Reducing Highway Runoff Pollution and Producing A Low-Cost Biorefinery Feedstock

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Abstract

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The emerging bioeconomy can offer climate change mitigation, energy security and independence, and rural economic development. Cellulosic ethanol can alleviate economic dependence on petroleum-derived fuels. Cellulosic ethanol biorefineries are economically hindered by complex conversion processes, which contribute to significant capital investment, and high feedstock costs; both of which contribute to significant operating expenses. In this study, a hypothesized cellulosic ethanol biorefinery, located in Centralia, Washington, is modeled to convert a 250,000 oven dry tons (ODT) of cellulosic biomass, hybrid poplar, into ethanol annually. This study applies integrates two approaches to reduce operating and capital costs of the proposed biorefinery with the goal of producing an economically competitive product.

Marginal land on roadsides can potentially produce a valuable agronomic product, hybrid poplar, that can be transported to a biorefinery for conversion to ethanol. Poplar production on

roadsides can be achieved at a lower cost than traditionally poplar plantations because other parties are incentivized to manage roadside poplar for the valuable ecosystem services it provides. This research shows that combining roadside poplar with traditional dedicated poplar feedstocks can reduce the feedstock cost of the biorefinery from $74.35/ODT to $69.35/ODT.

Strategic design and management of roadside poplar, in the form of vegetated filter strips (VFS), can provide valuable ecosystem services. VFSs have been shown to reduce the concentration of pollutants in runoff. Highway runoff pollution is responsible for damaging many roadside ecosystems. This analysis finds that implementing roadside VFSs in Western Washington can reduce 25% of TSS, copper, and zinc, 20% of phosphorus and nitrogen, and 20% of lead discharges from urban roadways in highly sensitive aquatic areas and 40% of TSS, copper, and zinc, 15% of phosphorus and nitrogen, and 30% of lead discharges from rural roadways in highly sensitive aquatic areas.

Feedstock cost reduction can be achieved by displacing high-cost dedicated poplar resources with residual poplar resources and poplar resources that provide ecosystem services. Capital costs can be reduced by constructing a biorefinery around a pre-existent powerplant, omitting the need for certain equipment to be newly constructed. This research found that these integrated approaches of cost reduction can reduce the minimum ethanol selling price (MESP) of a cellulosic ethanol biorefinery from $4.15/gallon to $2.89/gallon.

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1 THESIS INTRODUCTION

1.1 BACKGROUND

Establishing a bioeconomy offers an opportunity to merge economic growth with eco-friendly practices [1]. A bioeconomy is defined as the production and conversion of biological resources to value-added products. Forecasted changes in climatic conditions and exhaustion of finite fossil fuel resources motivate a shift to an economy based on renewable resources [1]. Shifting resource acquisition away from petroleum and towards renewable resources can encourage a circular and sustainable economy that functions with environmental responsibility [1]. The emerging bioeconomy can provide climate change mitigation, energy security, and rural economic development.

Fossil fuels are embedded in the current economic structure; they provide the industrial base for nearly all products in the economy [2]. Fossil fuel resources are refined and converted to produce chemicals, plastics, and fuels [3]. Petroleum-derived fuels provide a valuable source of energy that can provide electricity, heat, and transportation [4]. Continued reliance on petroleum resources subjects the economy to future volatility of common products [5]. The rise and fall of petroleum prices have a direct impact on the finances of nearly every market [2]. Dependence on fossil fuels can render an economy vulnerable to outside influences, forsaking economic security and independence [6].

Another concern with dependence on petroleum products is the detrimental impacts on the environment. Initially, petroleum is confined in underground carbon sinks. When petroleum is extracted and refined to fuel, carbon is removed from the ground and eventually emitted to the atmosphere. Large scale use of petroleum for energy consumption has significantly increased the amount of carbon in the atmosphere, which is the main contributor to climate change [7].

Unsustainable carbon emissions also adds societal costs such as loss of ecosystems [8], increasing frequency of wildfires [9], pollution induced health issues [10], rising sea levels [11], and decline in agricultural productivity [12]. These costs will eventually be accounted for as societies seek to mitigate the effects of these consequences.

Renewable fuels, such as biofuels, have been shown to reduce carbon emissions by reestablishing a circular flow of carbon [13]. Biofuels are produced from biomass, which sequesters carbon as it grows, creating a natural sink. Biofuels are combusted for energy, emitting greenhouse gasses (GHG), but in contrast to fossil fuels, the emitted GHGs were recently sequestered by the biomass that was grown to produce biofuels. Largescale biofuel production can alleviate climate change, establish energy independence and security, and develop rural economies.

1.1.1 Cellulosic Ethanol

The transportation sector is a leading source of GHG emissions in the United States [4]. The majority of transportation in the United States is reliant on internal combustion engines, which harness the energy of petroleum-derived fuels, such as gasoline [4]. Blending gasoline with ethanol from renewable resources can displace gasoline usage and reduce the net amount of GHGs emitted by the transportation sector. Ethanol is an alcohol that is commonly used as a fuel additive [14]. Ethanol is a well-researched renewable fuel typically produced from corn starch; however, ethanol can also be produced from cellulosic feedstocks. Cellulosic feedstocks include crop residues, wood residues, and dedicated energy crops. Cellulosic feedstocks can be waste from other industries or grown on marginal land [15] and also require less fertilizer and pesticides [16]. Cellulosic ethanol has lower net GHG emissions than corn ethanol and does not compete with the food sector [17]. Figure 1.1 compares the GHG emissions of common transportation fuels. Currently, cellulosic ethanol is costly to produce and is incapable of economically competing with ethanol derived from traditional feedstocks.

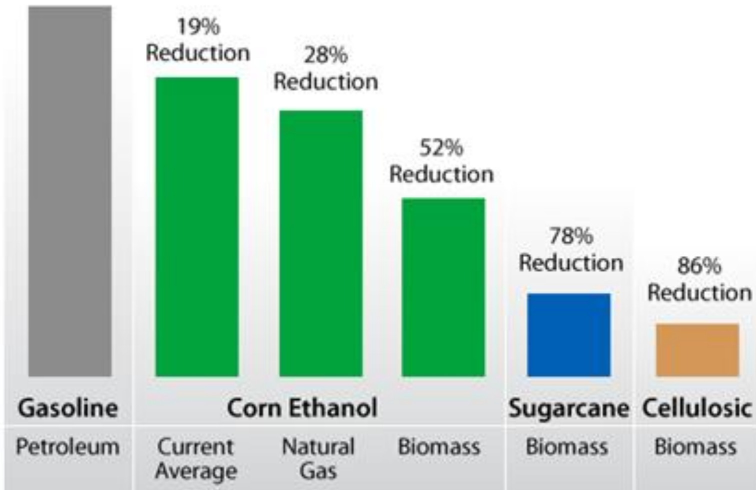


Figure 1.1 Greenhouse Gas Emissions of Transportation Fuels [17]

The Renewable Fuel Standard (RFS) is a program that was created under the Energy Policy Act of 2005 [18]. The purpose of the RFS program is to reduce GHG emissions and establish energy independence by replacing petroleum-based transportation fuels with renewable fuels [18]. The RFS set forth a renewable fuel volume requirement to increase the volume of renewable fuel production with each successive year. Figure 1.2 shows that the RFS considered cellulosic biofuels a renewable fuel with high potential for mass production.

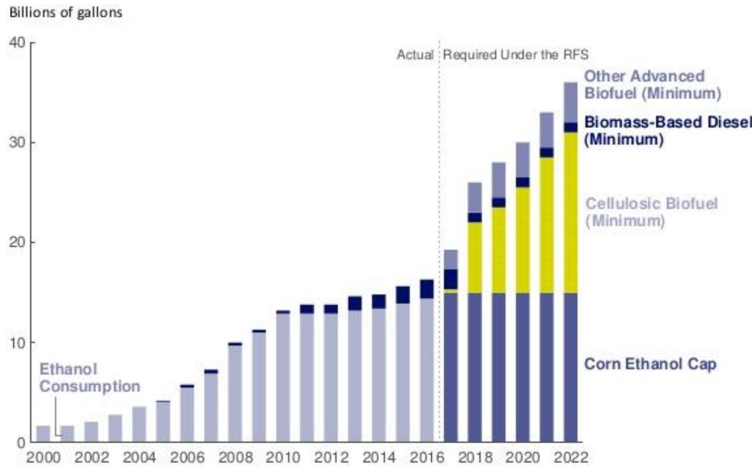


Figure 1.2 RFS mandated renewable fuel volume requirements [19]

Cellulosic ethanol production has failed to achieve the RFS's mandated volume requirement (Figure 1.3). Production of cellulosic ethanol is more complex than production of corn ethanol. Converting corn to ethanol is a straightforward process that requires starch, in corn, to be broken down to glucose monomers, which can be fermented to ethanol. Starch is easily hydrolyzed through application of heat and enzymes. On the other hand, liberating glucose monomers from cellulose is much more difficult because of the cellulosic material's recalcitrant properties. The complexity of cellulosic ethanol production has contributed to its higher cost of production, which is reflected in its shortcomings in the ethanol market.

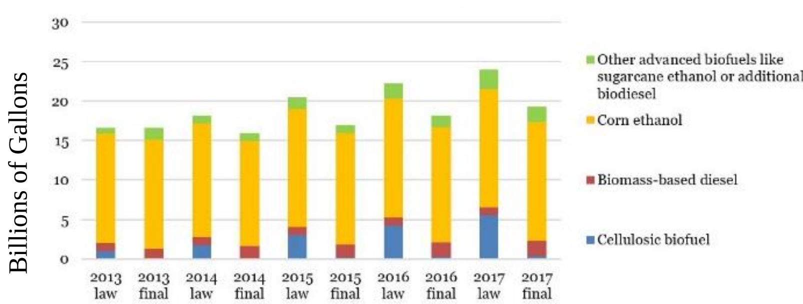


Figure 1.3 RFS mandated renewable fuel volumes compared to actual renewable fuel volumes [20]

1.1.2 BIOREFINERY

In this research, a hypothesized cellulosic ethanol biorefinery is located in Centralia, Washington. The biorefinery is modeled to convert a cellulosic biomass, hybrid poplar, into ethanol. In the model, 250,000 oven dry tons (ODT) of poplar wood chips are converted to ethanol annually. Conversion of wood chips to ethanol is achieved through systematic fractionation to expose the cellulose polymers. Once the cellulose polymers are accessible, enzymes can hydrolyze the cellulose to glucose monomers. The liberated glucose monomers can then be fermented to ethanol, which is isolated and sold as the final product.

1.2 THESIS OBJECTIVES

Traditionally, cellulosic ethanol biorefineries have encountered difficulty in producing an economically competitive product. Research has shown that cellulosic ethanol is more costly due to the complexity of the conversion process, which requires significant capital investment, and high feedstock costs that account for nearly 40% of operating expenses in a biorefinery [21]. This research seeks to achieve three objectives:

1) Assess the potential supply and cost of biomass feedstock produced on roadsides in Western Washington.

Marginal land on roadsides can potentially produce a valuable agronomic product, hybrid poplar, that can be transported to a biorefinery for conversion to ethanol. It is hypothesized that poplar can be produced on roadsides at a lower cost than on traditional poplar plantations because other parties are incentivized to manage roadside poplar for the valuable ecosystem services it provides. This research will analyze roadside land in Western Washington to determine the potential biomass supply that can be produced on roadside land and its associated costs.

2) Assess the environmental impact of highway runoff pollution reduction through strategic design and management of roadside biomass production.

Strategic design and management of roadside poplar, in the form of vegetated filter strips (VFS), can provide valuable ecosystem services. VFSs have been shown to reduce the concentration of pollutants in runoff. Highway runoff pollution is responsible for damaging many roadside ecosystems. This research will explore the environmental benefits of roadside poplar filter strips.

3) Perform a techno-economic analysis of a hypothetical cellulosic ethanol biorefinery in Centralia, Washington; accounting for feedstock cost and capital cost reductions.

Feedstock cost reduction can be achieved by displacing high-cost dedicated poplar resources with residual poplar resources and poplar resources that provide ecosystem services. Capital costs can be reduced by constructing a biorefinery around a pre-existent powerplant, omitting the need for certain equipment to be newly constructed. This research will analyze the effects of feedstock and capital cost reductions on the minimum selling price of the ethanol product.

2 ROADSIDE HYBRID POPLAR AS A LOW-COST FEEDSTOCK

2.1 BACKGROUND

Economic expansion has altered earth's landscapes, natural cycles, and environment [22]. Increasing carbon dioxide emissions contribute to climate change and ocean acidification [23]. Resource extraction and pollution damages ecosystems, threatening many of earth's species [8]. Expanding landscape development increases outlets of non-point source pollution [24]. Earth's natural water and carbon cycles have been altered and no longer function properly [23] [7].

2.1.1 STORMWATER RUNOFF POLLUTION

Developed land disrupts the hydrological cycle by introducing non-impervious surfaces to the terrain [25]. Water, from rainfall and snowmelt, that would have diffused through soils, evaporated, or infiltrated the ground instead flows freely across surfaces [25]. As water runs off rooftops, pavement, and highways, it drains into a common outlet, this is known as stormwater runoff [25]. Pollutants are entrained by stormwater flowing downstream and eventually discharged to a receiving body of water [24]. Developed land diminishes the opportunities for precipitation to be integrated to the natural water cycle, resulting in 20-30% more surface runoff [25]. Not only is there increased surface runoff, but the runoff has characteristics of a higher-energy, faster, and heavier flow [25]. The duration that water is retained on land is significantly reduced, leading to higher stream flows and flooding in the rainy season and lower stream flows in the dry season [25]. In Western Washington, untreated stormwater runoff can eventually enter the Puget Sound, regardless of the path it takes [26].

2.1.2 CLIMATE CHANGE

Economic dependence on petroleum-derived fuels has increased GHG emissions [2] [7]. Biofuels, such as cellulosic ethanol, can reduce GHG emissions by displacing petroleum-based fuels through blending [17]. The biomass grown for biofuels, or the feedstock, incur high costs due to land use and competition for other agronomic products [13]. A high cost feedstock has made producing an economically competitive biofuel difficult; however, low-cost feedstocks from marginal land could offer biofuels a much-needed competitive advantage.

2.1.3 Reducing Stormwater Runoff Pollution and GHG Emissions

A possible solution to repairing both the water and carbon cycles is roadside vegetated filter strips. A vegetated filter strip (VFS) is a slightly sloped roadside embankment that hosts vegetation [27]. The purpose of a VFS is to treat stormwater runoff from highways and roads before the stormwater reaches ecosystems downstream [27]. Roadside VFSs can improve the hydrological cycle by providing a cost-effective solution to reducing highway runoff pollution [28]. Vegetation, grown on roadside VFSs, can be harvested and transported to a biorefinery for conversion to fuels and chemicals. Roadside land can provide adequate area for cheap biomass production that does not compete with other agronomic land allocations.

2.1.4 Roadside Land

Converting roadside land to energy crop production sites can alleviate roadside maintenance costs while producing a valuable agronomic product. The Washington State Department of Transportation (WSDOT) manages over 97,500 acres of roadside land along 7,061 miles of state roadway [29]. Roadside lands are characterized as wasteland due to pollution from transportation exhaust deposition; this vacant land could alternatively provide energy crops with their necessitated land allocation [30]. Roadside land is marginal land that can encourage noxious weed and pest proliferation [29]. Land along roadways must be maintained, which can cost up to $300 per mile annually [29].

In this research, VFS sites will confined to the roadside land within Washington State's right-of-way. WSDOT's roadside manual outlines roadside management operations, which encompasses planning, design, and maintenance of roadside landscapes [29]. WSDOT is responsible for all roadside management within the public right-of-way in Washington. The right-of-way is public land that encompasses roadways and land adjacent to roadways.

Roadside land is managed to maintain defined functions categorized as operational, environmental, visual, and auxiliary functions [29]. Roadside land development is currently limited to the roadside functions described by the WSDOT roadside manual. Roadside operational functions must offer access control, provide adequate distance for sight, and accommodate areas for signs and utilities [29]. Environmental functions are required to protect and enhance natural and built surroundings [29]. Roadsides must function to preserve water quality, protect and improve the environment, provide a means for stormwater detention and retention, control noxious weeds, protect and connect habitats, and control erosion [29]. Roadside visual functions are designed to provide guidance and navigation, deter distraction, preserve scenic views, buffer against adjacent properties, and reduce glare [29]. Auxiliary functions provide additional operational, environmental, and visual functions for a complete roadway transportation system [29]. Figure 2.1 shows an example of the right-of-way boundaries that hosts roadway functions.

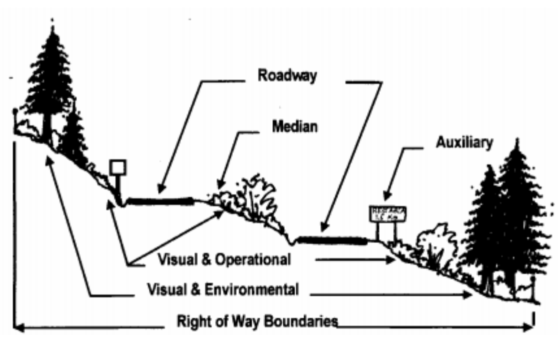


Figure 2.1 WSDOT operational functions in right-of-way [29]

Roadside land is managed according to a three-zone structure [29]. Each zone provides different functions to the roadway; therefore, each zone has different management requirements [29]. Species and site selection for VFSs should be heavily influenced by the roadside vegetation requirements set forth by WSDOT. Figure 2.2 shows an example of a roadway and its roadside zone structure.

