun to build anaerobic digesters on a smaller scale than the optimized estimates herein for processing animal manure. As well, global advances in technology are improving processes that will certainly decrease facility scale. Local or regional based systems are likely to be built in which capital outlay limits and system solutions are also beyond the project scope. Indeed, we acknowledge that the 2005 biomass inventory (basis for biomass estimates) is known to underestimate woody resources. These issues arise from the fact that the sophisticated modeling assessments herein have been applied to best available Washington data assuming technological applications that remain largely untested and biomass quantity estimates that attempt a reasonable prediction of actual resources. While Washington is a recognized leader in recycling, continued research will play a key role in the development of uses for recycled organics that will create fuels and energy for a sustainable local economy from renewable resources.

Methodology

The project methodology is summarized as follows:

1. Economic assessment models were established using MATLAB-SIMULINK platforms for all three conversion technologies, respectively. Ethanol production models for both bioconversion and gasification processes were developed according to the NREL conceptual designs that have been adopted in many papers, presentations, and technical reports (Wooley, Ruth et al. 1999; McAloon, Taylor et al. 2000; Aden, Ruth et al. 2002; Lynd, van Zyl et al. 2005; Huang, Ramaswamy et al. 2006; Phillips, Aden et al. 2007). The AD model was constructed based on International Water Association (IWA) Anaerobic Digestion Model No. 1 (ADM1) with additional parameters derived from research conducted at WSU (Zaher, Li et al. 2009).
2. Within all the feedstock available in Washington State, six types of material [crop residue, forest residue, municipal solid waste (MSW) paper, MSW wood residue, animal waste, and food waste] were studied as they represent the greatest biofuel potential because of their large quantities. Among these feedstocks, crop residue, forest residue, MSW paper, and MSW wood residue can be converted to bioethanol through fermentation or thermo-ethanol through gasification, while the other two can be processed using AD systems to generate biogas. Combinations of different feedstocks and technologies were analyzed for four sites (Longview, Ferndale, Spokane, and Ellensburg) as examples by virtue of processing models and GIS-based transportation models. All economic assessment results were summarized to create a best-fit determination matrix of current energy technologies for applicability to the feedstock types.
3. The GIS-based transportation models provided feedstock quantity and costs over different collection distances. These data were used as inputs to the processing MATLAB-SIMULINK models to generate final simulation results.
4. Besides costs of feedstock collection and processing, the delivery costs of ethanol were also analyzed. At each level of processing capacity, transportation costs from processing plants to six blending terminals in Washington State were added to costs accrued from terminals to E85 stations to derive the total distribution costs.
5. The project report was compiled as six parts to document the methods, analyses and conclusions. In the main report all the results are summarized for a quick overview of the entire project outcome. Much more detailed information on feedstock collection costs, processing costs, and distribution costs can be found in the first appendix. The second appendix includes descriptions and manuals for the three processing models established, with all the parameters listed.

Results

Individual costs for the entire biofuel delivery process were generated with respect to feedstocks, conversion technologies and site locations studied. Figure A1 demonstrates as an example (see appendices for additional figures) the relative costs of each of the components, including feedstock/transportation, processing, distribution, and the final delivery costs. While processing cost is an important contributor to overall costs, the study suggests that feedstock/transportation and delivery costs combined contribute approximately an equal share of the total cost.

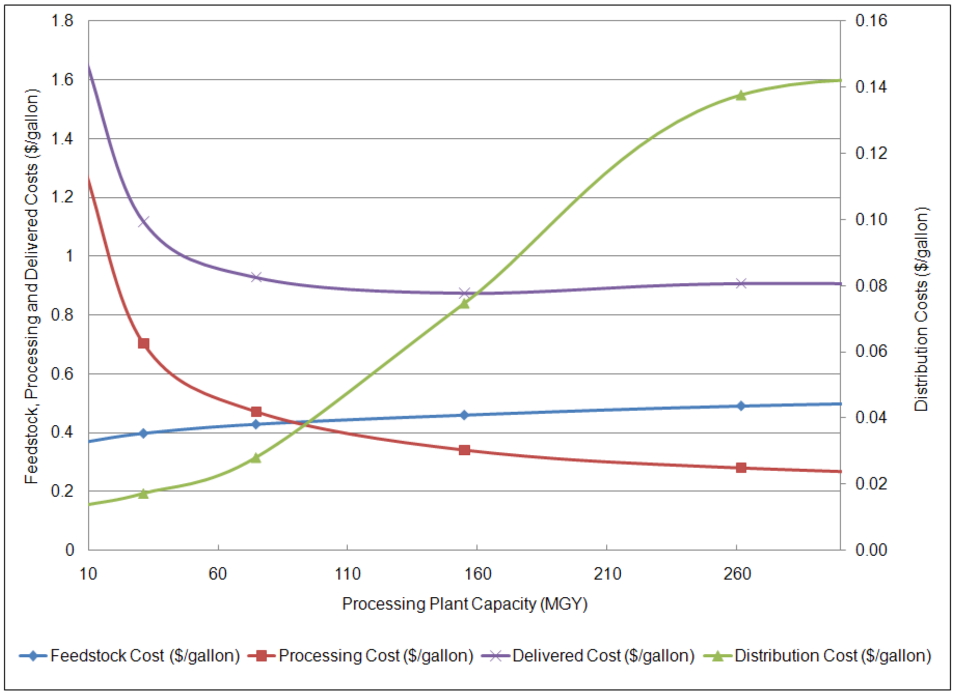


Figure A1: Breakdown of cost components against plant size (thermal-forest example)

With regard to other cost categories, transportation costs for both feedstock and ethanol were found to be $0.092/ton/mile and $0.00067/gallon/mile, respectively. From the least-cost perspective, the GIS model proposed four ethanol plants for the state. For crop residue, Spokane maintains its least-cost feedstock transportation advantage up to a 180-mile collection distance, and for forest residue, Longview takes the lead up to 180 miles. For all other feedstocks, Ellensburg seems to be the best least-cost location. Based on the model output, the processing cost of a thermo-ethanol facility from forest residue is significantly lower than that from fermentation. Similar results also apply to other feedstocks and scales. This difference is due to the low variable operating costs for thermo-ethanol as determined by the design configuration and, notably, other studies (Wooley et al, 1999; McAloon et al, 2000; Arden et al, 2000; Lynd et al, 2005; Philips et al, 2007; and Huang et al, 2009) also indicate that thermal ethanol production, even at the somewhat smaller scales found optimal for Washington state, is more cost effective than biological fermentation.

Analysis of the research data and conclusions as represented by the individual cost curves and overall plant size modeling corroborates previously held trends in commodity chemical production, namely that with increasing plant scale, economies of scale induce a reduction in processing costs, but simultaneously increase transportation costs as larger scale requires an ever growing radius of biomass collection/transportation. This results a tipping point whereby total delivered costs can be minimized by utilizing an optimal plant size which converges upon the nexus of the respective processing and transportation curves (Figure A2).

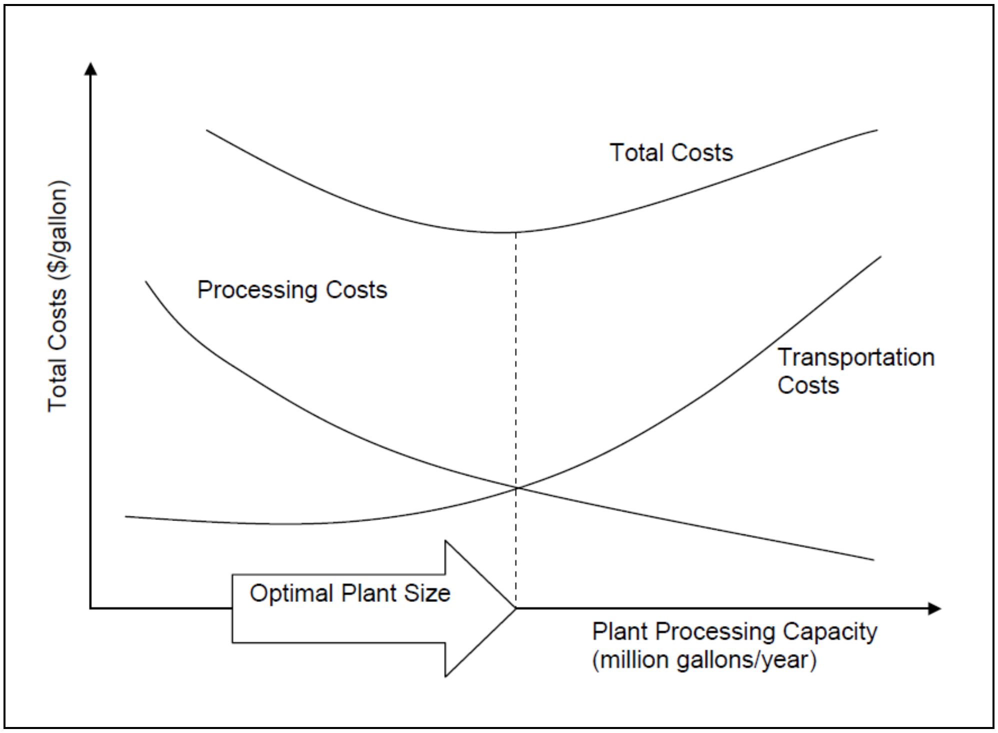


Figure A2: Schematic of relationship between costs and plant scale

Optimal plant sizes and locations were determined for the various scenarios involving the studied feedstocks, conversion technologies and distribution sites and are summarized in Table A1. Specifically for Spokane, the optimal size of a bioethanol plant using crop residue feedstocks is 125 MGY, with a lowest delivered cost of $1.31/gallon. For an Ellensburg-based thermo-ethanol plant using forest residue as feedstock, the optimal size expands to 155 MGY, and the lowest delivered cost drops to $0.87/gallon. For an MSW paper-based bioethanol plant located at Ellensburg, these two parameters are 137 MGY and $1.18/gallon. MSW wood residue is too small in quantity to be economical. For an AD system, because of the limitation of onsite treatment of effluent material, only small-scale (daily input <500 m^3) is valid for analysis. For animal waste, with a fixed feedstock cost, net income increases with scale. For food waste, the cost associated with feedstock transport has major impact, and a facility in the Spokane area seems to have the best financial performance under 200 m^3 of daily input.

Table A1. Summary of delivered costs, optimal plant size and location by feedstock (including ethanol distribution cost)

Feedstock Category	Delivered Costs by Processing Technology ($/gallon)		Optimal Plant Size (MGY) by Processing Technology		Optimal Location by Processing Technology	
	Bio-ethanol	Thermo-ethanol	Bio-ethanol	Thermo-ethanol	Bio-ethanol	Thermo-ethanol

Ag Residue	1.31	1.09	125	117	Spokane	Spokane
Forest Residue	1.26	0.87	117	155	Longview	Ellensburg
MSW (Wood Residue)	1.53	1.17	65	65	Spokane	Spokane
MSW (Paper)	1.26	1.08	132	165	Spokane	Spokane

Impact to the State

According to the data from the Energy Information Administration (2008), transportation gasoline consumption by Washington State was 64.75 million barrels for 2007. If this fuel demand was replaced with E10, there would be an ethanol demand of 272 million gallons per year. The model framework developed in this study can be used to evaluate different options. For example, one possible scenario for meeting such a demand based upon data compiled from this study as well as the previous inventory is construction and operation of two ethanol plants, one in Ellensburg area (155 MGY, forest residue) and the other in Spokane area (117 MGY, field residue). In addition to the ethanol produced an additional 43.9 MGY of other mixed-alcohols will be produced for co-product sales. Under this E10 satisfying scenario, 64.6% of total field residue and 21.4% of total forest residue are utilized. When the total transportation fuel replacement percentage of Washington State is increased to 30%, most available waste material will be consumed for ethanol production as shown in Table A2 and the ethanol delivered price may be little higher because of large plant size, while with more ethanol blending the state will benefit more from the gasoline import reduction and price reduction (Table A3).

The cost curves generated can provide useful information to government agencies and possible investors. They also suggest how to reduce the final delivered cost of energy products in Washington State. A desirable location with optimal scale is critical, and technology also plays a significant role in cost reduction. Another possible way to reduce cost is to use mixed feedstocks. Because many of the feedstocks are lignocellulosic in nature, it is possible to utilize them together. Analysis shows that if all available feedstocks were used within mixed-feedstock processes, the production cost would decline slightly, assuming no loss in system performance because of the mixed-nature. It is important to note, however, that all of the technical performance and cost data used in the analysis about the technologies were obtained from references which were reported with various assumptions as there is in general a lack of actual data from operating plants. The results of the analysis are therefore preliminary and need to be used only for references purpose with necessary caution. Nonetheless, the project results can be used to estimate relative importance of the major cost components in lignocellulosic ethanol production in the state of Washington. Additionally, the model framework can also be used to evaluate cost response to location and plant size.

Table A2. Comparison of two different fuel mandate scenarios

Scenario	MGY	Plant Specifics	Feedstock Consumption (Mt/yr and % of total)	Total Investment (MM$)	Total Salary (MM$)	Sales Tax (MM$)

E10	272	1 therm-ethanol, Ellensburg (155 MGY, forest residue)	1.74 /21.4	420.5	2.57	16.97
		1 therm-ethanol, Spokane (117 MGY, field residue)	1.55/64.6	386.8	2.53	15.61
E30	816	1 therm-ethanol, Ellensburg (262 MGY, forest residue)	2.93/36.2	627.4	2.87	25.34
		1 therm-ethanol, Longview (332 MGY, forest residue)	3.72/45.9	760.1	2.96	30.71
		1 therm-ethanol, Spokane (117 MGY, field residue)	1.55/64.6	386.8	2.53	15.61
		1 therm-ethanol, Spokane (165 MGY, MSW paper)	1.91/78.5	450.9	2.57	18.20

Table A3. Economic impact of varying ethanol blending scenarios

	E0	E10	E15	E20
Adjusted Gasoline Consumption MGY	2720	2830	2864	2948
Ethanol in Blend MGY	0	283	430	590
Saving per gallon $ (NREL2009 report)	0	0.15-0.5	0.2-0.59	0.18-0.63
Total Saving Billion $	0	0.54-1.41	0.57-1.69	0.53-1.86

INTRODUCTION

Developing a biofuel industry in Washington will result in multiple benefits to the state, such as promoting new economic development opportunities, reducing foreign oil import, and cutting greenhouse gas emissions. Washington State has various biomass resources that can be used as feedstock for biofuel production. According to the 2005 study funded by the Washington State Department of Ecology, Washington State produces about 17 million dry tons of biomass annually (http://www.ecy.wa.gov/biblio/0507047.html). The biomass includes under-utilized field residues, animal wastes, forestry residues, food packing/processing wastes, and municipal wastes. It would serve the great interests of the state and the industry if further analysis was made on different technological options for using these feedstocks. To meet such a need, Washington State University was contracted by the Washington Department of Ecology to analyze economic feasibility of using Washington State's bioresources. According to the matrix component shown in Table 1, this study assessed specific feedstock types (crop residue, forest residue, municipal solid waste (MSW) paper, MSW wood residue, animal waste, and food waste) inventoried from the earlier study against three conversion technologies (biochemical conversion via fermentation, gasification and anaerobic digestion) for determination of feedstock transportation, processing and total delivered costs for the produced biofuel. Fuel ethanol was selected as the targeted liquid fuel product because of the relative maturity of the technology and availability of technical data. Biogas produced from anaerobic digestion was selected as the product from waste materials because of the suitability of the technology. Farm-gate price of feedstocks, transportation costs, geographic biomass availability, production costs of biomass-to-product conversion, and product distribution costs were integrated in order to assess the final delivered biofuel costs for a variety of scenarios. To evaluate the economically feasible scale of cellulosic ethanol processing, proximity of the processing plants to market locations in the state were also considered. For that purpose, a GIS-based model was developed for cellulosic ethanol plant least-cost location decision support by integrating delivery market destinations. Models for the three different bioconversion technologies were established with the MATLAB-SIMULINK program platform to estimate production costs. After testing these models with NREL data, the models were run against data compiled in the first phase of this project (Frear et al. 2005) to produce various results. The subsequent parts of the report include (1) the methodologies for the analysis, (2) the main project findings, and (3) two appendices. The first appendix gives more detailed description of the cost factors associated with feedstock and the second appendix describes in more details the processing costs.

Table 1: Matrix Components

Feedstock Type	Conversion Technology	Least-Cost Locations
Crop Residue	Fermentation	Longview
Forest Residue	Gasification	Ferndale
MSW (Paper, Wood, Food)	Anaerobic Digestion	Spokane
Animal Waste		Ellensburg

METHODOLOGY

Determination of final delivered costs required the integration of numerous cost factors involved in feedstock supply, processing, and product distribution. These costs were obtained by estimation using the models developed. This methodology section describes the sequential steps completed to calculate unit operation costs ultimately used to determine final delivered biofuel prices.

GIS Overlays Development

As an initial step for geographically identifying potential refinery locations with the lowest feedstock transportation and distribution costs, the biomass was mapped in relation to the Washington State highway network using GIS. Figure 1 shows the distribution of the crop residue category in relation to the road network. Additional geographic distributions for the rest of the feedstock categories are provided in the Appendices. Considering different harvesting technologies, feedstock collection costs of agricultural crop residues and forest residues were derived during this study. Recovery costs of other sources of biomass, such as animal waste and MSW (including food waste, paper waste, and wood waste) were adopted from the recent research literature.

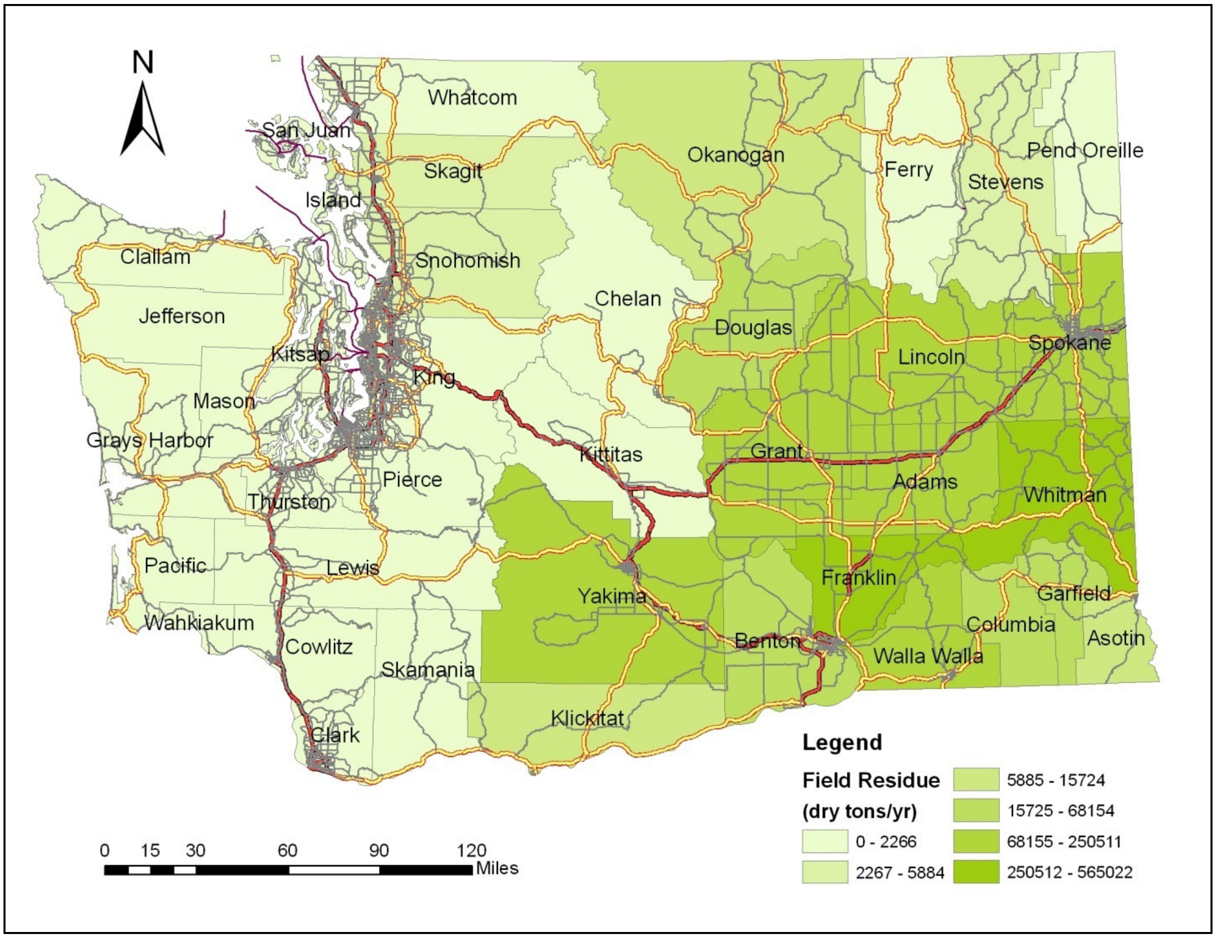


Figure 1: Geographic Distribution of Crop Residue in Relation to the Road Network

<u>Feedstock Collection Costs</u>

Crop Residue

Crop residue collection costs were derived using an economic engineering approach, combined with the survey data by Sokhansanj and Turhollow (2002) and Jenkins et al. (2000). The cost estimates for both large and small rectangular bales are summarized in Table 2. Based on calculations and the estimates found in recent literature, agricultural crop residues are considered to be available at $30 per dry ton farm-gate cost in this study. Detailed discussion is included in the Appendixes.

Table 2: Agricultural Crop Residue Harvesting and Transportation to Storage Facility

Operation/Activity	Costs ($/ton)	
	Large Rectangular Bales	Small Rectangular Bales
Swathing	5.51	4.80
Raking	1.70	1.70

Baling	10.80	9.66
Road-siding	4.54	4.54
Loading/Unloading	3.30	3.30
Transporting (field storage)[1]	3.32	3.32
Storage (under tarp)	2.26	2.26
Total Costs	31.43	29.58

Animal Manure
For the purposes of this report, the animal waste category includes five different manure types: dairy, cattle, horse, swine, and poultry. Considering the time sensitivity of feedstock transportation to support biofuel processing, dry manure (50% moisture content, see Appendix I, Table 9) cost estimates were used (i.e., $11.50 per dry manure) for this report. For additional information, see the Appendixes.

Forest Residue
More than 50% of the five main feedstock types (crop, animal waste, MSW, food packing/processing waste, and forestry) identified in Frear et al. (2005) is in the forest residue category. To derive a cost estimate for analysis in this project, a spreadsheet-based calculator was utilized: the Forest Residues Transportation Costing Model (FRTCM) developed by Rummer (2003).The resulting estimates were compared with estimates published in the recent literature on economic feasibility of forestry residue collection and transportation. Graf and Koehler (2000) evaluated the potential for ethanol production in Oregon using cellulosic feedstocks. That study reported the cost of removing and delivering forest thinnings to a facility within a 50-mile radius to be in a range of $28 to $40 per dry ton. These estimates were partially based on information provided by private mill owners in Oregon ($28–$35 per dry ton), and the Quincy Library Group Study that estimated the farm-gate cost of forest residue to be $40 per dry ton. In this study, the default values of the FRTCM calculator were modified to derive the cost of moving biomass from the forest to a site from where it can be hauled to a biorefinery. The flexibility of this model allows estimating biomass loading and hauling costs for different combinations of equipment. The estimates were found to be slightly above $40 per dry ton of biomass, if considering haul distance within 25 miles from the site (i.e., from the farm-gate). The second stage of the transportation expenses is included in the feedstock transportation to a biorefinery plant.

Municipal Solid Waste
Three types of feedstocks were considered under the MSW category: paper waste, food waste, and wood residue. According to Frear et al. (2005), the paper waste category represents about 14% of the total biomass identified in Washington State. However, the food waste and wood residue categories account for only 1.46% and 4.93% of the total, respectively. Because of their relatively low volumes, food waste and wood residue categories will be suitable as supplemental feedstocks. For purposes of this study, we assumed that about a $25 tipping fee (Graf and Koehler 2000) will be spent on transporting food waste and wood residues to a site (the first stage of transportation expenses). Therefore, in this study the delivered feedstock cost for these two categories included only the transportation expenses to the biorefinery. According to Graf and Koehler (2000), the prices for recycled and mixed paper waste ranges from $60 to $125 per dry ton. However, the methodology used to calculate the paper waste availability in the state of

[1] Transportation cost breakdown/details are provided in the Feedstock Transportation Costs section.

Washington considered a combination of the percentage of paper in MSW and recyclables (Frear et al. 2005). Therefore, we assumed the farm-gate cost of paper to be lower than the estimates found in Graf and Koehler. Several other sources (Baled Waste Paper Spot Market Prices 2009) reported spot market prices in the range of $22.50 to $30 (for mixed paper), $69 (baled corrugated cardboard), to more than $200 (for soft white paper) per ton depending on its quality. Based on spot market prices and the estimates obtained from the literature, in this report the $45 feedstock price per dry ton of paper waste was utilized.

Feedstock Transportation Cost Derivation

The derivation of feedstock transportation costs requires information on factor prices that determine the costs of a typical trucking firm (Casavant 1993). Per ton mile hauling costs of feedstocks were derived using an economic engineering approach that includes both fixed and variable costs of trucking operation for relevant truck configurations. Total trucking costs (Figure 2) include expenses such as fixed vehicle costs (truck and trailer, depreciation, and license fees, etc.), fixed business costs (management, insurance, interest, etc.) and variable costs (truck driver wages, fuel, repairs, maintenance, tires, miscellaneous; trailer repairs, maintenance, tires, miscellaneous). Further, per ton mile transportation costs were incorporated with feedstock farm-gate costs and haul distances to derive the delivered feedstock costs. With appropriate truck configuration (e.g., tanker trailer truck) and hauling origin/destination modifications, trucking costs for ethanol distribution were derived. In the final stage of the investigation, feedstock transportation and processing costs, combined with the distribution costs, allow derivation of the delivered cost of ethanol to alternative markets.

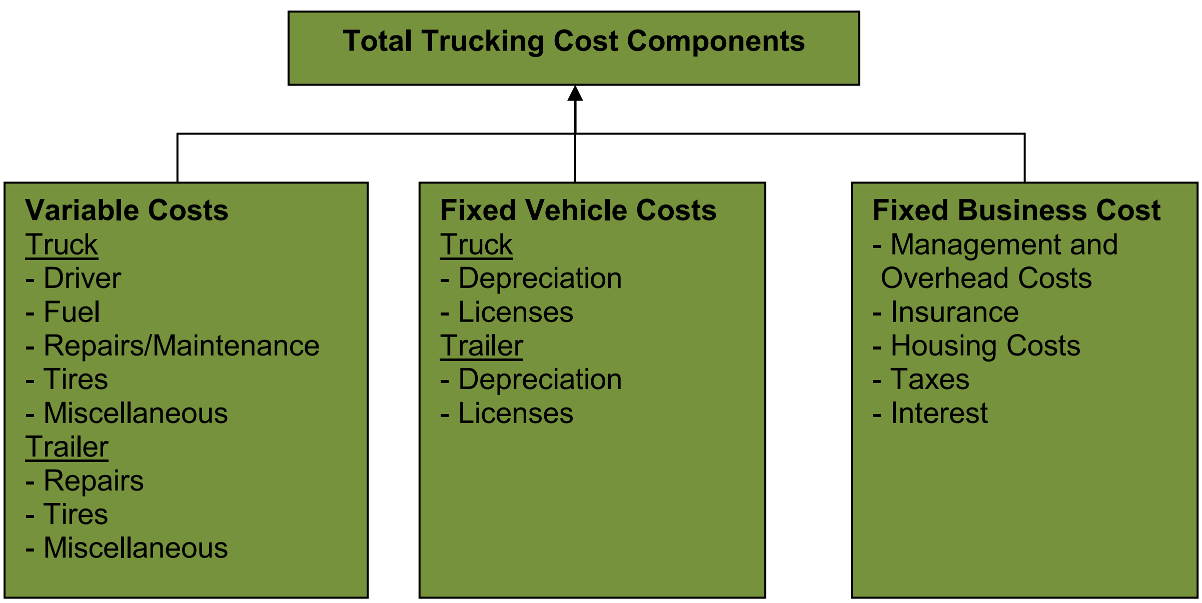


Figure 2: Total Trucking Cost Components

GIS Approach to Delivered Cost of Feedstocks

Feedstock categories included in this study have been spatially analyzed with the use of the GIS Network Analyst toolset to derive feedstock supply cost curves to potential biorefinery locations in the state (Figure 3).

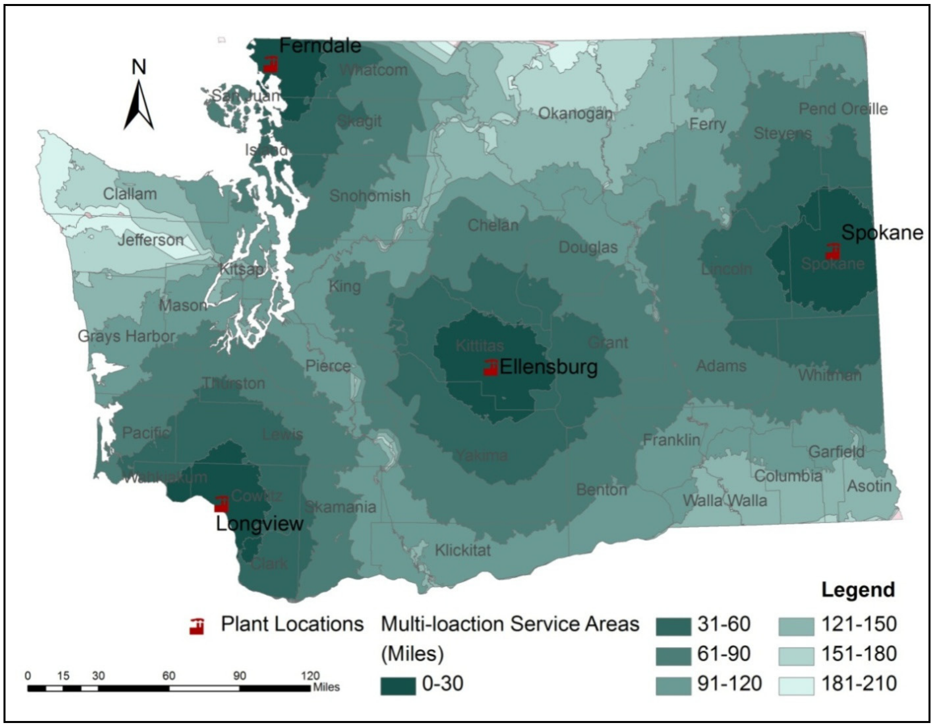


Figure 3: GIS Service Areas for Feedstock Transportation Cost Derivation

Using Census Feature Classification Codes (CFCCs),[2] speed limits have been assigned to all segments in the GIS roads shapefile (overlay file) to calculate haul distances and drive times to potential biorefinery locations. Different haul distances were used to estimate feedstock availability within each county. Further, the feedstocks' physical availability, farm-gate price, transportation costs (from fields to a biorefinery, and including loading/unloading), and geographic distribution (accounting for site-specific road infrastructure) information were combined to derive feedstock supply curves. From each biorefinery in the study area, per ton mile distribution costs have been calculated for ethanol distribution to alternative markets. To determine distribution costs, GIS methodology similar to the feedstock transportation costs was used by incorporating origin (processing plants/blending terminals) and destination (ethanol fueling station locations in the state) data.

GIS Model for Biofuel Plant Least-Cost Location Decisions

To support cellulosic ethanol plant least-cost location decisions, a GIS-based model was developed that integrates geographic distribution of biomass in the study area with associated transportation costs. The model was first tested using NREL (2007) data. Further, the model was used to analyze the state of Washington biomass data identified in the first phase of this project by Frear et al. (2005).

As an initial step of a multi-factor spatial optimization problem, including feedstock transportation and ethanol distribution costs, the influence of feedstock transportation costs was investigated on optimal location decisions. To achieve that goal, the feedstock resources (in this

[2] CFCCs provide an alphanumeric code for each line feature in the GIS road shapefile. Further, the codes are used to classify roads, railroads, water, and other linear features.

analysis, forest biomass and agricultural crop residue) were spatially analyzed relative to the road network and potential cellulosic ethanol plant locations in the state of Washington. The flexibility of the model allows spatial manipulation of the data for the least-cost location identifications considering both cumulative (e.g., agricultural crop and forest residue) and separate types of feedstock utilization scenarios.

The GIS-based model consists of three main parts. In turn, each of the parts includes several procedures (Figure 4). The first part builds a dataset by layering GIS shapefiles that are necessary for the analysis in this section. The second part involves GIS Network Analyst extension procedures for creating service areas (a shapefile of driving zones) around processing plants included in the study area, as well as for joining and relating that new shapefile (service areas) with existing GIS layers. These procedures are reiterated for each of the processing plant locations. The final part of the model incorporates spreadsheet operations for further analysis with the GIS-generated spatial data. In particular, it links steps in which annual ethanol processing capacities (using biomass-to-ethanol conversion rates) and truck transportation per ton mile costs are derived to identify the least-cost facility location.

Analytical results indicate that transportation costs differ according to the processing plant capacity, since the larger plants require more feedstock to support their production levels, hence longer haul distances. Figure 5 shows the relationship between feedstock transportation costs (per ton) and processing plant capacities in million gallons per year (MGY) for the combined agricultural crop residue utilization scenario. The location in Spokane maintains its least-cost feedstock transportation advantage for all processing capacities up to about 165 MGY. For this location, a processing capacity of 100 MGY can be supported with the available biomass within 130 miles from the plant location. To achieve the same level of ethanol processing, plants considering Longview and Ferndale locations will need to reach out almost twice as far as is required for the Spokane location. Depending on the type of the feedstock considered for ethanol processing, feedstock transportation costs differ because each type has different geographic distributions in the study area. The relationship between forest biomass transportation costs and annual ethanol processing for the same plant locations in the study was depicted in Figure 6.

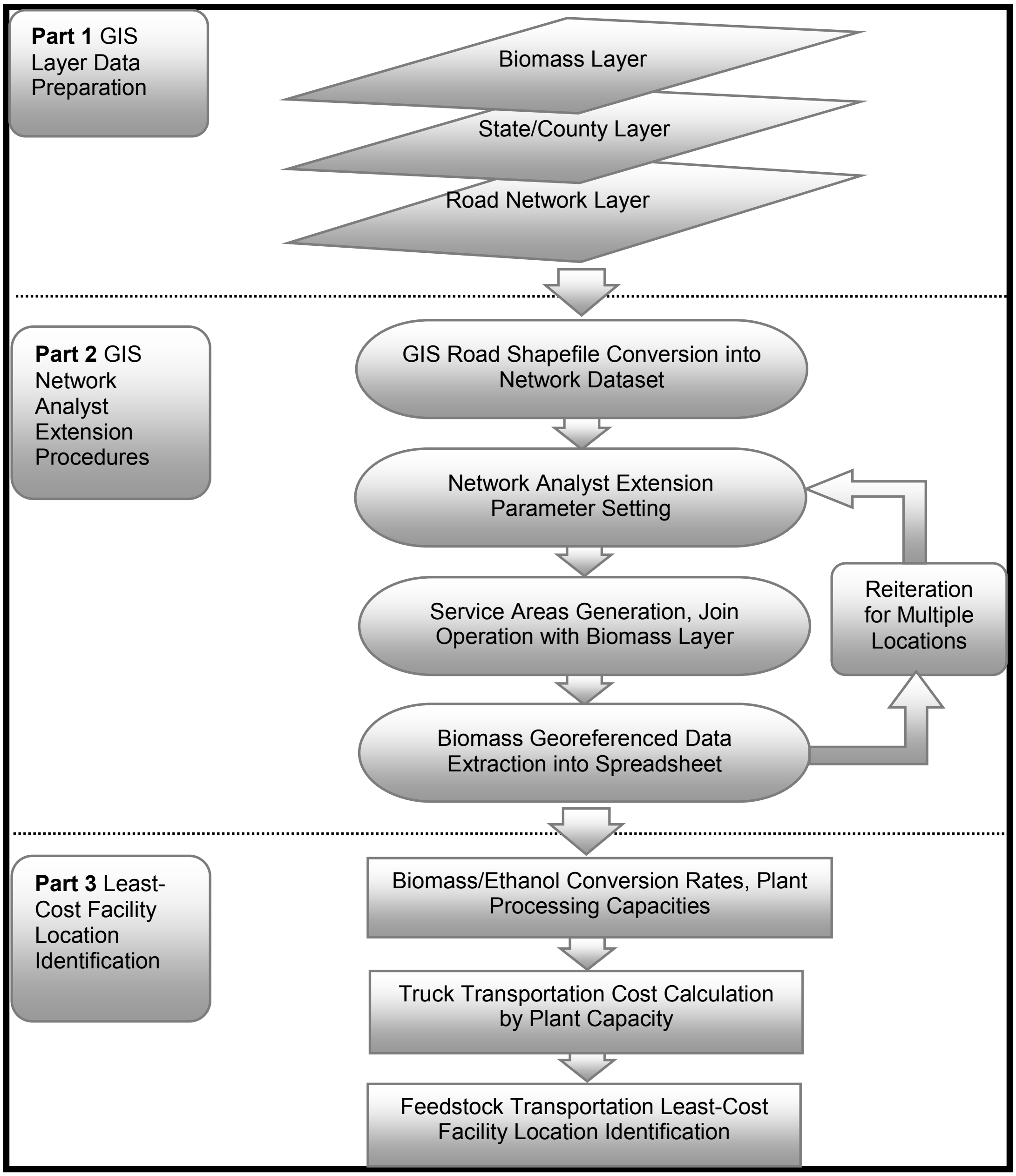


Figure 4: GIS-Based Feedstock Transportation Least-Cost Facility Location Decision Model

The previous location (Spokane) does not necessarily sustain its cost competitiveness when considering forest residue. As shown in Figure 6, for the processing capacities up to 350 MGY, the Longview location has the lowest transportation costs. This level of processing capacity can be supported by transporting feedstocks within 180 miles from the plant. The cost competitiveness results for the rest of the feedstock categories are discussed in the Appendix of this report.

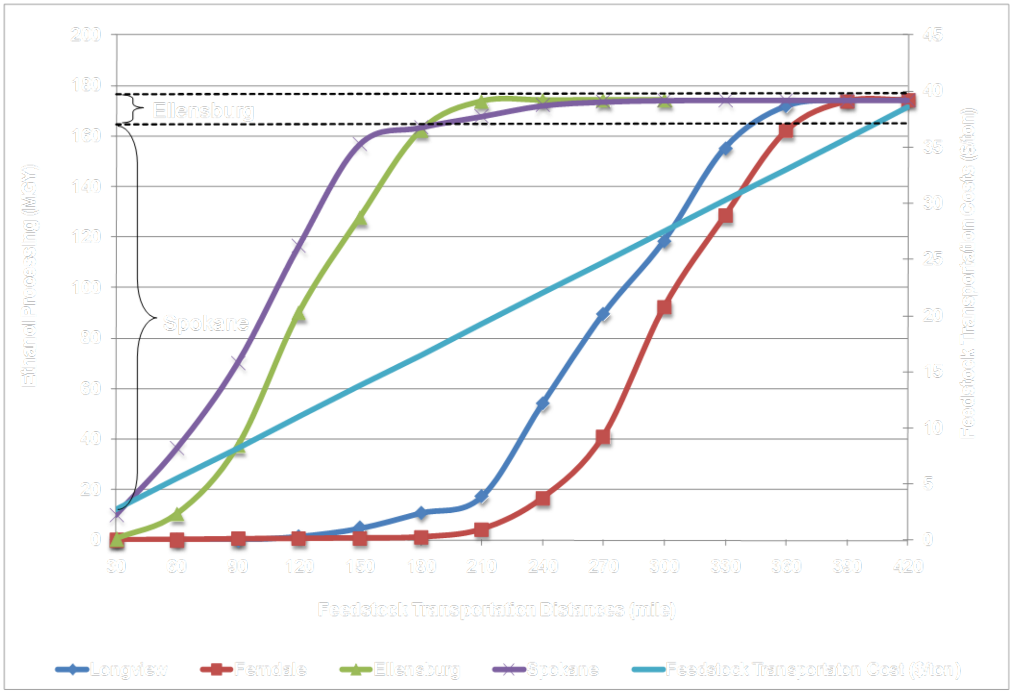


Figure 5: Feedstock Transportation Least-Cost Locations (Crop Residue)

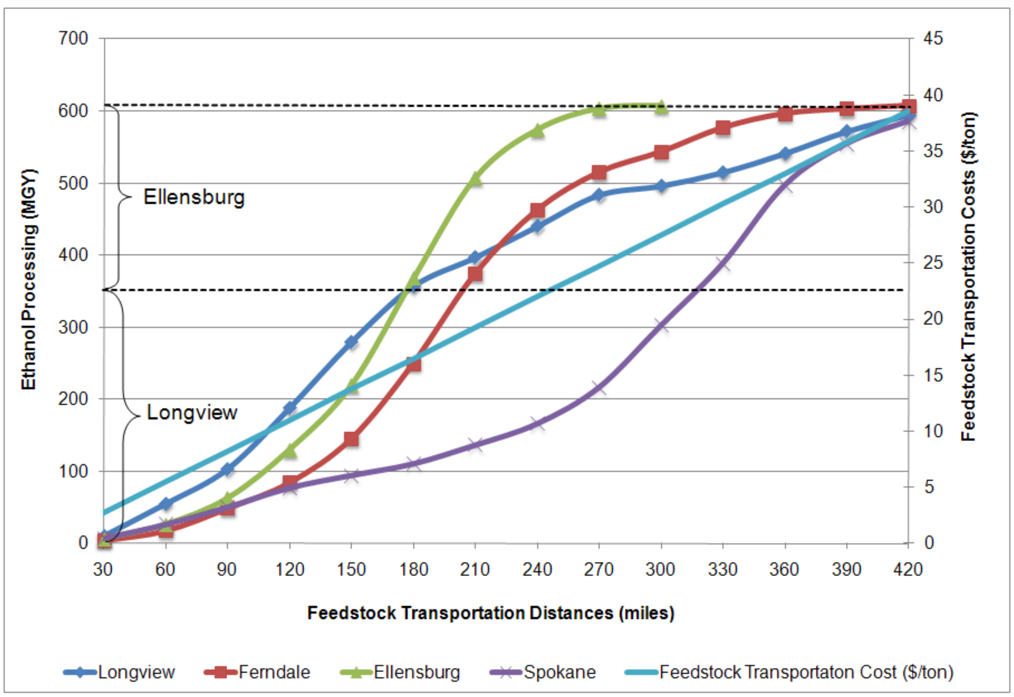


Figure 6: Feedstock Transportation Least-Cost Locations (Forest Residue)

<u>Feedstock Cost Sensitivity to Diesel Prices</u>

In addition to delivered feedstock cost sensitivity to farm-gate costs and haul distances, the feedstock costs at the refinery gate are sensitive to diesel prices. Fluctuations in diesel prices may influence the feedstock delivered costs because the fuel costs constitute about 46% of the per ton mile transportation costs (Figure 7). As illustrated in Figures 8, when diesel prices are in the range highlighted with dotted lines (Apr-07 through Oct-07), trucking costs stayed at almost the same level. However, the chart pattern illustrates that the trucking costs significantly increase as diesel prices, as highlighted with dotted lines (Jan-08 through Jun-08).

A sensitivity analysis with a range of diesel prices and incorporating different processing plant capacities was used to evaluate the delivered feedstock costs in relation to the different ethanol processing plant capacities. Diesel prices from November 2007 to June 2008 (EIA 2008b) were chosen to analyze the variation of feedstock delivered costs with different farm-gate costs ($20, $25, and $30) and small, medium and large plant capacities (20 MGY, 55 MGY, and 120 MGY). As shown in Figure 9, small-scale processing plants are comparatively less sensitive to diesel price increases in terms of the delivered feedstock costs, for all three of the farm-gate cost scenarios. In comparison, the influence of the increasing diesel prices on the delivered feedstock costs for the medium and large processing plants is considerably higher. In particular, as a result of increasing diesel prices since January 2008 (39% increase from January to June, 2008), the delivered costs of feedstocks for the 55 MGY plant increased by 3% considering $20 farm-gate costs, and 2% considering $25 and $30 farm-gate costs. Because larger plants involve more transportation activity, the delivered feedstock costs for the 120 MGY capacity plant increased by 4% considering $20 and $25 farmgate costs, and 3% for $30 farm-gate cost.

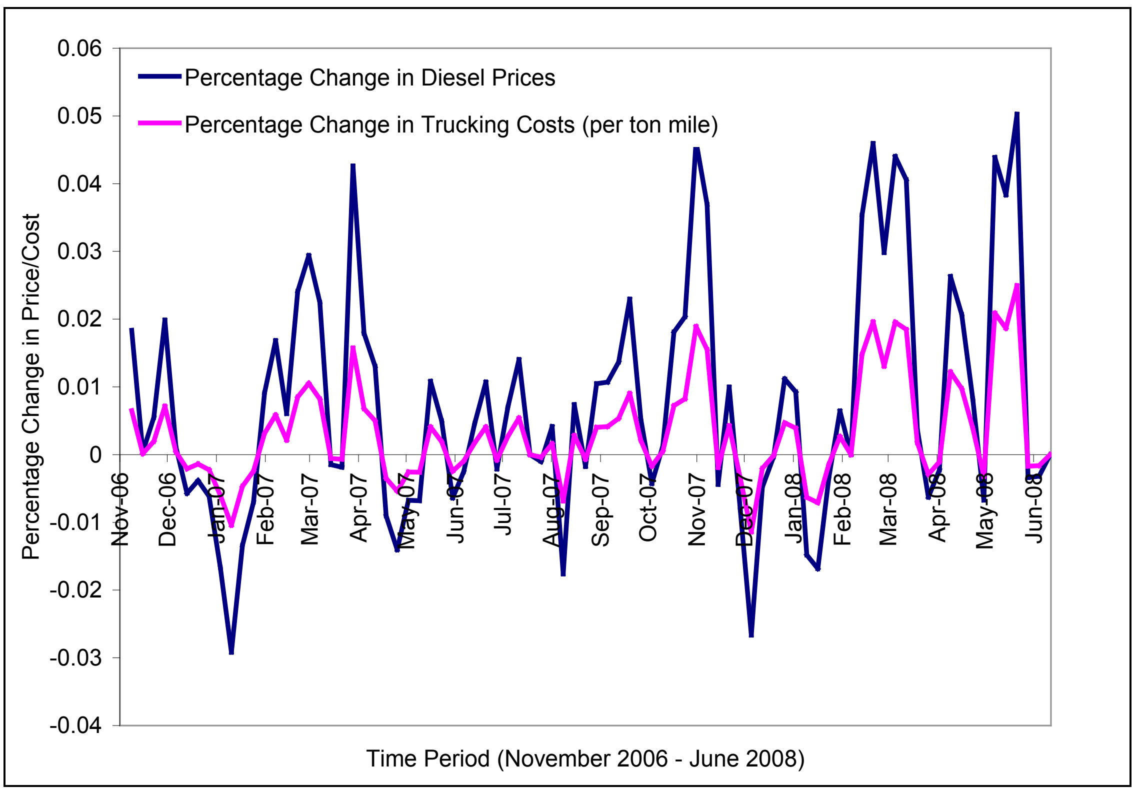
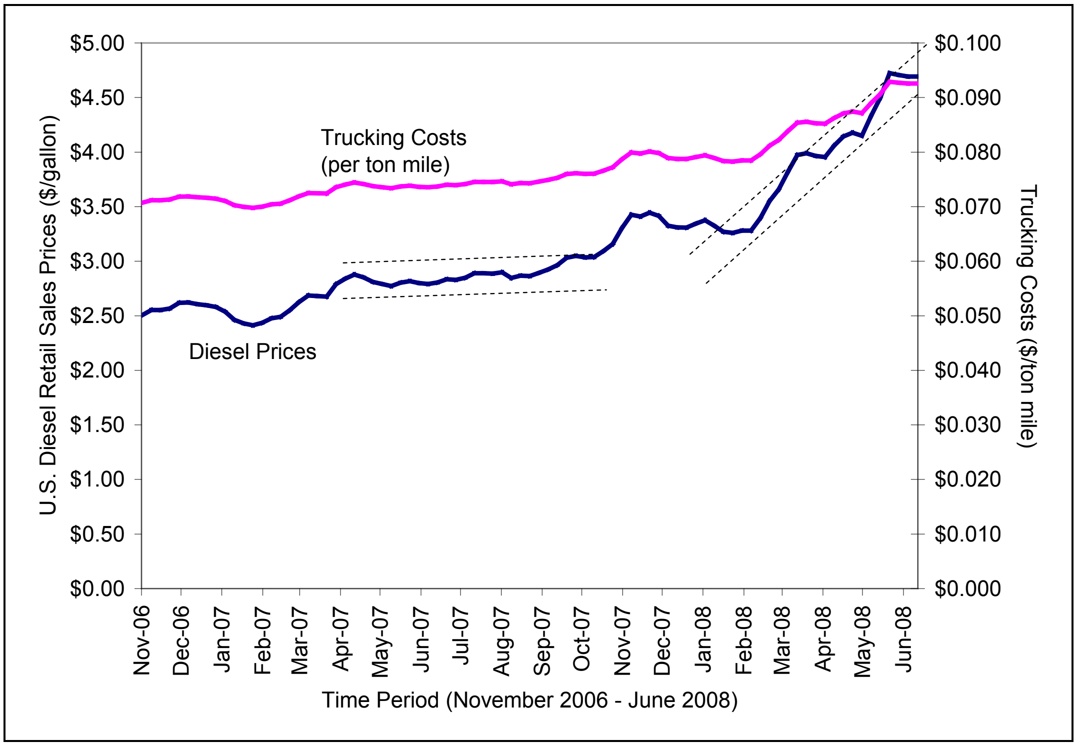


Figure 7: Percentage Change in Diesel Prices and Trucking Costs



Data Source: Diesel prices were obtained from EIA (2008)b.

Figure 8: U.S. Diesel Retail Sales Prices and Trucking Cost Sensitivity

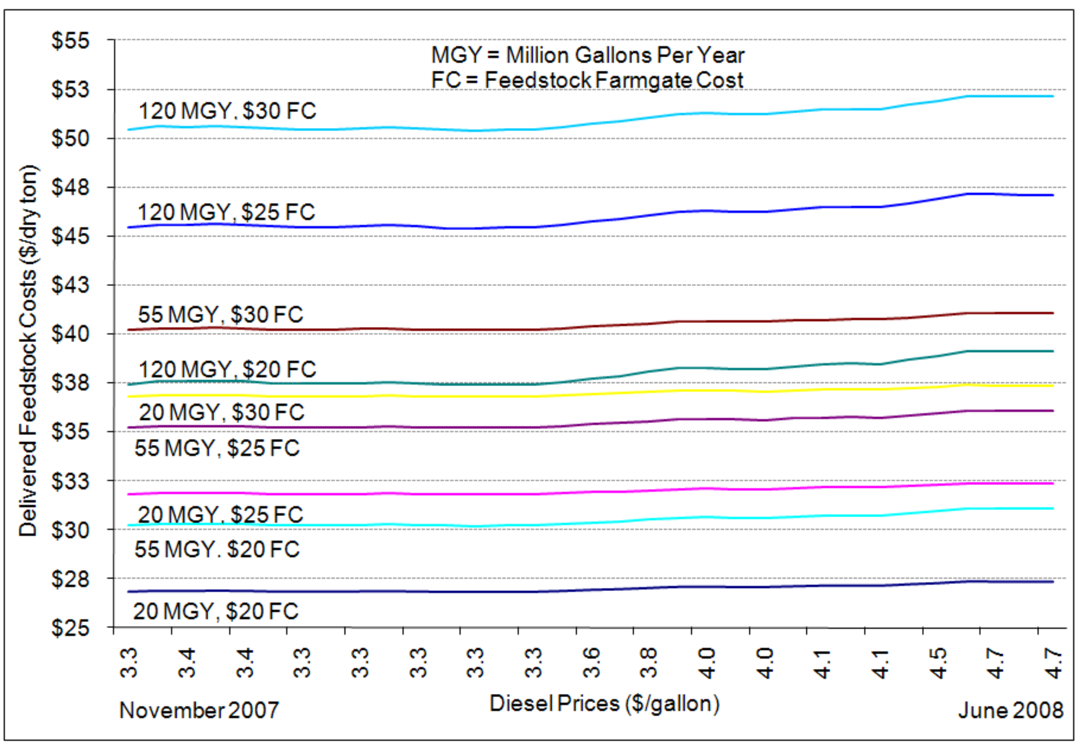


Figure 9: Delivered Feedstock Cost Sensitivity to Diesel Prices

Processing Costs Derivation

The ultimate goal of techno-economic assessments is a measure of profitability associated with certain biorefinery technology options. In the early stage of project development it is necessary to estimate the investment required and the cost of production so that the profitability of a biofuel plant can be assessed. Even if insufficient technical information is available to design a plant completely, users must still make an economic evaluation to determine whether it is economically and financially feasible. A biorefinery plant is more economically feasible when its design is more profitable than any other competing designs, and it is financially feasible when enough investment can be raised for project implementation. The traditional economic evaluation for a chemical engineering process may proceed in several steps:

i. Preparing a process flow diagram
ii. Calculating mass and energy flows
iii. Sizing major equipment
iv. Estimating the capital cost
v. Estimating the production cost
vi. Forecasting the product sales price
vii. Estimating the return on investment

Evaluation of certain conceptual processes, like a biorefinery, might be slightly different. Figure 10 shows a typical approach to process design and economic analysis (Aden, Ruth et al. 2002).

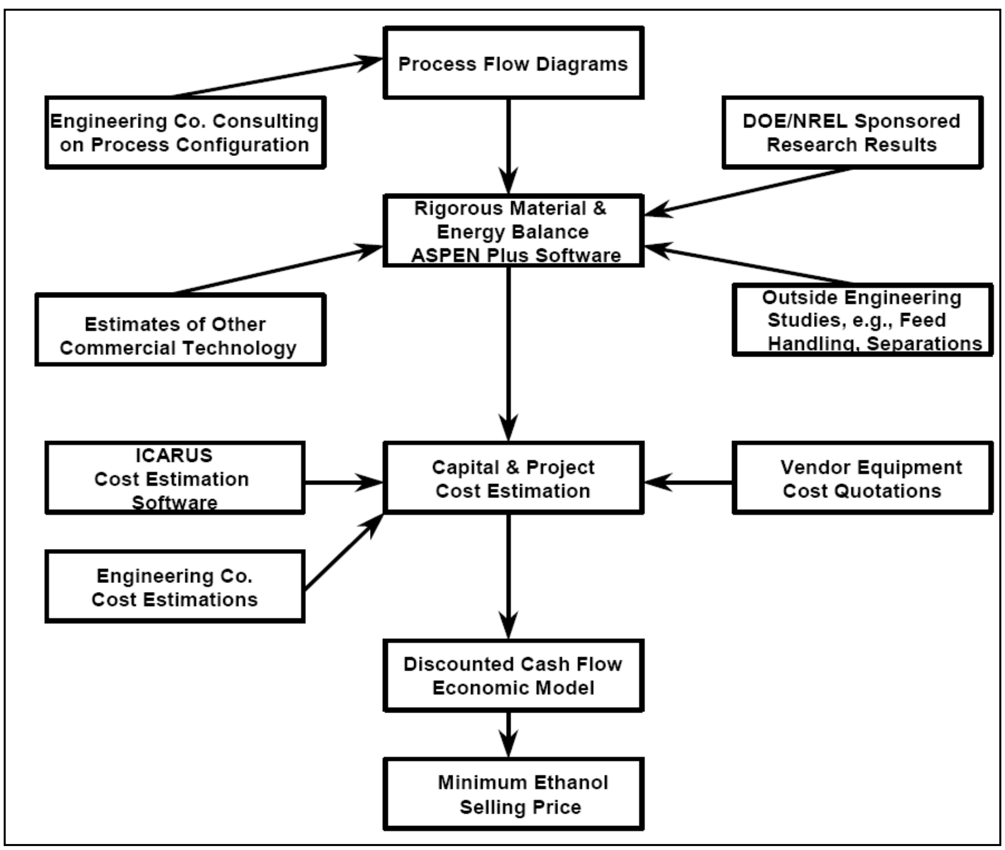


Figure 10: Typical Approach to Process Design and Economic Analysis (Aden, Ruth et al. 2002)

The final result of analysis is the minimum selling price of the product. This type of methodology has been widely accepted in other similar projects. The goal of the research is to provide a set of mathematical models as flexible assessment tools with acceptable accuracy for decision making in biorefinery process.

At the present time, most sustainable energy production is still in the R&D stage. Thus, the data used in this project are mainly based on other researchers' work. The principal function of this process assessment model is screening. Dozens of options in feedstocks and conversion processes exist, but few of them are feasible. Alternative processes may be estimated for comparison purposes based on the matrix of conceptual design assessment, or the costs of two or more alternative processes can be quickly estimated to see whether one is clearly superior or to eliminate clearly inferior options. As progress is made in the process assessments, more will be learned about the ultimate ideal configuration of future commercial facilities that convert biomass into energy and other useful by-products.

A complete modeling framework was developed for the assessment in this project as illustrated in Figure 11. The assessment process included separate cost analysis of feedstock and processing, and the integration of these results into the final production cost of the product. Data source and process model development procedure are described below.

Feedstock Data
The feedstocks in the database generated in the earlier biomass assessment work (Frear et al. 2005) was classified into four categories (fiber/starch/sugar, ultimate analysis, elemental analysis, other parameters). Each feedstock was characterized in terms of 33 parameters such as moisture, carbon, starch, cellulose, minerals, etc. (Liao, et al., 2007). This database can be used not only by researchers to conduct scientific studies, but also by farmers and producers to learn more about the agricultural and municipal residues they are producing. The characterization data were also used in the analysis of this project.

Process Flowcharts
The technological scheme converting feedstock to final products has been a major interest as many of the conversion processes are still under research and development with many new processes and approaches being developed with time. In the end, three common and basic conversion processes were chosen for analysis in this study and they included dilute acid pretreatment with simultaneous saccharification and co-fermentation (SSCF), biomass gasification with mix-alcohol synthesis, and anaerobic digestion (AD). Flowcharts of these methods were developed via reference and laboratory research. Aden et al. (2002) had already developed a set of detailed PFDs (process flow diagrams) on lignocellulose-to-ethanol conversion via diluted acid pretreatment and SSCF processes. Philips et al., (2007) in their final report, also presented a set of PFDs on production of thermochemical ethanol via indirect gasification and mixed alcohol synthesis of lignocellulosic biomass. Anaerobic digestion process flowcharts were developed by the Biomass Processing and Bioproduct Engineering Laboratory of WSU.

Chemical/Biochemical Dynamics
Data used in every step in the whole process were mostly gathered from research reports of similar processes. Certain other elements came from chemical engineering handbooks (S.Peters, D.Timmerhaus et al. 2003; Poling, Thomson et al. 2008).

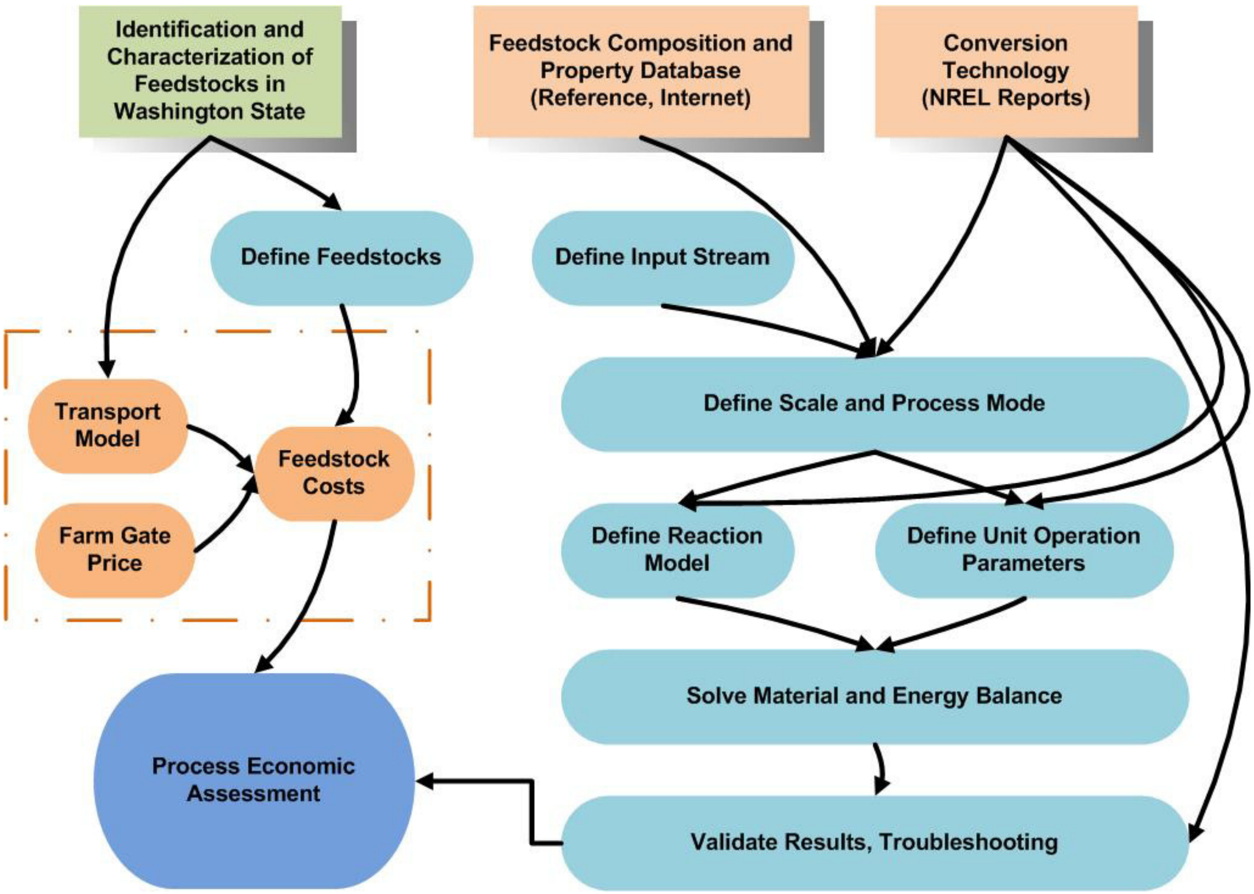


Figure 11: Working Process of Economic Assessment

For the model implementation, MATLAB-SIMULINK software was chosen because it provided a powerful environment for the development of flowchart-based simulation models. Different subsystems were developed by Simulink to characterize all the types of units used in biorefinery processes. The structure of a sample module is shown in Figure 12. The black part of the sample module represents the mass balance in the unit. The input to this part is the biomass stream from the process prior to it, while the main output will connect to the input port of the next unit operation. The red part of the sample module represents the energy balance, equipment investment, and raw material costs of the unit.

Models for Various Conversion Technologies

Mathematical models of the bioethanol and thermo-ethanol production processes consist of mass and energy balance equations. All processes are modeled assuming the hypothesis of steady state. Fourteen and seven modules are included, respectively, in the models to represent different unit operations in the bioethanol/thermo-ethanol production system. These modules provide three kinds of output:

- Mass stream in/out
- Energy stream in/out
- Equipment cost

In the system configuration module, quantity and characteristics (composition, cost) of the feedstocks can be defined. The feed-in quantity of the feedstock will determine the scale of the whole system. Based on mass/energy balance results, a list of system input/output streams can be generated automatically. Plus, cost information can be acquired from NREL's database or other sources. Variable operation costs can be estimated. Here, total salary was estimated based on the position categories and relative annual salary/personnel number information. For some positions, personnel numbers had to be adjusted according to the system scale (scale factors were acquired from outside references). With summarization of equipment costs generated by all the processing modules, the total installed equipment cost (TIEC) can be calculated. In this calculation, factors of scale and the chemical engineering plant cost index (CECPI) are included. Total project investment (TPI) as well as fixed operation costs could be estimated with these data. TPI, variable operation cost, and fixed operation cost data were used to estimate ethanol production costs.

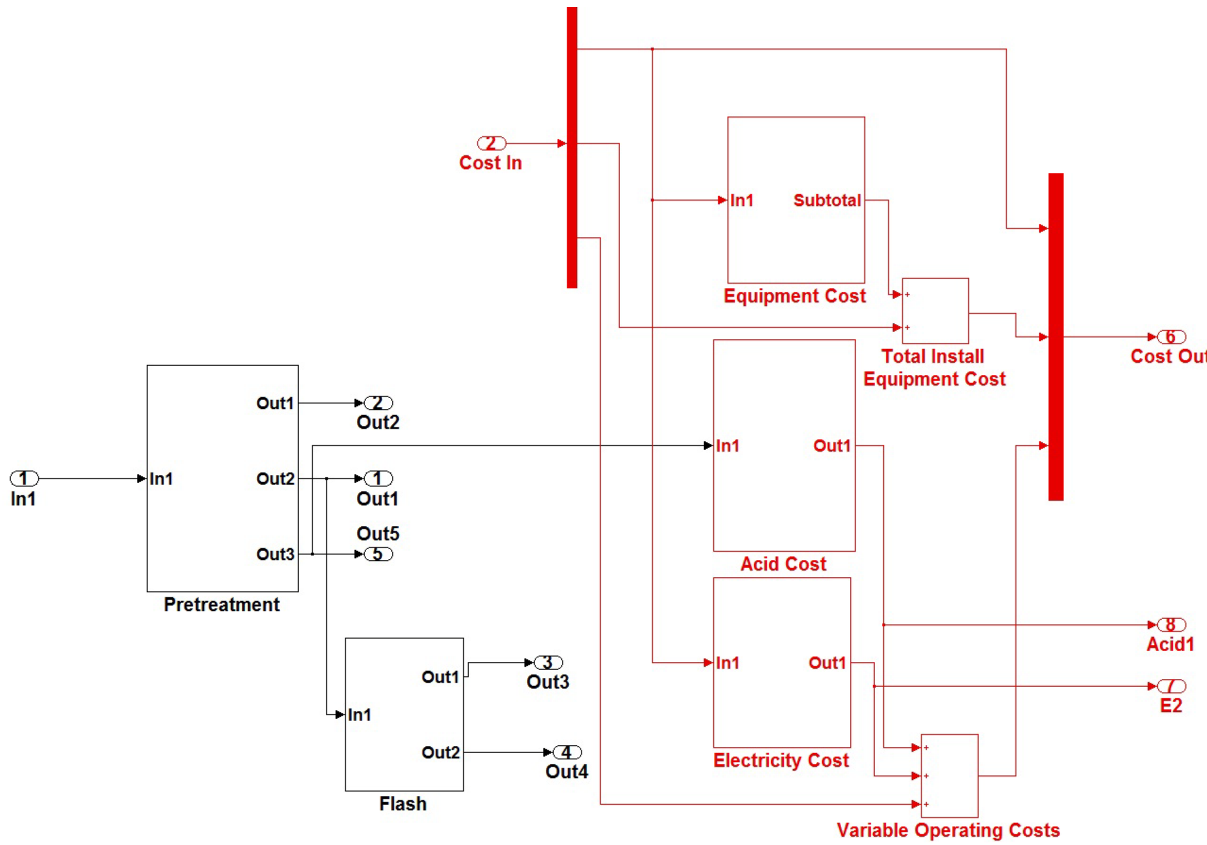


Figure 12: The Structure of a Sample Module

The AD process is often modeled using ADM1 (Batstone et al. 2002). Zaher et al. (2009) have developed GISCOD (a general integrated solid waste co-digestion model) based on ADM1. The main goal of this study was to develop and test a simulation tool of the AD process that is applicable to any combinations of waste streams using the simulation platform MATLAB-SIMULINK. A general co-digestion assessment model is still needed to support operation decisions at full-scale plants and to assist co-digestion research. Therefore, an AD process assessment model was developed for analysis work on animal waste and food waste. GISCOD is the core of this model and provides steady-state output estimation for the preconfigured AD process. Resulting data were stored in data files that could be utilized by subsequent assessment modules. In most cases studied, only the digester and generator unit were discussed. Biogas purification and nutrients recovery processes are two additional and important options for AD technology. Specific modules were developed to evaluate the economic impact on the performance of the whole system. Outputs of all four assessment modules were summarized in a data presentation module.

Economies of Scale

Economies of scale refer to the cost advantages as the processing capacity of the plant increases. A higher volume of processing will allow spreading total operational costs over many gallons of final product, thus lowering the total processing costs. However, this cost advantage can be “enjoyed” up to the level where an increasing feedstock transportation cost, required for higher processing volume, can be offset. As shown in Figure 13, per gallon processing costs tend to decrease with increasing processing capacity, since capital and operation expenses are spread over more gallons of processing. Economies of scale are large enough to compensate the increasing feedstock transportation costs up to the processing capacity where the total cost is at its lowest point (shown with an arrow in Figure 13). The lowest point on the total cost curve determines the optimal capacity for economically feasible ethanol processing. The transportation cost curve includes both feedstock transportation and ethanol distribution segments.

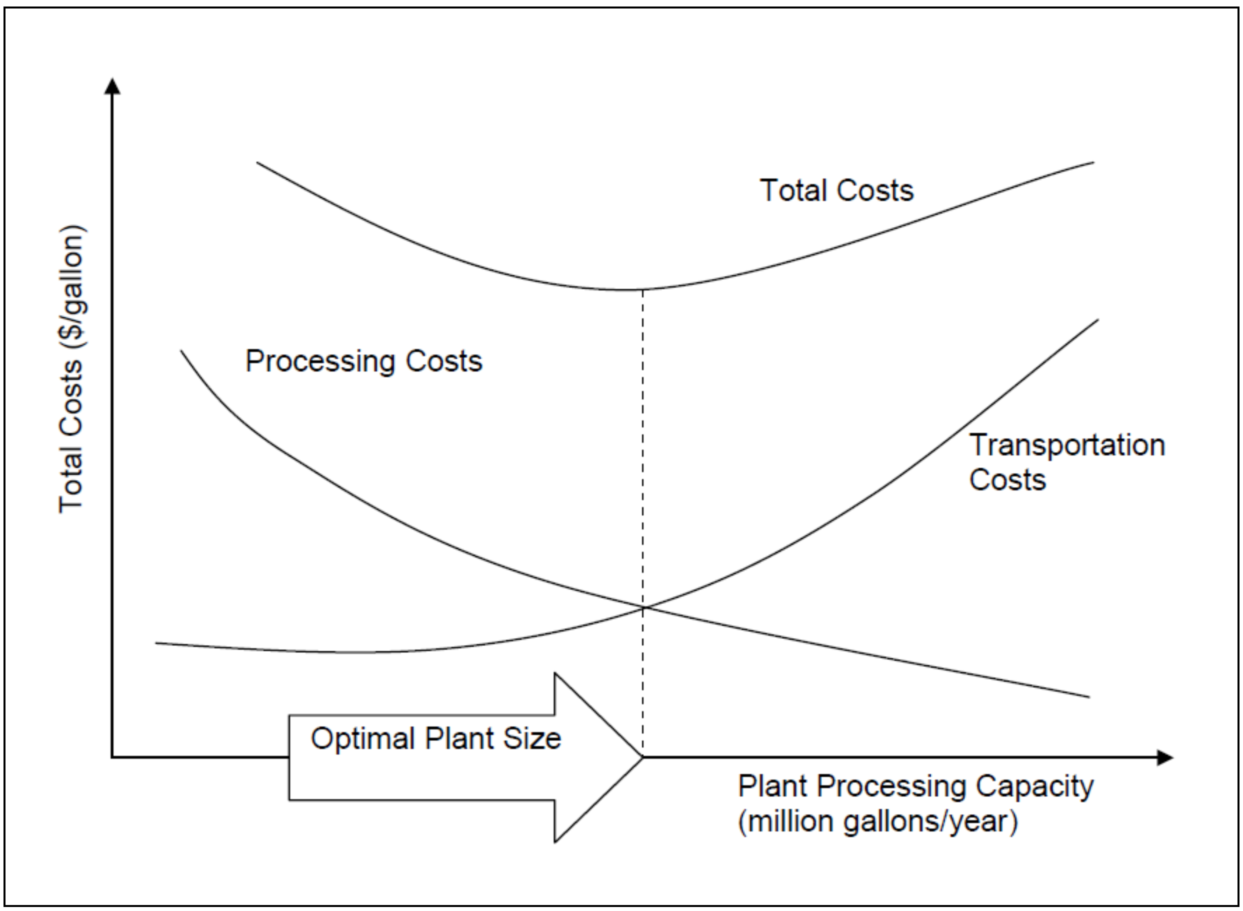


Figure 13: Total Delivered Costs and Processing Plant Optimal Size

Per ton mile transportation costs may differ depending on plant processing capacity, since larger plants require more feedstock to be processed. Cellulosic feedstocks, such as agricultural crop or forest residue, are geographically dispersed. Consequently, more feedstock demanded by larger plants requires longer-distance hauling, which consequently increases transportation expenses. Consequently, the tradeoff for the economies in scale in biomass-to-ethanol processing is the increasing feedstock transportation costs.

In addition to spatial characteristics such as feedstock production geography and market locations, the optimal plant size decision may involve other factors such as alternative transportation mode (rail, barge) accessibility. However, fundamental processing plant size decision making is based on two main components: increasing feedstock transportation costs and economies of scale in the (inside biorefinery) processing segment.

Distribution Costs Derivation

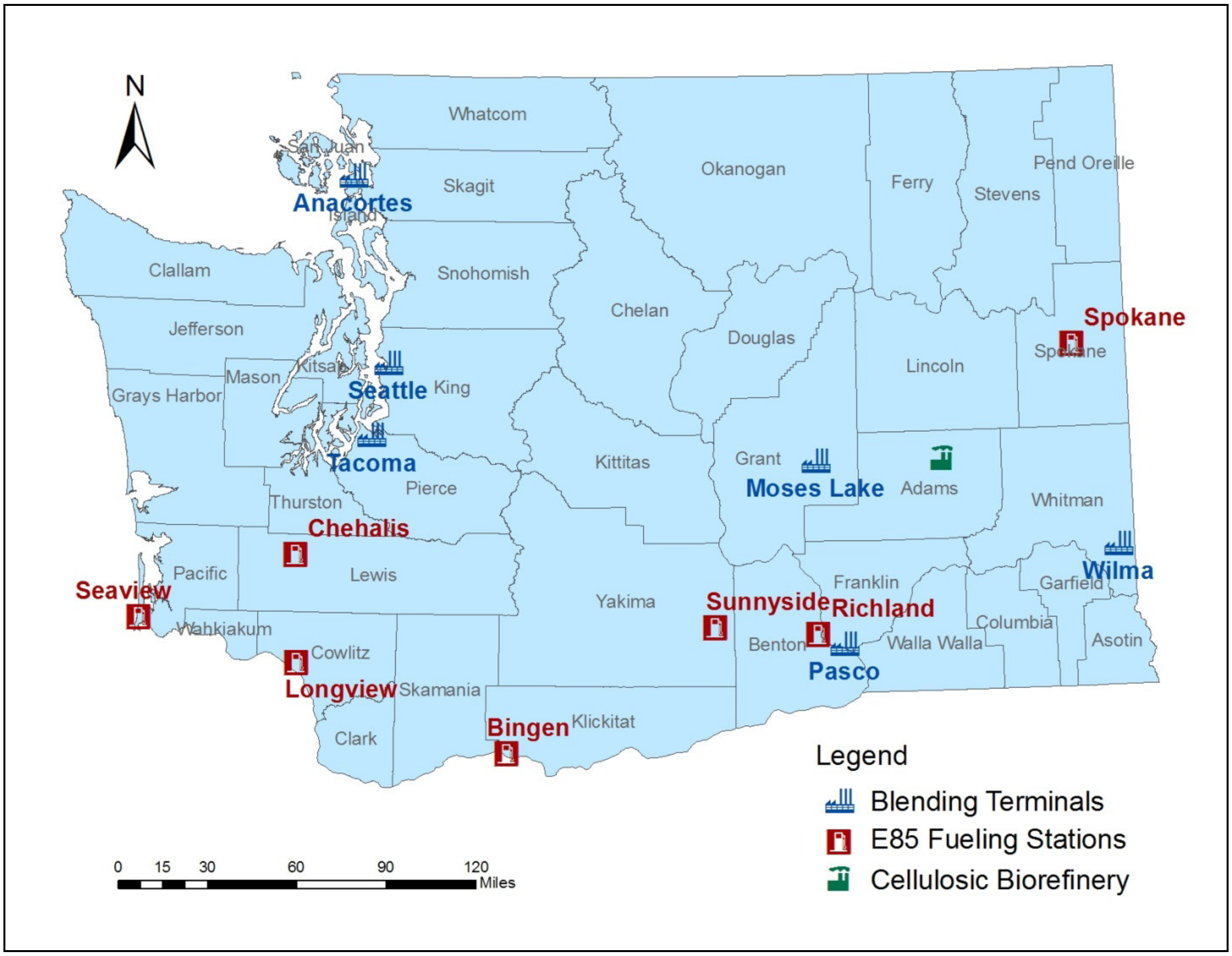
The ethanol distribution system consists of two parts. First, the processed ethanol is shipped to blending/distribution terminals (also known as racks). Racks also serve as storage facilities to which conventional gasoline is transported, through pipelines, barge, truck, or railroad nodes. At the blending terminals the pure ethanol is blended into E10 or E85 (depending on the demand), which is then distributed by tank trailer trucks to the fueling stations offering E85 or E10 ethanol blend. According to Johnson and Melendez (2007), terminal shipment and storage costs add about $0.04 per gallon to the cost of gasoline. The U.S. General Accounting Office (U.S. GAO 2007) estimated the overall cost of ethanol distribution, including shipments to blending terminals and distribution to gas stations, at $0.13 to $0.18 per gallon, depending on the proximity of markets from processing plants.

Figure 14 shows the distribution of existing blending terminals and E85 fueling stations in the state of Washington. The map includes only publicly accessible E85 fueling stations, leaving out three private or government-only facilities.

The economic engineering approach to calculating trucking costs used earlier in this report was modified to include tank trailers (different from flat-bed or drop-bed trailers considered for feedstock transportation). Because longer distances increase transportation costs, the same logic as with the transportation of feedstocks can be applied to understand the relationship between distribution costs and haul distances. Since fueling stations have limited storage capacity, the larger the volume of the processing plant, the farther away are the destinations that the ethanol needs to be distributed to reach more fueling stations. In addition, we used GIS least-cost or shortest-route identification tools to find optimal routes from an ethanol processing plant to existing blending terminals, and further, to fueling stations in the state of Washington.

Considering ethanol shipments from one processing plant, the cost of the distribution to blending terminals (first segment) is relatively fixed, since the distances from processing plants to the terminals are constant. However, the distribution distances from the blending terminals to E85 fueling stations (second segment) increase as soon as stations in the vicinity of the rack receive their full capacity volumes of ethanol blend.

Total distribution costs can be derived by combining shipment costs to terminals and distribution costs to E85 stations. It should be noted, however, that depending on the business structure, ethanol plants may choose to ship (sell) their production to blending terminals, leaving the rest of the costs to other businesses, called jobbers or middleman (Johnson and Melendez 2007). Alternatively, terminals that are owned by independent companies may purchase the ethanol from refineries, and blend and distribute the fuel themselves. Regardless of the business structure, the delivered costs to final markets include costs associated with both segments—shipment costs to terminals and distribution costs to ethanol blend fueling stations.



Data Source: E85 fueling station location information: National Ethanol Vehicle Coalition webpage (NAVC 2008); Blending Terminal location information: OPIS Rack Cities (2008).

Figure 14: State of Washington Blending Terminals (Racks) and E85 Fueling Station Locations

RESULTS

<u>Feedstock Transportation Costs</u>

The results show that the economic feasibility of biofuels processing in the state of Washington is significantly influenced by feedstock transportation and distribution costs. Because of the geographically varying distribution of the feedstock resources and increasing transportation costs for longer distances, all of the feedstock deposits cannot be utilized at the same expense. In turn, biomass-to-biofuel processing plant cost-minimizing location decisions are influenced by the type of the feedstock utilized, and vary depending by plant capacity.

By using a Spokane ethanol facility as example in the analysis, the relationship between increasing plant processing capacity (left vertical axis) and feedstock delivered costs per dry ton (right vertical axis) as haul distances increase was revealed in Figure 15. Depending on the feedstock category, the feedstock costs change accordingly. For instance, to support 150 MGY processing capacity, agricultural crop residue can feasibly be collected from about 150 miles from the biorefinery location. As depicted with the red line in the same figure, this residue can be transported at around $14 per ton. Alternatively, that level of processing can be supported by forest residue. However, with the forest residue, feedstock haul distances increase from 150 to about 220 miles, consequently increasing transportation costs from $14 to about $20 per ton of feedstock. Results for several other biorefinery locations in the state are provided in the Appendixes.

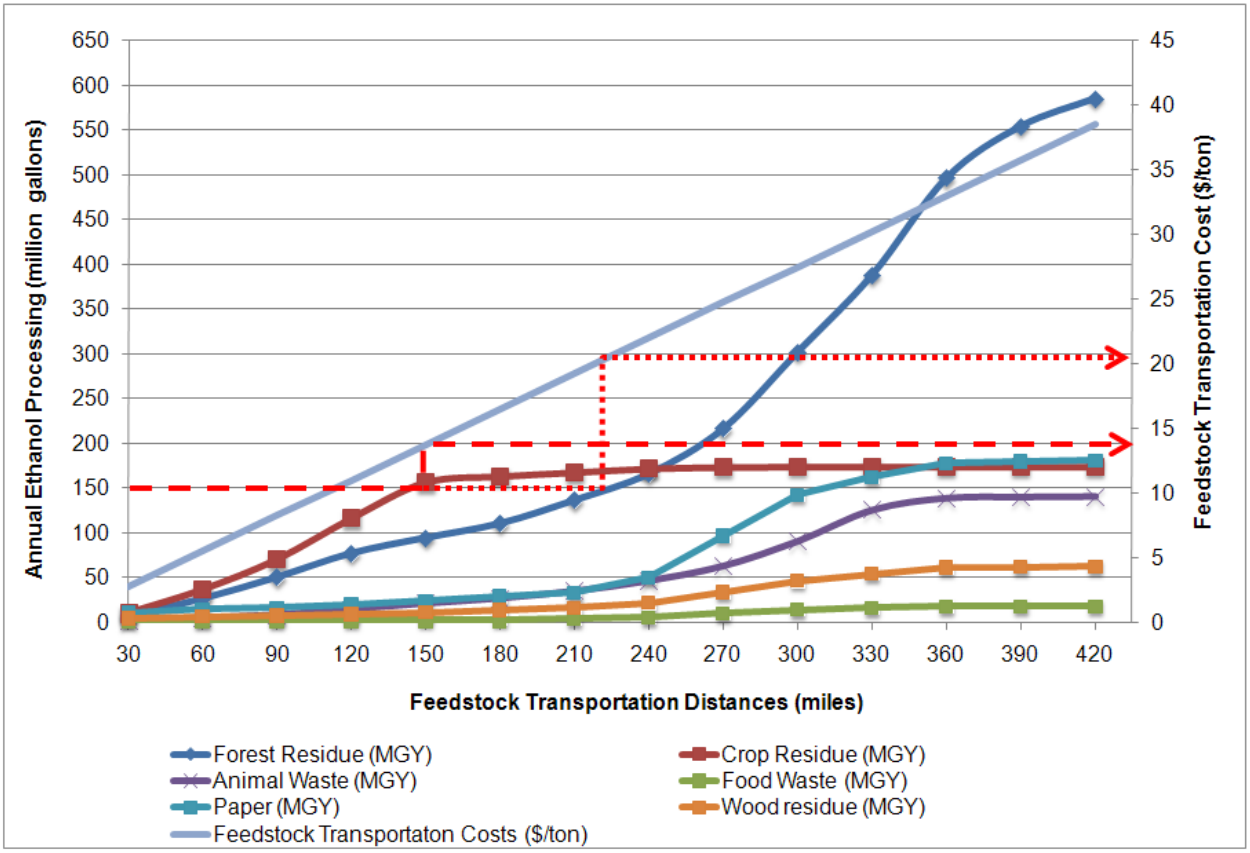


Figure 15: Feedstock Transportation Costs by Haul-Distances for Spokane Plant

<u>Processing Costs</u>

Crop Residue in Washington State

Crop residue (field residue) is one important resource of biofuel feedstocks. Because Washington State is one of the major wheat-producing states in the country, wheat straw accounts for nearly 80% of all crop residues. Washington State produces about 1,614,234 dry tons of wheat straw annually. Wheat straw is rich in cellulose and hemicelluloses, which is a potential raw material for commercial bioethanol production and gasification. Researchers in Washington State are interested in this kind of feedstock and have assessed the availability of wheat straw, the status of the conversion technologies, and the economics of ethanol production from wheat straw (Kerstetter and Lyons 2001).

From the estimation of biomass conversion into bioethanol or thermo-ethanol with the feedstock availability information from GIS system, several conclusions can be made (Figure 16 and 17).

1. Regarding the 420-mile collection distance, the maximum capacity for an ethanol plant built with crop residue as feedstock can only reach the scale of about 180 MGY due to the limitation of material.
2. If only based on model output, the gasification process shows some advantage over the SSCF process in production cost. But the models are based on two concept designs, and some technology barriers still need to be overcome for both of them—pretreatment units of bioethanol production, and the carbon conversion rate of the gasification process. There is no commercialized example for comparison, so one can only conclude that the gasification technology may have more potential.
3. In almost every curve, the 20 MGY scale can be seen as a tipping point for production cost. Because the minimum ethanol selling price (MESP) no longer decreases sharply with the increase of plant scale, this value can be seen as a threshhold for ethanol plant scale in Washington State.
4. From 60 MGY to 160 MGY, the ethanol production cost curve enters a “flat bottom” zone, which means the cost can be neglected in considering the system scale. For example, large-scale facilities may have lower ethanol production costs but the return on investment (ROI) per gallon also declines. This may be undesirable to potential investors.
5. Spokane and Ellensburg are the best choices for future facilities based on crop residue feedstock. This is mainly because of the availbility of feedstocks.
6. The upper limit of facility scale will be determined by the market capacity. If the delivery cost were taken into account, there must be an optimized facility scale which balances the production cost and delivery cost.