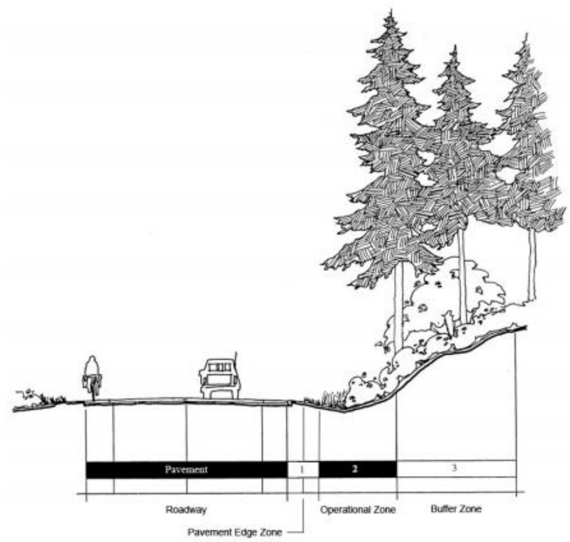


Figure 2.2 WSDOT roadside management zones [29]

Zone 1 is also known as the pavement edge zone. The pavement edge zone is directly adjacent to the roadway and is a vegetation-free or low growing vegetation area [29]. Mechanical and chemical maintenance activities, such as mowing and herbicide use, are applied to Zone 1 areas to maintain driver's sight distance, storm water drainage/filtration, noxious weed control, and pavement preservation [29]. Zone 2 is an operational zone, in which vegetation may exist, however its stem diameter must be less than 4 inches [29]. Zone 2 is mechanically and chemically maintained to preserve sign visibility and sight distance, provide area for vehicle recovery, and control weeds [29]. Zone 3 is a buffer zone that contains native or naturally growing vegetation

[29]. WSDOT seeks to encourage desirable and self-sustaining vegetation in Zone 3, which reduces management operations and maintenance costs [29].

2.2 OBJECTIVE

The objective of this research is to assess the potential supply and cost of biomass feedstock produced on roadsides in Western Washington for a biorefinery located in Centralia, Washington.

2.3 METHODS

To assess the potential supply and cost of biomass produced on roadsides a candidate biomass species was chosen, available roadside areas were identified, using Western Washington as a case study, and biomass production and transportation costs were applied to determine the potential biomass supply and its associated costs.

2.3.1 SPECIES SELECTION

Selecting a species that has desirable characteristics, such as a high yield on marginal land, is important; however, safety, environmental, and regulatory concerns should hold most of the weight in species selection. Table 2.1 lists biomass species characteristics that are desirable for roadside biomass production. In this research, hybrid poplar was chosen as the candidate species. Short-rotation poplar is a high-yield, perennial energy crop [31] that can be grown on marginal land [32]. Poplar production does not require annual plowing and necessitates minimal fertilizer and herbicide input [33]. Poplar satisfies many of the desired characteristics for roadside biomass production, shown in Table 2.1; however it violates compliance with approved WSDOT seed mixes [29]. Ultimately, poplar was chosen as the candidate species for this model due to the large amount of poplar production data in Western Washington [34].

Table 2.1 Desired species characteristics for roadside biomass production

Category	Desired Characteristic	Source
Physiological Traits	High yield	[30]
	Perennial	[30]
	Adaptable to marginal land	[30]
Road Safety Limitations	Stem diameter less than 4 inches	[29]
	No need for annual plowing	[30]
	Non-wood	[29]
Environmental Limitations	Non-invasive	[29]
	Washington native	[29]
	Minimal fertilizer requirement	[30]
	Minimal herbicide requirement	[30]
	Complies with approved WSDOT seed mixes	[29]

2.3.2 SITE SELECTION & AREA AVAILABILITY

Two methods were used to determine area availability and select sites for implementing roadside VFSs along major roadways in Western Washington. The first method used the Integrated Roadside Management Plans (IRVM), provided by WSDOT, to estimate the baseline area available. The second method utilizes Geographic Information Systems (GIS) to identify available areas within the right-of-way (ROW) of major roadways.

2.3.2.1 INTEGRATED ROADSIDE MANAGEMENT PLAN

WSDOT maintains an IRVM to track routine maintenance of vegetation along highways in Washington [35]. An IRVM discloses an annual report that describes current roadside vegetation management activities. IRVMs are geo-specific; the IRVMs that apply to Western Washington include the Northwest, Olympic, and Southwest regions. Each region's IRVM outlines the approach to roadside vegetation management requirements for the given year [35]. An IRVM is organized into groups of roadside maintenance activities, which delegate the roadside zone for each activity [35]. Data from each IRVM for 2019 was extracted to reflect the amount of area that was currently being mechanically mowed in Western Washington. This method relied on the assumptions that mowing areas, provided by the IRVMs, could accommodate biomass production because these areas (1) already housed vegetation and (2) were easily accessible by machinery.

Three maintenance operations were extracted from each IRVM to establish the amount of area mechanically maintained. Safety mowing is defined as routine mechanical cutting of vegetation in Zone 2 [36]. Safety mowing is necessary in areas where taller vegetation is present and must be annually or semi-annually trimmed for visibility [36]. Tree and brush control occurs in Zones 2 and 3 and is defined as periodic trimming of brush and trees intruding on roadway operations or visibility [36]. Nuisance vegetation control is employed to establish desirable vegetative communities [36]. In nuisance vegetation control, undesirable vegetation is identified and mechanically removed [36]. Nuisance vegetation control is mainly applied to vegetation in Zone 3 [36]. Based on the WSDOT Roadside Manual, Zones 2 and 3 were the most suitable areas for implementing roadside biomass production without negatively impacting current roadside functions [29].

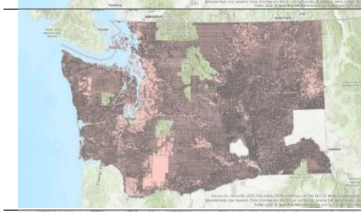
2.3.2.2 Geographic Information Systems

GIS techniques were used to quantify the potential locations and area of VFS sites. GIS analysis occurred as follows. (1) The Washington state right-of-way was identified and mapped for Western Washington. (2) A land cover map [37] was used to identify areas that are available for VFS siting within the state right-of-way . (3) A final map was prepared depicting the state right-of-way in Western Washington with areas that were available for VFS sites. Data produced through this GIS analysis was used to predict roadside poplar production sites, area availability, and transportation distances from each harvest site to a theoretical biorefinery in Centralia, Washington.

2.3.2.2.1 MAP DATA COLLECTION

Map data was collected to provide the necessary geographical data for this analysis. The maps used in this analysis originate from reputable GIS sources and are as current as possible. Table 2.2 summarizes the map data used in this analysis.

Table 2.2 Map data collection

	**Washington County Map** [38] Washington County Boundaries Source: WA Department of Natural Resources Year: 2018 Data Type: Shapefile feature class Geometry: Polygon
	**Washington Tax Parcel Map** [39] Current Tax Parcels Source: Washington Geospatial Open Data Portal Year: 2019 Data Type: Geodatabase Feature Class Geometry: Polygon
	**Washington State Major Routes Map** [40] State Routes of Washington State 1:24,000 Source: WSDOT Year: 2019 Data Type: Shapefile Feature Class Geometry: Line
	**National Land Cover Map** [37] NLCD 2016 Land Cover (CONUS) Multi-Resolution Land Characteristics Consortium Year: 2016 Data Type: Raster

2.3.2.2.2 GEOGRAPHIC REGION CONSTRUCTION

The geographic region for Western Washington, was constructed by selecting the counties in Western Washington on the Washington County Map. All the other maps were clipped to conform to the shape of Western Washington. The geographic region construction operation is shown in Figure 2.3 below.

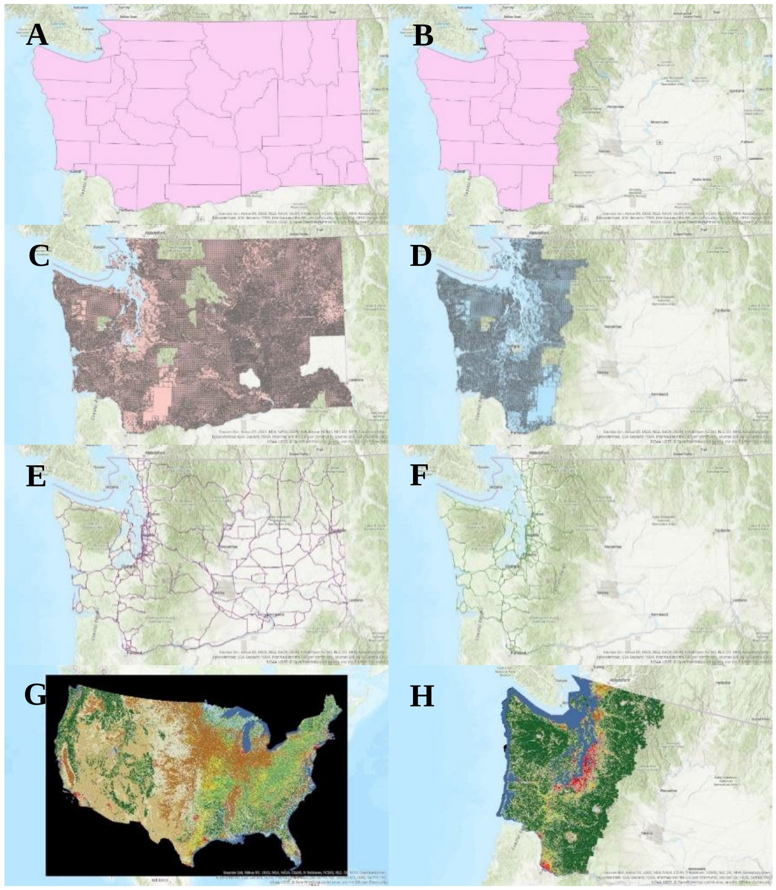


Figure 2.3 Geographic region construction of Western Washington

In Figure 2.3, The Washington County Map, represented by the map in Figure 2.3.A, underwent a selection to select counties in the Western Washington region, the product is shown Figure 2.3.B. The map in Figure 2.3.C represents the Washington Tax Parcel Map, which was clipped by the map in Figure 2.3.B to produce the map in Figure 2.3.D. The Washington State Major Routes Map, represented by the map in Figure 2.3.E, was clipped by the map in Figure 2.3.B to produce the map in Figure 2.3.F. And the National Land Cover Map, represented by the map in Figure 2.3.G, was clipped by the map in Figure 2.3.B to produce the map in Figure 2.3.H. Maps D, F, and H in Figure 2.3 will be used to determine the state right-of-way and potential VFS sites in the following sections.

2.3.2.2.3 STATE RIGHT-OF-WAY CONSTRUCTION

After extensive map data research, it was apparent that a map depicting the state right-of-way in Washington was not available. Therefore, a right-of-way map was generated for this analysis. To derive the state right-of-way, a tax parcel map was utilized under the assumption that right-of-way land is not taxed. Non-taxed right-of-way land is represented by blank spaces in the tax parcel map, which could represent the right-of-way. The tax parcel map was reversed to omit taxed parcels and select non-taxed parcels, this generated a map of the state right-of-way in Western Washington. The right-of-way map construction process is shown in Figure 2.4.

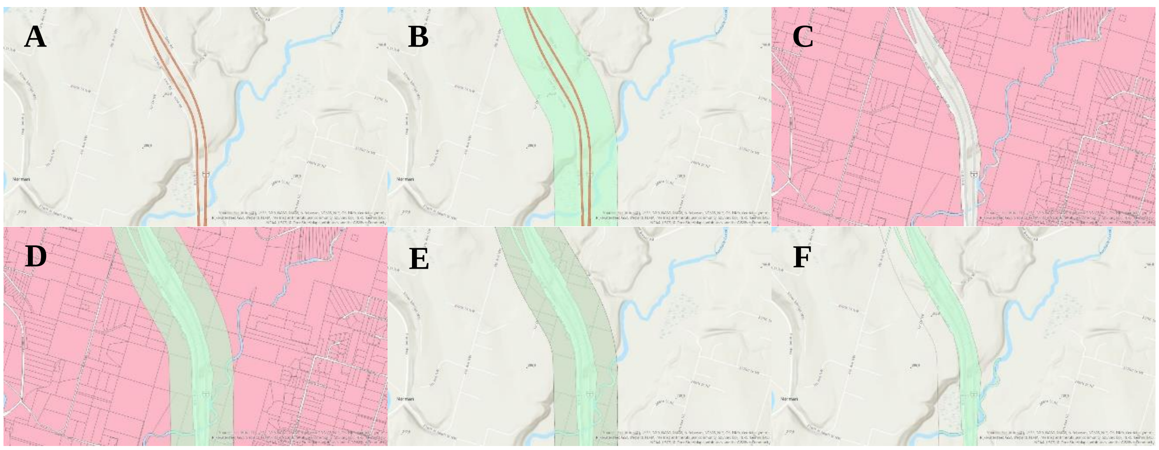


Figure 2.4 State right-of-way construction in Western Washington

Figure 2.4 begins with Washington State Major Routes Map, which is zoomed in and shown in Figure 2.4.A. The map in Figure 2.4.A was buffered to produce the map in Figure 2.4.B. A 500-foot buffer was applied to both sides of the major state route lines in Map A to produce a 1000-foot wide polygon that encapsulated the major roadways in Western Washington, shown in Map B. This encapsulation had two purposes. (1) To increase data processing efficiency and (2) provide a canvas from which the state right-of-way could be carved from. The map in Figure 2.4.C is a zoom in on a location in the Washington Tax Parcel Map. The buffered Washington State Major Routes Map, from Figure 2.4.B was overlaid on the Washington Tax Parcel Map to produce the map in Figure 2.4.D. In Figure 2.4.E, the Washington Tax Parcel Map has been clipped by the buffered Washington State Major Routes map, this step was included to increase data processing efficiency. The map in Figure 2.4.E was inverted to produce the state right-of-way map shown in Figure 2.4.F. This inversion was performed by erasing the buffered Washington State Major Routes (Map B) map with the clipped Washington Tax Parcel Map (Map E). This erasing operation left behind the empty spaces in the Washington Tax Parcel Map, which represents the state right-of-way on major routes in Western Washington. The resultant map of this operation is called the Right-of-Way Map.

2.3.2.2.4 ROADSIDE LAND AVAILABILITY

Roadside Land availability was determined through land cover data that was overlaid with the right-of-way map. Land cover data classifies land into open land, water, developed land, barren land, forest, shrubland, grassland, cultivated land, and wetlands [37]. This provided a suitable method for assessing land availability within the right-of-way. The roadside land availability operation is shown in Figure 2.5.

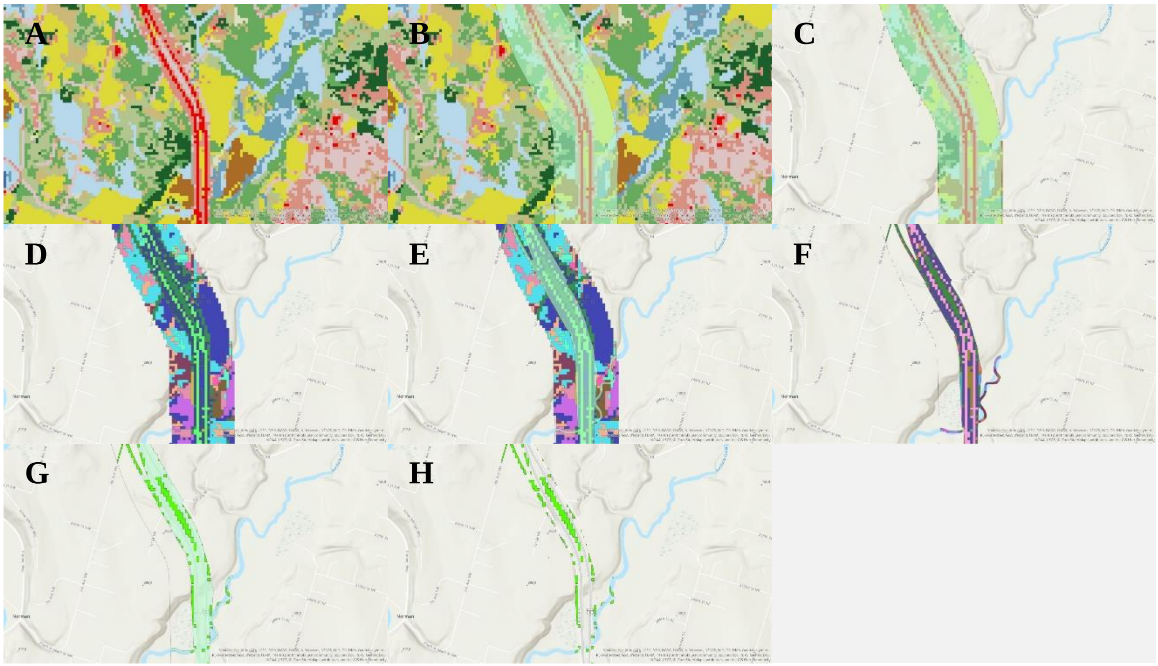


Figure 2.5 Roadside land area availability

Figure 2.5.A is a zoomed in portion of the National Land Cover Map. In Figure 2.5.A, the red lines represent developed land, in this case a major roadway, the other colors represent different classifications of land, such as open land, water, barren land, forest, etcetera. The first step in determining roadside land availability was to reduce the amount of data present to improve processing efficiency. This step is shown in Figure 2.5.B and 2.5.C. In Figure 2.5.B, the buffered Washington State Major Routes Map is overlaid on the National Land Cover Map. The National Land Cover Map was clipped by the buffered Washington State Major Routes Map in Figure 2.5.C, and the clipped National Land Cover Map is shown on its own in Figure 2.5.D. The goal of this operation was to determine the land availability within the state right-of-way; therefore, National Land Cover Map must conform to the Right-of-Way Map. Figure 2.5.E shows the Right-of-Way Map overlaid on top of the clipped National Land Cover Map. The clipped National Land Cover Map was clipped with the Right-of-Way Map to produce the map shown in Figure 2.5.F. The National Land Cover Map in Figure 2.5.F, which now conforms to the state right-of-way,

underwent a selection process. The selection process selected land that is classified as open land, barren land, shrubland, and grassland. This analysis assumed that these land types were adequate areas for poplar production. The bright green pixels in Figure 2.5.G represent land available for poplar production within the state right-of-way. The final step in this process was to remove the suitable poplar production land polygons that had areas smaller than one acre. This step was performed to produce the final map shown in Figure 2.5.H.

2.3.2.2.5 TRANSPORTATION DISTANCE DETERMINATION

Transportation distances to the Centralia biorefinery were determined for each individual site. Network Analyst on GIS was used to calculate the shortest route from individual sites to the biorefinery. Figure 2.6 below shows an example route distance calculation using GIS Network Analyst. In Figure 2.6, the squares represent VFS sites and the circle represents the Centralia biorefinery. The blue line is the shortest route from the selected VFS site to the biorefinery. Transportation costs were applied to route distances from each site to the biorefinery to determine the biorefinery-gate cost of roadside poplar. Transportation costs are further discussed in the following section.

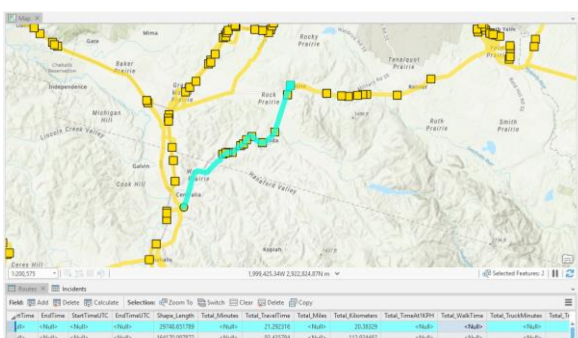


Figure 2.6 GIS Network Analyst transportation distance example

2.3.3 BIOMASS PRODUCTION AND TRANSPORTATION COSTS

Hybrid poplar production costs were adapted from the Greenwood Resources Production Cost Calculator [34]. Hybrid poplar production requires site preparation, establishment, maintenance, harvest, and site restoration. Greenwood Resources plans hybrid poplar production costs in a 22-year plantation life cycle, which includes a 2-year establishment phase, six 3-year poplar production phases, and a 1-year restoration phase [34]. Roadside poplar production costs on VFSs were modified to a harvest and ship scenario that removes establishment, maintenance, and restoration costs from Greenwood's poplar cost analysis. The harvest and ship scenario for roadside poplar production operated under the assumption that a third-party, such as WSDOT, had an incentive to oversee establishment and maintenance of roadside VFSs, while the biorefinery was responsible for harvest and transportation of the poplar. Transportation costs were based on the route distance from the poplar production site to the biorefinery and backhaul costs were proportional to the transportation distance. Data on dedicated poplar plantation sites was obtained through collaboration with Amira Chowyuk [34]. The poplar production yield on marginal land was assumed to be 7.8 ODT/year and half of that yield during establishment cycles [34]. Table 2.3 describes the costs for each phase of the dedicated poplar and roadside poplar production and transportation scenarios.

Table 2.3 Poplar production cost breakdown [34]

Cycles	1	1	1	6	6	1	22			
Phase	Site Prep, Planting Stock, Establishment (Crop Year 0) ($/acre)	Two-Year Establishment Cycle, Crop Care (Crop Years 1-3) ($/acre)	Two-Year Establishment Cycle, Harvest (Crop Year 3) ($/acre)	Three-Year Coppice Cycle, Crop Care (Crop Years 4-21) ($/acre)	Three-Year Coppice Cycle, Harvest (Crop Years 6, 9, 12,15,18, 21) ($/acre)	Restoration (Crop Year 22) ($/acre)	Administrative Expenses ($/acre)	Transportation ($/mile/ODT)	Backhaul ($/mile)	Farm-Gate Cost ($/ODT)
Dedicated Poplar	$347.00	$124.00	$326.00	$216.00	$613.00	$77.00	$69.00	$0.31	0.5x Transportation	$49.70
Roadside Poplar	$0.00	$0.00	$326.00	$0.00	$613.00	$0.00	$0.00	$0.31	0.5x Transportation	$27.02

2.3.4 SUPPLY CURVE DEVELOPMENT

A supply curve was used to assess the cost of poplar at a given annual supply. The capacity of a biorefinery is directly related to the amount of biomass it processes per year. A poplar supply curve was constructed with the location of the biorefinery and feedstock production data. In this analysis the theoretical biorefinery is in Centralia, Washington. Feedstock production data, such as poplar production site locations and transportation costs were used to determine the plant-gate cost of each ton of biomass delivered to the biorefinery. To develop a supply curve, each poplar production site's plant-gate cost and supply was determined. The plant-gate costs and supply from each site were then ranked from the lowest plant-gate costs to the highest plant-gate costs. As the biorefinery's capacity increased, the next cheapest source of biomass was chosen and assimilated into the supply. The plant-gate costs and supply of the biorefinery were plotted in a graph with the annual supply on the x-axis and the plant-gate costs of biomass per ODT on the y-axis. The outcome of this graph was a supply curve that showed the marginal increase in biomass costs for each supply addition. The moving average of this function was calculated to determine the average cost of biomass at a given biorefinery capacity.

2.4 RESULTS & DISCUSSION

The purpose of this analysis was to determine the potential available supply and associated cost of poplar from roadside biomass production in Western Washington. According to the IRVM data, the total mowing area in Western Washington is 6,315 acres. Table 2.4 summarizes data extracted from the IRVMs. The data is divided among three regions in Western Washington, including the Northwest, Olympic, and Southwest regions. Compiling mowing data from the IRVMs provides a quick method for determining the amount of area where VFSs could be implemented. Although the IRVMs provided a starting point for determining the amount of area available for roadside VFS implementation, the data is incomplete as there could be more area available that is not currently maintained. Also, the area data from IRVMs was not location specific, therefore transportation costs could not be calculated from this data. IRVM data was not sufficient for a thorough analysis on VFS implementation in Western Washington; however, it did serve as a benchmark for the area availability estimate performed in GIS.

Table 2.4 IRVM mowing areas in Western Washington for 2019

Roadside Operation	**Safety Mowing**	**Tree and Brush Control**	**Nuisance Vegetation Control**	**Source**
Region	Zone 2	Zones 2 & 3	Zone 3	
Units	Acres	Acres	Acres	
Northwest	1,075	470	180	[36], [41]–[44]
Olympic	1,500	670	200	[45]
Southwest	1,475	650	95	[46]–[49]
Total	4,050	1,790	475	**Total: 6,315 acres**

Figure 2.7 shows the potential roadside poplar production sites from the GIS analysis. In Figure 2.7, the Centralia biorefinery is depicted as a yellow square. Roadside poplar production sites are depicted as pink circles; a larger pink circle represents a larger site area. The VFS Site Map, shown in Figure 2.7, shows that 13,800 acres of roadside land in Western Washington is available for conversion to VFS sites. The IRVM baseline roadside area analysis showed that there were at least 6,300 acres of available roadside land in Western Washington. The GIS results are slightly larger than double that of the IRVM plans, but this result could be due to the IRVM plans only accounting for currently mowed areas. The cumulative poplar yield from all the sites in the VFS Site Map would sum to 93,000 ODT/year at an average cost of $75.11/ODT.

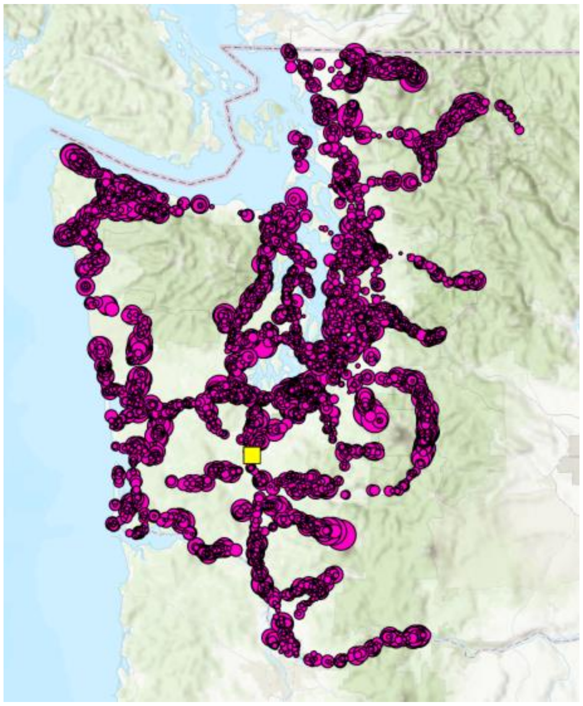


Figure 2.7 Potential roadside poplar production sites

This analysis first determined the total area of potential roadside production through GIS, then poplar production economics and yield assumptions were applied to determine the total poplar supply available. GIS network analyst determined the transportation distance from each site to the biorefinery and transportation economics were applied to determine the transportation cost from roadside sites to the biorefinery. This information collectively determines the supply and cost of poplar from each potential roadside site.

Figure 2.8 is a graph that compares the marginal supply curves of dedicated poplar and roadside poplar. In Figure 2.8, the next cheapest biomass is chosen for each separate source and assimilated into their respective supply curves. The marginal cost supply curve reveals that at around 40,000 ODT/year roadside poplar begins to become more expensive than dedicated poplar. The marginal cost supply curves are averaged to produce average cost supply curves, which are shown in Figure 2.9.

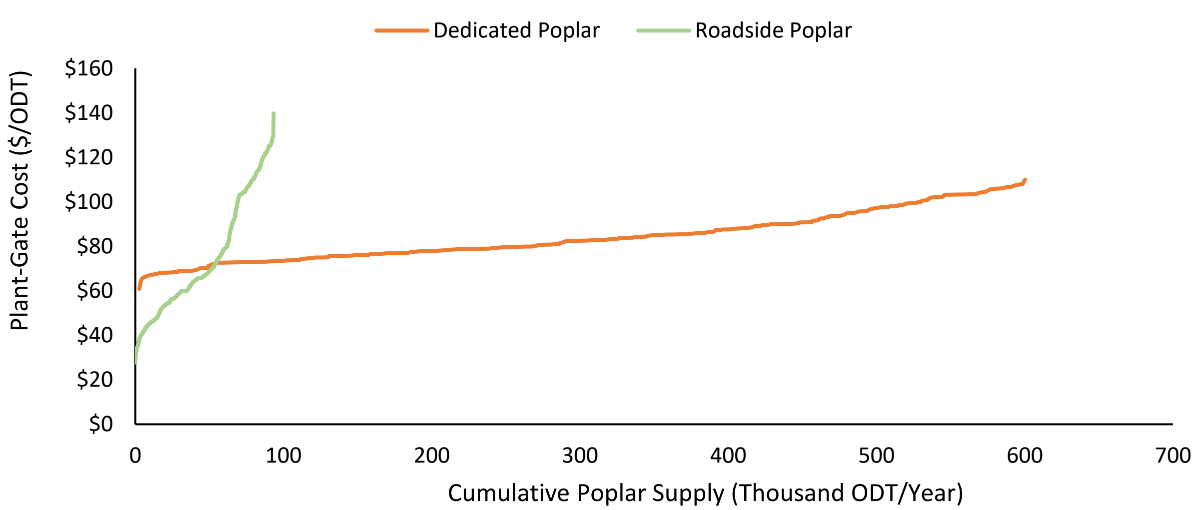


Figure 2.8 Roadside poplar and dedicated poplar marginal cost supply curve comparison

Figure 2.9 shows the average cost of roadside poplar at the biorefinery gate and compares it to the average cost of dedicated poplar at the biorefinery gate. The supply curves in Figure 2.9 reveal that roadside poplar has a much lower cost than dedicated poplar at low supplies. For example, at 25,000 ODT/year, 50,000 ODT/year, and 75,000 ODT/year roadside poplar costs an average of $46.93/ODT, $54.59/ODT, and $64.96/ODT, respectively. Whereas at 25,000 ODT/year, 50,000 ODT/year, and 75,000 ODT/year, dedicated poplar costs an average of $66.77/ODT, $68.09/ODT, and $69.61/ODT, respectively. The supply of roadside poplar reaches a maximum at 93,000 ODT/year; at this supply roadside poplar costs an average of $75.11/ODT, which is more expensive than dedicated poplar ($70.33/ODT at 93,000 ODT/year).

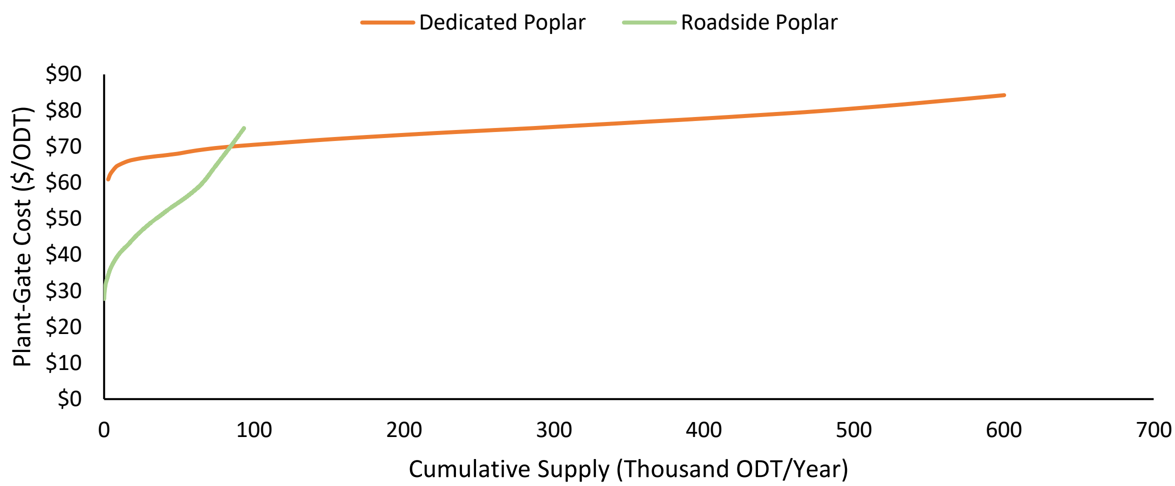


Figure 2.9 Roadside polar and dedicated average cost poplar supply curve comparison

In Figure 2.10 the dedicated poplar and roadside poplar average cost supply curves are combined. This combined supply curve selects the next cheapest biomass source as the supply increases. Figure 2.10 shows that utilizing a combined poplar supply from roadside production sites and dedicated production sites can decrease the average cost of poplar for any given annual supply. Specifically, at 250,000 ODT/year the average cost of combined poplar is $69.35/ODT and the average cost of dedicated poplar is $74.35/ODT. Therefore, by supplementing the Centralia biorefinery with low-cost roadside poplar resources, in addition to the dedicated poplar resources, the average cost of the feedstock can be reduced by $5.00/ODT.

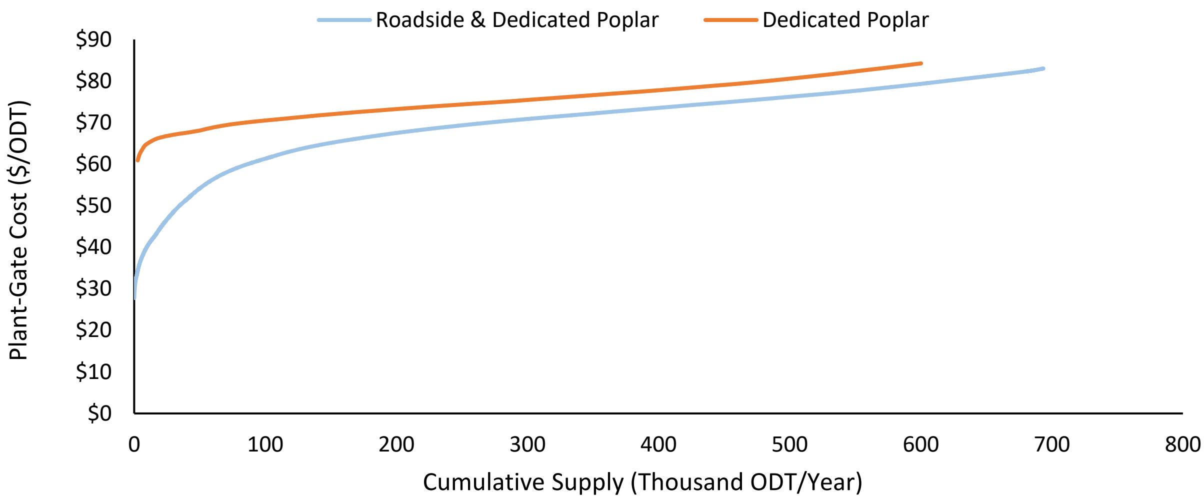


Figure 2.10 Dedicated and roadside poplar combined supply curve

Figure 2.10 shows that the cost of poplar can be reduced by combining dedicated poplar resources with non-conventional poplar resources; however, Figure 2.10 does not elaborate on the ratios of poplar sources at given supplies. Table 2.5 explores the combined poplar average cost supply curve in more detail by describing the amount of dedicated poplar and roadside poplar, with their associated costs, at given biorefinery capacities. Table 2.5 shows that at a low biorefinery capacity, such as 50,000 ODT/year, roadside poplar makes up the majority of the feedstock. As the capacity of the biorefinery increases, dedicated poplar is integrated into the supply and eventually makes up the majority of poplar in the combined poplar supply.