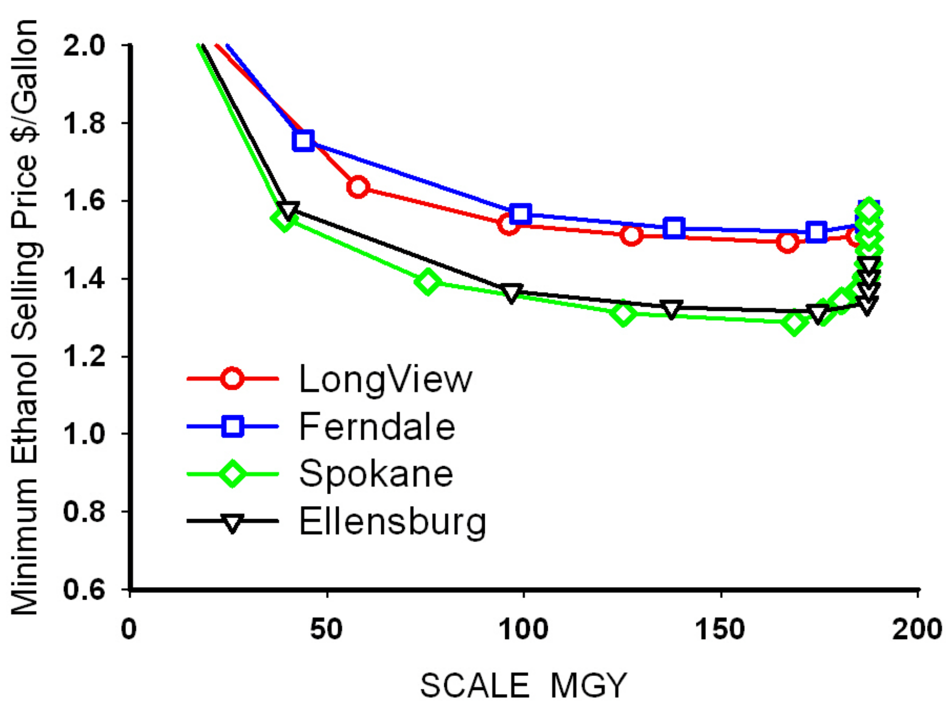


Figure 16: Cost Curve for Bioethanol Production with Crop Residue as Feedstock

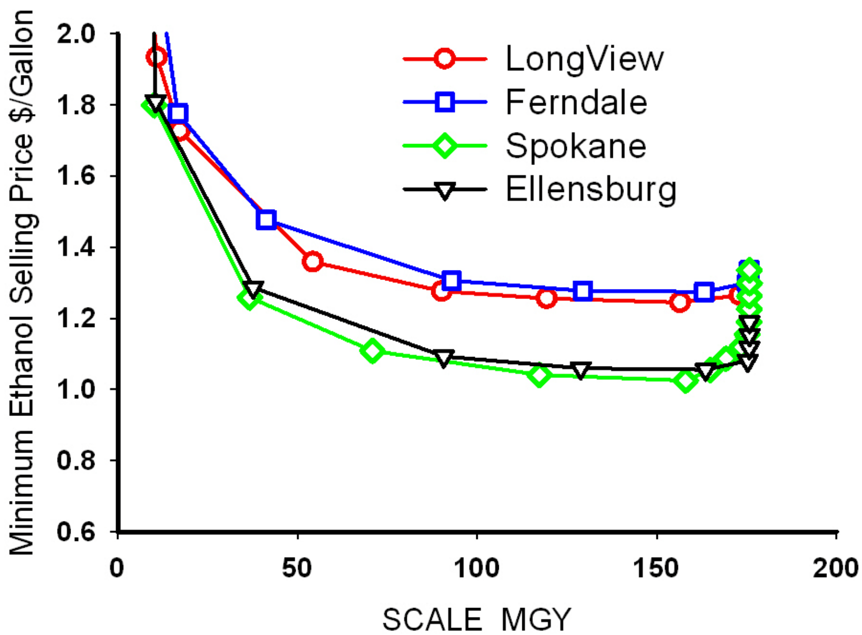


Figure 17: Cost Curve for Thermo-ethanol Production with Crop Residue as Feedstock

Forest Residue in Washington State

The forest products industry generates large amounts of residual biomass as timber is harvested and manufactured into marketable goods such as lumber and paper. Forest-derived biomass may originate directly from the forest (logging residues) or from timber processing mills (primary mill residues). According to the Phase 1 report (Frear, et al. 2005), 8 million tons of forest residues are distributed all over the Washington state annually.

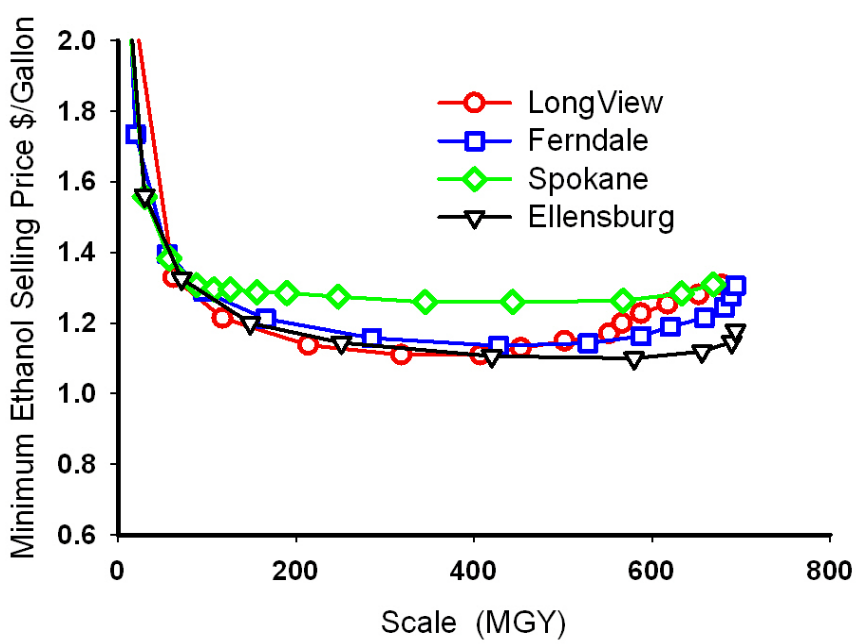


Figure 18: MESP $/Gallon for Bioethanol Production with Forest Residue as Feedstock

The huge quantity of forest residue feedstocks has a theoretical potential to produce up to nearly 800 MGY of ethanol within the same transportation distance as crop residue, and it has four to five times the maximum output as using crop residue as feedstock. From the standpoint of biofuel output, this feedstock can be seen as the most important in Washington State.

For forest residue, the gasification process also shows some advantages but this still needs more confirmation. Ellensburg is the least cost site for biofuel production due to feedstock availability, but Longview has a lower cost for bioethanol production at less than 400 MGY (Figures 18 and 19).

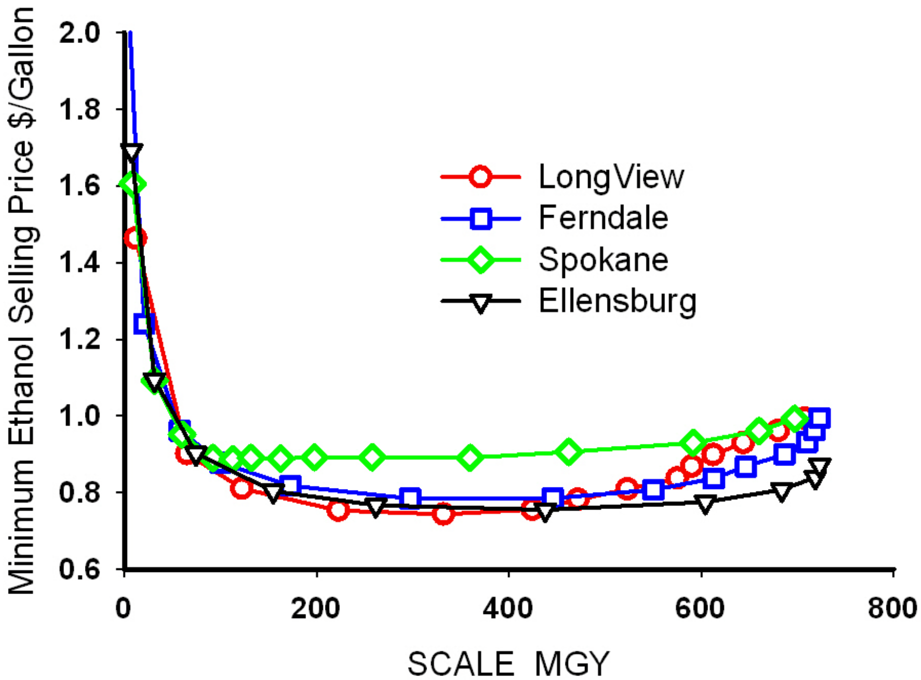


Figure 19: MESP $/Gallon for Thermo-ethanol Production with Forest Residue as Feedstock

Municipal Waste in Washington State

For decades, countless individuals, institutions, communities, and companies have tried to find creative ways to reduce and better manage municipal waste through a coordinated mix of practices that includes source reduction, recycling (including composting), and landfill. Among these practices, using biorefinery technology to convert them into sustainable energy has gained a great deal of attention.

In the earlier report (Frear, et al. 2005), 45 potential feedstock sources in Washington State were geographically identified, categorized, and mapped at a county level; 34 of them are municipal wastes. In this project, some of the very low-quantity feedstocks included in the earlier report have been eliminated and the remaining feedstocks have been grouped according to their similarities. Of all these materials, four types of feedstock are of large quantity—animal waste, food waste, paper, and wood residues—and were chosen for investigation. Cellulose materials, waste paper, and wood residues are good feedstock for ethanol production, and animal waste and food waste can be processed by AD to generate biogas or electricity.

The composition of waste paper in terms of sugar content was not provided by the earlier report. Mixed waste paper data used in our bioethanol model were acquired from a Washington State Energy Office (WSEO) report (WSEO, 1991).

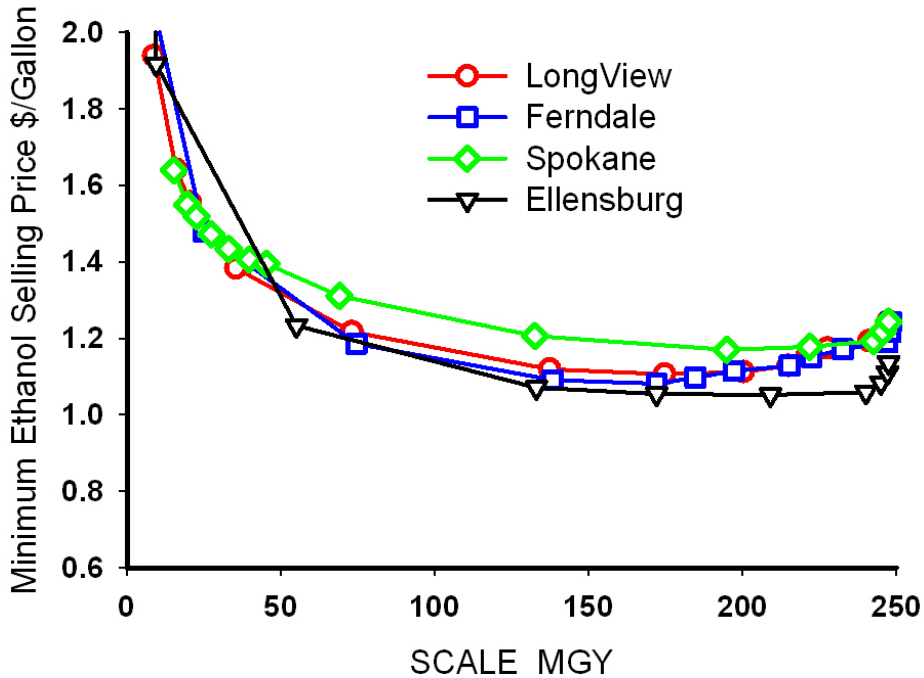


Figure 20: MESP $/Gallon for Bioethanol Production with Waste Paper as Feedstock

Paper has a nearly 20% percent higher yield compared with other lignocellulosic-biomass materials because of its higher cellulose content. The composition we used here is residential mixed waste paper (sample was taken from the curbside program of the City of Olympia, WA). If the feedstock were mainly commercial mixed waste paper (paper from offices), which contains more cellulose and less lignin, more ethanol would be generated (Figure 20).

Animal Waste and Food Waste

Anaerobic digestion is a series of processes in which microorganisms break down biodegradable material in the absence of oxygen. It is widely used to treat wastewater sludge and organic waste because it leads to volume and mass reduction of the input material while producing biogas which is chiefly methane. In Washington State, the first anaerobic digester for a dairy was installed at the Vander Haak Dairy in 2004.This dairy utilizes food waste and manure to feed the digester. Our system simulation and economic assessment used data from this project as the main parameters resource. The effluent of the AD process contains large quantities of nitrogen and phosphate which need to be disposed of on-site, so a scale limit was set for our analysis work. The simulation could only treat a maximum quantity of 500 ton/day (wet weight) feedstocks. Under this assumption, the possible tipping fee for excessive effluent liquid can be neglected.

If animal waste is used as the feedstock for AD systems, there would be enough feedstock that meets or exceeds the criterion of 500 ton/day within 30 miles of every site we tested. An analysis of system financial feasibility was performed under different feedstock input rates and result is shown in Figure 21. Currently, the main saleable product of AD process is electricity.

Even taking green tag of electricity and credit provided by govenments into account, the total revenue is still often uncomparable with the cost of maintainance and equipment depreciation. So the process is often not profitable if electicity is the sole product. With stable feedstock transportation costs, the final system net income per ton of waste increases due to the reduction in processing cost. In this case, if there are any tipping fees for animal waste, the income value may become positive as in Figure 22 with a $25/ton tipping fee for food waste. Food waste used as feedstock for an AD system is more economical, and the system net income is higher when there are more feedstocks and within shorter transportation distance. The amount of food waste is limited in some cases, thus the relatve tansportation cost is too high to win over the processing cost reduction. From this standpoint, small-scale local facilities for food waste treatment seem to be better choices.

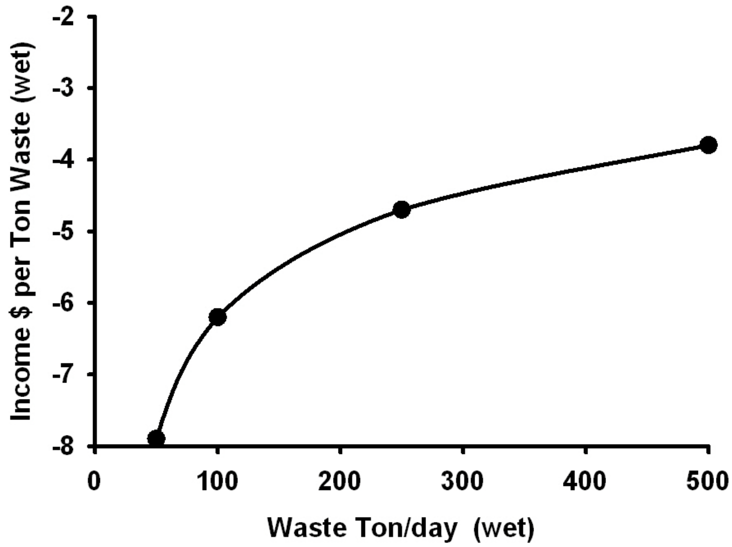


Figure 21: AD Process Negative Net Income Compared with Manure Input under Zero Tipping

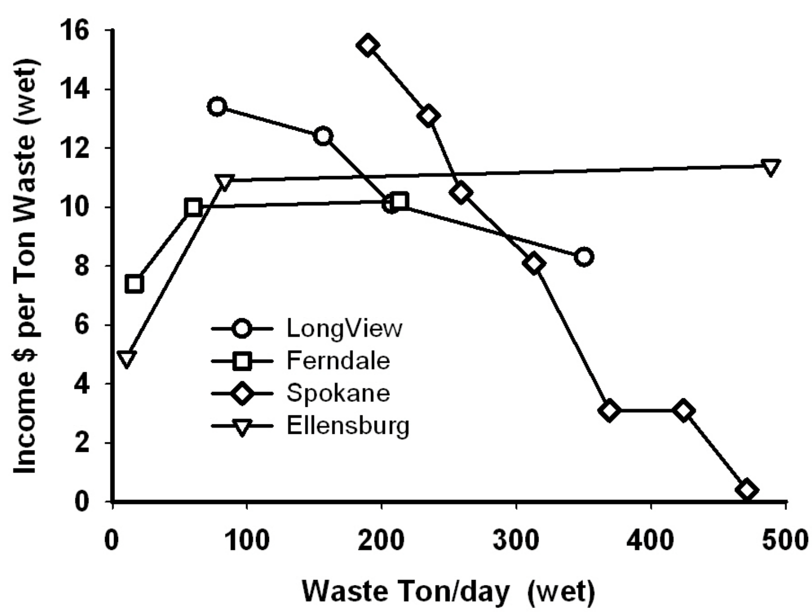


Figure 22: Site Comparison of Financial Returns in an AD Food Waste Facility

Multi-Feedstocks for Ethanol Production
Because most of our feedstocks are lignocellulosic materials that have similar composition, they may be used to produce ethanol in the same facility. The advantages of multi-feedstocks for ethanol production are further reduction in feedstock cost and elevation of potential number of facilities. If the universal system's performances on every possible feedstock are assumed the same, the ethanol production cost will be reduced. We used all-lignocellulosic materials (crop residue, forest residue, wood residue, and waste paper) as feedstocks to the system and estimated the production cost based on Ellensburg's data. The results are shown in Figures 23 through 26.

Reduction of feedstock cost accounts for the primary production cost decline. For bioethanol processes, this effect is more distinct. Under real conditions, all systems must be optimized for specific raw materials, and there would be more unpredictable negative effects on conversion processes with the increment of feedstock types. Impacts of final ethanol yield reduction are analyzed for both processes, and the result shows that 10% less ethanol yield would lead to loss of cost advantage for the multi-feedstock strategy.

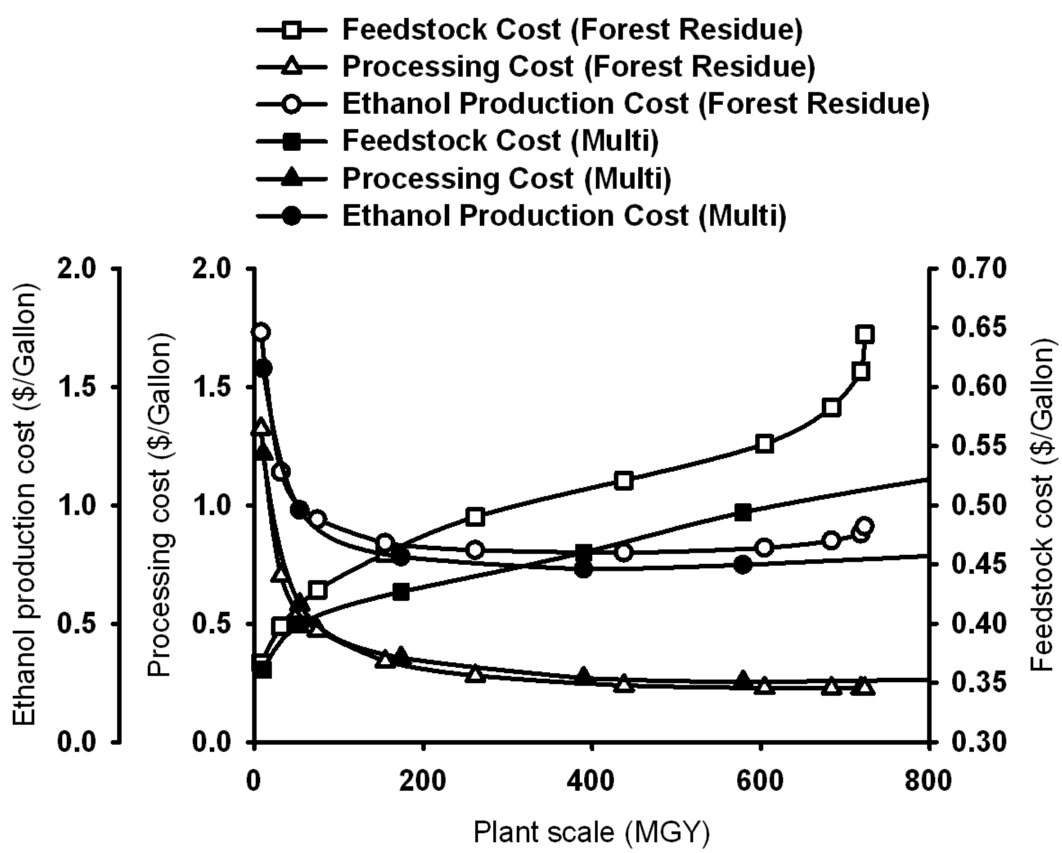


Figure 23: Cost Curve for Thermo-ethanol Production with Multi-Feedstock

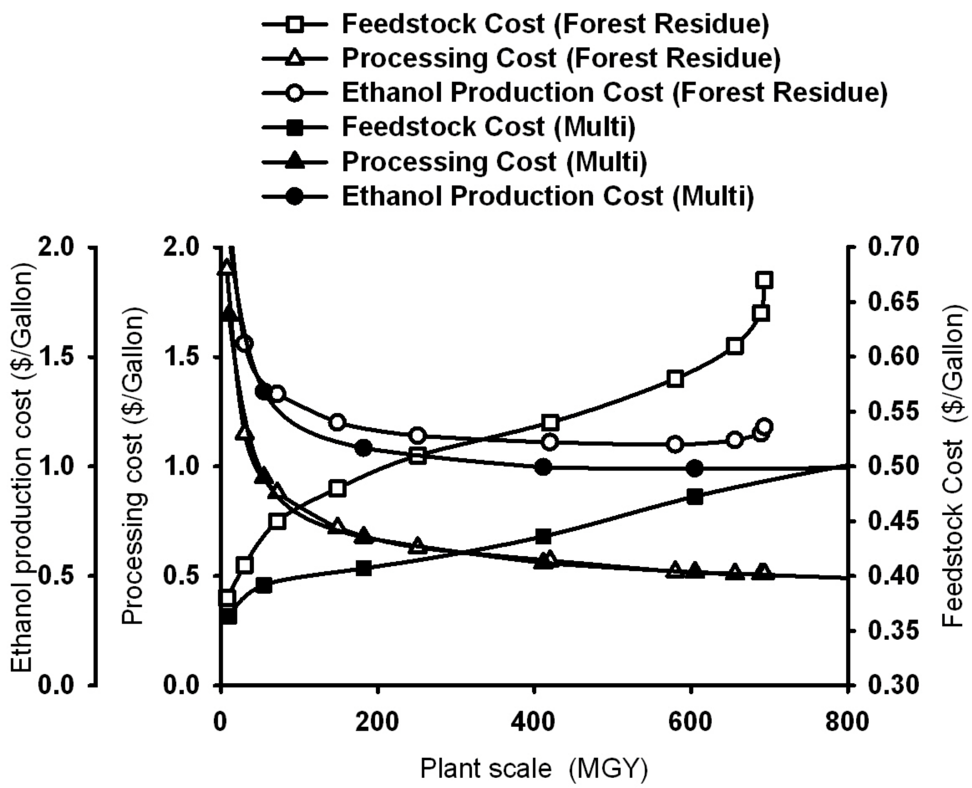


Figure 24: Cost Curve for Bioethanol Production with Multi-Feedstock

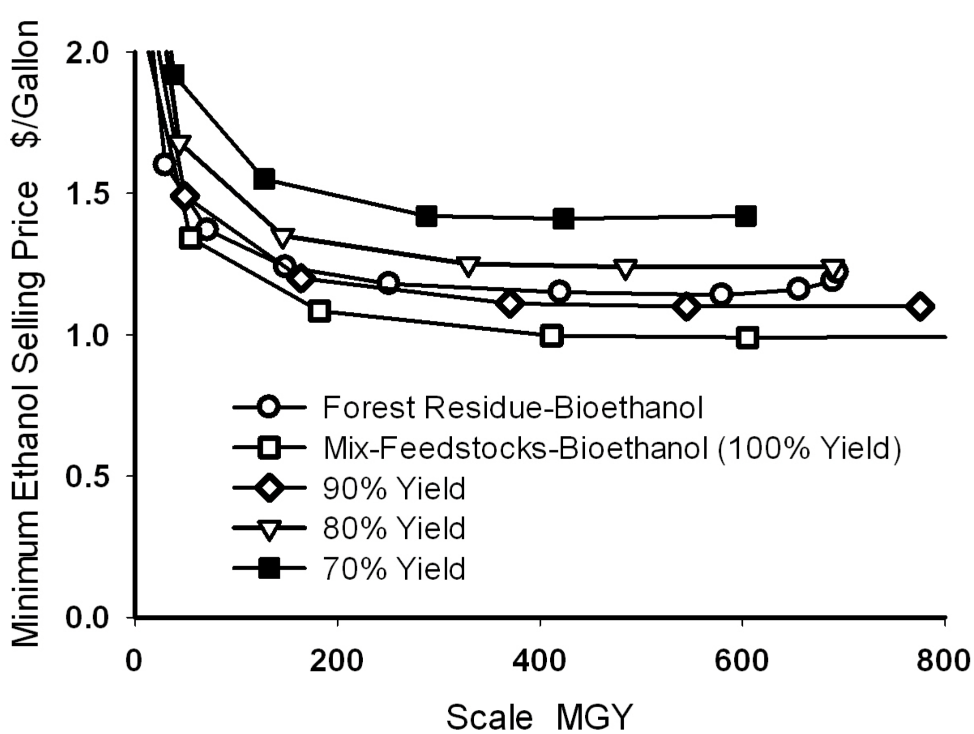


Figure 25: Impacts of Ethanol Yield Reduction on Production Cost of Bioethanol Processes

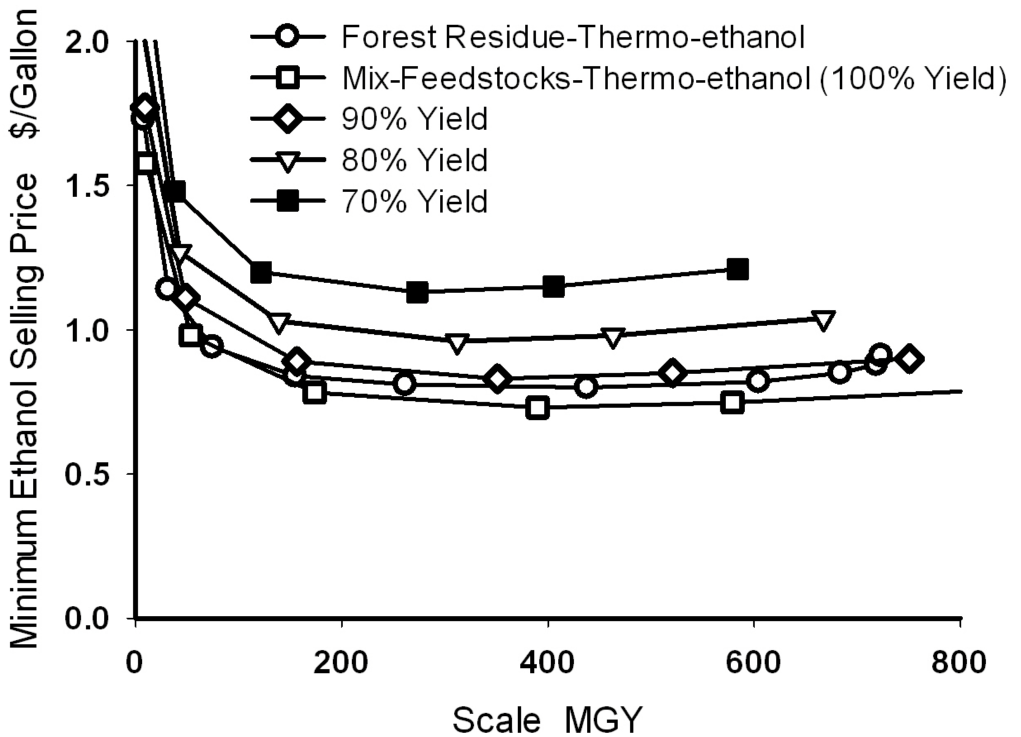


Figure 26: Impacts of Ethanol Yield Reduction on Production Cost of Thermo-ethanol Processes

Distribution Costs

At each level of the biofuel processing scale, distribution costs from processing plants to blending terminals can be added to costs accrued from terminals to biofueling stations to derive the total distribution costs. Applying per gallon mile truck transportation costs to increasing distances, distribution costs result in an upward-sloping curve ranging from $0.013 to $0.138 per gallon for 100 to 200 MGY processing plants, respectively (Figure 27).

GIS least-cost or shortest-route identification tools were used to find optimal routes from an ethanol processing plant to existing blending terminals and fueling stations in the state of Washington. For the first part of the spatial analysis, biorefinery, existing blending terminals, and E85 station location information were combined (Figure 28). For the second part, distribution routes from blending terminals to E85 fueling stations were identified with the use of GIS Network Analyst Origin-Destination Cost Matrix solver.

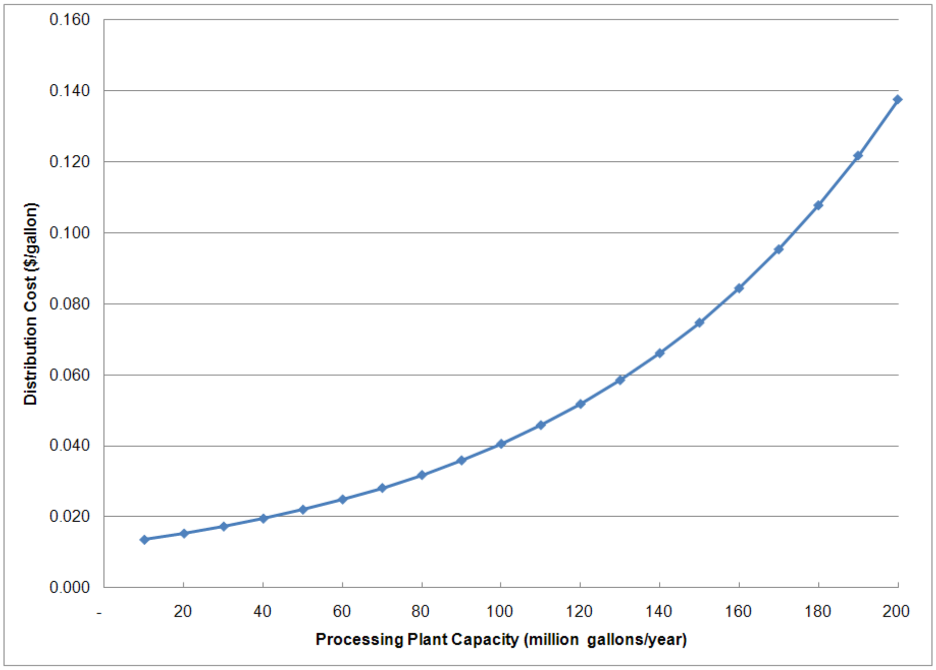


Figure 27: Distribution Costs per Gallon of Ethanol by Processing Plant Capacity

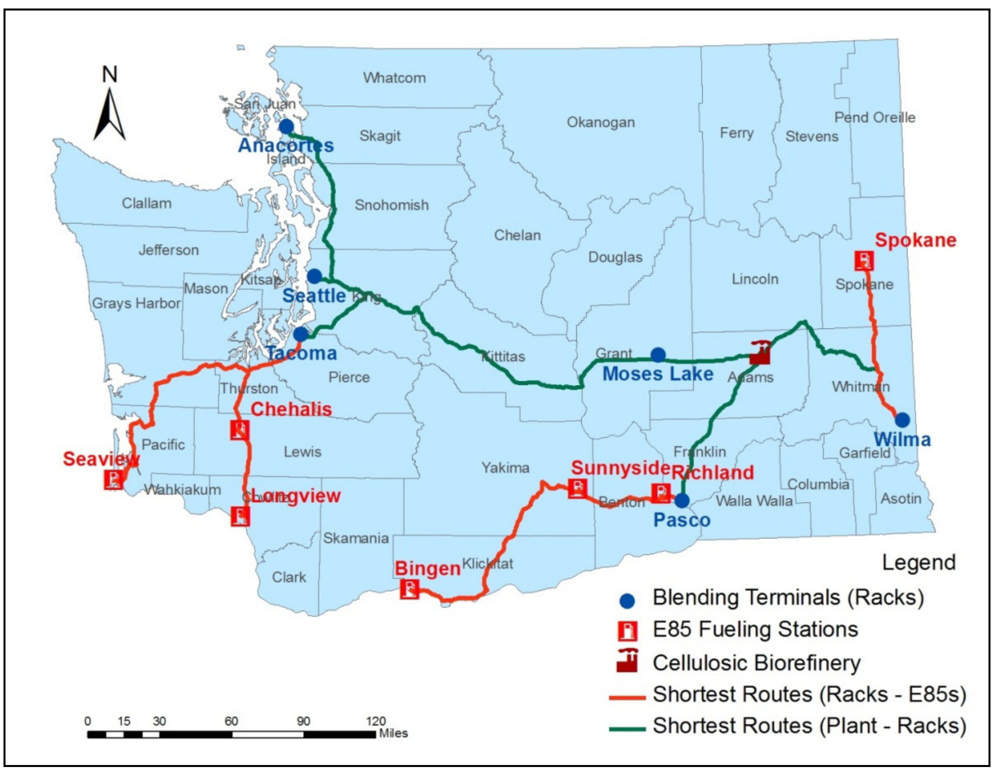


Figure 28: Shortest Routes from Processing Plant to Blending Terminals and E85 Fueling Stations

The resulting least-cost destinations (blending terminals) from the cellulosic biorefinery are as follows: Moses Lake ($0.03/gallon), Pasco ($0.05/gallon), Wilma ($0.07/gallon), Seattle ($0.15/gallon), Tacoma ($0.16/gallon), and Anacortes ($0.20/gallon) (Figure 29).The consideration of only one processing plant and six blending terminal locations makes the computation of optimal routes relatively straightforward, but also over simplified. However, with the growing ethanol industry that will eventually result in increasing number of processing plants and E85 fueling stations, the route optimization can be complicated. Therefore, this methodology is useful to derive route optimization and distribution costs with multiple ethanol processing plants serving hundreds of fueling stations in the state.

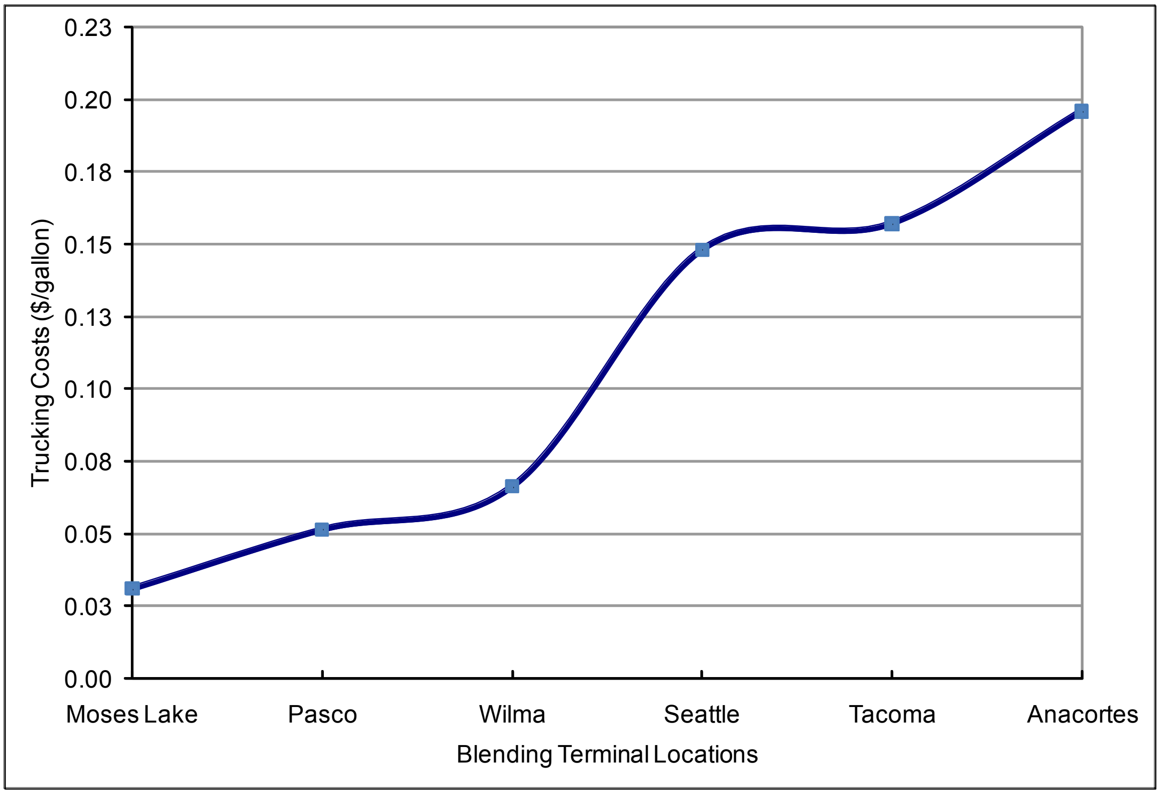


Figure 29: Ethanol Distribution Costs from Processing Plant to Washington's Blending Terminals

Figure 30 shows per gallon trucking costs associated with the final segment—the distribution of ethanol from blending terminals to existing E85 fueling stations. Note that only three blending terminals (in Tacoma, Pasco, and Wilma) were plotted as origins against all seven E85 fueling stations. Terminals in Seattle, Anacortes, and Moses Lake are relatively farther away and therefore were dropped by the GIS Network Analyst Closest Facility toolset. To finalize the distribution cost calculations for the entire distribution path, starting from the processing plant in eastern Washington to all E85 fueling stations through the three closest blending terminals, costs for both segments were combined (Figure 31). Resulting transportation costs for the ethanol distributed through the terminal in Pasco increased to $0.06, $0.09, and $0.16 per gallon for E85 stations in Richland, Sunnyside, and Bingen, respectively. Per gallon distribution costs through the Tacoma terminal start with $0.20 in Chehalis, and increase to $0.22 and $0.25 for the E85 destinations in Longview and Seaview, respectively. Given the current geographic distribution of E85 fueling stations, only one distribution route was identified for the fueling station in Spokane through the terminal in Wilma, resulting in $0.12 per gallon transportation costs.

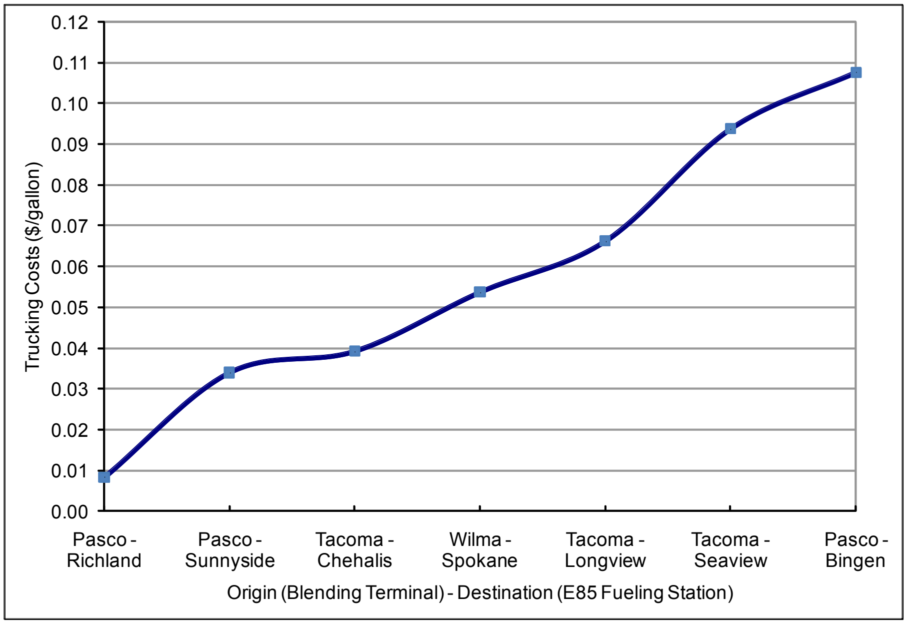


Figure 30: Ethanol Distribution Costs from Washington's Blending Terminals to E85 Fueling Stations

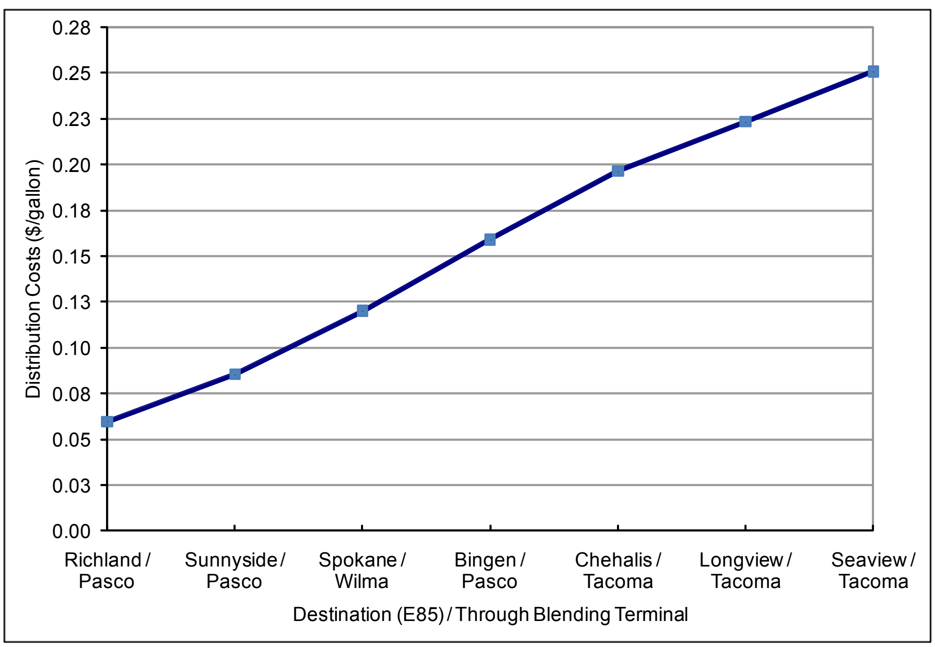


Figure 31: Distribution Costs from the Processing Plant through Three Blending Terminals to All E85 Fueling Stations in the State

As mentioned earlier, for the second part of the spatial investigation an origin-destination cost matrix was created to rank the least-cost distribution routes from blending terminals to the state's E85 gas stations. For this part of the analysis, the GIS Network Analysis toolset uses location information to rank distribution routes according to the lowest to highest transportation costs. Currently, with only six origins (blending terminals) and seven destinations (E85 stations (resulting in a 6×7 cost matrix), the current computation is relatively easy. However, with the development of the industry, the methodology may be used to include hundreds of trips originating from existing blending terminals to future E85 stations in the state.

Figure 32 shows a map with connection lines[3] illustrating the distance-based cost ranking for the routes from the blending terminal to E85 fueling stations in the state. For each of the blending terminal locations, route information was considered for calculating the closest E85 station location, and to rank them according to the transportation costs.

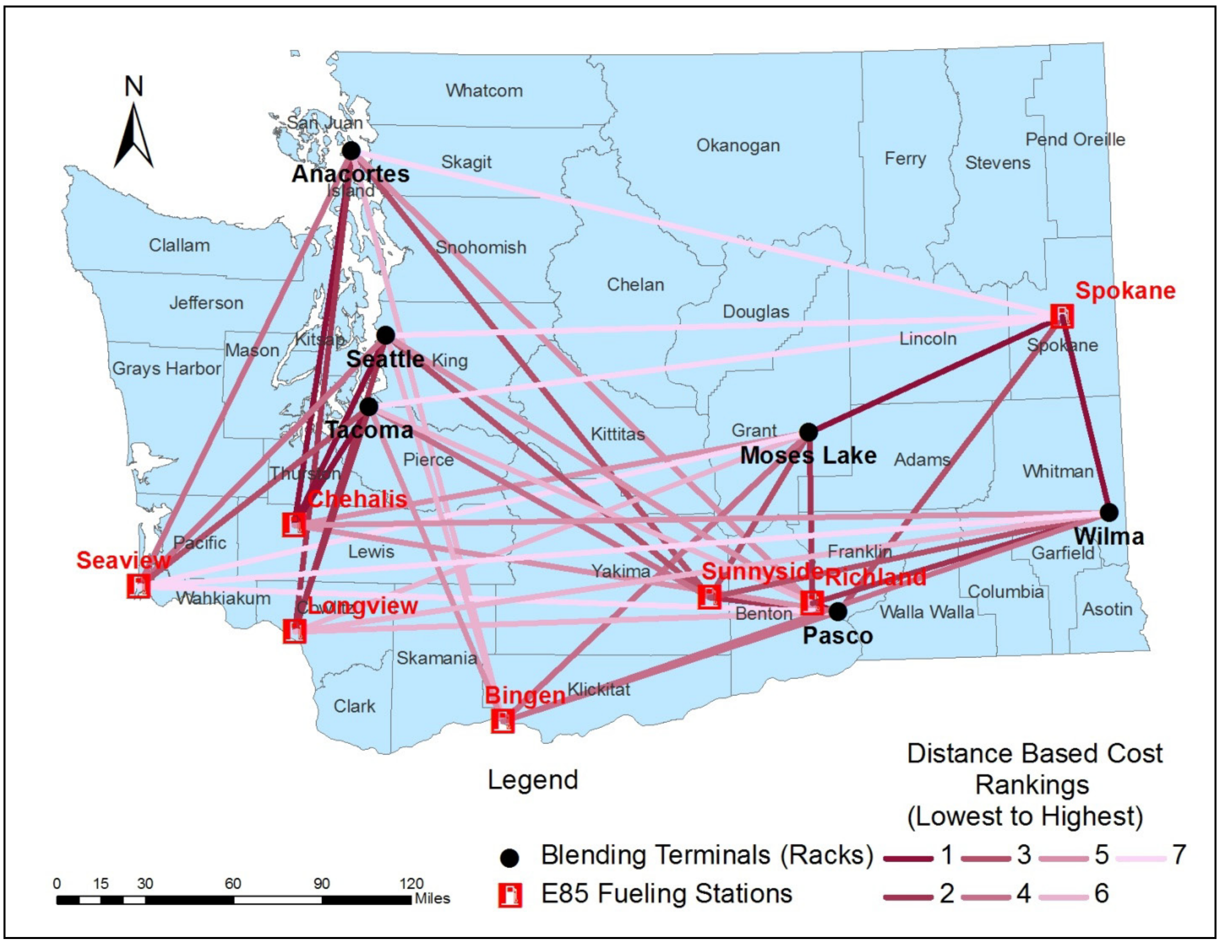


Figure 32: Map for GIS Origin (Blending Terminal) Destination (E85 Fueling Station) Distance-Based Cost Matrix

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[3] Despite the lines in the map being shown as straight lines, the information they provide is based on origin-destination highway distances. To keep the map clear, the Washington's highway layer was not included.

<u>Delivered Costs</u>

This section of the report combines feedstock transportation, processing, and distribution costs to derive the delivered cost of biofuel to alternative markets. Results shown in the figures below include estimates using both bioethanol and thermo-ethanol conversion technologies. The feedstock transportation, processing, and distribution calculations were made for several potential biorefinery locations in the state. In this section, results for only least-cost locations are shown. Cost estimates for the rest of the locations can be found in the Appendixes. Figure 33 shows feedstock collection and transportation, plant processing, and distribution cost estimates (cumulatively representing delivered costs) using crop residue data.

As shown in Figure 33 the processing cost curve is downward-sloping because of the economies of scale (the costs are spread over more gallons of production). However, costs for both feedstock transportation and distribution are positively correlated with the production scale. Therefore, the delivered cost curve is downward-sloping up to a certain processing capacity level (as discussed earlier) after which the curve slopes upward. The lowest point on the delivered cost curve ($1.31 per gallon) represents the least cost of ethanol production using crop residue. For this particular location (Spokane), the optimal size of the processing plant is125 MGY. The lowest delivered cost estimate has important implications for the processing plant optimal size decisions. In particular, the corresponding plant capacity (MGY) on the horizontal axis shows the optimal size of the processing plant, given the feedstock type and the processing technology that was considered here.

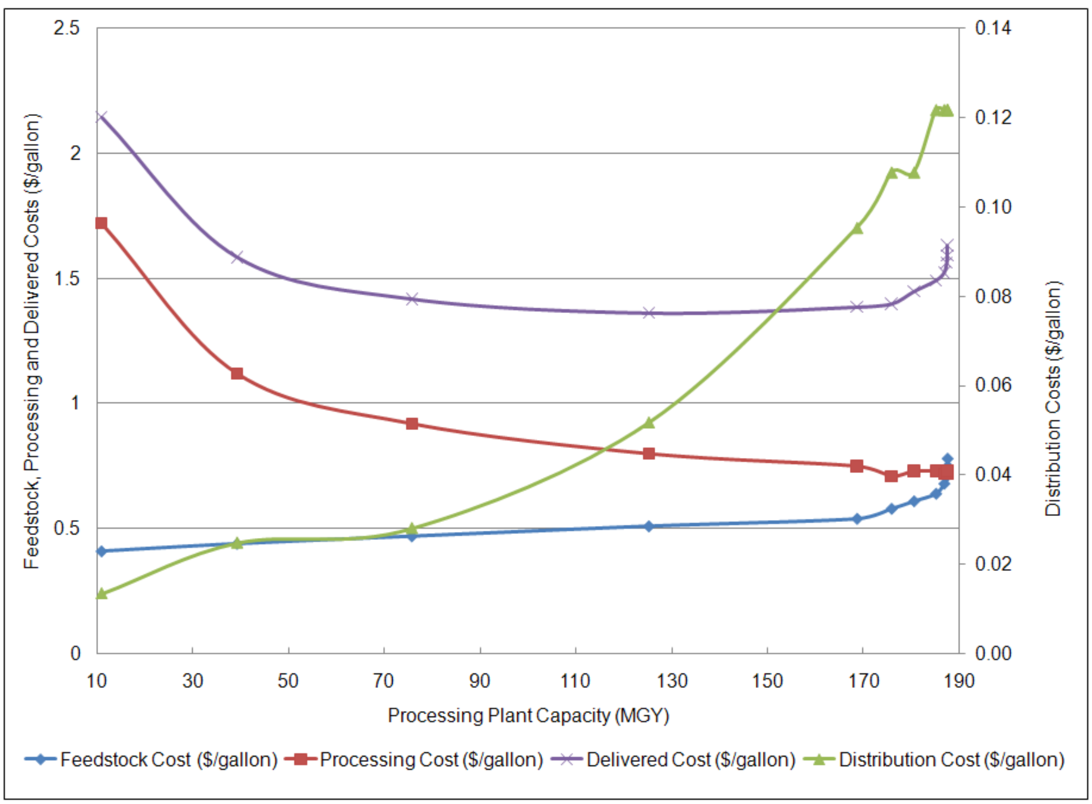

Figure 33: Delivered Cost of Bioethanol Using Crop Residue

Figure 34 shows the delivered cost estimates using gasification technology for converting crop biomass into alcohol. The interpretation for downward-sloping processing and increasing transportation costs is similar to what was described for the biological conversion technology above. The lowest point on the delivered cost curve ($1.09 per gallon) represents the least cost of ethanol production using crop residue. The optimal size of the processing plant using gasification conversion technology is 117 MGY.

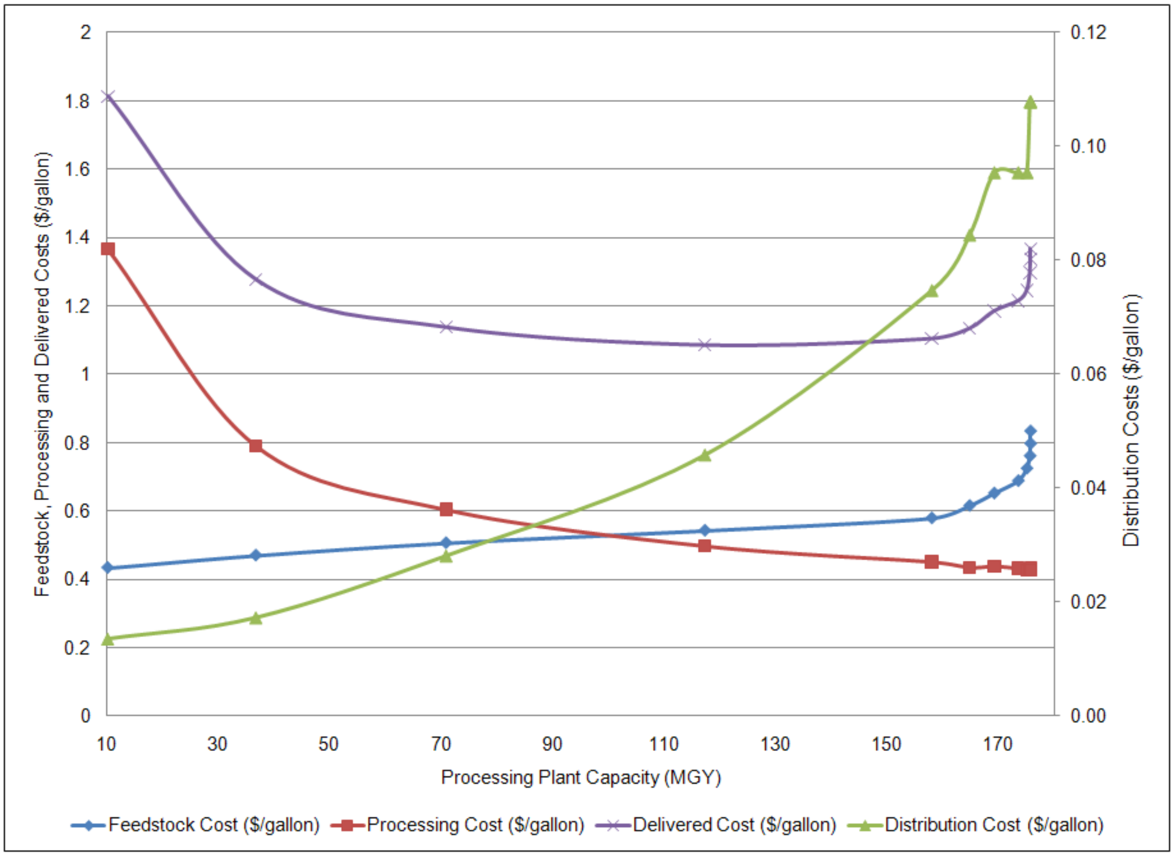

Figure 34: Delivered Cost of Thermo-ethanol Using Crop Residue (Gasification)

Figure 35 shows the delivered cost estimates using bioethanol technology for converting forest biomass into alcohol. The interpretation for downward-sloping processing and increasing transportation costs is similar to what was described for the biological conversion technology above. The lowest point on the delivered cost curve ($1.26 per gallon) represents the least cost of ethanol production using forest residue. The optimal size of the processing plant (Longview location) using bioethanol conversion technology is 117 MGY.

Figure 36 shows the delivered cost estimates using gasification technology for converting forest biomass into alcohol. The interpretation for downward-sloping processing and increasing transportation costs is similar to what was described for the biological conversion technology above. The lowest point on the delivered cost curve ($0.87 per gallon) represents the least cost of ethanol production using forest residue. The optimal size of the processing plant using gasification conversion technology at this location (Ellensburg) is 155 MGY.

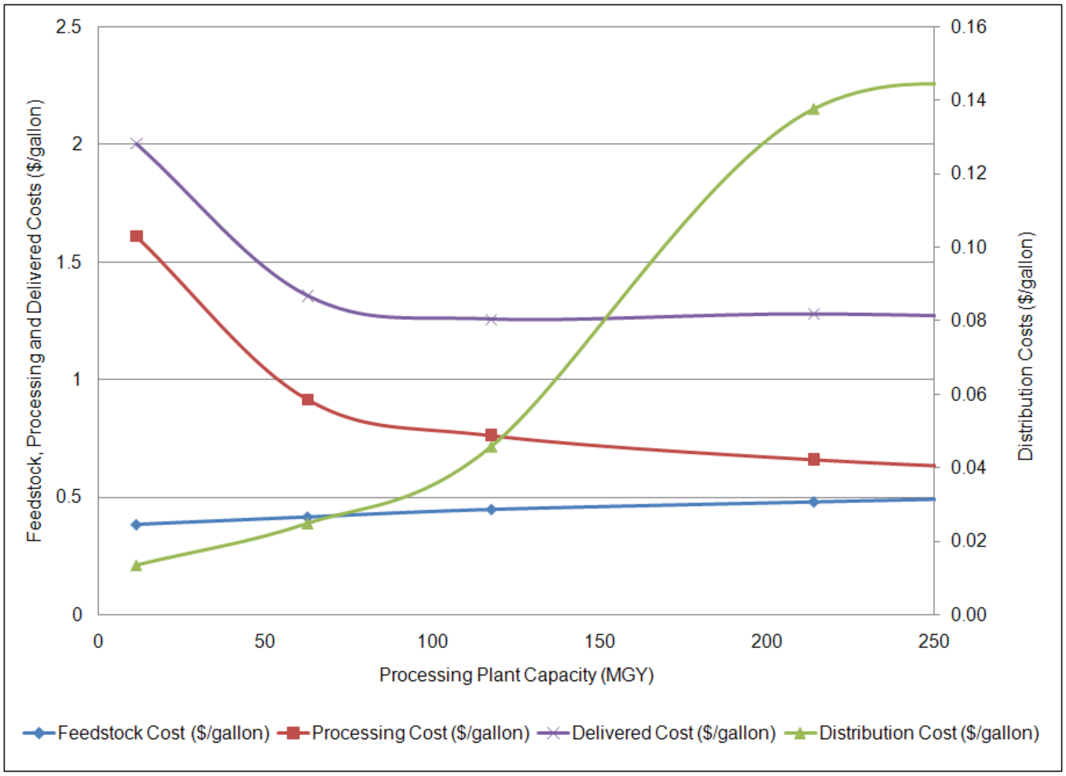

Figure 35: Delivered Cost of Bioethanol Using Forest

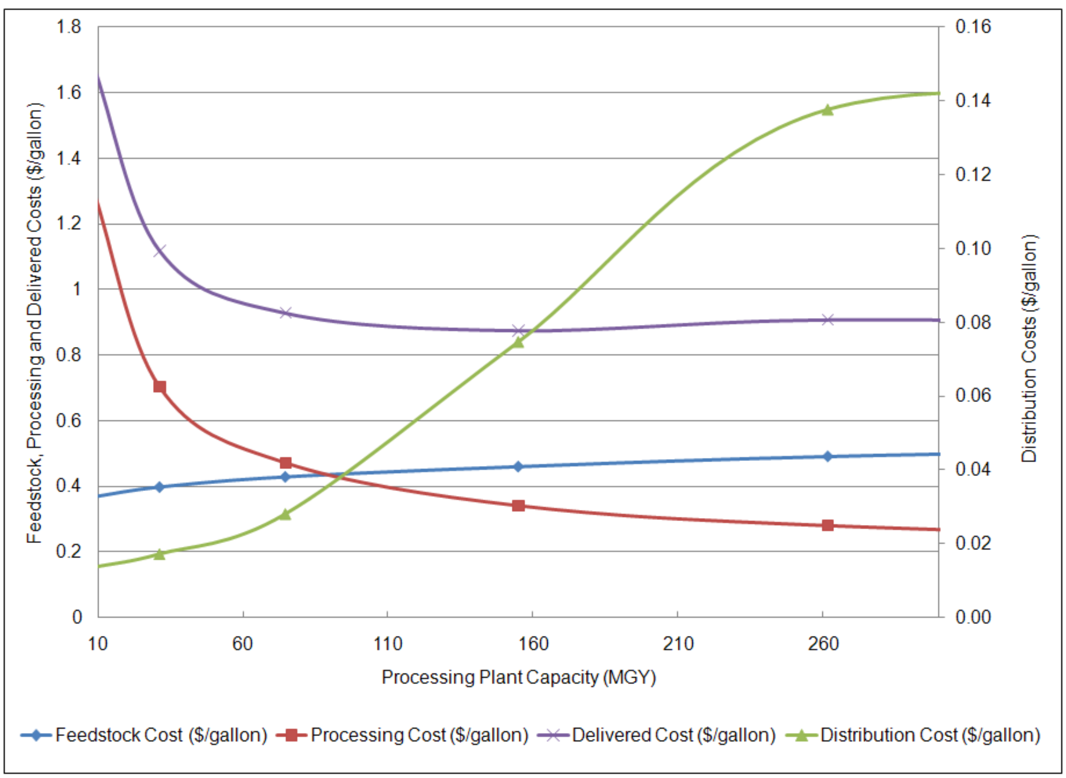

Figure 36: Delivered Cost of Thermo-ethanol Using Forest Residue

Summary and Limitations

In this project, impacts of facility scale and location selection were analyzed with regard to ethanol production and anaerobic digestion processes using the major types of biomass in Washington State. The project results show the relative weight of different cost components and the cost change in response to the scale of ethanol plant and the locations. Anaerobic digesters are capacity scale limited due to the relatively high water content of feedstocks forcing high transport costs over relatively short distances, and high capital costs to build Large systems Thus, the feedstock distribution had limited effects on the economics. While for the ethanol facilities, both the reduction of processing costs and increasing of feedstock costs are directly impacted by the scale of the plant capacity. The project results advance the previous efforts (Frear, 2005), providing more specific information for prospecting feasibilities of bioethanol production in Washington and for decision and policy making. It needs to be pointed out that the analysis of processing cost for both ethanol technologies was based largely on the NREL framework and reported parameter values without independent verifications (Aden, Ruth et al. 2002; Phillips, Aden et al. 2007). Due to the infancy of the industry and respective conversion processes for lignocellulosic biofuel production, there is a lack of reliable data derived from actual plant performance, thus all the parameters used in the models are based on best estimation. For example, the conversion rate for C5 sugar utilization in SSCF process is specified with microorganisms and feedstock, while the parameters we used in the model is the value represent the future technology levels in 5 or 10 years. Therefore, the results presented in the project must be interpreted with such limitations in mind. As technology develops and more actual plant performance data become available, the results and the conclusion may change. Therefore, the results should be used as reference and relative numbers that are closely dependent on the model parameters used.

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APPENDIX I

This appendix is an extended version of the transportation cost derivations summarized above.

Biomass Inventory Technology and Economics Assessments*

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* The following is supplemental material for the final report.

List of Acronyms

DOE	U.S. Department of Energy
EISA	Energy Independence and Security Act
EIA	Energy Information Administration
GIS	Geographic Information Systems
MGY	Million Gallons per Year
NREL	National Renewable Energy Laboratory
NADO	National Association of Development Organizations
RFS	Renewable Fuel Standard
TRG	Transportation Research Group
TPEC	Total Purchased Equipment Cost
TPI	Total Project Investment
TIEC	Total Installed Equipment Cost
TPIC	Total Project Indirect Cost
WSU	Washington State University

APPENDIX ORGANIZATION

Introduction and Background section introduces the objectives of this report, which is a part of the agreement between the Washington State Department of Ecology, and the Department of Biological Systems Engineering, and the School of Economic Sciences at Washington State University (WSU). It also provides an overview of the recent developments around cellulosic ethanol processing and the challenges facing the biofuels industry in general. The section concludes with description of the Geographic Information Systems (GIS) methodology used for the feedstock collection and distribution cost derivations.

Geographic Distribution of Feedstocks introduces the spatial distribution of feedstocks in the study area by mapping available types of feedstocks in relation to the Washington State highway network using GIS.

An Overview of Transportation Modes section discuses alternative modes of transportation and compares carrying capacities for each mode.

Feedstock Production and Transportation section provides an extensive review of recent literature investigating cellulosic feedstocks harvesting and transportation methods. It also includes an economic engineering approach for deriving cellulosic feedstock transportation costs using truck transportation mode.

GIS Approach to Delivered Cost of Feedstocks (NREL Data) section demonstrates the application of GIS for deriving the delivered cost of feedstocks to a biorefinery in the state of Washington. This section uses data from NREL as a case study. Later in the report, we use this methodology to analyze Frear et al. (2005) data.

GIS Analysis for Biofuel Plant Least-Cost Plant Location Decisions (NREL Data) section introduces a GIS-based model (using NREL data) to support cellulosic ethanol plant least-cost location decisions by integrating geographic distribution of biomass in the study area with associated transportation costs.

GIS Approach to Delivered Feedstock Costs (Frear et al. Data) section introduces the results of the GIS method for deriving the delivered cost of feedstocks using biomass data identified in the first phase of this project (Frear et al. 2005).

GIS Analysis for Biofuel Plant Least-Cost Location Decisions (Frear et al. Data) section introduces the results found by applying the GIS-based methodology for identifying ethanol plant least-cost locations using to Frear et al. (2005) data.

Economic Analysis of Ethanol Processing Costs section develops an economic modeling of cellulosic ethanol plants with different processing capacities. Resulting per-gallon ethanol processing costs were used for the delivered costs derivation.

Delivered Costs section concludes the report by combining the feedstock transportation, processing, and distribution costs to derive the delivered cost of ethanol to alternative markets.

Introduction and Background

After many years of experimental processing, cellulosic ethanol has recently gained significant attention as a next generation of advanced fuels that will partially eliminate environmental and economic consequences of petroleum fuels and corn-based ethanol processing. In addition to considerable environmental benefits, the main advantages of cellulosic feedstocks are their resource abundance, higher energy returns (for several dedicated feedstocks), and competitive production costs (McLaughlin et al. 2002). However, besides the current technological (biomass-to-ethanol conversion) challenges with cellulosic feedstocks processing, there are numerous issues to be investigated. Such considerations include feedstock transportation and ethanol distribution costs, which may influence the viability of the industry through total delivered costs of the final product—the ethanol blend.

The current financial/economic crisis has imposed many obstacles for the effective implementation of the Renewable Fuel Standard (RFS) as mandated by the Energy Independence and Security Act (EISA) of 2007. Nevertheless, according to a recent U.S. Department of Agriculture (USDA) long-term projections report (USDA 2009), the ethanol industry is projected to expand in 2009. Despite the processing technological barriers (for the cellulosic ethanol) and logistical bottlenecks at the feedstock producer level, the DOE forecasts that 11 billion gallons of ethanol will be produced in 2009 (EIA 2008a). Another source suggests a potential capacity reaching more than 13 billion gallons of processing by the end of 2009 (Bevill *et al.*2008).

However, with the increasing levels of ethanol processing, the transportation infrastructure that is utilized for both feedstocks transportation and ethanol distribution needs to be improved accordingly. To accommodate the logistics of both corn- and cellulose-based feedstocks, considerable improvements are needed for all three modes of transportation—rail, barge, and truck. Because cellulosic feedstocks are geographically dispersed, the transportation infrastructure load will need to be adjusted and rebalanced. Given the current absence of commercial-scale cellulosic biorefineries and the existing transportation bottlenecks, the ethanol industry expansion forecasts above are conditioned on considerable improvements on every segment of the ethanol supply chain.

This Appendix is a component of the study investigating Washington's biomass resources, which is a part of an agreement between Washington State Department of Ecology and the Department of Biological Systems Engineering and the School of Economic Sciences at Washington State University. In this report, as a continuation of Phase I (Biomass Inventory Technology and Economics Assessments) under the agreement, the Transportation Research Group (TRG) at the WSU School of Economic Sciences analyzed the economic feasibility of cellulosic ethanol processing. The analyses include investigation of feedstock harvesting, transportation, processing, and distribution costs.

The earlier part of the study had geographically identified and categorized potential biomass sources in the state of Washington at the county level. The sources of biomass for cellulosic ethanol processing included field residue, animal waste, forestry residue, food packing/processing waste, and municipal waste categories. This study expands the previous work by spatially investigating types of available biomass and incorporates geographically varying road infrastructure and hauling distances from fields to prospective biorefineries, as well as from biorefineries to markets throughout the state of Washington.

As an initial step for geographically identifying feedstock transportation and distribution cost-minimizing potential refinery locations, the biomass was mapped in relation to the Washington State highway network using GIS. Considering different harvesting technologies, feedstock collection costs of agricultural crops residue and forest residue were derived. Recovery costs of other sources of biomass, such as animal manure and municipal solid waste (MSW) were adopted from the recent research literature. Per ton mile hauling costs of feedstocks were derived using an economic engineering approach that includes both fixed and variable costs of trucking operation for relevant truck configurations. Total trucking costs include expenses such as fixed vehicle costs (truck and trailer, depreciation, and license fees, etc.), fixed business costs (management, insurance, interest, etc.) and variable costs (truck: driver wages, fuel, repairs, maintenance, tires, miscellaneous; trailer: repairs, maintenance, tires, miscellaneous).

Due to the spatially variable availability characteristic, the total biomass that was identified in the first phase of this project cannot be fully utilized at the same expense. To assess the delivered costs of the feedstocks to biorefineries, the farm-gate price of feedstocks, transportation costs, biomass availability, and geographic distribution information were integrated. In addition, to avoid inaccurate evaluation of economic feasibility or volumes of cellulosic ethanol processing, we considered the proximity of the processing plants to market locations as well. For that purpose, we have developed a GIS-based model to support cellulosic ethanol plant least-cost location decisions by integrating delivery market destinations. After testing the model with NREL data, we used the data compiled in the first phase of this project (Frear et al. 2005).

Six types of biomass—agricultural crop residue, forest residue, animal waste, food waste, wood residue, and paper waste—have been spatially analyzed with the use of the GIS Network Analyst toolset to derive the delivered costs (supply curves) of feedstocks to biorefineries in the state. These supply curves were further combined with the internal plant processing costs. From each biorefinery in the study area, per ton mile distribution costs have been calculated for ethanol distribution to alternative markets. To determine distribution costs, GIS methodology similar to the feedstock transportation costs was used by incorporating origin (processing plants/blending terminals) and destination (ethanol fueling station locations in the state) data.

Geographic Distribution of Feedstocks

According to biomass inventory assessment findings (Frear et al. 2005), Washington State's biomass is underutilized by 16.9 million annual tons. Another source, NREL, had geographically identified forest residue, crop residue, urban wood, primary mill, and methane emissions from landfill as the primary sources of biomass in the state. Based on the 75 gallon per dry ton biomass-to-ethanol conversion rate, NREL (2007) data show that only the agricultural crop residue category (which is 20% of the state's total biomass available) could support up to 130 MGY ethanol processing.

Figure 37 shows the geographic distribution of agricultural crop residue in the state of Washington in relation to the state highway network using Frear et al. 2005 data. Consisting of 13 counties,[4] the southwest region produces more than 95% of the state's agricultural crop residues. Considering economically feasible feedstock collection and a 75 gallon per dry ton biomass-to-ethanol conversion rate, this reveals underutilization of biomass equivalent to 170 MGY ethanol processing. However, because of increasing transportation distances (required for larger processing capacities), all of the identified available residue cannot be utilized at the

[4] The 13 counties are Adams, Asotin, Benton, Columbia, Douglas, Franklin, Garfield, Grant, Lincoln, Spokane, Walla Walla, Yakima, and Whitman.

same expense. Consequently, to ensure economically feasible production, processing plants considering crop residue as a feedstock need to optimize their locations or processing capacity based on the "affordable" feedstock distribution, although the optimal location is primarily sensitive to feedstock transportation distances, the proximity of blending terminals and final markets is also important. We analyzed the proximity of markets to processing plants in the distribution costs section.

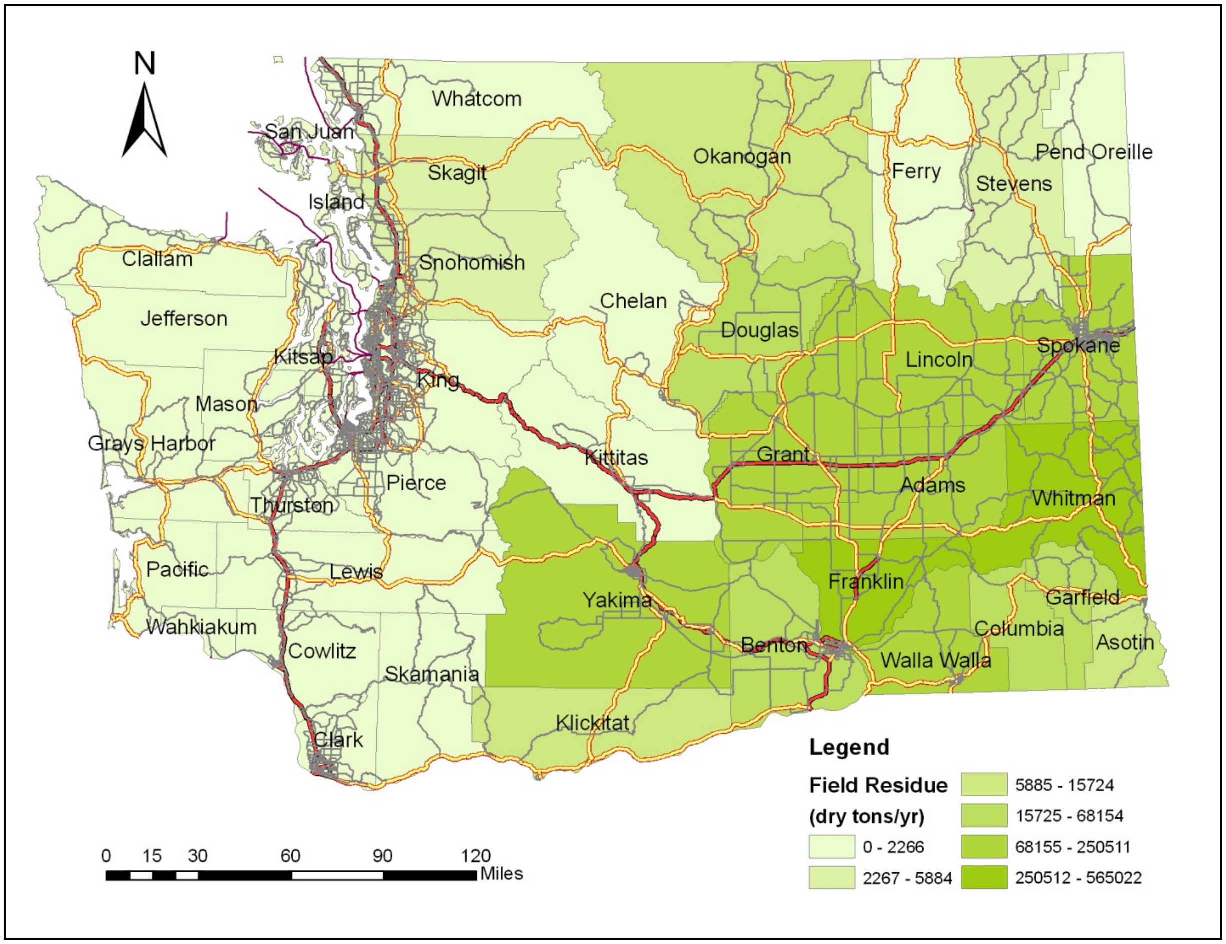


Figure 37: Geographic Distribution of Crop Residue in Relation to the Road Network

For agricultural crop residue in particular, besides the transportation cost component there are issues concerning soil fertility after the crop residue is harvested. The required quantity of the biomass to be left on the field to ensure soil fertility may adversely impact the delivered costs. By assessing county-level availability of wheat straw and the economics of ethanol processing in the state of Washington, Kerstetter and Lyons (2001) used a five-year average of crop yields to develop biomass supply curves for the hypothetical biorefinery location. As a result, considering the 20 MGY capacity ethanol facility, the study found that the price of the delivered straw is highly sensitive to the amount of straw left on the ground to ensure soil fertility and sustainable crop production. Additionally, the amount of residue that needs to be left on the field for soil fertility may differ according to soil type, crop type, and region-specific weather conditions.

The next feedstock category, forest residue, includes logging residues and other removals such as unconsolidated slash, chips, and comminuted or bundled residues. Separation of different parts (sorting) of the three, such as leaves and needles, stumps, etc., is important because, depending on its form, preprocessing, drying, and storage may influence the quality of the feedstock. As shown in Figure 38 forest residue is mostly distributed throughout the western and partially in the northern part of the state.

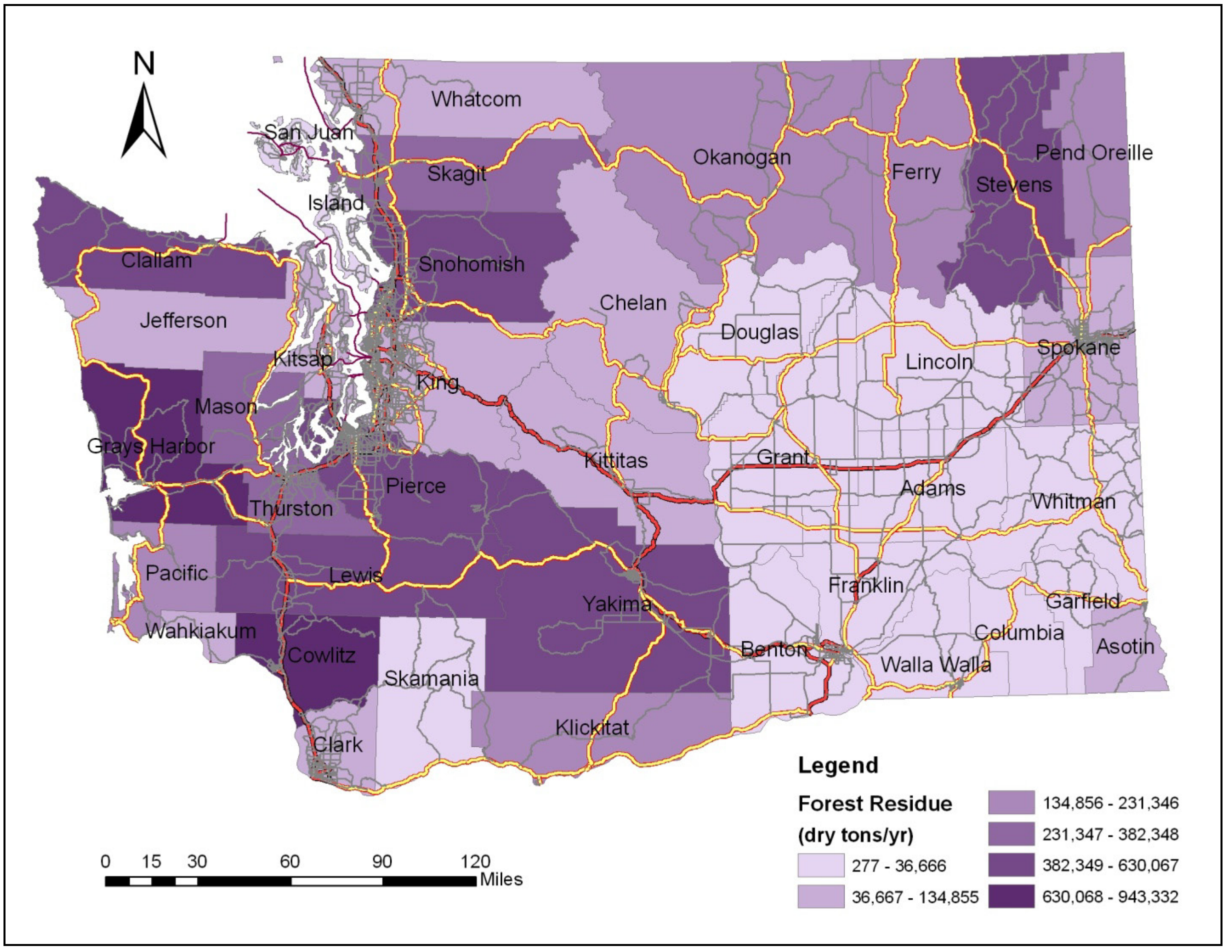


Figure 38: Geographic Distribution of Forest Residue in Relation to the Road Network

Geographic distributions of different types of biomass, such as animal manure, urban wood residues, primary and secondary mill residues, methane emissions from landfills, and domestic wastewater treatment are provided in the Frear et al (2005).

An Overview of Transportation Modes

Only recently has one of the most important considerations for successful and reliable development of the ethanol industry—the economics of transportation—gained proper attention (Morrow et al. 2006). Transportation issues regarding cellulosic feedstock shipments to ethanol processing plants, and outbound shipments of ethanol to blending terminals and to the end-users are the key components for cost-competitiveness of the industry (NADO 2007).

Depending on numerous factors that vary according to the local transportation infrastructure, the mode of transportation for different segments of the biofuels processing may differ (Figure 39). Among others, the main factors include proximity of feedstock sources to biorefineries and blending terminals to markets, size of the shipments, form of the feedstock, and alternative (rail/barge) modes accessibility.

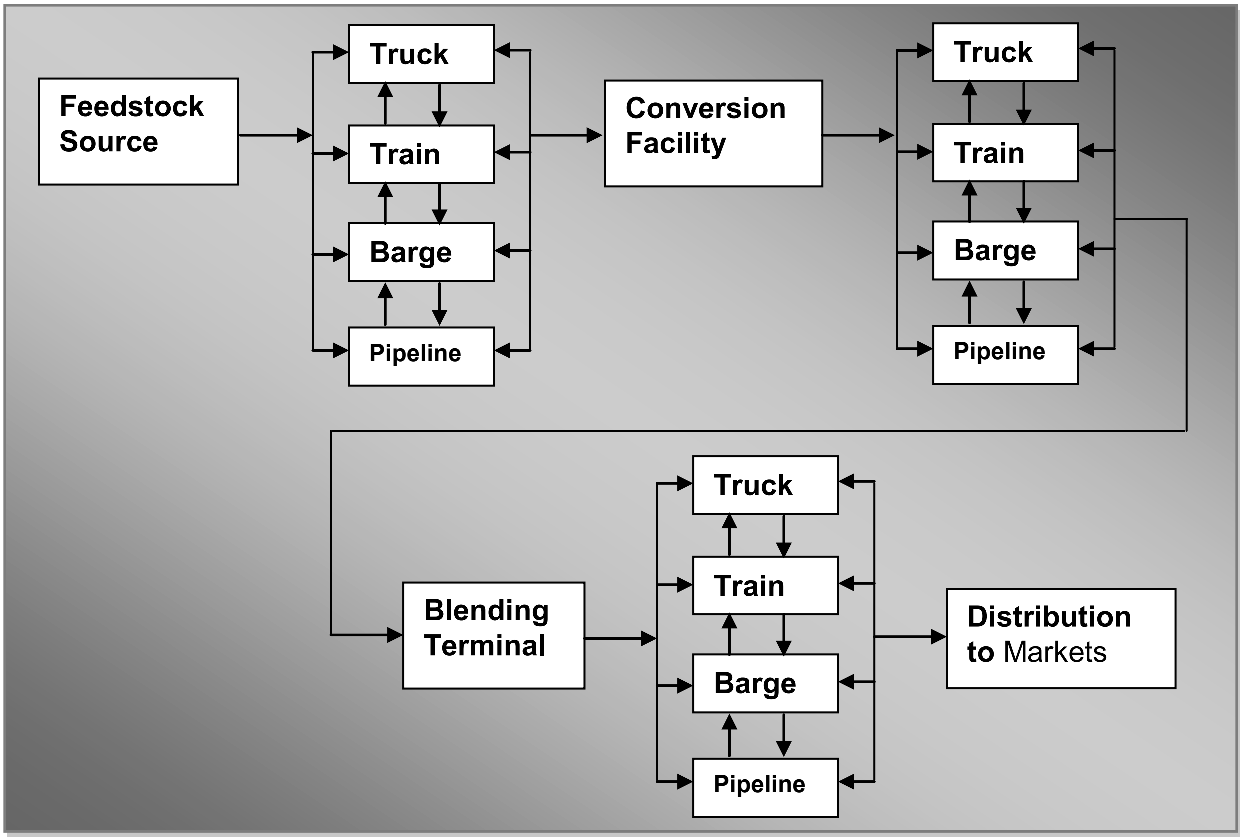


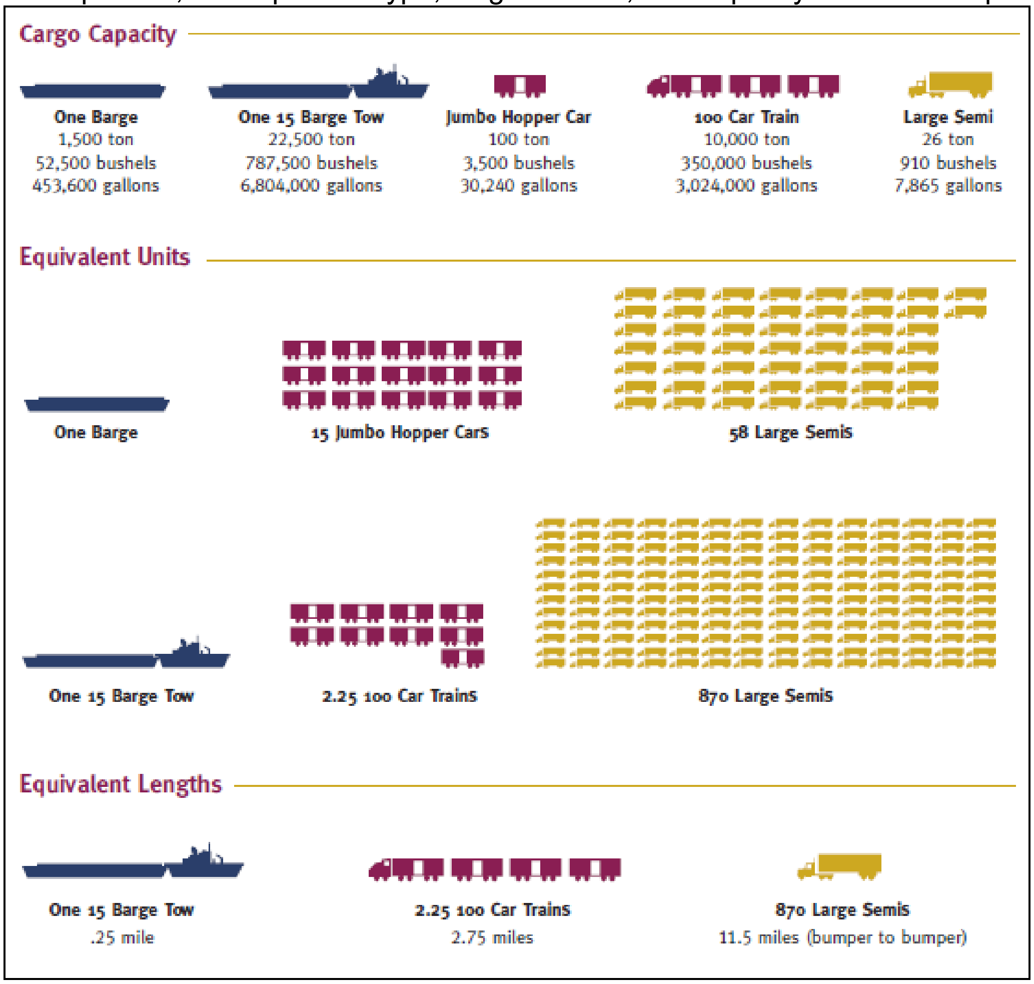
Figure 39: Modes of Transportation for Different Stages of Biofuels Processing

According to the DOE (2003), all of the current biomass and biofuel transportation efficiencies need considerable improvements. Rail transportation can be more cost-efficient for ethanol transportation when certain conditions are met. Large-size processing plants requiring longer-distance shipments (less dependent on time) prefer rail transportation for cost minimization purposes. However, general drawbacks of the rail mode include current shortage of rail tank cars, longer time periods required to fill a unit train (NADO 2007), and high capital costs. Although the rail option can be more efficient for point-to-point shipments, its immobility can directly affect the delivery times (reliability issue) of feedstock to conversion facilities, especially for small and mid-size processing plants (Casavant and Jessup 2007).

If accessibility and some additional conditions are met, waterborne transportation, complemented by truck transportation, can be the lowest-cost option for ethanol transportation from processing plants to the blending terminal segment. According to Stevens (2008) and the Iowa Department of Transportation (2008), one barge tow with capacity of 22,500 tons is equivalent to two and one-quarter 100-car trains or 870 large semi-trucks (Figure 40) Nevertheless, even with its large capacity (beneficial for highway congestion issues) and fuel efficiency, barge transportation has numerous limitations concerning accessibility, speed of delivery, and its aging infrastructure (Stevens 2008).

Other options, such as pipeline transportation, have been investigated as an alternative to reduce traffic congestion created by feedstock hauling trucks and to minimize processing costs. Most notably among others, Kumar et al. (2005) compared the cost of transporting corn stover by truck and pipeline (on a wet basis) at 20% solids concentration. As suggested by the authors, a wide variation of previously reported trucking costs made the comparison useful only with the mid-range of variable trucking costs ($0.1167 per dry-ton-kilometer). Under this scenario, pipeline transportation revealed a 20% reduction in transportation costs for the plant with the capacity of 1.4 million dry tons per year (~105 MGY). However, transportation modes such as pipelines require more technological investigation (due to ethanol's water-attracting characteristic) to make the system operational (McCormick et al. 2003).

Casavant and Jessup (2007) categorized economic attributes including cost, market coverage, degree of competition, traffic/product type, length of haul, and capacity of truck transportation.



Source: Iowa Department of Transportation (2008).

Figure 40: Truck, Rail, and Barge Mode Carrying Capacity Comparisons

Combined with service attributes that involve speed, availability, consistency/delivery time, loss/damage, and flexibility, truck transportation is by far the most flexible option for feedstock transportation. For the purposes of transportation cost analyses in this study, only truck transportation is considered.

Feedstock Production and Transportation

The delivered cost of feedstocks contains collection and transportation cost components. The collection or harvesting part is a function of several considerations, including resource availability, equipment used, and harvesting methods. Loading, transporting to a nearby storage facility, and unloading are oftern included in the harvesting costs. The feedstock transportation costs from sources (fields or storage facilities) to conversion facilities are included in the feedstock transportation part of the delivered cost. Because of a variety of factors involved in the process, the previous literature suggests a range of feedstock farm-gate costs.

Given the geographic distribution of the cellulosic biomass, such as crop residue in the state, the marginal delivered cost of the feedstock is expected to increase for larger-capacity processing plants because the hauling distances become longer. Although for a specific feedstock the collection costs may be comparatively similar from one geographic area to another, longer-distance transportation directly affects the delivered cost of the feedstock. This is explained by increasing feedstock demand required to support larger-capacity conversion plants.

<u>Feedstock Collection Characteristics</u>

Agricultural Crop Residue

One of the commonly accepted methods to derive feedstock supply curves that include both harvesting and transportation cost calculations is a spreadsheet-based model. Sokhansanj et al. (2006) developed the spreadsheet-based Integrated Biomass Supply Analysis and Logistics (IBSAL) model that incorporates weather conditions to calculate corn stover collection costs using the baling system. Consisting of a four-step operation, including combining, shredding, baling, and stacking, the overall cost of stover harvesting was found to be $23.27 per dry ton. Assuming flat-bed trailers carrying about 36 rectangular bales, and front-end loaders equipped with special bale grabbers for loading/unloading and stacking the bales, the IBSAL model simulation resulted in $35.76 per dry ton transportation cost for travel distances ranging from 32 to 160 km. Since the distance of feedstock transportation directly influences delivered costs, many spreadsheet-based estimates in the previous research reports were found for only specific haul-destinations.

Sokhansanj and Turhollow (2002) examined two methods to calculate corn stover collection baseline costs. Assuming a fully mechanized harvesting and transport system, and a five-mile distance to the storage, costs for collecting corn stover residue totaled $19.70 and $21.40 per dry ton for round and for rectangular bales, respectively. The difference in cost was explained by the additional operation and higher equipment cost for the rectangular baling system.

Another feedstock recovery method that recently gained attention is preprocessing of feedstocks before transporting to processing facility. Atchison and Hettenhaus (2003) introduced innovative methods for calculating harvesting, storage, and transportation costs of corn stover. To account for collection delays, feedstock drying and densification methods were investigated, which were found to increase costs from $35 to around $50 per dry ton. In comparison with baling, the one-pass harvest method resulted in a significant cost reduction.

Depending on the yield, net returns to a farmer were $22 to $47 per acre, while baling totaled $16 to $22 per acre for the same harvesting area.

Comparing rail and truck efficiencies, Atchison and Hettenhaus (2003) emphasize the limitations of rail transportation depending on local infrastructure situations/constraints. However, if the feedstock supply area is economically expanded (up to a 300-mile distance) by locating additional harvesting sites, the collection costs using rail transportation were found to be in the $3 to $10 per dry ton range, compared to more than $15 per dry ton for the trucking option.

Perlack and Turhollow (2002) investigated the logistics of four different methods to estimate harvesting, handling, and transporting costs of corn stover to a biorefinery. The authors assumed conventional equipment for baling, and trucks and flat-bed trailers for the transportation of collected stover to a storage. Large round and large rectangular baling methods resulted in costs of $44 to $49 per dry ton for harvesting, storage, and haulage, including procurement costs.

Perlack and Turhollow (2002) introduced an economic engineering assessment of corn stover harvesting and transportation for 500 to 4,000 tons per day-capacity ethanol processing facilities. The study considered fast tractors transferring large bales of corn stover from fields to storage, which then were hauled to a biorefinery using flat-bed trailers carrying 29 large bales. The feedstock costs for several biorefinery capacities were investigated to understand the economies of scale associated with processing costs. However, the feedstock delivery distances were calculated using a straight-line method from field to a biorefinery with a road winding factor, which partially eliminates local road infrastructure characteristics. According to this study's findings, the delivered cost of stover increased from $44.80 to $53.70 per ton for the 500 and 4,000 tons per day-capacity biorefineries, respectively.

Another research paper (Sokhansanj and Fenton 2006) developed a dynamic model to simulate harvesting and transportation costs for crop residues and switchgrass incorporating four different collection options. According to these researchers, baling is the most common and widely used method for crop residue harvesting.[5] Factors affecting the size and mode of transportation include the frequency of biomass supply to a biorefinery, the density of biomass, proximity of the biomass source to the biorefinery, and the transportation infrastructure between biomass sources and the processing plants. They found that the biggest impact on the transportation mode decision is ascribed to the physical form and quality of the biomass.

Jenkins et al. (2000) used surveys and time-and-motion studies to evaluate performance and economics of rice straw harvest, transport, and storage systems for industrial applications. Analyzing three types of bales, the study found that total harvest costs range from as low as $7.50 to a high of $42.79 per ton of rice straw. The large bales had an average total harvest cost of $12.77 per dry ton. Transportation costs for the large bales (assuming flat-bed trailers with19-ton payloads) had been estimated as $9.10 per ton for a 32-km one-way haul distance. This cost included loading and unloading costs accounting for $4.58 per ton of straw and a distance-dependent cost of $0.14 per ton-kilometer.

[5] A procedure for the crop residue harvesting slightly differs from corn stover operations, since a combine is processing most part of the straw. In the case of corn stover, the majority of the corn stalk is left on the ground, and is then shredded and made ready for baling.

Switchgrass and Short-Rotation Woody Crops

Kumar and Sokhansanj (2007) used the previously developed spreadsheet-based method (Sokhansanj et al. 2006) to model three biomass collection and transportation systems for switchgrass. Delivered costs to a biorefinery with the capacity of 1,841 dry tons per day totaled $44 to $47 per dry ton for both round and square bales. Loafing, chopping-piling, and chopping-ensiling methods resulted in $37, $40, and $48 per dry ton, respectively. Comparable results ($40 per dry ton) for the switchgrass farm-gate costs were found in McLaughlin et al. (2002). According to the authors, switchgrass is an economically feasible feedstock and will significantly contribute to biofuel industry advancements.

Graham et al. (1997) summarized nationwide county-level energy crop yields, acreage of land suitable for energy crops, and farm-gate price predictions from the Oak Ridge Energy Crop County-Level (ORECCL) database. The average farm-gate price for short-rotation woody crop (SRWC) production in the state of Washington was predicted to be $86.13 per dry ton, emphasizing aforementioned variation in research conclusions.

Harvesting and Transportation Costs Comparison

As mentioned eariler, there is a wide disparity in previous research recommendations on the feedstock supply system cost components. In the harvesting component, the variation partially depends on methods and equipment used, and processing plant size assumptions. Generally comprised of combining, shredding, baling and stacking operations, feedstock harvesting costs were found to be in about the $14 to $35 per dry ton range. Table 3 summarizes harvesting costs considering different harvesting methods found in selected papers.

Table 3: Harvesting Costs (per Dry Ton)

<table>
<tr><th>Author/s Name</th><th>Feedstock Name</th><th colspan="5">Harvesting Options/Methods</th></tr>
<tr><td rowspan="2">Kumar and Sokhansanj (2007)[a]</td><td rowspan="2">Switchgrass</td><td>Square Bales</td><td>Round Bales</td><td>Loafing</td><td>Chopping-Piling</td><td>Chopping-Ensiling</td></tr>
<tr><td>$24.10</td><td>$22.62</td><td>$13.67</td><td>$14.81</td><td>$22.63</td></tr>
<tr><td rowspan="2">Sokhansanj et al. (2006)</td><td rowspan="2">Stover</td><td colspan="5">Baling[b]</td></tr>
<tr><td colspan="5">$19.16[c] (21.12 $ Mg^{-1})</td></tr>
<tr><td rowspan="2">Sokhansanj and Fenton (2006)</td><td rowspan="2">Switchgrass and Crop Residues</td><td>Square Bales</td><td>Loafing</td><td>Chopping Dry – Piling</td><td colspan="2">Chopping Moist – Ensiling</td></tr>
<tr><td>$23.72</td><td>$19.69</td><td>$35.71</td><td colspan="2">$35.12</td></tr>
<tr><td rowspan="2">Sokhansanj and Turhollow (2002)[d]</td><td rowspan="2">Corn Stover</td><td colspan="2">Round Bales</td><td colspan="3">Rectangular Bales</td></tr>
<tr><td colspan="2">$19.70</td><td colspan="3">$21.40</td></tr>
<tr><td rowspan="2">Perlack and Turhollow (2002)[e]</td><td rowspan="2">Corn Stover</td><td>Large Round Bales</td><td>Large Rectangular Bales</td><td>Unprocessed Pickup – High Cost</td><td colspan="2">Unprocessed Pickup – Low Cost</td></tr>
<tr><td>$24.80</td><td>$22.25</td><td>$26.80</td><td colspan="2">$21.67</td></tr>
</table>

[a] Calculations did not include production costs such as machinery operations, seeds, fertilizers, lime, herbicides, land charges, reseeding, etc.
[b] Harvesting methods were not specified.
[c] The value was converted from \$ Mg^{-1} to \$/ton using 1.102 conversion rate.
[d] See the paper for additional assumptions.
[e] Calculations include delivery to a storage for the facility with 4,000 dry tons per day processing capacity.

Table 4 provides estimates from recent research literature on transportation costs considering fixed and variable haul distances. Many of these studies estimated the amount of feedstock availability within a given straight-line radius around biorefineries by assuming average yields and average production costs for the entire study area. The variation in feedstock transportation costs ranging from around \$7 to \$29 per dry ton can partially be explained by the different haul distance and truck configuration assumptions.

Table 4: Transportation Costs (per Dry Ton)

Author/s Name	Feedstock Name	Harvesting Options/Truck Configurations			
Kumar and Sokhansanj (2007)[a]	Switchgrass	Load Bale – Truck (Stationary Grinder) \$21.19	Bale or Loaf is Ground (Mobile Grinder) – Truck \$23.19		Ground Biomass (Pile or Silage) – Truck \$25.32
Sokhansanj et al. (2006)[b]	Stover	Rectangular bales are placed on the trailers using bale grabbers \$29.45 [c] (32.45 \$ Mg^{-1})			
Sokhansanj and Fenton (2006)[d]	Switchgrass and Crop Residues	Large square bale – flat-bed trailer (variable distance: 20–100 km) \$19.41		Large square bale – flat-bed trailer (fixed distance: 100 km) \$25.83	
Perlack and Turhollow (2002)[e]	Corn Stover	Large Round Bales \$10.06	Large Rectangular Bales \$10.62	Unprocessed Pickup – High Cost \$7.32	Unprocessed Pickup – Low Cost \$7.32

[a] The transportation cost includes loading, traveling, and unloading expenses and is averaged over a year.
[b] The transportation cost includes grinding, transporting, loading, and unloading.
[c] The value is converted from \$/Mg^{-1} to \$/ton using 1.102 conversion rate.
[d] The transport operations used for the cost calculation include loading, traveling, unloading, stacking, and grinding.
[e] A facility with 4,000 dry ton/day processing capacity was considered.

Factors that influence delivered feedstocks costs, including weather conditions, proximity of feedstock collection area to biorefineries, and road infrastructure, may differ from one geographic region to another. Therefore, an economic evaluation of transportation costs should account for varying haul distances and local transportation infrastructure.

Crop Residue Collection Process and Costs

Feedstock cost is one of the most important components for analyzing the viability of both corn- and cellulose-based ethanol production. To calculate the cost of agricultural residue harvesting, transportation to storage facility, and the transportation costs to biorefineries, several components have to be considered: 1) physical characteristics of residue: form/condition; 2) field operations: swathing, raking, shredding, baling, stacking, loading, transporting to nearby storage facility, and unloading; 3) equipment used for field operations, its service life, as well as capital costs and maintenance; and 4) wages, tax, interest, and insurance expenses. Figure 41 shows the feedstock collection process for five different collection methods for agricultural crop residue, modified from Sokhansanj and Fenton (2006).

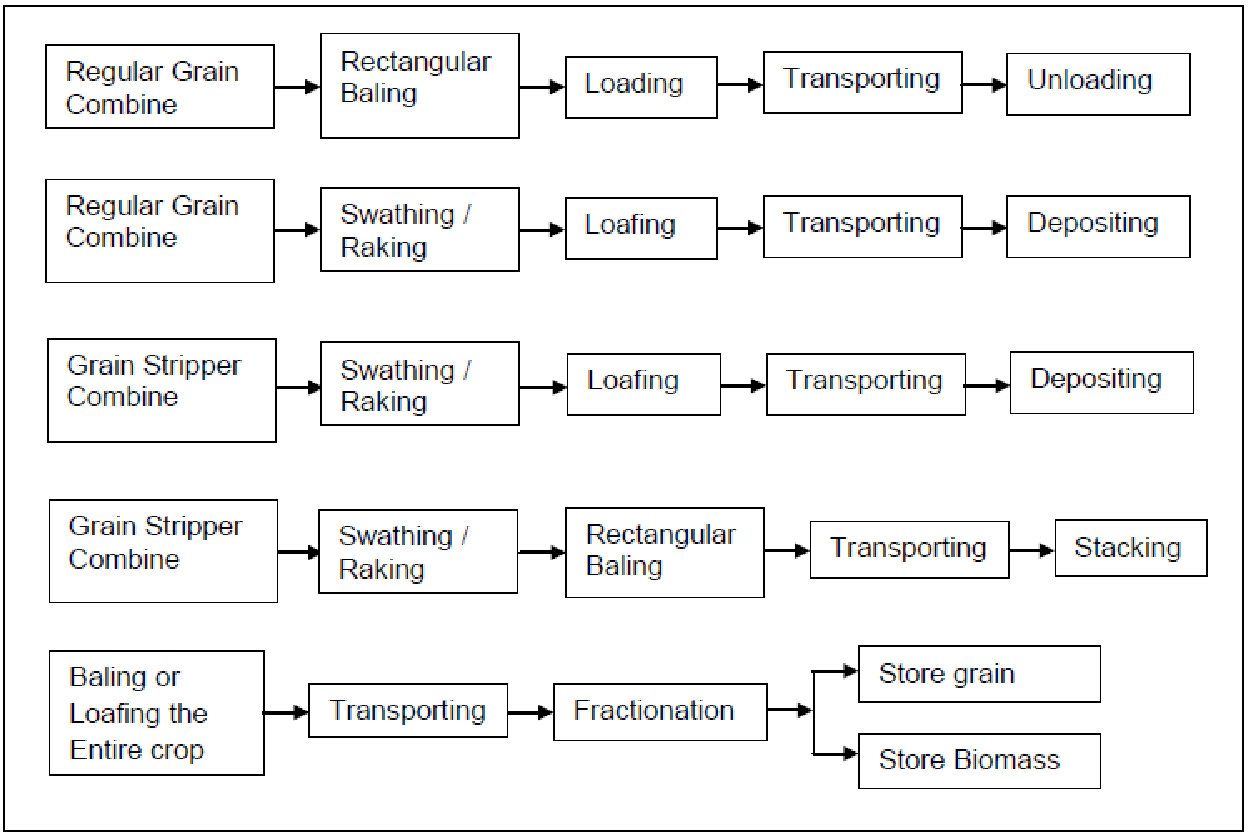


Figure 41: Collection Methods for Agricultural Crop Residue (Straw)

The straw is ready for harvesting as a feedstock for biofuel processing after the grain harvest. Using a regular grain combine, two methods are presented in the flowcharts: baling and loafing. Similar to a regular grain combine, baling and loafing operations can be performed using a grain stripper combine.[6] The raking operation (when applicable) is used before baling when straw height is less than 0.15 m. Raking forms windrows from swathed straw, which allows catching more wind and thus allows quicker drying. It also increases the volume of straw to be processed

[6] The grain stripper uses rows of polyurethane plastic teeth to strip grain from stems, and leaves the stems rooted in the ground.

by the baling equipment. Figure 42 provides similar flowcharts for four corn stover harvesting methods.

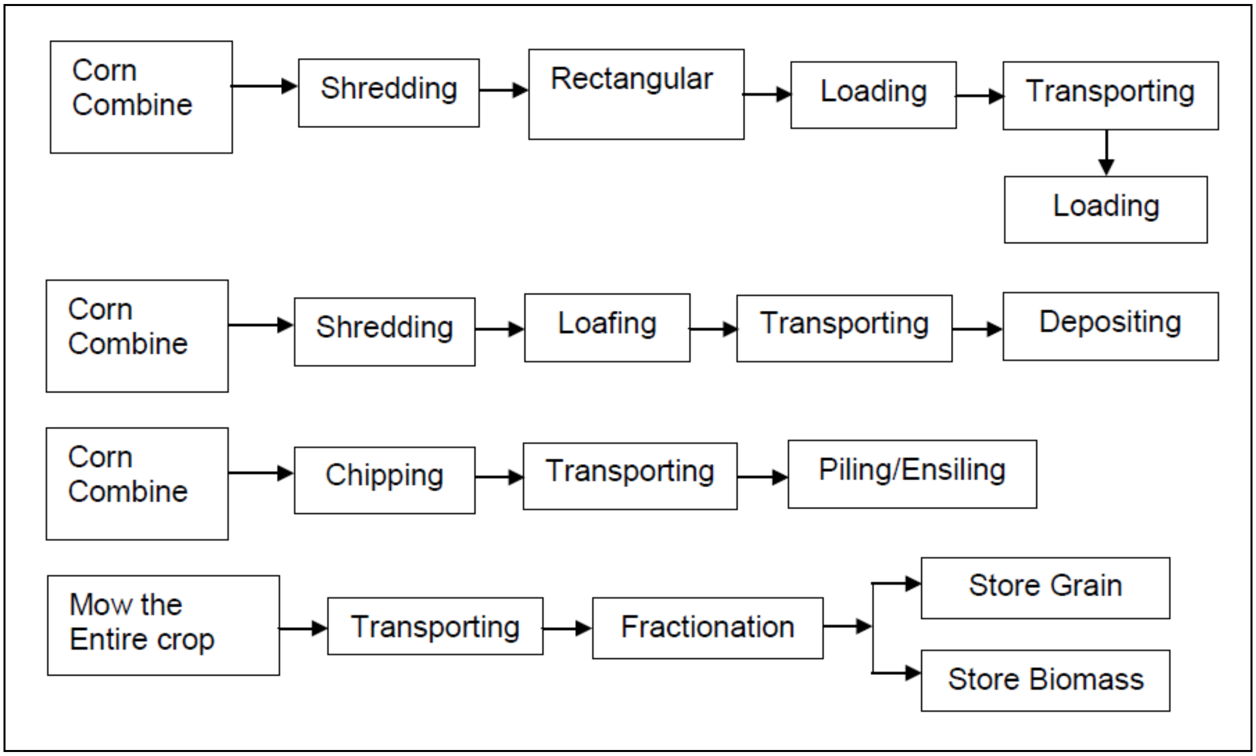


Figure 42: Collection Methods for Agricultural Crop Residue (Corn Stover)

Generally, the rectangular or round baling option is found to be the most accepted method for straw harvesting (Cundiff 1996). Within those two options, considering an economic feasibility of feedstock transportation to biorefineries, rectangular bales are more convenient for flat-bed trailer loadings. The dimensions of conventional types of bales used for commercial straw harvesting are presented in Table 5.

Table 5: Predominant Bale Types, Dimensions, Volume, and Weight

Bale Type	**Dimensions (m)**	**Volume (m^3)**	**Weight (~kg, dry matter)**
Small Rectangular	0.4 × 0.6 × 1.2	0.3	32
Large Rectangular (Hesston Type)	1.2 × 1.2 × 2.4	3.5	600
Large Rectangular (Freeman Type)	0.9 × 1.2 × 2.4	2.6	450

Source: Jenkins et al. (2000).

Depending on moisture level, the speed and capacity of swathing and raking operations may differ. Due to the relatively light weight of the equipment, soil moisture affects the speed of the operation less than the straw moisture (Jenkins et al. 2000). The relationship between soil/straw moisture and the speed of different operations, such as raking, swathing, and baling is shown in Table 6.

Table 6: Seasonality of Straw/Soil Moisture and Harvesting Operations Speed

Operation	Straw Moisture (% w.b.)[1]	Soil Moisture (% w.b.)	Average Speed (mile/hour)
Raking			
Fall	19	18	6.96
Spring	11	32	4.47
Swathing			
Fall	29	21	3.35
Spring	12	24	1.5
Baling			
Fall, small bales, $0.4\times0.6\times1.2$	11	19	2.42
Fall, large bales, $0.9\times1.2\times2.4$	10	28	3.97
Fall, large bales, $1.2\times1.2\times2.4$	12	18	4.03
Spring, large bales, $1.2\times1.2\times2.4$	11	24	5.22
Road-Siding			
Fall, small bales, $0.4\times0.6\times1.2$	9	15	–
Fall, large bales, $0.9\times1.2\times2.4$	11	29	–
Fall, large bales, $1.2\times1.2\times2.4$	12	22	–
Spring, large bales, $1.2\times1.2\times2.4$	11	–	–

Source: Jenkins et al. (2000)
[1] Wet basis percentage.

The loafing method shown in the flowcharts above differs from baling by forming large stacks of straw. One of the advantages with the loafing option is that the harvesting, densification, and transportation to the storage area are performed with one piece of equipment. Note that if the grain stripper combine is used with the baling option, then the loading, transportation, and unloading steps are the same as baling with the regular grain combine described above.

Simultaneously with the baling operation, a bale accumulator collects the bales in groups of four and transports them to a nearby storage facility. Another method used for bale collection from fields is road-siding, which essentially is a process of moving the bales from the field to the edge of the field. Both of these operations are included in the transporting part depicted in the collection methods flowchart. In the next step of the process, the bales are loaded with a front-end loader onto flat-bed trucks and transported to the storage facility.

The Feedstock Harvesting and Transportation section includes figures with the equipment discussed in the crop residue harvesting process.

The most common truck configurations used for transporting the bales to storages are trucks with flat-bed or drop-bed trailers. Due to an additional space, drop-bed trailers carry more payload compared to flat-bed trailers. On average, semi-trucks with flat-bed trailers can carry up to 20 tons payload weight with large Freeman-type large bales. At the storage facility, bales are unloaded using loader equipment. Table 7 shows the relationship between bale size and payload, average loading/unloading time, as well as travel speed and time.

Table 7: Characteristics of Bale Transportation to Storage Facility

Bale Dimensions (meter)	Number of Bales	Payload (Mg)	Average Loading Time (min)	Average Travel Distance (mile)	Average Travel Time (min)	Average Travel Speed (miles/hour)	Average Unloading Time (min)
Double Flat-Bed Trailer							
Small $0.4 \times 0.6 \times 1.2$	460–512	14.5	32	91.3	122	44.7	22
Large $0.9 \times 1.2 \times 2.4$	42–48	18.1	15	8.7	17	31.7	16
Large $1.2 \times 1.2 \times 2.4$	28–30	16.3	21	155.4	188	49.7	14
Double Drop-Bed Trailer							
Large $1.2 \times 1.2 \times 2.4$	36–38	19.1	29	28	41	41	31

Source: Jenkins et al. (2000)

A direct relationship exists between farm equipment repair and maintenance costs and their lifetime hours of operation. Figure 43 shows the relationship between tractor lifetime hours of operation and total repair costs, based on Edwards (2002) data. This may suggest that for the short term, new equipment purchase increases capital investments, but for the long run (as shown in Figure 43), significant savings in terms of relatively low repairs costs may be gained.

At a given level of operation hours, a four-wheel-drive tractor accumulates less repair expenses compared to a two-wheel-drive tractor. After around 4,500 hours of operation, the rate of repair costs as percentage of a new list price significantly increases for both two- and four-wheel-drive tractors, as well as for baling and swathing equipment.

Field activity average costs were derived using an economic engineering approach, combined with the survey data by Sokhansanj and Turhollow (2002) and Jenkins et al. (2000). The results for both large and small rectangular bales are summarized in Table 8. Images of feedstock harvesting machinery and transportation can be found in the Feedstock Harvesting and Transportation Efficiencies section of the supplemental material. Based on our calculations (Table 8) and the estimates found in the recent literature, in this study the agricultural crop residue is considered to be available at $30 per dry ton farm-gate cost.

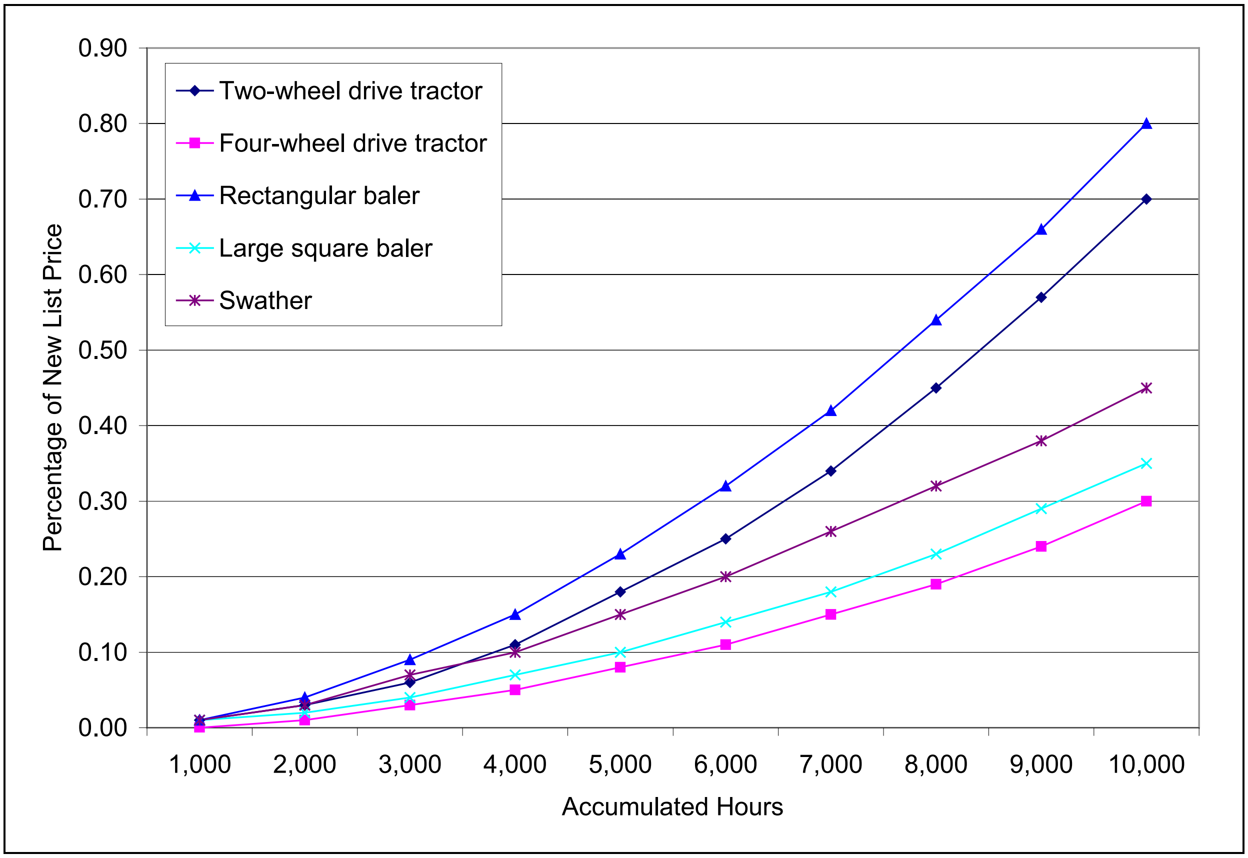


Figure 43: Lifetime Hours of Operation and Repairs Costs as Percentage of New List Price

Table 8: Agricultural Crop Residue Harvesting and Transportation to Storage Facility (Average Costs)

Operation/Activity	Costs ($/ton)	
	Large Rectangular Bales	Small Rectangular Bales
Swathing	5.51	4.80
Raking	1.70	1.70
Baling	10.80	9.66
Road-siding	4.54	4.54
Loading/Unloading	3.30	3.30
Transporting (field storage)[7]	3.32	3.32
Storage (under tarp)	2.26	2.26
Total Costs	31.43	29.58

[7] Transportation cost breakdown/details are provided in the Feedstock Transportation Costs section.

Animal Waste Feedstock Cost

For the purpose of this report, the animal waste feedstock category includes five different manure categories: dairy, cattle, horse, swine, and poultry. Several research papers have attempted to assess the transportation costs and net benefits of using animal manure for crop production. The potential use of animal waste for ethanol processing purposes may change public opinion about health and environmental degradation from increased geographic concentration of manure stacks and odors (Fleming et al. 1998). However, similar to other commodities with low value-mass ratios, the net benefit of manure utilization is influenced by the haul distance and the nutrient content. High transportation costs limit the distance that animal waste can be economically hauled (Keplinger and Hauck 2006). Additionally, the transportation costs are also influenced by timeliness of collection and depth of manure scraping (to keep the dirt content below 60% and moisture content below 20%).

Whittington et al. (2007) conducted an industry survey and reported poultry litter estimates for manure transportation costs in Mississippi. Using the collected data, the authors derived the transportation cost function as follows: $C_m = 0.1 + 0.002 \times D$, where C_m is the per-ton-mile cost of transportation, D is the distance traveled, 0.1 is the fixed cost associated with shipping poultry litter, and $0.002 \times D$ represents the variable costs incurred with the shipment. As mentioned above, manure may be shipped with varying moisture contents. Table 9 provides a summary of manure transportation cost estimates for different moisture contents found in recent literature (Ghafoori et al. 2007; Aillery et al. 2005; Ribaudo et al. 2003).

Table 9: Manure Transportation Costs

Manure	Moisture Content (%)	Variable Cost ($ per-ton-km)	Fixed Cost ($ per ton)
Lagoon Manure	99	0.22	2.31
Slurry Manure	95	0.22	2.31
Dry Manure	50	0.08	11.57

The estimates in Table 9 suggest that lagoon and slurry forms of manure are suitable for short-haul distances. If this type of feedstock can consistently be produced and is available for ethanol processing, localized processing may eliminate high transportation costs. However, moisture-reduced manure is easier to transport (Goodwin et al. 2007). Considering the time sensitivity of feedstock transportation to support consistent ethanol processing, we use dry manure cost estimates (i.e., $11.5 per dry manure[8]) in this report. Goodwin et al. (2007) estimated plastic-wrapped baled poultry litter procurement costs similar to those shown in Table 9. For transportation distances below 150 miles, that study reports $3.35 per mile, and $2.70 for distances more than 150 miles.

Forest Residue Feedstock Cost

More than 50% of the five main feedstock types (crop residue, animal waste, MSW, food packing/processing waste, and forestry residue) identified in Frear et al. (2005) is the forest residue category. To derive a cost estimate for analysis in this report, we used the spreadsheet-based calculator Forest Residues Transportation Costing Model (FRTCM) developed by Rummer (2003). The resulting estimates were compared with estimates published in the recent literature on the economic feasibility of forestry residue collection and transportation.

Graf and Koehler (2000) evaluated the potential for ethanol production in Oregon using cellulosic feedstocks. That study reported the cost of removing and delivering forest thinnings to a facility within a 50-mile radius to be in a range of $28 to $40 per dry ton. The estimates were partially based on information provided by private mill owners in Oregon ($28–$35 per dry ton), and another source (The Quincy Library Group Study) that estimated the "farm-gate" cost of forest residue to be $40 per dry ton.

In this study we modified the default values of the FRTCM calculator to derive the cost of moving biomass from the forest to a site from where it can be hauled to a biorefinery. The flexibility of this model allows estimating biomass loading and hauling (to a site) costs for different combinations of equipment. The estimates were found to be slightly above $40 per dry ton of biomass, if considering haul distance within 25 miles from the site (i.e., from the farm-gate). The second stage of the transportation expenses is included in the feedstock transportation to a biorefinery part.

Municipal Solid Waste Feedstock Cost

Three types of feedstocks were considered under the MSW category: paper waste, food waste, and wood residue. According to Frear et al. (2005), the paper waste category represents about 14% of the total biomass identified in the state. However, food waste and wood residue categories account for only 1.46% and 4.93% of the total, respectively. Because of their relatively low volumes, the food waste and wood residue categories would be suitable as supplemental feedstocks. For purposes of this study, we assumed that about a $25 tipping fee (Graf and Koehler 2000) will be spent on transporting food waste and wood residues to a site (the first stage of transportation expenses). Therefore, in this study the delivered feedstock cost for these two categories includes only the transportation expenses to the biorefinery.

According to Graf and Koehler (2000), the prices for recycled and mixed paper waste ranges from $60 to $125 per dry ton. However, the methodology used to calculate the paper waste availability in the state of Washington considered a combination of the percentage of paper in MSW and recyclables (Frear et al. 2005). Therefore, we assume the "farm-gate" cost of paper to be lower than the estimates found in Graf and Koehler (2000). Several other sources (Baled Waste Paper Spot Market Prices 2009) reported spot market prices in a range of $22.5 to $30 (for mixed paper), $69 (baled corrugated cardboard), to over $200 (for soft white paper) per ton depending on its quality. Based on spot market prices and the estimates found in the literature, in this report we consider $45 feedstock price per dry ton of paper waste.

GIS Studies

Graham et al. (1996) developed a GIS-based modeling system to identify potential and optimal bioenergy feedstock locations. This system was designed to model the supply cost of feedstock (energy crops) taking into account spatial variation of resources. The authors adopted an interdisciplinary approach involving information on land use, soil quality, climate, highway networks, as well as environmental and economic models to determine the marginal cost of feedstock supply from potential locations where energy crops might be grown. As a first step of the four-component modeling, the study mapped the availability of energy cropland in the study area. In the next step, expected yield and a farm-gate cost of the energy crops were defined. Further, the potential farm-gate feedstock supply was identified and the marginal cost of delivery was mapped to the biorefinery destinations. In the last component, the study mapped and ranked the potential biorefinery locations in the study area based on feedstock delivery costs.

Graham et al. (2000) and Zhan et al. (2005) introduced another GIS approach to map the delivered cost surface for a study area that accounted for spatial variation of the factors affecting collection and transportation costs. The study also identified least-cost locations for collecting and transporting biomass to processing plants. Another study involving GIS (Noon et al. 1996) extended and applied GIS-based modeling system to forecast the most promising areas for biofuel processing plants in a specific region. Their results revealed considerable correlation between variation of switchgrass costs (throughout the study area) and biorefinery plant sizing, as well as facility location decisions. Considering consistent construction and labor costs across the study area, the authors found that the delivery cost of the feedstock is the main determinant in the variable cost of the ethanol processing.

Langholtz et al. (2006) conducted a woody biomass feasibility study for 27 counties in the southeastern U.S. states. Detailed explanations were provided about the utilization of the GIS Network Analyst tool to assess the economic feasibility of the woody biomass available in the study area. Taking into account the spatial distribution and variability of the biomass resources, transportation costs were combined with the procurement costs in order to derive the delivered costs.

Feedstock Transportation Costs

An Economic Engineering Framework

Trucking costs can be derived using several cost measurements, such as cost per ton, cost per mile, or cost per ton mile. Depending on the objective of the study, the type of the cost measurement may vary. For the analysis in this study, cost per ton mile measure is used.

The derivation of feedstock transportation costs requires information on factor prices that determine costs of a typical trucking firm (Casavant 1993). Trucking costs can be separated into categories, such as fixed vehicle costs, fixed business costs, and variable costs. Fixed vehicle costs include expenses such as depreciation and licenses for both truck and trailer. Fixed business costs consist of management, insurance, housing, taxes, and interest cost components. Variable costs for a truck include expenses associated with drivers' wages, fuel expense, repair and maintenance, and tires; the trailer part of the variable costs includes repair, maintenance, and tire-related expenses (Figure 44). To understand the derivation of the total trucking costs with an economic engineering approach, each of the cost components is briefly discussed in the following paragraphs. Further, these values will be used to derive the total trucking costs, which in turn will be used for the feedstock transportation cost calculations and feedstock supply curve constructions.

Variable Costs

Variable costs vary with the number of trips or distances driven by trucks. For instance, long-distance trips require more fuel, more driver wages, more repair costs, and result in quicker tire wear-out. The following part of the Variable Costs section provides descriptions for each of the cost components, which are summarized in the Total Costs per Ton Mile section of this report.

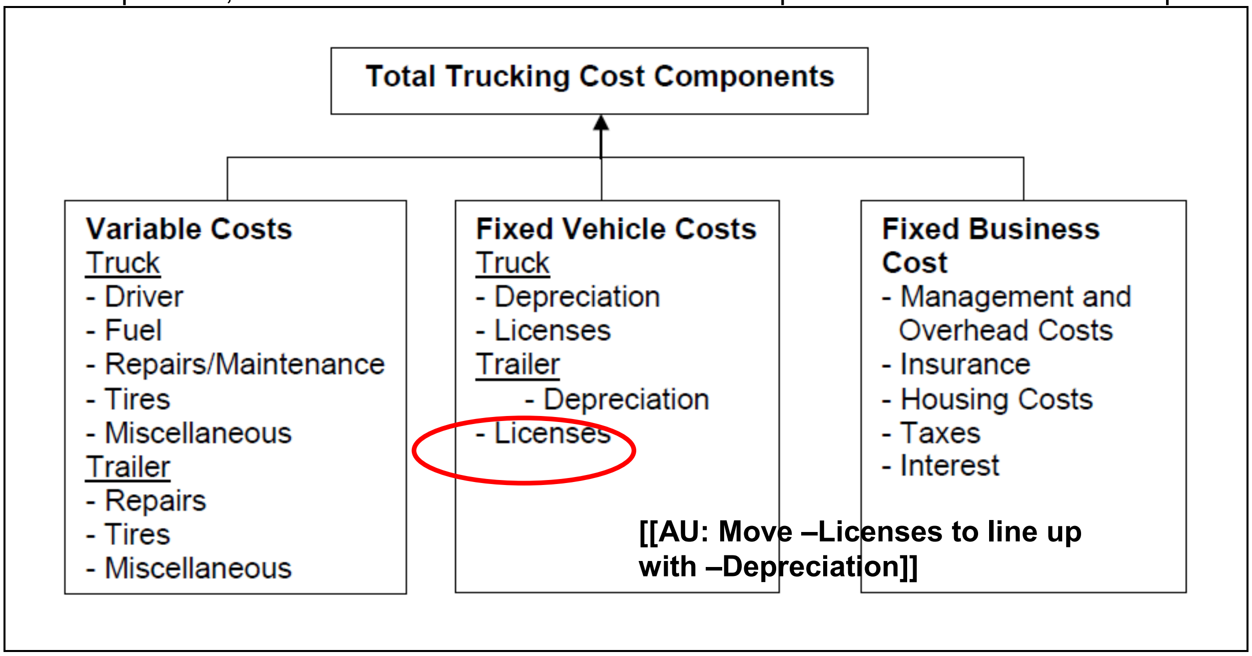


Figure 44: Total Trucking Cost Components

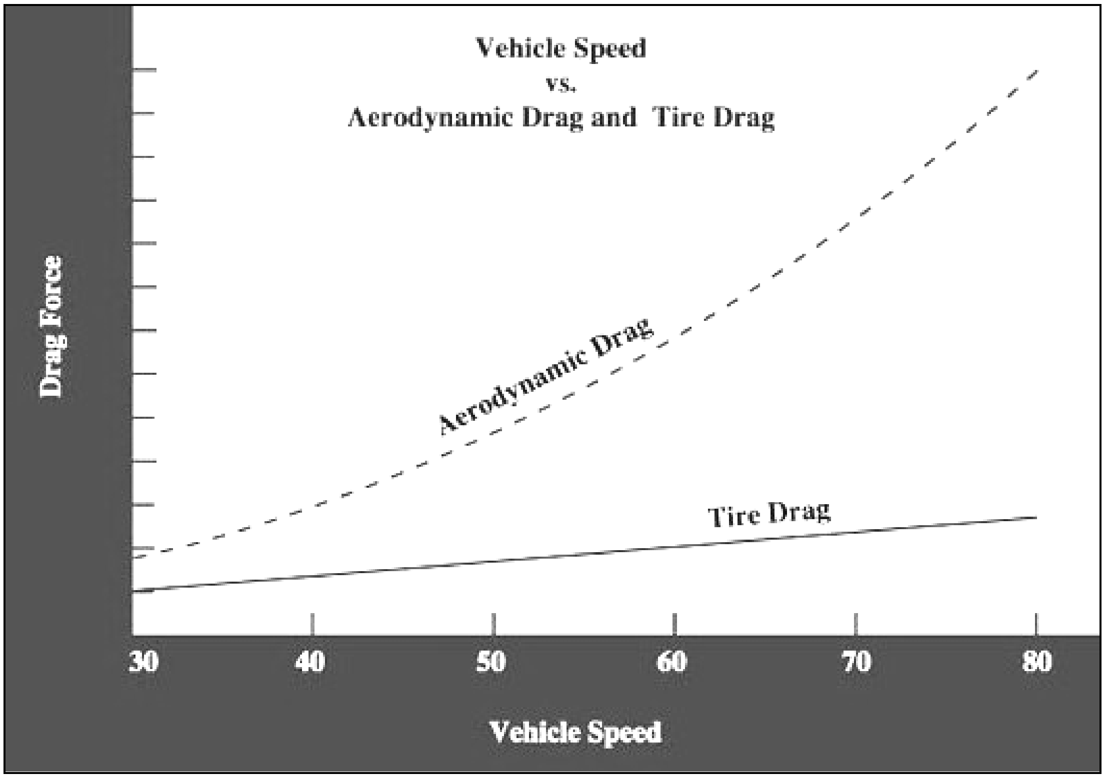
Driver Wages

Similar to the various measurements for trucking costs, driver wages may have different forms, such as a percentage of the freight bill, or based on number of trips, hours of drive time, or mileage driven (Casavant 1993). The most accepted measure, a time-based wage, was considered for the analysis in this study. Driver wages may also vary depending on the type of the haul (short haul: the driver is home every night; long haul: requires overnight trips).

As reported by the U.S. Bureau of Labor Statistics, classified as Truck, and Heavy Truck-Trailer Drivers, the average hourly wage was $17.41 in 2007 (U.S. Department of Labor 2007). Sometimes a combination of haul distance and hours of operation are used to determine driver wages. For instance, in addition to per mile pay, driver wages for the haul distances over 60 miles may include time of loading and unloading activity. According to the findings from a truck costing model for grain transportation reported by Trimac Consulting Services (Trimac 1999), depending on truck configuration and local infrastructure, per mile wages may range from 18 to 28 cents. Most per mile driver wages for truck and trailer configurations were observed within the 26 to 28 cents range, occasionally reaching 30 to 32 cents per mile. Considering 45- to 60-mph driving speed, these estimates are closely comparable with the rates provided by the U.S. Department of Labor (2007) report.

Fuel Cost

With current crude oil prices (EIA 2008c), fuel costs are considered (as shown in the sensitivity analysis in the Total Cost per Ton Mile section) to be one of the most significant components of the variable costs. In addition to the fuel price itself, several very important factors affecting a truck's fuel economy include its payload weight, tire pressure (affected by vehicle gross weight and tire rolling resistance), tire type, vehicle aerodynamics (affected by vehicle speed, truck's front area and shape), and traffic congestion. Figure 45 below shows the relationship between the vehicle driving speed and both aerodynamic and tire drag force levels, which (drag forces) may influence/increase the vehicle fuel consumption.



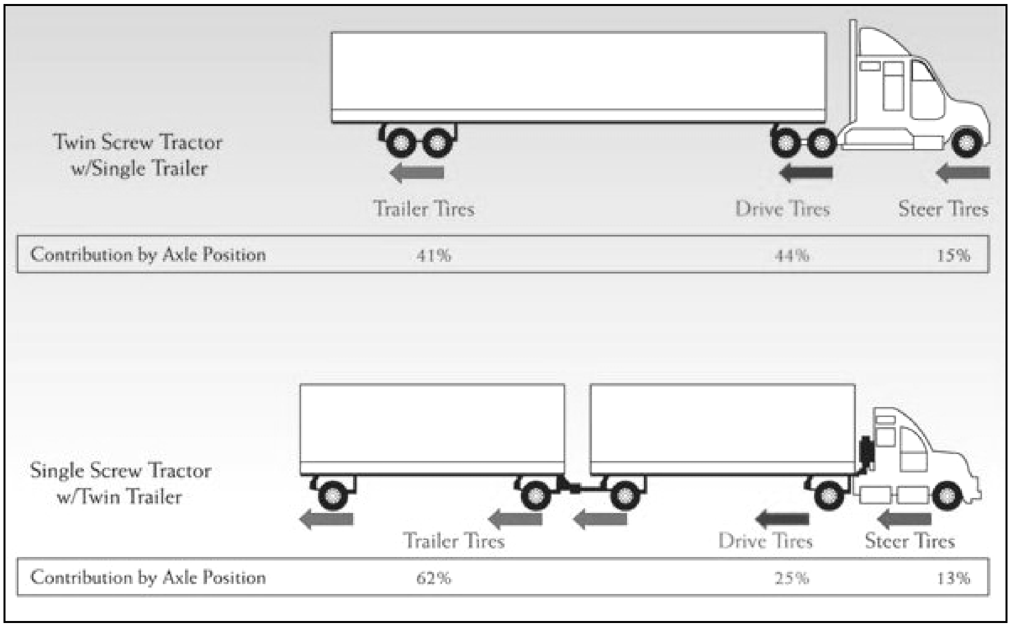
Source: Goodyear Tire & Rubber Company, Commercial Tire Systems (2008)

Figure 45: The Relationship between Vehicle Drive Speed and Drag Force

Depending on different truck configurations, the fuel economy also depends on factors such as the drag force distribution between steer, drive, and trailer tires (Goodyear Tire & Rubber Company 2008). For instance, according to Figure 46, 85% of the tire rolling resistance is attributed to drive and trailer tires (truck and trailer configuration), or 87% in the case of a truck and double trailer. Information on tire rolling resistance distribution between steer, drive, and trailer tires helps in identifying axle groups that contribute to the vehicle fuel consumption level.

According to a recent DOE report by Kodjak (2004), as well as the University of Washington and Washington State University Log Trucking Study (2008), trucking firms reported an average of 5.5 miles per gallon fuel efficiency. For time-based trucking cost derivation, fuel costs can be calculated by combining an average price of diesel $4.50 per gallon (EIA 2008c), 45-mph average driving speed, and 5.5 miles per gallon fuel efficiency. Using year-to-date average diesel prices (EIA 2008c), fuel costs reach $36.80/hour. [9]

[9] Fuel Expense per hour of Drive = [fuel price x (mph / fuel efficiency)] = 4.50 ($/gal) x 45 / 5.5 (gal/hr) = $36.80/hr.



Source: Goodyear Tire & Rubber Company, Commercial Tire Systems (2008)

Figure 46: Truck and Trailer Tire Drag Force Distribution

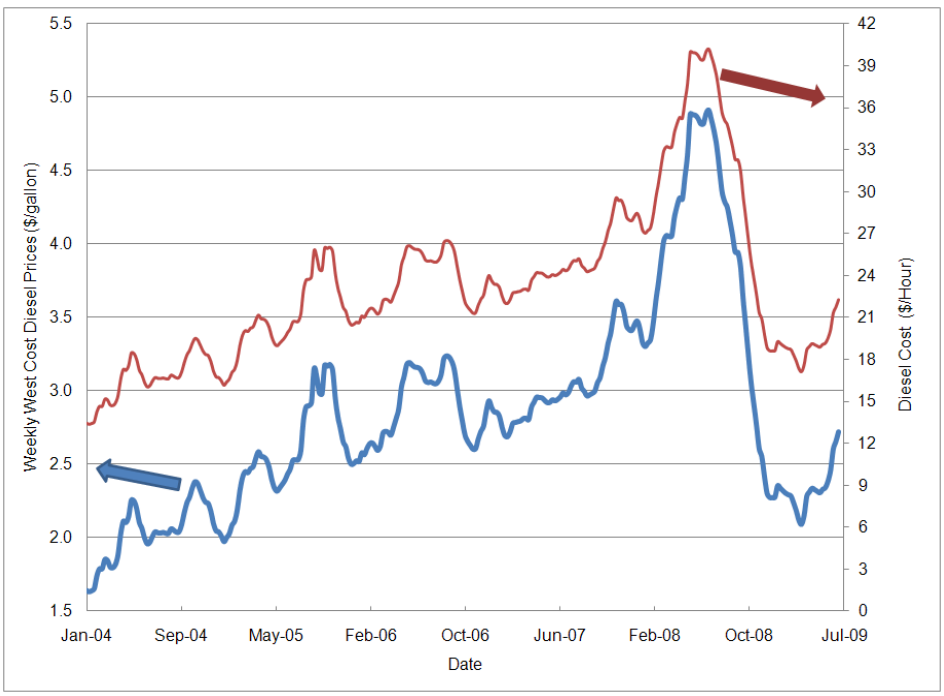


Figure 47: Weekly West Cost Diesel Prices

Figure 47 shows the relationship between weekly diesel prices and per hour diesel costs. Annual fuel expenses for purposes in this study were calculated using the following formula:

Further, depending on the necessity, the annual costs can be converted to per mile, per ton, or per ton mile basis. To measure the effects of the increasing fuel prices on trucking costs, a diesel price sensitivity analysis was conducted and is discussed in the Total Cost per Ton Mile section. A sensitivity analysis is useful to examine the variation of the delivered cost of a biofuel under investigation based on petroleum fuel price fluctuations.

Repair and Maintenance Cost

Repair and maintenance costs may differ depending on the drivers' ability to make some of the repairs on their vehicles, which makes the calculation of this cost component difficult. The total repair and maintenance costs include lubrication, engine repairs, tune-ups, and other part repairs. There are several factors that may lower repair costs, including relatively flat geography, the initial newer condition of the purchased vehicle, as well as the number of daily operation hours and even different management policies. Repair costs per vehicle are lower for trucking firms owning big fleets of trucks, since labor (repair/maintenance) costs are spread over many vehicles and parts are obtained at the wholesale rate. On the contrary, smaller firms may spend more on a labor force that serves only few vehicles, and usually purchase parts at usual commercial rates. The lubrication portion of the repair and maintenance annual costs per truck is calculated by assuming 10% of fuel costs mentioned earlier:

The annual repair costs (further converted to per ton mile measure) were calculated using a $0.17 per mile repair cost estimate obtained from Trimac Consulting Services (Trimac 1999), and information on annual miles driven by each truck was obtained from the University of Washington and Washington State University Log Trucking 2008 Study:[10]

Tire Cost

Tire cost calculations are relatively straightforward. Although the lifetime mileage of truck tires varies depending on the placement (drive, steer, and trailer), for the purposes of this study an average lifetime per tire was used. Ten tires costing $400 each, with 60,000 average lifetime miles per tire for the truck, and eight tires with the same purchase price with 72,000 average lifetime miles for the trailer were considered for calculating the tire cost component (University of Washington and Washington State University Log Trucking Study 2008). Further, incorporating 20-ton average payload weights, the tire costs per ton mile were derived:

[10] 1999 conversion rate for USD: CAD was used for converting into US dollars; the distance measure was converted from kilometers to miles. Annual miles driven are calculated assuming three relatively short haul trips per day (50 miles one way), or two trips at 75 miles one way per day.

Fixed Vehicle and Business Costs

The fixed vehicle costs change with the size of the fleet owned by the trucking firm, while mileage driven does not alter them. Expenses such as depreciation and annual license fees increase with the number of trucks in a fleet. Fixed business costs for a typical trucking firm include insurance, garaging costs, taxes, and interest.

Depreciation

Depreciation is a cost resulting from wear or aging of machinery over time. Trucking firm equipment costs are associated with trucks and trailers. The magnitude of the wear may lower the value of the equipment above or below the current market price of similar equipment. The depreciation cost is significant when equipment with newer technology is introduced in the marketplace (Edwards 2002). An economic engineering approach considers either aging or the estimated useful life years of the equipment as a basis for calculating depreciation costs. For the purposes of this study, 10 years of truck and trailer ownership was considered.

Another component needed to calculate depreciation is a salvage value of the equipment—an estimated value of the truck and trailer (in this case) at the end of the useful or accounting period. Based on salvage value as percentage of the new list price of machinery (provided in the Trucking Cost Calculation section) and 10 years of equipment ownership, the salvage value was calculated as a 26% of the new list price of the truck and 35% for the trailer. Further, the annual depreciation was calculated as a new list price less the salvage value of the truck and trailer over years of ownership:

License and Tax Fees

License and tax fees differ from state to state, by mileage driven, and by the type of commodities hauled (Casavant 1993). License fee and tax information was obtained from the Washington State Department of Licensing (WADOL, 2008).[11] To obtain per mile or per ton expenses, fees can be divided by the average miles driven per truck or by the annual tons hauled, respectively. Alternatively, using both annual miles driven and tons hauled, license fees per ton mile can be derived.

Insurance Fees

Insurance expenses are usually much less than interest costs, but still constitute part of the trucking firms' fixed costs. In addition to cargo insurance, trucking firms usually carry full insurance on new trucks and trailers to ensure replacement in case of physical damage. According to a phone interview conducted with Gordon Trucking Inc., (2009) the following formula was used to calculate truck and trailer insurance fees:

[11] In addition to estimates provided by the Washington State Department of Licensing, a phone interview was conducted with the Gordon Trucking Inc. operations management department.

Interest/Return on Investment

The lender of money for capital investments determines the rate of interest to charge. If the trucking firm is using a combination of borrowed money and its own capital, then the average of the opportunity cost for that capital and the interest rate charged by the lender should be calculated. The interest can also be calculated using the return on investment (ROI) approach. ROI for a trucking firm is considered to be a part of equipment (truck and trailer) costs, which can be calculated using the following formula (Casavant 1993):

where *PP* is the purchasing price of the equipment and *SV* is the salvage value (discussed in the Depreciation section above).

Total Cost per Ton Mile

The per ton mile transportation cost of feedstocks to biorefineries can be derived by combining the aforementioned fixed and variable cost components for the truck and trailer, and fixed (trucking) business costs. Further, the per ton mile transportation costs can be incorporated with the feedstock farm-gate costs and haul distances to derive the delivered feedstock costs. With appropriate truck configuration (e.g., tanker trailer truck) and hauling origin/destination modifications, trucking costs for ethanol distribution can be derived. Lastly, feedstock transportation and processing costs, combined with the distribution costs, will make up the delivered cost of the ethanol to alternative markets.

As mentioned earlier, an economic engineering approach allows combining all of the components that the total trucking costs comprise. Table 10 lists necessary input values and units of measurement for the truck transportation cost calculations.

Further, these input values were used for the truck transportation total cost calculations shown in Table 11. Fixed cost calculations require information on interest rate, time period of equipment ownership, equipment purchase price, and expected salvage value, as well as information on insurance and license fees.

Table 10: Truck Transportation Cost Calculation Inputs (Feedstock Hauling)

Component	Units	Truck	Trailer (Flat-bed, Drop-bed)
Purchase Price	$	110,000	25,000
Time period of Ownership	years	10	10
Expected Salvage Value	$	28,600	8,750
Annual Cost of Repairs	$	14,005	500
Number of Tires	number	10	8
Replacement Cost per Tire	$	400	400
Lifetime per Tire	miles	60,000	72,000

Annual Miles Driven	miles	80,700	–
Annual Tons Hauled	tons	16,140	–
Interest Rate	%	0.07	–
Price of Fuel	$/gallon	4.61	–
Fuel Efficiency	miles/gallon	5.5	–
Average Hauling Speed	miles/hour	45	–
Annual Cost of License	$	2,000	–
Annual Cost of Insurance	$	220	–
Driver Labor Rate	$/hour	17.41	–

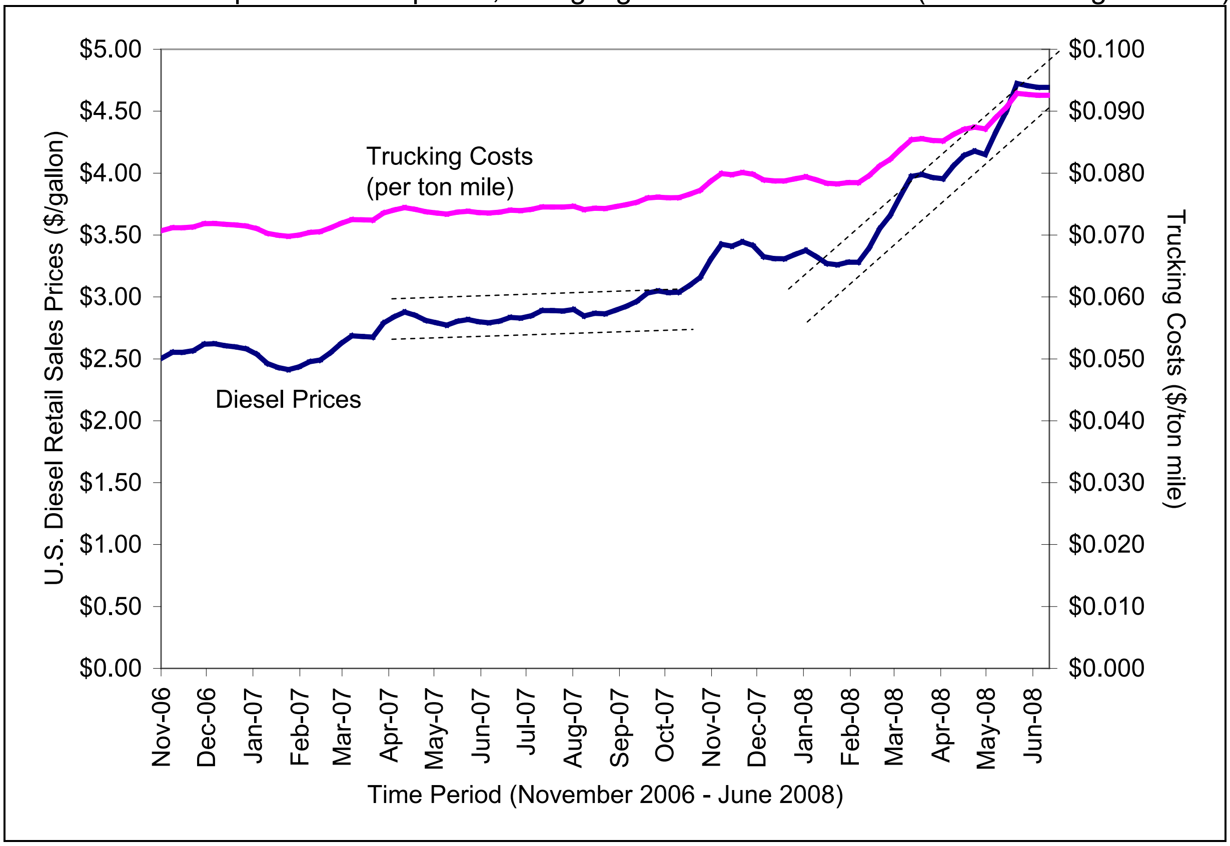
Note: Trailer components that are not applicable for the total cost calculation are not listed.

Additionally, costs that vary depending on annual miles driven or annual tons hauled (variable costs) involve repair and maintenance, tire, fuel, and labor costs. While trucking costs were derived on both per ton and per mile basis, for the purposes of this study the per ton mile measure is utilized for further feedstock transportation and ethanol distribution cost derivations.

Table 11: Truck Transportation Total Costs (Feedstock Hauling)

Description	Truck ($/year)	Trailer ($/year)	Total Cost ($/year)	Total Cost ($/ton)	Total Cost ($/mile)	Total Cost ($/ton/mile)
Fixed Costs						
Capital Recovery (Interest and Depreciation)	13,592	2,926	16,518	1.023	0.205	0.010
Insurance and License	2,220	250	2,470	0.153	0.031	0.002
Total Fixed Costs	15,812	3,176	18,988	1.176	0.235	0.012
Variable Costs						
Repair Cost	14,005	500	14,505	0.899	0.180	0.009
Tires Cost	5,380	3,587	8,967	0.556	0.111	0.006
Fuel Cost	67,641	–	67,641	4.191	0.838	0.042
Lubrication Cost	6,764	–	6,764	0.419	0.084	0.004
Labor Cost	31,222	–	31,222	1.934	0.387	0.019
Total Variable Costs	125,012	4,087	129,099	7.999	1.600	0.080
Total Costs	**140,824**	**7,263**	**148,086**	**9.175**	**1.835**	**0.092**

In addition to delivered feedstock cost sensitivity to farm-gate costs and haul distances, the feedstock costs at the refinery gate are sensitive to diesel prices. Fluctuations in diesel price may influence the feedstock delivered costs, since the fuel costs constitute about 46% of the per ton mile transportation costs. As illustrated in Figure 48, when diesel prices are in a relatively stable range, as highlighted with dotted lines (Apr-07 through Oct-07), trucking costs stayed at almost the same level. However, the chart pattern illustrates that the trucking costs significantly increase as diesel prices trend upward, as highlighted with dotted lines (Jan-08 through Jun-08).



Data Source: Diesel prices were obtained from EIA (2008)b.

Figure 48: U.S. Diesel Retail Sales Prices and Trucking Cost Sensitivity

Not surprisingly, as illustrated in Figure 49, trucking costs are significantly sensitive to fuel prices, which according to the calculations above (Table 11) comprise about 46% of the total transportation per ton mile costs.

A sensitivity analysis with a range of diesel prices and incorporating different processing plant capacities was used to evaluate the delivered feedstock costs in relation to the different ethanol processing plant capacities. Diesel prices from November 2007 to June 2008 (EIA 2008b) were chosen to analyze the variation of feedstock delivered costs with different farm-gate costs ($20, $25, and $30) and small, medium, and large plant capacities (20 MGY, 55 MGY, and 120 MGY). As shown in Figure 50, small-scale processing plants are comparatively less sensitive to diesel price increases in terms of the delivered feedstock costs, for all three of the farm-gate cost scenarios.

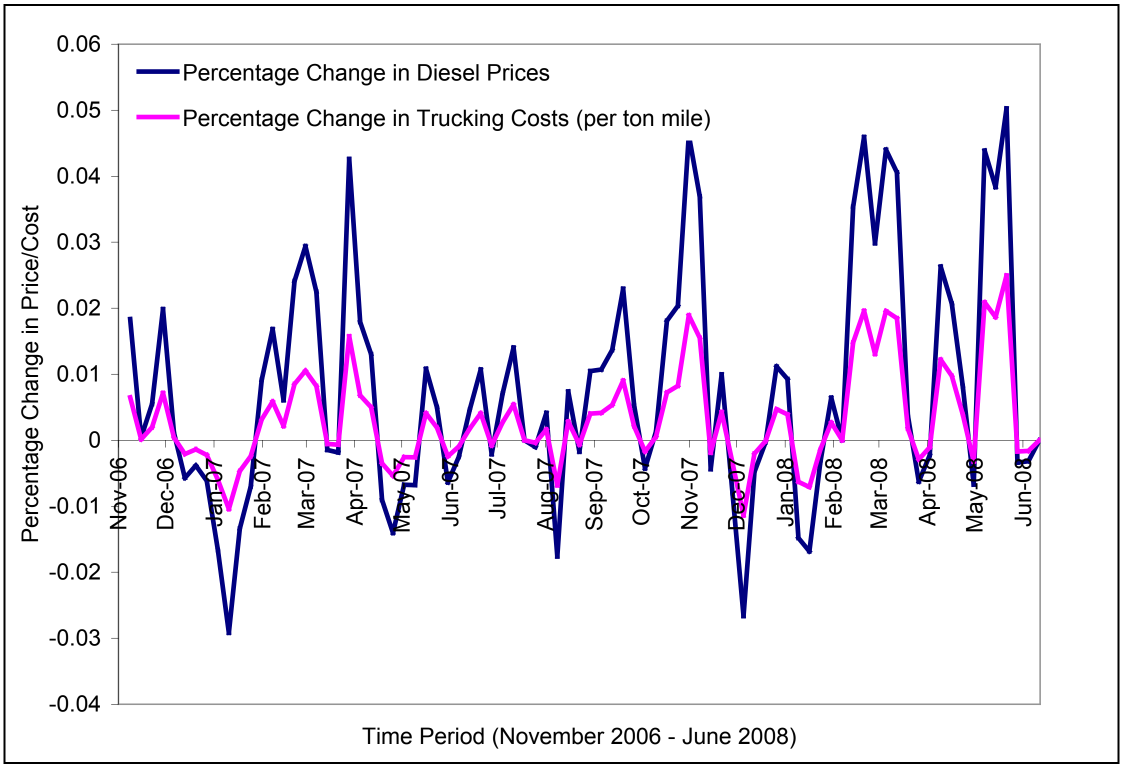


Figure 49: Percentage Change in Diesel Prices and Trucking Costs

In comparison, the influence of increasing diesel prices on the delivered feedstock costs for the medium and large processing plants is considerably higher. Particularly, as a result of increasing diesel prices since January 2008 (39% increase from January to June, 2008), the delivered costs of feedstocks for the 55 MGY plant increased by 3% considering $20 farm-gate costs, and 2% considering $25 and $30 farm-gate costs. Because larger plants involve more transportation activity, the delivered feedstock costs for the 120 MGY capacity plant increased by 4% considering $20 and $25 farm-gate costs, and 3% for $30 farm-gate cost.

Besides the cost components such as fuel prices, there are other factors that influence the transportation costs. Per ton mile transportation costs may differ depending on plant processing capacity, since larger plants require more feedstock to be processed. Cellulosic feedstocks, such as crop residue, are geographically dispersed. Consequently, more feedstock demanded by larger plants requires longer-distance hauling, which consequently increases transportation expenses. As derived earlier in this section, 9.2 cents per ton mile trucking cost was used in combination with the feedstock farm-gate cost (derived in the Feedstock collection Process and Cost section) to calculate the delivered cost of feedstock to biorefineries.

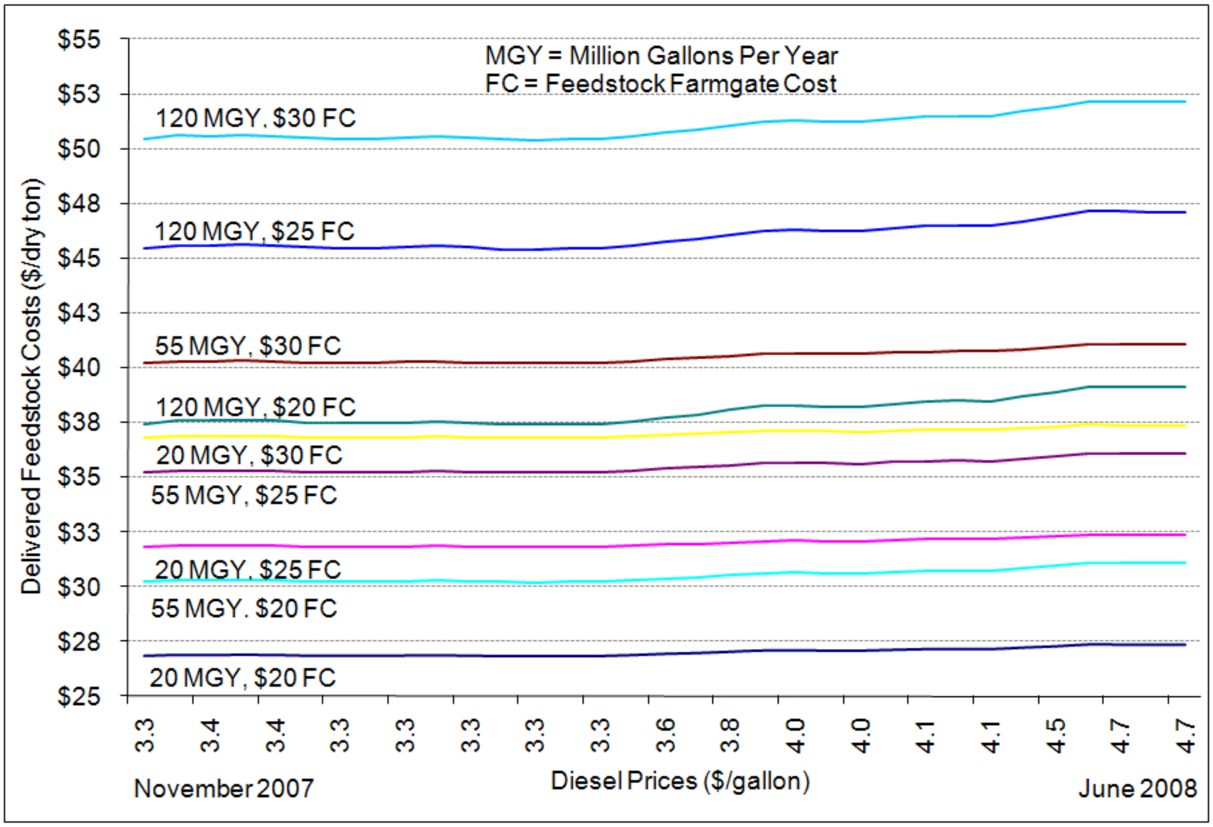


Figure 50: Delivered Feedstock Cost Sensitivity to Diesel Prices

Figure 51 shows the relationship between increasing plant processing capacity and feedstock delivered costs on per dry ton and per gallon basis (using NREL data). These costs may also differ by the type of feedstock utilized for the ethanol processing. Nevertheless, the upward-sloping delivered cost curves emphasize that the overall amount of the feedstock available in the region cannot be utilized at the same expense. The tradeoff for the economies in scale is the increasing transportation costs. The overall delivered (final) cost dependence on the geographic dispersion of feedstocks and markets introduce the importance of the optimal processing plant size concept.

In addition to spatial characteristics, such as feedstock production geography and market locations, the optimal plant size decision involves factors such as alternative transportation mode (rail, barge) accessibility. However, the fundamentals of the processing plant size decision making involve two main components: increasing feedstock transportation costs and economies of scale in the processing segment. As shown in Figure 52 (also discussed in the Processing Costs and Economies of Scale section), per gallon processing costs tend to decrease with increasing processing capacity, since capital and operation expenses are spread over more gallons of processing. Economies of scale are large enough to offset the increasing feedstock transportation costs up to the processing capacity where the total cost is at its lowest point (shown with an arrow in Figure 52). The lowest point on the total costs curve determines the optimal capacity for economically feasible ethanol processing. The transportation cost curve includes both feedstock transportation and ethanol distribution segments.

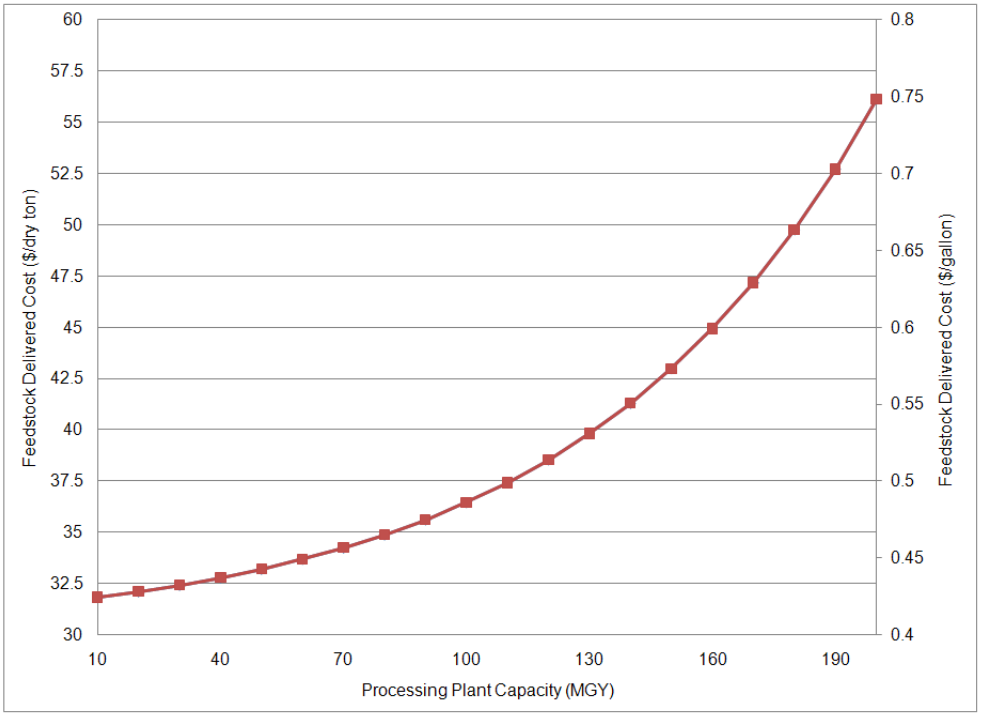


Figure 51: Feedstock (Crop Residue) Delivered Costs to Biorefineries by Processing Capacity

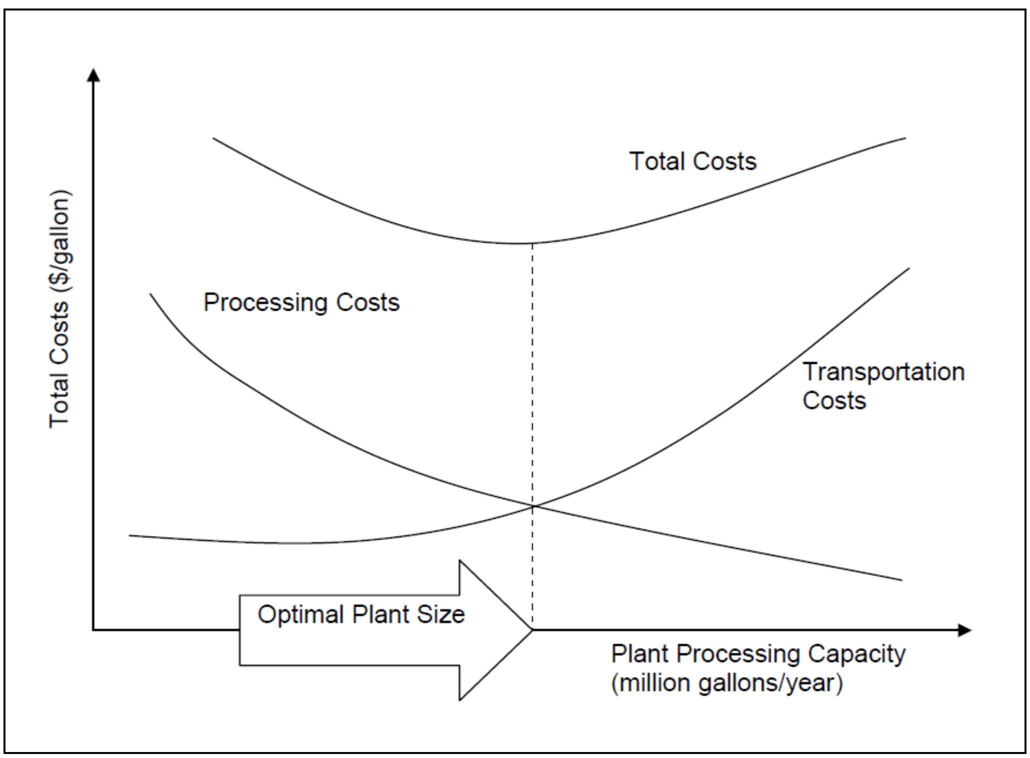


Figure 52: Total Delivered Costs and Processing Plant Optimal Size

GIS Approach to Delivered Cost of Feedstocks (NREL Data)

In this section, GIS with NREL (2007) data was used to spatially investigate the delivered costs of feedstocks. The methodology is then utilized to analyze the state of Washington biomass data identified in the first phase of this project (Frear et al. 2005). Feedstock transportation costs were derived for multiple processing plant locations in the state. Further, the optimal processing plant locations in terms of least feedstock transportation costs were identified in the GIS Analysis for Biofuel Plant Least-Cost Location Decisions (NREL Data) section.

GIS Analysis for Eastern Washington (Crop Residue)

Introduction

The study area includes 12 counties that produce 93% of the state's agricultural crop residues (shown above, in Figure 37). The annual crop residue available in the study area (roughly 1.6 million dry tons) can support up to 122.5 MGY processing (using a 75 gallon per dry ton biomass-to-ethanol conversion rate). However, because of the geographic distribution of the biomass and increasing transportation costs resulting from longer haul distances, the above capacity cannot be supported at the same feedstock expense.

We used the GIS Network Analyst Extension toolset to investigate the geographic distribution of crop residue in each of the haul areas of the 12-county study area in relation to the Washington State highway system. Using Census Feature Classification Codes (CFCCs),[12] speed limits were assigned to all segments in the GIS roads shapefile to calculate haul distances and drive times for a specific biorefinery location.[13] Assuming truck transportation, six haul time categories with 30-minute intervals (up to 3-hour haul time) were used to estimate feedstock availability within each county and each haul distance area. Further, the residue physical availability, farm-gate price, transportation costs (from fields to a biorefinery) including loading/unloading, and geographic distribution (accounting for site-specific road infrastructure) information were combined to derive feedstock supply curves. In this case study, the truck and flat-bed trailer configuration was considered for transporting crop residue bales from field facilities (storage) to the ethanol processing plants. We used per ton mile transportation costs derived in the Total Cost per Ton Mile section.

The results show that there is no fixed price for the delivered cost of feedstocks. Harvesting costs differ by collection methods, and transporation rates differ by drive times and haul distances as well as by truck configuration. Therefore, depending on the processing plant capacity, the feedstock costs will differ accordingly. The subsequent section describes 1) GIS procedures for calculating resource availability by haul distances/times for each county in the state; 2) the procedure for converting the GIS road shapefile into a network dataset and assigning speed limits to the highway network file; and 3) the procedures for generating spatial data to construct the supply curves.

[12] CFCC provides an alphanumeric code for each line feature in the GIS road shapefile. Further, the codes are used to classify roads, railroads, water, and other linear features.

[13] A shapefile is a name of the file used in Geographic Information Systems that contains nontopological geometry and attribute information for the spatial features (roads in our case) in a data set. Feature information such as geometry and attributes (e.g., length of the segment, name, location, etc.) is stored as a shape containing a set of vector coordinates.

GIS Data and Procedures

The GIS procedures started with querying out counties in the study area from the state of Washington biomass shapefile, obtained from the NREL GIS Data and Analysis Tools website (NREL 2007). Biomass shapefiles include counties (depicted as polygons) with attribute information such as area, boundaries, population, etc., and spatial information such as latitude, longitude, and projection type. The attribute table (which can be exported to a spreadsheet file) of the shapefile contains annual availability of crop and forest residues, animal manure, and municipal solid waste feedstock categories. The U.S. Census Topologically Integrated Geographic Encoding and Referencing (TIGER) roads layers for the study area were obtained through the Environmental Systems Research Institute (ESRI) website (ESRI, 2009). County road shapefiles were merged to form one road network for the entire study area. After joining the CFCCs to highway shapefile attribute tables, the length measure of line features was converted from feet into miles. This allowed calculating travel/driving time for each road segment (and entire route) using the following formula:

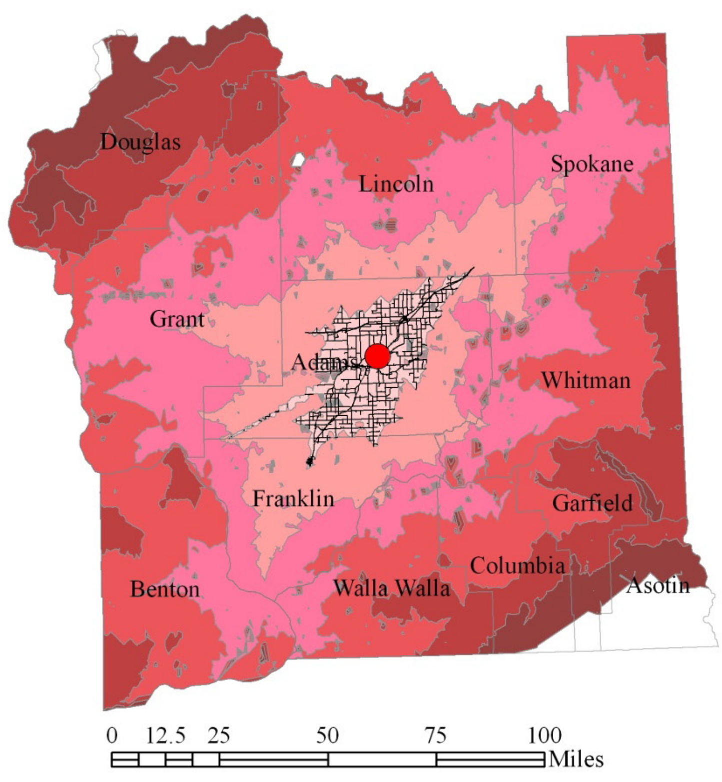


Figure 53: Service Areas by Haul Times with Highlighted Roads within 30-Minute Intervals

Using the GIS Network Analyst[14] extension toolset, first the road shapefile was converted into network dataset. Then the service area layers, as shown in Figure 53, were mapped. In the middle of the study area is the geographic location of a cellulosic ethanol processing plant, in Ritzville, Washington. Note that in order to keep the map simple, the road layer was made visible only in the 0–30-minute haul zone.

Hereafter, the term *haul zone/s* is used to refer to the service area/s mapped by the GIS Network Analyst Service Area function as shown in Figure 53. Haul zones were calculated with 30-minute intervals (up to 180 minutes of drive time) from the origin (processing plant) using travel time as a cost attribute. For example, in the 30-minute interval zone, all biomass can be transported from the field to the plant within 30 minutes of drive time. The next haul zone is mapped as a 31–60 minute haul zone, meaning the amount of feedstock available in that zone takes from 31 to 60 minutes of drive time for transporting to the plant. The same logic applies to 61–90 minutes and to the rest of the haul zones.[15]

Haul zones were saved as a separate layer (shapefile), which then was joined with the biomass layer such that for each haul zone the feedstock amount in tons is available. Since the biomass data were initially available per county, it is not possible to simply "cookie cut" the biomass layer with the haul zones. Instead, the haul zone layer was first merged with the biomass layer using the ArcMap *Union* spatial analyst function. Then the areas within the boundaries of haul zones can be selected from the merged layer (biomass and haul zones) and saved as another layer. In this selected layer the areas (in square miles) for each of the haul zones in each county were calculated using the ArcMap *Geometry* calculation tool. Finally, the attribute table was exported into the spreadsheet format. Without a doubt, the spatial manipulation of the data as enabled by the GIS is not conceivable by solely spreadsheet-based models used in many studies investigating feedstock transportation. Based on the GIS-generated data, geographically varying resource availability and the feedstock supply curves are constructed and discussed in the Feedstock Supply Curve construction (Crop Residue) section.

Feedstock Supply Curve Construction (Crop Residue)

The attribute table of the resulting GIS data layer (includes feedstock and haul zone information) was summarized by haul distances and exported to a spreadsheet, allowing identification of the feedstock amount available in each haul zone at the county level. Figure 54 depicts resulting crop residue availability by haul time and by county in the study area. The availability curves can be expressed in two ways. In Figure 54 the amount of feedstock in each haul zone is shown as the amount available only in that zone. Alternatively, the cumulative availability of crop residue in the study area can be depicted, such that increasing haul time results in increasing availability of feedstocks.

Depending on the specific objective, both methods of expressing feedstock availability can be useful. Suppose, for example, a processing plant can currently "afford" to haul feedstocks from at most two hours of drive time from their location. If the processing facility operations

[14] The GIS Network Analyst extension toolset enables network-based spatial analysis, such as finding the closest facility from a particular location, identifying routes, finding driving directions, and mapping service areas based on distance (miles) and/or travel time (minutes) from/to specific locations.

[15] The term *haul area* differs from the *haul zone* by including all inner zones. For example, a 60-minute haul area includes feedstock available from both 0–30 and 31–60-minute haul zones. Similarly, a 90-minute haul area includes everything from the origin (processing plant) to the outer boundaries of the 61–90-minute haul zone. The same explanation is applicable to the rest of the haul areas.

management is interested in knowing the amount of feedstock that is available within the next (third) hour of drive time, then the representation form in the Figure 54 will be more useful. In other words, given the geographic distribution of feedstock, by driving one more hour (to reach more distant areas), Figure 54 shows the resource availability specifically in that new zone. If additional expenses from driving one more hour are considered, the figure can inform the cost of those additional feedstocks.