Table 2.5 Supply contribution of dedicated and roadside poplar

Capacity (ODT/Year)	Dedicated Poplar Supply (ODT/Year)	Dedicated Poplar Average Cost ($/ODT)	Roadside Poplar Supply (ODT/Year)	Roadside Poplar Average Cost ($/ODT)	Average Cost ($/ODT)
50,003	4,266	$62.45	45,737	$53.39	$54.17
100,949	48,789	$68.01	52,160	$55.21	$61.40
151,856	97,006	$70.40	54,850	$56.01	$65.21
204,659	147,012	$71.91	57,647	$56.92	$67.69
250,631	191,506	$73.04	59,125	$57.42	$69.35
300,083	239,598	$74.13	60,486	$57.90	$70.86
350,044	287,494	$75.14	62,551	$58.62	$72.19
401,501	338,040	$76.32	63,462	$58.97	$73.57
450,723	386,664	$77.45	64,058	$59.22	$74.86
505,100	439,705	$78.80	65,394	$59.82	$76.34

Table 2.5 is visualized in Figure 2.11. Figure 2.11 shows the proportion of poplar resources that contribute to total supply as the capacity of the biorefinery increases. In Figure 2.11 the columns correspond to the primary y-axis, which is the supply input to the biorefinery. The lines are plotted against the secondary y-axis, which is the average cost of the given biomass supply. The x-axis of the lines corresponds to the capacity of the biorefinery. Figure 2.11 demonstrates that as the capacity of the biorefinery increases, the portion of dedicated poplar increases. This results in a stronger pull on the average cost of the mixed supply towards the average cost of dedicated poplar. This is visualized by the blue line, which trends towards the average cost of dedicated poplar as the capacity increases. The absolute amount of roadside poplar slightly increases as the capacity of the biorefinery increases and still manages to reduce the mixed poplar average cost; however, this effect is dampened as more dedicated poplar is incorporated in the supply.

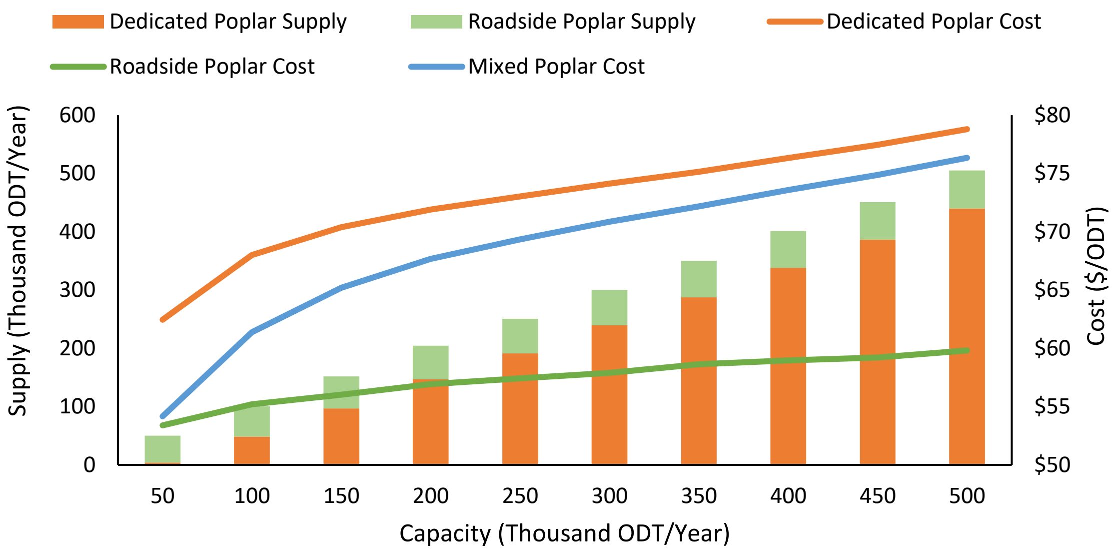


Figure 2.11 Supply contribution of dedicated and roadside poplar and its effects on biomass cost

Roadside poplar initially has a low cost at low supplies because the sites in closest proximity to the biorefinery (lower transportation costs) are selected first. As the roadside poplar supply increases, the sites further from the biorefinery are selected, which cost more due to increased transportation distances. This close-proximity site-selection dynamic results in a steep supply curve that quickly increases in average cost as the supply increases. To elaborate on this finding, a graph is produced to visualize the contribution of transportation costs and harvest costs for roadside poplar in the harvest and ship scenario. In Figure 2.12, a column from Figure 2.11 is isolated and analyzed. The top green fraction of the left column in Figure 2.12 represents the roadside poplar fraction of the biomass supply at a 250,000 ODT/year biorefinery capacity. The column on the right in Figure 2.12 shows the contribution of harvest and transportation costs to the cost of roadside poplar at the given supply.

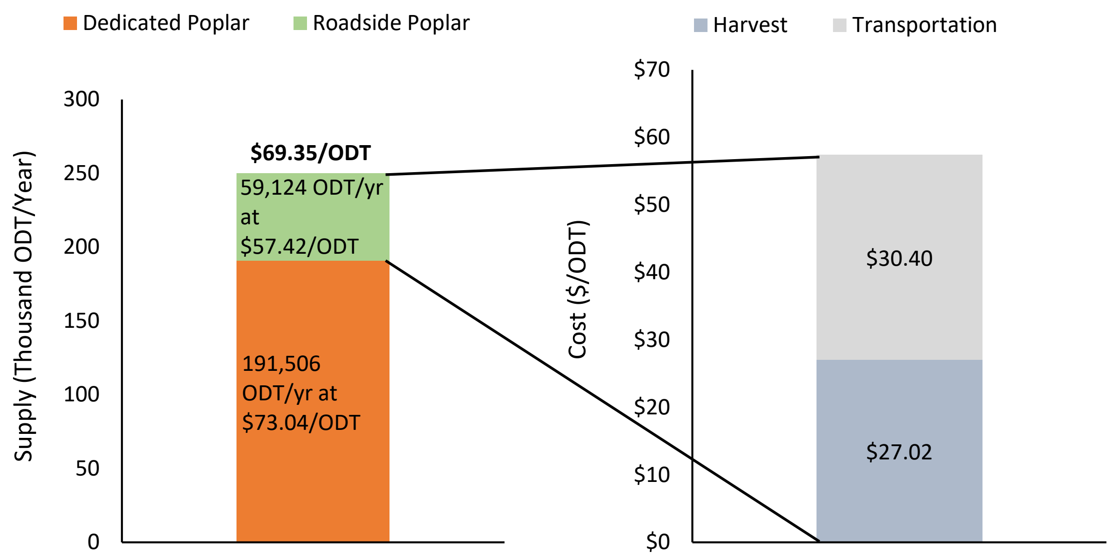


Figure 2.12 Cost contribution of harvest and transportation on roadside poplar cost at 250,000 ODT/year

2.5 Conclusion & Recommendations

This analysis has determined that the feedstock costs for a Centralia biorefinery, processing 250,000 ODT of poplar per year, can be reduced by $5 per ODT by supplementing poplar resources from roadside production sites. Nearly 40,000 ODT/year of roadside poplar can be used before it becomes more expensive than dedicated poplar sources. Roadside poplar has proven to be cheaper than dedicated poplar at lower supplies by providing ecosystem services. Poplar grown for the purpose of ecosystem service can reduce production costs by providing incentives to third parties to participate in the establishment and maintenance of the crops. Roadside poplar production can incentivize public parties, such as WSDOT and the Washington State Department of Ecology, by reducing pollution emission from roadways. Through strategic design, poplar can be produced on roadsides in VFSs, which have been shown to reduce contaminants in highway runoff.

Although, the large supply and low-cost of roadside poplar seems promising, there are still many steps necessary to solidify this research. In terms of accuracy, formal right-of-way plans in

Western Washington should be obtained. A landcover map with smaller pixels would provide more accurate insight on the land availability within the right-of-way. A slope map should also be applied to the GIS model to determine if certain areas are too inclined for poplar production. There is highway safety concern with trees planted near the road, therefore a more feasible candidate species should be investigated, such as a species of grass.

In conclusion, roadside poplar production could be a low-cost source of biomass for a biorefinery; however, there are still many logistical barriers to overcome.

3 ROADSIDE HYBRID POPLAR AS AN ECOSYSTEM SERVICE

3.1 BACKGROUND

Stormwater runoff is defined as precipitation that flows in the form of surface water [50]. Prior to land development, stormwater would seep into the ground or evaporate through vegetation [26] [51]. On significant amounts of land, vegetation has been removed and covered with impervious surfaces, such as roads and rooftops, which surface water cannot infiltrate [26] [51]. Stormwater is produced during storm events when rain falls on impervious surfaces and is unable to penetrate the ground [50] [51]. Unable to infiltrate underlying soils, stormwater flows in large volumes to streams, lakes, wetlands, and rivers [50] [52]. Stormwater runoff can cause flooding, erosion, and habitat destruction [50]. As stormwater flows downstream it picks up a variety of different pollutants, which eventually get deposited in ecosystems [26] [51]. Stormwater runoff has been identified as the most significant contributor of pollution to the Puget Sound [26]. This research will focus on strategic design and management of vegetation on roadsides in Western Washington to reduce stormwater runoff pollution.

3.1.1 HIGHWAY RUNOFF

A significant amount of stormwater runoff is produced on major roadways. Highway runoff has received significant attention due to the abundance of toxic pollutants it carries [53]. The magnitude of highway runoff pollution is determined by variables including traffic characteristics, maintenance policies, surrounding land use, and climatic conditions [54]. WSDOT operates 40,000 acres of paved surfaces in Washington and is responsible for controlling highway runoff pollution [55].

3.1.2 CLEAN WATER ACT

The Clean Water Act is a US federal law that aims to restore the integrity of the Nation's surface waters [55]. This is done by regulation of pollutant discharge to surface water, such as rivers, lakes, streams, and coastal waters [56]. The Clean Water Act controls stormwater pollution through the National Pollutant Discharge Elimination System (NPDES) [55]. In Washington, WSDOT was issued an NPDES permit, which requires WSDOT to monitor and evaluate stormwater management infrastructure on highways [55].

3.1.3 SOURCES OF POLLUTION IN HIGHWAY RUNOFF

Between precipitation periods pollutants accumulate on highway surfaces from operation of the transportation system [54]. During storm events, these constituents are transported downstream with highway runoff. Table 3.1 compiles a list of common constituents found in highway runoff and identifies their primary sources.

Table 3.1 Source of pollution in highway runoff [57]

Constituent	Primary Sources
Particulates	Pavement wear, vehicles, atmosphere, maintenance, snow/ice abrasives, sediment disturbance
Nitrogen (N), Phosphorus (P)	Atmosphere, roadside fertilizer application
Lead (Pb)	Leaded gasoline, tire wear, lubricating oil and grease, bearing wear
Zinc (Zn)	Tire wear, motor oil, grease
Iron (Fe)	Autobody rust, steel highway structures, engine parts
Copper (Cu)	Metal plating, bearing wear, engine parts, brake lining wear, fungicides and insecticides use
Cadmium (Cd)	Tire wear, insecticide application
Chromium (Cr)	Metal plating, engine parts, brake lining wear
Nickel (Ni)	Diesel fuel and gasoline exhaust, lubricating oil, metal plating, brake lining wear, asphalt paving
Manganese (Mn)	Moving engine parts
Bromide (Br-)	Exhaust
Cyanide	Anticake compound used to keep deicing salt granular
Sodium (Na), Calcium (Ca)	Deicing salts, grease
Chloride	Deicing salts
Sulfate	Roadway beds, fuel, deicing salts
Petroleum	Spills, leaks, blow-by motor lubricants, antifreeze, hydraulic fluids, asphalt surface leachate
Herbicides, Pesticides	Spraying of highway right of ways, atmospheric deposition
Pathogen bacteria	Soil litter, bird droppings, trucks hauling livestock/stockyard waste
Rubber	Tire wear
Methanol	Windshield wiper fluid, brake fluid

3.1.4 HIGHWAY RUNOFF CHARACTERIZATION

WSDOT has been conducting ongoing research on the contaminants in highway runoff through a monitoring program to establish baseline stormwater discharge information [58].

WSDOT's highway runoff monitoring sites were strategically selected to characterize runoff from highly urban, urban, and rural roadway sites in Western Washington [58]. Site monitoring stations and weather tracking allowed WSDOT to sample highway runoff during storm events and determine the event mean concentration (EMC) for constituents in highway runoff. An EMC is the concentration of constituents in stormwater runoff during a storm event. The following sections will discuss significant constituents in highway runoff and their EMCs, which were provided by WSDOT's Highway Runoff Characterization Report in 2012-2014 [58].

3.1.4.1 Total Suspended Solids

TSS is directly correlated to the turbidity of a body of water [58]. Sediment is the main component of TSS in surface water runoff [59]. However, sediment typically caries other pollutants, such as heavy metals [58]. An increase of TSS in a body of water can deplete water quality through sedimentation of stream beds, habitat alteration, and light reduction [58]. Sediment suspended in highway runoff eventually settles in lakes, streams, and other bodies of water [59]. Once sediment is introduced to ecosystems it can prevent light from reaching aquatic plants, suffocate aquatic organisms, and disrupt fish spawning areas [59]. Table 3.2, from WSDOT's highway runoff monitoring program shows the EMCs of TSS stormwater monitoring sites.

Table 3.2 EMCs (mg/L) of TSS in WSDOT stormwater monitoring program [58]

Monitoring Site	Minimum	Median	Maximum	Mean	Standard Deviation	CV	*n*
Pilchuck 01 (urbanized)	21	55.5	117	60.33	26.16	0.43	18
Everett 01 (highly urbanized)	23	51.5	132	58.75	34.77	0.59	12
Everett 04 (highly urbanized)	36	58.5	109	64.67	21.89	0.34	18
SR9 01 (rural)[1]	16	44	161	61.50	40.58	0.66	18
Pines 01 (urbanized)	27	54.5	117	63.38	30.19	0.48	8

3.1.4.2 Nutrients

Nutrient pollution is a significant threat to aquatic ecosystems that has resulted in serious environmental issues [60] [61]. Nitrogen and phosphorous are essential nutrients for plant growth

[58]. In aquatic ecosystems, nitrogen and phosphorous support algae and aquatic plant growth, which provide food and habitats for aquatic organisms [60] [61]. Plant and algal growth are limited by the abundance of nitrogen and phosphorous [59]. When too much nitrogen and phosphorous are introduced to aquatic ecosystems, algal growth rates exceed the thresholds that aquatic ecosystems can handle [60] [61]. Significant increases of algae populations in aquatic ecosystems can deplete water quality, alter habitats, and reduce oxygen that is essential for the survival of most aquatic organisms [60] [61]. WSDOT's stormwater monitoring program tracks the EMCs of Total Phosphorus (TP) and Total Kjeldahl Nitrogen (TKN) in highway runoff. TP is a measure of organic and inorganic phosphate; the EMCs of TP are shown in Table 3.3 [58]. TKN is a measure of the total organic nitrogen and ammonia; the EMCs of TKN are shown in Table 3.4 [58].

Table 3.3 EMCs (mg/L) of TP in WSDOT stormwater monitoring program [58]

Monitoring Site	Minimum	Median	Maximum	Mean	Standard Deviation	CV	*n*
Pilchuck 01 (urbanized)	0.0562	0.1014	0.266	0.1148	0.0503	0.44	18
Everett 01 (highly urbanized)	0.0423	0.1120	0.258	0.1148	0.0597	0.52	11
Everett 04 (highly urbanized)	0.0533	0.114	0.268	0.1224	0.0555	0.45	17
SR9 01 (rural)	0.0335	0.076	0.141[1]	0.0841	0.0299	0.36	17
Pines 01 (urbanized)	0.109	0.156	0.272	0.1763	0.0650	0.37	7

Table 3.4 EMCs (mg/L) of TKN in WSDOT stormwater monitoring program [58]

Monitoring Site	Minimum	Median	Maximum[1]	Mean	Standard Deviation	CV	*n*
Pilchuck 01 (urbanized)	0.57	1	1.96	1.13	0.42	0.37	13
Everett 01 (highly urbanized)	0.85	1.6	3.9300	1.94	1.09	0.56	11
Everett 04 (highly urbanized)	0.46	1.4	4.29	1.63	1.00	0.61	13
SR9 01 (rural)	0.61	1.2	3.06	1.46	0.79	0.54	14
Pines 01 (urbanized)	0.69	0.96	3.57	1.55	1.37	0.88	4

3.1.4.3 METALS

Metals in highway runoff pose a significant effect on aquatic life [58] [62]. Heavy metals can degrade water quality and harm aquatic organisms by interfering with photosynthesis, respiration, growth, and reproduction [63] [61]. In highway runoff, metals are either particle-bound or dissolved [58]. Particle-bound metals are adhered to suspended solids that are eventually conveyed to downstream ecosystems [58]. Dissolved metals have higher bioavailability, thus a stronger impact on aquatic ecosystems; however particulate-bound metals may still influence aquatic life [58]. Significant metals considered in the WSDOT stormwater monitoring program include Copper (Cu), Zinc (Zn), and Lead (Pb). The EMCs in highway runoff of Cu, Zn, and Pb are shown in Tables 3.5, 3.6 and 3.7, respectively.