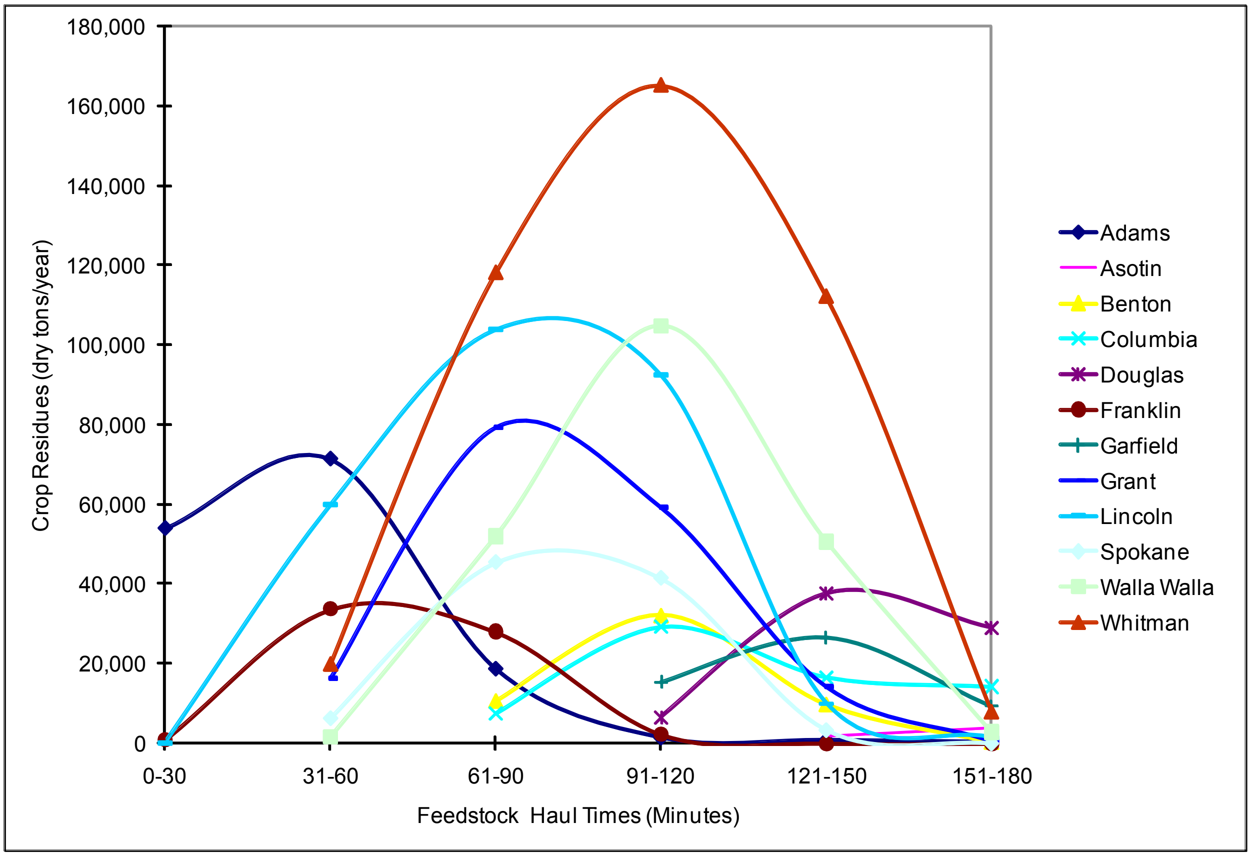


Figure 54: Crop Residue Biomass Availability by Haul Times (from a Biorefinery) for the Counties in the Study Area

As shown in Figure 54, the biomass availability sharply increases starting from the 31–60-minute haul zone and reaches its highest levels of availability at the 61–90-minute zone for Grant, Lincoln, and Spokane counties. Adams and Franklin counties reach their highest levels within the 31–60-minute interval. The availability in the counties Whitman, Walla Walla, Benton, and Columbia counties peaks within the 91–120-minute haul zone. Finally, the availability in Douglas and Garfield counties starts within the 91–120-minute haul zone and reaches its highest level within the 121–150-minute haul zone.

On the other hand, if the interest is in knowing the total supply of the feedstock within certain haul time, Figure 55 will be more useful since it shows cumulative availability of feedstocks. In Figure 55, Adams, Lincoln, and Whitman counties reach their maximum cumulative availability within 90, 130, and 160 minutes of drive time, respectively. In comparison, feedstocks to be transported from Garfield and Douglas counties require haul distances starting from 120 miles.

Derivation of feedstock supply curves (Figure 56) involves several components. First, the processing plant capacity that the existing/available feedstock can support was determined using 75 gallons per dry ton biomass-to-ethanol conversion rate. Another important measure is the resource availability within various haul time zones around the biorefinery. Haul times used for the supply curve construction were adjusted for transportation delays, such as stops, turns, and slow-speed road segments. The relationship between the delivered cost of a feedstock per dry ton (specifically for the ethanol processing plant depicted in Figure 53) and the annual feedstock availability, processing plant capacity, feedstock haul times (in minutes) and distances (miles) are depicted in Figure 56.

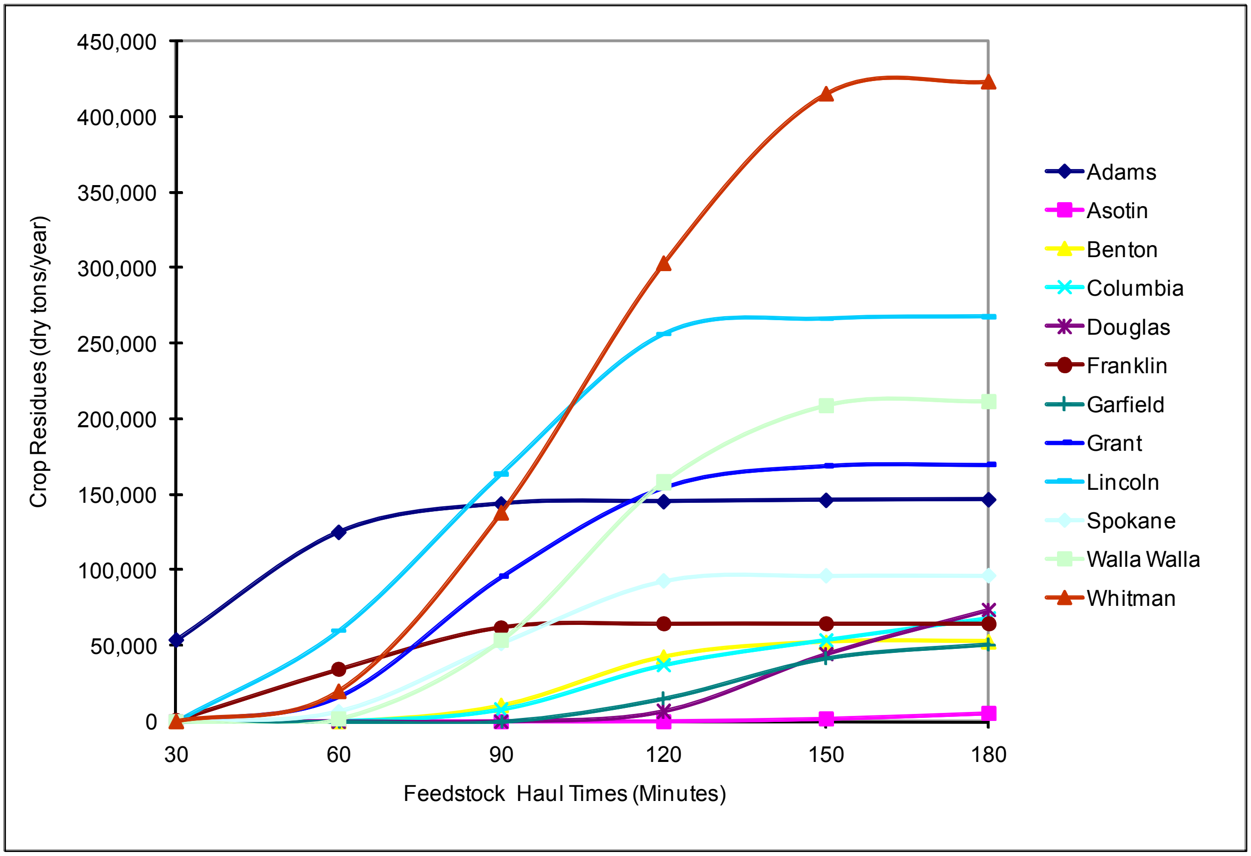


Figure 55: Cumulative Crop Residue Biomass Availability by Haul Times (from a Biorefinery) for the Counties in the Study Area

On the horizontal axis, the first line represents the amount of crop residue available within the boundaries of a specific haul zone. The second line shows an incremental plant capacity in million gallons per year that the feedstock (cumulatively) available in a given haul zone can support. The delay-adjusted distance measure is included in order to fine-tune the haul times. The slopes of the curves in Figure 56 reveal the magnitude of the positive relationship between increasing haul times or increasing feedstock amount required by larger processing plants and the delivered cost of feedstock for all of the three feedstock farm-gate cost scenarios. Depending on the plant annual processing capacity, supply curves provide information on the delivered cost of feedstock. For example, for the geographic location of the 55 MGY proposed plant (mapped in Figure 53), the delivered cost was found to be $25.51 per dry ton considering a feedstock farm-gate cost of $20. More feedstock, and thus higher processing capacity (up to 122.47 MGY), could be supported within the area under investigation by increasing haul distances. However, the delivered cost of feedstock will increase accordingly ($31.01 per dry ton).

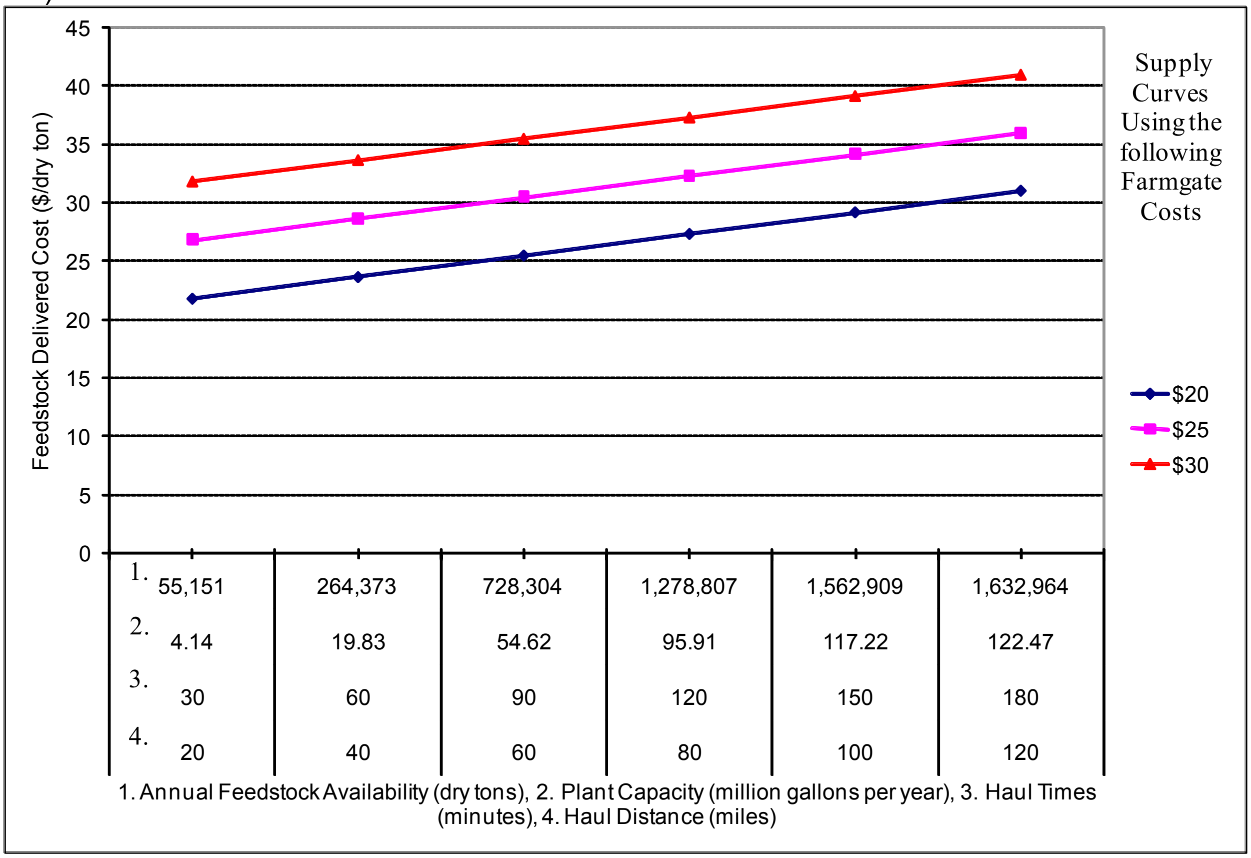


Figure 56: Feedstock Supply Curves Using $20, $25, and $30 per Dry Ton Farm-Gate Costs

Supply curves constructed using GIS-generated data help in assessing the optimal size of the plant given not only the feedstock availability in the study area, but also the geographic distribution and local road infrastructure. However, to assess the benefits from the economies of scale, processing costs need to be investigated as well. This may partially alter the delivered cost of the final product—ethanol blend.

Conclusion

Feedstock supply curves suggest that, depending on the processing plant capacity, transportation costs may significantly influence the delivered cost of feedstock. Thus, larger-capacity plants are not necessarily advantageous from economy of scale as it pertains to the feedstock production costs because more capacity requires longer feedstock haul distances. The economic viability of ethanol processing is partially influenced by the delivered feedstock costs. Due to the spatially variable feedstock availability, the total biomass that is available in any region cannot be fully utilized at the same expense. Therefore, as a part of the interrelated structure of both ethanol processing and distribution, transportation costs prove to be a key component of a feasible feedstock supply system.

GIS Analysis for Western Washington (Forest Residue)

GIS Procedures

The road shapefiles for the study area counties and Census Feature Classification Codes (CFCCs) were obtained from the same source described in the GIS Analysis for Eastern Washington (Crop Residue) section. Using the same procedures described in the crop residue analysis part, the CFCCs were joined to the roads shapefile attributes table and travel times were calculated using the following formula:

Using the GIS Network Analysis toolset, the service area layers (originating from the southeastern part of the state) have been mapped (Figure 57). The origin is the actual geographic location of currently corn-based ethanol processing plant with the capacity of 55 MGY located in Clark county (southwestern part of the state). Note that in order to keep the map simple, the road layer was not displayed. Following similar procedures described for crop residue feedstock, haul zones were calculated with 30-minute intervals (up to 300 minutes of drive time) from the origin (plant location) using travel time as the primary cost attribute.

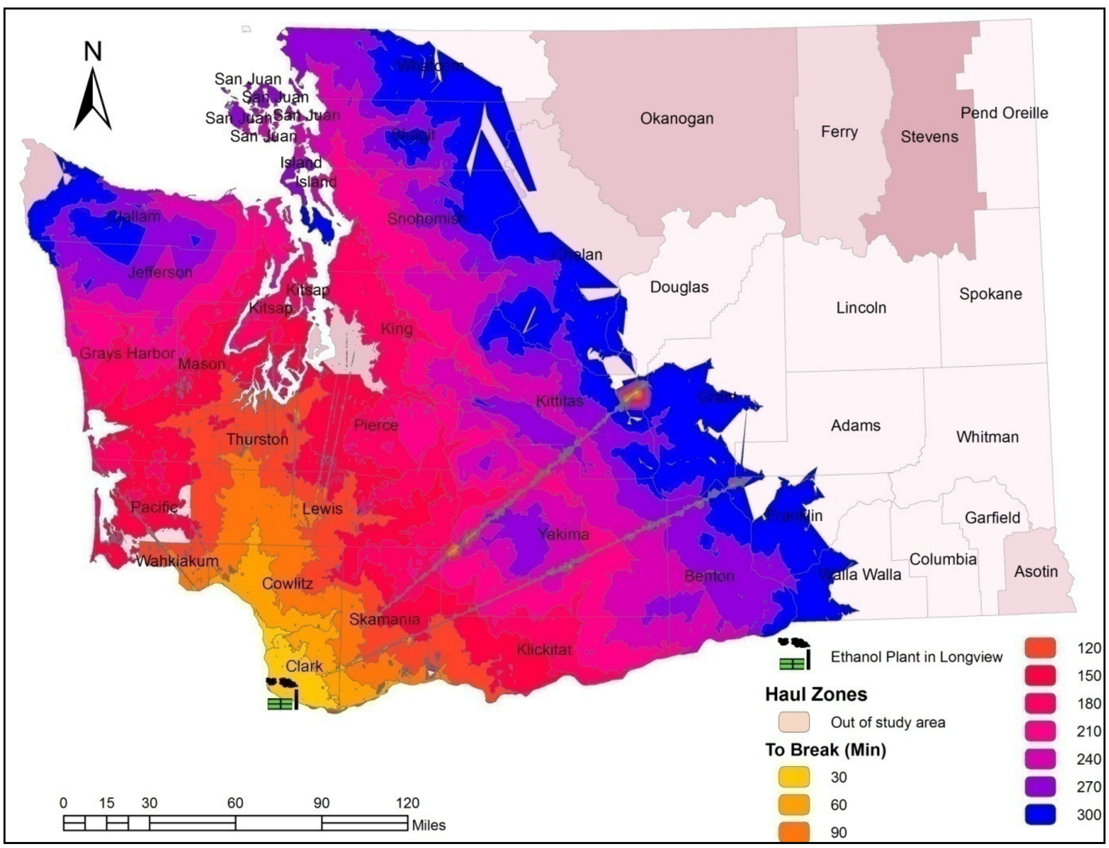


Figure 57: Forest Residue Availability by Haul Times

Feedstock Supply Curve Construction (Forest Biomass)

Feedstock supply curves were constructed following similar procedures described in the GIS Analysis for Crop Residue section. The feedstock availability in each haul zone and the cumulative availability are depicted in Figure 58 and Figure 59, respectively. Figure 58 can be more useful when information on feedstock availability within the next haul time category is needed.

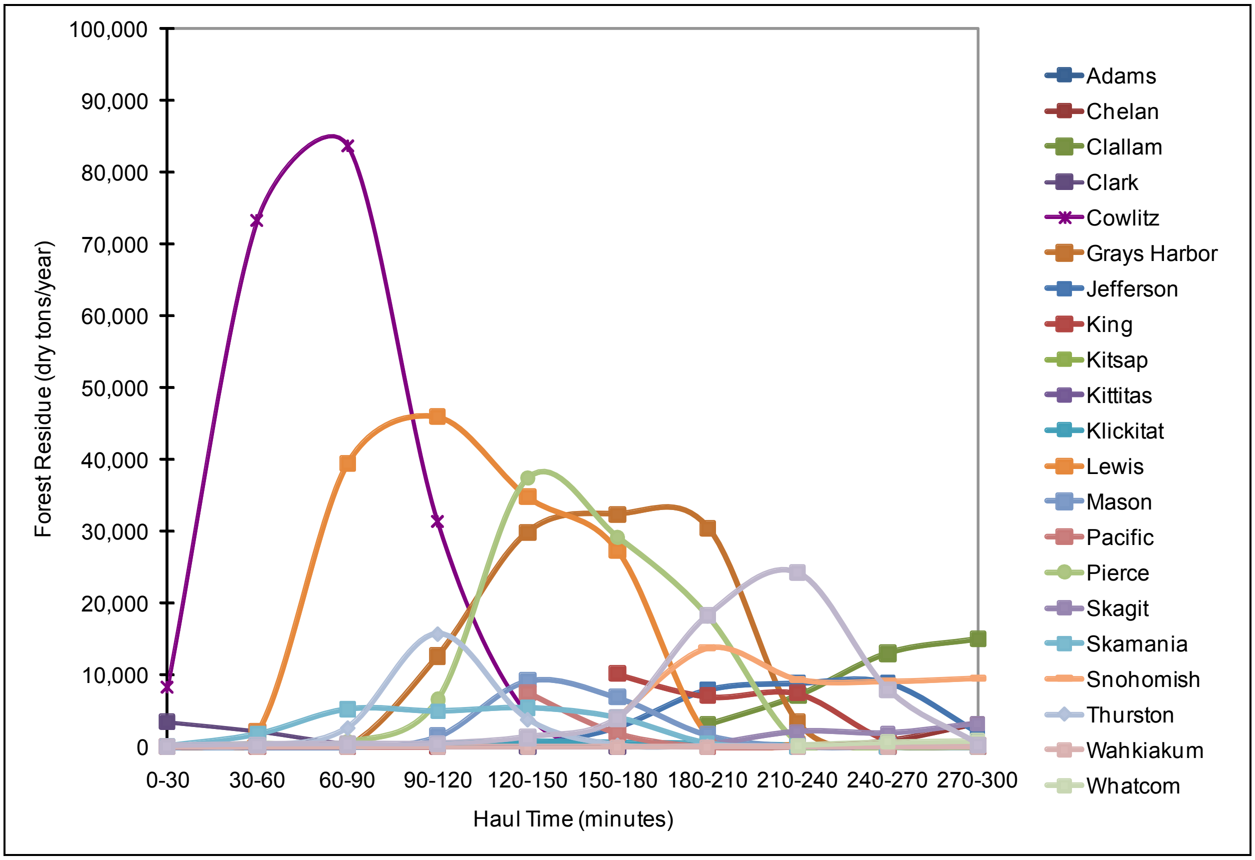


Figure 58: Forest Residue Biomass Availability by Haul Times

As shown in Figure 58, the biomass availability reaches the highest levels of availability in the 60–90-minute zone for Cowlitz county, in the 90–120-minute zone for Lewis county, in the 120–150-minute zone for Pierce county, in the 180–210-minute zone for Grays Harbor County, and in the210–240-minute zone for Yakima county. In Figure 59, resource availability in Grays Harbor and Pierce counties reach maximum cumulative availability at around 210 minutes of haul time; Cowlitz and Lewis counties reach maximum resource availability at around 120 and 180 minutes of drive time, respectively.

Figure 60 shows the relationship between the delivered cost of feedstock per dry ton and cumulative feedstock availability, as well as cumulative plant capacity, distances, and haul times. On the horizontal axis, the first measure shows the plant capacity and the second line represents the amount of forest residue availability. The distance measure was included to complement the haul times.

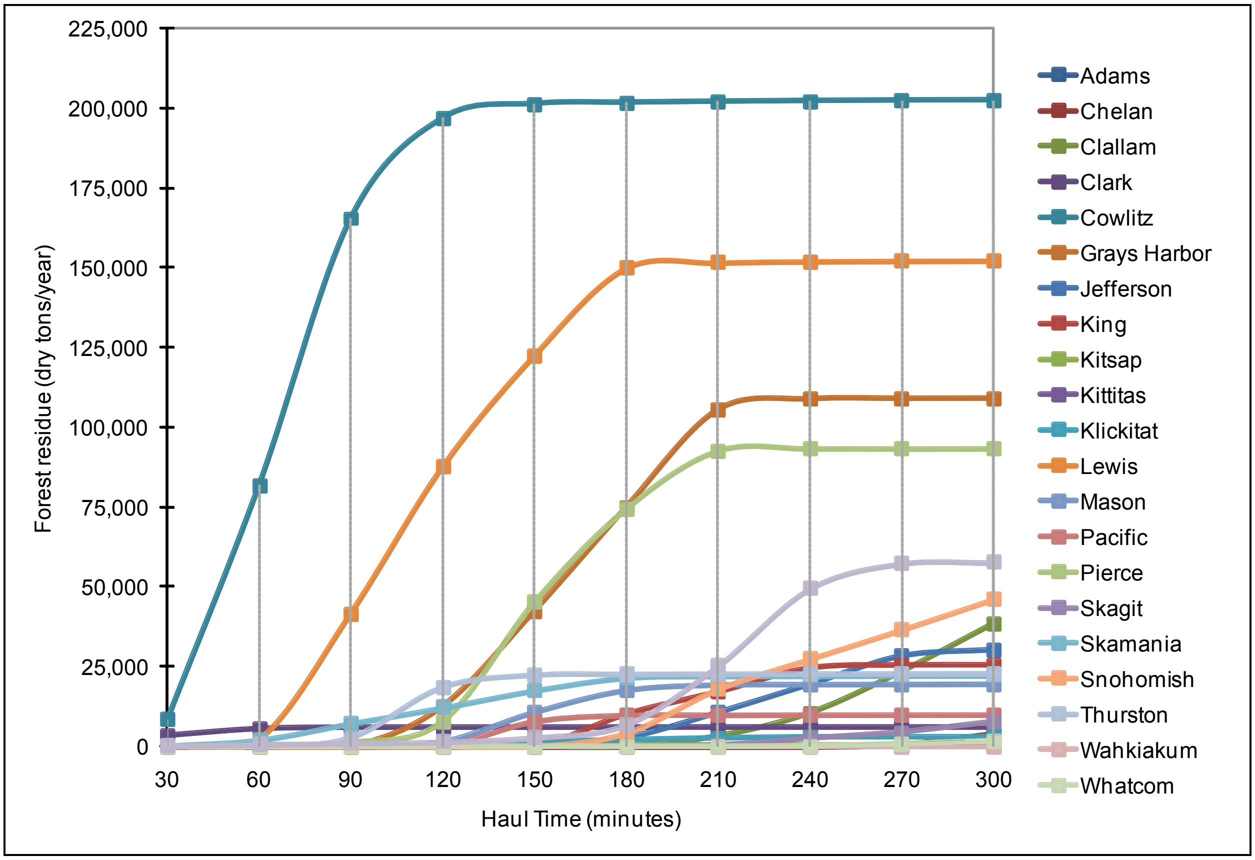


Figure 59: Cumulative Forest Residue Biomass Availability by Haul Times

Conclusion

As with crop residue feedstock, depending on the plant capacity the delivered cost of forest residue varies. For the geographic location of the operating plant (mapped in Figure 57), the delivered cost of forest residue feedstock that supports the (current) 55 MGY ethanol processing capacity was found to be $52.82 per dry ton. By increasing haul distances with consideration of increasing delivered costs, higher processing capacity (up to 64 MGY) can be supported within the area under investigation.

Feedstock supply curves derived for forest residue suggest that processing plant capacity and the geographic distribution of feedstocks may significantly influence the delivered cost of feedstock. Thus, similar to plants utilizing crop residue as a feedstock, the larger-capacity plants need (enough) processing cost reductions due to the economies of scale to offset increasing feedstock transportation costs.

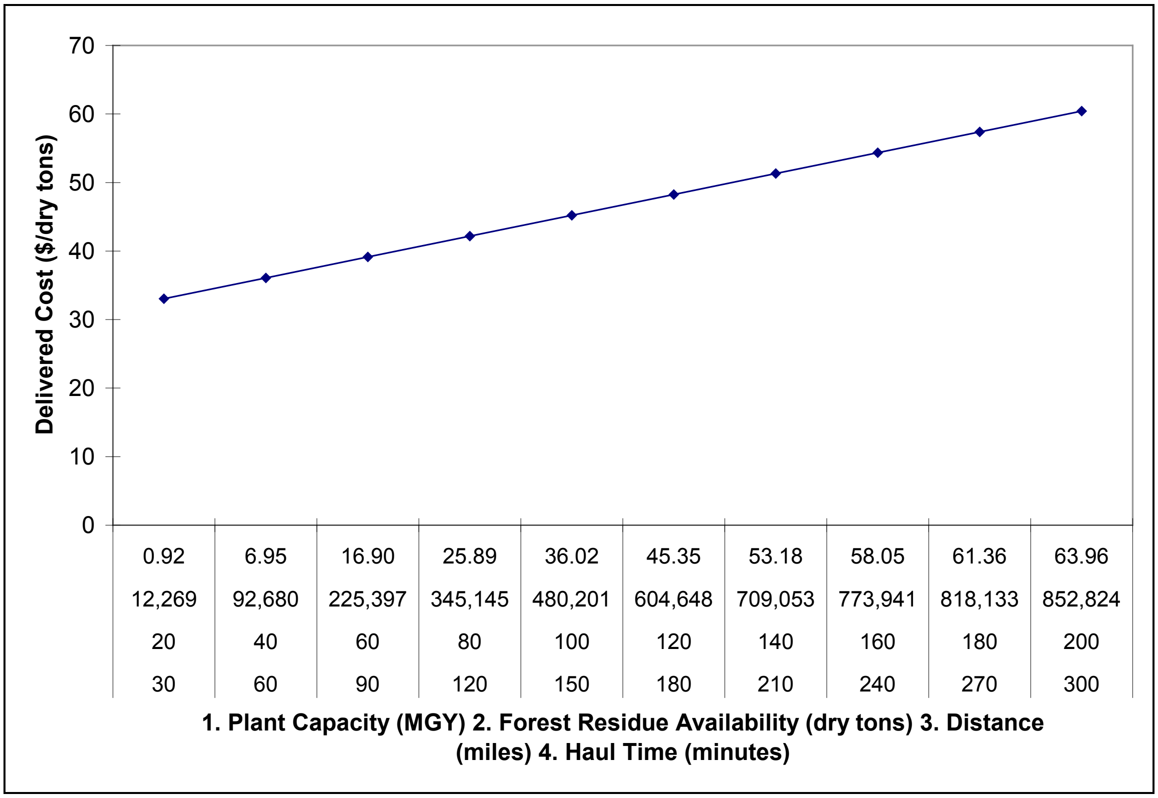


Figure 60: Feedstock Supply Curve (Cumulative)

GIS Analysis for Biofuel Plant Least-Cost Plant Location Decisions (NREL Data)

In this section we introduce a GIS-based model [using NREL (2007) data] to support cellulosic ethanol plant least-cost location decisions by integrating geographic distribution of biomass in the study area with associated transportation costs. Similar to the feedstock transportation GIS analysis above, the methodology is then utilized to analyze the state of Washington biomass data identified in the first phase of this project (Frear et al. 2005).

As an initial step of a multi-factor spatial optimization problem, including both feedstock transportation and ethanol distribution cost, we investigated the influence of feedstock transportation costs on optimal location decisions. To achieve that purpose, the feedstock resources (in this analysis, forest biomass and agricultural crop residue) were spatially investigated relative to the road network and potential cellulosic ethanol plant locations in the state of Washington. The flexibility of the model allows spatial manipulation of the data for the least-cost location identifications considering both cumulative and separate types of feedstock utilization scenarios. Study results show that the ethanol plant transportation cost-minimizing location decisions are significantly influenced by the type of the feedstock utilized, and vary depending on the plants' processing capacities.

<u>GIS Model</u>

Data

The GIS data were obtained from NREL's Dynamic Maps, GIS Data and Analysis Tools webpage (NREL 2007). According to the same source, the cumulative availability of the forest biomass and agricultural crop residue in the state is over 2.7 million annual dry tons, indicating a potential to process more than 200 million gallons of ethanol annually. Crop residue procurement prices and per ton mile truck transportation costs (for both types of feedstock) were used as derived in the Feedstock Production and Transportation section of this report. For the forest biomass procurement prices, estimates were adapted from relatively recent studies (Gan and Smith 2006; Asikainen et al. 2002; Rummer et al. 2003; and Puttock 1995). Study area road shapefiles were obtained from the Environmental Systems Research Institute website (ESRI 2007).

Structure

The GIS-based model consists of three main parts. In turn, each of the parts includes several procedures (Figure 61). The first part builds a dataset by layering GIS shapefiles that are necessary for the analysis in this section. The second part involves GIS Network Analyst extension procedures for creating service area (a shapefile of driving zones) around processing plants included in the study area, as well as for joining and relating that new shapefile (service areas) with existing GIS layers. Reiteration of the procedures is undertaken for each of the processing plant locations. The final part of the model incorporates spreadsheet operations for further analysis with the GIS-generated spatial data. In particular, it links steps in which annual ethanol processing capacities (using biomass-to-ethanol conversion rates) and truck transportation per ton mile costs are derived for the least-cost facility location identification.

GIS Procedures

This section provides details on the GIS procedures for calculating feedstock resource availability by county and by specified haul distances. It also describes procedures for assigning driving speed limits to the road segments and for generating datasets for the feedstock transportation costs derivation.

The biomass shapefile, indicated in Part 1 of Figure 61, represents a geographical layer with attribute information such as area and boundaries of biomass distribution, and spatial information such as latitude, longitude, and type of the map projection (e.g., transformation of a spheroid surface to a flat map while maintaining spatial relationships). Integration with the state/county shapefile provides annual availability information for agricultural crop residue and forest biomass by county level (cumulatively mapped in the following Figure 62).

Simultaneously, Census Feature Classification Codes (CFCCs) were joined to the GIS roads shapefile's attribute table. This procedure assigns speed limits to each of the road segments, which in turn, allows driving distances from each processing plant to the feedstock sources to be calculated.

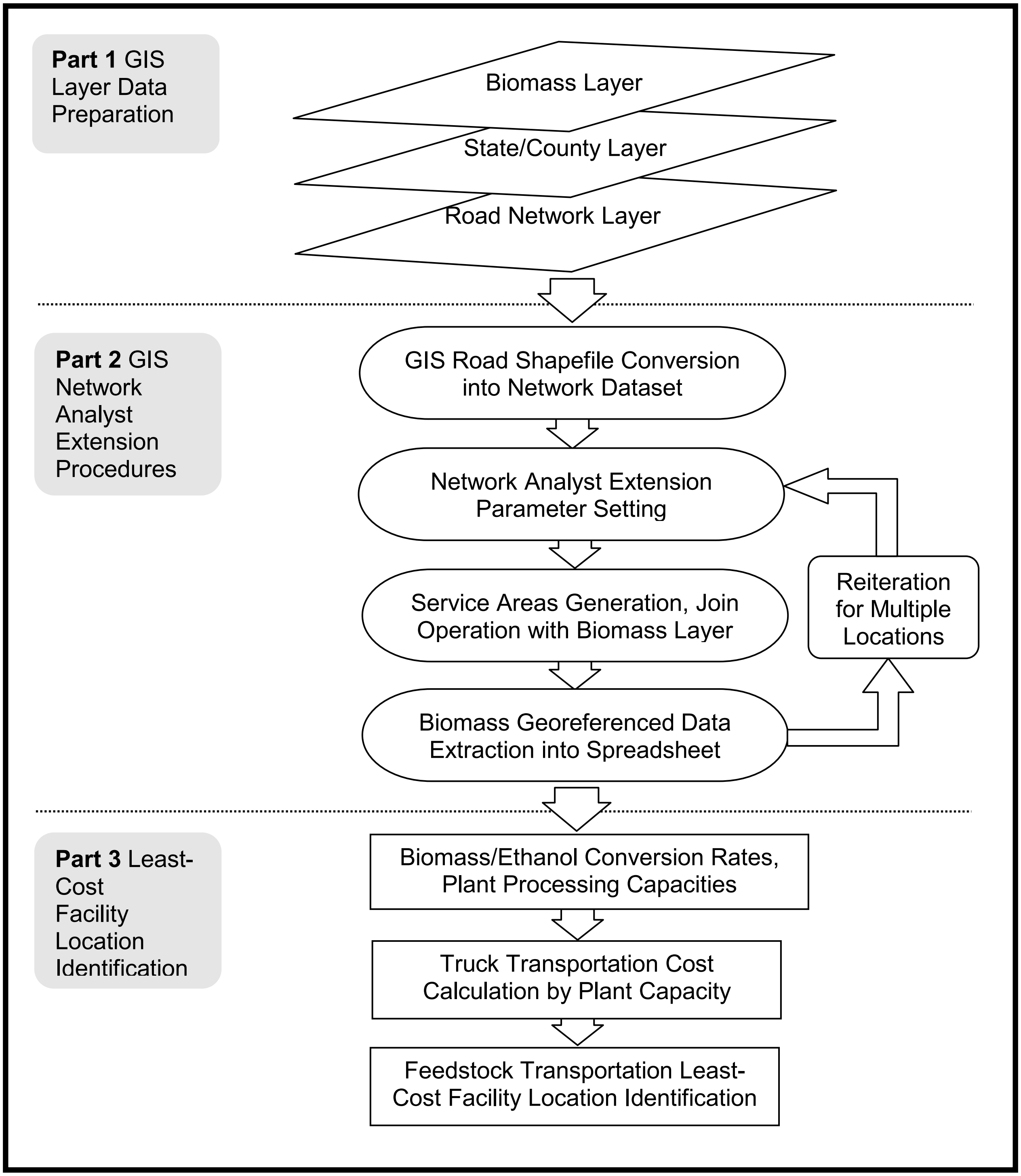


Figure 61: Flowchart of GIS-Based Feedstock Transportation Least-Cost Facility Location Decision Model

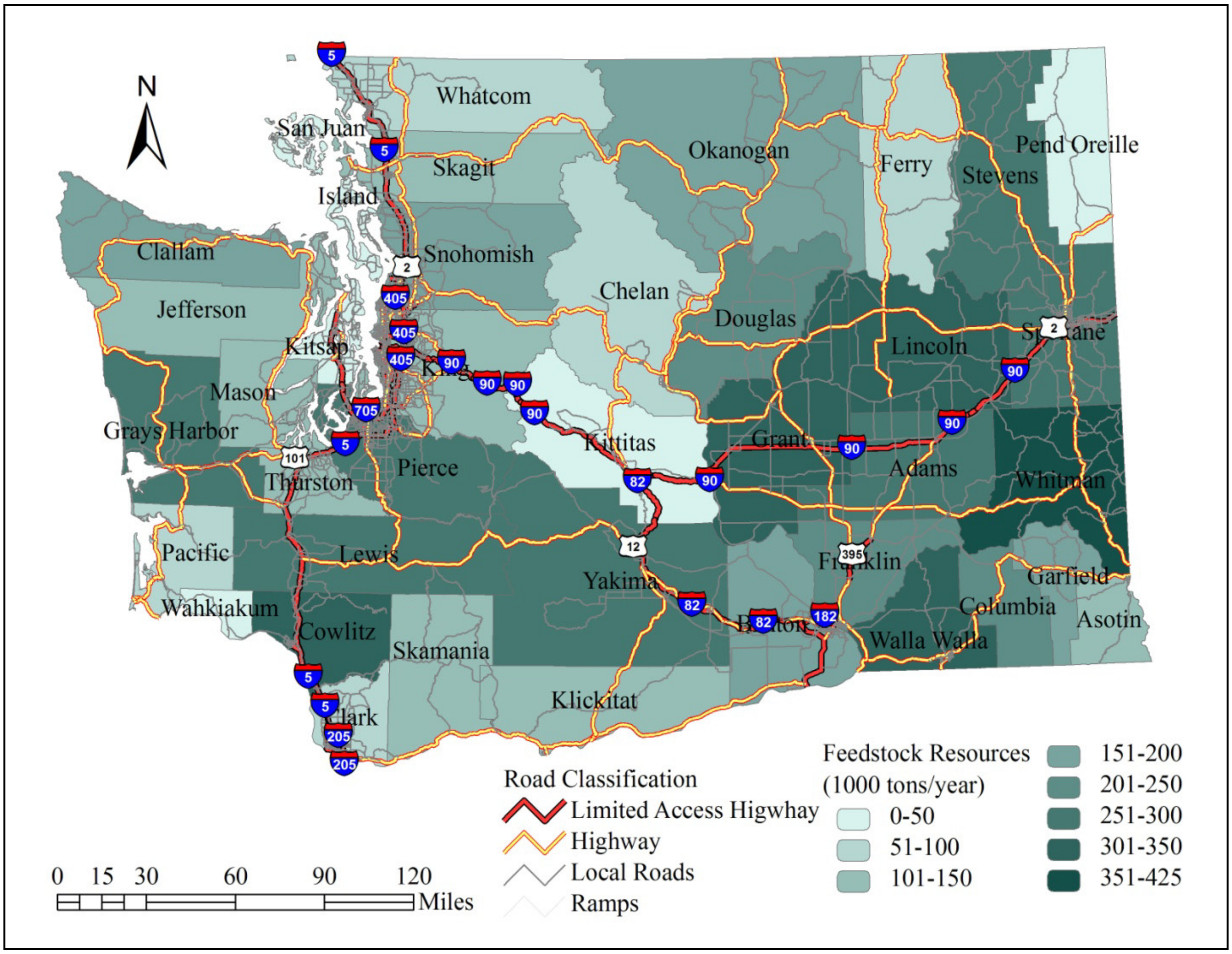


Figure 62: Distribution of Forest Biomass and Agricultural Crop Residues in the State of Washington

Procedures in Part 2 of the model involve a GIS Network Analyst extension toolset, which enables network-based spatial analysis such as finding the closest facility from a particular location, identifying routes and driving distances to reach specified areas, and generating service areas (distance-based buffer zones) around points of interest. As an initial step, the GIS road shapefile was converted into a network dataset (using GIS *ArcCatalog* software). GIS network datasets are constructed from spatial features—lines, points, and turns—which build an advanced connectivity model for transportation networks. The next step sets parameters for the service area generation, such as driving distance bands (in miles), processing plant locations, and cost attributes.

To identify the feedstock resource availability within increasing driving distances around ethanol processing plants, the service areas cover the entire state at 30-mile increments. For instance, within the 30-mile buffer, all available feedstocks will require a 30-mile length haul (maximum) to be transported from the field to the processing plant. The cost attribute for service areas generation was set as a distance in miles, and the four proposed ethanol facility locations have been loaded as points where the feedstock needs to be transported. The rationale for selected processing plant locations is that all of them are currently at the planning or feasibility study stage (Lyons 2008). After the generation of service areas (depicted in Figure 63), the resulting distance-based layers were joined with the biomass layer, such that for each service area the available feedstock/biomass amount in annual tons is identified at the county level.

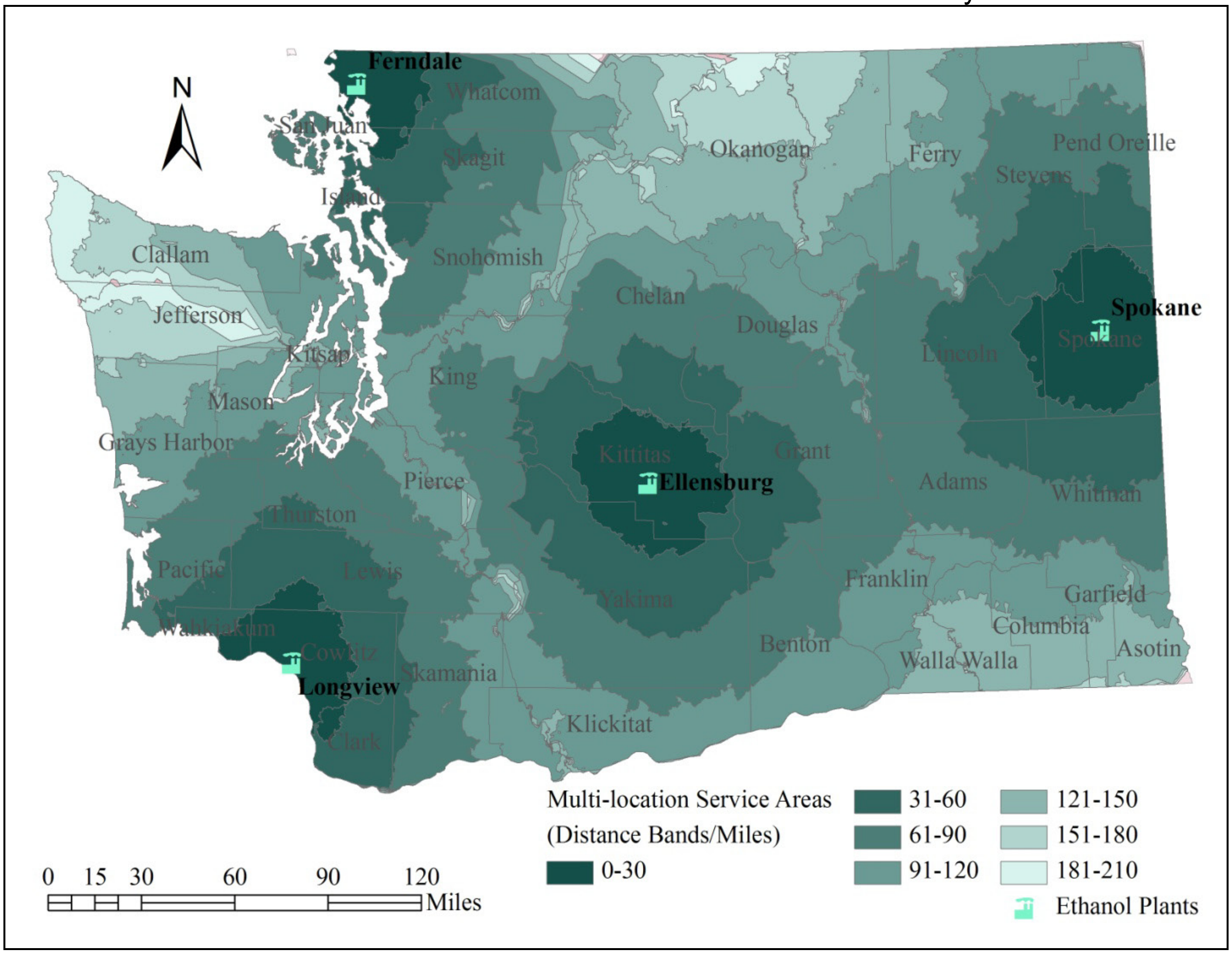


Figure 63: Service Areas around Four Proposed Ethanol Facilities

Since the biomass data were available per county, several additional steps were implemented to extract the county availability information, within each driving distance. First, the information within the service area boundaries of the merged (service area with biomass layer) layer was selected and saved as a separate layer. In this selected layer the geographic area (in square miles) for each of the service areas within boundaries of each county was calculated using the GIS ArcMap Geometry Calculation tool. As the last step of Part 2, the attribute table of the merged shapefile was exported into a spreadsheet. Finally, to specify the availability of biomass in each of the service areas at the county level, the service area proportions were calculated by dividing service areas (in square miles, within respective counties) by the area of the county itself. Reiteration of procedures was carried out for all four processing plant locations depicted in Figure 63.

The final part of the model incorporates per ton mile transportation costs, considering loading/unloading delays, physical availability, and the geographic distribution of the biomass, allowing delivered feedstock costs to be derived. Using 75 gallons of ethanol per dry ton of feedstock conversion rate, driving distances varied by different processing plant capacities (reaching to 210 MGY) were identified (U.S. DOE 2007). This finally allowed transportation costs per ton of feedstock by processing plant capacity to be derived. Integration of per ton mile transportation costs, physical availability of feedstock, and its distribution enabled identifying least-cost processing plant location as affected by the feedstock transportation costs. Further, as discussed in the Results section, this approach allows ranking plant locations according to the type of feedstock utilized (agricultural crop residue vs. forest biomass) and according to the plant processing capacity.

Results

Analytical results indicate that transportation costs differ according to the processing plant capacity, since the larger plants require more feedstock to support their production level, hence longer haul distances. Figure 64 shows the relationship between feedstock transportation costs (per ton) and processing plant capacities (MGY) for the combined (forest biomass and agricultural crop residue) feedstock utilization scenario. The location in Spokane maintains its least-cost feedstock transportation advantage for all processing capacities up to 130 MGY. For this location, a processing capacity of 100 MGY can be supported with the available biomass within only 120 miles from the plant location. To achieve the same level of ethanol processing, plants considering Longview and Ferndale locations will need to reach out twice as far as is required for the Spokane location.

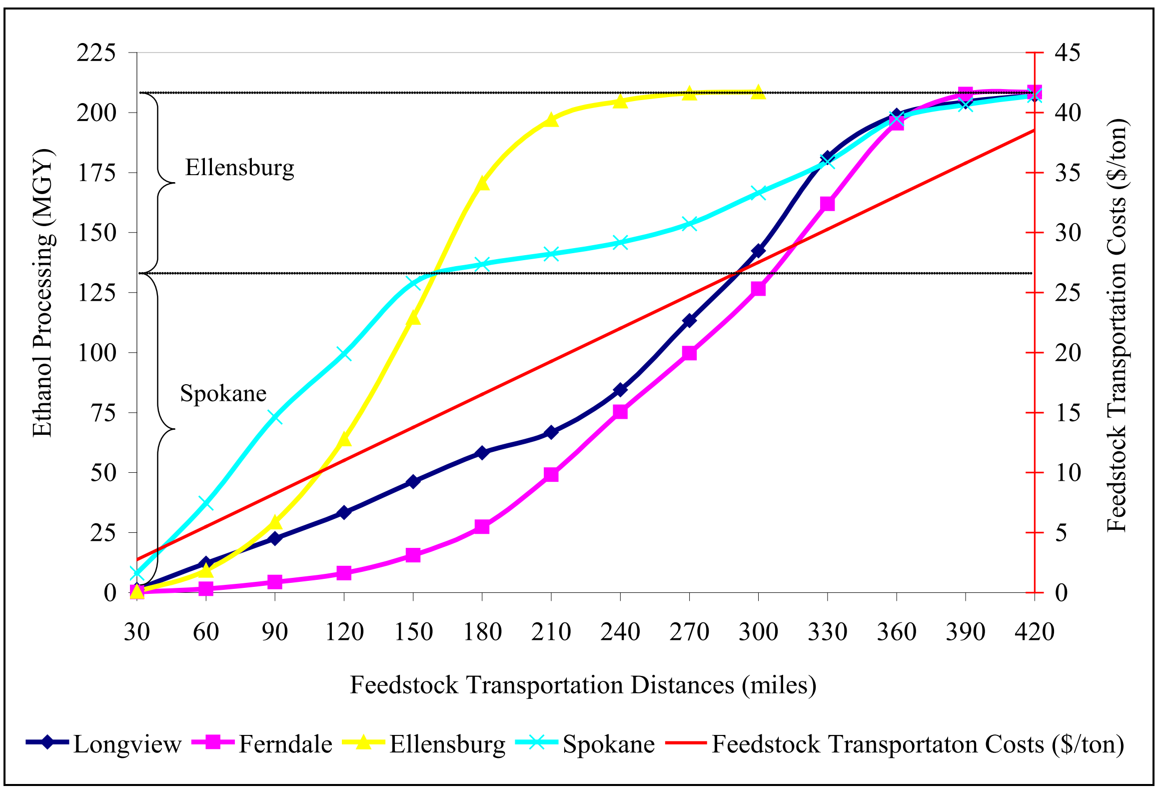


Figure 64: Feedstock Transportation Costs by Processing Plant Capacity (Forest Biomass and Agricultural Crop Residue Combined)

For processing capacities over 130 MGY, the location with the lowest feedstock transportation cost is Ellensburg. A maximum of 210 MGY processing can be achieved using resources within 300 miles around the plant. Locations in Longview and Ferndale were not found to be competitive in this scenario, which considers cumulative (forest and agricultural residue) availability of feedstock resources. Depending on the type of the feedstock considered for ethanol processing, transportation costs differ because each type has different geographic distributions in the study area. To compare results with that of the cumulative feedstock utilization scenario, forest biomass was analyzed separately. The relationship between forest biomass transportation costs and annual ethanol processing for the same plant locations in the study is depicted in Figure 65. Spokane does not necessarily sustain its cost competitiveness when considering feedstocks separately. One of the obvious reasons for considering a separate feedstock scenario is processing/conversion technology restrictions pertaining to different types of feedstocks.

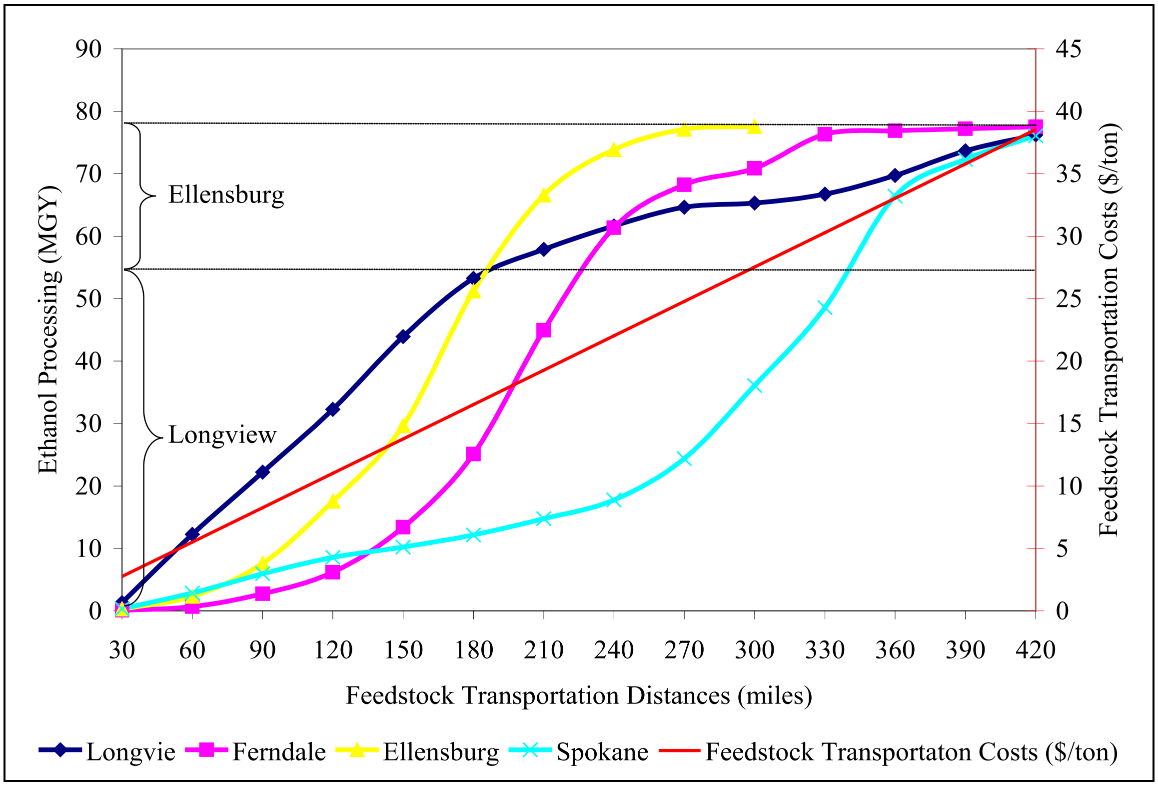


Figure 65: Feedstock Transportation Costs by Processing Plant Capacity (Forest Biomass)

As shown in Figure 65, for processing capacities up to 55 MGY, the Longview location shows the lowest transportation costs when considering forest biomass only. This level of processing capacity can be supported by transporting feedstocks within 180 miles around the plant. For larger capacities (reaching up to 78 MGY at maximum), the Ellensburg location provides the lowest transportation costs. In contrast to the cumulative biomass scenario, the Spokane location is not cost competitive for any of the processing capacities when considering forest biomass only. The Ferndale location has the highest transportation costs for both cumulative and separate feedstock utilization scenarios.

Conclusions

Ethanol processing plant optimal location decisions depend on many factors, including costs associated with feedstock transportation and ethanol distribution. In this section we investigated the least-cost locations in the state of Washington pertaining to the feedstock transportation at different levels of ethanol processing. Because of the spatially variable distribution of the feedstock resources and increasing transportation costs for longer distances, all of the feedstock deposits cannot be utilized at the same expense. Additionally, it was demonstrated that for different processing capacities, optimal plant locations vary according to the type of the feedstock. The GIS approach discussed in this section allowed spatial manipulation of data considering multiple geographic locations in the study area, which provides more accurate evaluation of available feedstock resources within specified distances from processing plants. Finally, the flexibility of the model enables its application to any geographic area. In further steps, the model will be used to analyze the feedstock types identified in the first phase of this project (Frear et al. 2005).

GIS Approach to Delivered Feedstock Costs (Frear et al. Data)

Using the GIS procedures tested with the NREL data, we estimated the availability and the delivered cost of feedstocks using Frear et al. (2005) data. Figures below show the relationship between feedstock transportation costs and plant processing capacities by haul distances for four potential biorefinery locations in the state. GIS maps with 30-mile increasing service areas (buffer zones) are provided for each of the locations. Considering forest residue feedstock for the Vancouver/Longview location (Figures 66 and 67), a 100 MGY plant requires feedstocks to be transported from about 90 miles of haul distance.

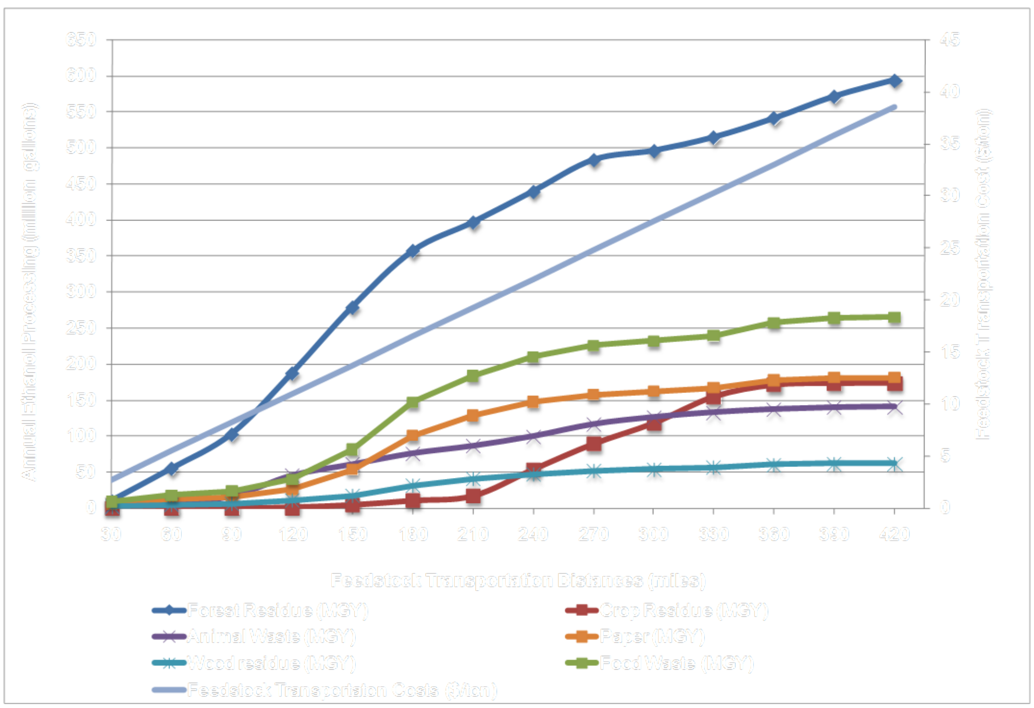


Figure 66: Feedstock Transportation Costs by Haul Distances for Vancouver/Longview Plant

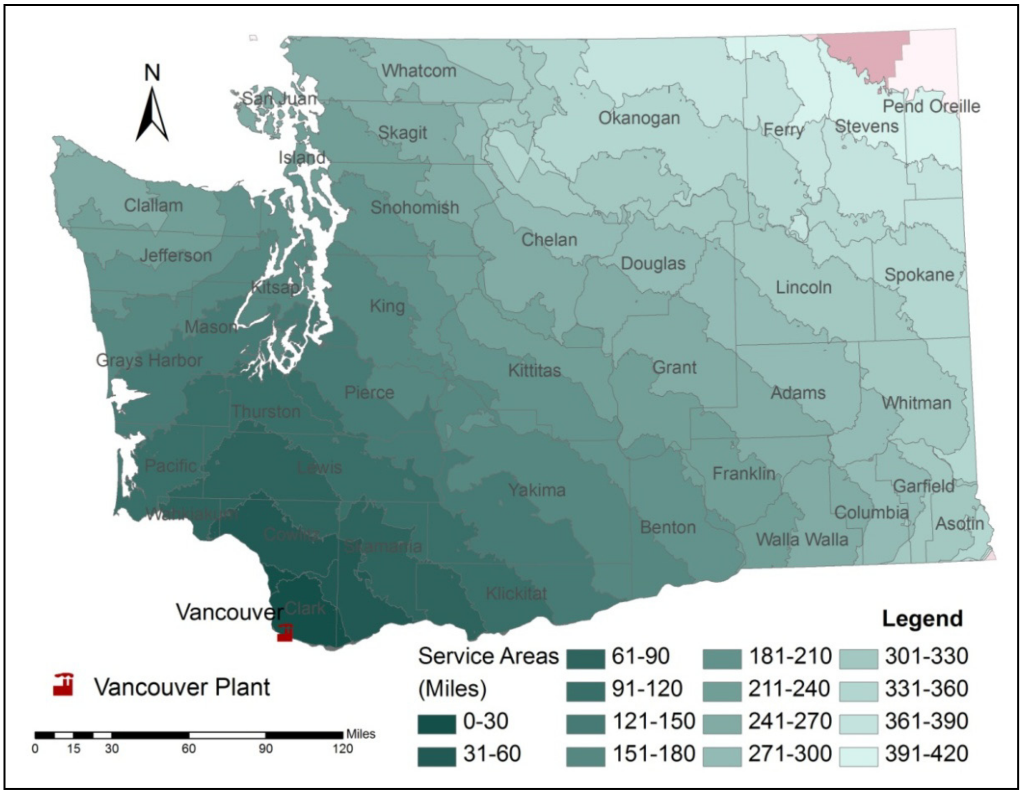


Figure 67: Service Areas for Vancouver/Longview Plant

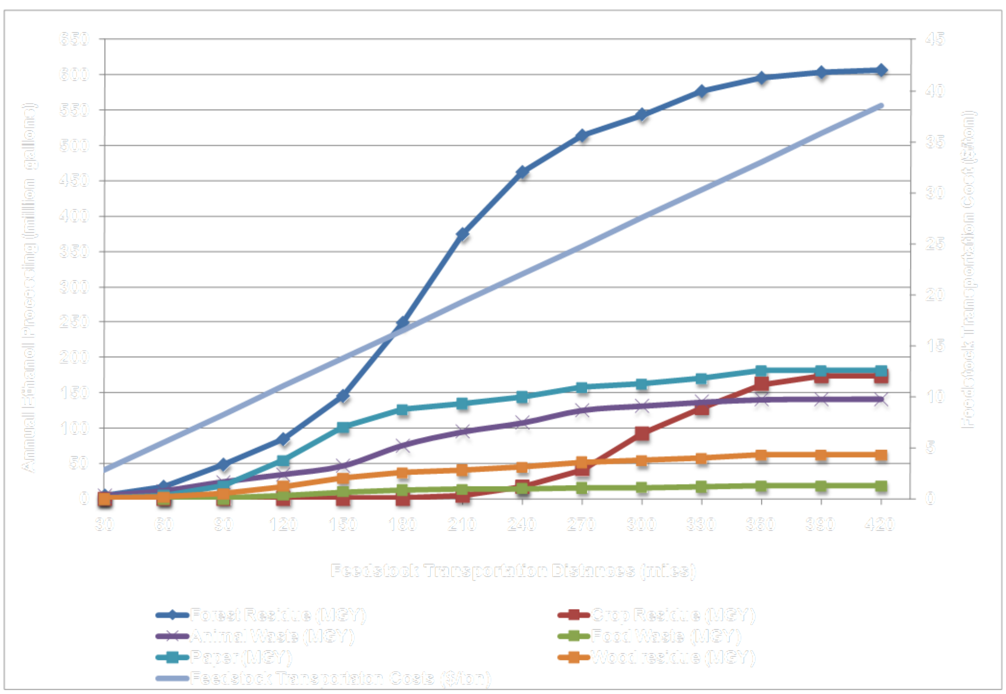


Figure 68: Feedstock Transportation Costs by Haul Distances for Ferndale Plant

As shown in Figures 68 and 69, considering forest residue feedstock for the Ferndale location, a 100 MGY plant requires feedstocks to be transported from about 130 miles of haul distance. To support the same capacity of ethanol processing from paper residue (for example), feedstocks need to be transported from within a 150-mile distance from the potential biorefinery location, thus increasing transportation costs.

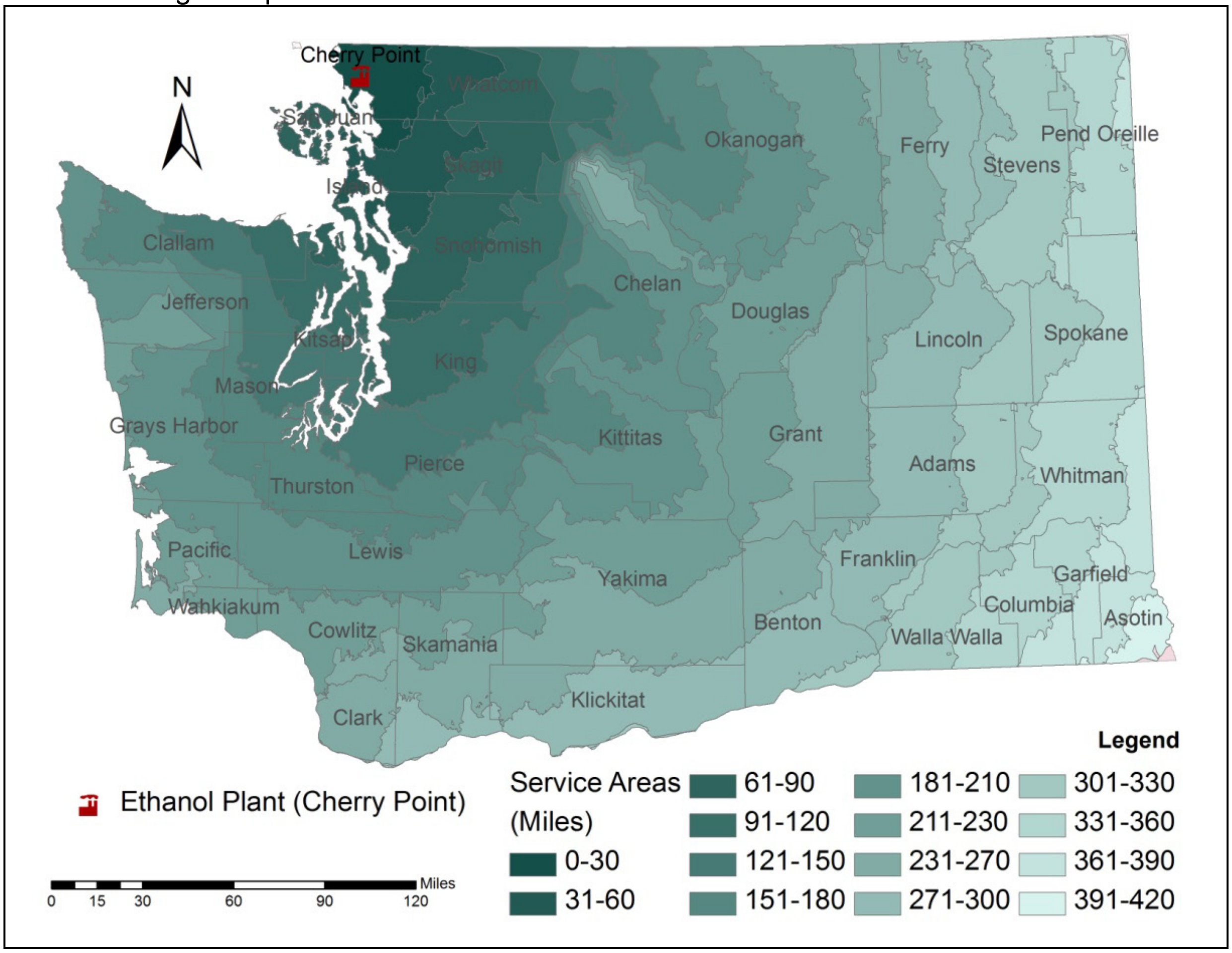


Figure 69: Service Areas for Cherry Point/Ferndale Plant

Based on Figures 70 and 71, a ~150 MGY processing plant can be supported by feedstocks collection from only 150 miles of haul distance from the potential biorefinery in Spokane. To support the same capacity of ethanol processing from forest residue, feedstocks need to be transported from about 230 miles from the biorefinery location. Feedstock transportation costs increase respectively.

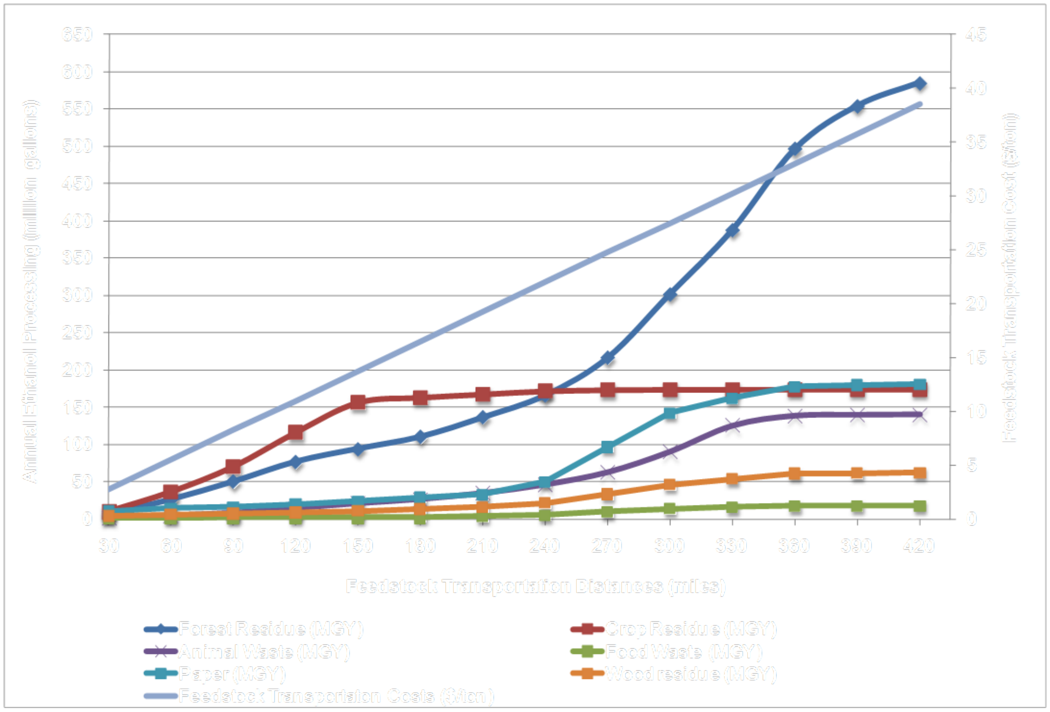


Figure 70: Feedstock Transportation Costs by Haul Distances for Spokane Plant

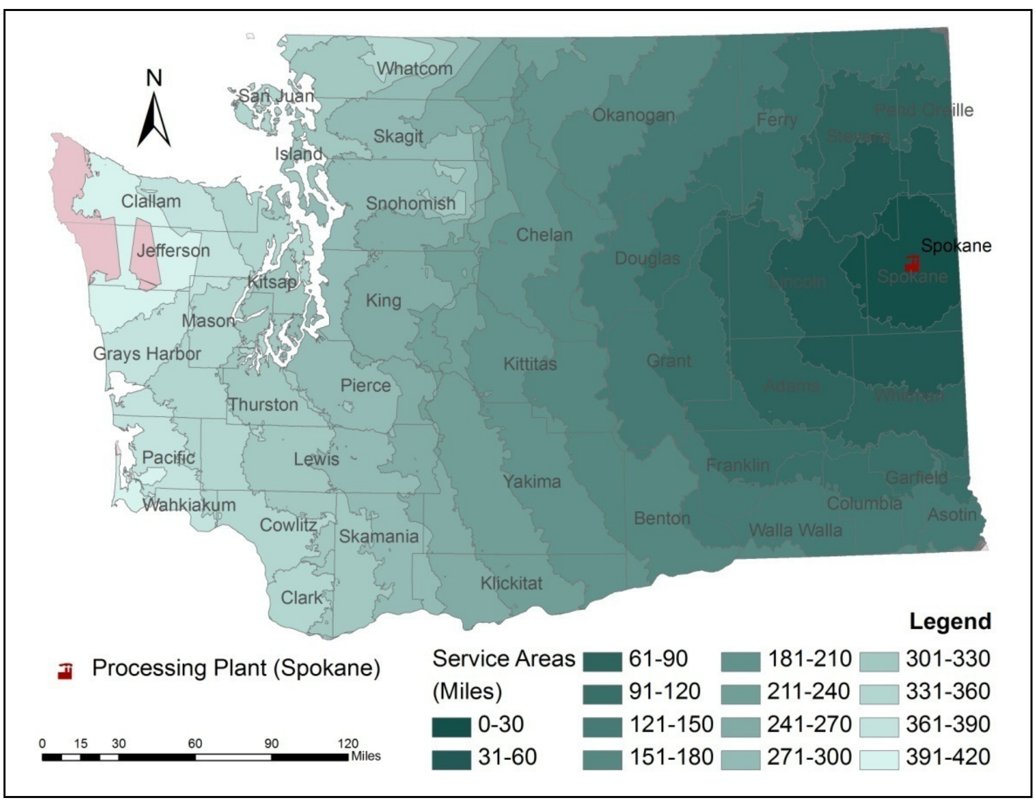


Figure 71: Service Areas for Spokane Plant

According to the results shown in Figures 72 and 73, considering forest residue feedstock for the Ellensburg location, a 100 MGY plant requires feedstocks to be transported from about 100 miles of haul distance. To support the same capacity of ethanol processing from crop or paper residue, the haul distance increases to about 120 miles from the biorefinery location.

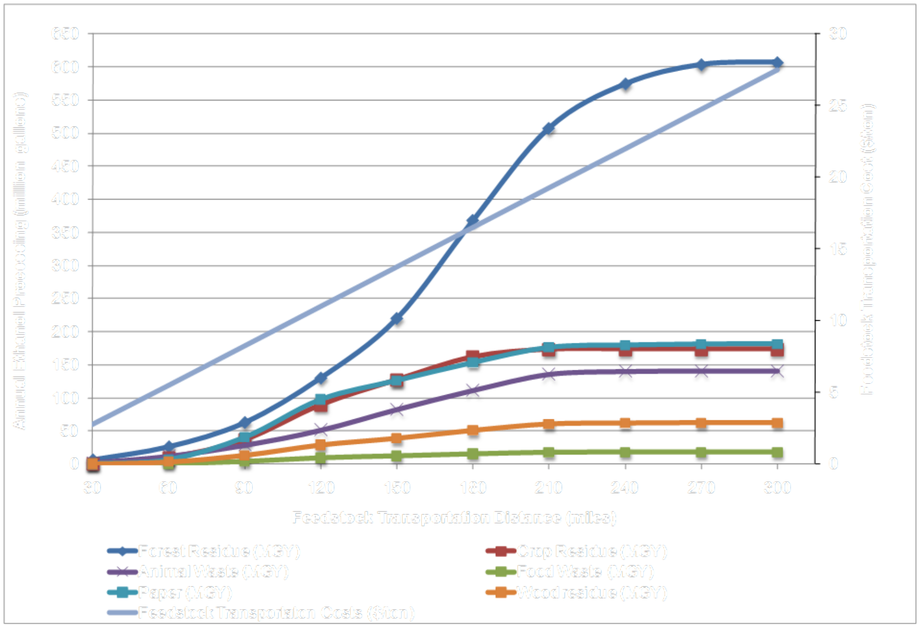


Figure 72: Feedstock Transportation Costs by Haul Distances for Ellensburg Plant

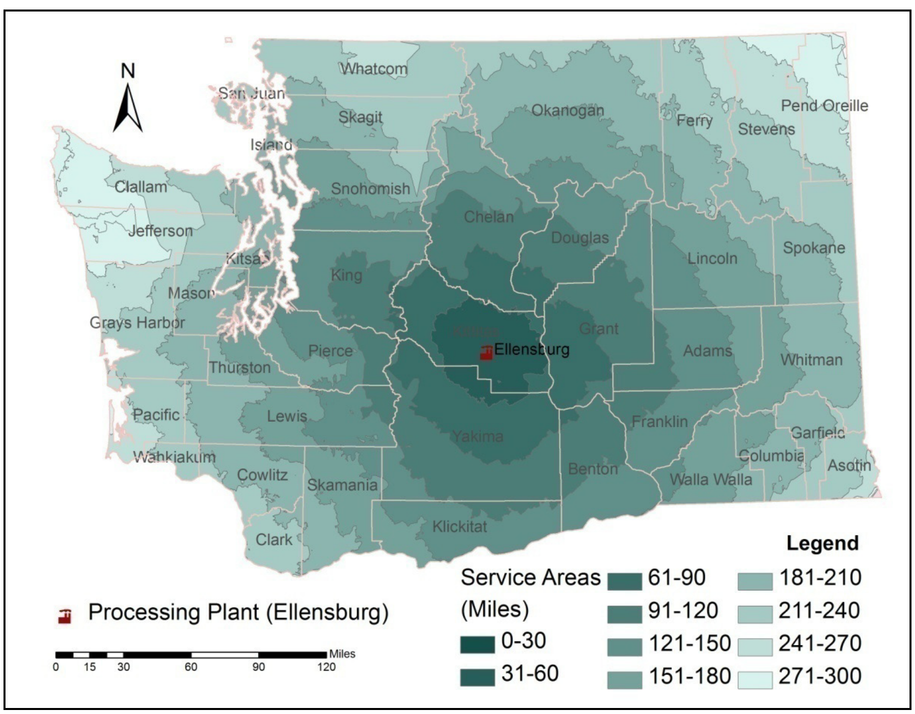


Figure 73: Service Areas for Ellensburg Plant

GIS Analysis for Biofuel Plant Least-Cost Location Decisions (Frear et al. Data)

In this section we introduce results using the GIS biofuel plant least-cost location decision model introduced earlier in this report. The model provides information to support cellulosic ethanol plant least-cost location decisions by integrating geographic distribution of biomass in the study area with associated transportation costs. The GIS procedures are similar to the pilot model tested above. Figure 74 shows feedstock collection service areas covering the study area in 30-mile increments.

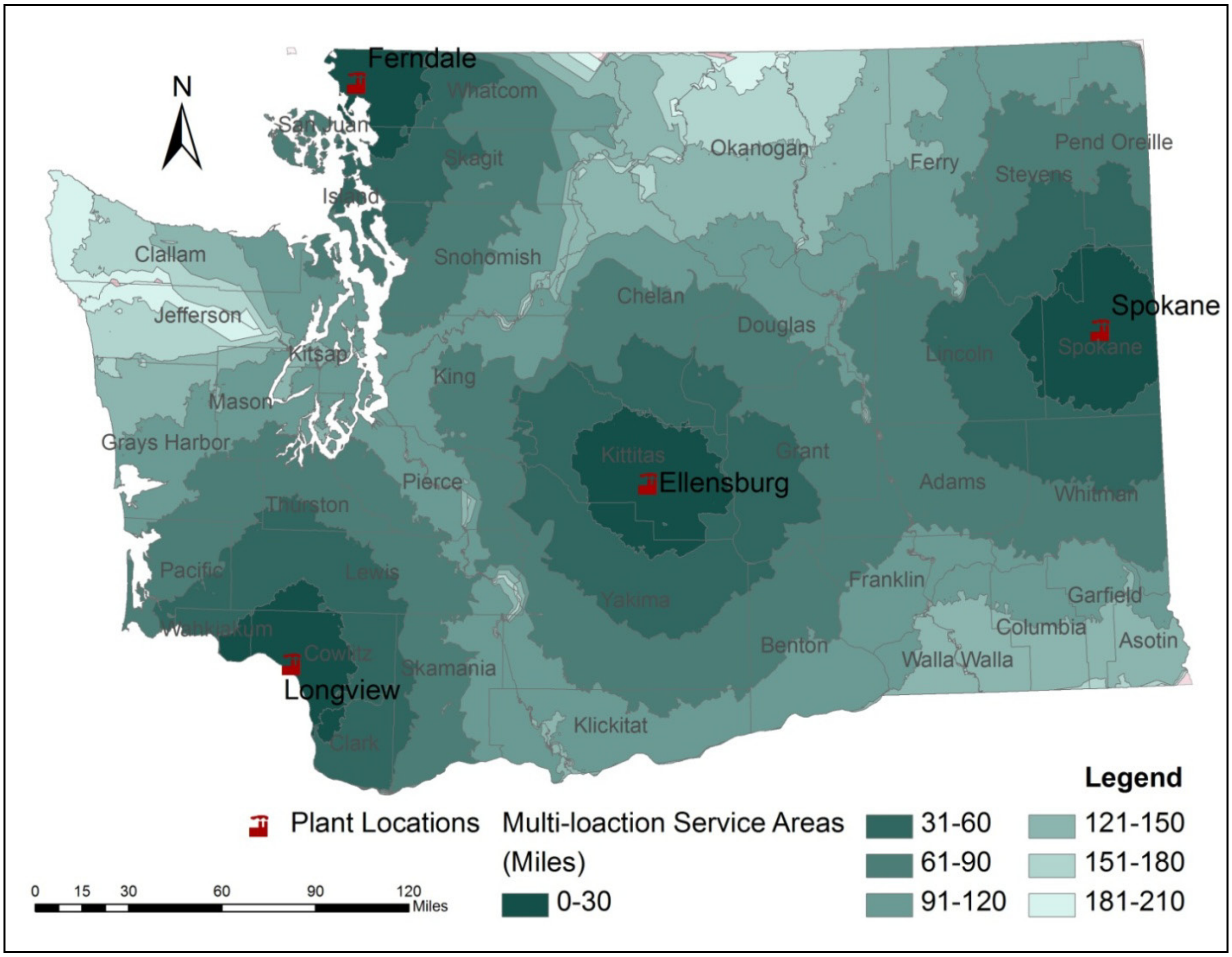


Figure 74: Multi-Location Service Areas for Four Plants in the State of Washington

As shown in Figure 75, the results indicate that transportation costs increase with increasing processing plant capacity, since the larger plants require more feedstock to support their production level, hence longer haul distances. Figure 75 shows the relationship between feedstock transportation costs (per ton) and processing plant capacities (MGY) for agricultural crop residue utilization scenario.

The location in Spokane maintains its least-cost feedstock transportation advantage for all processing capacities up to 165 MGY. For this location, a processing capacity of 100 MGY can be supported with the available biomass within about 105 miles from the plant location. To achieve the same level of ethanol processing, plants considering the Ellensburg location need to reach out about 120 miles from the plant. Longview and Ferndale locations will require hauling twice as far as is required for the Spokane location.

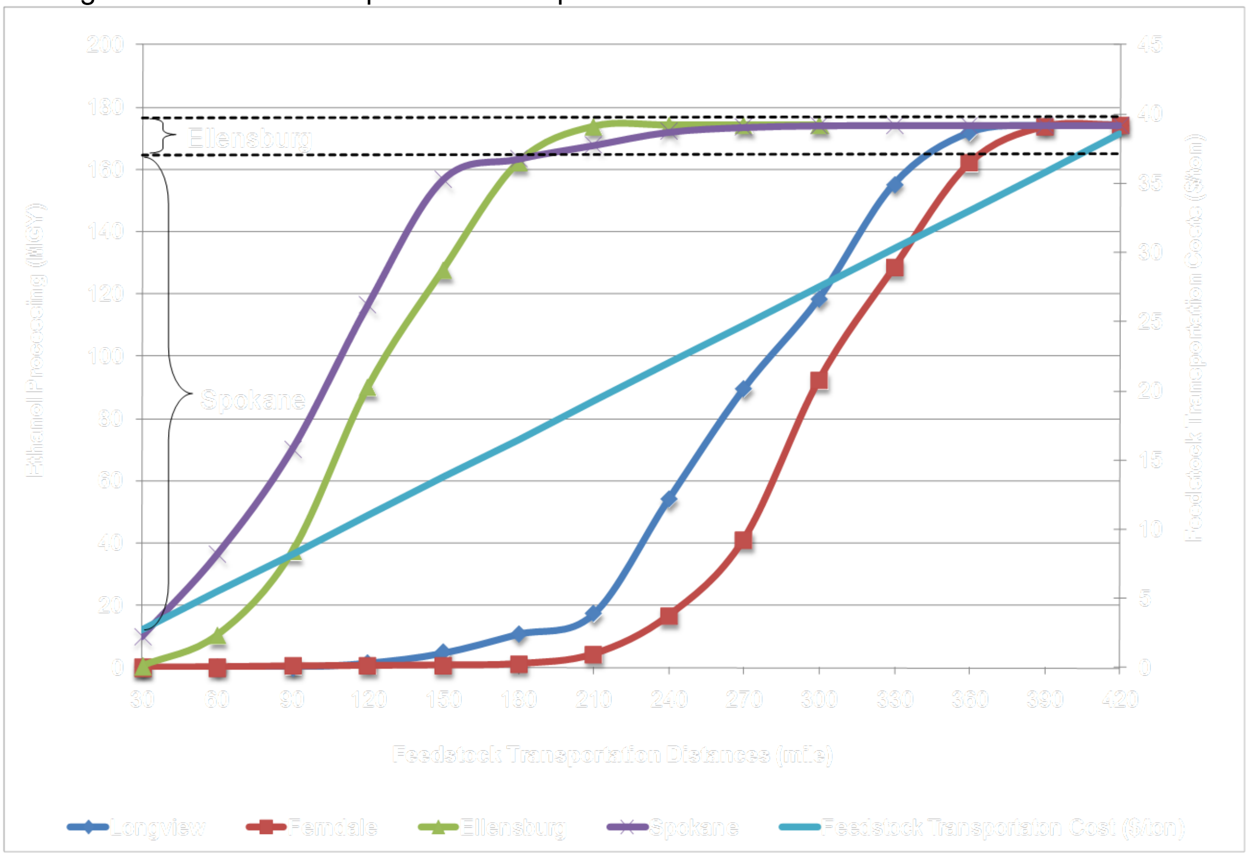


Figure 75: Feedstock Transportation Least-Cost Locations (Crop Residue)

Figure 76 shows the relationship between feedstock transportation costs (per ton) and processing plant capacities (MGY) for the forest residue utilization scenario. The location in Longview maintains its least-cost feedstock transportation advantage for all processing capacities up to 350 MGY. For this location, a processing capacity of 100 MGY can be supported with the available biomass within about 90 miles from the plant location. To achieve the same level of ethanol processing, plants considering the Ellensburg location need to reach out about 110 miles from the plant. Ferndale and Spokane locations will require feedstocks to be transported from 130- and 160-mile haul distances, respectively.

Figure 77 shows the relationship between feedstock transportation costs (per ton) and processing plant capacities (MGY) for the animal waste utilization scenario. Given the geographic distribution of animal manure in the state, the Ellensburg location has advantage over all three locations for all processing scales. For this location, a processing capacity of 100 MGY can be supported with the available biomass within about 160 miles from the plant location. To achieve the same level of ethanol processing, plants considering the Ferndale and Longview locations need to reach out about 220 and 240 miles from the plant, respectively.

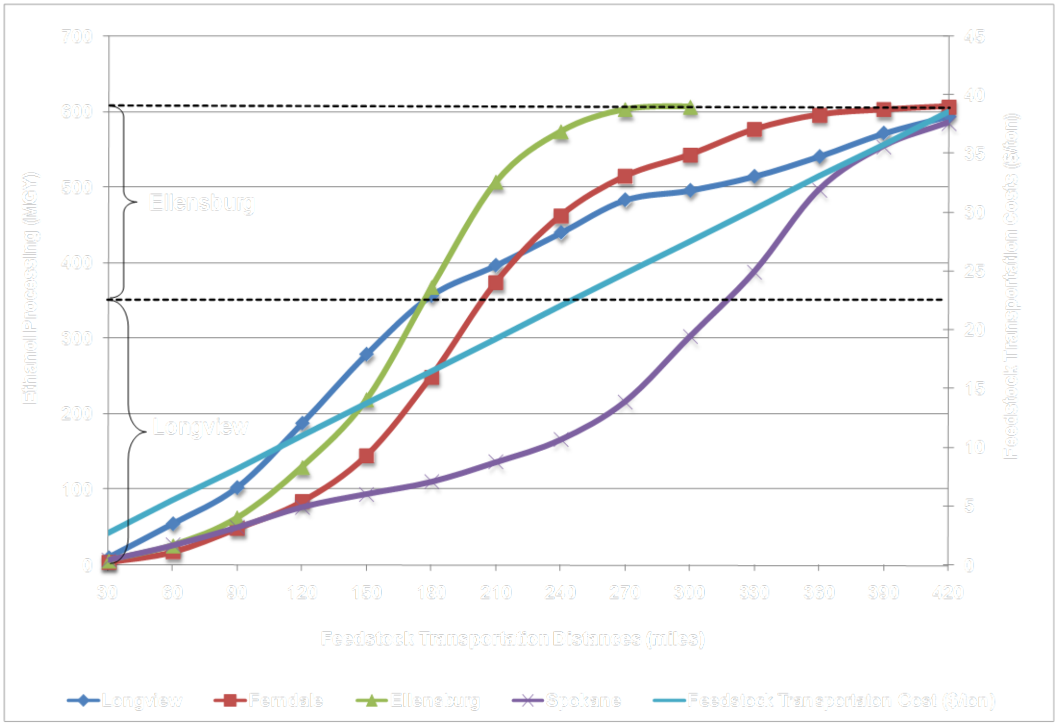


Figure 76: Feedstock Transportation Least-Cost Locations (Forest Residue)

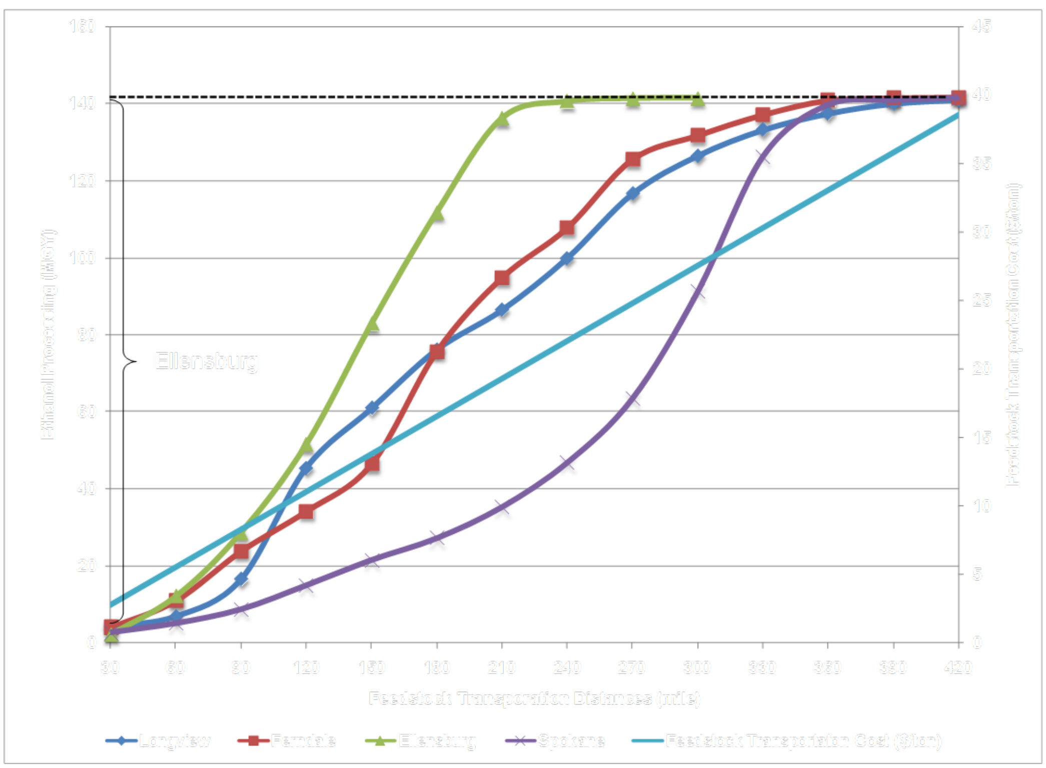


Figure 77: Feedstock Transportation Least-Cost Locations (Animal Waste)

Figure 78 shows the relationship between feedstock transportation costs (per ton) and processing plant capacities (MGY) for the food waste utilization scenario. Again, given the geographic distribution of food waste in the state, the Ellensburg location has advantage over the other three locations for all processing scales. The Longview location is cost-competitive for only small-scale production (under 2 MGY). Feedstocks transported from about 200 miles can support only about 18 MGY processing, respectively increasing the transportation costs.

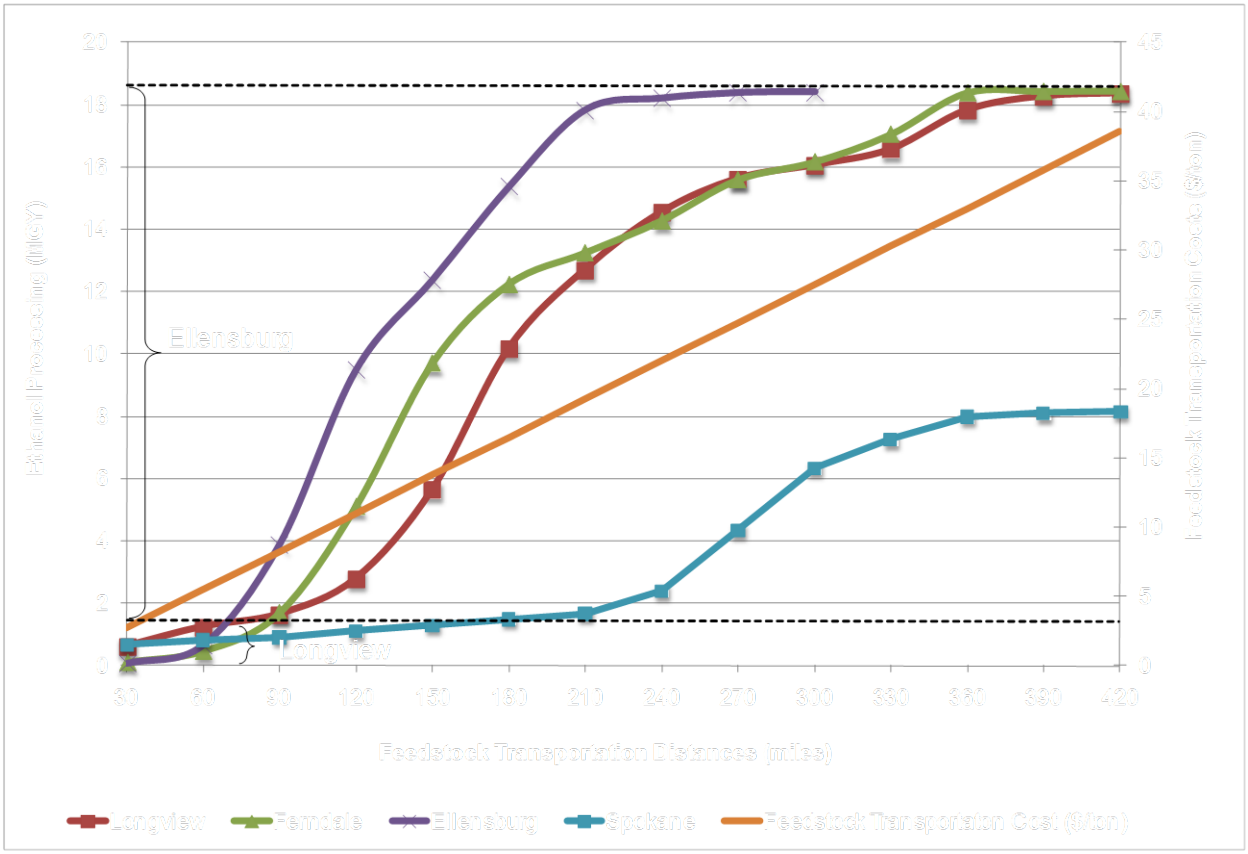


Figure 78: Feedstock Transportation Least-Cost Locations (Food Waste)

Figure 79 shows the relationship between feedstock transportation costs (per ton) and processing plant capacities (MGY) for the paper waste utilization scenario. Similar to the previous two feedstock categories, the Ellensburg location has advantage over the other three locations for processing scales above 10 MGY. For this location, a processing capacity of 100 MGY can be supported with the available biomass within about 110 miles from the plant location. To achieve the same level of ethanol processing, plants considering the Ferndale and Longview locations need to reach out about 150 and 180 miles from the plant, respectively.

Figure 80 shows the relationship between feedstock transportation costs (per ton) and processing plant capacities (MGY) for the wood residue utilization scenario. The location in Ellensburg shows the least-cost feedstock transportation advantage for processing capacities above 7 MGY. For this location, a processing capacity of 50 MGY can be supported with the available biomass within about 180 miles from the plant location. To achieve the same level of ethanol processing, plants considering Longview and Ferndale locations need to reach out about 250 miles from the plant.

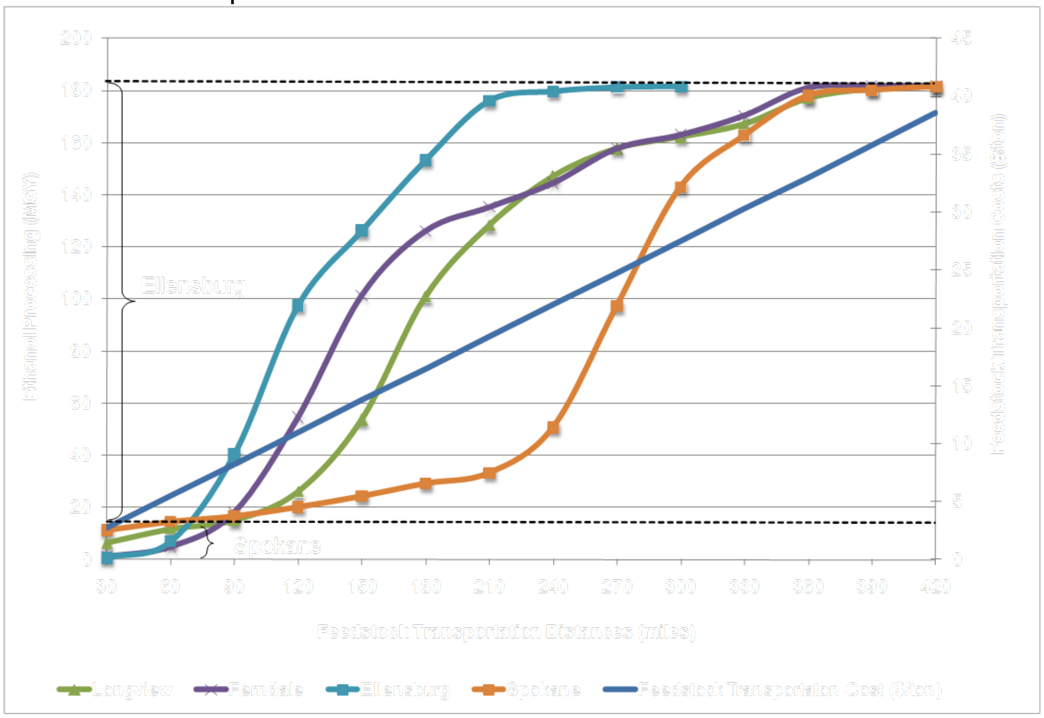


Figure 79: Feedstock Transportation Least-Cost Locations (Paper Waste)

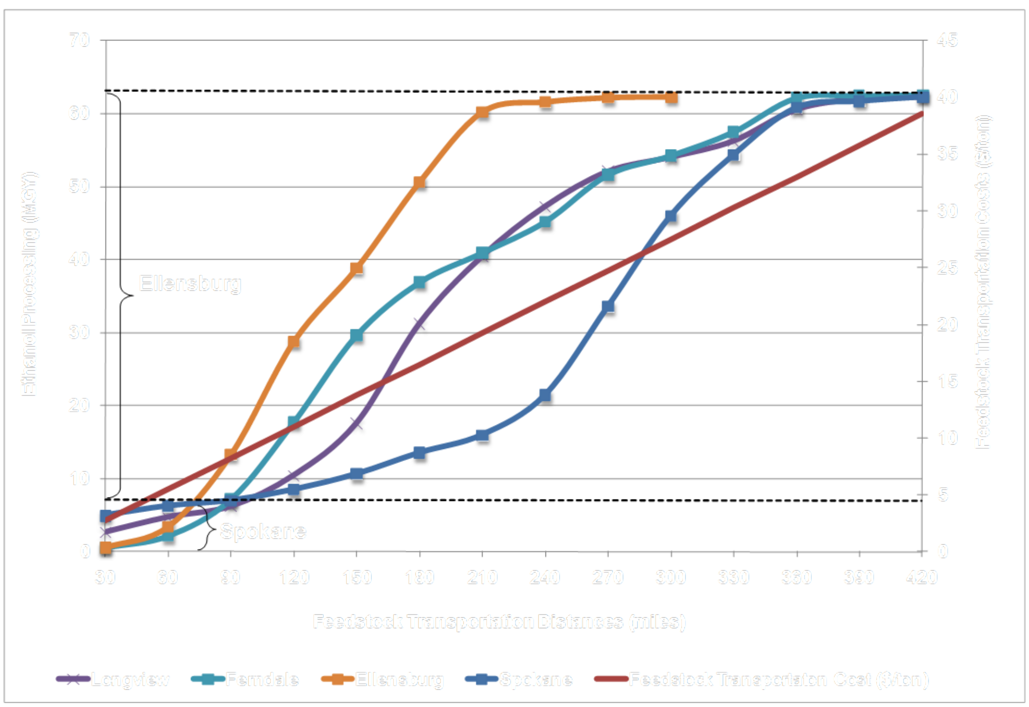


Figure 80: Feedstock Transportation Least-Cost Locations (Wood Residue)

Figures 81 and 82 show additional results for cumulative feedstocks—crop and forest residues, and animal waste combined with MSW.

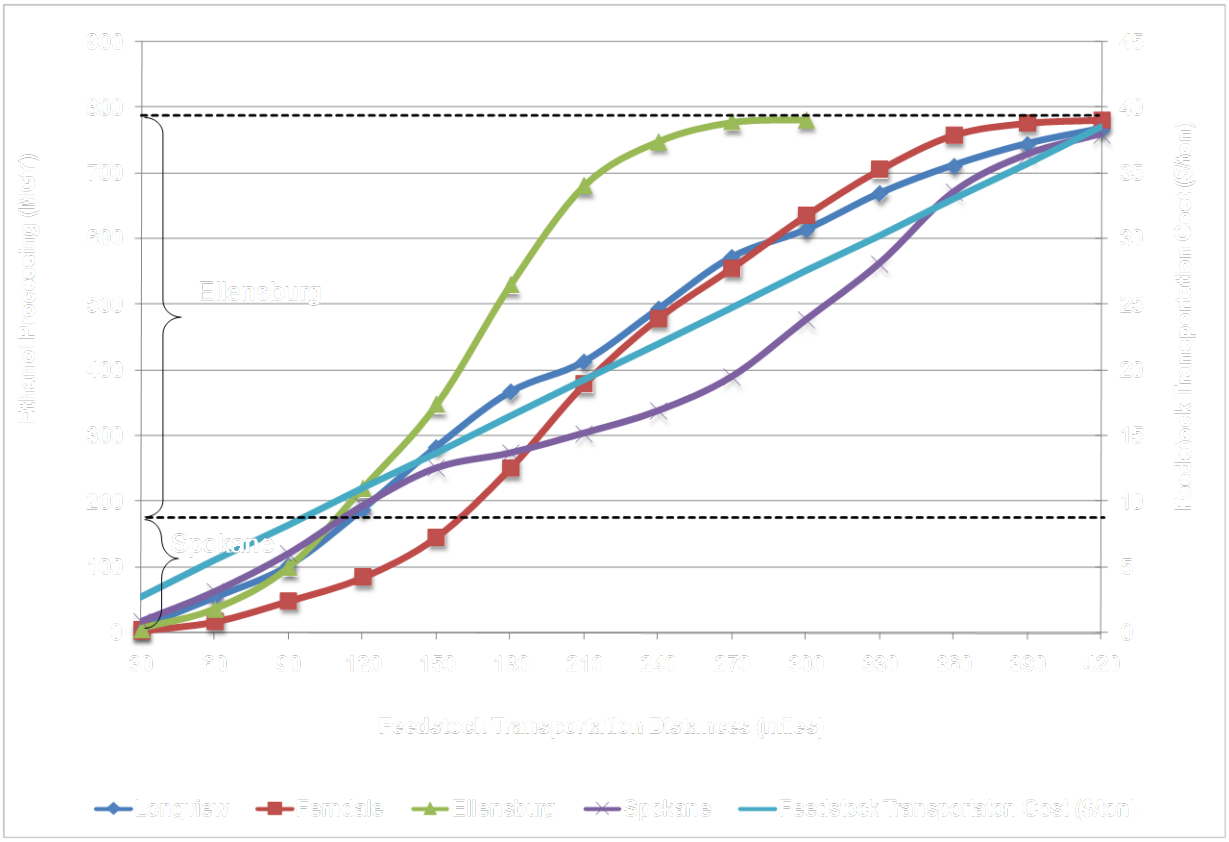


Figure 81: Feedstock Transportation Least-Cost Locations (Crop and Forest Residue)

Distribution Costs

Distribution Infrastructure Overview

Depending on market locations, distribution costs may influence the total delivered costs of the ethanol blend. Partially complemented by truck transportation, rail is one of the current primary modes of transportation for ethanol distribution from processing plants to blending terminals. However, the limited capacity of the current railroad system, combined with increasing mandated levels of biofuel processing (EISA 2007), suggests an immediate need for considerable improvements, both in terms of transportation capacity and its economic feasibility (U.S. GAO 2007).

Despite pipeline transportation's economic and environmentally promising benefits, such as traffic congestion and emissions reductions, thus far no dedicated networks exist for ethanol shipments via pipelines, either to blending terminals or to final markets. Additionally, due to a number of technical problems (including ethanol's moisture-attracting characteristic), existing gasoline pipelines are not suitable for ethanol distribution. While this mode of transportation needs further technological investigation, an improvement of existing railroad infrastructure and further investigation of the cost-competitiveness of the truck transportation mode remain critical.

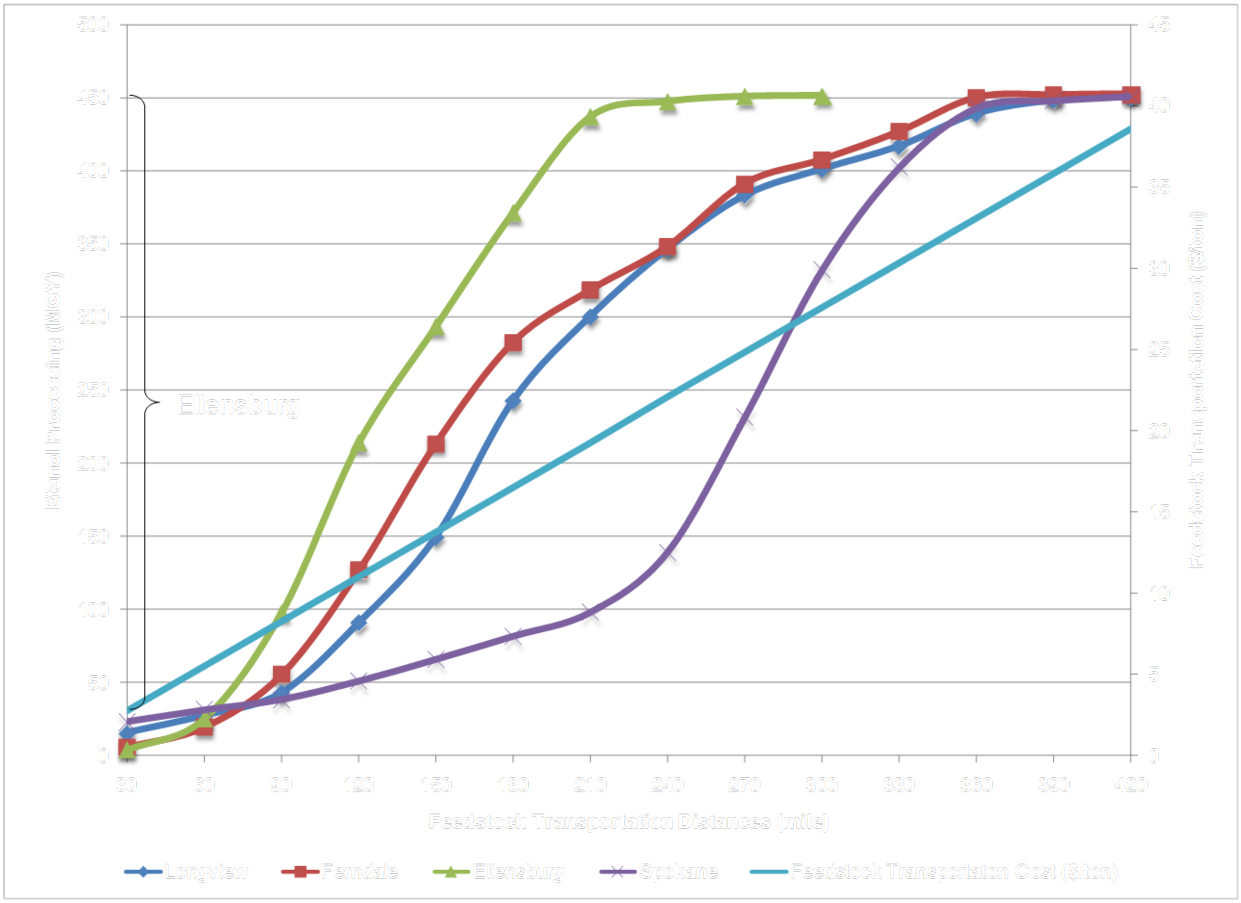


Figure 82: Feedstock Transportation Least-Cost Locations (Animal Waste and MSW)

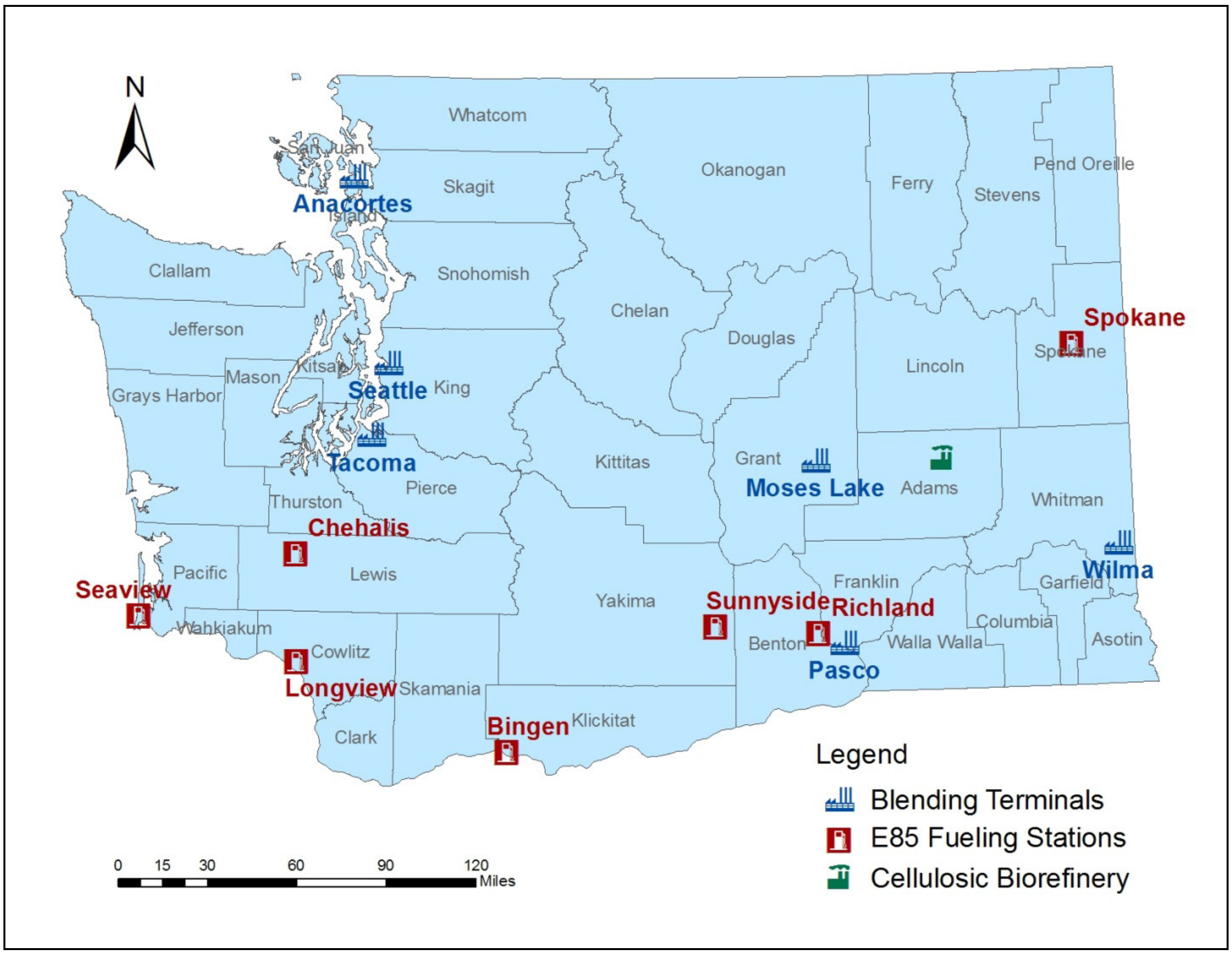
The distribution infrastructure improvements include capital investments associated with ethanol fueling stations as well. According to the U.S. Government Accountability Office (U.S.GAO 2007), in 2007 only about 1% of fueling stations in the United States had capacity/efficiency to offer E85 fuel.[16] Given mandated levels of cellulosic ethanol processing for the next decade, this limited capacity of the existing distribution infrastructure, including transportation efficiency and existing E85 fueling stations availability, may create considerable obstacles for the development of the emerging cellulosic ethanol industry. Therefore, further economic feasibility investigation of transportation modes, such as truck, is critical in increasing the number of gas stations (at "least-cost" locations) offering ethanol blend, since efficient operation of retail stations partially depends on a steady supply system.

The ethanol distribution system consists of two segments. First, the processed ethanol is shipped to blending/distribution terminals (also known as racks). Racks also serve as storage facilities that the conventional gasoline is transported to via pipelines, barge, truck, or railroad

[16] Blend of 85% ethanol and 15% gasoline.

modes. At the blending terminals the pure ethanol is blended into E10 or E85 (depending on the demand), which is then distributed by tank trailer trucks to the fueling stations offering E85 or E10 ethanol blend. According to Johnson and Melendez (2007), terminal shipment and storage costs add about $0.04 per gallon to the cost of gasoline. The U.S. GAO (2007) estimated the overall cost of ethanol distribution, including shipments to blending terminals and distribution to gas stations, at $0.13 to $0.18 per gallon depending on the proximity of markets from processing plants.

Distribution costs derived in this report include both shipment costs to the blending terminals in the state (using the least-cost/distance approach), and to the E85 fueling stations, with spatially optimized routes using GIS. Figure 83 shows the distribution of existing blending terminals and E85 fueling stations in the state of Washington. The map includes only publicly accessible E85 fueling stations, leaving out three private or government-only facilities.



Data Source: E85 fueling station location information: National Ethanol Vehicle Coalition webpage (NAVC 2008); Blending terminal location information: OPIS Rack Cities (2008).

Figure 83: State of Washington Blending Terminals (Racks) and E85 Fueling Station Locations

An Economic Engineering Calculation of Trucking Costs for Distribution

The economic engineering approach to calculating trucking costs used earlier in this report was modified to include tank trailers (different from flat-bed or drop-bed trailers considered for feedstock transportation). Table 12 provides modified input values needed for both fixed and variable cost components of trucking costs. Descriptions provided in the Economic Engineering Framework section are correspondingly applicable to the fixed and variable cost components shown in Table 13. First, trucking cost per gallon of ethanol has been derived, which was further converted into per mile and per gallon mile measures needed for the ethanol distribution cost derivations.

Table 12: Truck (Tank Trailer) Transportation Cost Calculation Inputs (Ethanol Distribution)

Component	Units	Truck	Tank Trailer
Purchase Price	$	110,000	50,000
Time Period of Ownership	years	10	10
Expected Salvage Value	$	28,600	17,500
Annual Cost of Repairs	$	9,336	1,000
Number of Tires	number	10	8
Replacement Cost per Tire	$	400	400
Lifetime per Tire	miles	60,000	72,000
Annual Miles Driven	miles	53,800	–
Annual Gallons Hauled	tons	2,690,000	–
Interest Rate	%	0.07	–
Price of Fuel	$/gallon	4.61	–
Fuel Efficiency	miles/gallon	5.5	–
Average Hauling Speed	miles/hour	45	–
Annual Cost of License	$	2,000	–
Annual Cost of Insurance	$	220	–
Driver Labor Rate	$/hour	17.41	–

Table 13: Truck and Tank Trailer Transportation Total Costs (Ethanol Distribution)

Description	Truck ($/year)	Trailer ($/year)	Total Cost ($/year)	Total Cost ($/gallon)	Total Cost ($/mile)	Total Cost ($/gallon/mile)
Fixed Costs						
Capital Recovery (Interest and Depreciation)	13,592	5,852	19,444	0.007	0.361	0.00007
Taxes, Insurance, and License	2,220	500	2,720	0.001	0.051	0.00001

Total Fixed Costs	15,812	6,352	22,164	0.008	0.412	0.00008
Variable Costs						
Repair Cost	9,336	1,000	10,336	0.004	0.192	0.00004
Tires Cost	3,587	2,391	5,978	0.002	0.111	0.00002
Fuel Cost	45,094	–	45,094	0.017	0.838	0.00017
Lubrication Cost	4,509	–	4,509	0.002	0.084	0.00002
Labor Cost	20,815	–	20,815	0.008	0.387	0.00008
Total Variable Costs	83,341	3,391	86,732	0.032	1.612	0.00032
Total Costs	**99,153**	**9,743**	**108,896**	**0.040**	**2.024**	**0.00067**

Per Gallon Mile Costs

As mentioned earlier, the basics of deriving the total distribution costs involves two parts: distribution to blending terminals (racks), followed by the distribution to final markets (E85 or E10 fueling stations in the state). Because longer distances increase transportation costs, the same logic as with the transportation of feedstocks can be applied to understand the relationship between distribution costs and haul distances. To support larger-capacity processing plant operations, feedstocks need to be transported for longer distances, consequently increasing transportation costs. Alternatively, since fueling stations have limited storage capacity, the larger the volume of the processing plant, the longer are the distances that the ethanol needs to be distributed to reach out more fueling stations.

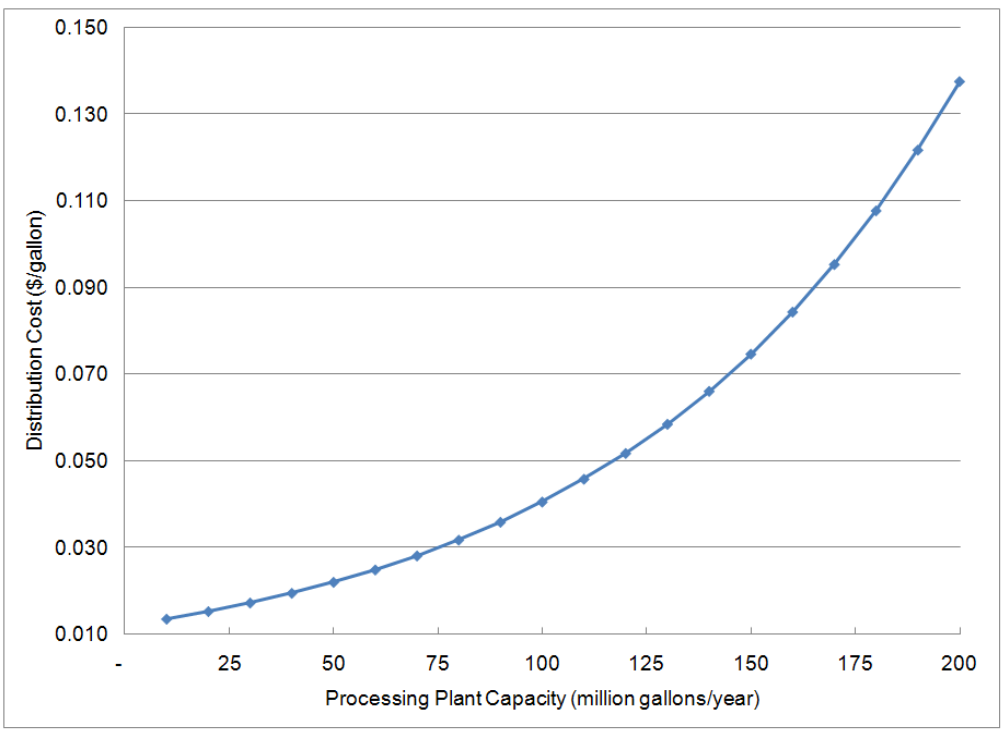


Figure 84: Distribution Costs per Gallon of Ethanol by Processing Plant Capacity

If we consider ethanol shipments from one processing plant, the cost of the distribution to blending terminals (first segment) is relatively fixed, since the distances from processing plants to the terminals are constant. However, the distribution distances from the blending terminals to E85 fueling stations (second segment) increase as soon as stations in the vicinity of the rack receive their full capacity volumes of ethanol blend (E85 or E10). Total distribution costs can be derived by combining shipment costs to terminals and distribution costs to E85 stations. It should be noted, however, that depending on the business structure, ethanol plants may choose to ship (sell) their production to blending terminals, leaving the rest of the costs to other businesses, called jobbers or middleman (Johnson and Melendez 2007). Alternatively, terminals that are owned by independent companies may purchase the ethanol from refineries, and blend and distribute the fuel themselves. Regardless of the business structure, the delivered costs to final markets still include costs associated with both segments—shipment costs to terminals and distribution costs to ethanol blend fueling stations.

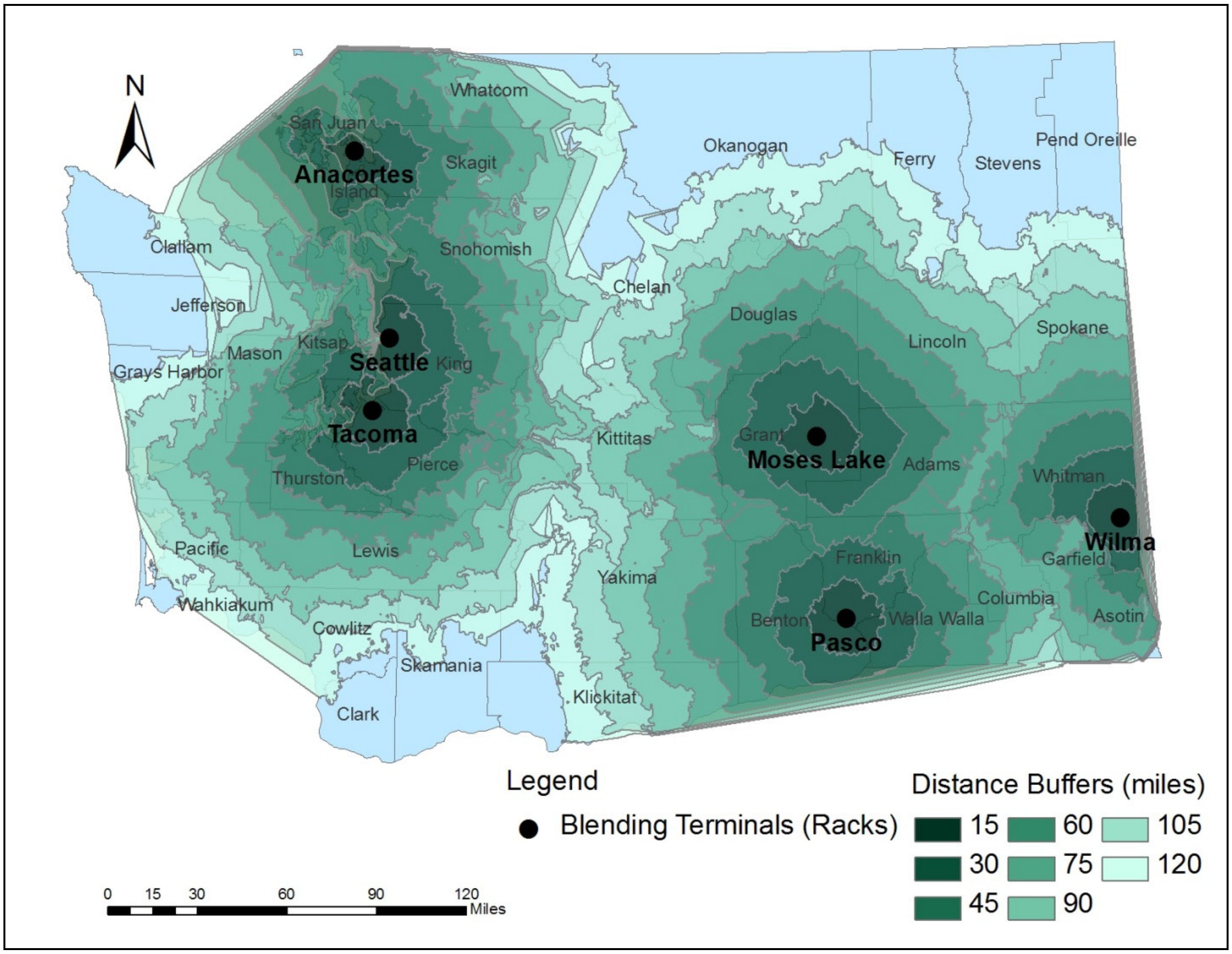


Figure 85: Blending Terminals with 15-, 30-, 45-, 60-, 75-, 90-, 105-, and 120-Mile Distance Buffers

At each level of processing capacity, transportation costs from processing plants to blending terminals can be added to costs accrued from terminals to E85 stations to derive the total distribution costs. Applying per gallon mile truck transportation costs to increasing distances, distribution costs result in an upward-sloping curve ranging from $0.013 to $0.138 per gallon for 100 to 200 MGY processing plants, respectively (Figure 84). E85 fueling stations (shipment destinations) were assumed to have a tank/storage capacity of 8,000 gallons on average, dispensing 8 gallons per minute, 10 hours a day, and 300 days a year, based on a gas stations study conducted by Geyer (2008). The sequence of ethanol distribution to E85 stations was assumed to be ranked according to the proximity to the blending terminals (origins). In other words, E85 stations that are within the boundaries of the first distance band from the distribution terminal (created using GIS, refer to Figure 85) are served first. Once the capacity of the stations in the first distance band is filled, stations in the second distance band are supplied, and so forth.

Figure 85 shows the map of state's current blending terminals surrounded with 15-, 30-, 45-, 60-, 75-, 90-, 105-, and 120-mile distance buffers, which were created with the ArcGIS Network Analyst Service Area tool. The outer boundary of each distance band represents the maximum distance from the blending terminal. For example, all E85 fueling stations that are within the first distance buffer have a maximum distance of 15 miles from a given blending terminal. To avoid multiple use of the same E85 station in the overlapping distance band areas, the GIS Network Analyst Service Area tool eliminates points (E85 stations) that were once considered to be supplied from a blending terminal.

GIS Investigation of Distribution Costs for Existing Infrastructure

This section presents a case study in which the distribution costs are calculated for the existing E85 fueling stations in the state. As with feedstock transportation, ethanol distribution costs can be spatially investigated with the use of GIS. Particularly, GIS least-cost or shortest-route identification tools were used to find optimal routes from an ethanol processing plant to existing blending terminals, and further, to fueling stations in the state of Washington. For this part of the spatial analysis, location information of a cellulosic biorefinery, existing blending terminals, and E85 stations (depicted in Figure 83) was considered. For the second part, distribution routes from blending terminals to E85 fueling stations were identified with the use of the GIS Network Analyst Origin-Destination Cost Matrix solver.

The concept of shortest route has different interpretations. The cost attribute for optimal route calculation can be set as drive time (minutes), since same-distance routes can have different speed limits, resulting different drive times. Alternatively, GIS can incorporate driving distance (miles) as a cost attribute for optimal route calculations. For purposes in this part of the report, distance information was used as a cost attribute for the GIS optimal route, as well as origin-destination cost ranking calculations.

First, the processing plant, blending terminals, and E85 fueling stations were mapped as shown in Figure 86. The GIS Network Analyst Closest Facility toolset was utilized to solve for optimal routes identification that originate from one processing plant in eastern Washington and reach all existing E85 stations in the state through six blending terminals. After the optimal route determination, spatial information regarding distances and drive times, facility (plant) and object (blending terminal) ID and other route details can be extracted into spreadsheet. Part of the extracted attribute table information regarding the processing plant to blending terminal segment is summarized in the Trucking Cost Calculation Tables section.

To derive the distribution costs, per gallon mile trucking rates found in the Economic Engineering Construction of Trucking Costs for Distribution section were utilized. The resulting least-cost destinations (blending terminals) from the cellulosic biorefinery are as follows: Moses

Lake ($0.03/gallon), Pasco ($0.05/gallon), Wilma ($0.07/gallon), Seattle ($0.15/gallon), Tacoma ($0.16/gallon), and Anacortes ($0.20/gallon) (Figure 87). The consideration of only one processing plant and six blending terminal locations makes the computation of optimal routes relatively straightforward. However, with the growing ethanol industry that will eventually result in increasing numbers of processing plants and E85 fueling stations, the route optimization can be complicated. Therefore, this methodology is useful for the route optimization and distribution costs derivation with multiple ethanol processing plants serving hundreds of fueling stations in the state.

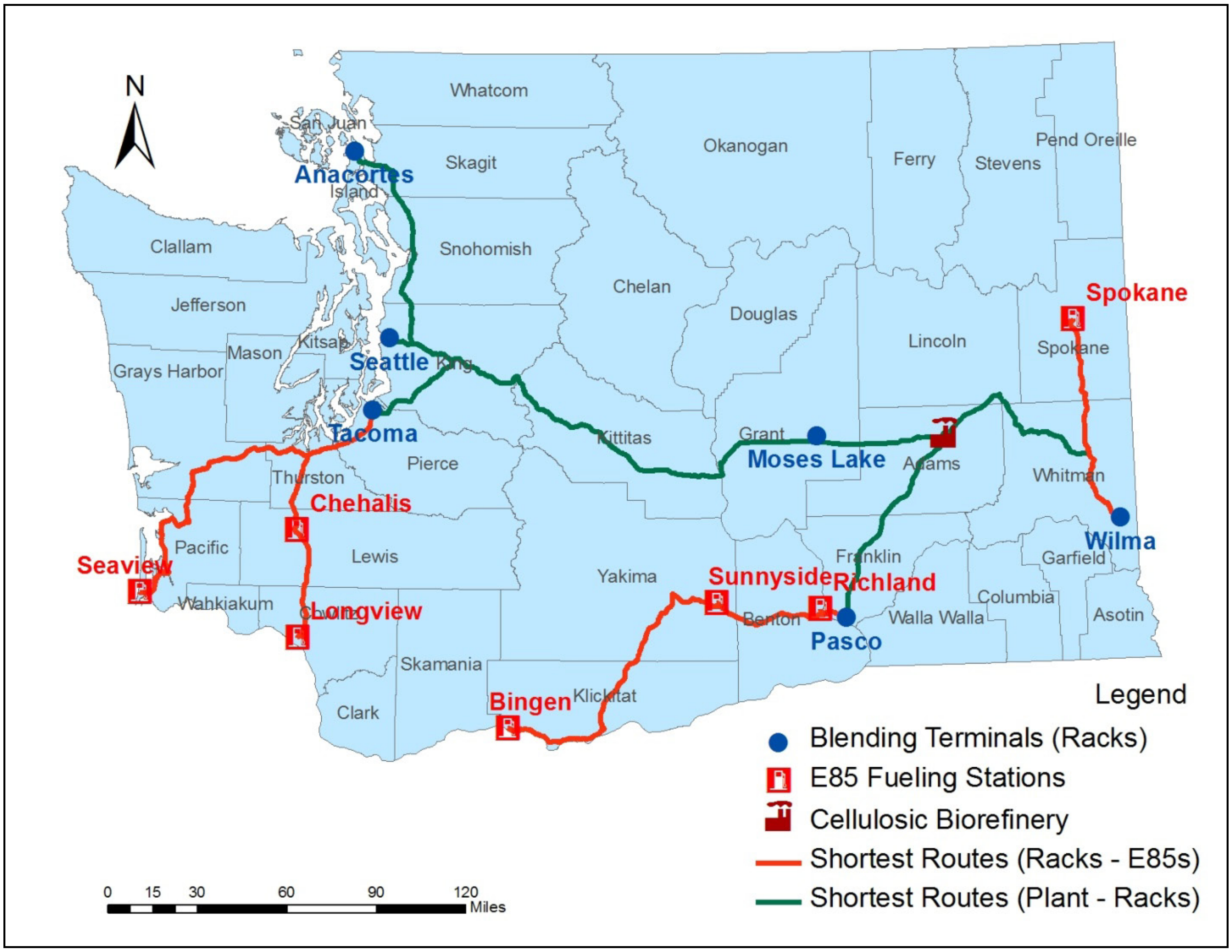


Figure 86: Shortest Routes from Processing Plant to Blending Terminals and E85 Fueling Stations

Figure 88 shows per gallon trucking costs associated with the final segment, the distribution of ethanol from blending terminals to existing E85 fueling stations (also in the Trucking Cost Calculation Tables section). Note that only three blending terminals (in Tacoma, Pasco, and Wilma) were plotted as origins against all seven E85 fueling stations. Terminals in Seattle, Anacortes, and Moses Lake are relatively farther away and therefore were dropped by the GIS Network Analyst Closest Facility toolset.

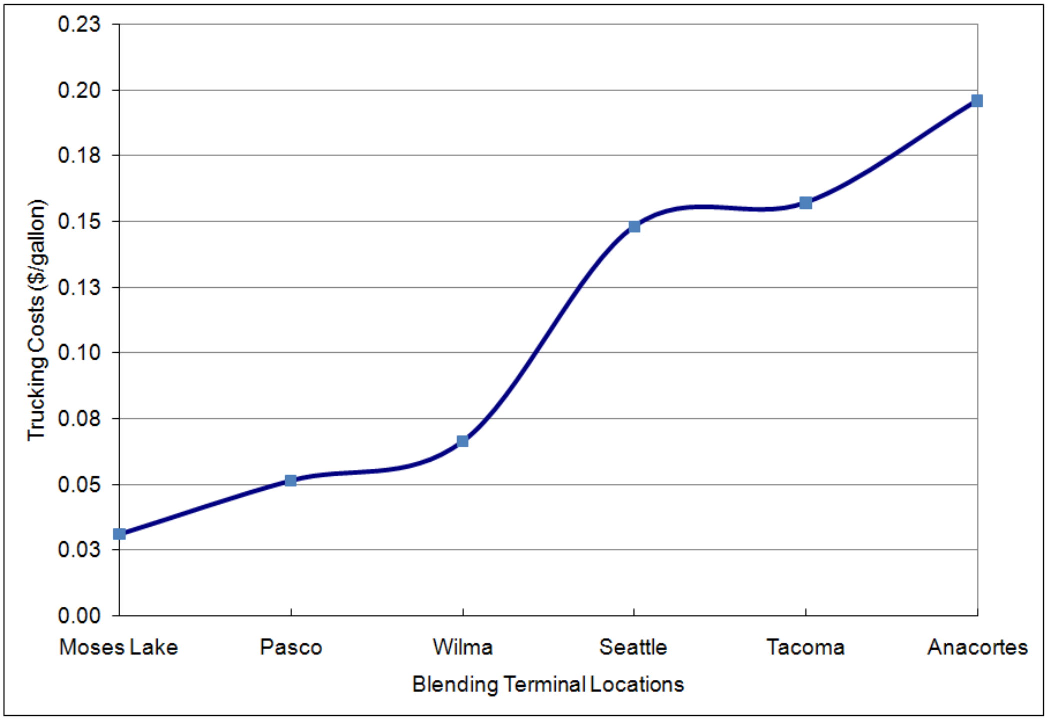


Figure 87: Ethanol Distribution Costs from Processing Plant to Washington's Blending Terminals

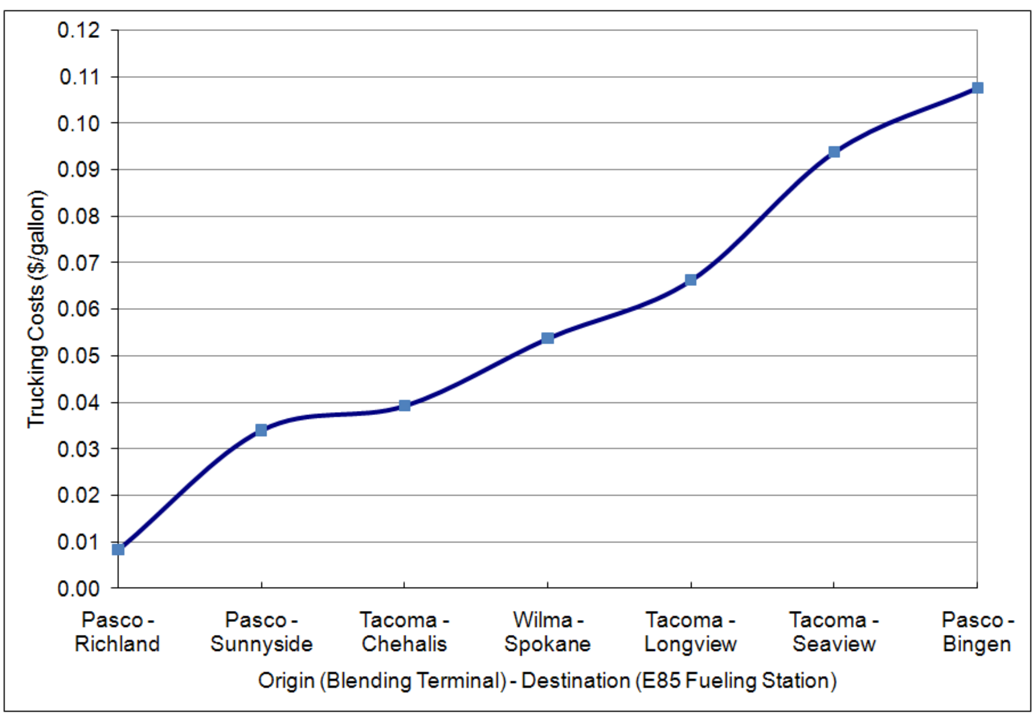


Figure 88: Ethanol Distribution Costs from Washington's Blending Terminals to E85 Fueling Stations

To finalize the distribution cost calculations for the entire distribution path, starting from the processing plant in the eastern Washington to all E85 fueling stations through the three closest blending terminals, costs for the both segments were combined (Figure 89). Resulting transportation costs for the ethanol distributed through the terminal in Pasco increase to $0.06, $0.09, and $0.16 per gallon for E85 stations in Richland, Sunnyside, and Bingen, respectively. Per gallon costs for the distribution through the Tacoma terminal start with $0.20 in Chehalis and increase to $0.22 and $0.25 for the E85 destinations in Longview and Seaview, respectively. Given the current geographic distribution of E85 fueling stations, only one distribution route was identified for the fueling station in Spokane through the terminal in Wilma, resulting in $0.12 per gallon transportation costs.

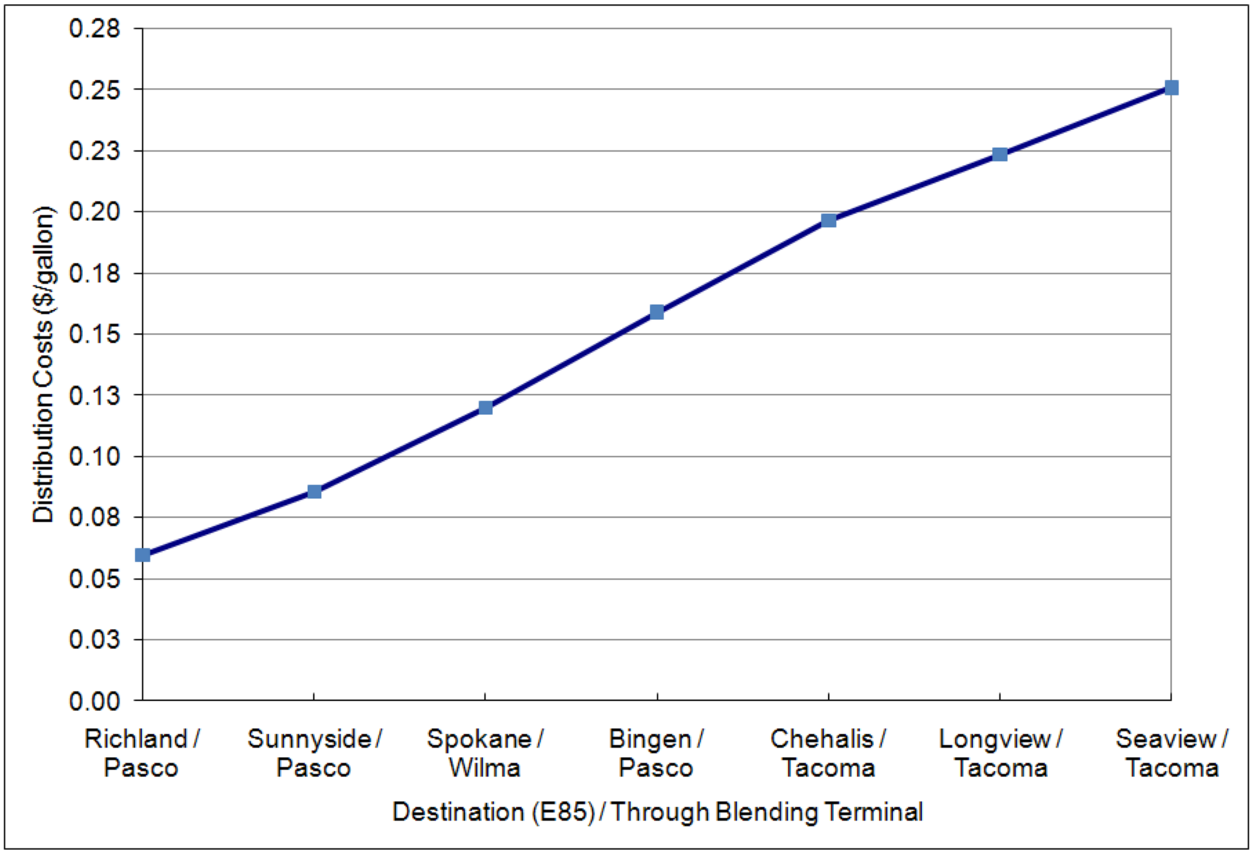


Figure 89: Distribution Costs from the Processing Plant through Three Blending Terminals to All E85 Fueling Stations in the State

As mentioned earlier, for the second part of the spatial investigation, an origin-destination cost matrix was created to rank the least-cost distribution routes from blending terminals to the state's E85 gas stations. For this part of the analysis, the GIS Network Analysis toolset used location information to rank distribution routes according to the lowest to highest transportation costs. Currently, with only six origins (blending terminals) and seven destinations (E85 stations (resulting in a 6 $\times$ 7 cost matrix), the current computation is relatively easy. However, with the development of the industry, the methodology may be useful to include hundreds of trips originating from existing blending terminals to future E85 stations in the state. Figure 90 shows a map with connection lines[17] illustrating the distance-based cost ranking for the routes from the blending terminal to E85 fueling stations in the state. For each of the blending terminal locations, route information was considered for calculating the closest E85 station location, and to rank them according to the transportation costs.

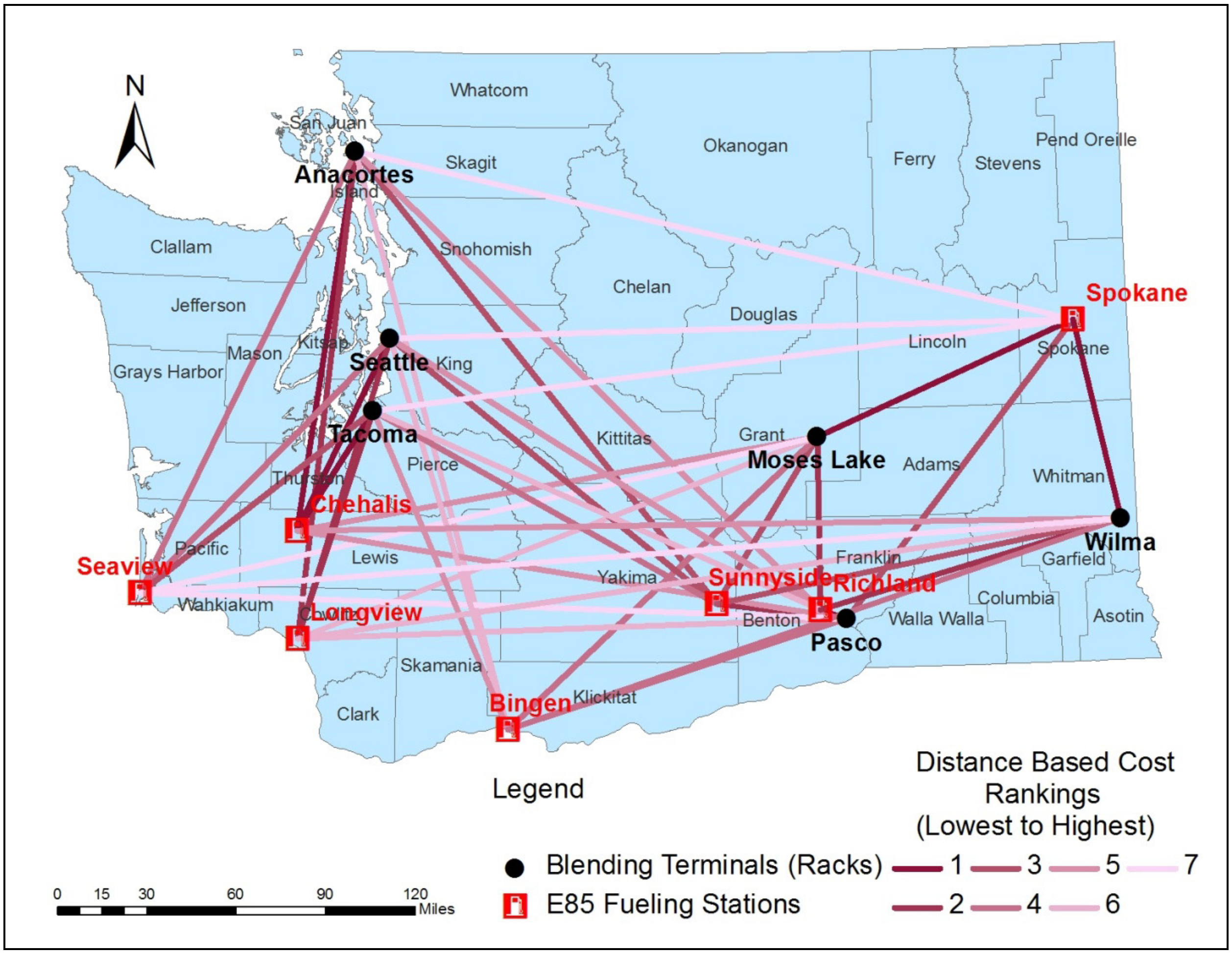


Figure 90: Map for GIS Origin (Blending Terminal) Destination (E85 Fueling Station) Distance-Based Cost Matrix

To make this cost matrix useful for any biorefinery location considering the existing six blending terminals for the ethanol distribution, the specific cellulosic biorefinery location (discussed above) was not included as an origin. Similar to the Closest Facility calculation used for optimal route identification (described above), the attribute information regarding the origin-destination matrix can be extracted into spreadsheets. The summary of the origin-destination attribute table data is provided in the Trucking Cost Calculation Tables section.

[17] Despite the lines in the map being shown as straight lines, the information they provide is based on origin-destination highway distances. To keep the map clear, Washington's highway layer was not included.

Delivered Costs

Below are a series of figures outlining the determined delivered costs for the various scenarios being studied (Figures 91-98).

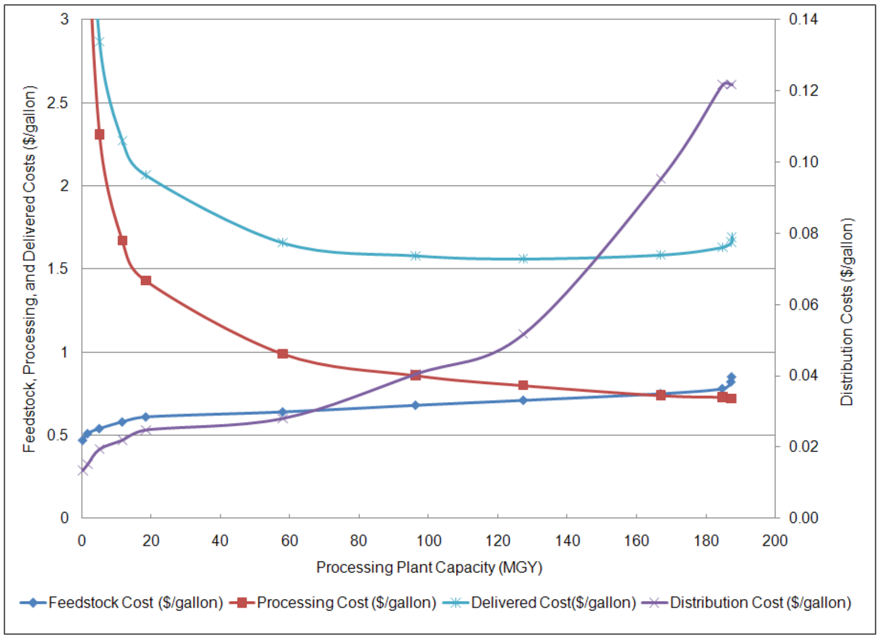


Figure 91: Delivered Cost of Bioethanol Using Crop Residue (Longview)

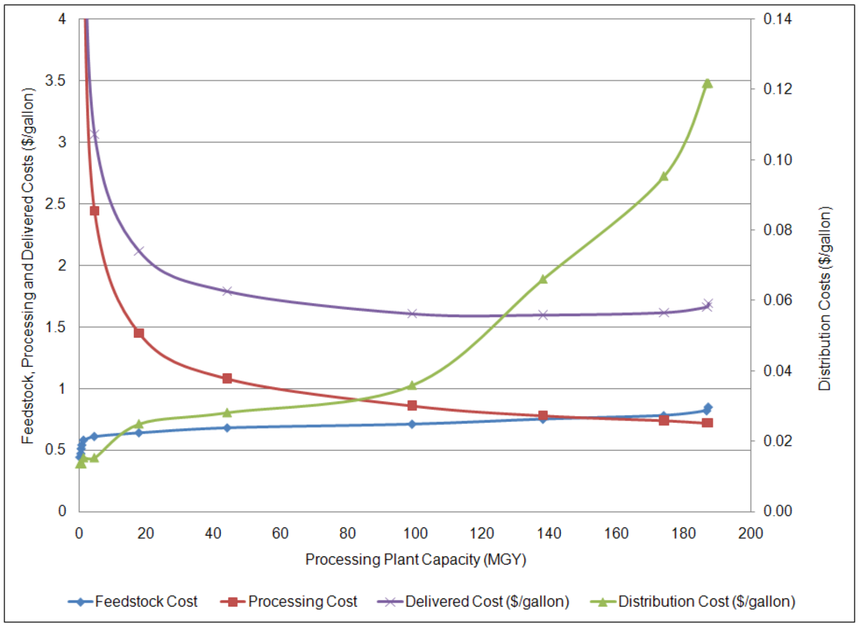


Figure 92: Delivered Cost of Bioethanol Using Crop Residue (Ferndale)

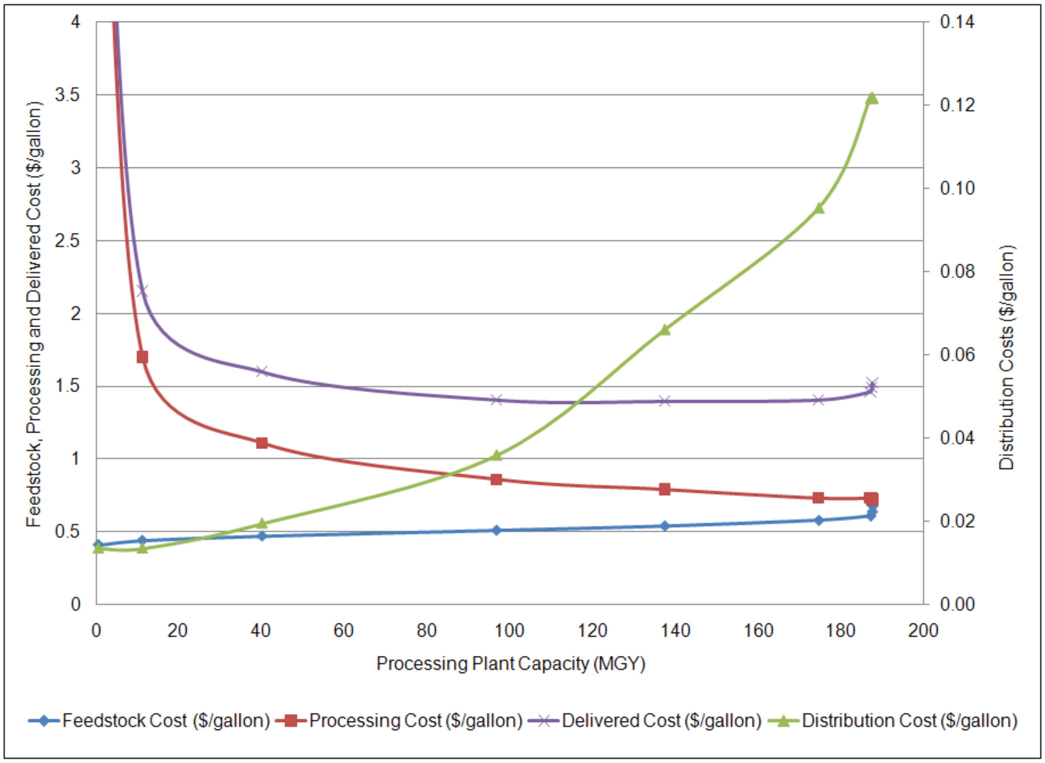


Figure 93: Delivered Cost of Bioethanol Using Crop Residue (Ellensburg)

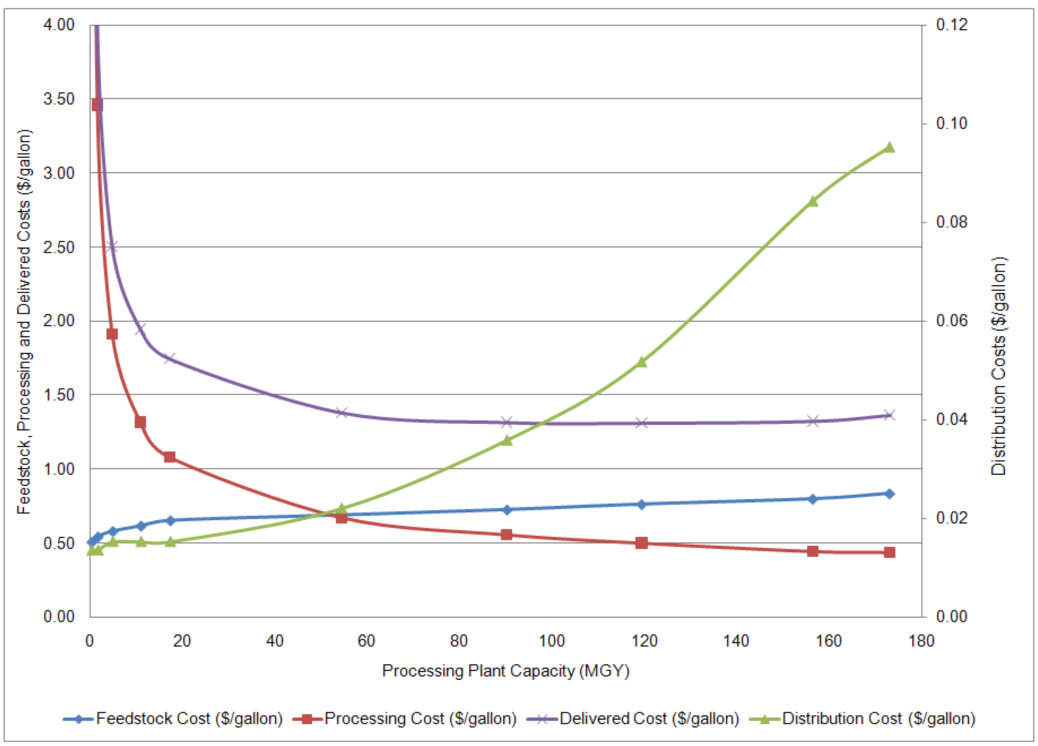


Figure 94: Delivered Cost of Thermo-ethanol Using Crop Residue (Longview)

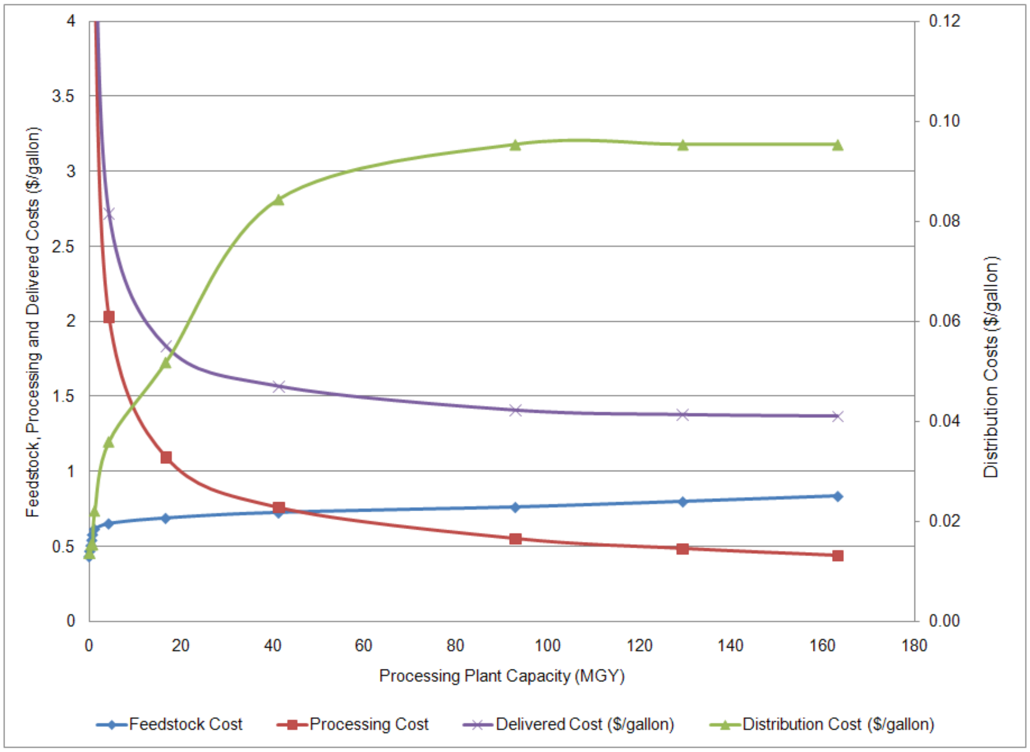


Figure 95: Delivered Cost of Thermo-ethanol Using Crop Residue (Ferndale)

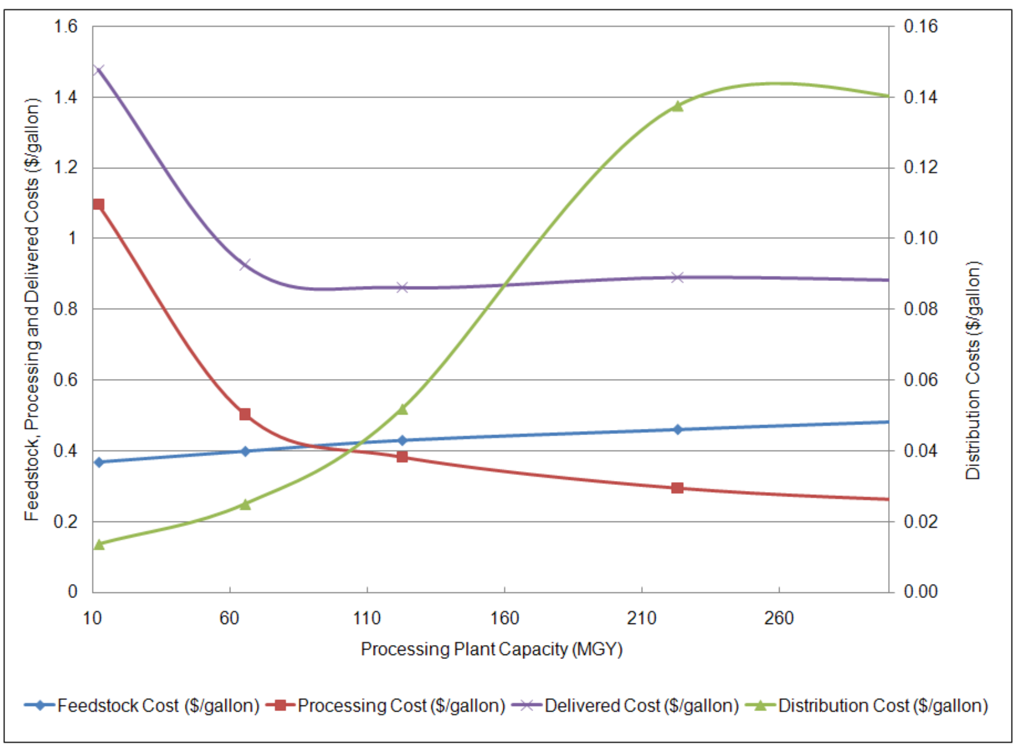


Figure 96: Delivered Cost of Thermo-ethanol Using Forest Residue (Longview)

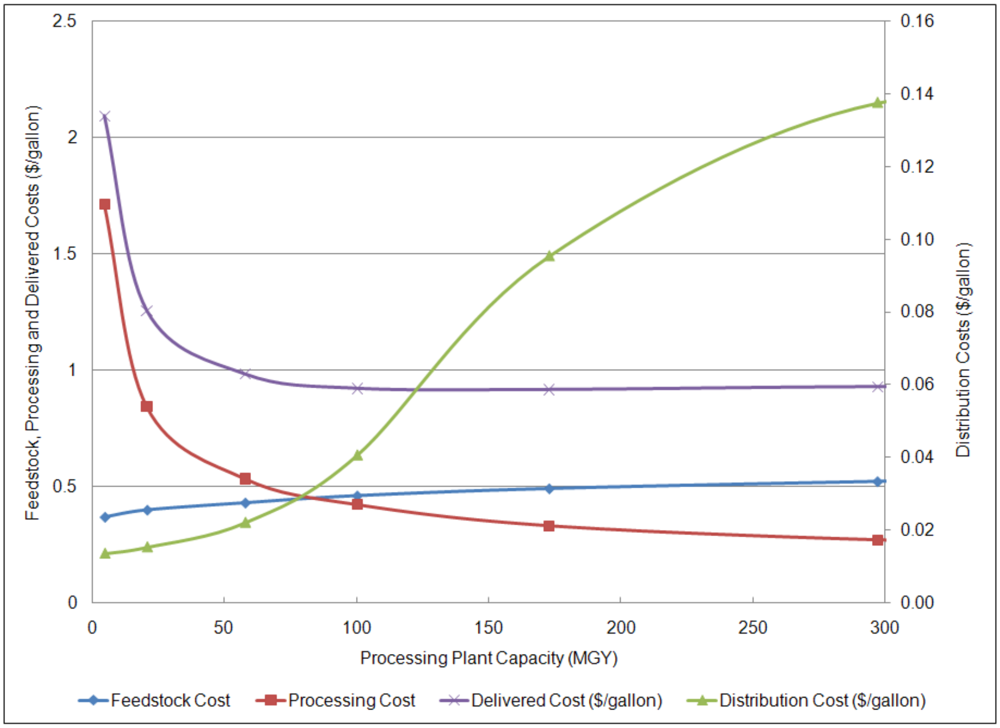


Figure 97: Delivered Cost of Thermo-ethanol Using Forest Residue (Ferndale)

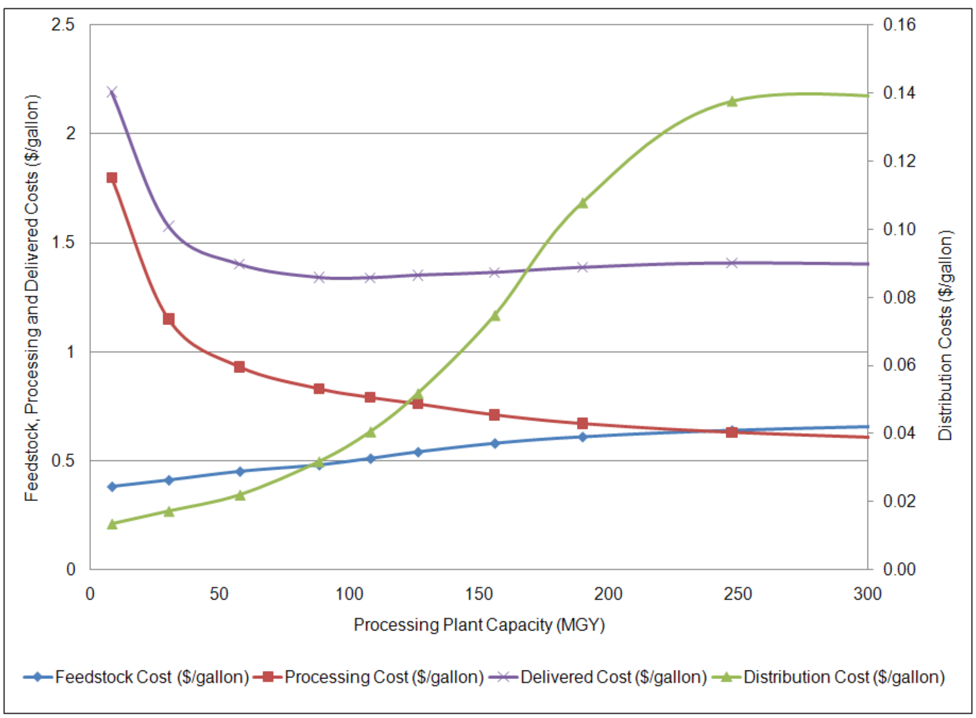


Figure 98: Delivered Cost of Thermo-ethanol Using Forest Residue (Spokane)

Supplemental Materials

Geographic Distribution of Biomass in the State of Washington

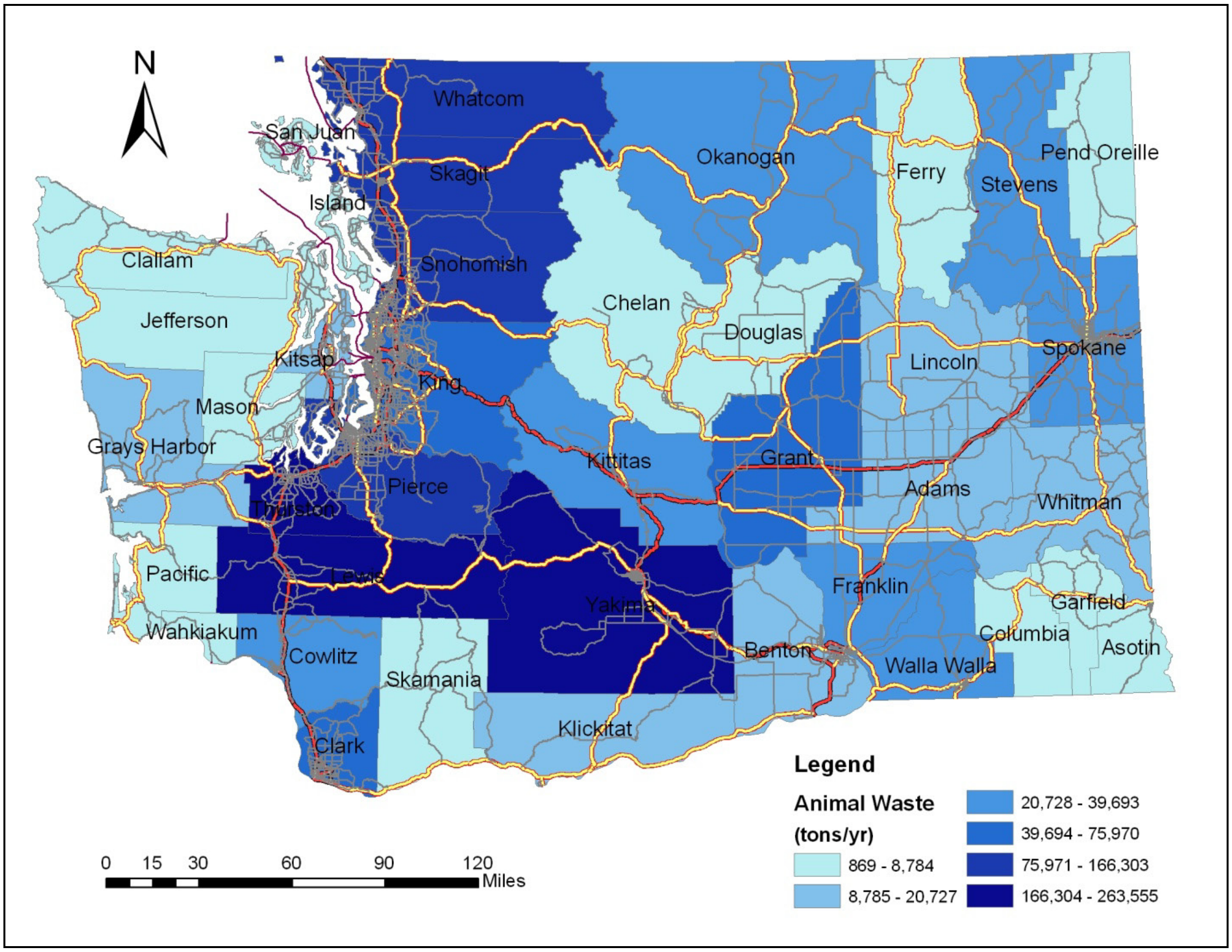


Figure 99: Geographic Distribution of Animal Waste Residue in Relation to the Road Network

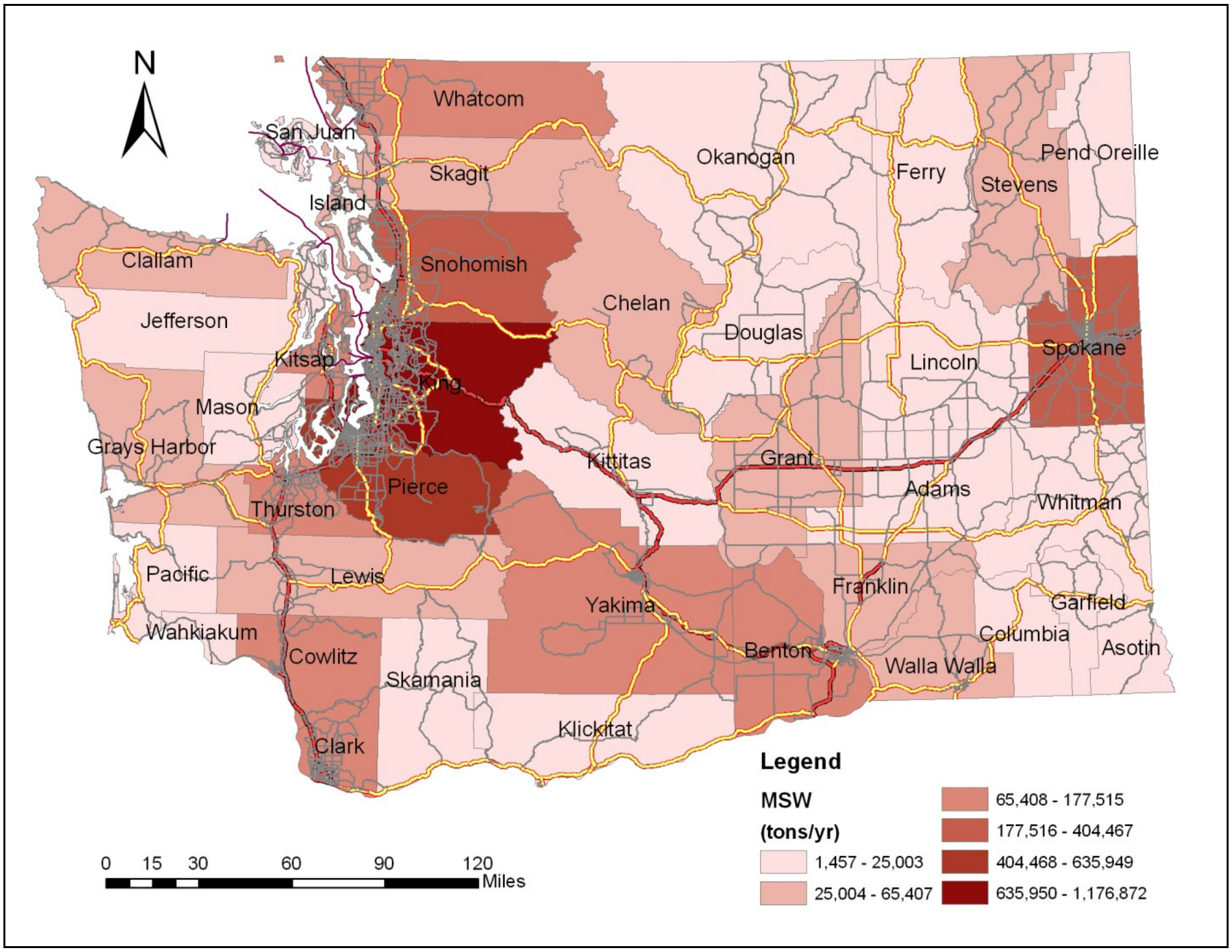


Figure 100: Geographic Distribution of Municipal Solid Waste in Relation to the Road Network