Table 3.5 EMCs (ug/L) of Cu in WSDOT stormwater monitoring program [58]

Total Recoverable Copper (µg/L)							
Highway Monitoring	**Minimum**	**Median**	**Maximum**	**Mean**	**Standard Deviation**	**CV**	***n***
Pilchuck 01 (urbanized)	11.4	22.4	36.1	23.29	6.97	0.30	11
Everett 01 (highly urbanized)	21.7	38.6	51.8	38.48	11.49	0.30	9
Everett 04 (highly urbanized)	19.6	33.1	64.8	37.85	16.77	0.44	10
SR9 01 (rural)	9.43	16.6	26.1	16.38	4.55	0.28	11
Pines 01 (urbanized)	18.6	22.35	37.2	24.68	6.73	0.27	6
Dissolved Copper (µg/L)							
Highway Monitoring	**Minimum**	**Median**	**Maximum**	**Mean**	**Standard Deviation**	**CV**	***n***
Pilchuck 01 (urbanized)	3.99	6.3	9.9	6.48	1.85	0.29	11
Everett 01 (highly urbanized)	6.05	12.7	38.9	17.19	10.22	0.59	9
Everett 04 (highly urbanized)	5.48	12.0	37.5	15.14	10.27	0.68	10
SR9 01 (rural)	1.4	5.11	7.62	4.87	2.14	0.44	10
Pines 01 (urbanized)	8.8	10.8	15.8	11.11	2.78	0.25	5

Table 3.6 EMCs (ug/L) of Zn in WSDOT stormwater monitoring program [58]

Total Recoverable Zinc (µg/L)							
Monitoring Site	**Minimum**	**Median**	**Maximum**	**Mean**	**Standard Deviation**	**CV**	***n***
Pilchuck 01 (urbanized)	56	98.8	130	97.30	27.82	0.29	11
Everett 01 (highly urbanized)	64.5	92.9	215	115.73	52.77	0.46	9
Everett 04 (highly urbanized)	84.3	169	257	165.63	52.89	0.32	10
SR9 01 (rural)	37.3	58.1	133	66.61	27.39	0.41	11
Pines 01 (urbanized)	79.3	99.15	192	110.20	42.14	0.38	6
Dissolved Zinc (µg/L)							
Monitoring Site	**Minimum**	**Median**	**Maximum**	**Mean**	**Standard Deviation**	**CV**	***n***
Pilchuck 01 (urbanized)	14.9	19.6 H	32.1	20.06	5.32	0.27	11
Everett 01 (highly urbanized)	27.7	40.5	82.5	50.17	20.81	0.41	9
Everett 04 (highly urbanized)	40.6[1]	83.3	94.9	77.29	16.79	0.22	9
SR9 01 (rural)	17.1	24.6	34	24.15	4.72	0.20	10
Pines 01 (urbanized)[2]	15.7	31.3	42.6	30.48	11.39	0.37	5

Table 3.7 EMCs (ug/L) of Pb in WSDOT stormwater monitoring program [58]

Total Recoverable Lead (μg/L)

Monitoring Site	Minimum	Median	Maximum	Mean	Standard Deviation	CV	*n*
Pilchuck 01 (urbanized)	35.4	35.4	35.4	NA	NA	NA	1
Everett 01 (highly urbanized)	3.05	5.94	8.83	5.94	4.09	0.69	2
Everett 04 (highly urbanized)	4.17	5.77	7.36	5.77	2.26	0.39	2
SR9 01 (rural)	1.92	3.98	7.64	4.67	2.34	0.50	7
Pines 01 (urbanized)	3.97	5.92	12.1	6.74	3.01	0.45	6

Dissolved Lead (μg/L)

Monitoring Site	Minimum	Median	Maximum	Mean	Standard Deviation	CV	*n*
Pilchuck 01 (urbanized)	0.665	0.665	0.665	NA	NA	NA	1
Everett 01 (highly urbanized)	0.12	0.176	0.232	0.176	0.079	0.45	2
Everett 04 (highly urbanized)	0.156	0.193	0.23	0.193	0.052	0.27	2
SR9 01 (rural)	0.085	0.12	0.136	0.115	0.020	0.17	6
Pines 01 (urbanized)	0.1	0.28	0.55	0.30	0.18	0.60	5

3.1.5 BEST MANAGEMENT PRACTICES

Best management practices (BMPs) are measures of controlling water pollution. BMPs are designed to treat precipitation where it falls, providing a suitable control mechanism for highway runoff pollution [64]. Runoff pollution control by BMPs is achieved through three mechanisms. Volume control reduces the volume of stormwater discharged to the environment [64]. Peak discharge control reduces the flow rate of runoff, lengthening the time surface water spends in a system before being discharged [64]. Water quality control improves the quality of runoff emitted through soil infiltration, filtering, and biological processes [64]. WSDOT employs BMPs to reduce highway runoff pollution in certain areas.

3.1.6 VEGETATED FILTER STRIPS

VFSs are a BMP that can treat highway runoff pollution [28]. A VFS can be described as a slightly sloped strip of land that houses vegetation, such as grass or trees [27]. VFSs can be strategically placed as roadside embankments to treat highway runoff [27]. As runoff passes through a VFS its velocity is reduced, allowing sediments and other suspended solids to filter out, encouraging biological uptake, and permitting time for infiltration to underlying soils [27].

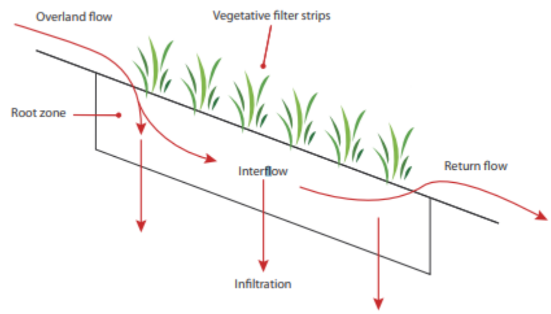


Figure 3.1 VFS design [39]

VFS performance in pollution reduction has been well studied, however the constituent removal rate of a VFS is highly dependent on the VFS design and site-specific variables. A properly functioning VFS can effectively remove 35-60% of TSS, 60-65% of phosphorus, and 30-45% of nitrogen [28]. Alternatively, the Federal Highway Administration recorded VFS pollutant removal effectiveness as 70% TSS, 10% TP, 30% TKN, and 40-50% metal reductions [65]. The International Stormwater BMP Database has extensive archives on BMP performance in the USA and has compiled data on the constituent removal rate for many VFSs. Figure 3.2 shows constituent EMCs in stormwater runoff before and after VFS treatment, this data was extracted from the International Stormwater BMP Database [66].

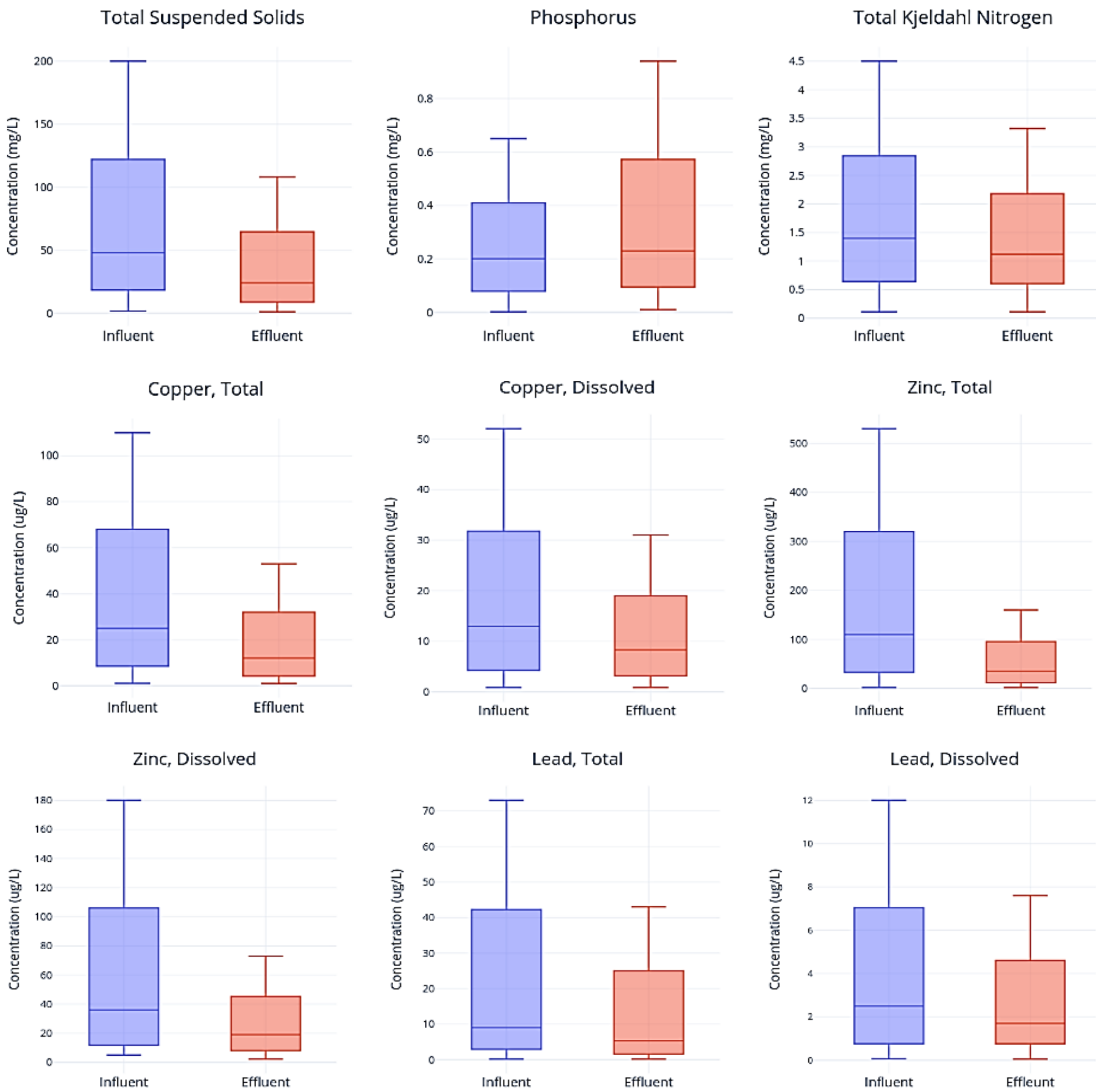


Figure 3.2 EMC of stormwater runoff constituents before and after treatment with VFS [66]

3.2 Objective

The objective of this research is to assess the efficacy of highway runoff pollution reduction through strategic design and management of roadside vegetation in the form of VFSs.

3.3 Methods

The annual storm load coming off highways and the annual storm load coming off highways with VFS retrofits must be determined. An annual storm load was defined as the mass of constituents emitted through stormwater runoff in one year. In this analysis the annual storm load was calculated through the average EMCs of constituents in highway runoff and volume of runoff emitted from highways in Western Washington. The volume of runoff emitted from major roadways in Western Washington was calculated by multiplying the surface area of the roadways by the average annual rainfall. The potential VFS sites were mapped in Section 2, this map data was coupled with Western Washington roadway data to determine which roadways can be retrofitted with VFSs, under the assumption that all potential VFS sites derived in Section 2 were retrofitted with VFSs. Finally, VFS removal efficiencies were applied to determine the annual storm load of highways in Western Washington with implemented roadside VFSs. The annual storm load of roadway areas with VFS retrofits was compared to the current annual storm load of roadway areas (without VFS retrofits) to assess the efficacy of roadside VFS implementation on highways in Western Washington.

3.3.1 Highway Runoff Pollution Concentration

The first step in this analysis was to establish a baseline highway runoff pollutant EMC, or highway runoff pollution concentration, for pollutants of interest. This data was extracted from the WSDOT Highway Runoff Characterization Report [58]. As shown in Tables 3.2-3.7 WSDOT reports the average EMCs for each constituent in two highly urbanized, one urbanized, and one rural roadside monitoring site in Western Washington and one urbanized roadside monitoring site in Eastern Washington. In this analysis, the data was adapted to conform to two categories of interest, which are urban and rural roadside sites in Western Washington. To adapt the WSDOT stormwater monitoring data into these two categories, the eastern Washington site was omitted, and the two highly urbanized sites were reclassified as urbanized sites. This data manipulation resulted in the EMC of constituents in urban and rural settings from three averaged urban sites and one rural site in Western Washington. The highway runoff pollution concentration is summarized in Table 3.8. This environmental impact analysis will operate under the assumption that urban and rural roadways in Western Washington will emit the same highway runoff pollutant concentration as described in Table 3.8.

Table 3.8 Average highway runoff EMCs from urban and rural roadways, adapted from WSDOT Highway Runoff Characterization Report [58]

Roadway Class	TSS (mg/L)	TP (mg/L)	TKN (mg/L)	Cu, Total (ug/L)	Cu, Dissolved (ug/L)	Zn, Total (ug/L)	Zn, Dissolved (ug/L)	Pb, Total (ug/L)	Pb, Dissolved (ug/L)
Urban	61.25	0.12	1.57	33.21	12.94	126.22	14.31	5.86	0.18
Rural	61.50	0.08	1.46	16.38	4.87	66.61	4.72	4.67	0.12

3.3.2 VFS REMOVAL EFFICIENCY

To determine the potential highway runoff pollution reduction though roadside VFS implementation, the VFS pollution removal rate must be known. This data was derived from the International Stormwater BMP database and other literature sources. In Table 3.9, the VFS removal rate for each constituent is shown from four separate literature sources. The final row in Table 3.9 is the assumed VFS removal rate for this analysis.

Table 3.9 VFS pollutant removal rates from literature

Source	TSS (mg/L)	TP (mg/L)	TKN (mg/L)	Cu, Total (ug/L)	Cu, Dissolved (ug/L)	Zn, Total (ug/L)	Zn, Dissolved (ug/L)	Pb, Total (ug/L)	Pb, Dissolved (ug/L)
[66]	50%	-14%	20%	52%	36%	68%	47%	41%	32%
[28]	35-60%	60-65%	30-45%	NA	NA	NA	NA	NA	NA
[65]	70%	10%	30%	40-50%	NA	40-50%		40-50%	NA
[67]	50%	20%	20%	40%	40%	40%	40%	40%	40%
VFS Performance	**50%**	**20%**	**20%**	**50%**	**36%**	**50%**	**40%**	**40%**	**30%**

3.3.3 GEOGRAPHIC INFORMATION SYSTEMS

GIS was utilized to determine the total roadway area of highways and the roadway area of highways with retrofitted VFSs in Western Washington. This analysis was performed through map data collection, geographic region construction, roadway area construction, urban and rural roadway designation, sensitive aquatic area designation, and VFS roadway coverage assessment.

3.3.3.1 MAP DATA COLLECTION

Map data was collected to provide the necessary geographical data for this analysis. The maps used in this analysis originate from reputable GIS sources and were as current as possible. Table 3.10 summarizes the map data used in this analysis.

Table 3.10 Map data used in environmental impact assessment

	**Washington County Map** [38] Washington County Boundaries Source: WA Department of Natural Resources Year: 2018 Data Type: Shapefile feature class Geometry: Polygon
	**Washington State Major Routes Map** [40] State Routes of Washington State 1:24,000 Source: WSDOT Year: 2019 Data Type: Shapefile Feature Class Geometry: Line
	**Washington State Lanes Map** [40] Washington State Lane Data Source: WSDOT Year: 2014 Data Type: Shapefile Feature Class Geometry: Line
	**Urban – Rural Road Designation Map** [40] Urban – Rural Road Classification Source: WSDOT Year: 2014 Data Type: Shapefile Feature Class Geometry: Line
	**Sensitive Aquatic Areas Map** [40] Roads by Sensitive Aquatic Areas Source: WSDOT Year: 2014 Data Type: Shapefile Feature Class Geometry: Line

	**VFS Sites Map** Potential VFS Sites in Western Washington Source: Hisham El-Husseini Year: 2019 Data Type: Shapefile Feature Class Geometry: Polygon

3.3.3.2 GEOGRAPHIC REGION CONSTRUCTION

The geographic region construction operation was performed to establish geographic specificity to Western Washington. Figure 3.3 shows two examples of conforming map data to fit Western Washington.

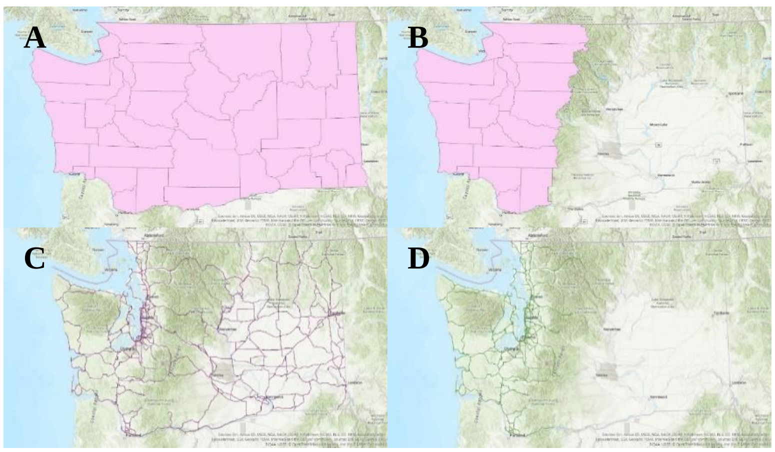


Figure 3.3 Geographic region construction of Western Washington

The geographic region construction is shown in Figure 3.3, which begins with the Washington County Map in Figure 3.3.A. The Washington County Map underwent a selection process to select counties that are in Western Washington. The result of the selection process is isolation of the counties in Western Washington, which is shown in Figure 3.3.B. The rest of the maps described in the map data collection section underwent a clipping process to conform them to the Western Washington Map (Figure 3.3.B). An example of this operation is shown in Figure 3.3 as Figure 3.3.C is clipped to produce Figure 3.3.D.