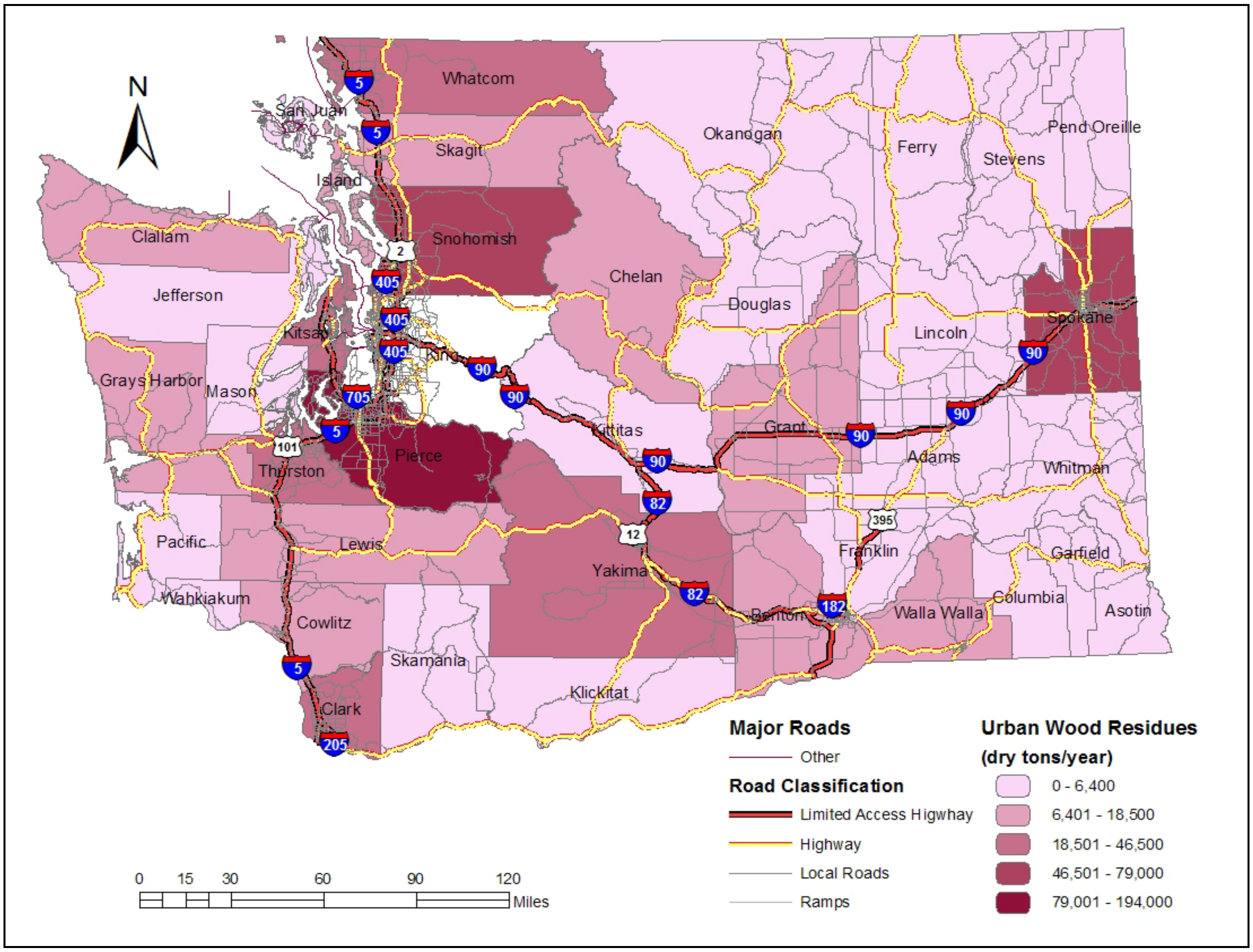


Figure 101: Geographic Distribution of Urban Wood Residue in Relation to the Road Network (NREL Data)

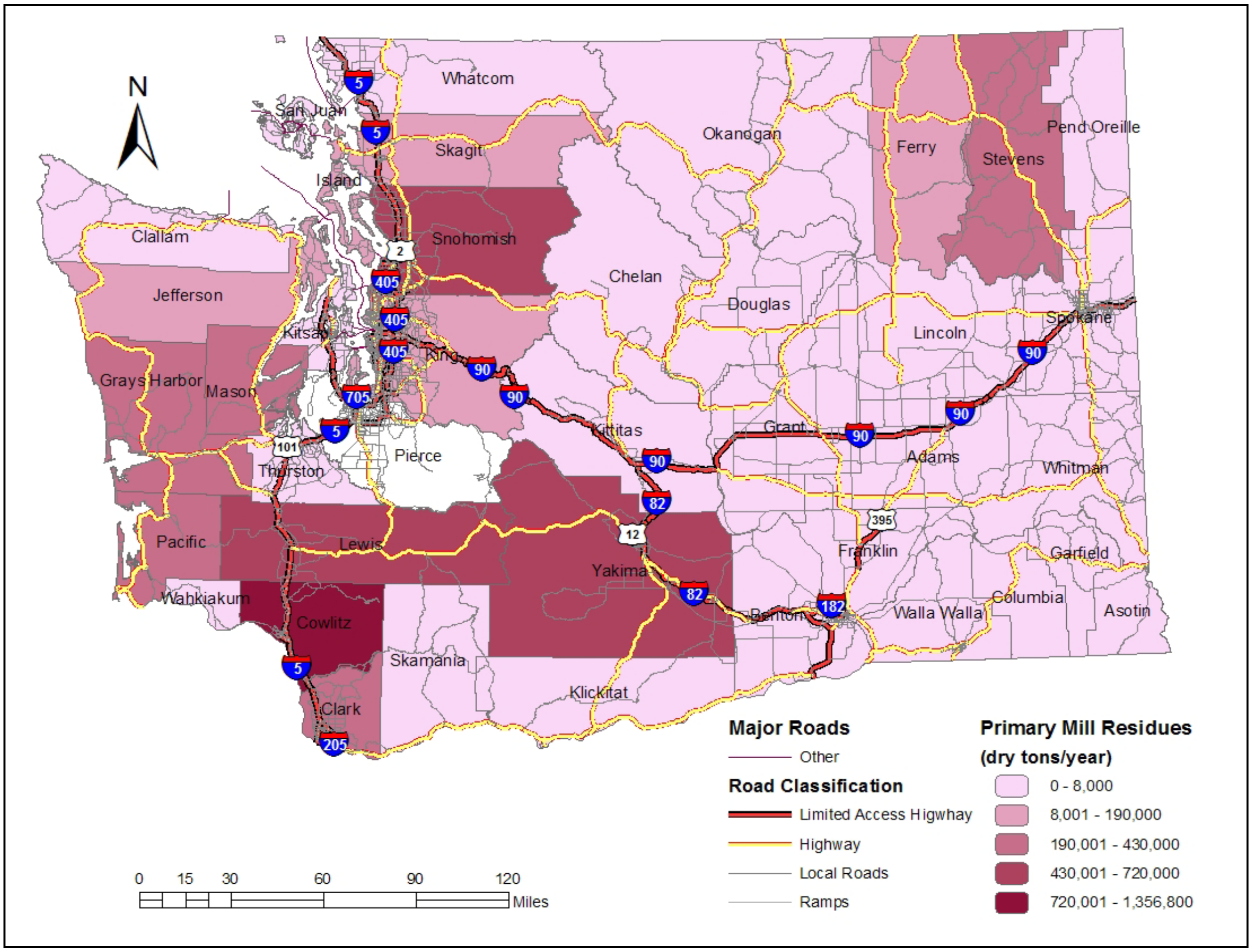


Figure 102: Geographic Distribution of Primary Mill Residue in Relation to the Road Network (NREL Data)

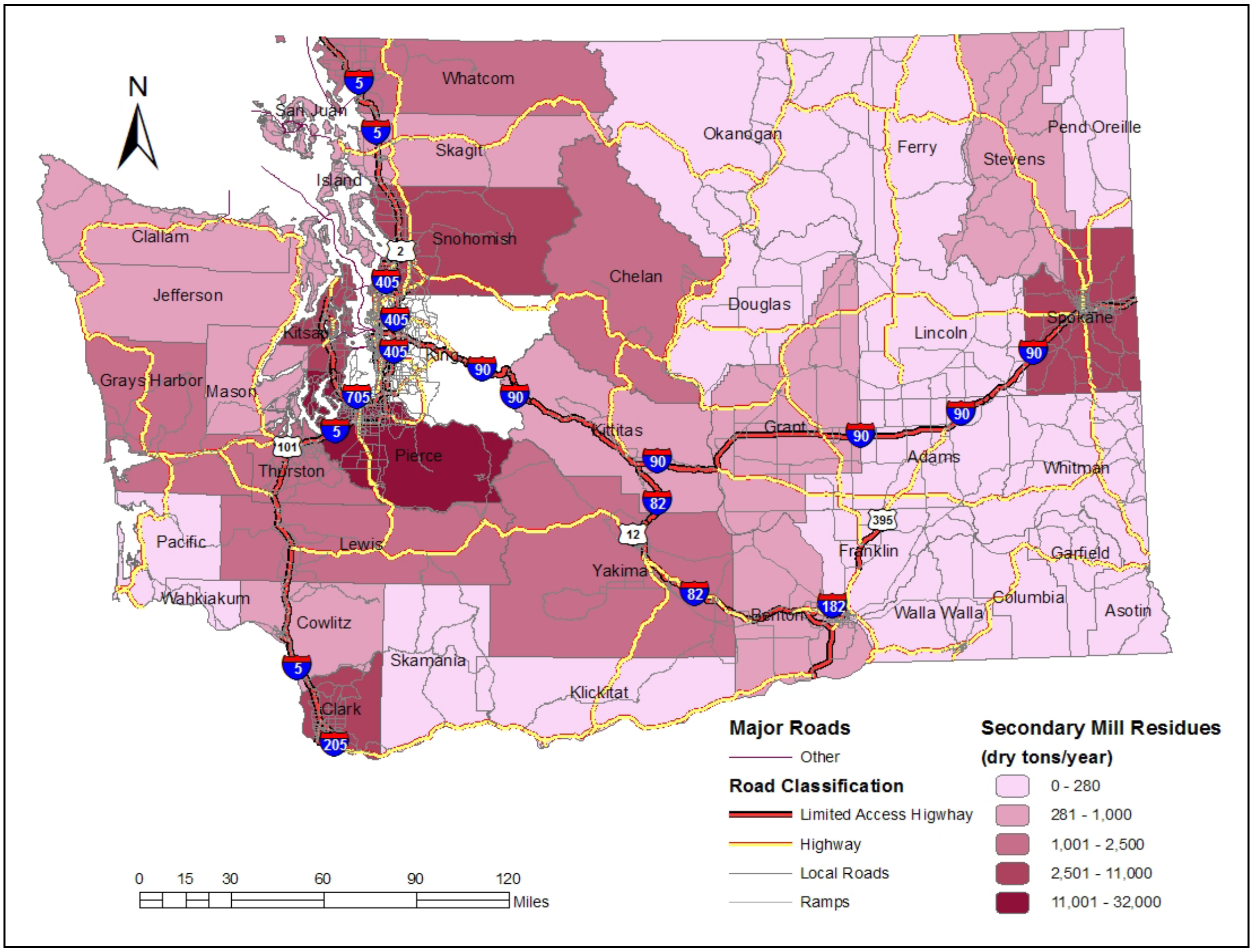


Figure 103: Geographic Distribution of Secondary Mill Residue in Relation to the Road Network (NREL Data)

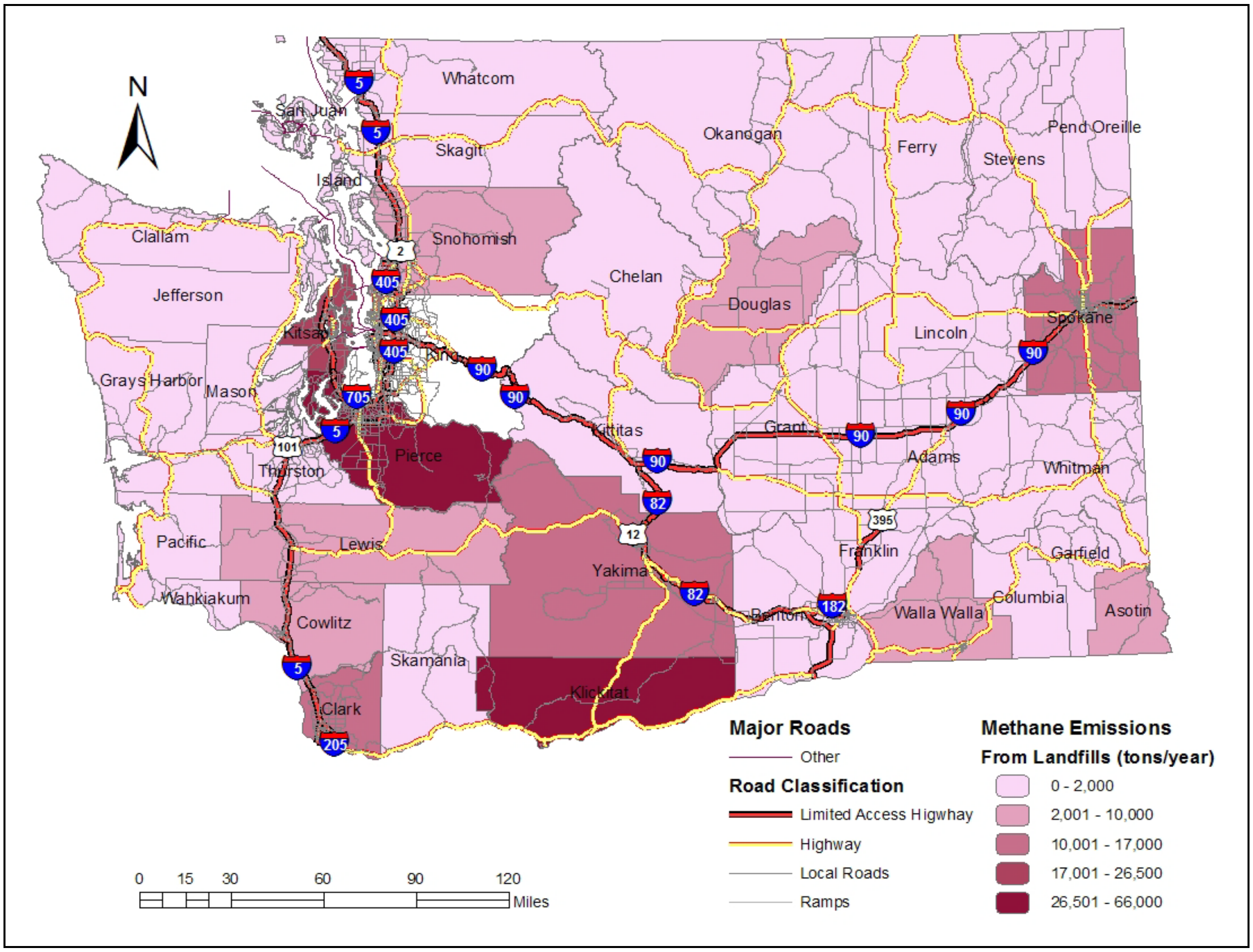


Figure 104: Geographic Distribution of Methane Emissions from Landfills in Relation to the Road Network (NREL Data)

Figure 105: Raking Process

Source: www.truckpaper.com

Figure 106: Raking Equipment

Figure 107: Swathing Process

Figure 108: Baling Process (Large Bales: Large Bales: 1.2 × 1.2 × 2.4 m)

Figure 109: Baling Process (Small Bales: 0.4 × 0.6 × 1.2 m)

Figure 110: Road-Siding Process (Large Bales: 1.2 × 1.2 × 2.4 m)

Figure 111: Road-Siding Process (Large Bales: 1.2 × 1.2 × 2.4 m)

Figure 112: Loading Drop-Bed Trailer Truck (Large Bales: 1.2 × 1.2 × 2.4 m)

Figure 113: Transporting Large Bales with Double Flat-Bed

Trailer

Source: www.truckpaper.com

Figure 114: Drop-Bed Trailer

Source: www.truckpaper.com

Figure 115: Flat-Bed Trailer

Trucking Cost Calculation Tables

Table 14: Lifetime Hours of Machinery Operation and Repairs Costs as Percentage of New List Price

	Accumulated Hours									
Type of Machinery	**1,000**	**2,000**	**3,000**	**4,000**	**5,000**	**6,000**	**7,000**	**8,000**	**9,000**	**10,000**
Two-Wheel Drive Tractor	1%	3%	6%	11%	18%	25%	34%	45%	57%	70%
Four-Wheel Drive Tractor	0%	1%	3%	5%	8%	11%	15%	19%	24%	30%
	200	400	600	800	1,000	1,200	1,400	1,600	1,800	2,000
Moldboard Plow	2%	6%	12%	19%	29%	40%	53%	68%	84%	101%

Heavy-Duty Disk	1%	4%	8%	12%	18%	25%	32%	40%	49%	58%
Tandem Disk	1%	4%	8%	12%	18%	25%	32%	40%	49%	58%
Chisel Plow	3%	8%	14%	20%	28%	36%	45%	54%	64%	74%
Field Cultivator	3%	7%	13%	20%	27%	35%	43%	52%	61%	71%
Harrow	3%	7%	13%	20%	27%	35%	43%	52%	61%	71%
Roller-Packer, Mulcher	2%	5%	8%	12%	16%	20%	25%	29%	34%	39%
Rotary Hoe	2%	6%	11%	17%	23%	30%	37%	44%	52%	61%
Row Crop Cultivator	0%	2%	6%	10%	17%	25%	36%	48%	62%	78%

	200	400	600	800	1,000	1,200	1,400	1,600	1,800	2,000
Corn Picker	0%	2%	4%	8%	14%	21%	30%	41%	54%	69%
Combine (Pull)	0%	1%	4%	7%	12%	18%	26%	35%	46%	59%
Potato Harvester	2%	5%	9%	14%	19%	25%	30%	37%	43%	50%
Mower-Conditioner	1%	4%	8%	13%	18%	24%	31%	38%	46%	55%
Mower-Conditioner (Rotary)	1%	3%	6%	10%	16%	23%	31%	41%	52%	64%
Rake	2%	5%	8%	12%	17%	22%	27%	33%	39%	45%
Rectangular Baler	1%	4%	9%	15%	23%	32%	42%	54%	66%	80%
Large Square Baler	1%	2%	4%	7%	10%	14%	18%	23%	29%	35%
Forage Harvester (Pull)	1%	3%	7%	10%	15%	20%	26%	32%	38%	45%

	300	600	900	1,200	1,500	1,800	2,100	2,400	2,700	3,000
Forage Harvester (SP)	0%	1%	2%	4%	7%	10%	13%	17%	22%	27%
Combine (SP)	0%	1%	3%	6%	9%	14%	19%	25%	32%	40%
Windrower (SP)	1%	2%	5%	9%	14%	19%	26%	35%	44%	54%
Cotton Picker (SP)	1%	4%	9%	15%	23%	32%	42%	53%	66%	79%

	100	200	300	400	500	600	700	800	900	1,000
Mower (Sickle)	1%	3%	6%	10%	14%	19%	25%	31%	38%	46%
Mower (Rotary)	0%	2%	4%	7%	11%	16%	22%	28%	36%	44%
Large Round Baler	1%	2%	5%	8%	12%	17%	23%	29%	36%	43%
Sugar Beet Harvester	3%	7%	12%	18%	24%	30%	37%	44%	51%	59%
Rotary Tiller	0%	1%	3%	6%	9%	13%	18%	23%	29%	36%
Row Crop Planter	0%	1%	3%	5%	7%	11%	15%	20%	26%	32%
Grain Drill	0%	1%	3%	5%	7%	11%	15%	20%	26%	32%
Fertilizer Spreader	3%	8%	13%	19%	26%	32%	40%	47%	55%	63%

	200	400	600	800	1,000	1,200	1,400	1,600	1,800	2,000
Boom-Type Sprayer	5%	12%	21%	31%	41%	52%	63%	76%	88%	101%
Air-Carrier Sprayer	2%	5%	9%	14%	20%	27%	34%	42%	51%	61%
Bean Puller-Windrower	2%	5%	9%	14%	20%	27%	34%	42%	51%	61%
Stalk Chopper	3%	8%	14%	20%	28%	36%	45%	54%	64%	74%
Forage Blower	1%	4%	9%	15%	22%	31%	40%	51%	63%	77%
Wagon	1%	4%	7%	11%	16%	21%	27%	34%	41%	49%

Forage Wagon	2%	6%	10%	14%	19%	24%	29%	35%	41%	47%

Source: Edwards (2002)

Table 15: Salvage Value as a Portion of New List Price of Field Machinery

	30–79 hp Tractor			**80–149 hp Tractor**			**150+ hp Tractor**			**Combine, Forage Harvester**		
Annual Hours	**200**	**400**	**600**	**200**	**400**	**600**	**200**	**400**	**600**	**200**	**400**	**600**
Age (years)												
1	65%	60%	56%	69%	68%	68%	69%	67%	66%	79%	69%	63%
2	59%	54%	50%	62%	62%	61%	61%	59%	58%	67%	58%	52%
3	54%	49%	46%	57%	57%	56%	55%	54%	52%	59%	50%	45%
4	51%	46%	43%	53%	53%	52%	51%	49%	48%	52%	44%	39%
5	48%	43%	40%	50%	49%	49%	47%	45%	44%	47%	39%	34%
6	45%	40%	37%	47%	46%	46%	43%	42%	41%	42%	35%	30%
7	42%	38%	35%	44%	44%	43%	40%	39%	38%	38%	31%	27%
8	40%	36%	33%	42%	41%	41%	38%	36%	35%	35%	28%	24%
9	38%	34%	31%	40%	39%	39%	35%	34%	33%	31%	25%	21%
10	36%	32%	30%	38%	37%	37%	33%	32%	31%	28%	23%	19%
11	35%	31%	28%	36%	35%	35%	31%	30%	29%	26%	20%	17%
12	33%	29%	27%	34%	34%	33%	29%	28%	27%	23%	18%	15%
13	32%	28%	25%	33%	32%	32%	27%	26%	25%	21%	16%	13%
14	30%	27%	24%	31%	31%	30%	25%	24%	24%	19%	14%	12%
15	29%	25%	23%	30%	29%	29%	24%	23%	22%	17%	13%	10%
16	28%	24%	22%	28%	28%	27%	22%	21%	21%	16%	11%	9%
17	26%	23%	21%	27%	27%	26%	21%	20%	19%	14%	10%	8%
18	25%	22%	20%	26%	25%	25%	20%	19%	18%	13%	9%	7%
19	24%	21%	19%	25%	24%	24%	19%	18%	17%	11%	8%	6%
20	23%	20%	18%	24%	23%	23%	17%	17%	16%	10%	7%	5%

Source: Edwards (2002)

Table 16: Salvage Value as a Portion of New List Price of Machinery

Machine Age (years)	**Plows**	**Other Tillage**	**Planter, Drill, Sprayer**	**Mower, Chopper**	**Baler**	**Swather, Raker**	**Vehicle**	**Other**
1	47%	61%	65%	47%	56%	49%	42%	69%
2	44%	54%	60%	44%	50%	44%	39%	62%
3	42%	49%	56%	41%	46%	40%	36%	56%
4	40%	45%	53%	39%	42%	37%	34%	52%
5	39%	42%	50%	37%	39%	35%	33%	48%
6	38%	39%	48%	35%	37%	32%	31%	45%
7	36%	36%	46%	33%	34%	30%	30%	42%
8	35%	34%	44%	32%	32%	28%	29%	40%

9	34%	31%	42%	31%	30%	27%	27%	37%
10	33%	30%	40%	30%	28%	25%	26%	35%
11	32%	28%	39%	28%	27%	24%	25%	33%
12	32%	26%	38%	27%	25%	23%	24%	31%
13	31%	24%	36%	26%	24%	21%	24%	29%
14	30%	23%	35%	26%	22%	20%	23%	28%
15	29%	22%	34%	25%	21%	19%	22%	26%
16	29%	20%	33%	24%	20%	18%	21%	25%
17	28%	19%	32%	23%	19%	17%	20%	24%
18	27%	18%	30%	22%	18%	16%	20%	22%
19	27%	17%	29%	22%	17%	16%	19%	21%
20	26%	16%	29%	21%	16%	15%	19%	20%

Source: Edwards (2002)

Table 17: Plant to Blending Terminal Optimal Route Attribute Table

Object ID (Blending Terminal)	Facility ID (Ethanol Plant)	Facility Rank	Object Name (Blending Terminal)	Total Drive Time (minutes)	Total Distance (miles)	Trucking Costs ($/gallon)
27	11	1	Moses Lake	45.85	45.93	0.03
28	11	1	Pasco	77.26	76.18	0.05
31	11	1	Wilma	118.81	98.25	0.07
29	11	1	Seattle	201.64	219.36	0.15
30	11	1	Tacoma	222.75	232.75	0.16
26	11	1	Anacortes	272.48	290.27	0.20

Table 18: Blending Terminal to E85 Fueling Station Optimal Route Attribute Table

Object ID (E85)	Facility ID (Racks)	Name (Rack - E85)	Total Minutes	Total Distance **[[AU: need units]]**	Trucking Costs ($/gallon)
35	14	Pasco - Richland	15.4	12.4	0.01
38	14	Pasco - Sunnyside	49.6	50.4	0.03
33	16	Tacoma - Chehalis	53.3	58.2	0.04
37	17	Wilma - Spokane	96.4	79.7	0.05
34	16	Tacoma - Longview	91.0	98.2	0.07
36	16	Tacoma - Seaview	144.9	139.0	0.09
32	14	Pasco - Bingen	175.6	159.4	0.11

Table 19: GIS Origin-Destination Cost Matrix Data in Relation to per Gallon Trucking Costs

Object ID	Name (From - To)	Origin ID (Rack)	Destination ID (E85)	Destination Rank by Shortest Drive Time	Total Minutes	Total Distance **[[AU: Need units]]**	Trucking Costs ($/gallon)
1	Anacortes - Chehalis	1	2	1	157.4	165.4	0.11
2	Anacortes - Longview	1	3	2	195.0	205.5	0.14
3	Anacortes - Sunnyside	1	7	3	234.6	248.5	0.17
4	Anacortes - Seaview	1	5	4	249.0	246.3	0.17
5	Anacortes - Richland	1	4	5	271.4	287.9	0.19
6	Anacortes - Bingen	1	1	6	306.8	305.4	0.21
7	Anacortes - Spokane	1	6	7	325.6	349.3	0.24
8	Moses Lake - Spokane	2	6	1	98.9	105.0	0.07
9	Moses Lake - Richland	2	4	2	101.2	82.7	0.06
10	Moses Lake - Sunnyside	2	7	3	121.3	101.5	0.07
11	Moses Lake - Bingen	2	1	4	219.2	212.7	0.14
12	Moses Lake - Chehalis	2	2	5	232.3	245.0	0.17
13	Moses Lake - Longview	2	3	6	265.6	264.7	0.18
14	Moses Lake - Seaview	2	5	7	323.9	325.8	0.22
15	Pasco - Richland	3	4	1	15.4	12.4	0.01
16	Pasco - Sunnyside	3	7	2	49.6	50.4	0.03
17	Pasco - Spokane	3	6	3	130.2	135.0	0.09
18	Pasco - Bingen	3	1	4	175.6	159.4	0.11
19	Pasco - Chehalis	3	2	5	235.7	231.0	0.16
20	Pasco - Longview	3	3	6	255.8	251.9	0.17
21	Pasco - Seaview	3	5	7	351.4	326.4	0.22
22	Seattle - Chehalis	4	2	1	80.7	88.2	0.06
23	Seattle - Longview	4	3	2	118.4	128.2	0.09
24	Seattle - Sunnyside	4	7	3	163.8	177.6	0.12
25	Seattle - Seaview	4	5	4	172.3	169.0	0.11
26	Seattle - Richland	4	4	5	200.6	217.0	0.15
27	Seattle - Bingen	4	1	6	230.1	228.2	0.15
28	Seattle - Spokane	4	6	7	254.7	278.4	0.19
29	Tacoma - Chehalis	5	2	1	53.3	58.2	0.04
30	Tacoma - Longview	5	3	2	91.0	98.2	0.07
31	Tacoma - Seaview	5	5	3	144.9	139.0	0.09
32	Tacoma - Sunnyside	5	7	4	184.9	191.0	0.13
33	Tacoma - Bingen	5	1	5	202.7	198.2	0.13
34	Tacoma - Richland	5	4	6	221.7	230.4	0.16
35	Tacoma - Spokane	5	6	7	275.8	291.8	0.20
36	Wilma - Spokane	6	6	1	96.4	79.7	0.05
37	Wilma - Richland	6	4	2	179.5	148.6	0.10
38	Wilma - Sunnyside	6	7	3	213.7	186.7	0.13
39	Wilma - Bingen	6	1	4	339.7	295.7	0.20

40	Wilma - Chehalis	6	2	5	386.5	384.8	0.26
41	Wilma - Longview	6	3	6	419.9	404.5	0.27
42	Wilma - Seaview	6	5	7	478.1	465.6	0.31

APPENDIX II

Biomass Inventory Technology and Economics Assessments

Process Technology Comparison for Each Feedstock (WSU)

By

Bioprocessing and Bioproducts Laboratory

Biological System Engineering Department

Washington State University

List of Acronyms

AD	Anaerobic Digestion
BBEL	Bioprocessing and Bioproducts Laboratory
CECPI	Chemical Engineering Plant Cost Index
DOE	U.S. Department of Energy
GIS	Geographic Information Systems
IRR	Internal Rate of Return
LC	Lignocellulosic
MESP	Minimum Ethanol Selling Price
MGY	Million Gallons per Year
NREL	National Renewable Energy Laboratory
PFD	Process Flow Diagram
ROI	Return on Investment
SSCF	Simultaneous Saccharification and Co-Fermentation
TPEC	Total Purchased Equipment Cost
TPI	Total Project Investment
TIEC	Total Installed Equipment Cost
TPIC	Total Project Indirect Cost
USDA	U.S. Department of Agriculture
WSU	Washington State University

Introduction and Background

A particular objective in the overall study was to develop biorefinery process models for techno-economic analysis of possible waste to energy processes based on the available Washington State feedstock data. Specific software modules for fermentation, gasification and AD were developed upon extensive review of the literature on general process technology. With the MATLAB-based software modules, biorefinery processes were modeled as integration of different unit operations. Capital depreciation and distribution costs estimation were also included in these models. The cost curves of three main processes—fermentation, gasification, and AD—were generated. Four types of biomass—agricultural crop and forest residue, municipal solid waste (MSW), and animal waste—were analyzed.

Overview of the Processing Assessment Model

The ultimate goal of techno-economic assessments is a measure of profitability associated with certain biorefinery technology options. Biorefinery plants are built to make a profit; thus, in the early stage of project development it is necessary to estimate the investment required and the cost of production. Even if insufficient technical information is available to design a plant completely, users must still make an economic evaluation to determine whether it is economically and financially feasible. A biorefinery plant is economically feasible when its design is more profitable than any other competing designs, and it is financially feasible when enough investment can be raised for project implementation. The traditional economic evaluation for a chemical engineering process may proceed in several steps:

i. Preparing a process flow diagram
ii. Calculating mass and energy flows
iii. Sizing major equipment
iv. Estimating the capital cost
v. Estimating the production cost
vi. Forecasting the product sales price
vii. Estimating the return on investment

Evaluation of certain conceptual processes, like a biorefinery, might be slightly different. Figure 116 shows a typical approach to process design and economic analysis (Aden, Ruth et al. 2002). The final result of analysis is the minimum selling price of the product. This type of methodology has been widely accepted in other similar projects. A problem is possible limitations at the initial stage of R&D because too many resources might be required for make such a thorough evaluation. Here, certain simple analyses were based on Excel spreadsheet formulas, and mass and energy flow calculations with system simulations were replaced by some simpler equations. Their results are obviously too rough to reveal overall differences between various technology options (e.g., when the pretreatment method for lignocellulosic biomass changes, adjustments may be found in some other units of the whole project). The goal of the research is to provide a set of flexible assessment tools with acceptable accuracy for decision making in biorefinery development.

At this time, most biofuel production is still in the R&D stage. Thus, this project could only move forward by referring to other researchers' works (e.g., those who have come to understand a reaction system by gaining basic theoretical data, or those who have proved out certain basic process feasibilities, or those who have produced new information on a specific process such as lignocellulosic material pretreatment). The principal function of this process assessment model is screening. Dozens of options in feedstocks and conversion processes exist, but few of them are feasible. Alternative processes may be estimated for comparison purposes based on the matrix of conceptual design assessment, or two or more alternative processes can be quickly costed out to see whether one is clearly superior or to eliminate clearly inferior options. As progress is made in the process assessments, more will be learned about the ultimate ideal configuration of future commercial facilities that convert waste into energy and other useful by-products.

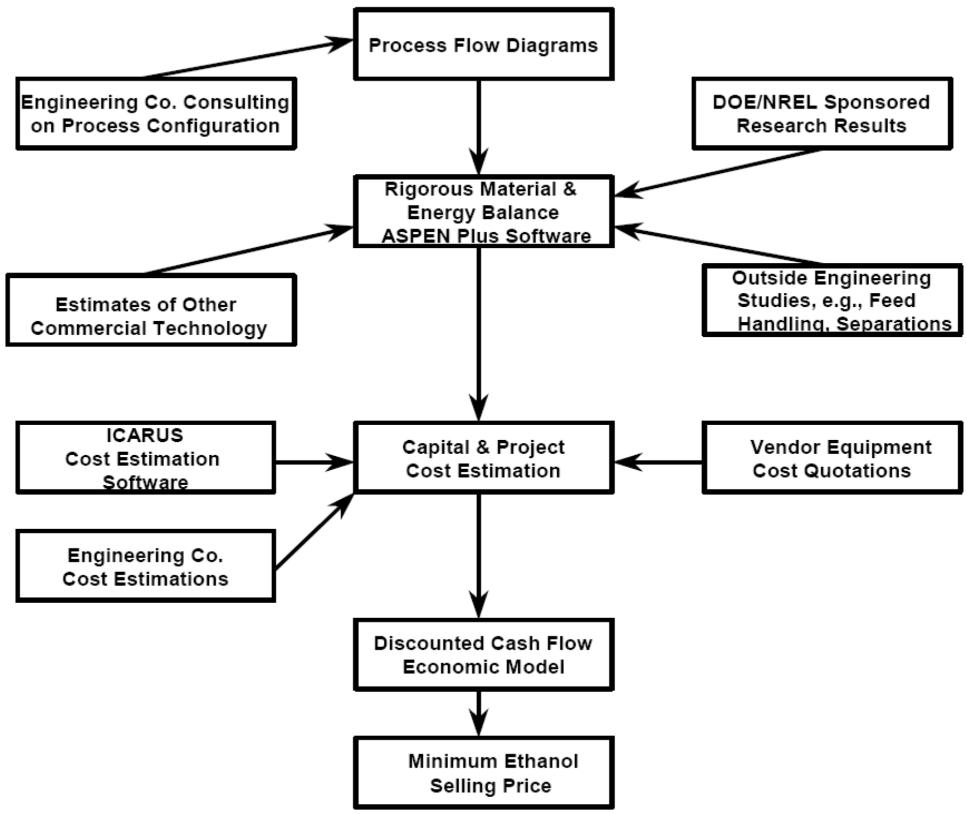


Figure 116: Typical Economic Assessment Process

Figure 117 schematically summarizes the research approach for this process modeling component to the project. **Three distinct levels of data were required in the modeling process** within the process modeling stream.

Feedstock Data
The feedstock database generated in the earlier biomass assessment work (Frear, 2005) is configured into four categories (fiber/starch/sugar, ultimate analysis, elemental analysis, other parameters), and includes 33 parameters such as moisture, carbon, starch, cellulose, minerals, etc. This database can be used not only by researchers to conduct scientific studies, but also by farmers and producers to learn more about the agricultural and municipal residues they are producing.

Process Flowcharts
The technological scheme connecting feedstock to final products has been a traditional concern as many of the conversion processes are still under research and development with many new processes and approaches being developed with time. In the end, three common and basic conversion processes were chosen for analysis in this study and they include dilute acid pretreatment with simultaneous saccharification and co-fermentation (SSCF), biomass gasification with mix-alcohol synthesis, and anaerobic digestion (AD). Flowcharts of these methods were developed via reference and laboratory research. Aden et al. (2002) had already developed a set of detailed PFDs (process flow diagrams) on lignocellulose-to-ethanol conversion via diluted acid pretreatment and SSCF processes. Philips et al., (2007) in their final report, also presented a set of PFDs on production of thermochemical ethanol via indirect gasification and mixed alcohol synthesis of lignocellulosic biomass. Anaerobic digestion process flowcharts were developed by the Biomass Processing and Bioproducts Engineering Laboratory.

Chemical/Biochemical Dynamics
Data used to describe every step in the whole process were mostly gathered from research reports of similar processes. Certain other elements came from chemical engineering handbooks (S.Peters, D.Timmerhaus et al. 2003; Poling, Thomson et al. 2008).

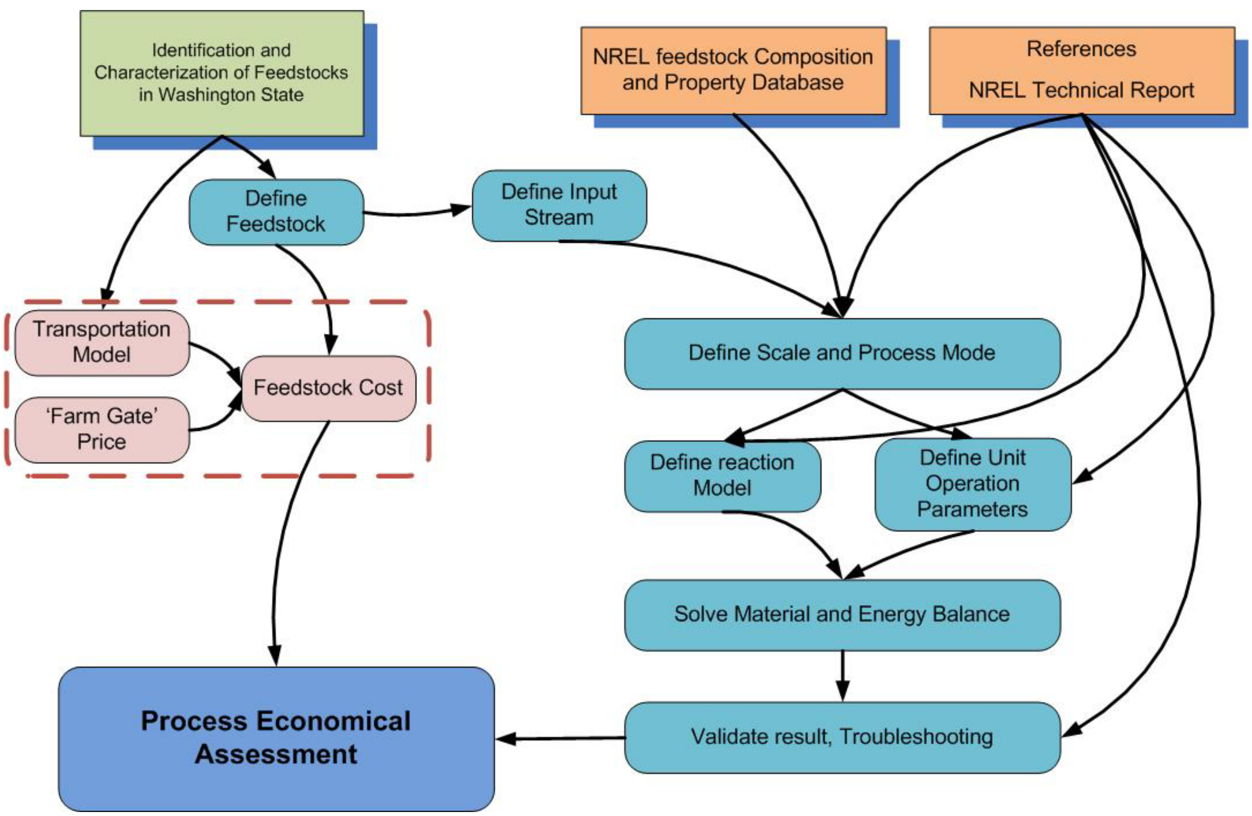


Figure 117: Working Process of Economic Assessment

For this project, MATLAB and Simulink software were chosen because they provide a powerful environment for the development of flowchart-based simulation models. Different subsystems are developed by Simulink to characterize all kinds of units used in biorefinery processes. The structure of a sample module is shown in Figure 118. The upper part of the sample module represents the mass balance in the unit. The input of this part is the mass stream from the process before it, while the main output will connect to the input port of the next unit. The red part of sample module represents the energy balance, equipment investment, and raw material costs of the unit.

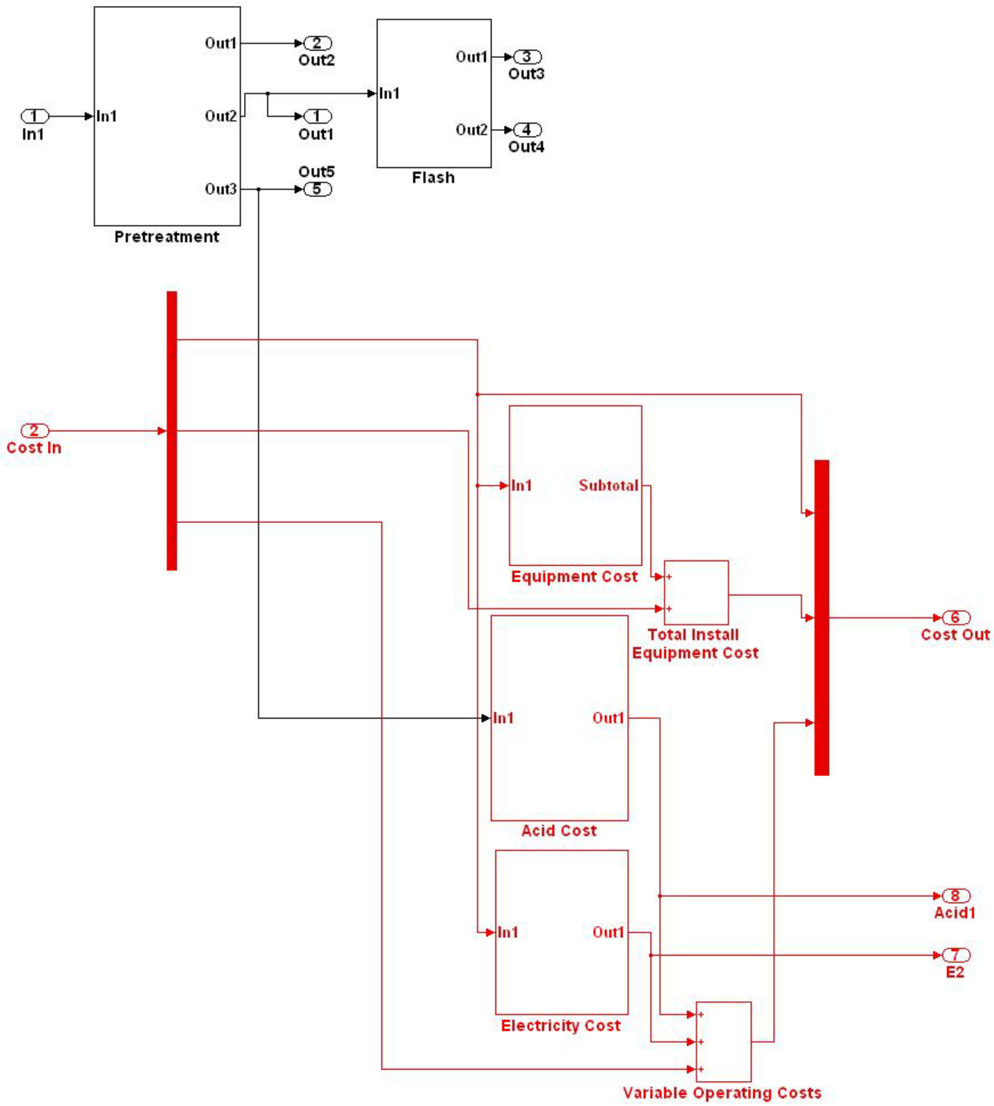


Figure 118: The Structure of a Sample Module

Biomass Conversion Processing Cost Assessment

Lignocellulosic Biomass-to-Bioethanol Conversion Process

Background

The disadvantages of fossil fuel-derived transportation fuels (greenhouse gas emissions, pollution, resource depletion, unbalanced supply demand relations) are strongly reduced or even absent with bio-transportation fuels. Of all biofuels, ethanol is already produced on a fair scale (about 14 to 26 million tons worldwide), and is easily applicable in transportation area because it can be mixed with gasoline. The United States consumed 80,000 barrels per day of ethanol in 1996 and is expected to consume 180,000 barrels per day in the reference case in 2010 (Figure 119). Ethanol is already commonly used as an "oxygenate" for reformulated and high-oxygenated gasoline in a 10% ethanol/90% (E10) gasoline blend. Adapted auto engines can use a blend of 85% ethanol/15% gasoline (E85) or even 95% ethanol (E95). Ethanol addition increases octane and reduces CO, VOC, and particulate emissions of gasoline. Numerous studies have been done in recent years evaluating the life cycle impacts of bioethanol, and there is now strong evidence that all bioethanol production is mildly to strongly beneficial from a climate protection and a fossil fuel conservation perspective (von Blottnitz and Curran 2007).

About 90% of all currently consumed ethanol is derived from sugar or starch crops by fermentation; the rest is produced synthetically. The bulk of the production and consumption is located in Brazil and the United States. Fermentation technologies for sugar and starch crops are very well developed but have certain limits: These crops have a high value for food application, and their sugar yield per hectare is very low. Ethanol can also be made from lignocellulosic biomass such as agricultural crop residues, switchgrass, and other agricultural wood crops.

The bioconversion process from lignocellulosic biomass to ethanol consists basically of four steps: pretreatment, enzymatic hydrolysis, fermentation, and distillation. To increase the yield of hydrolysis, a pretreatment step is needed that softens the biomass and breaks down the stable woody structures to a large extent, thus facilitating the enzymatic attack on lignocellulosic residues. Choices in the pretreatment technology affect not only the yield of both pretreatment and subsequent process steps, but also the equipment involved in the whole system. Diluted acid pretreatment has been used for many decades but has environmental consequences. Enzymatic processes are supposedly more environmentally sound but the costs can be relatively high. Another developed pretreatment method is "steam explosion" wherein the breakdown of structural components is aided by heat in the form of steam (thermo), shear forces due to the expansion of moisture (mechano), and hydrolysis of glycosidic bonds (chemical).

The hydrolysis and fermentation steps only convert a portion of sugars into ethanol. Future overall performance depends strongly on the development of cheaper and more efficient microorganisms and enzymes. Newer microorganisms may also allow for combining more process steps in one reactor, such as fermentation of different sugars like C5 sugars (xylose) and C6 sugars (glucose).

The present production costs of ethanol shows a broad range, mostly depending on the feedstocks and conversion technologies (Mitchell, Bridgwater et al. 1995; Zimbardi, Ricci et al. 2002; Hamelinck, van Hooijdonk et al. 2003; Wingren, Soderstrom et al. 2004; Hamelinck, van Hooijdonk et al. 2005; Lynd, van Zyl et al. 2005; Huang, Ramaswamy et al. 2006; Galbe, Sassner et al. 2007; Sassner, Galbe et al. 2008). For example, according to a USDA report dated July, 2006, *The Economic Feasibility of Ethanol Production from Sugar in the United States* (USDA 2006), the cost of producing ethanol from sugarcane in Brazil is estimated at about $0.81 per gallon, excluding capital costs. Like corn in the United States, the relatively low feedstock cost of sugarcane in Brazil makes this process economically competitive. However, due to the disadvantages of sugar or starch crops feedstock, massive research has been on lignocellulosic biomass. Wooley et al. (Wooley, Ruth et al. 1999) presented a very detailed analysis on the configuration of producing bioethanol from hardwood feedstock via SSCF technology; with their ethanol production cost turned out to be $1.44/gallon. Aden et al. (Aden, Ruth et al. 2002) calculated $1.07/gallon of bioethanol under the configuration of producing bioethanol from corn stover feedstock via SSCF technology and dilute acid pretreatment. Cost reductions reside in altering the feedstock, improving individual process steps, far-reaching process integration, enzyme cost reduction, and utilization of remaining lignin materials.

Table 20: Summary of Estimated Ethanol Production Costs ($/gal)[1]

Cost Item	**U.S. Corn Wet Milling**	**U.S. Corn Dry Milling**	**U.S. Sugarcane**	**U.S. Sugar Beets**	**U.S. Molasses[3]**	**U.S. Raw Sugar[3]**	**U.S. Refined Sugar [3]**	**Brazil Sugarcane[4]**	**E.U. Sugar Beets[4]**
Feed Costs[2]	0.40	0.53	1.48	1.58	0.91	3.12	3.61	0.30	0.97
Process Costs	0.63	0.52	0.92	0.77	0.36	0.36	0.36	0.51	1.92
Total Costs	1.03	1.05	2.40	2.35	1.27	3.48	3.97	0.81	2.89

[1]Excludes capital costs.
[2]Feedstock costs for U.S. corn wet and dry milling are net feedstock costs; feedstock costs for U.S sugarcane and sugar beets are gross feedstock costs
[3]Excludes transportation costs.
[4]Average of published estimates

Process Configuration

An NREL report (Aden, Ruth et al. 2002) provides a detailed process design and economic analysis for the conversion of corn stover to ethanol via dilute acid pretreatment and SSCF. This research output had already been accepted by many other groups. Lynd et al (2005) also estimated ethanol production costs based on the modeling framework developed in this report. Likewise, much of the modeling framework for this study was based on the NREL study.

NREL assumptions have the lignocellulosic biomass delivered to the feed handling area for storage and size reduction. From there the biomass is conveyed to pretreatment and detoxification. In this area, the biomass is treated with dilute sulfuric acid catalyst at a high temperature for a short time, liberating the hemicellulose sugars (xylose) and other compounds. Flash and overliming technologies are applied to remove compounds liberated in the pretreatment that are toxic to the fermenting organism. Detoxification is applied only to the liquid portion of the hydrolysis stream. Cellulase enzyme preparation is added to the hydrolyzate in the saccharification reactor that is maintained at a temperature to optimize the enzyme's activity. A split of saccharified slurry and nutrients are combined with an initial seed inoculum and culture in seed fermentation vessels until there are enough cells to inoculate the main fermentors. The fermenting organism is supposed to ferment glucose and xylose to ethanol, but will not convert mannose and galactose. The inoculum, along with other nutrients, is added to the main ethanol fermentor along with the partially saccharified slurry at a reduced temperature due to the thermal tolerance of fermenting organism. After several days of separate and combined saccharification and co-fermentation, most of the cellulose and xylose will have been converted to ethanol. The resulting biofuel is sent to product recovery.

Distillation and molecular sieve adsorption are used to recover ethanol from the raw fermentation and produce 99.5% ethanol. A column removes the dissolved CO_2 and most of the water, and the rectification column concentrates the ethanol to a near azeotropic composition. Then all water in this mixture is removed by vapor phase molecular sieve adsorption. The distillation bottom liquid is evaporated by waste heat. The solids from distillation and the concentrated syrup are sent to the combustor for production of electricity and process heat.

System Model

A mathematical model was established with the MATLAB-Simulink platform based on the frameworks mentioned above. The mathematical modeling of the process consists of mass and energy balance equations. All equipment is modeled assuming the hypothesis of steady state. Fourteen modules are included in the model to represent different units in the bioethanol production system. A description of the module structure can be found in the Methodology section of this report. Detailed module information can be acquired from the manual of the SSCF process model. These modules provide three kinds of output:

- Mass stream in/out
- Energy stream in/out
- Equipment cost

In the system configuration module, quantity and characteristics (composition, cost) of the feedstock can be defined. The feed-in quantity of the feedstock will determine scale of the whole system. Based on mass/energy balance results, a list of system input/output streams can be generated automatically. Plus, cost information can be acquired from NREL's database or other sources. Variable operation costs can be estimated. Here, total salary was estimated based on the position categories and relative annual salary/ personnel number information. For some positions, personnel numbers had to be adjusted according to the system scale (scale factors were acquired from outside references). With summarization of equipment costs generated by all the processing modules, the total installed equipment cost (TIEC) can be calculated. In this calculation, factors of scale and the chemical engineering plant cost index (CECPI) are included. Total project investment (TPI) as well as fixed operation costs can be estimated with these data. TPI, variable operation cost, and fixed operation cost data will be inserted into an Excel spreadsheet. Using Excel's economics function and parameters provided by references (So and Brown 1999; Aden, Ruth et al. 2002), ethanol production costs can be estimated.

<u>Lignocellulosic Biomass to Thermo-ethanol Conversion Process</u>

Background

The other major technology route to achieving the fuels production goals is via gasification of the biomass followed by catalytic synthesis to liquid fuels. Gasification is a process in which biomass is partially oxidized to form the following combustible gases under high temperature: carbon monoxide, hydrogen, and methane. Noncombustible products, carbon dioxide and water, are also formed. Then the carbon dioxide content is reduced to carbon monoxide and water. The gas generated by this process is called syngas and can be used as an intermediate of chemical synthesis to generate industrial products. In the area of sustainable energy production, two important products are ethanol and biodiesel (via the Fischer-Tropsch process).

Biomass can have a wide range of physical and chemical properties that affect its conversion into bioenergy, such as ethanol. One of the benefits of thermo-chemical conversion processes relative to fermentation technologies is the ability to convert a wide variety of biomass feedstocks regardless of their sugar and lignin contents. For example, even the lignin part in biomass can be converted by the gasification process.

From 1980 to 1989, SAIC (Science Applications International Corp., San Diego, CA) compared the cost of producing methanol with six gasification concepts (Stevens 1994). Results showed that although the gasification components of the system have quite different costs based on the technology routes, the overall cost of the system turned out to be less variable. The methanol production cost ranged from \$0.65 to \$0.77 per gallon with biomass feedstock priced at \$25/ton. Lau et al. (Lau, Bowen et al. 2003) applied the Hysys® design and simulation package to simulate hydrogen production by biomass gasification. Three feedstocks (sugarcane bagasse, nut shell, and switchgrass) were tested. Hydrogen production costs for the three feedstocks at various dry feed rates ranged from \$6.67 to \$10.23 per gallon. A 2007 NREL report (Phillips, Aden et al. 2007) documents a detailed process design and economic analysis for the conversion of wood chips to ethanol via a thermo-chemical approach, using low-pressure gasification followed by mixed alcohol synthesis. The production cost was estimated to be \$1.01 per gallon under various assumptions of technology (based upon a 2012 research target), markets, and financing.

Process Configuration

The NREL report (Phillips, Aden et al. 2007) described above provided a detailed process design and economic analysis for the conversion of wood chips to thermochemical ethanol via indirect gasification and mixed alcohol synthesis. We used their process design as our modeling framework.

The lignocellulosic biomass is delivered to the feed handling area of the processing plant for size reduction and drying. Then the dry biomass is conveyed to a low-pressure, indirectly heated circulating fluidized bed (CFB) gasifier, which is heated by circulating hot medium between the gasifier vessel and the char combustor. Before entering the synthesis reactor, the syngas must be reformed, quenched, compressed, and treated to have acid gas concentrations (H_2S, CO_2) reduced. In the tar reformer (an isothermal fluidized bed reactor), the tars in the syngas are reformed to additional CO and H_2; deactivated reforming catalyst is separated from the effluent syngas and regenerated on-line. The H_2S is reduced in an amine unit to elemental sulfur and is stockpiled for disposal, while the CO_2 removed from syngas in the same unit is vented to the atmosphere. After all the gas clean-up processes are completed, the syngas is further compressed and heated to synthesis reaction conditions of 1,000 psia and 570°F (300°C).

The mixed alcohol synthesis reactor is a fixed-bed reactor system that contains the MoS_2 catalyst. Besides methanol and ethanol, a series of alcohols (propanol, butanol, and pentanol) can be synthesized at the same time. After the reactor, the effluent is cooled to 110°F (43°C) through a series of heat exchangers while maintaining high pressure. The liquid alcohols are then separated by condensing and sent to the product recovery area. The unconverted syngas will be recycled back to the tar reformer.

The liquid stream from the synthesis reactor is dehydrated by molecular sieves. The separated gas phase is recycled back to the tar reformer, and the dehydrated main stream is sent to the crude alcohol distillation column where most of the ethanol and almost all the methanol are separated. The remaining liquids are cooled down and stored as higher alcohols. Methanol is further separated by the methanol column and sent back to the molecular sieves as a flushing stream, then combined with water that has been removed from the alcohol stream and recycled back to the alcohol synthesis section. 99% of the ethanol is recovered and a small portion of methanol from the bottom of the methanol column is also cooled down and stored as final product.

System Model

Seven modules are included in the model to represent different unit operations in the thermochemical production system. Procedures that are similar to the biological conversion process as described before were followed in developing the system model. .

A mathematical model had been established on the MATLAB-Simulink platform based on the frameworks mentioned above. The mathematical modeling of the process consists of mass and energy balance equations. All equipment is modeled assuming the hypothesis of steady state.

<u>Anaerobic Digestion</u>

Background

The AD process is a widely applicable technology to green energy production, odor control, and waste treatment. The AD process includes a series of processes in which microorganisms break down organic biodegradeable materials in the absence of oxygen. Acid-forming bacteria break down organic matter into simple organic acids. Methane-forming bacteria then act on these acids. Almost any organic material can be processed with AD, including biodegradable waste materials such as waste paper, grass clippings, leftover food, sewage, and animal waste. The gas produced, commonly referred to as biogas, consists of methane (around 60% of the total), carbon dioxide, water vapor, ammonia, and hydrogen sulfide.

System Model

The AD process is often modeled using IWA Anaerobic Digestion Model No. 1 (ADM1) (Batstone et al. 2002) as a means to separate the enzymatic hydrolysis of solid wastes from the metabolic reactions utilizing soluble substrates. Zaher et al. (2009) have developed GISCOD (a general integrated solid waste co-digestion model) based on ADM1. The main goal of this study was to develop and test a simulation tool of the AD process that is applicable to any combinations of waste streams using the simulation platform MATLAB-Simulink. A general co-digestion assessment model is still needed to support operation decisions at full-scale plants and to assist co-digestion research. Thus, we developed an AD process assessment model with the structure shown in Figure 119. GISCOD is the core of this model and provides steady-state output estimation for the preconfigured AD process. Resulting data were stored in data files that could be utilized by the following for assessment modules. In most cases studied, only the digester and generator unit were discussed. Biogas purification and nutrients recovery processes are two additional and important options for AD technology. Specific modules were the

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developed to evaluate the economic impact on the performance of whole system. Outputs of all four assessment modules were summarized in data presentation module.

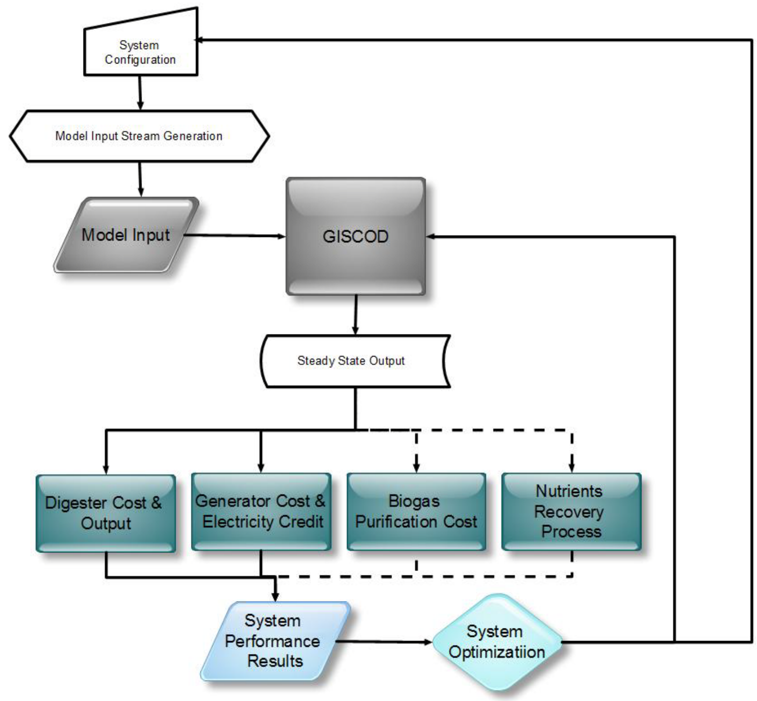

Figure 119: System Definition for AD Module

Economic Model

The TPI, variable operating costs, and fixed operating costs data were generated automatically by the process models developed, and were input to a spreadsheet-based discounted cash flow (DCF) model to determine the minimum ethanol selling price (MESP) per gallon of ethanol produced under the constraint condition that the net present value of the whole project will be zero. The methodology used in this section is the same as that used by Aden et al. (Aden, Ruth et al. 2002) and Philips et al. (Phillips, Aden et al. 2007). The discount rate, depreciation method, income tax rates, plant life, and construction start-up duration that needed to be specified for the economic model were obtained from these references. The economic parameters used in the model are listed in Table 21. Sensitivity analysis was also performed to demonstrate the effect of technology options on the economic viability of the process.

Table 21: Economic Parameters for the AD Model

Assumption	Value
Internal Rate of Return (After-Tax)	10%
Debt/Equity	0%/100%
Plant Life	20 years
General Plant Depreciation	200% DDB
General Plant Recovery Period	7 years
Steam Plant Depreciation	150% DDB
Steam Plant Recovery Period	20 years
Construction Period	2.5 years
First 6 Months Expenditures	8%
Next 12 Months Expenditures	60%
Last 12 Months Expenditures	32%
Start-Up Time	6 months
Revenues	50%
Variable Costs	75%
Fixed Costs	100%
Working Capital	5% of Total Capital Investment
Land Cost	6% of Total Purchased Equipment Cost (Cost taken as an expense in the first construction year)

Source: (Phillips, Aden et al. 2007)

RESULTS AND DISCUSSION

Crop Residue in Washington State

Introduction

Crop residue (field residue) is one important resource of biofuel feedstocks. Because Washington State is one of the major wheat-producing states in the country, wheat straw covers nearly 80% of all crop residues (Frear et al., 2005). Researchers in Washington State are interested in this kind of feedstock and have assessed the availability of wheat straw, the status of the conversion technologies, and the economics of ethanol production from wheat straw (Kerstetter and Lyons 2001). Washington State has about 1,614,234 dry tons of wheat straw annually. As a woody material, wheat straw is rich in cellulose and hemicelluloses, which is a potential raw material for commercial bioethanol production and gasification. Traditional bioethanol production first changes the structure of the biomass to release xylose, and then uses cellulase to hydrolyze cellulose into glucose. Glucose and xylose can be converted into ethanol by microorganisms. Many processes with different pretreatment methods had been evaluated (Szczodrak and Fiedurek 1996; Saha and Cotta 2006; Chenet al. 2007; Chen, et al. 2008; Linde, Jet al. 2008; Qureshi, et al. 2008; Saha, et al. 2008; Liu, Bischoff et al. 2009; Pan, et al. 2009). Another technique is to use a gasifier to convert biomass into syngas (Bridgwater 1995; Bridgwater, Toft et al. 2002; McKendry 2002; Bridgwater 2003; Lau, Bowen et al. 2003; Tembo, Epplin et al. 2003; Faaij 2006; Gribik, Mizia et al. 2007). This technology is about a century old but disappeared soon after the Second World War. However, increased fuel prices and environmental concerns have renewed interest in this old technology; gasification has become a more modern and quite sophisticated technology that has many applications in biomass processing.

Analysis Results

Economic assessment results indicate that, with proper site selection based on the GIS model, feedstock costs can be controlled at a relatively stable level. In this case, as the final ethanol production output rises from 20 MGY to 120 MGY, the feedstock costs increase only $0.06/gallon, which can be easily offset by processing cost reductions (Figure 120). The production costs have almost the same trend as the processing costs, but feedstock costs increase sharply at the 100 MGY level and above. It is remarkable that 20 MGY seems to be a shift point for the ethanol production cost curve. When the output scale reaches this threshold, cost changes level out.

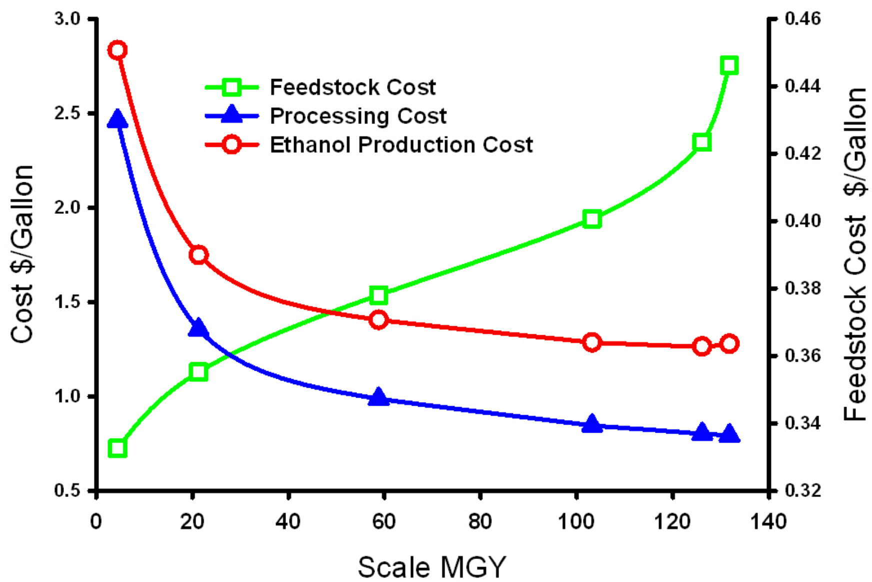

Figure 120: Cost Curve for Bioethanol Production from Crop Residue

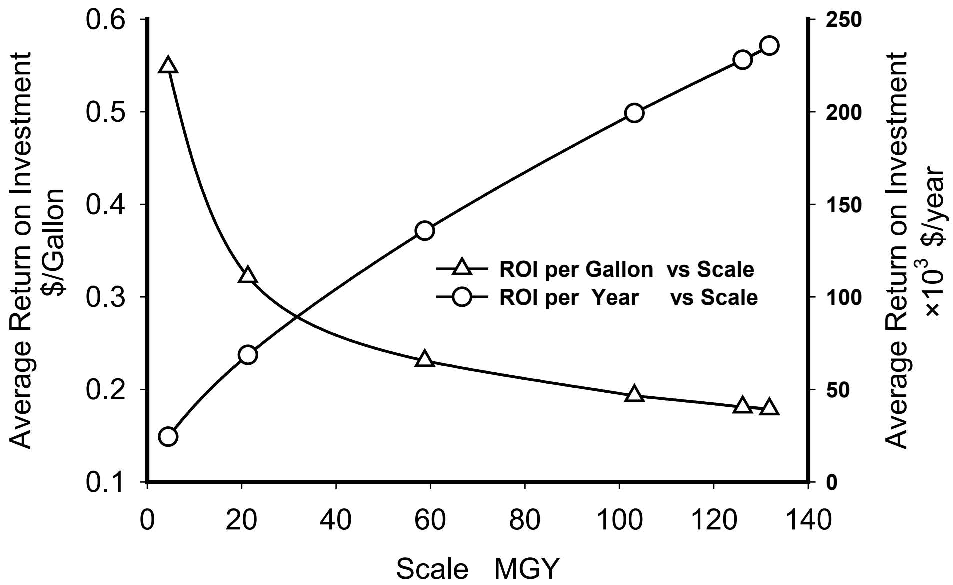

Figure 121: Return on Investment vs. Ethanol Production Scale

Figure 121 presents the return on investment for all of the production scales. Because the assessment process estimates MESP under fixed IRR, ROI for every gallon of bioethanol keeps decreasing due to the decline in the ethanol selling price. Because projects with high ROI may be more attractive to potential investors, this could be a disadvantage of large-scale projects. With the same feedstock, the gasification process has lower production costs compared to the SSCF option (Figures 122 and 123). Lower variable costs and higher credit from additional value added higher alcohols simultaneously produced via the process are the reasons. The cost curves reveal the same profile as previous one, as did the return on investment curve. The average return is reduced due to declining ethanol prices.

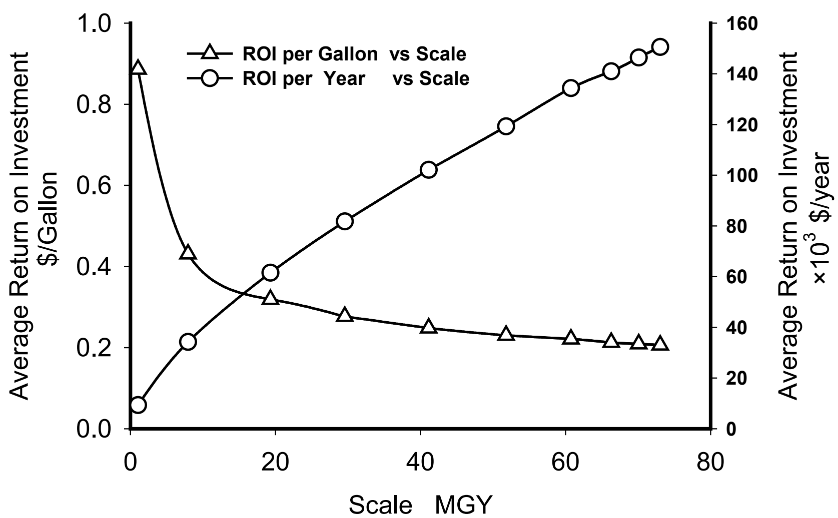

Figure 122: Cost Curve for Ethanol Production from Crop Residue via Gasification

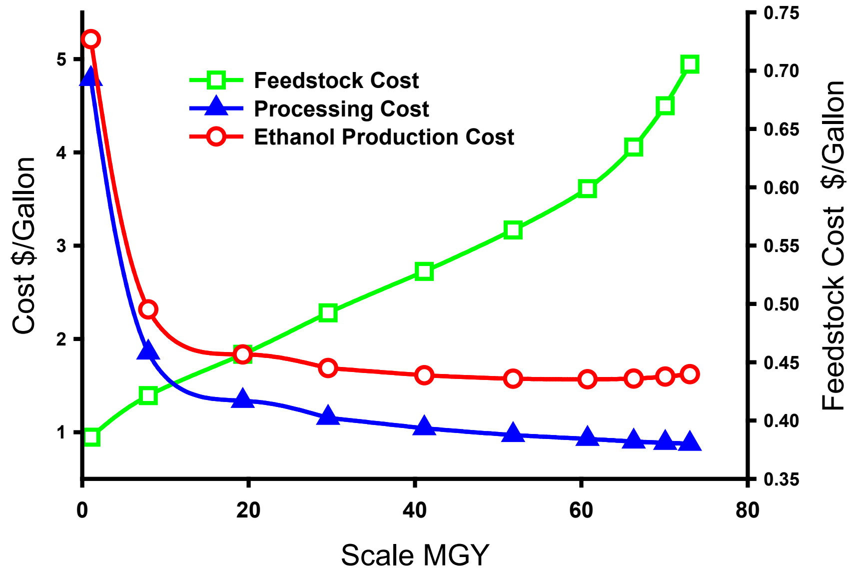

Figure 123: Return on Investment vs. Ethanol Production Scale

Sensitivity Analysis

Pretreatment Yield and Cost

Pretreatment is one of the crucial steps in ethanol production; it hydrolyzes the hemicellulose to monomer sugars (Gregg and Saddler 1996; Eggeman and Elander 2005; Galbe and Zacchi 2007). Because xylan makes up a significant part of the hemicellulosic sugar in biomass, pretreatment yield has a great impact on the final yield and cost of the biofuel production system (Figures 124 and 125).

Figure 124: Impact of Pretreatment Yields on Ethanol Production

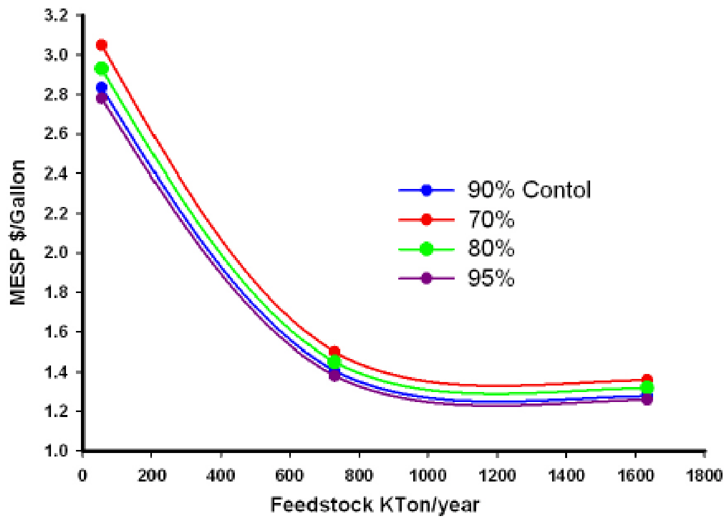

Figure 125: Impact of Pretreatment Yields on Ethanol Production Cost

The effects of pretreatment yields on ethanol production are magnified by scale-up. At small-scale production, the difference in MESP value is much more obvious. From 70% to 95% yield, there are a $0.27/gallon increase in MESP and a 12.7 MGY decrease in ethanol production.

Sugar Utilization

In addition to glucose and xylose, there are other sugars contained in biomass that can be converted into biofuel, including the C5 sugar arabinose and the C6 sugars galactose and mannose. These sugars were not considered to be used by the production strains and processes, but other research suggests the possibility of utilizing these sugars for ethanol production (Finn, Bringer et al. 1984; Alterthum and Ingram 1989; Zhang 1998; Lin and Tanaka 2006); and therefore may be part of our commercial biofuel production in the future.

Table 22: Sensitivity Results for Sugar Utilization in Ethanol Production

Feedstock	Sugar		Ethanol Production (MGY)	Change %	Ethanol Selling Price ($/gallon)	Changes from Original Value
	Item	Content %				
Crop Residue	Arabinose	2.35	107.6		1.24	–0.05
	Galactose	0.75	104.7		1.27	–0.02
	Mannose	0.31	103.8		1.28	–0.01
	Based on crop residue, 1,279,000 ton/year					
Forest Residue	Arabinose	0.75	61.5		1.55	–0.02
	Galactose	2.02	63.0		1.51	–0.06
	Mannose	0.89	61.8		1.54	–0.03
	Based on forest residue, 709,053 ton/year					

Co-Product Yields

Electricity is the main co-product of the SSCF process. The stable lignin part and all remaining sludge are sent to the combustor to burn. The heat generated is then converted into steam and electricity by turbine. “Higher alcohols” are higher-molecular-weight alcohols created by alcohol synthesis. Their price is set according to the price of gasoline because it is anticipated that the higher alcohols would make excellent gasoline additives or gasoline replacements in their own right (no engine testing was done in this study).

Table 23: Sensitivity Results by Cost Impact (Based on Crop Residue, 1,279,000 Ton/Year)

Parameter	Value		Ethanol Selling Price ($/gallon)	Changes From Original Value
	Model Preset	Sensitivity		
Electricity Credit	$0.0444/ KWh	0	$1.39	+$0.10
		$0.02/ KWh	$1.34	+$0.05
		$0.06/ KWh	$1.25	–$0.05
Higher Alcohols Credit	$1.15/Gallon	0	$1.18	+$0.18
		60%	$1.08	+$0.08
		80%	$1.04	+$0.04

Production Cost Estimation

Based on feedstock collection, transportation and distribution work completed by the Transportation Research Group (TRG) at WSU (Appendix I), four central locations in Washington State for biomass collection have been suggested as being ideal for biomass processing. Feedstock quantities and transportation costs for all categories of feedstocks as provided by the TRG were incorporated with process modeling outputs to develop total delivered cost curves for the respective locations and their matrix of scenarios.