3.3.3.3 ROADWAY MAP CONSTRUCTION

The roadway map is an essential piece of data because the roadway area of highways in Western Washington were multiplied by the annual rainfall in Western Washington to calculate the total volume of runoff emitted from highways. After searching through GIS databases, it was concluded that there is no map that had roadway area data, therefore, a roadway map was constructed for this analysis. Construction of the roadway map began with the Washington State Lanes Map, from the WSDOT GIS database. The lanes map is a line shapefile that represent highways, the highway lines carry data for roadway widths, which were buffered to produce a polygon shapefile of the roadway areas. The roadway map construction operation is shown in Figure 3.4.

Figure 3.4 Roadway map construction to determine roadway area

The map in Figure 3.4.A represents the Washington State Lanes Map. The Washington State Lanes Map had a line geometry type; however, it is necessary to derive a surface area of major roadways in Western Washington for this analysis. The Washington State Lanes Map had data embedded within each line that described the number of lanes on the given road line and their associated widths. A buffer was applied to Washington State Lanes Map in Figure 3.4.A to extrapolate polygon shapes from the lines. The buffer was applied as a function of the number of lanes and their associated widths to achieve this extrapolation. The result of the buffered Washington State Lanes Map is a Roadway Area Map of Western Washington, which is shown in Figure 3.4.B.

3.3.3.3.1 URBAN AND RURAL ROADWAY DESIGNATION

Urban and rural roadways possess different pollutant concentrations in highway runoff due to variations in roadway operations [58]. To reflect the varied pollutant concentration in this analysis an Urban-Rural Road Designation Map, from the WSDOT GIS Database, was used to designate urban and rural surroundings of roadways. Figure 3.5 shows the urban and rural roadway designation operation

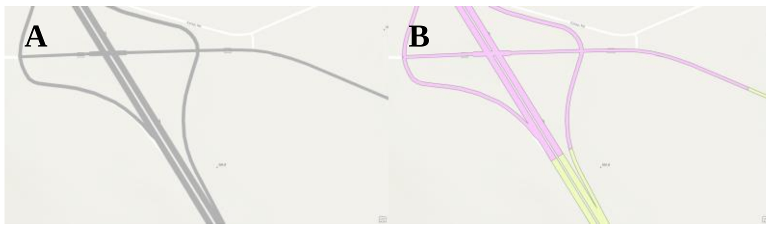


Figure 3.5 Urban and rural roadway designation operation

The urban-rural roadway classification operation began with the Roadway Area Map in Figure 3.5.A, which was produced in the roadway map construction section. The Roadway Area Map was overlaid on the Urban-Rural Road Designation Map. A select-by-location function was applied to the overlaid maps to define roadway area fragments in the Roadway Area Map by their urban-rural classifications. Following the select-by-location function, an extraction was performed to generate a new roadway map layer that inherits the urban-rural definition of road fragments in the Urban-Rural Road Designation Map. For example, if a road was classified as an urban road in the Urban-Rural Road Designation Map, the roadway polygon on top of this road in the Roadway Area Map inherited an urban designation. The product map is an Urban-Rural Classified Roadway Area Map, which is shown in Figure 3.5.B. In Figure 3.5.B, the roadway areas highlighted in pink represent urban roadways, and the roadways highlighted in light green represent rural roadways.

3.3.3.3.2 Sensitive Aquatic Area Designation

In this analysis it was important to determine if roadways retrofitted with VFSs are placed in suitable locations. To understand where suitable roadway locations are, this analysis refers to the Sensitive Aquatic Areas Map, provided by WSDOT. Pollution reduction in sensitive areas is more meaningful, thus it is an integral part of this analysis. The Sensitive Aquatic Areas map was a line shapefile that designates major roads with an aquatic sensitivity classification. Roads in this shapefile are classified as high sensitivity, medium sensitivity, and low sensitivity; unclassified roads are assumed to be in non-sensitive aquatic areas. The sensitive aquatic area designation process is shown in Figure 3.6.

Figure 3.6 Sensitive aquatic area designation operation

The Sensitive Aquatic Areas Map was overlaid with the Roadway Area Map to identify roadway areas that are in sensitive aquatic areas. A select-by-location function was applied to the overlaid maps to define roadway polygons in the Roadway Area Map according to their aquatic sensitivity. An extraction followed by the select-by-location function generated a new roadway map layer that inherited the aquatic sensitivity characteristics from the Sensitive Aquatic Areas Map. This procedure resulted in roadway polygons in the Roadway Area Map that contain definitions for their given aquatic sensitivity classification, this new map is called the Aquatic Sensitivity Classified Roadway Area Map. The map in Figure 3.6.A shows the Roadway Area Map overlaid on the Sensitive Aquatic Areas Map. The product, Aquatic Sensitivity Classified Roadway Areas Map, is shown in Figure 3.6.B. In Figure 3.6.B, the roadway areas highlighted red are in high sensitivity aquatic areas, the roadways highlighted orange are in medium sensitivity aquatic areas, the roadways highlighted yellow are in low sensitivity aquatic areas, and the unhighlighted roadways are not in sensitive aquatic areas.

3.3.3.4 VFS Coverage

Pollution reduction can only occur on roadways that were retrofitted with VFSs. This operation used the VFS Site Map and the Roadway Area Map to identify roadway polygons that were eligible for pollution reduction through VFS implementation. This analysis assumed that roadway polygons that are adjacent to VFS sites are eligible for pollution reduction and that any runoff emitted from these roadway fragments would undergo treatment through the adjacent VFS. Roadway polygons within 100 feet of VFS sites were selected through a select-by-location function to determine the roadways that were adjacent to VFS sites. The selected polygons were extracted to produce a new map layer; the new map layer is called VFS Covered Roadway Areas Map. Figure 3.7.A shows the Roadway Area Map overlaid with the VFS Site Map. In Figure 3.7.A, the gray polygon depicts the roadway area and the green polygons depict VFS sites. Figure 3.7.B shows the VFS Covered Roadway Areas Map, which was extracted so that only roadway polygons within 100 feet of a VFS are present in the map layer. The roadway polygons within 100 ft of a VFS are depicted by the light blue polygons and the VFS sites are shown in green, which remain from the VFS Site Map.

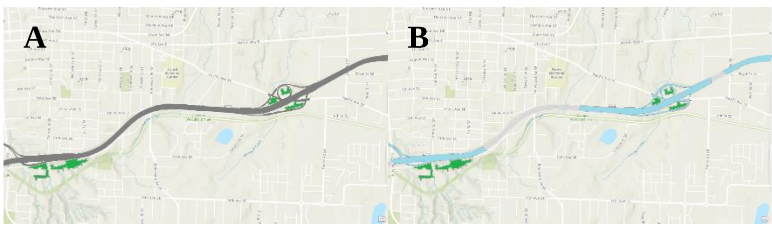


Figure 3.7 Identifying roadways with VFS coverage (roads within 100 ft of a VFS)

3.3.4 ANNUAL STORM LOAD

The final step in this analysis was to calculate the current annual storm load and VFS retrofitted annual storm load from highways in Western Washington. This was achieved by processing the maps generated in the previous sections, which include the Urban-Rural Classified Roadway Area Map, Aquatic Sensitivity Classified Roadway Area Map, and VFS Covered Roadway Map. The three maps were overlaid on top of each other and underwent a selection process to determine the areas of specified categories. For example, a selection process could select for urban roads in highly sensitive aquatic areas that were adjacent to VFS sites. This selection process output the total area of urban roads in highly sensitive aquatic areas that were adjacent to VFS sites in Western Washington. Likewise, this selection process could determine the total roadway area for rural roads that were in non-sensitive aquatic areas in Western Washington. This selection process was performed with such combinations to determine the total area of each category in Western Washington. These categories are shown in the diagram in Figure 3.8.

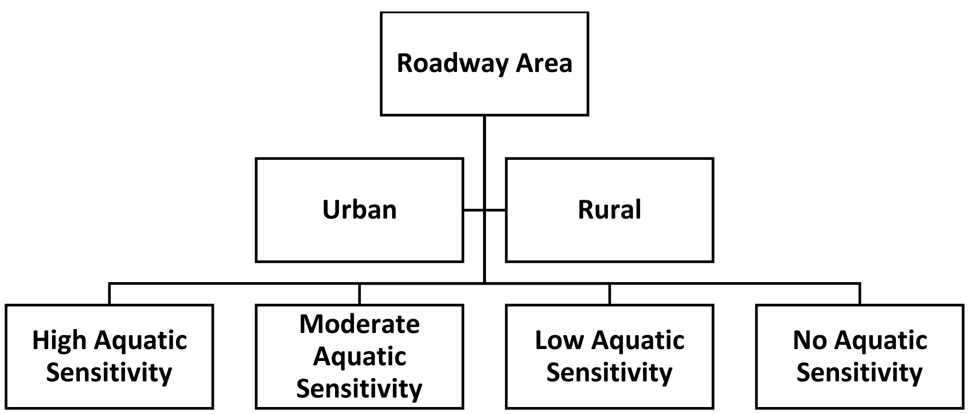


Figure 3.8 Roadway area classifications.

Once the area of each category described in Figure 3.8 was determined, the annual runoff volume emitted from highways could be calculated. The annual runoff volume emitted from highways was calculated by multiplying the classified roadway areas by the average rainfall in

Western Washington, 66.03 inches [68]. Next, the volume of highway runoff was multiplied by the average EMC of constituents in highway runoff, respective to urban and rural areas. This calculation produced the current annual storm load from highways in Western Washington; this equation is shown in Equation 3.1 and the calculation is shown in Table 3.10. In Table 3.10, the area of each classified roadway was multiplied by the average annual rainfall in Western Washington to produce a volume (ft^3). The average EMCs of constituents were given as concentrations (g/ft^3), which were multiplied by the volume of rainfall emitted from major roads in Western Washington to obtain the annual storm load for each roadway classification.

$$Storm\ Load = (EMC) * (Average\ Annual\ Rainfall) * (Roadway\ Surface\ Area)$$

Equation 3.1 Calculating annual storm load

Table 3.10 Calculating annual storm load from EMCs, roadway areas, and annual rainfall

Roadway Classification	Sensetive Aquatic Area Designation	Area (ft^2)	Average Rain (ft/year)	TSS (g/ft³)	TP (g/ft³)	TKN (g/ft³)	Cu, Total (g/ft³)	Cu, Dissolved (g/ft³)	Zn, Total (g/ft³)	Zn, Dissolved (g/ft³)	Pb, Total (g/ft³)	Pb, Dissolved (g/ft³)	TSS (kg/year)	TP (kg/year)	TKN (kg/year)	Cu, Total (kg/year)	Cu, Dissolved (kg/year)	Zn, Total (kg/year)	Zn, Dissolved (kg/year)	Pb, Total (kg/year)	Pb, Dissolved (kg/year)
Urban	High	110,000,000	6	1.73	3.32E-03	4.44E-02	9.40E-04	3.66E-04	3.57E-03	4.05E-04	1.66E-04	5.22E-06	1,100,000	2,100	28,000	580	230	2,200	250	100	3.20
	Medium	92,000,000	6	1.73	3.32E-03	4.44E-02	9.40E-04	3.66E-04	3.57E-03	4.05E-04	1.66E-04	5.22E-06	880,000	1,700	22,000	480	190	1,800	210	84	2.60
	Low	30,000,000	6	1.73	3.32E-03	4.44E-02	9.40E-04	3.66E-04	3.57E-03	4.05E-04	1.66E-04	5.22E-06	290,000	550	7,300	160	60	590	67	27	0.86
	None	320,000,000	6	1.73	3.32E-03	4.44E-02	9.40E-04	3.66E-04	3.57E-03	4.05E-04	1.66E-04	5.22E-06	3,100,000	5,900	79,000	1,700	650	6,300	720	290	9.30
Rural	High	110,000,000	6	1.74	2.38E-03	4.13E-02	4.64E-04	1.38E-04	1.89E-03	1.34E-04	1.32E-04	3.26E-06	1,100,000	1,500	25,000	290	85	1,200	82	82	2.00
	Medium	49,000,000	6	1.74	2.38E-03	4.13E-02	4.64E-04	1.38E-04	1.89E-03	1.34E-04	1.32E-04	3.26E-06	470,000	640	11,000	120	37	510	36	35	0.87
	Low	23,000,000	6	1.74	2.38E-03	4.13E-02	4.64E-04	1.38E-04	1.89E-03	1.34E-04	1.32E-04	3.26E-06	220,000	300	5,200	58	17	240	17	17	0.41
	None	170,000,000	6	1.74	2.38E-03	4.13E-02	4.64E-04	1.38E-04	1.89E-03	1.34E-04	1.32E-04	3.26E-06	1,600,000	2,300	39,000	440	130	1,800	130	130	3.10

To determine the VFS retrofitted annual storm load from highways, the VFS covered roadway area was divided by the total roadway area for each roadway classification. This produced a value that corresponded to the percent of roadway that could be treated by VFSs for each roadway classification. Next, the annual storm load for each constituent (kg/year) was multiplied by the VFS Roadway Coverage (%), for each classification, and the associated VFS removal rate (%) for the specified constituent, which was determined in Section 3.3.2. The product of this multiplication was the amount of pollutants removed through VFS sites on major roadways in Western Washington. To obtain the new storm load on roadways in Western Washington with retrofitted VFSs, the amount of pollutants removed through VFS sites was subtracted from the original storm load for each constituent and roadway classification. These operations are performed in Table 3.11 and their respective equations are shown in Equation 3.2 and Equation 3.3.

$$Pollutants\ Removed\ by\ VFS = (EMC) * (Average\ Annual\ Rainfall) * (VFS\ Roadway\ Coverage) * (VFS\ Removal\ Rate)$$

Equation 3.2 Calculating annual pollution removal by VFSs

$$Storm\ Load\ with\ VFS\ Retrofits = Storm\ Load - Pollutants\ Removed\ by\ VFS$$

Equation 3.3 Calculating storm load of major roadways in Western Washington after VFS retrofits

Table 3.11 Calculating the annual storm load on roadways after VFS implementation

	Roadway Classification	Sensetive Aquatic Area Designation	Area (ft^2)	Average Rain (ft/year)	VFS Roadway Coverage (%)	TSS (kg/year)	TP (kg/year)	TKN (kg/year)	Cu, Total (kg/year)	Cu, Dissolved (kg/year)	Zn, Total (kg/year)	Zn, Dissolved (kg/year)	Pb, Total (kg/year)	Pb, Dissolved (kg/year)
Annual Storm Load Before VFS Implementation	Urban	High	110,000,000	5.5	52%	1,100,000	2,100	28,000	580	230	2,200	250	100	3
		Medium	92,000,000	5.5	42%	880,000	1,700	22,000	480	190	1,800	210	84	3
		Low	30,000,000	5.5	45%	290,000	550	7,300	160	60	590	67	27	1
		None	320,000,000	5.5	35%	3,100,000	5,900	79,000	1,700	650	6,300	720	290	9
	Rural	High	110,000,000	5.5	76%	1,100,000	1,500	25,000	290	85	1,200	82	82	2
		Medium	49,000,000	5.5	73%	470,000	640	11,000	120	37	510	36	35	1
		Low	23,000,000	5.5	63%	220,000	300	5,200	58	17	240	17	17	0
		None	170,000,000	5.5	70%	1,600,000	2,300	39,000	440	130	1,800	130	130	3
	Total		910,000,000	5.5	52%	8,700,000	15,000	220,000	3,800	1,400	15,000	1,500	770	22
VFS Removal Rate						50%	20%	20%	50%	36%	50%	40%	40%	30%
Annual Storm Load After VFS Implementation	Urban	High	110,000,000	5.5	52%	800,000	1,800	25,000	430	190	1,600	200	82	3
		Medium	92,000,000	5.5	42%	690,000	1,500	21,000	380	160	1,400	170	70	2
		Low	30,000,000	5.5	45%	220,000	500	6,700	120	51	460	55	22	1
		None	320,000,000	5.5	35%	2,500,000	5,500	73,000	1,400	570	5,200	620	250	8
	Rural	High	110,000,000	5.5	76%	660,000	1,200	22,000	180	62	720	57	57	2
		Medium	49,000,000	5.5	73%	300,000	550	9,500	79	27	320	25	25	1
		Low	23,000,000	5.5	63%	150,000	260	4,500	40	13	160	13	12	0
		None	170,000,000	5.5	70%	1,100,000	1,900	34,000	290	98	1,200	91	90	2
	Total		910,000,000	5.5	52%	6,400,000	13,000	190,000	2,900	1,200	11,000	1,200	610	19

3.4 RESULTS & DISCUSSION

The results provided by this environmental impact assessment include the total area of major highways in Western Washington, with their accompanying VFS coverage, and the contaminant reduction in highway runoff through VFS implementation. Figure 3.9 shows the area of major roadways in Western Washington according to their sensitive aquatic area classification. Western Washington roadways are fragmented into urban and rural classifications, then into their aquatic sensitivity classification. These categories are represented on the x-axis of Figure 3.9. The y-axis of Figure 3.9 represents the area of roadway for each designation in the x-axis. Each category in the x-axis possesses two data points. The first data point is the total area of roadway for the given category. The second data point is the area of roadway in that category that can be retrofitted with VFSs. Roadways in highly sensitive aquatic areas are of utmost significance in this analysis because they bear the largest environmental impact. As seen in Figure 3.9, nearly half of the urban roadway area classified as highly sensitive can be retrofitted with VFSs and almost three quarters of rural roadways classified as highly sensitive can be retrofitted with VFSs.