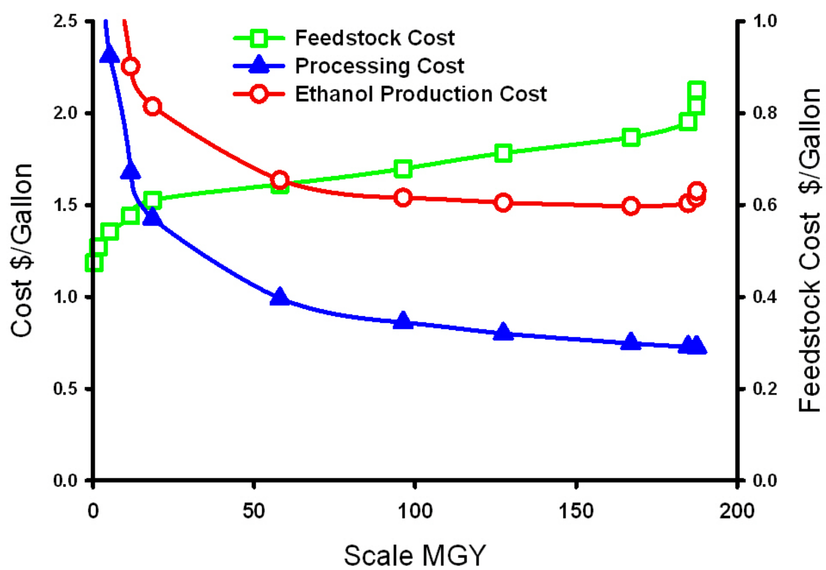

Figure 126: Longview Cost Curve for Biological Fermentation Process (Crop Residue)

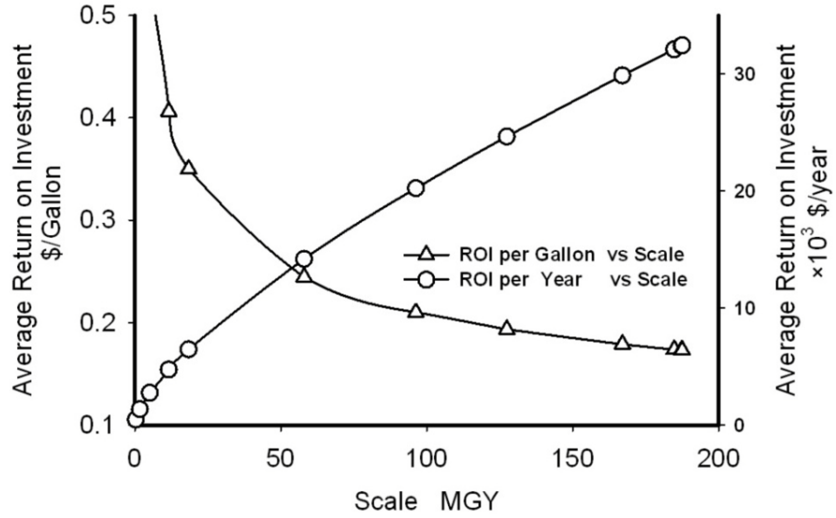

Figure 127: Longview Return on Investment for Biological Fermentation Process (Crop Residue)

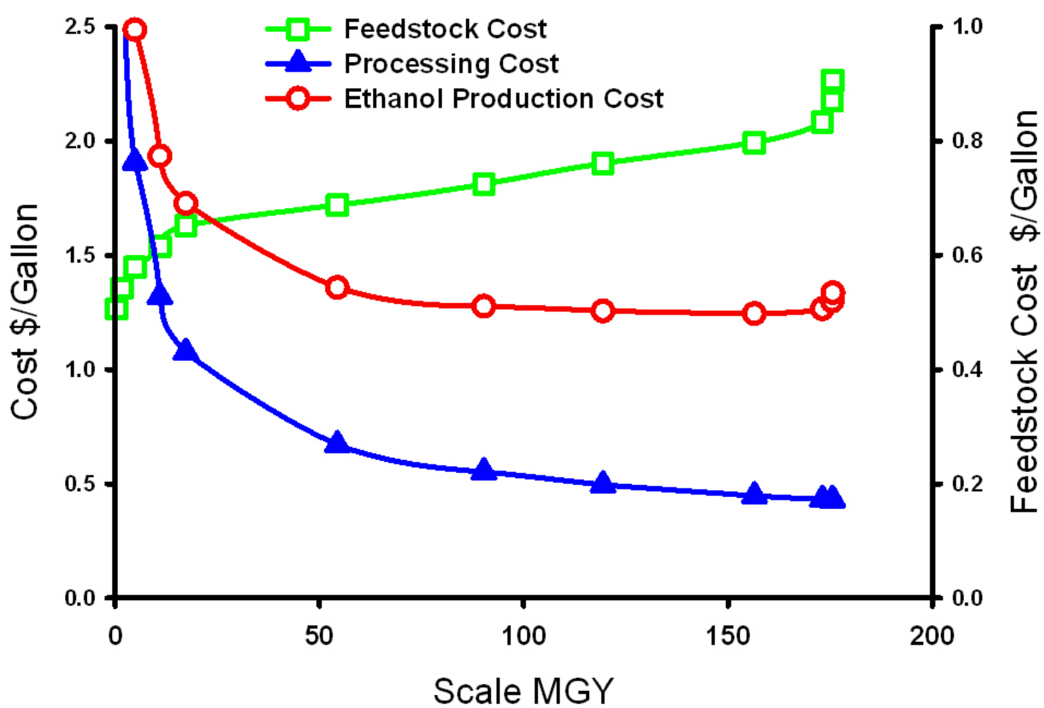

Figure 128: Longview Cost Curve for Gasification Process (Crop Residue)

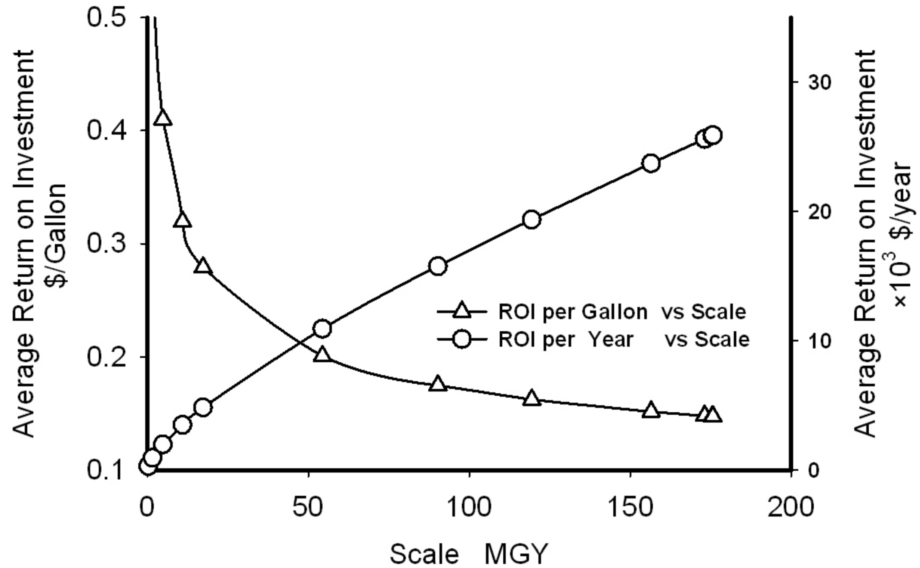

Figure 129: Longview Return on Investment for Gasification Process (Crop Residue)

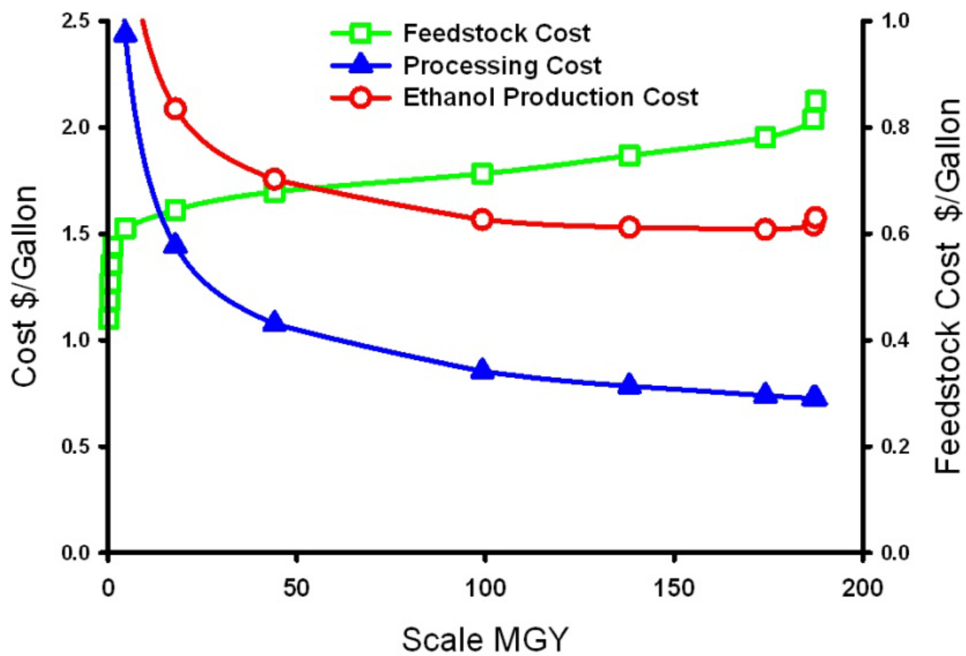

Figure 130: Ferndale Cost Curve for Biological Fermentation Process (Crop Residue)

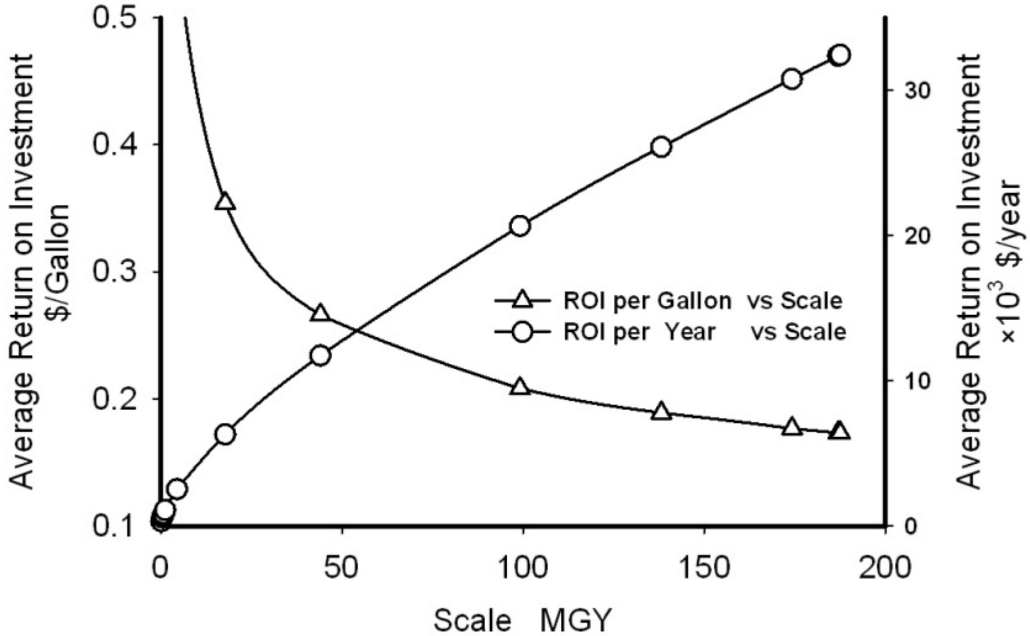

Figure 131: Ferndale Return on Investment for Biological Fermentation Process (Crop Residue)

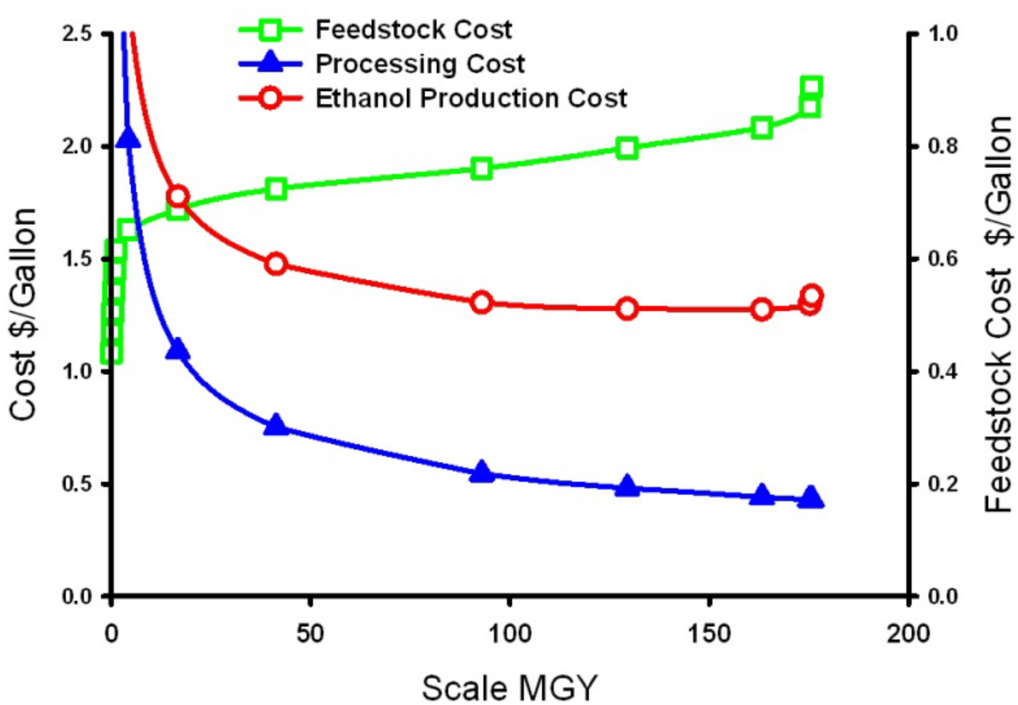

Figure 132: Ferndale Cost Curve for Gasification Process (Crop Residue)

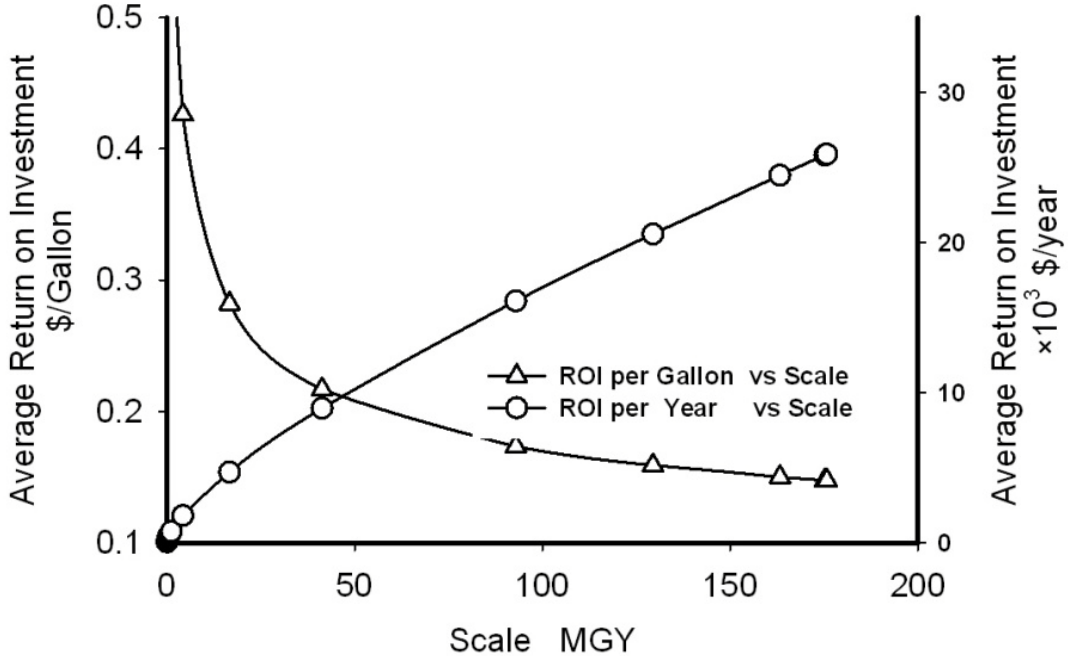

Figure 133: Ferndale Return on Investment for Gasification Process (Crop Residue)

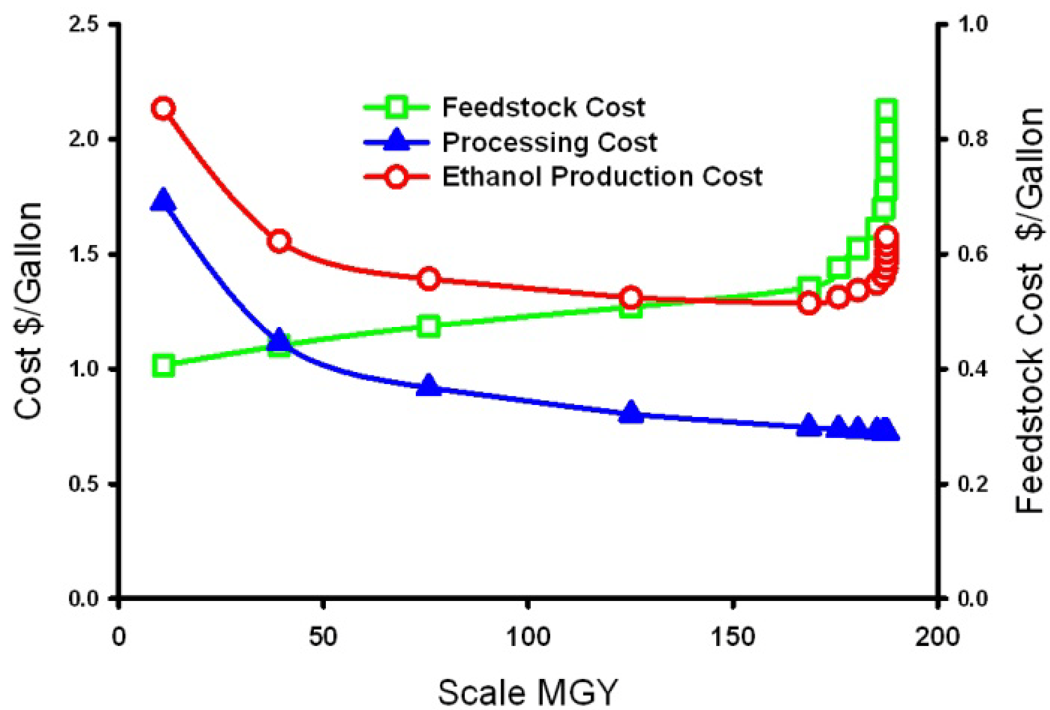

Figure 134: Spokane Cost Curve for Biological Fermentation Process (Crop Residue)

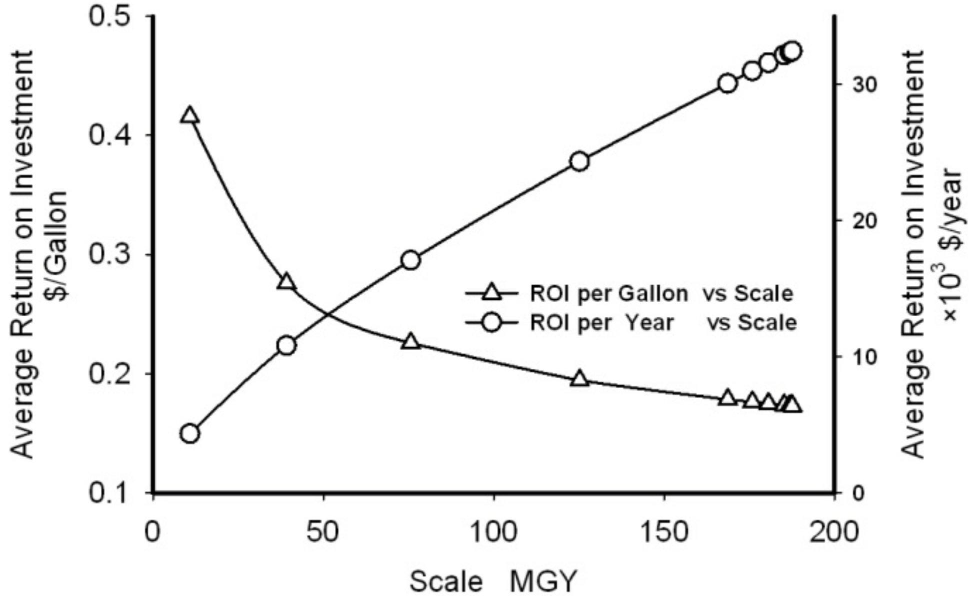

Figure 135: Spokane Return on Investment for Biological Fermentation Process (Crop Residue)

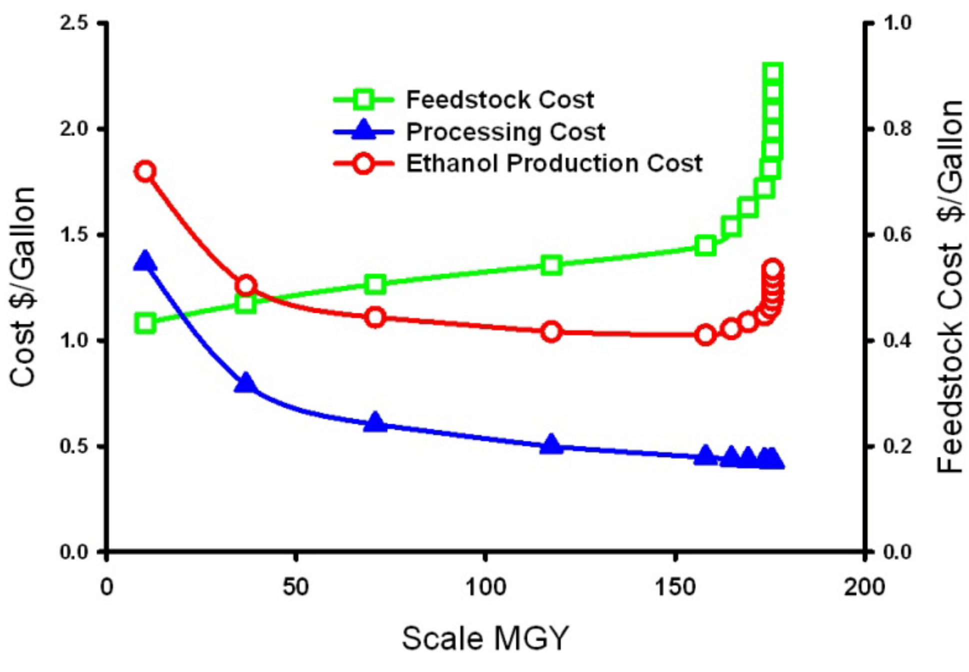

Figure 136: Spokane Cost Curve for Gasification Process (Crop Residue)

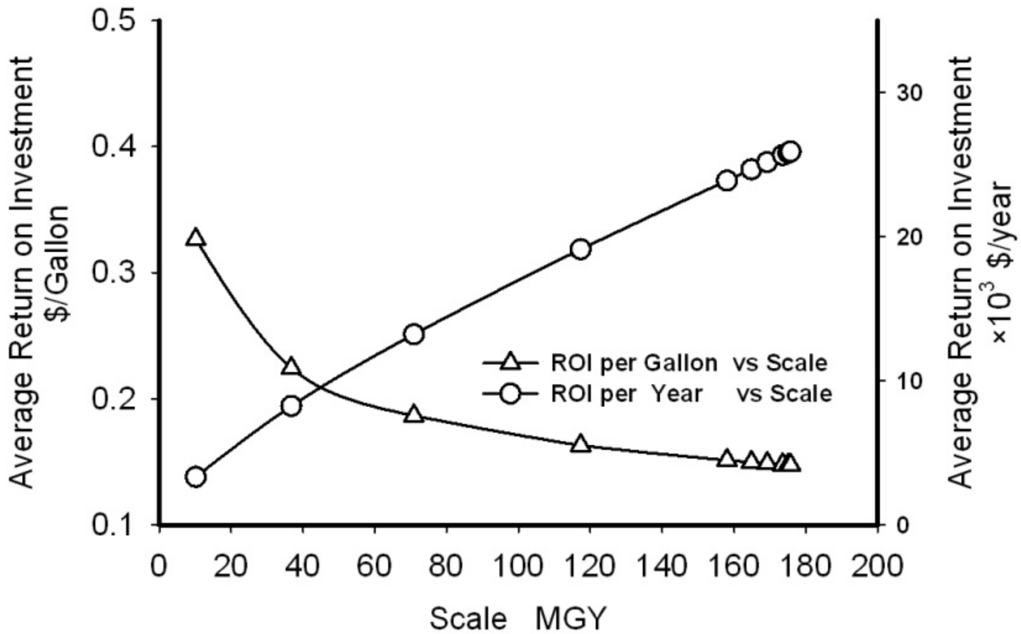

Figure 137: Spokane Return on Investment for Gasification Process (Crop Residue)

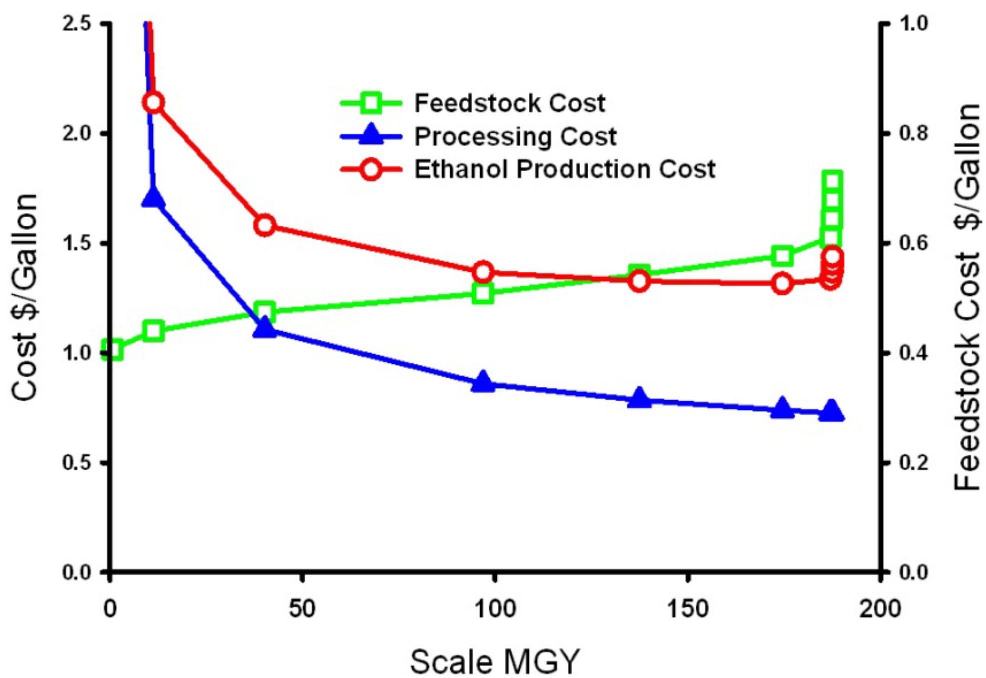

Figure 138: Ellensburg Cost Curve for Biological Fermentation Process (Crop Residue)

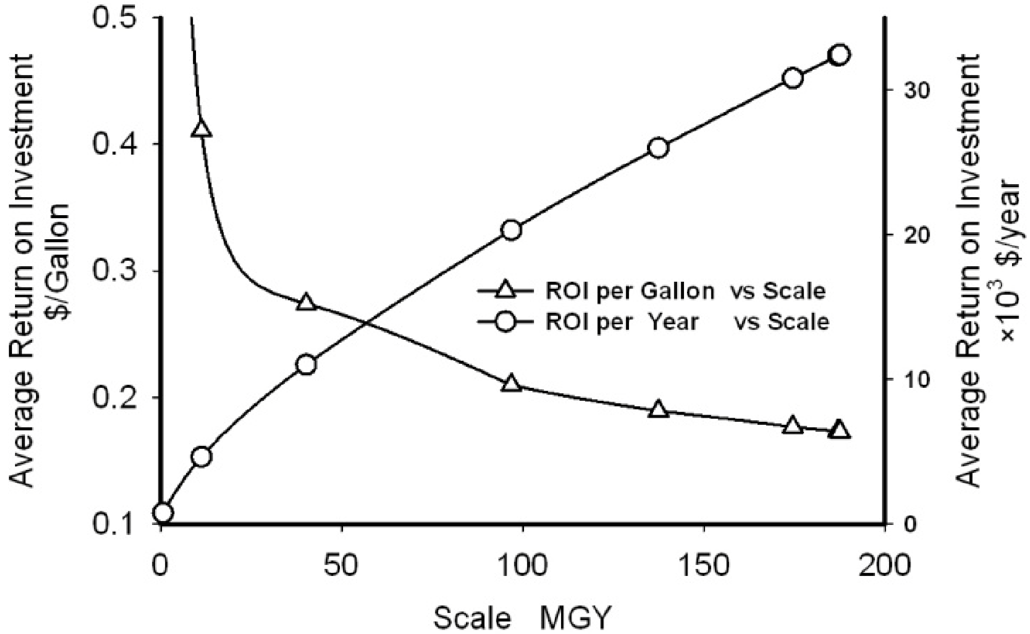

Figure 139: Ellensburg Return on Investment for Biological Fermentation Process (Crop Residue)

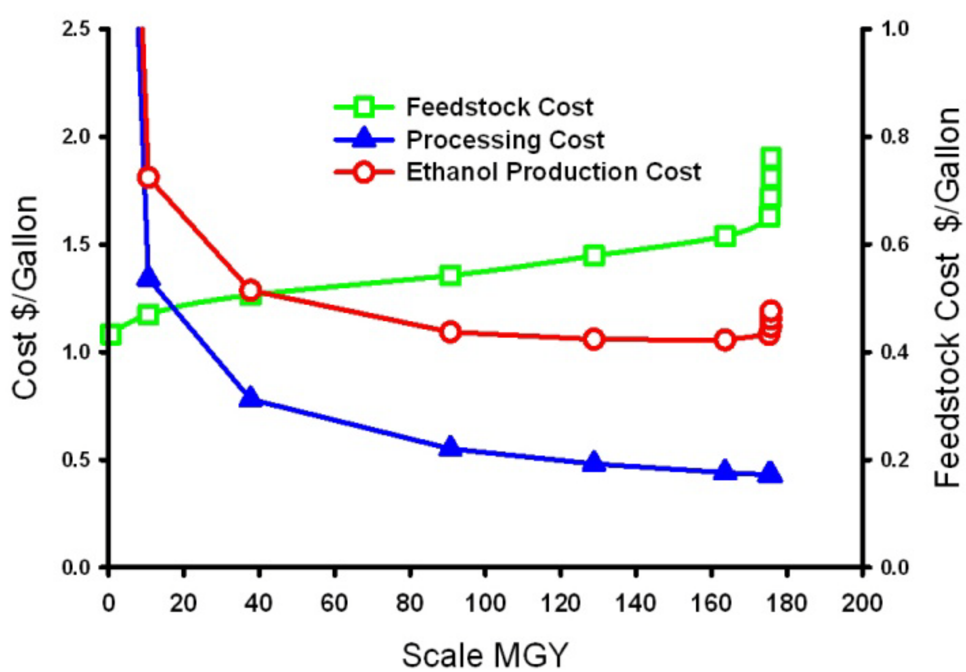

Figure 140: Ellensburg Cost Curve for Gasification Process (Crop Residue)

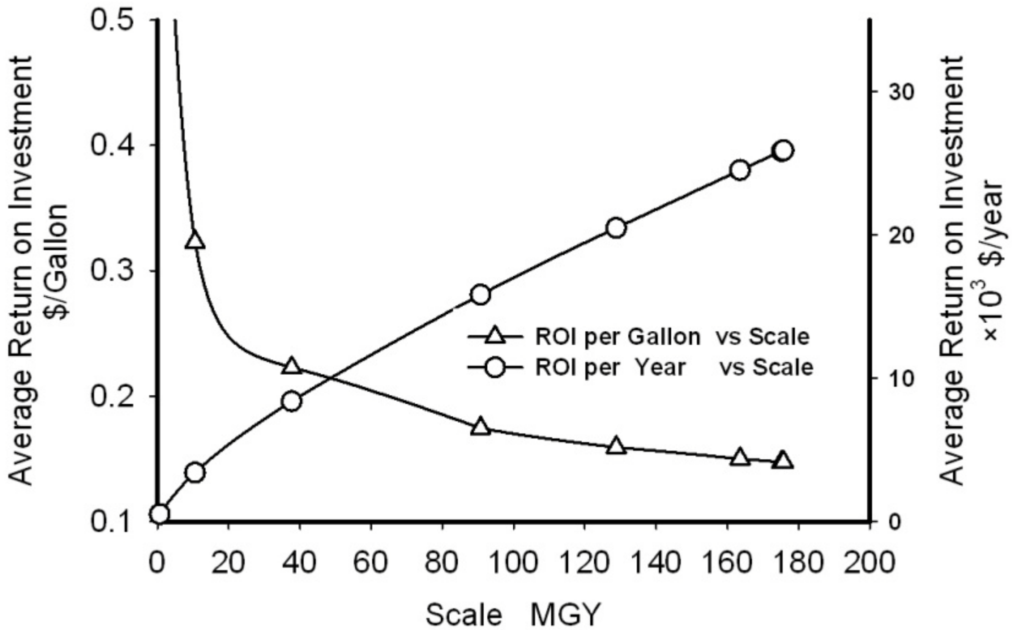

Figure 141: Ellensburg Return on Investment for Gasification Process (Crop Residue)

Discussion

Several conclusions can be drawn from the cost curves developed from the fusion of the transportation and processing models.

1. Regarding the 420-mile collection distance, the maximum capacity for an ethanol plant built with crop residue as feedstock can only reach the scale of about 180 MGY due to the limitation of material.
2. If only based on model output, the gasification process shows some advantage over the SSCF process in production cost. However, our models are based on two concept designs, and some technology barriers still need to be overcome for both of them—pretreatment units of bioethanol production, and the carbon conversion rate of the gasification process. There is no commercialized example for comparison, so we can only conclude that the gasification technology may have more potential (Figures 142-143).
3. In almost every curve, the 20 MGY scale can be seen as a tipping point for production cost. Because ethanol MESP no longer decreases sharply with the increase of plant scale, this value can be seen as a threshhold for ethanol plant scale in Washington State.
4. From 60 MGY to 160 MGY, the ethanol production cost curve enters a “flat bottom” zone, which means the cost can be neglected in considering the system scale. For example, large-scale facilities may have lower ethanol production costs but the ROI per gallon also declines. This may be undesirable to potential investors.
5. The upper limit of facility scale will be determined by the market capacity. If the delivery cost were taken into account, there must be an optimized facility scale which balances the production cost and delivery cost.

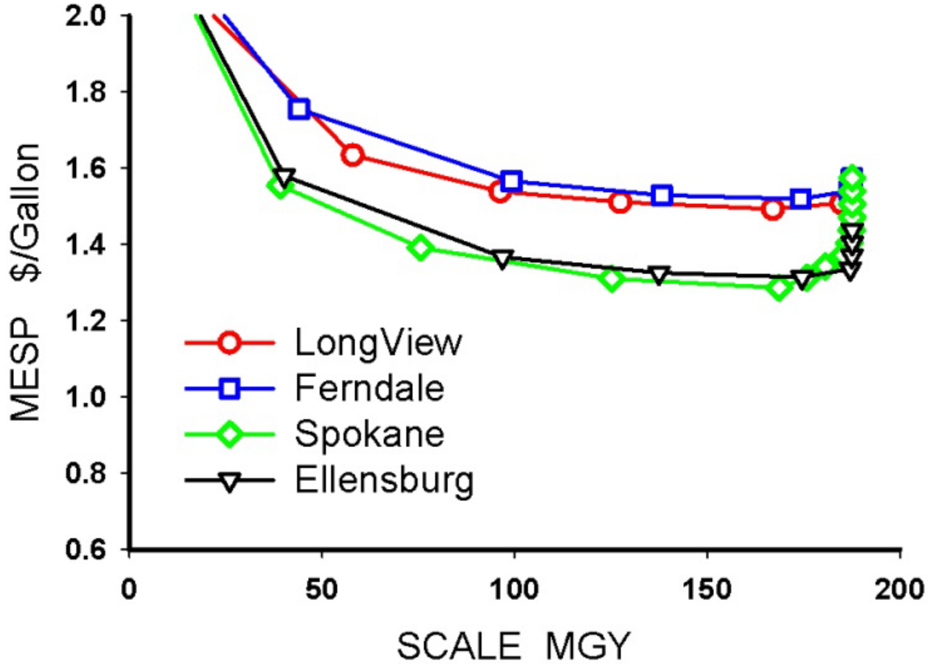

Figure 142: Cost Curve for Bioethanol Production with Crop Residue as Feedstock

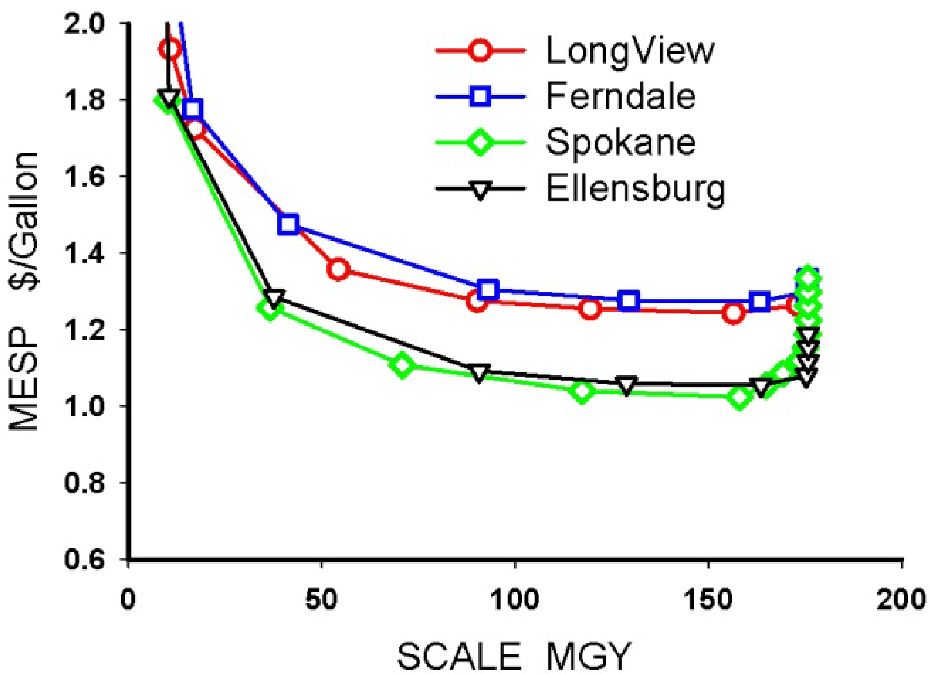

Figure 143: Cost Curve for Thermo-ethanol Production with Crop Residue as Feedstock

Forest Residue in Washington State

Introduction

The forest products industry generates large amounts of residual biomass as timber and is harvested and manufactured into marketable goods such as lumber and paper. Forest-derived biomass may originate directly from the forest (logging residues) or from timber processing mills (primary mill residues). According to the earlier report (Frear et al., 2005), about 8 million tons of forest residues are produced from Washington State annually.

Analysis Results

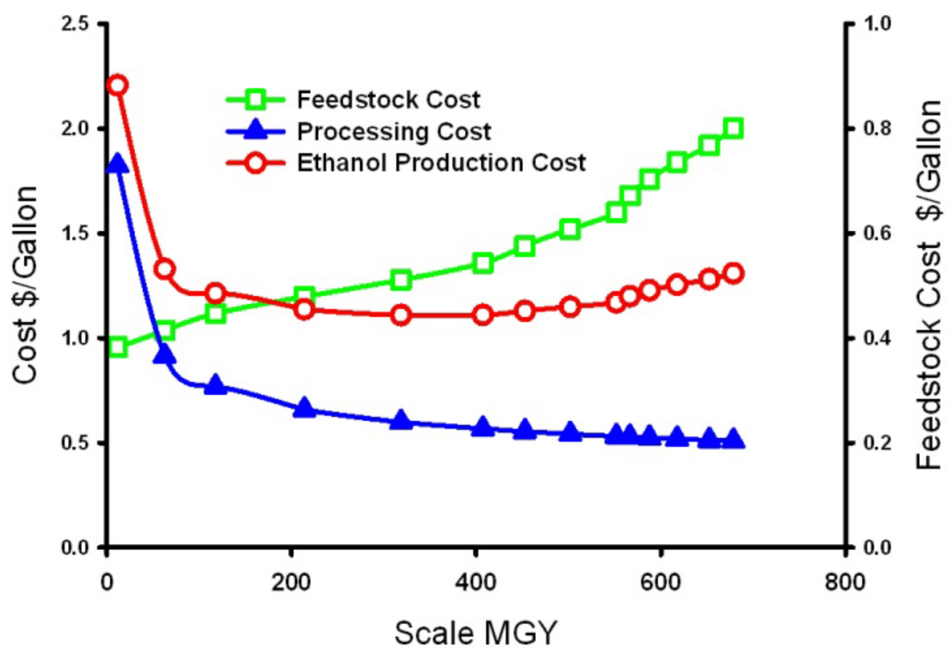

Figure 144: Longview Cost Curve for Biological Fermentation Process (Forest Residue)

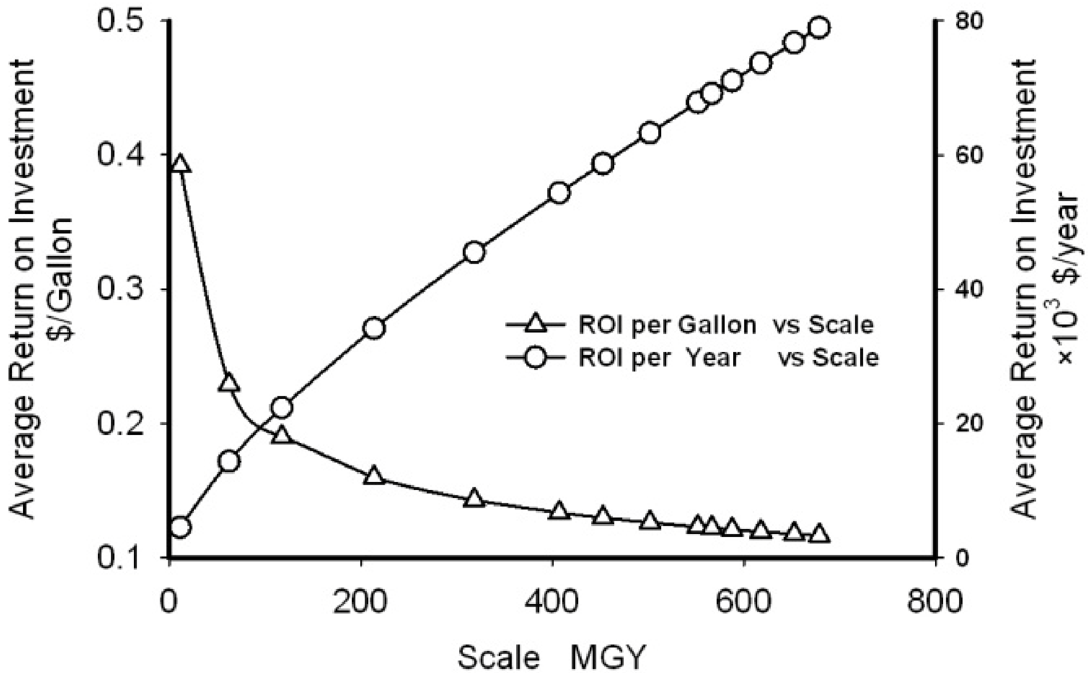

Figure 145: Longview Return on Investment for Biological Fermentation Process (Forest Residue)

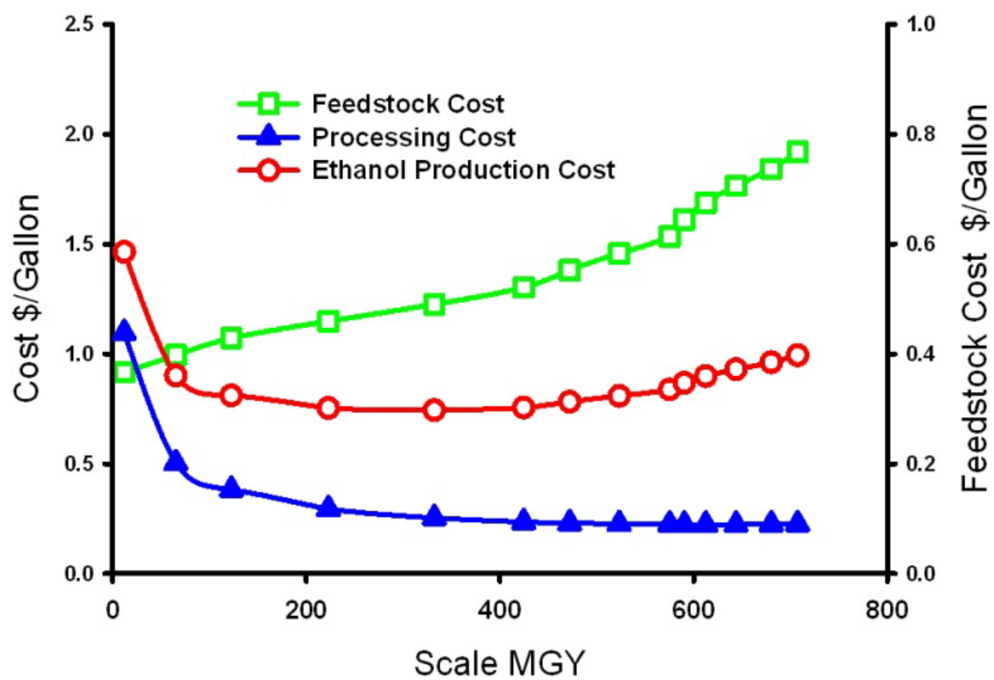

Figure 146: Longview Cost Curve for Gasification Process (Forest Residue)

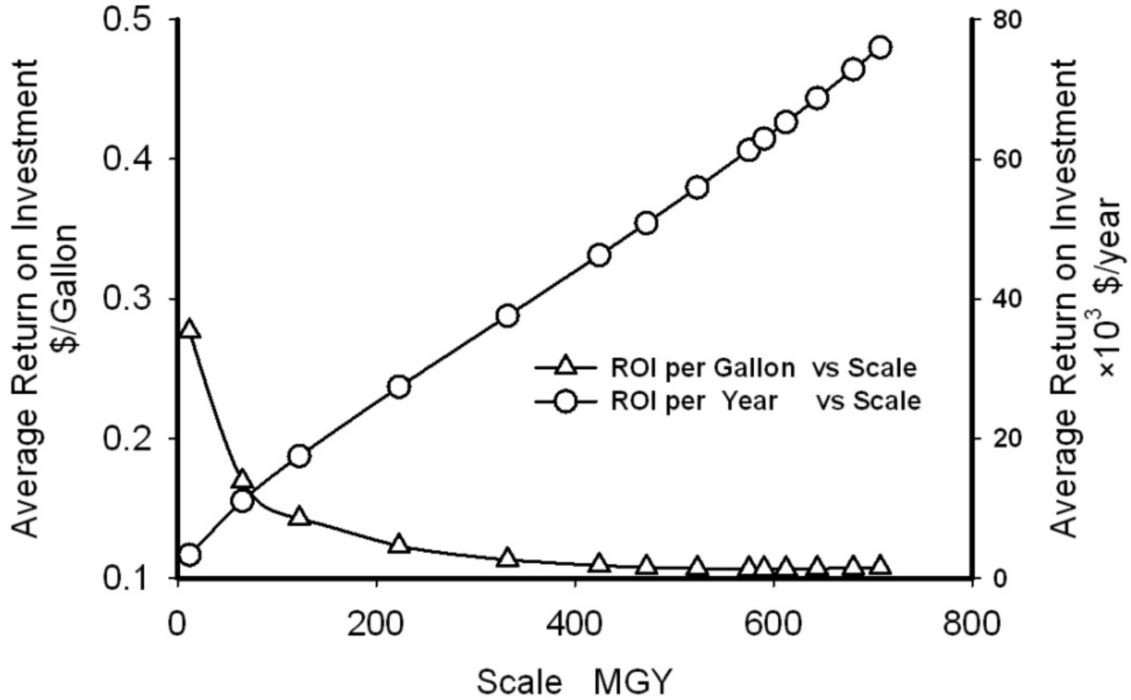

Figure 147: Longview Return on Investment for Gasification Process (Forest Residue)

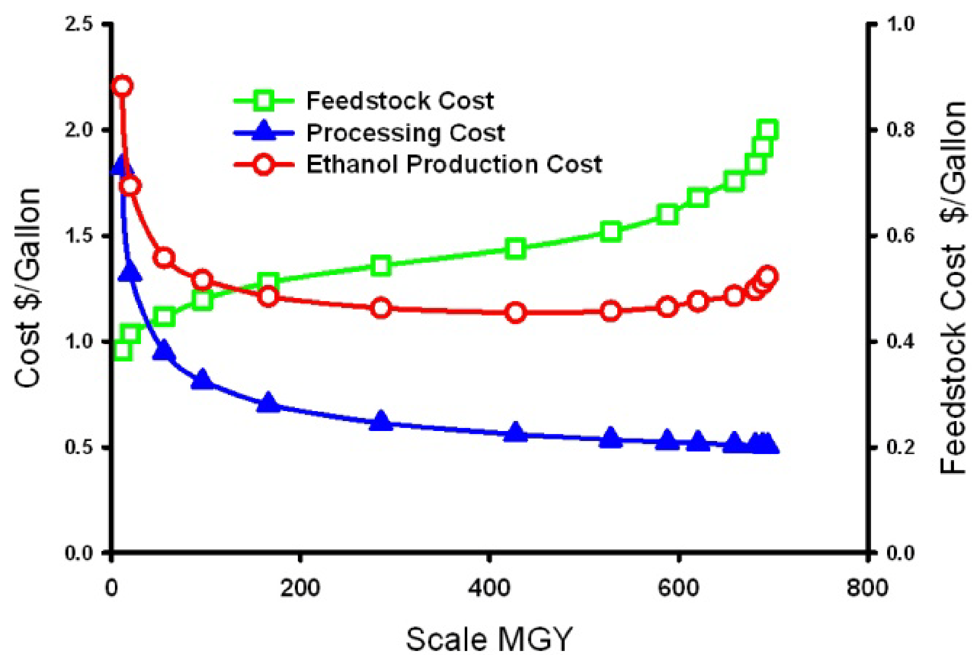

Figure 148: Ferndale Cost Curve for Biological Fermentation Process (Forest Residue)

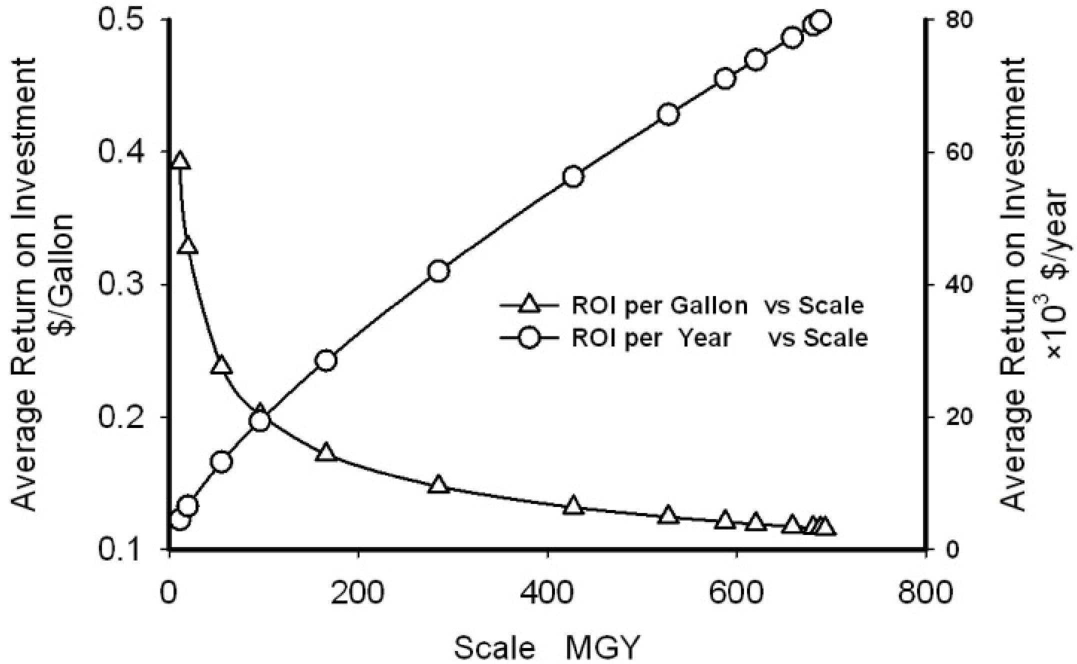

Figure 149: Ferndale Return on Investment for Biological Fermentation Process (Forest Residue)

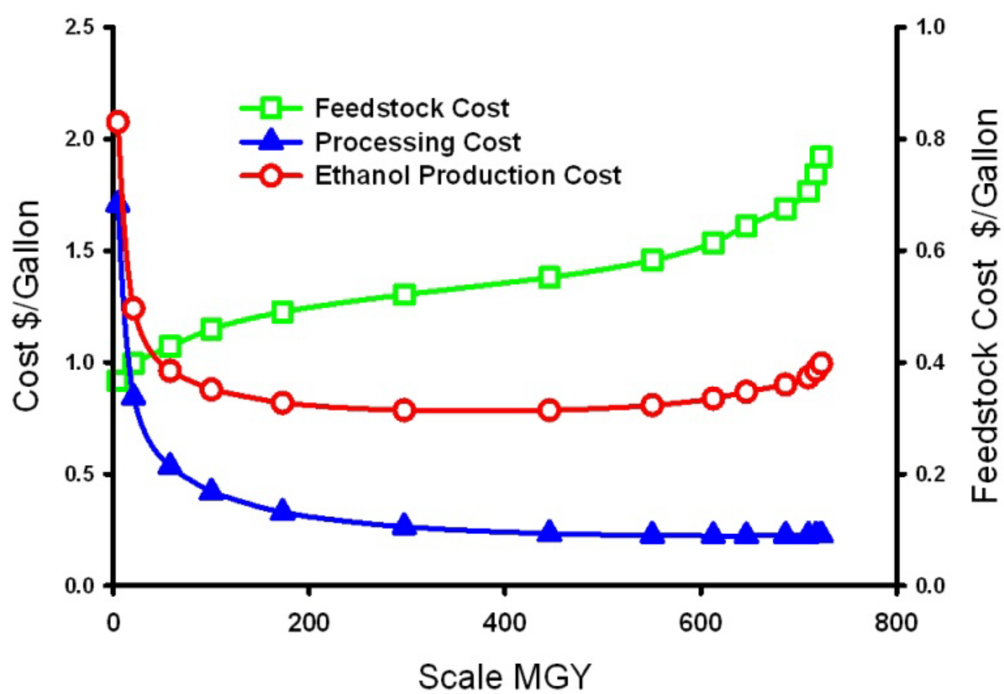

Figure 150: Ferndale Cost Curve for Gasification Process (Forest Residue)

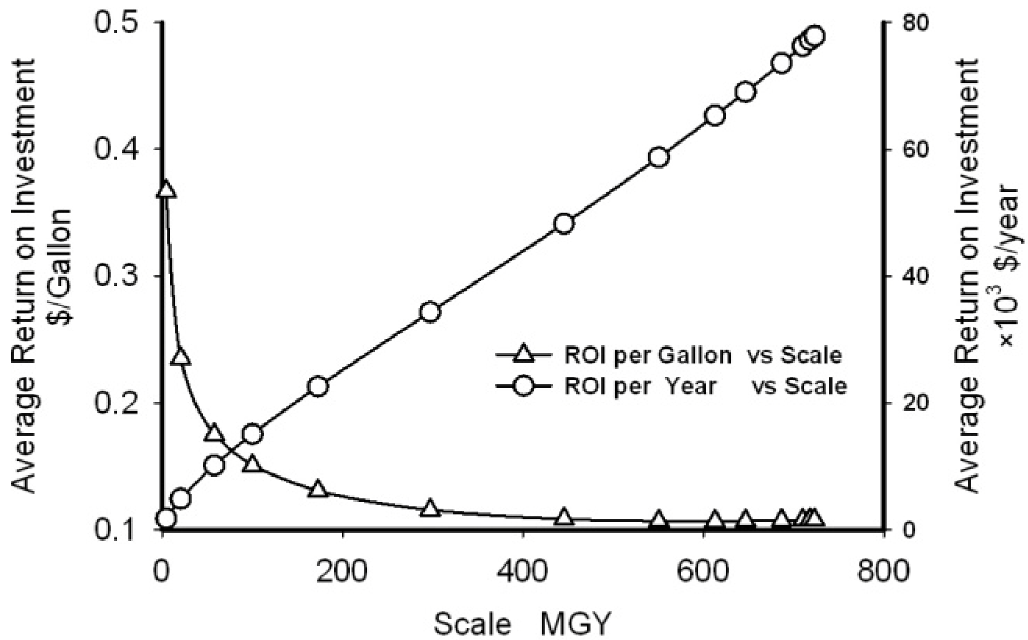

Figure 151: Ferndale Return on Investment for Gasification Process (Forest Residue)

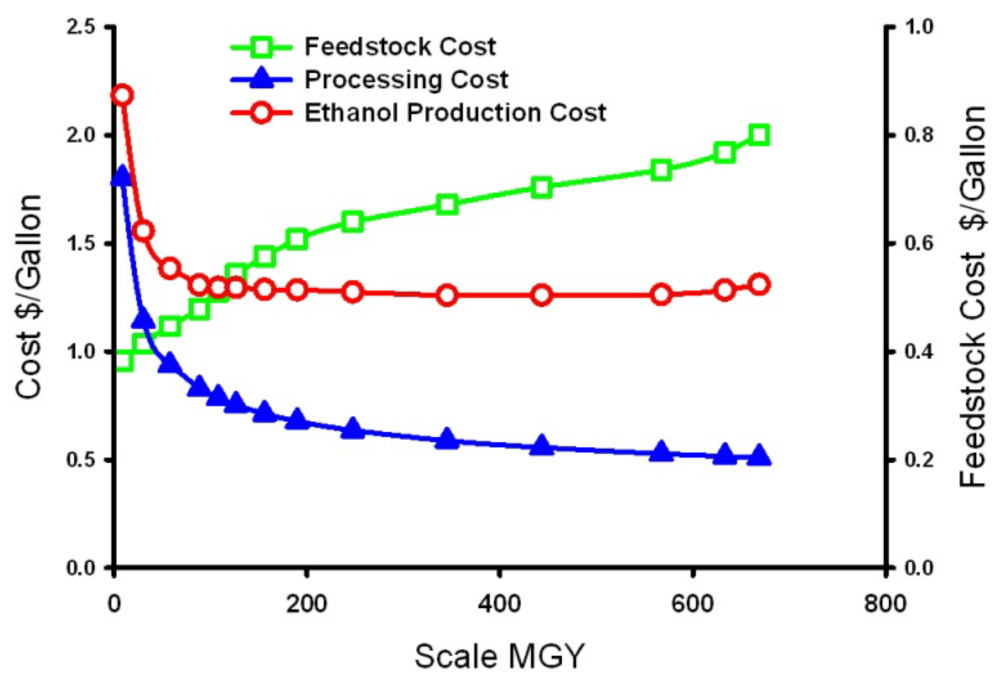

Figure 152: Spokane Cost Curve for Biological Fermentation Process (Forest Residue)

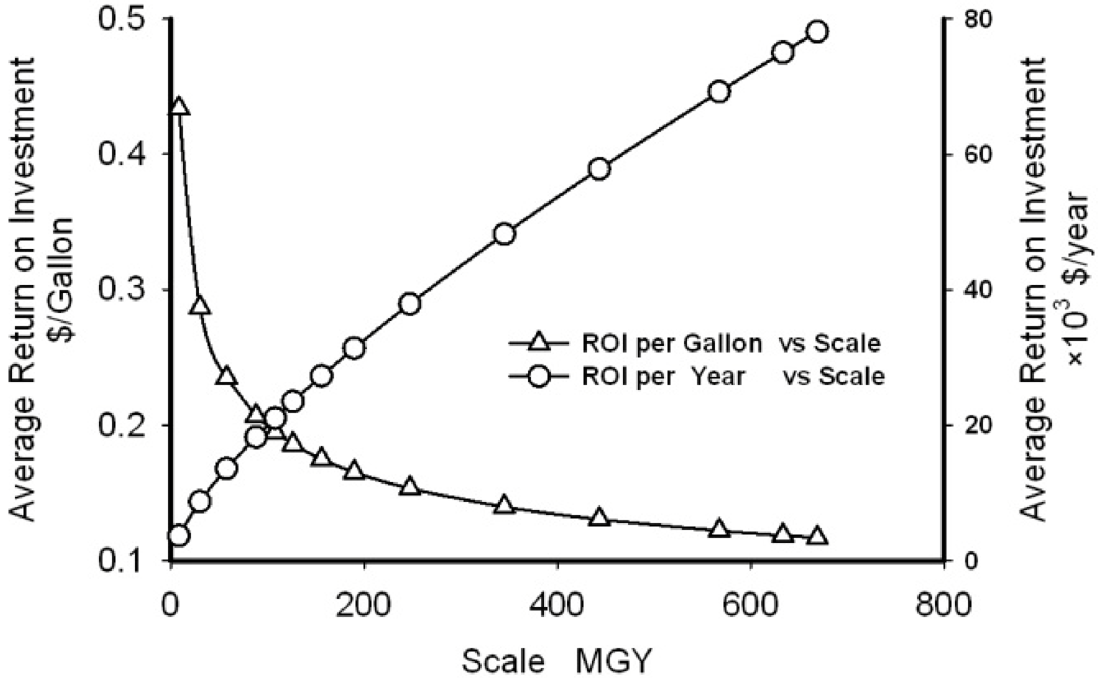

Figure 153: Spokane Return on Investment for Biological Fermentation Process (Forest Residue)

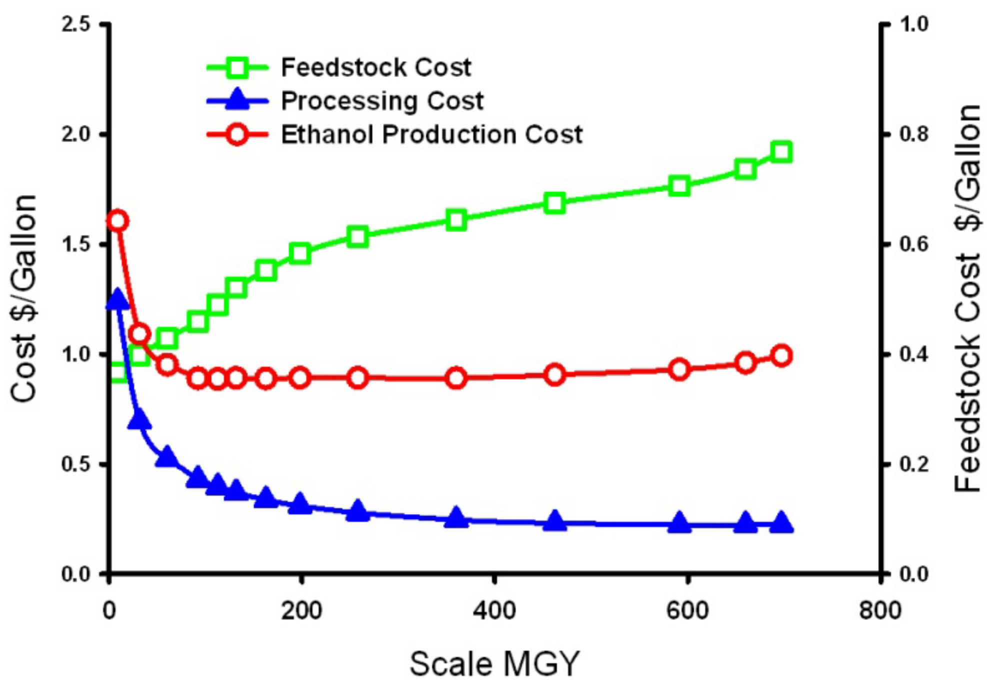

Figure 154: Spokane Cost Curve for Gasification Process (Forest Residue)

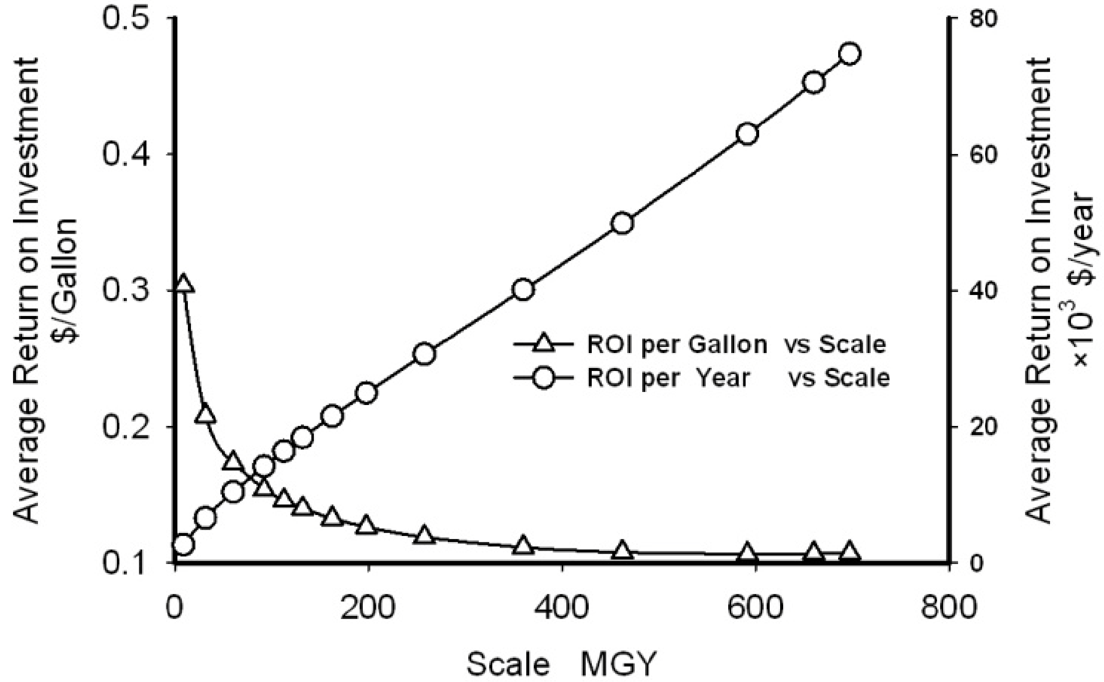

Figure 155: Spokane Return on Investment for Gasification Process (Forest Residue)

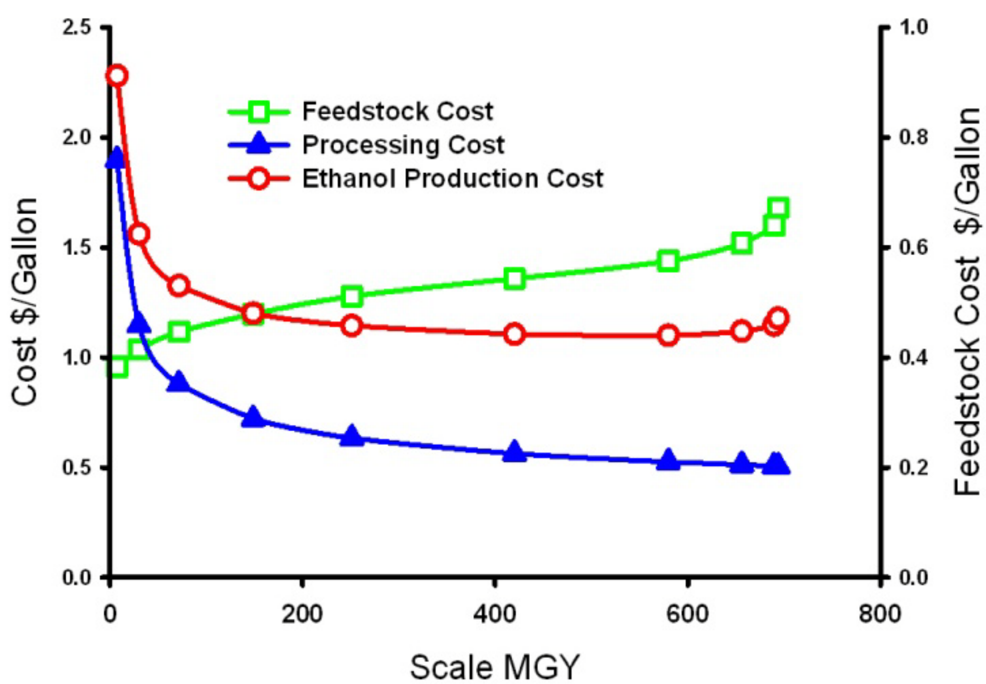

Figure 156: Ellensburg Cost Curve for Biological Fermentation Process (Forest Residue)

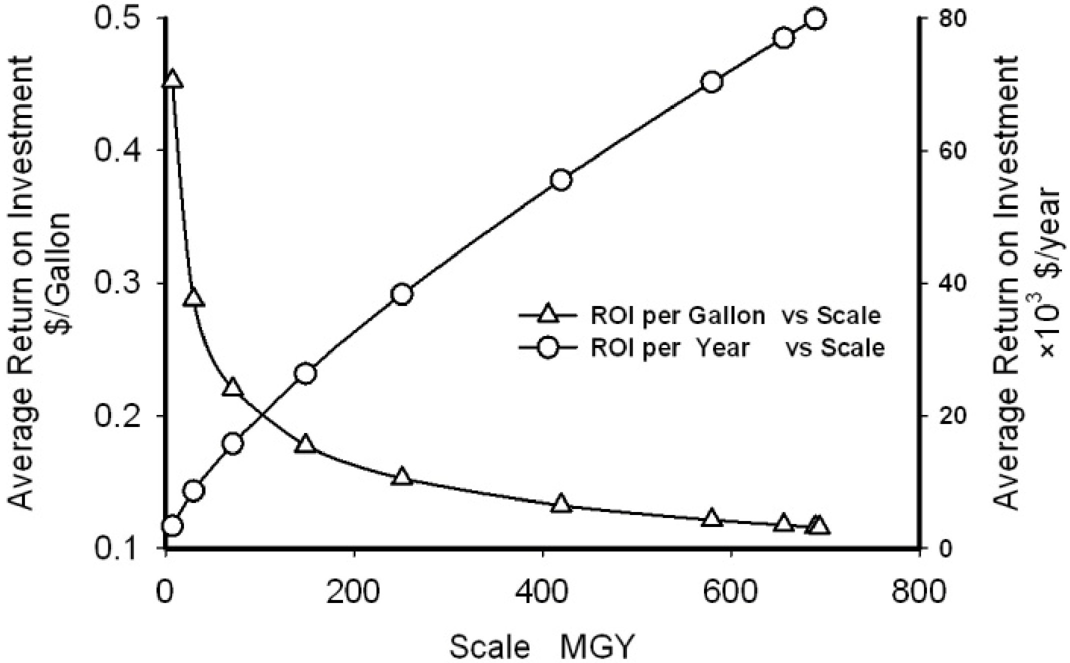

Figure 157: Ellensburg Return on Investment for Biological Fermentation Process (Forest Residue)

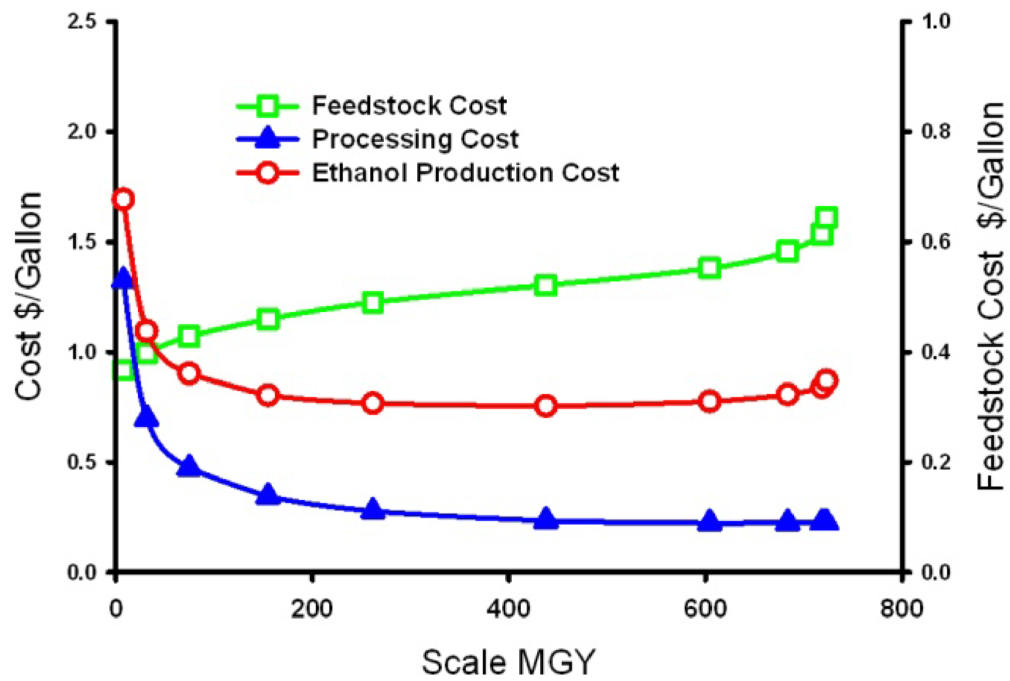

Figure 158: Ellensburg Cost Curve for Gasification Process (Forest Residue)

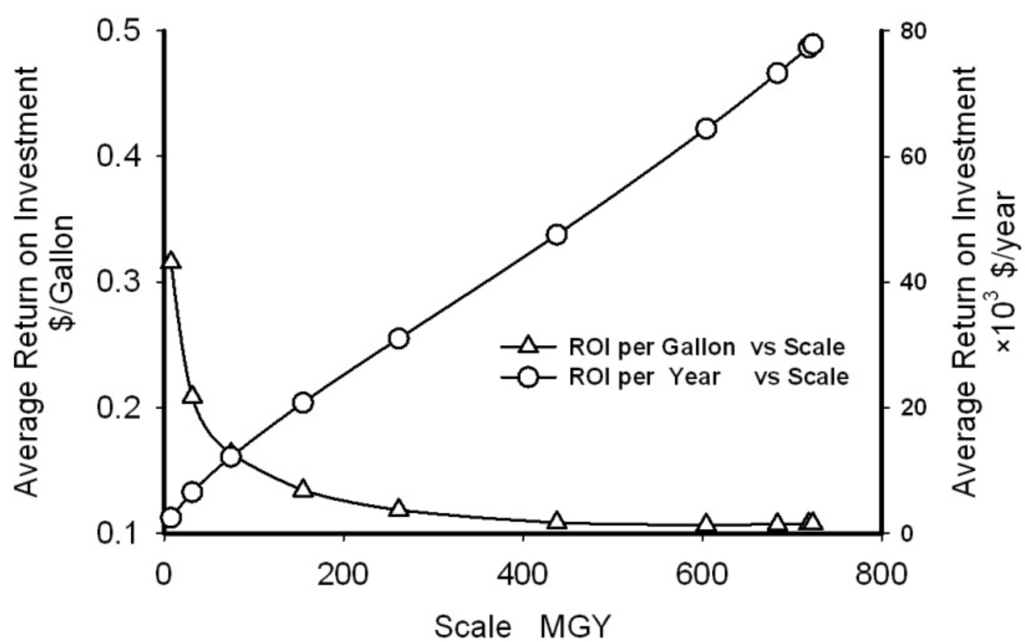

Figure 159: Ellensburg Return on Investment for Gasification Process (Forest Residue)

Discussion

The large quantity of forest residue feedstocks has a theoretical potential to produce up to nearly 800 MGY of ethanol within the same transportation distance as crop residue, and it has four to five times the maximum output as using crop residue as feedstock. From the standpoint of biofuel output, this feedstock can be seen as the most important in Washington State. For forest residue, the gasification process also shows some advantages but this still needs more confirmation. Ellensburg is the least cost site for biofuel production due to feedstock availability, but Longview has a lower cost for bioethanol production at less than 400 MGY.

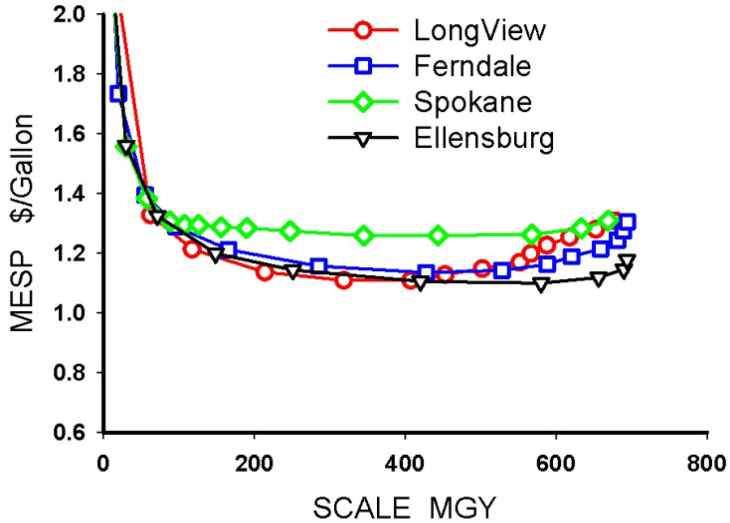

Figure 160: Cost Curve for Bioethanol Production with Forest Residue as Feedstock

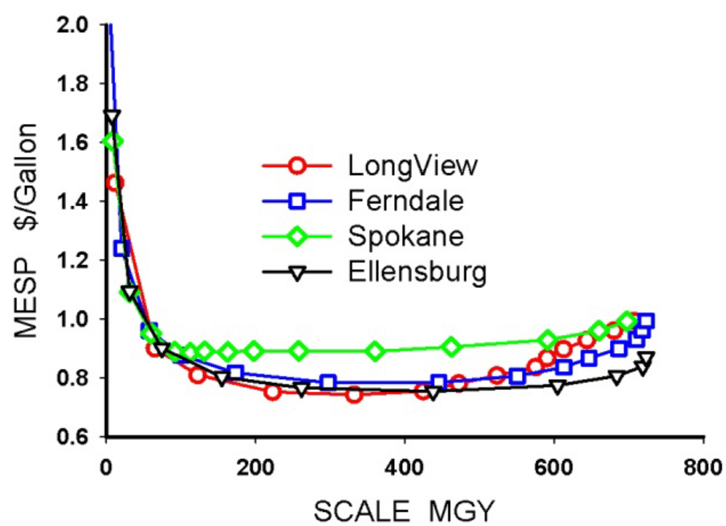

Figure 161: Cost Curve for Thermo-ethanol Production with Forest Residue as Feedstock

Municipal Waste in Washington State

Introduction

For decades countless individuals, institutions, communities, and companies have tried to find creative ways to reduce and better manage municipal waste through a coordinated mix of practices that includes source reduction, recycling (including composting), and landfill disposal. Among these practices, using biorefinery technology to convert them into sustainable energy has gained a great deal of attention.

Table 24: Waste Material in Washington State

Item of Feedstocks	Total (ton/year)	Item of Feedstocks	Total (ton/year)
Dairy Manure	457,032	Cull Onions	2,322
Cattle Manure	242,404	Cull Potatoes	91,412
Horse Manure	407,160	Cull Apples	41,039
Swine Manure	13,632	Cull Miscellaneous Fruit	8,934
Poultry Manure	784,577	Asparagus Butts	667
Total Animal Waste	1,904,805	Food Packing Totals	144,374
Apple Pomace	27,794		
Grape Pomace	19,254	Poultry Feathers	7,932
Berry Pomace	1,938	Poultry Meat Processing Waste	5,479
Misc. Fruit Pomaces	11,865	Beef Meat Processing Waste	35,842
Cheese Whey	44,255	Pork Meat Processing Waste	280
Potato Solids	19,177	All Animal Mortality	5,857
Asparagus Trimmings	120	Fish Waste	7,995
Mixed Vegetables	14,744	Shellfish Waste	3,674
Food Processing Waste	139,148	Total Animal Processing Waste	67,058
Total Food Waste	246,011		
Yard Non-Wood	421,489		
Yard Burn	35,826		
Other Organics	42,152		
Paper	2,428,084		
Wood Residue	834,057		
Yellow Grease	18,486		
Brown Grease	20,528		
Biosolids	94,820		
Total Municipal Waste	4,141,452		

In the earlier report (Frear et al., 2005), 45 potential feedstock sources in Washington were geographically identified, categorized, and mapped at a county level; 34 of them are municipal waste. In this research phase, some of the very low-quantity feedstocks studied in the earlier phase have been eliminated and the remaining feedstocks have been grouped according to their similarities. Of all these materials, four types of feedstock are of large quantity—animal waste, food waste, paper, and wood residues—and were chosen for investigation.

MSW Waste Paper

Ethanol production from waste paper had been proposed for many years (WSEO 1991; Wayman, Chen et al. 1992; Wayman, Chen et al. 1993; Brooks and Ingram 1995). Three feedstocks (waste paper, paper pulp, and pulp sludge) were involved in most of that previous research. Mixed waste paper data used in the bioethanol model were acquired from a Washington State Energy Office (WSEO) report (WSEO, 1991). The price for waste paper packed for transportation was acquired from www.scrapindex.com/paper.html. There are two prices for mixed paper listed on that website, TL and LTL. According to the explanation on the website, the TL price refers to sorted and prepared materials packaged and ready for shipment in typical full truck-load quantity weight, whereas LTL refers to "less than full truck load." In our model, we used the TL price of $29.25 /ton for the waste paper basic cost.

Production Cost

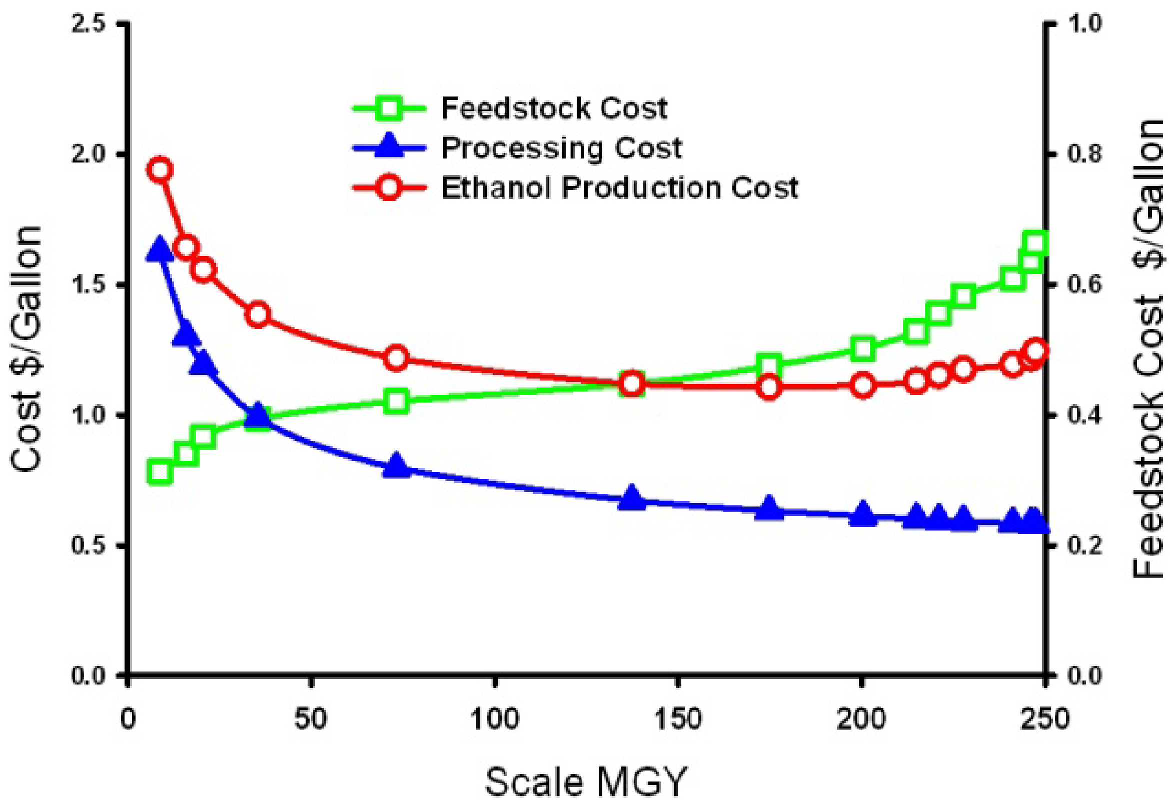

Figure 162: Longview Cost Curve for Biological Fermentation Process (MSW Paper)

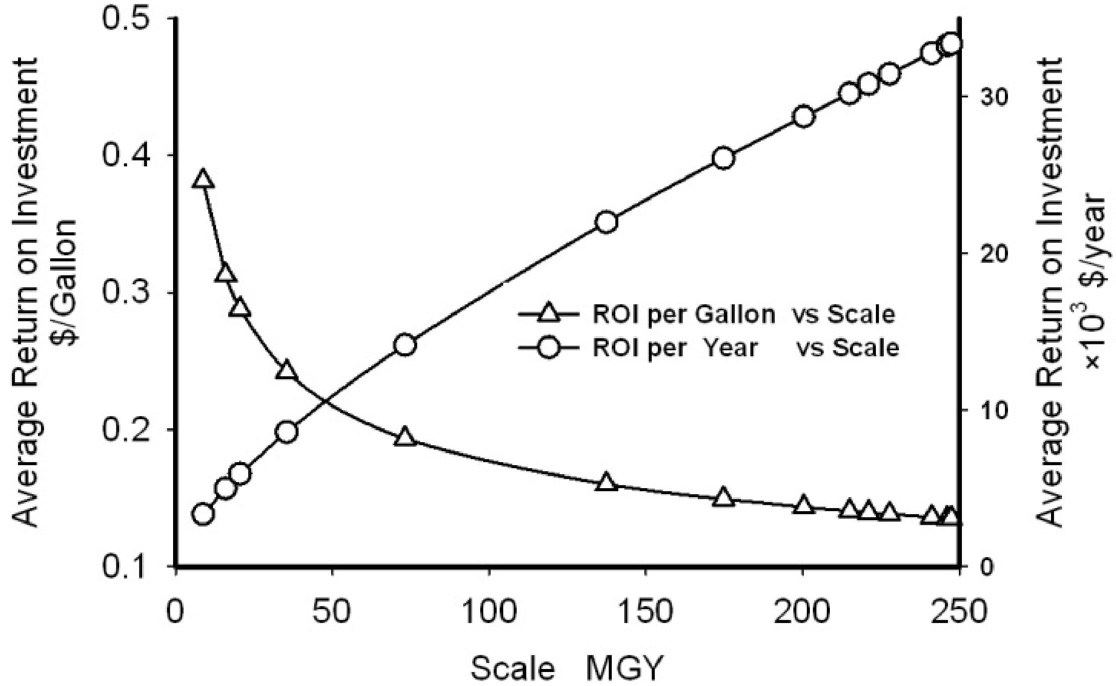

Figure 163: Longview Return on Investment for Biological Fermentation Process (MSW Paper)

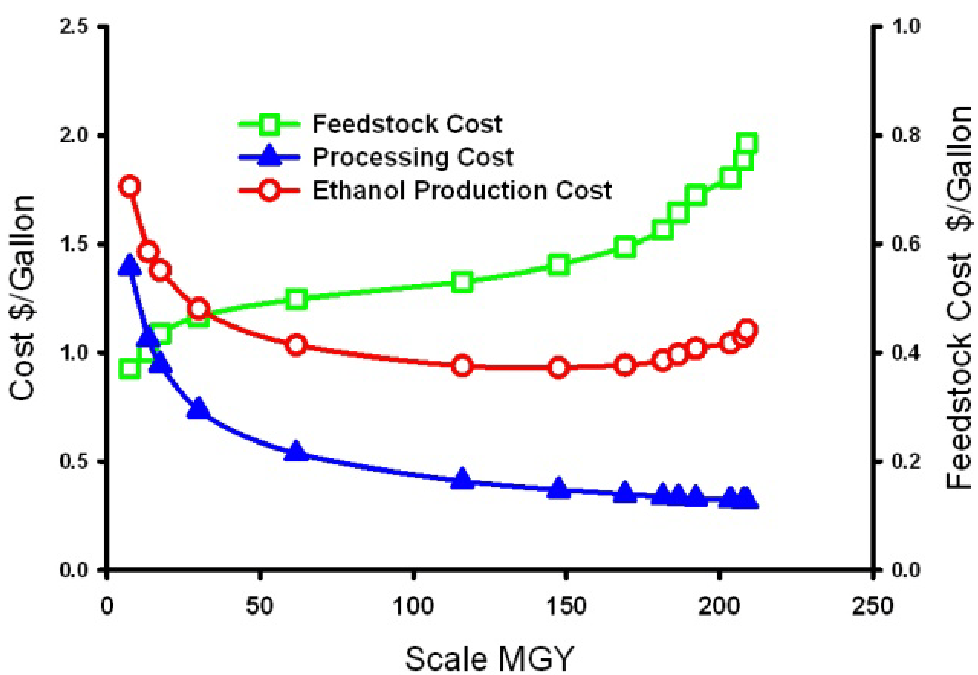

Figure 164: Longview Cost Curve for Gasification Process (MSW Paper)

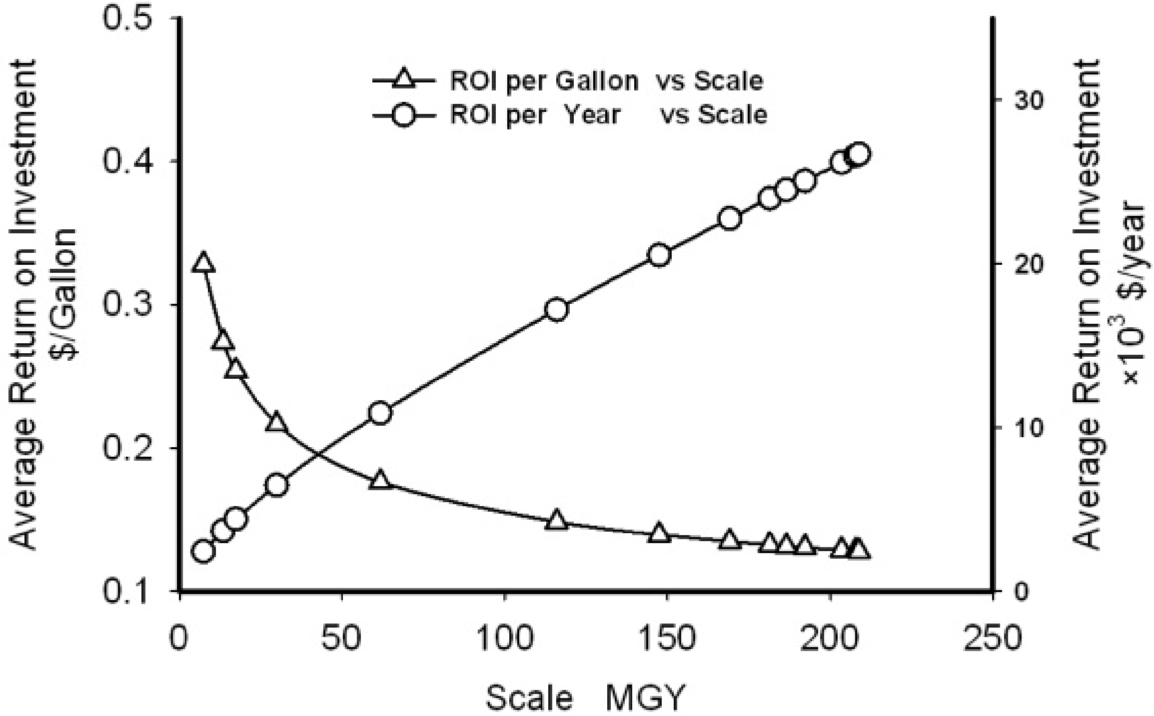

Figure 165: Longview Return on Investment for Gasification Process (MSW Paper)

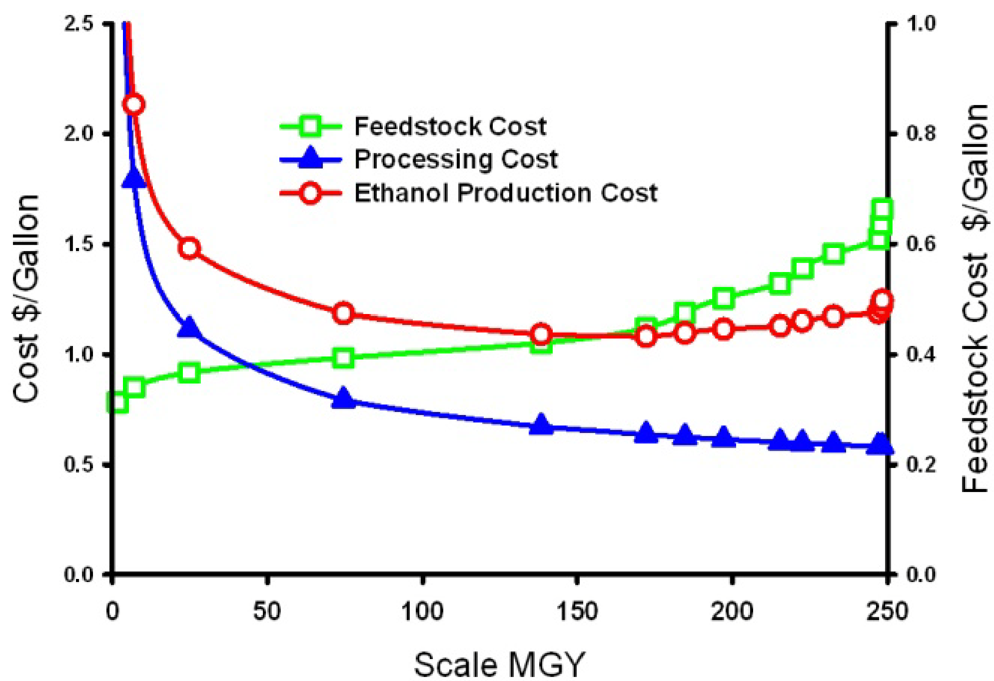

Figure 166: Ferndale Cost Curve for Biological Fermentation Process (MSW Paper)

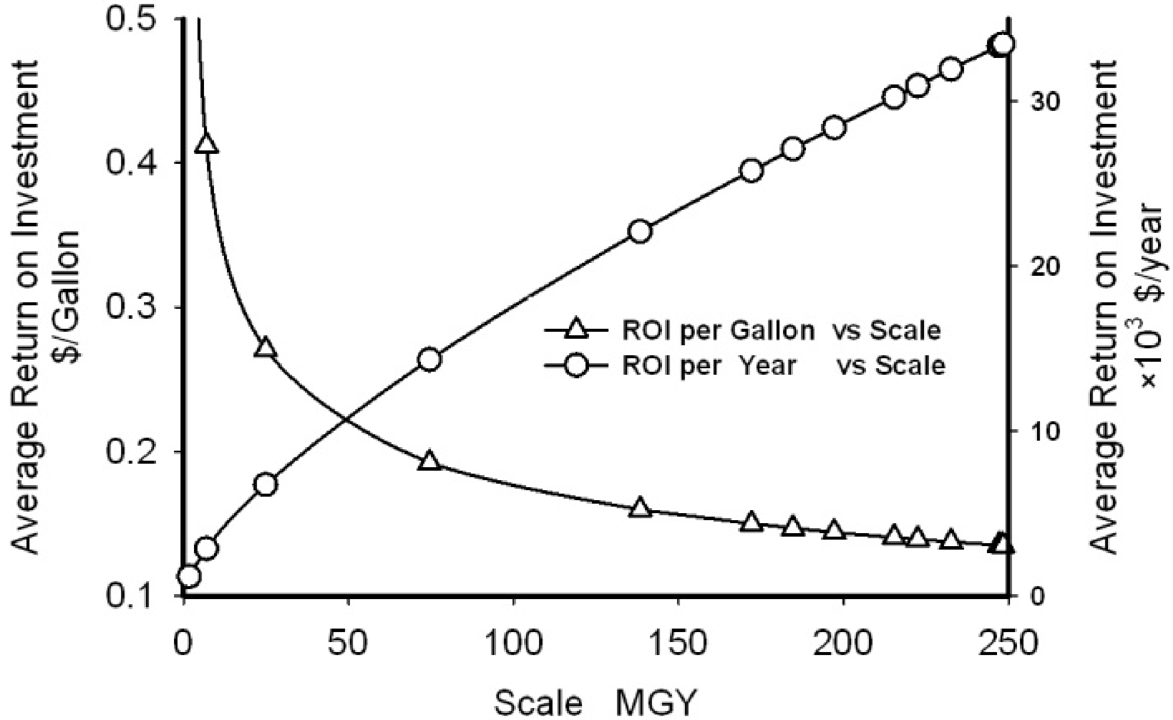

Figure 167: Ferndale Return on Investment for Biological Fermentation Process (MSW Paper)