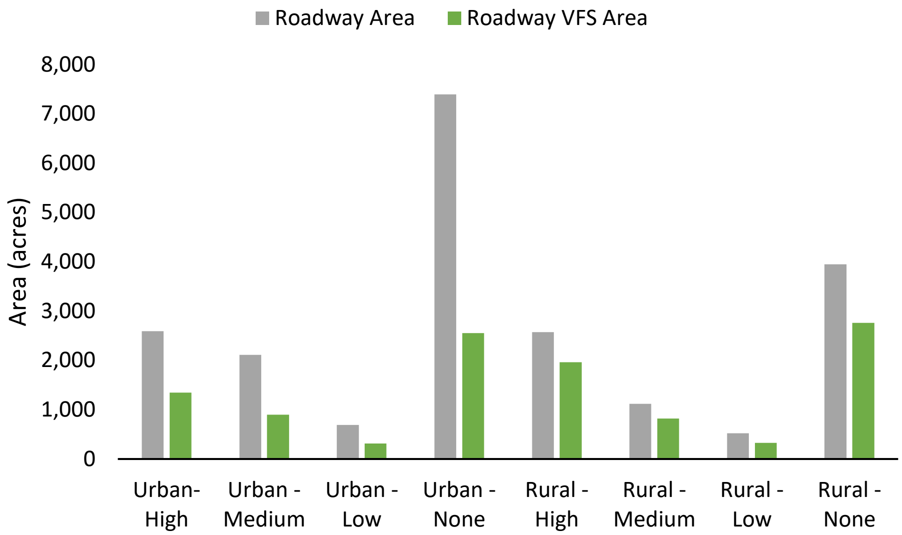


Figure 3.9 Classified roadway area and associated VFS coverage

Figure 3.10 focuses on the total pollution reduction through VFS implementation on roadsides in Western Washington. In Figure 3.10, the annual storm loads are shown for TSS, Phosphorus, Nitrogen, Copper, Zinc, and Lead. Figure 3.10 shows the current storm load for each of these contaminants and the resultant storm load for the contaminants if VFSs were retrofitted on each available site. As shown in Figure 3.10, a significant amount of pollution emitted from major roadways in Western Washington can be reduced. Specifically, around 26% of TSS, 13% of TP, 13% of TKN, 23% of total Cu, 14% of dissolved Cu, 26% of total Zn, 20% of dissolved Zn, 20% of total Pb, and 13% of dissolved Pb can be removed from highway runoff before it is discharged to receiving waters.

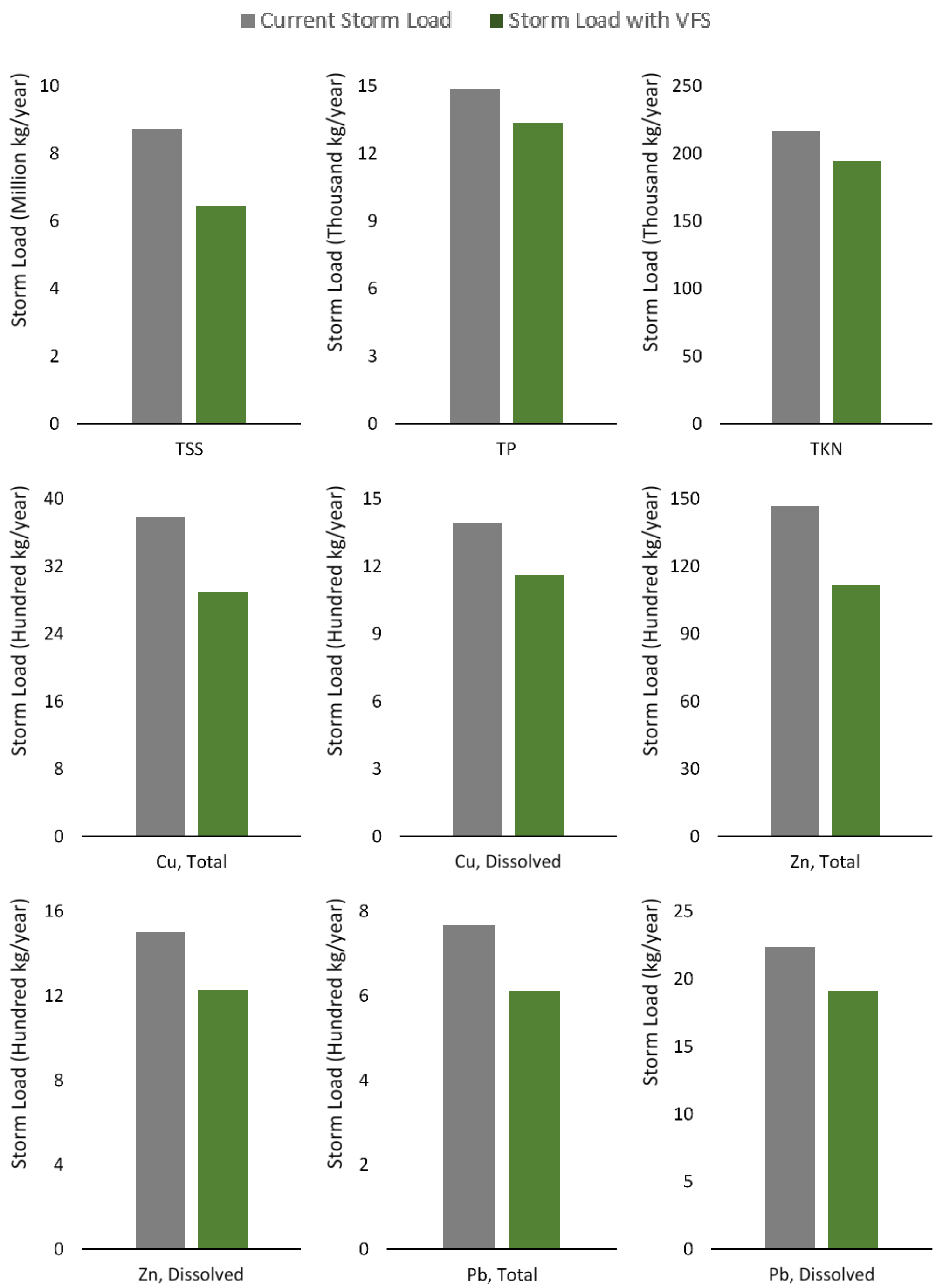


Figure 3.10 Current annual storm load and VFS retrofitted storm load from highways in Western Washington

Figure 3.11 shows the contaminant reduction through VFS implementation on urban highway roadsides in Western Washington. Contaminant reduction is shown for each aquatic sensitivity designation (High, Medium, Low, None). As an example, 25% of TSS, copper, and zinc, 20% of phosphorus and nitrogen, and 20% of lead discharges can be reduced from urban roadways in highly sensitive aquatic areas.

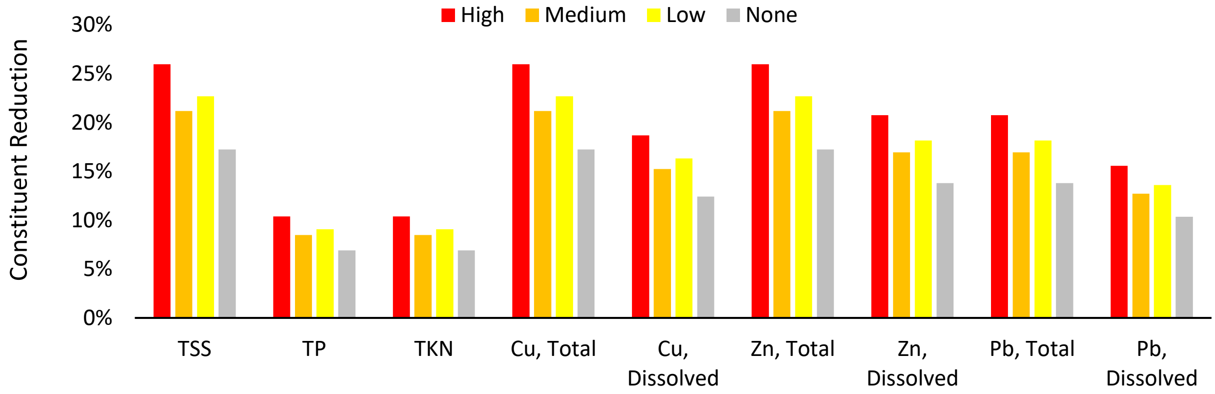


Figure 3.11 Constituent reduction in sensitive aquatic urban areas

Figure 3.12 is similar to Figure 3.11; however, the data reflects rural roadways in Western Washington. From Figure 3.12, nearly 40% of TSS, copper, and zinc, 15% of phosphorus and nitrogen, and 30% of lead discharges can be reduced from rural roadways in highly sensitive aquatic areas.

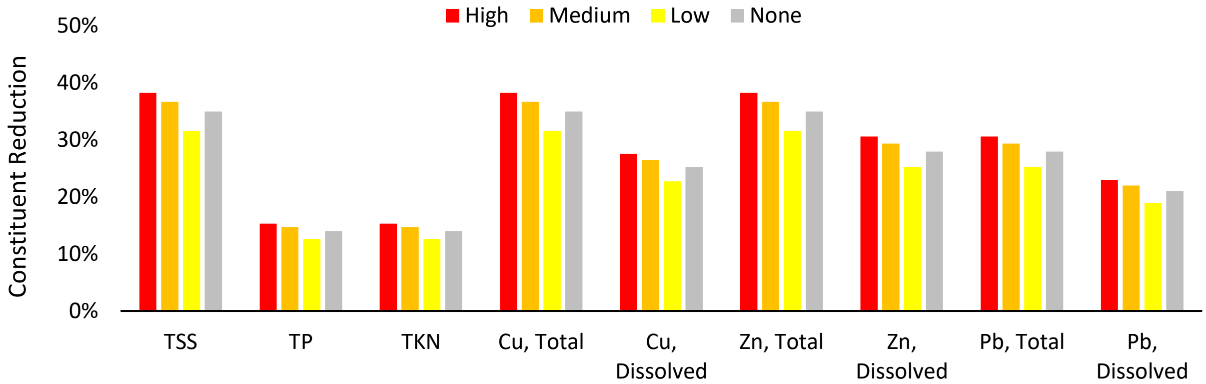


Figure 3.12 Constituent reduction in sensitive aquatic rural areas

3.5 CONCLUSION & RECOMMENDATIONS

Implementing roadside VFSs in Western Washington can reduce highway runoff pollution. Roadways are a significant contributor to non-point source pollution. The ecological implications of contaminants in roadway runoff are little understood; yet, significant amounts of pollutants are entering the environment through this vector. This analysis has shown that retrofitting VFSs on available roadside locations in Western Washington can reduce the amount of pollutants discharged to the environment through highway runoff. Specifically, around 2 million kg/year of TSS, nearly 2000 kg/year of TP, 22,000 kg/year of TKN, 1000 kg/year of total Cu, 200 kg/year of dissolved Cu, 3500 kg/year of total Zn, 300 kg/year of dissolved Zn, 150 kg/year of total Pb, and 3 kg/year of dissolved Pb can be removed from highway runoff before it is discharged to receiving waters. In terms of highway runoff pollution in highly sensitive aquatic urban areas, VFS retrofits can significantly reduce contaminant emissions. TSS, total Cu, and total Zn emissions can be reduced by 25%. TP and TN emissions can be reduced by 10%. Dissolved Cu, dissolved Zn, and total Pb can be reduced by nearly 20%. And dissolved Pb emissions can be reduced by 15%. In terms of highway runoff pollution in highly sensitive aquatic rural areas, VFSs can also significantly reduce highway runoff pollution emissions. Specifically, TSS, total Cu, and total Zn emissions can be reduced by nearly 40%. TP and TKN emissions can be reduced by 15%. Dissolved Cu, dissolved Zn, and total Pb emissions can be reduced by nearly 30%. And dissolved Pb emissions can be reduced by 20%. Highway runoff pollution needs to be addressed and roadside VFSs provide a low-cost solution to highway runoff pollution reduction. Roadside VFSs provide a promising solution to reducing highway runoff pollution in Western Washington.

4 TECHNO-ECONOMIC ANALYSIS OF CELLULOSIC ETHANOL BIOREFINERY

4.1 BACKGROUND

This analysis evaluated the economics of constructing a cellulosic ethanol biorefinery in Western Washington. The biorefinery will convert biomass to ethanol in a process designed by the National Renewable Energy Laboratory (NREL) that was modified to process hybrid poplar [69]. Here, a case study was performed to optimize the profitability of the biorefinery. The evaluated cases were based on a biorefinery, located in Centralia, Washington, processing 250,000 ODT of hybrid poplar, annually. The base case in this evaluation was a biorefinery processing poplar grown on dedicated pastureland, referred as the dedicated poplar, stand-alone biorefinery. The second case was a biorefinery processing poplar from mixed sources; including sawmill residuals, poplar grown for ecosystem services, and dedicated poplar, this case is referred as the mixed poplar, stand-alone biorefinery. The third case was based on a biorefinery that is co-located with a powerplant and processes dedicated poplar, referred as the dedicated poplar, integrated biorefinery. The final case was a biorefinery that processes poplar from mixed sources and is co-located with a powerplant, this biorefinery is referred as the mixed poplar, integrated biorefinery. The following sections will discuss the biorefinery process design.

4.1.1 NREL BIOREFINERY OVERVIEW

The cellulosic ethanol production process in this techno-economic analysis was adapted from the NREL "Process Design and Economics for Biochemical Conversion of Lignocellulosic Biomass to Ethanol" report published in 2011 [69]. In NREL's model, corn stover was converted to ethanol through dilute-acid pretreatment, enzymatic hydrolysis, and fermentation [69]. The process design is shown in Figure 4.1 and the following sections will discuss the unit-operations of the process.

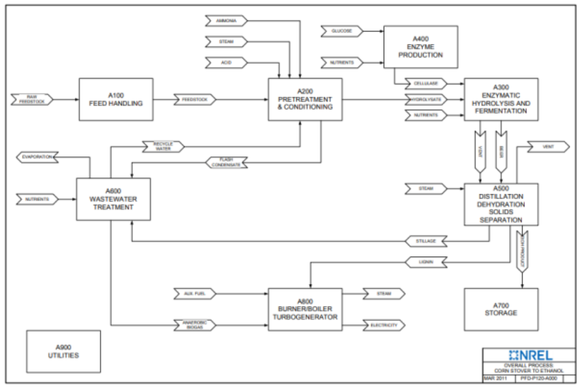


Figure 4.1 Process overview diagram [69]

4.1.1.1 FEED HANDLING

Feed handling is the first unit-operation in this bioconversion. The purpose of feed handling is to receive incoming biomass [69]. Corn stover is the feedstock in this bioconversion. In this process design, feedstock is delivered to a central supply depot that preprocesses the biomass to assure homogeneity in particle size distribution, moisture content, and bulk density [69]. From the supply depot, the preprocessed corn stover is delivered to the biorefinery by truck. At the biorefinery, minimal storage and handling of the feedstock is needed [69]. The biomass is then conveyed to the pretreatment reactor from the feed handling system [69].

The process flow diagram for feed handling is shown in Figure 4.2. Incoming trucks carrying biomass arrive at weighing and unloading stations [69]. Conveyers transport the biomass to a concrete storage dome for short-term storage [69]. Then biomass is stored in queue for conveyance to the pretreatment reactor [69].

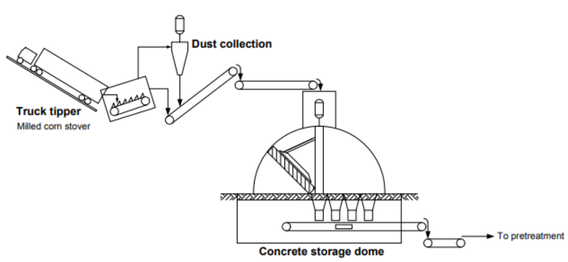


Figure 4.2 Feed handling diagram [69]

4.1.1.2 PRETREATMENT AND CONDITIONING

The pretreatment and conditioning unit-operation prepares the biomass for enzymatic hydrolysis [69]. Biomass is treated with sulfuric acid catalyst and heat to liberate hemicellulose and disrupt the plant cell wall structure [69]. Hemicellulose is released from the lignocellulosic complex, solubilized, and degraded to monomeric sugars. The plant cell wall is disrupted through partial lignin solubilization and reduction of cellulose crystallinity and chain length [69]. Degradation products that are toxic to fermentation, such as acetic acid and furfurals, can form if the pretreatment severity is too high [69]. After the biomass is pretreated, ammonia is added to the slurry to increase the pH for optimal enzymatic hydrolysis conditions [69].

The pretreatment reaction occurs in two stages. In the first stage of pretreatment, biomass is treated in a horizontal screw-feed reactor with higher severity and a lower residence time [69]. In this stage, hemicellulose is liberated; however, the majority of hemicellulose remains in oligomeric form [69]. In the second pretreatment stage, the slurry enters a new pretreatment reactor with lower severity and a longer residence time [69]. Oligomeric hemicellulose is degraded to monomeric sugars in the second pretreatment stage [69]. Low severity in the second pretreatment reactor reduces the probability of toxic degradation product generation [69]. After both pretreatment stages, the slurry is flash cooled, which vaporizes some water, acetic acid, and furfural [69]. Flash vapor is condensed and directed to wastewater treatment [69]. The hydrolysate slurry is cooled by dilution water and enters the conditioning reactor [69]. In the conditioning reactor, ammonia is added to raise the pH of the hydrolysate slurry [69]. The pretreatment and conditioning unit-operation is shown in Figure 4.3.