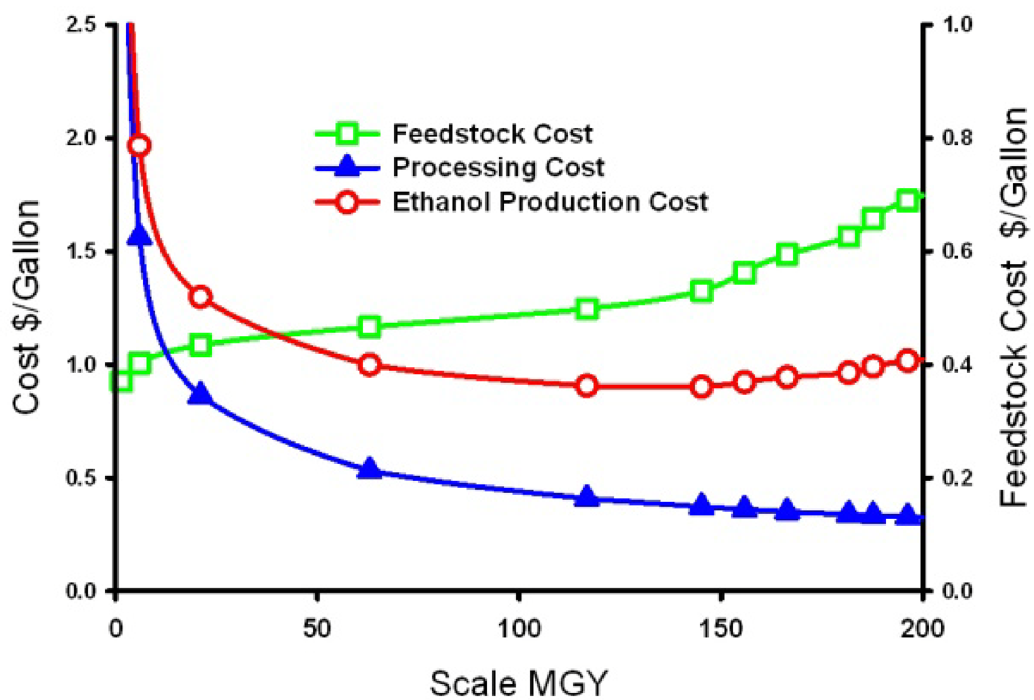

Figure 168: Ferndale Cost Curve for Gasification Process (MSW Paper)

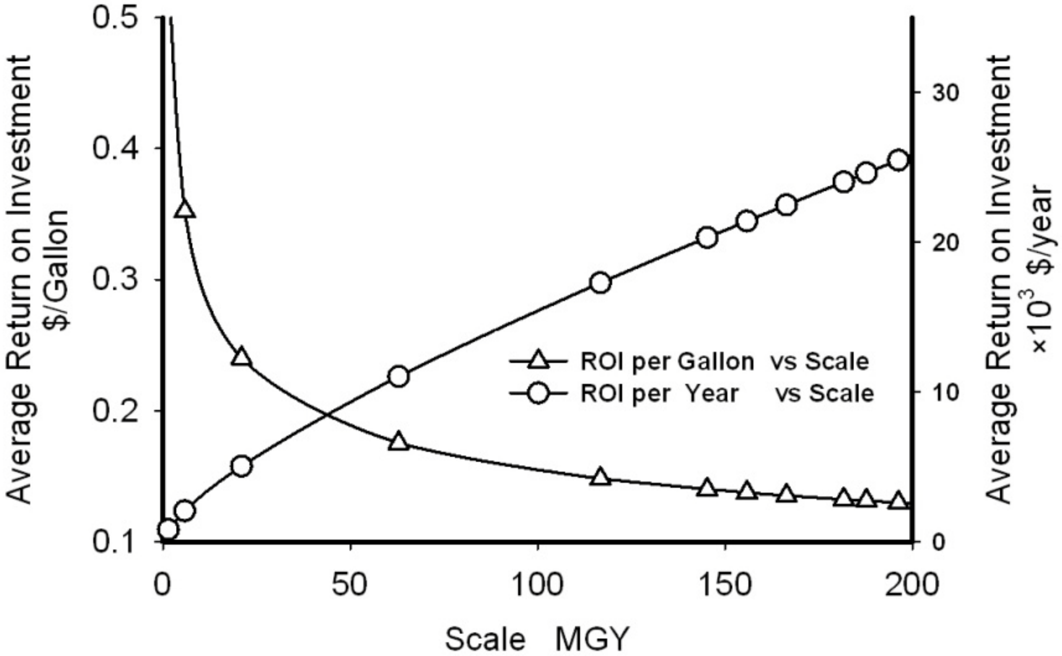

Figure 169: Ferndale Return on Investment for Gasification Process (MSW Paper)

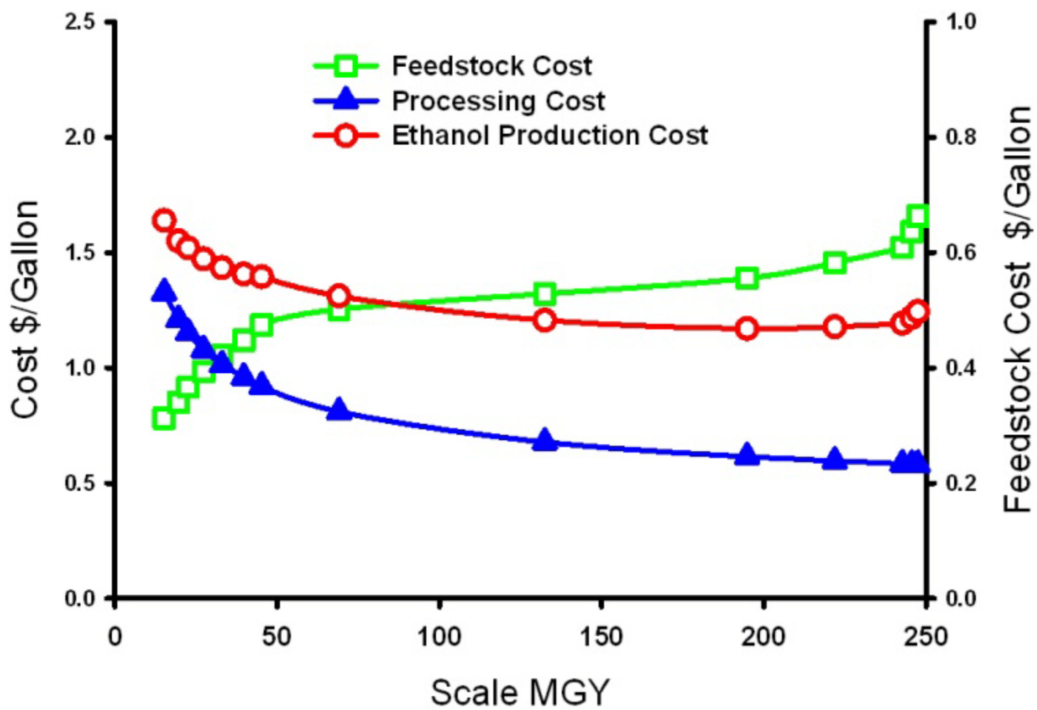

Figure 170: Spokane Cost Curve for Biological Fermentation Process (MSW Paper)

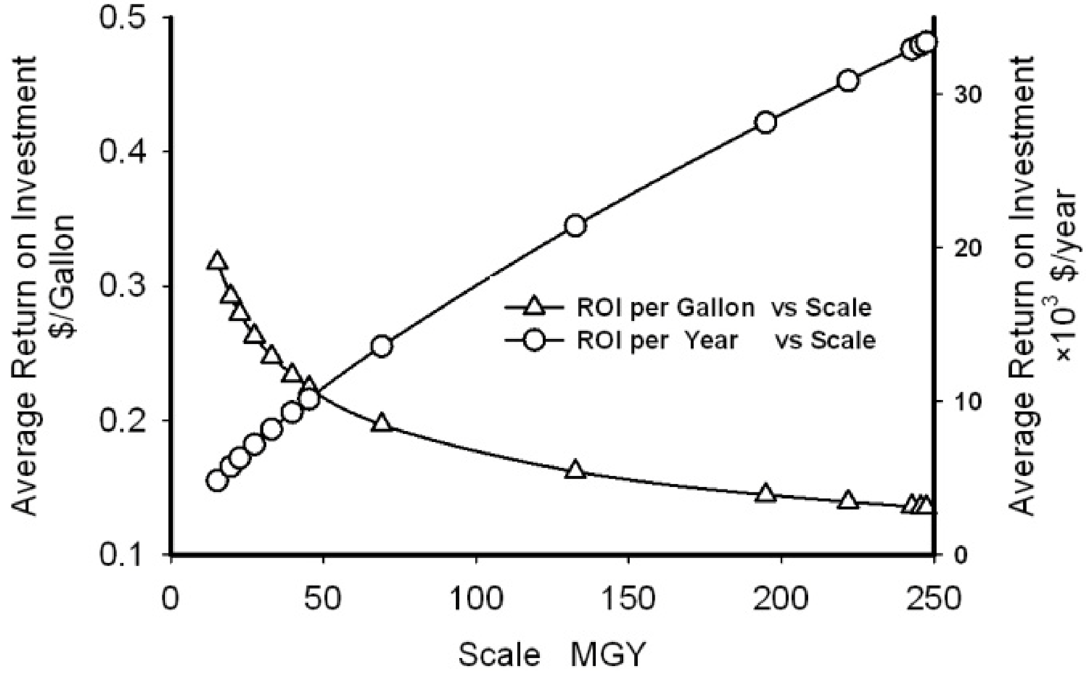

Figure 171: Spokane Return on Investment for Biological Fermentation Process (MSW Paper)

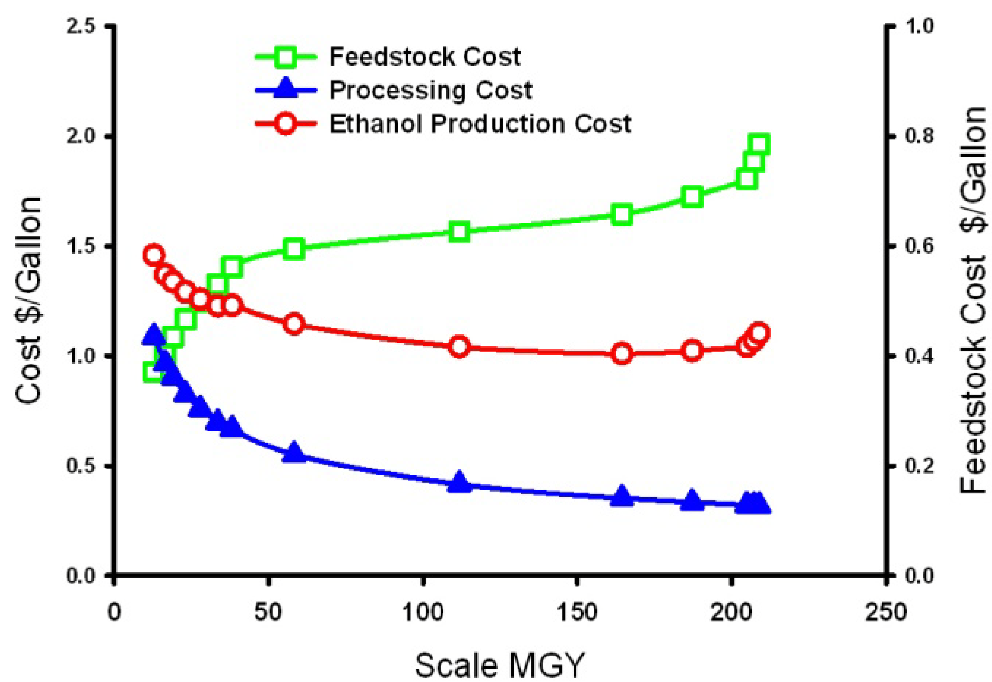

Figure 172: Spokane Cost Curve for Gasification Process (MSW Paper)

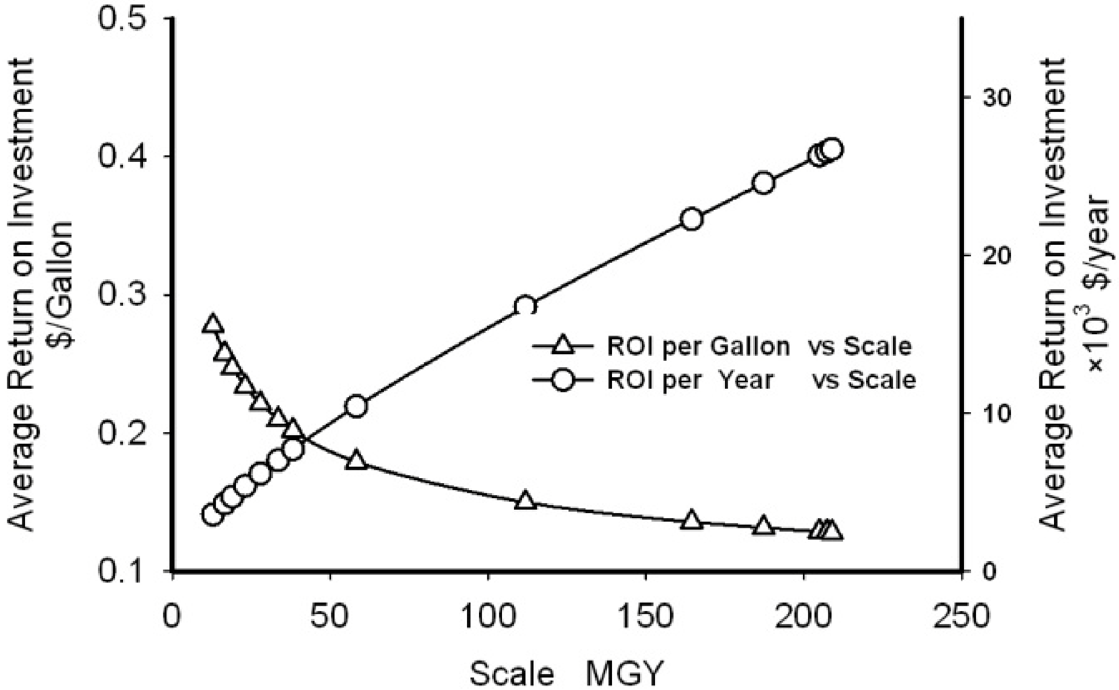

Figure 173: Spokane Return on Investment for Gasification Process (MSW Paper)

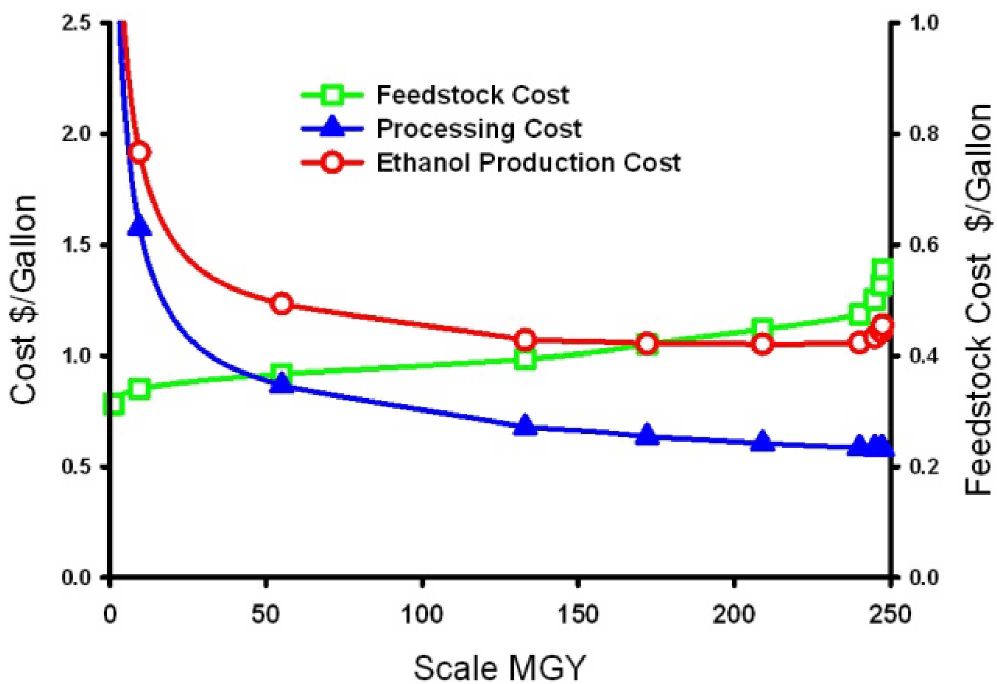

Figure 174: Ellensburg Cost Curve for Biological Fermentation Process (MSW Paper)

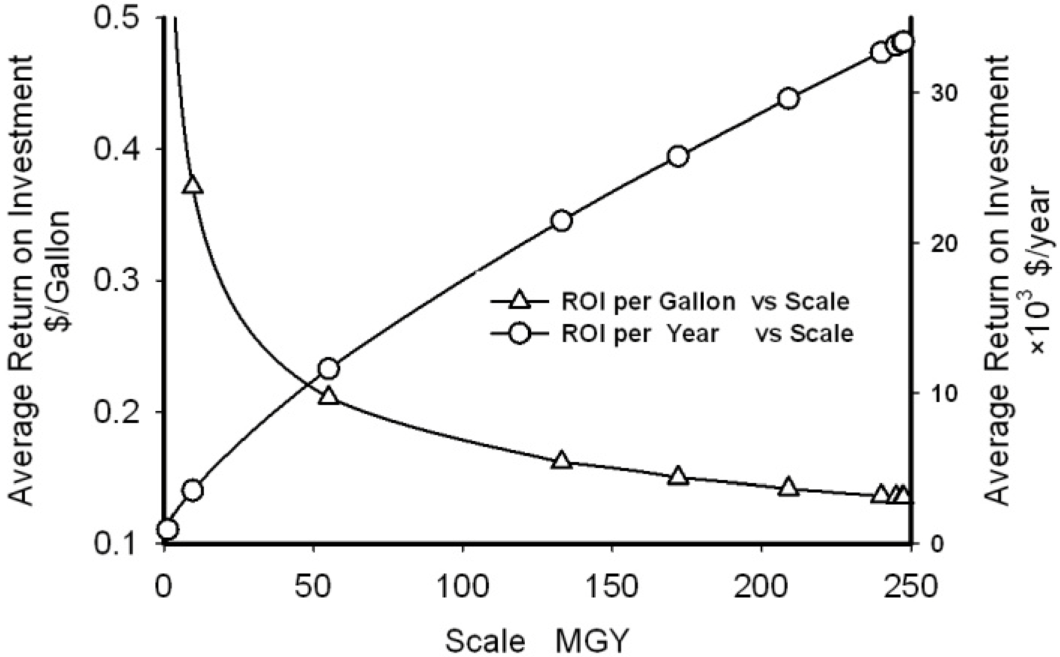

Figure 175: Ellensburg Return on Investment for Biological Fermentation Process (MSW Paper)

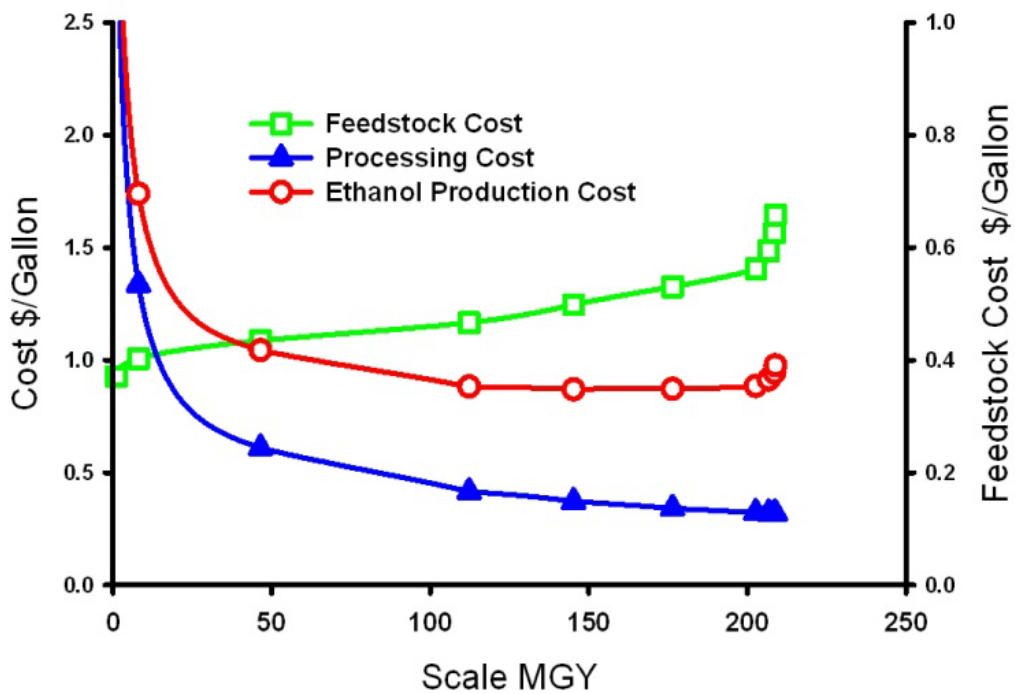

Figure 176: Ellensburg Cost Curve for Gasification Process (MSW Paper)

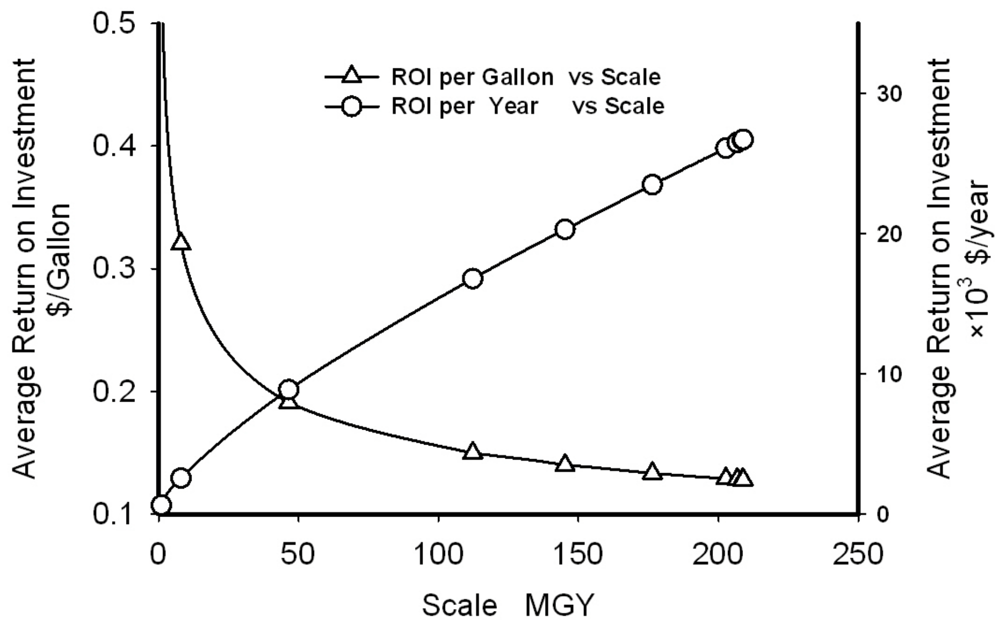

Figure 177: Ellensburg Return on Investment For Gasification Process (MSW Paper)

Discussion

Paper has a nearly 20% percent higher yield compared with other lignocellulosic-biomass material because of its higher cellulose content. The composition we used here was residential mixed waste paper (sample was taken from the curbside program of the City of Olympia, WA). If the feedstock were mainly commercial mixed waste paper (paper from offices), which contains more cellulose and less lignin, more ethanol would be generated.

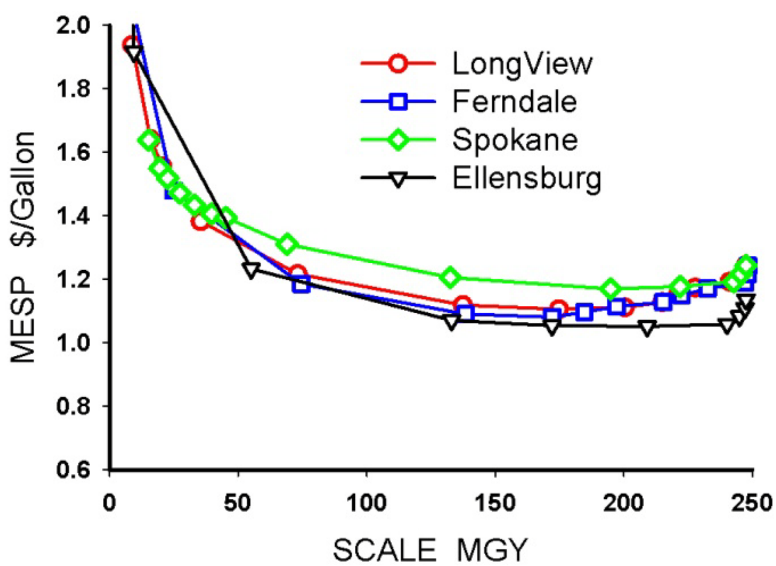

Figure 178: Cost Curve for Bioethanol Production with Waste Paper as Feedstock

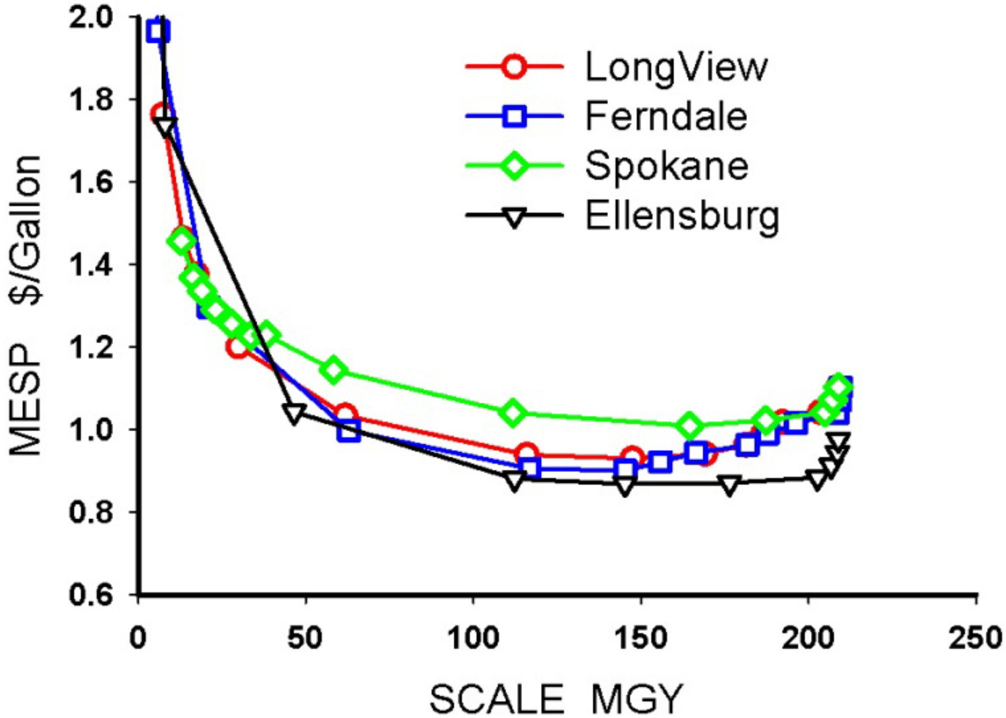

Figure 179: Cost Curve for Thermo-ethanol Production with Waste Paper as Feedstock

Wood Residue

Wood residues are generated in Washington State by manufacturers, users of wooden pallets and containers, wholesalers and retailers of wood products, and construction and demolition of residential and commercial properties. Today recovery wood residue from manufacturers is a mature, well established practice. Most of these feedstocks are burned for energy generation. Because wood residue has the same composition as forest residue, ethanol production from wood residue provides another option for its recovery. The main factor that needs to be discussed is the production cost, which includes both the transportation costs and processing costs. Here, a basic cost of $30/ton for wood residue feedstock was acquired from a West Virgina report (http://na.fs.fed.us/ss/03/ea_logresidue.pdf).

Production Cost Estimation (Phase 1 Database)

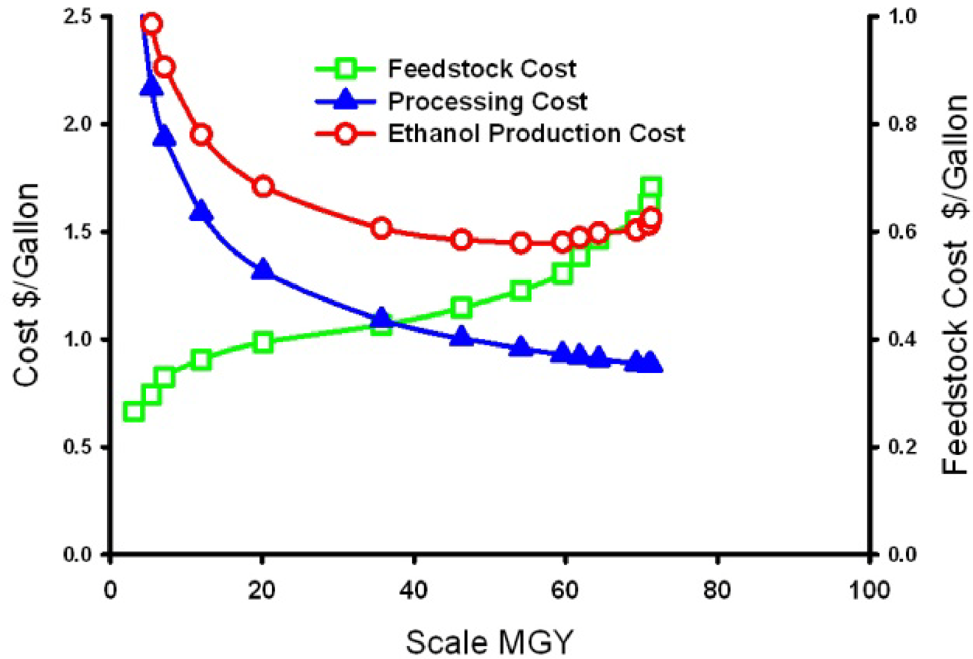

Figure 180: Longview Cost Curve for Biological Fermentation Process (MSW Wood Residue)

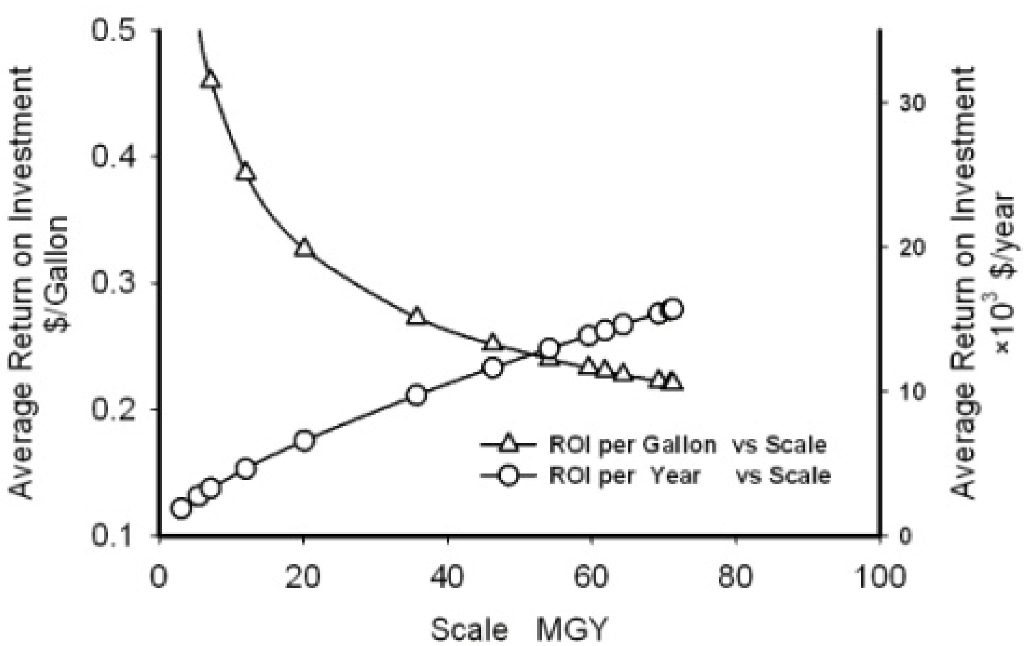

Figure 181: Longview Return on Investment for Biological Fermentation Process (MSW Wood Residue)

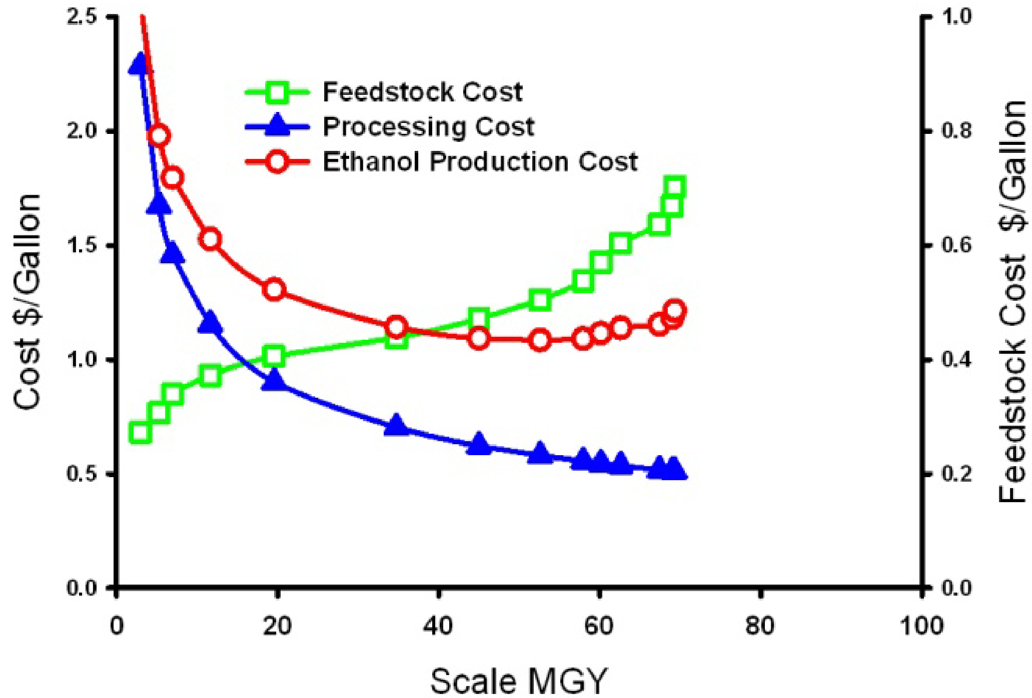

Figure 182: Longview Cost Curve for Gasification Process (MSW Wood Residue)

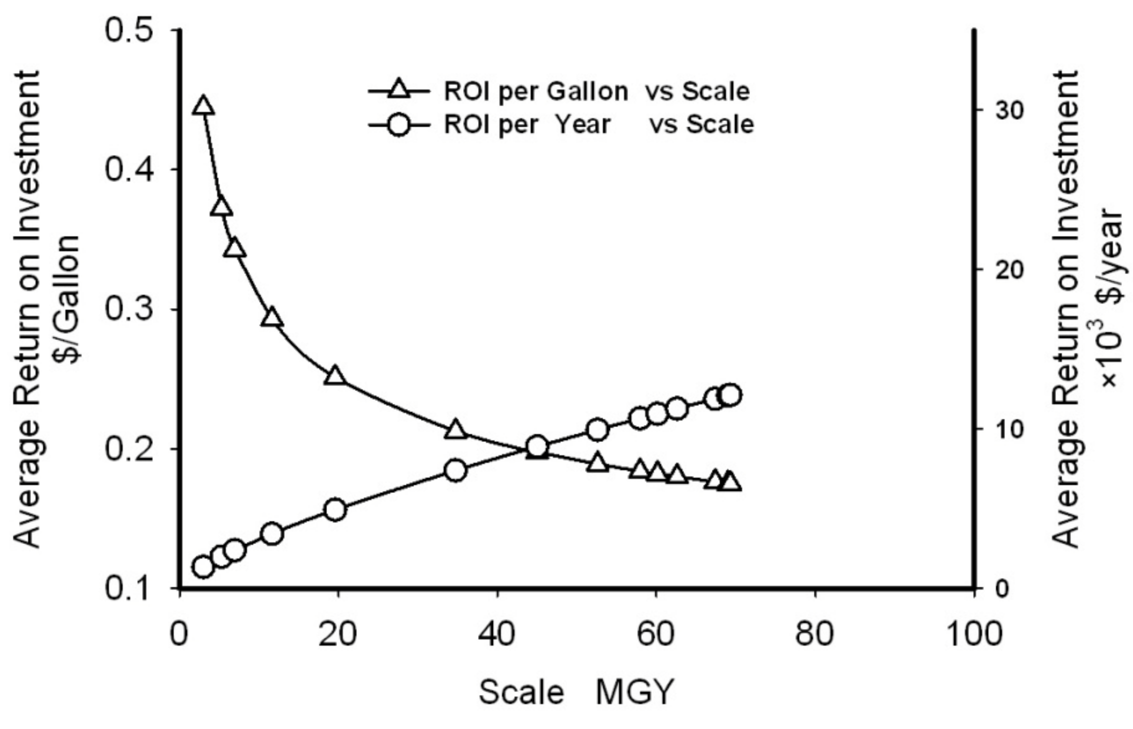

Figure 183: Longview Return on Investment for Gasification Process (MSW Wood Residue)

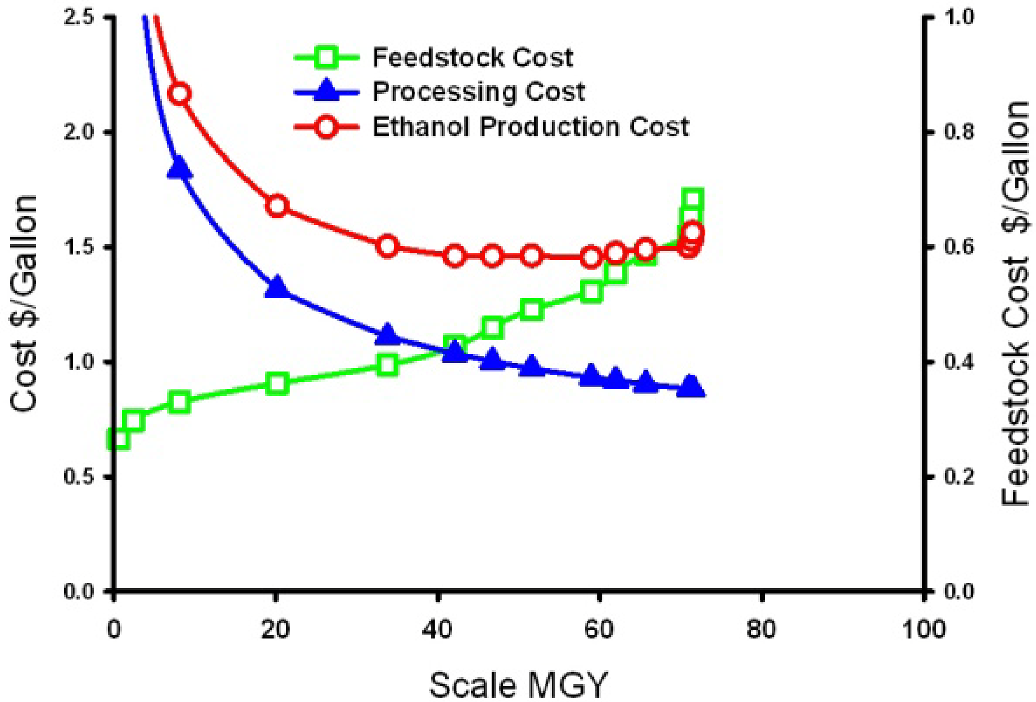

Figure 184: Ferndale Cost Curve for Biological Fermentation Process (MSW Wood Residue)

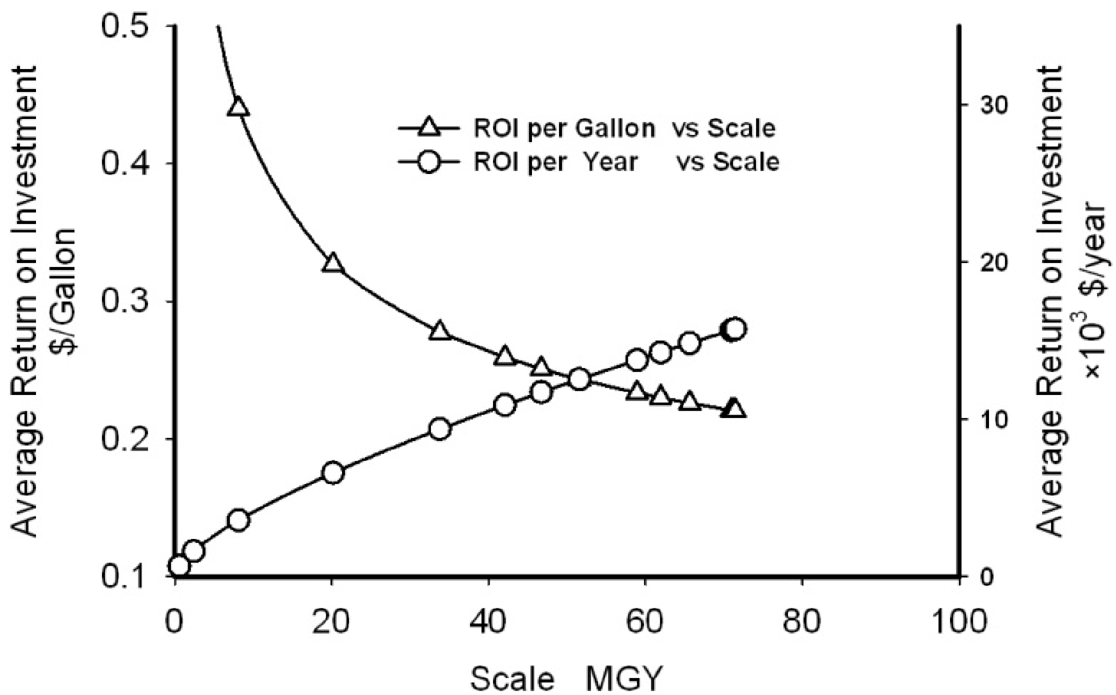

Figure 185: Ferndale Return on Investment for Biological Fermentation Process (MSW Wood Residue)

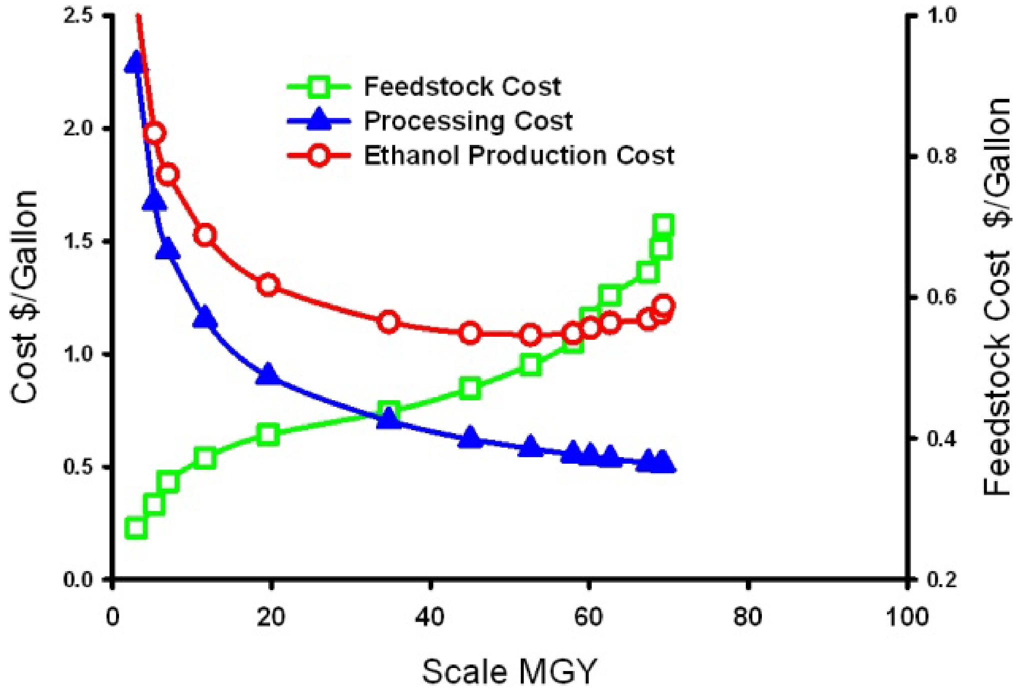

Figure 186: Ferndale Cost Curve for Gasification Process (MSW Wood Residue)

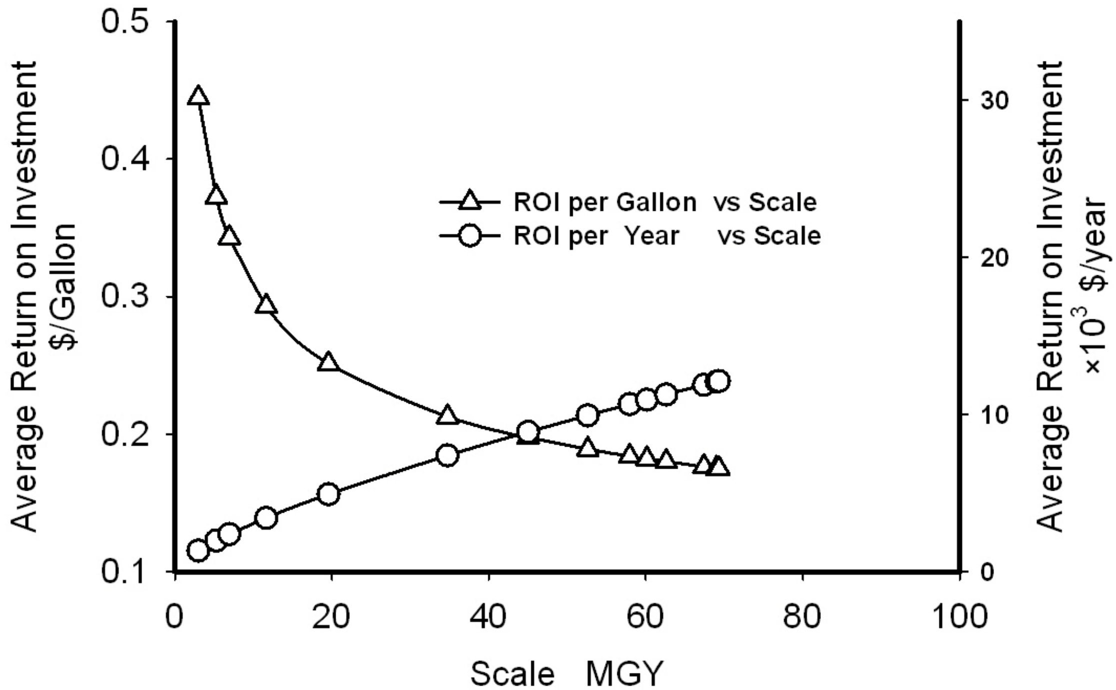

Figure 187: Ferndale Return on Investment for Gasification Process (MSW Wood Residue)

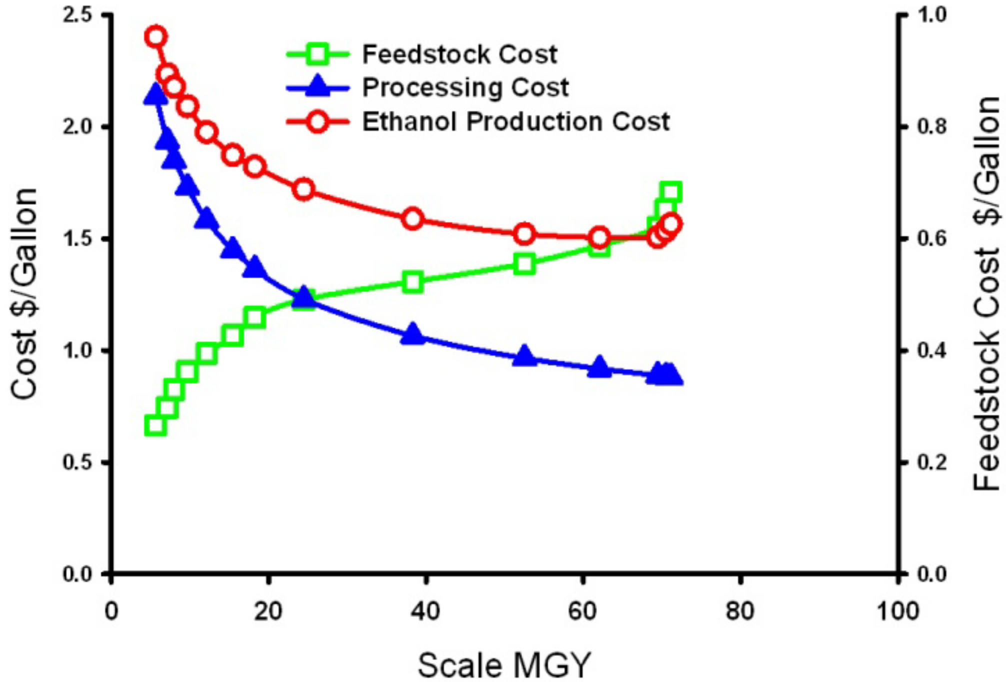

Figure 188: Spokane Cost Curve for Biological Fermentation Process (MSW Wood Residue)

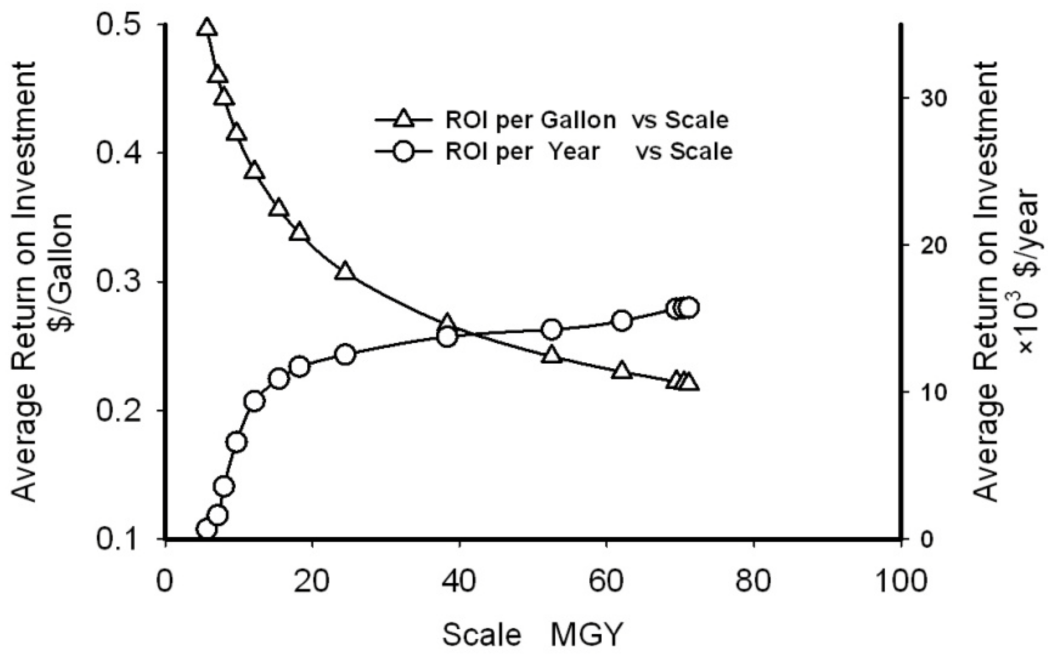

Figure 189: Spokane Return on Investment for Biological Fermentation Process (MSW Wood Residue)

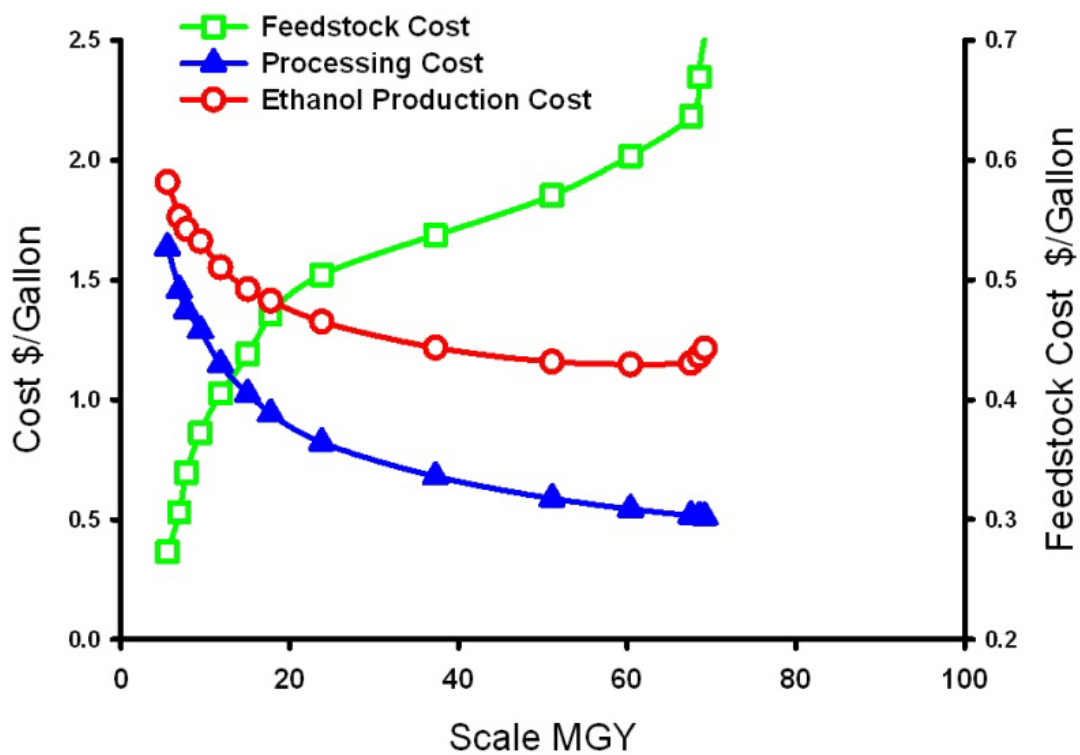

Figure 190: Spokane Cost Curve for Gasification Process (MSW Wood Residue)

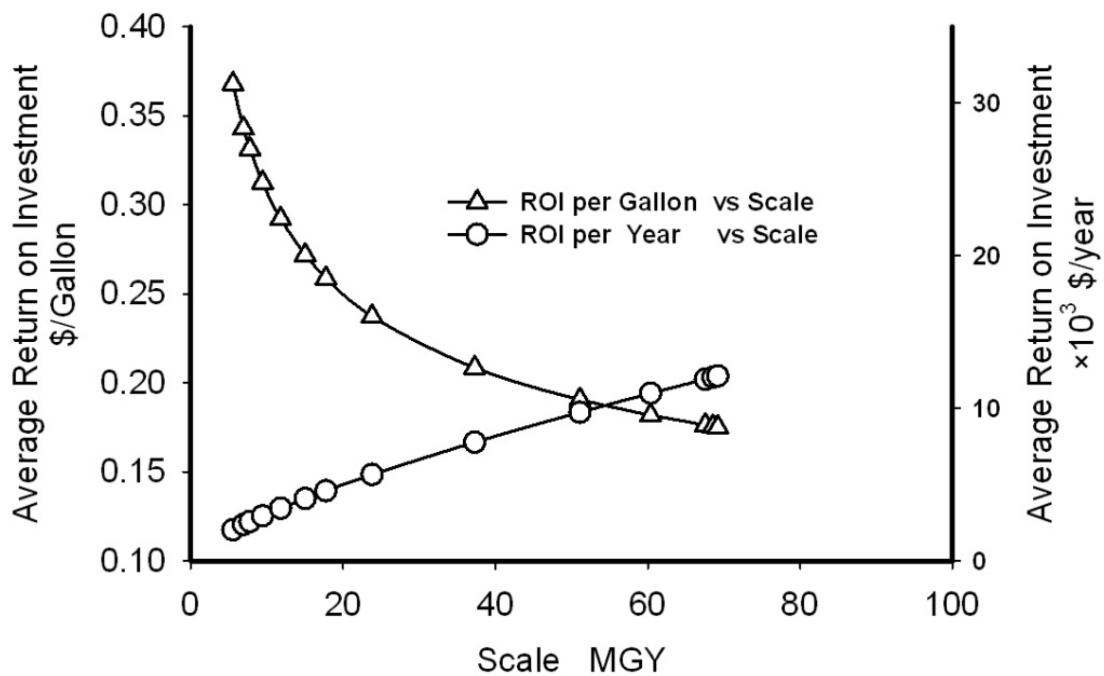

Figure 191: Spokane Return on Investment for Gasification Process (MSW Wood Residue)

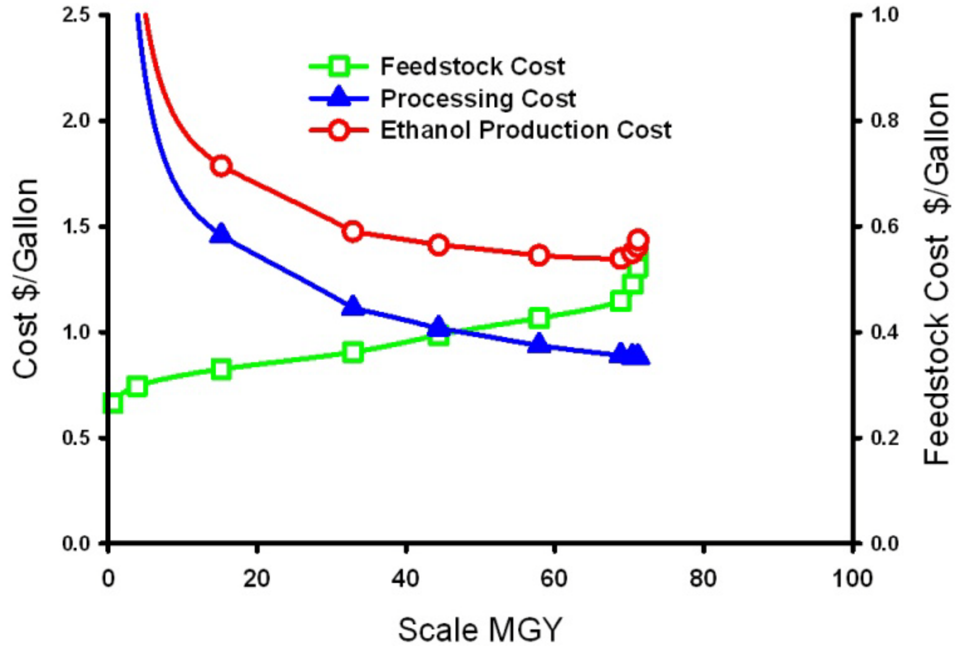

Figure 192: Ellensburg Cost Curve for Biological Fermentation Process (MSW Wood Residue)

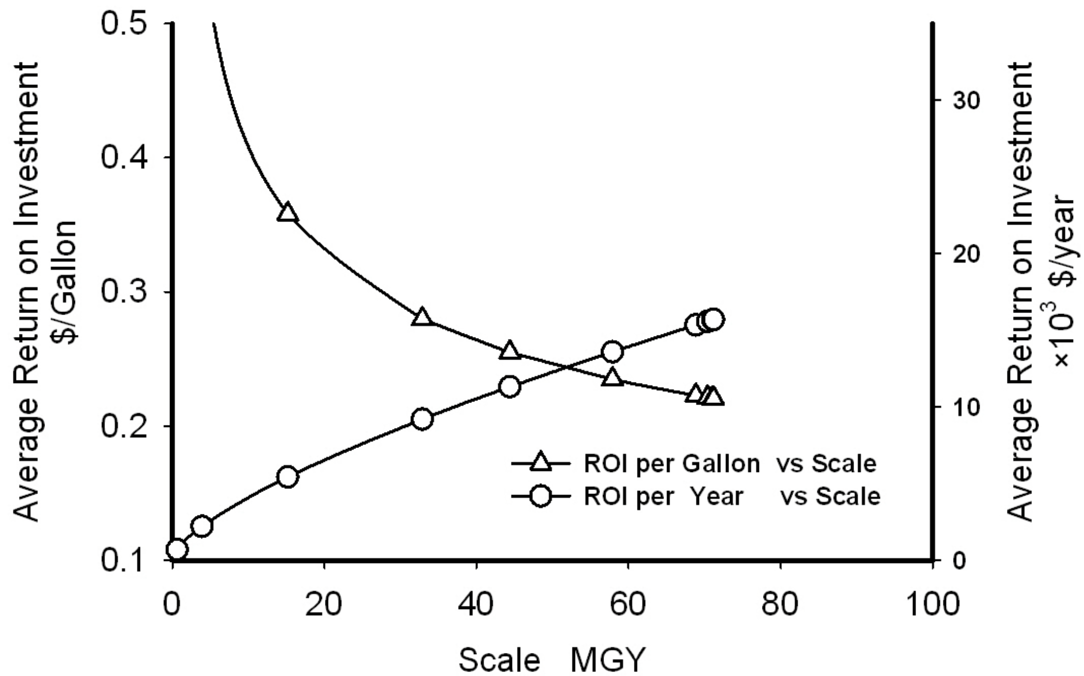

Figure 193: Ellensburg Return on Investment for Biological Fermentation Process (MSW Wood Residue)

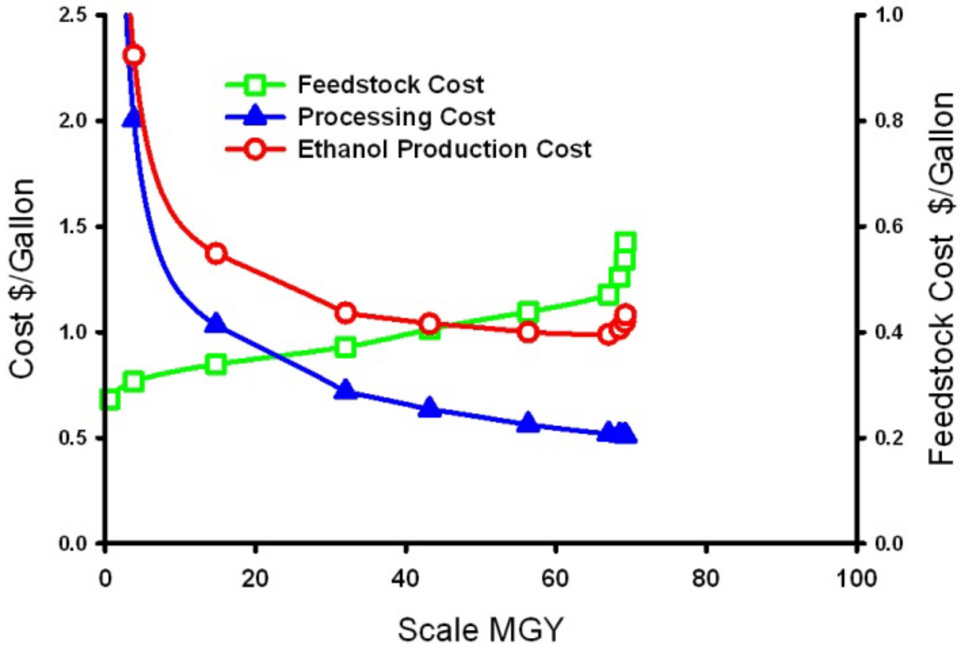

Figure 194: Ellensburg Cost Curve for Gasification Process (MSW Wood Residue)

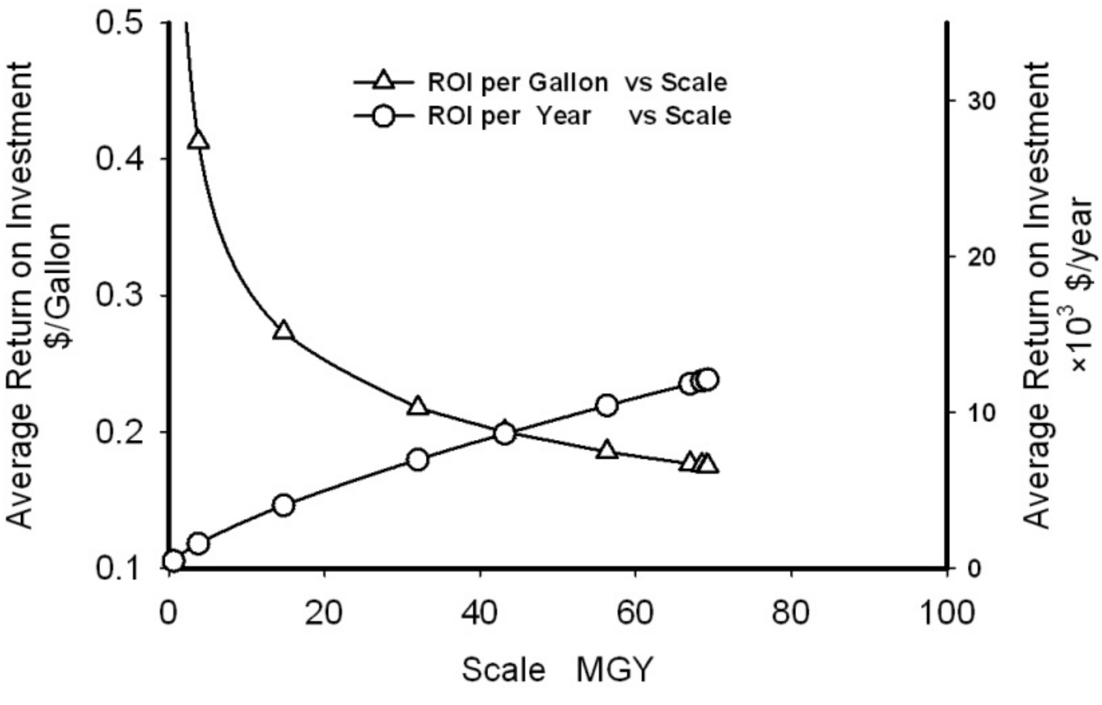

Figure 195: Ellensburg Return on Investment for Gasification Process (MSW Wood Residue)

Discussion

With as long as 420 miles distance for feedstock collection, less than 100 MGY scale can be reached with all the available feedstock input into the ethanol production system. The production cost also stays at a high level due to the small scale. Analysis results shows that building a facility by only utilizing this feedstock is not econimically valid. This part of MSW can be uses as supplement feedstock for some already existing ethanol producers that use lignocellulosic-biomass as feedstock.

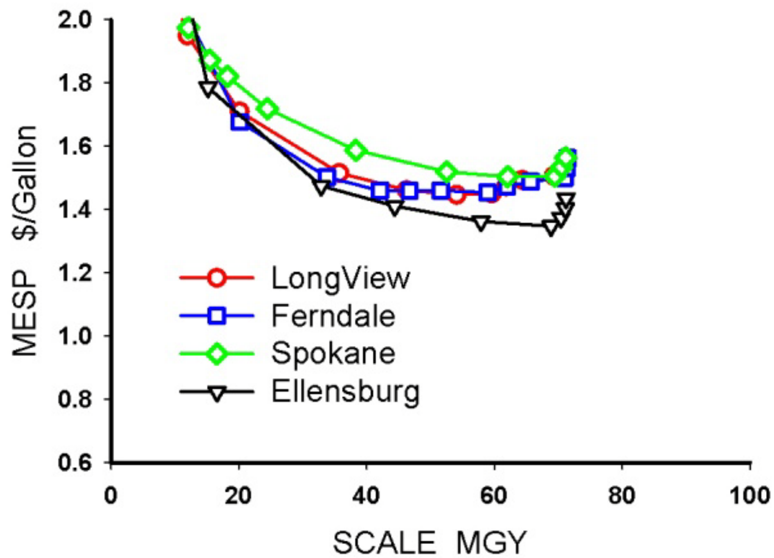

Figure 196: Cost Curve for Bioethanol Production with MSW Wood Residue as Feedstock

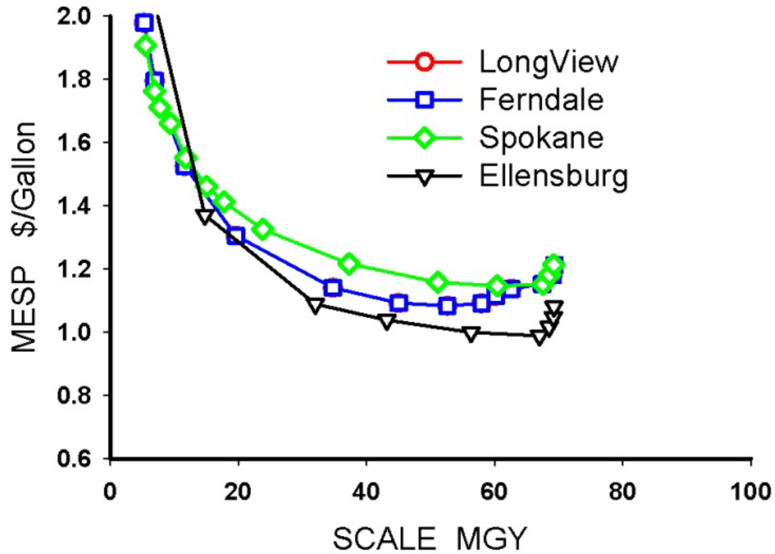

Figure 197: Cost Curve for Thermo-ethanol Production with MSW Wood Residue as Feedstock

Animal Waste and Food Waste

Anaerobic digestion (AD) is a series of processes in which microorganisms break down biodegradable material in the absence of oxygen. It is widely used to treat wastewater sludges and organic waste because it provides volume and mass reduction of the input material. Our system simulation and economic assessments in this report used data from an existing Washington State co-digestion AD unit as the main parameters resource. Effluent of the AD process contains large quantities of nitrogen and phosphate that need to be disposed of on-site. Therefore, we set a scale limit of a maximum 500 ton/day (wet weight) of feedstocks. Under this assumption, possible tipping fees for excessive effluent liquid can be neglected.

If animal waste is used as the feedstock for AD systems, there would be enough feedstock that exceeds the limit of 500 ton/day within 30 miles of every site we tested. An analysis of system financial feasibility was performed under different feedstock input rates and result is shown in Figure 198. With stable feedstock transportation costs, the final system net income per ton of waste increases due to the reduction in processing cost. In this case, if there are any tipping fees for animal waste, the income value may become positive as in Figure 199 with a $25/ton tipping fee for food waste. Food waste used as feedstock for an AD system is much more economical, and the system net income is higher when there are more feedstocks and less transportation distance. From this standpoint, small-scale facilities in Longview and Spokane area seem to be better choices.

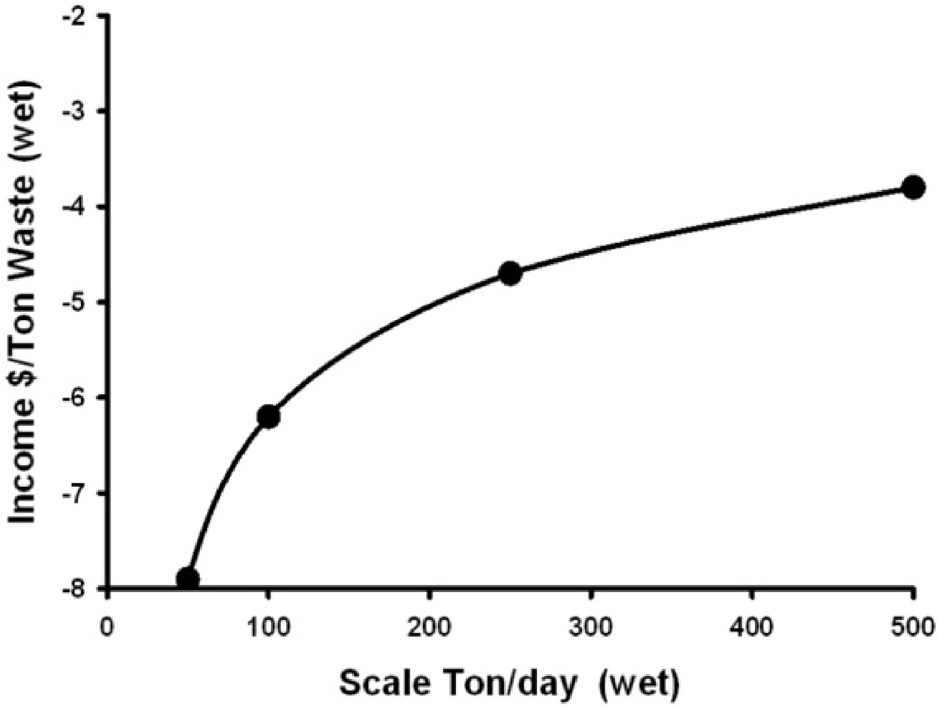

Figure 198: With a Fixed Feedstock Price, the Return on Investment in AD Processes Increases with Manure Input

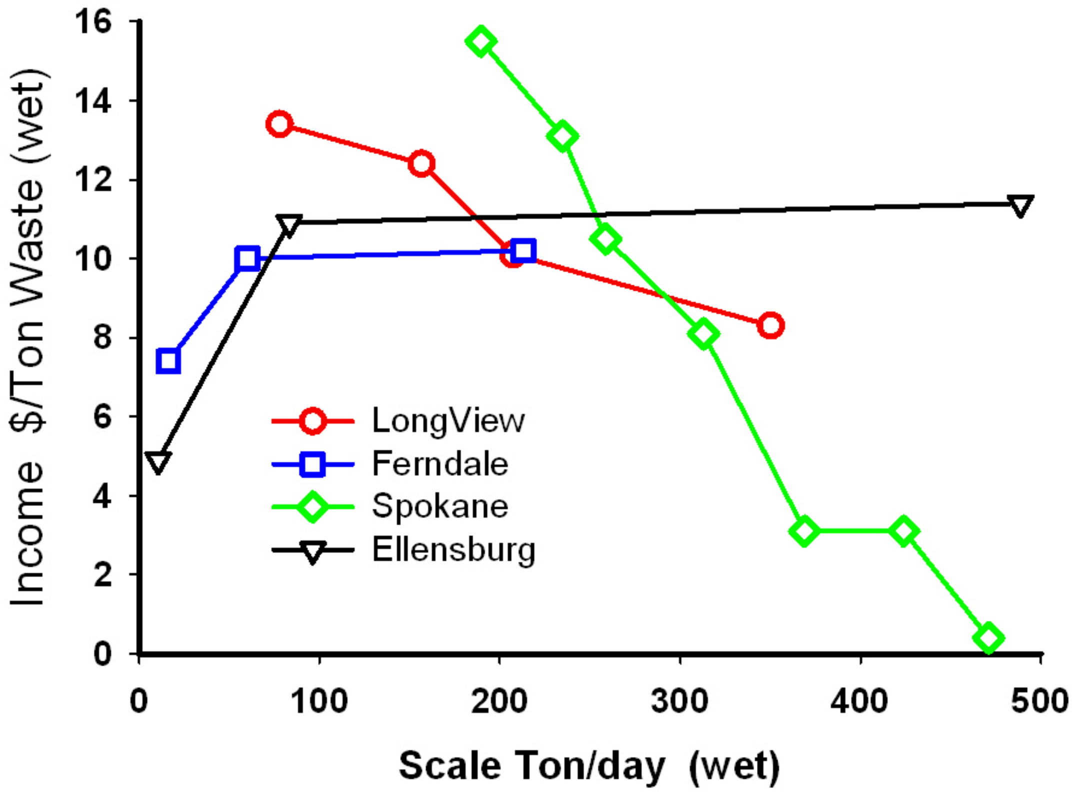

Figure 199: Site Comparison of Financial Returns in an AD Food Waste Facility

Tables 25 and 26 show detailed results of our economic assessment of AD processes. For each ton of animal waste or food waste treated by AD methods, the facility can earn some money or are not totally dependent on the tipping fee, which means government policy will determine the future of AD facilities. If there were strong support from the government for AD processes because of the evironmental benefits, AD processes would become much more popular.

Table 25 also demonstrates the economic validity of nitrogen recovery from AD process effluent. Elston and Karmarkar (Elston and Karmarkar 2003) from the Foster Wheeler Power Group presented a conceptual design for ammonia stripping. In their design, steam was used as a medium for ammonia stripping in the stripping column. In their estimation, more than 99.5% of the ammonia can be recovered. We presumed that energy for steam generation can be covered by the waste heat from biogas combustion, and we established a module in the AD model for nitrogen recovery. The result reveals that, with the aid of ammonia stripping equipment and with 500 M^3 wet dairy manure as the input to the AD system, 11,422 kmol of nitrogen (equal to 194 tons of pure ammonia) can be recovered per year. But the cost is very high: the energy required for stripping exceeded the energy output of electricity from biogas burning, which makes it impractical for commercial application. Better technologies with lower energy inputs need to be developed to accomplish this important task.

Table 25: AD Process Economic Assessment Results (Animal Waste 500 M3/day)

Item	Unit	Value
Liquid Volume	M^3	11,000
Gas Volume	M^3	1,100
Load Rate	M^3/day	500
Feedstock TS		7.2%
Gas Flow Rate	M^3/day	13,066
Liquid Flow Rate	M^3/day	500
Compost	Kg/day	8,367
Electricity Output	kWh/year	6,308,962
Optional		
Power for N Stripper	kWh/Year	47,898,051
N Recovery	Kmol/Year	11,422
Sale Price for 25% Ammonia Water	$/year	136,693

Item	$/year
Revenue	
Electricity Produced	220,814
Green Tags from Electricity[1]	94,634
Carbon Credits	47,317
Renewable Energy Tax Credits	28,390
Tipping Fees	0
Compost	18,324
Operating Costs	
Delivery	73,584
Maintenance	274,440
Ownership Costs	
Taxes and Insurance	126,606
Depreciation	631,533
Total	–696,684
Income per Ton Waste ($/ton)	–3.8

Optional	
Revenue	
Electricity Produced	220,814
Green Tags from Electricity[1]	94,634
Carbon Credits	47,317
Renewable Energy Tax Credits	28,390
Tipping Fees	0
Compost	18,324
25% Ammonia Water	136,693
Operating Costs	
Delivery	73,584
Maintenance	274,440
Power for Stripper	1,676,432
Ownership Costs	
Tax and Insurance	126,606
Depreciation	984,005
Total	–2,725,588
Income per Ton Waste ($/ton)	–14.90

Table 26: AD Process Economic Assessment (Food Waste, Ellensburg, 90-Mile Haul Distance)

Item	**Unit**	**Value**
Liquid Volume	M^3	10,754
Gas Volume	M^3	1,075
Load Rate	M^3/day	489
Feedstock TS		29.1%
Gas Flow rate	M^3/day	34,472
Liquid Flow Rate	M^3/day	489
Compost	Kg/day	12,176
Electricity Output	kWH/year	17,900,906

Revenue	**$/year**
Electricity Produced	626,532
Green Tags from Electricity[1]	268,514
Carbon Credits	134,257
Renewable Energy Tax	80,554

Credits	
Tipping Fees	4,460,300
Compost	26,665
Operating Costs	
Delivery	1,480,820
Maintenance	778,689
Ownership Costs	
Taxes and Insurance	189,073
Depreciation	1,106,233
Total	2,042,005
Income per Ton Waste ($/ton)	11.40

Multi-Feedstocks for Ethanol Production

Because most of the feedstocks are lignocellulosic materials that have similar contents, they may be used to produce ethanol in the same system. The advantages of multi-feedstocks for ethanol production are further reduction in feedstock cost and elevation of the potential facility scale upper limit. If the performance on every possible feedstock is the same, the ethanol production cost will be reduced. Here all lignocellulosic materials (crop residue, forest residue, wood residue, and waste paper) as feedstocks are assumed to be fed to the system and the production costs were estimated based on Ellensburg's data. The results are shown in Figures 200 and 203.

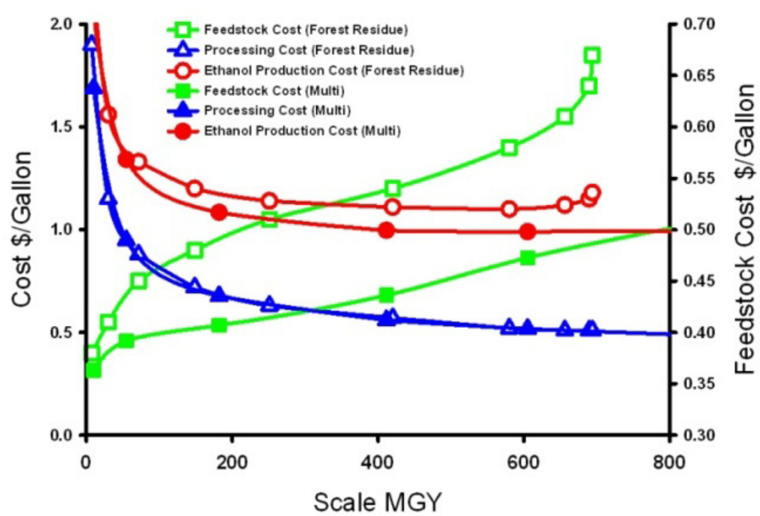

Figure 200: Cost Curve for Bioethanol Production with Multi-Feedstocks

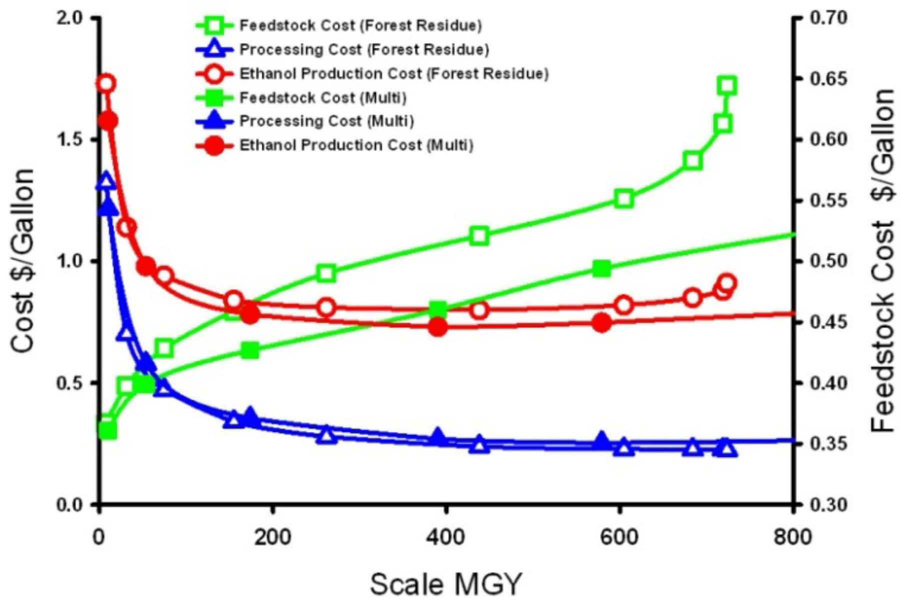

Figure 201: Cost Curve for Thermo-ethanol Production with Multi-Feedstocks

Reduction of feedstock cost accounts for most of the production cost decline. For the bioethanol process, this effect is more distinct. Under actual conditions, all systems must be optimized for specific raw materials and there would be more unpredictable negative effects on the conversion process with the increments of feedstock types. Here the impacts of final ethanol yield reduction are analyzed for both processes, and the result shows that a 10% lower ethanol yield would lead to the loss of the cost advantage for the multi-feedstock strategy.

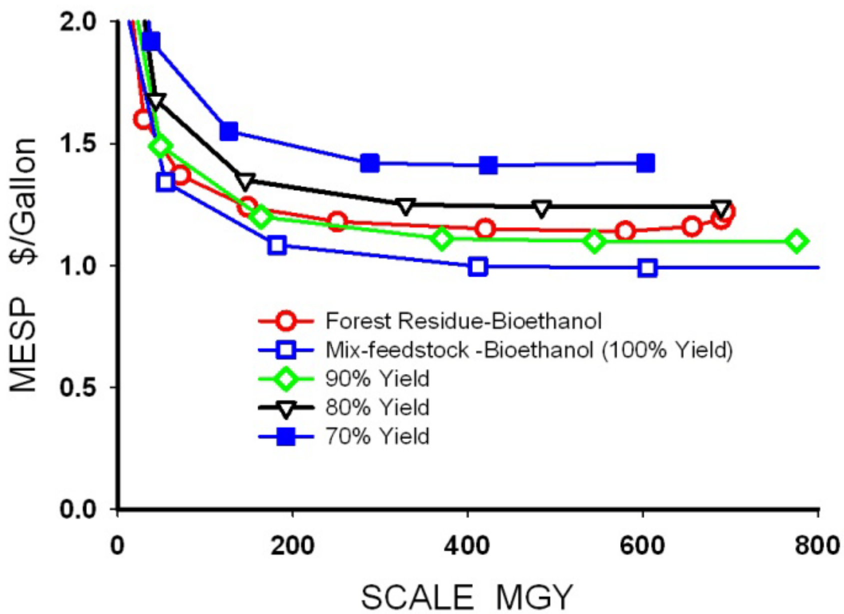

Figure 202: Impacts of Ethanol Yield Reduction on Production Cost of Bioethanol Process

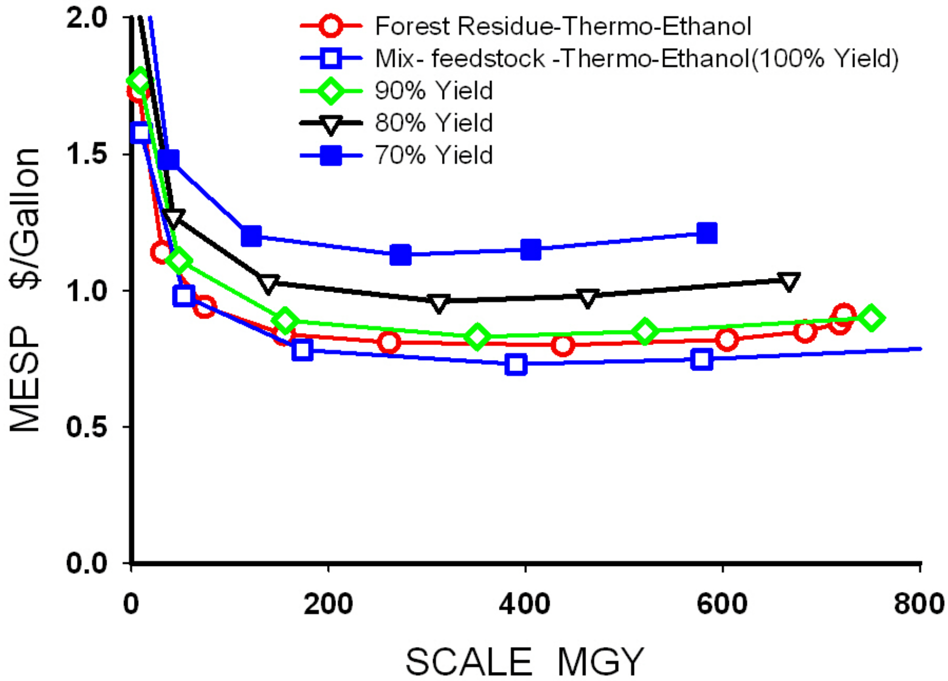

Figure 203: Impacts of Ethanol Yield Reduction on Production Cost of Thermo-ethanol Process

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