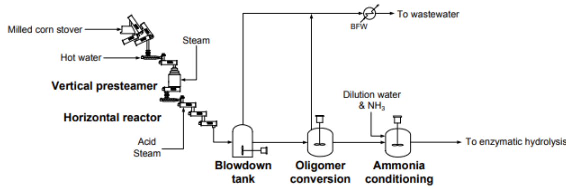


Figure 4.3 Pretreatment and conditioning diagram [69]

4.1.1.3 ENZYMATIC HYDROLYSIS AND FERMENTATION

Enzymatic hydrolysis is biological reactions that convert the hydrolysate slurry to monomeric sugars for conversion to ethanol. After pretreatment, most of the sugars in the hemicellulose should be in monomeric from; however, the cellulose is still intact and in solid form, which must be broken down to liberate the glucose monomers. Enzymatic hydrolysis catalyzes the hydrolysis of cellulose to glucose with cellulase enzymes. Once the cellulose in the hydrolysate slurry has been converted to glucose it can be fermented by an ethanologen, along with other sugars from the hemicellulose [69]. The ethanologen that carries out the fermentation of sugar to ethanol is *Zymomonas Mobilis,* which can consume both xylose and glucose [69].

The slurry from pretreatment and conditioning is directed to a continuous high-solids reactor inoculated with cellulase to begin enzymatic hydrolysis [69]. Over the course of enzymatic hydrolysis, the cellulosic solids are saccharified, reducing the viscosity of the slurry and allowing it to be pumped to a parallel bioreactor [69]. Enzymatic hydrolysis is concluded in the bioreactor, then the ethanologen is inoculated in the mixture [69]. After inoculation, fermentation to ethanol ensues in the bioreactor. Once fermentation is complete, the beer is transferred to a storage tank prior to distillation [69].

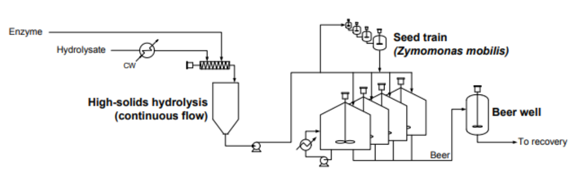


Figure 4.4 Enzymatic hydrolysis and fermentation diagram [69]

4.1.1.4 Cellulase Enzyme Production

Cellulase enzymes for enzymatic hydrolysis are produced in the cellulase enzyme production unit-operation. Cellulase is a mixture of enzymes that catalyze the hydrolysis of cellulose [69]. Cellulase enzymes can be produced through secretion from a fungus known as *Trichoderma Reesei*.

In the NREL process design *T. Reesei* is grown through a seed train in a media that promotes cellulase secretion [69]. Once the *T. Reesi* population has propagated, it is sent to a submerged aerobic cultivation reactor for fermentation where cellulase is secreted [69]. The cellulase is then separated from the fermentation broth and used in enzymatic hydrolysis [69].

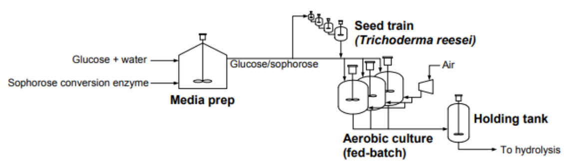


Figure 4.5 Cellulase enzyme production diagram [69]

4.1.1.5 Product Recovery

In the product recovery unit-operation, the beer from fermentation is separated into ethanol, liquids, and solids [69]. The ethanol fraction is further purified to produce a final product. Liquids are directed to wastewater treatment, and solids are sent to the combustor [69].

Beer, from fermentation, enters the first distillation column where most of the water is removed [69]. The remaining liquids are sent to another distillation column where ethanol is further purified and more water is removed [69]. After the second distillation column, the remaining liquid is mostly ethanol, which undergoes molecular sieve absorption to produce the final ethanol product [69]. Solids from the first beer column are sent to a lignin separator, which separates lignin from stillage [69]. Stillage is directed to wastewater treatment and lignin is sent to the combustor [69].

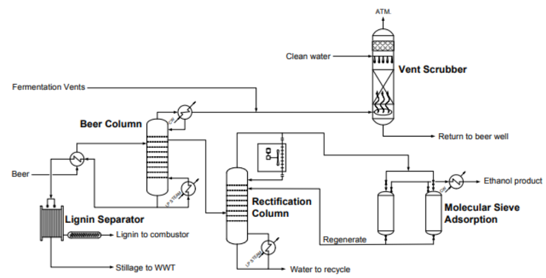


Figure 4.6 Product recovery diagram [69]

4.1.1.6 COMBUSTOR, BOILER, AND TURBOGENERATOR

The combustor, boiler, and turbogenerator section of the biorefinery is used to burn organic by-product streams [69]. Burning combustible streams reduces solid waste disposal costs and generates enough electricity and steam for the biorefinery to be self-sufficient [69].

4.1.1.7 WASTEWATER TREATMENT

The wastewater treatment unit-operation treats all liquid waste streams from the ethanol production process. Beer stillage, cooling tower blowdown, boiler blowdown, and pretreatment flash streams all enter wastewater treatment together. These combined streams undergo anaerobic digestion, which produces combustible biogas [69]. The remaining waste stream from anaerobic digestion then undergoes aerobic digestion. Aerobic digestion generates clean water that can be recycled in the process and a sludge stream that can be combusted [69].

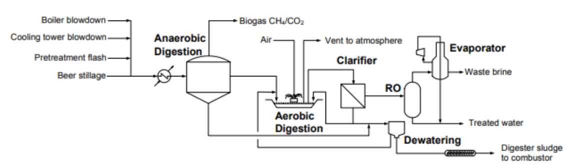


Figure 4.7 Wastewater treatment diagram [69]

4.1.1.8 STORAGE

This section of the biorefinery accommodates storage for ancillary chemicals and the ethanol product [69]. Ethanol, ammonia, corn steep liquor, sulfuric acid, water, gasoline, and diammonium phosphate are all stored in tanks in this section [69].

4.1.1.9 UTILITIES

The utilities section of the biorefinery tracks all utilities needed in ethanol production [69]. Specifically, the utilities tracked are cooling water, chilled water, plant and instrument air, process water, and electricity [69].

4.1.2 CENTRALIA BIOREFINERY OVERVIEW

The hypothesized biorefinery in this analysis is similar to the biorefinery described in the NREL analysis; however, there are a few key differences. The Centralia biorefinery will be processing hybrid poplar instead of corn stover. The Centralia biorefinery will operate on a much smaller scale, 250,000 ODT of feedstock per year, rather than NREL's 773,000 ODT of feedstock per year [69]. And the biorefinery will be built in Western Washington. The Centralia biorefinery will also undergo design optimizations that can improve the profitability of the biorefinery. Design optimizations considered in this analysis include lower-cost feedstock utilization for operating cost reductions and co-location for capital cost reductions.

4.1.2.1 BIOREFINERY LOCATION

The biorefinery in this analysis has a hypothesized location in Centralia, Washington. The biorefinery site location was chosen as a result from the Geospatial Bioenergy Systems Model (GBSM), which identifies the most profitable locations for a biorefinery in the Pacific Northwest [40]. The GBSM site selection model is based on profit optimization factors, including low-cost pastureland availability for feedstock production, climatic conditions for adequate rainfall to circumvent crop irrigation, and access to ethanol markets [34]. Centralia was selected as a prime location due to opportunities for co-location with existing powerplants.

4.1.2.2 FEEDSTOCK

Feedstock costs account for a significant portion of operating costs in a biorefinery [34]. Dedicated poplar production on 50% converted pastureland within 100 km of the Centralia biorefinery has an average cost of $74.35 at 250,000 ODT/year [34]. A significant reduction in the feedstock cost will improve profitability for the biorefinery. Poplar cost reduction is achieved by incorporating cheaper poplar sources into the biorefinery's feedstock. Low-cost poplar sources include hardwood sawmill residuals and poplar grown for ecosystem services. Poplar cost data in this research has been attained through collaboration with Amira Chowyuk and through the roadside poplar cost analysis in the previous section.

Sawmill residuals are a large source of cheap hardwood biomass; the available supply and associated cost of hardwood sawmill residuals in Western Washington was determined to develop its supply curve [34]. Poplar that offers ecosystem services presents an opportunity for a low-cost feedstock because the production costs can be offset by introducing a vested third party. Ecosystem services typically provide desirable outcomes to other parties, which can be incentivized to participate in the establishment and growth of poplar for ecosystem services. Poplar, grown for wastewater treatment, allows wastewater treatment facilities in Western Washington to discharge effluent from wastewater treatment to poplar plantations during times of no release to rivers [34]. Poplar costs can be divided between wastewater treatment facilities, who establish and maintain the poplar production sites, and the biorefinery, who is responsible for harvest and shipment of the poplar to the biorefinery [34]. The roadside poplar production, as an ecosystem service, operates on the same mechanics as the wastewater treatment poplar; however, the party responsible for establishing and maintaining poplar in this case is WSDOT. These three alternative hardwood biomass sources provide feedstock at a lower cost, Figure 4.8 shows supply curves comparing dedicated poplar to the low-cost poplar sources available in Western Washington. Figure 4.9 combines the poplar supply curves to generate one supply curve that represents the price of mixed poplar at given supplies, it is compared to the supply curve of dedicated poplar. At 250,000 ODT/year the price of mixed poplar is $48.82, which is much lower than the price of dedicated poplar at that supply, $74.35. Incorporating alternative poplar sources for the biorefinery feedstock is an effective technique for reducing operating costs; the effects of feedstock cost reduction will be explored in this techno-economic analysis.

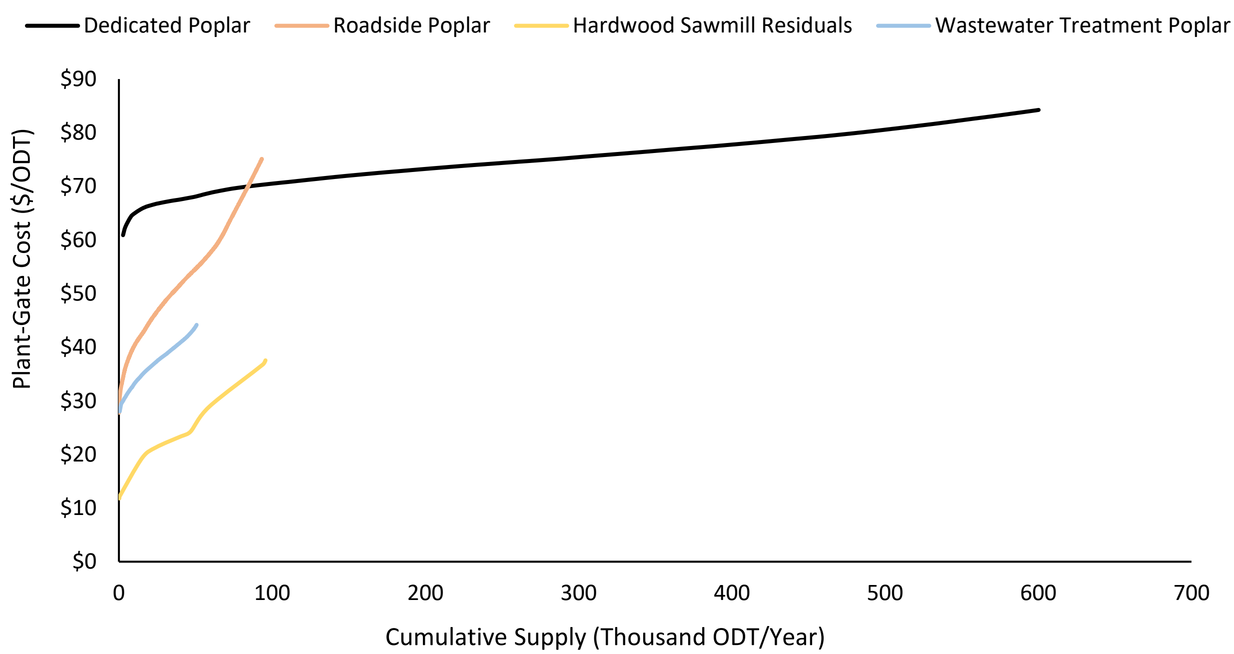


Figure 4.8 Hardwood source supply curve comparison

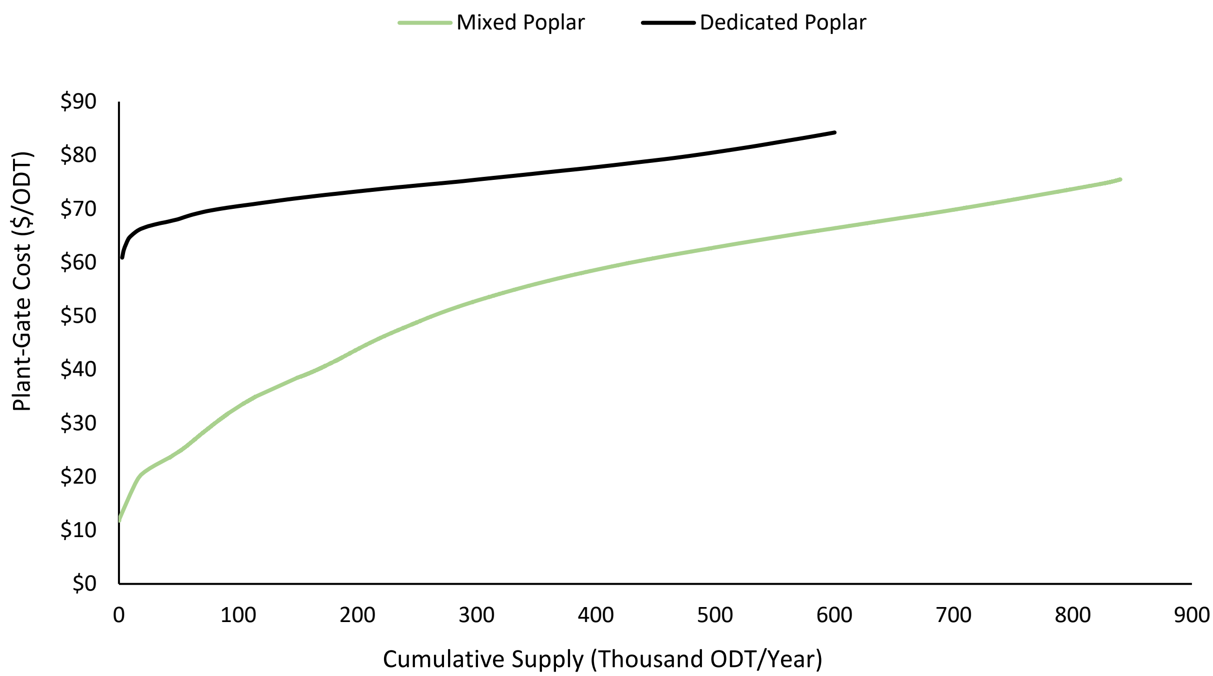


Figure 4.9 Supply curves comparison of mixed hardwood sources and dedicated poplar

4.1.2.3 CO-LOCATION

Co-locating a biorefinery with a powerplant can decrease capital costs by eliminating the requirement for certain sections of the biorefinery. Centralia, Washington is home to the TransAlta coal-fired powerplant, which is set to be phased out by 2025 [34]. Currently, there is an effort to extend the TransAlta powerplant operation beyond 2025 by transitioning the coal-fired powerplant to a natural gas powerplant [34]. The TransAlta powerplant transition represents an opportunity for co-location of the biorefinery adjacent to the natural gas powerplant. Co-locating the biorefinery with a powerplant can eliminate the combustor, boiler, turbogenerator, and wastewater treatment sections of the biorefinery, significantly reducing capital costs for the biorefinery. The combustor, boiler, and turbogenerator section can be eliminated from the biorefinery by displacing the powerplants input gas for combustion of waste streams from the ethanol production process [34]. Figure 4.10 shows a process flow diagram of the powerplant boiler and turbine. The powerplant will be combusting natural gas in the boiler, which will be slightly displaced by thick waste from the multi-effect evaporator in the biorefinery. The high-pressure steam from the boiler will generate electricity through a turbine, some of which will be used to power the biorefinery. Medium-pressure steam and hot water from the turbine can also be utilized in the biorefinery. The wastewater treatment section of the biorefinery can be eliminated by incorporating a multi-effect evaporator that concentrates liquid waste [34]. Concentrated liquid waste from the multi-effect evaporator can then be combusted by the powerplant's excess capacity. Co-locating the Centralia biorefinery with a pre-existent powerplant will reduce capital costs for the biorefinery, the effects of capital cost reduction will be explored in this techno-economic analysis.

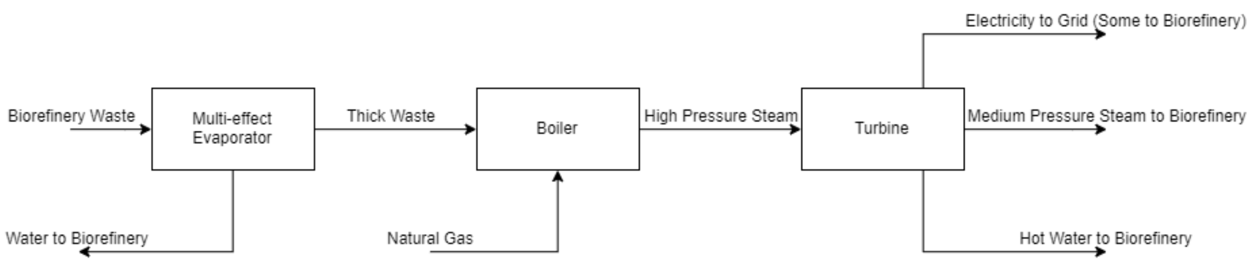


Figure 4.10 Integrated powerplant co-located with biorefinery

4.2 OBJECTIVE

The objective of this research is to perform a techno-economic analysis on the cellulosic ethanol biorefinery in Centralia, Washington. This analysis will determine the minimum ethanol selling price (MESP) of the Centralia biorefinery, apply capital and operating cost reduction modifications to the biorefinery model, and evaluate their effect on the resultant MESP.

4.3 METHODS

NREL's model is modified to reflect the process design in this analysis by altering variables and unit-operations. The following sections will discuss changes made to the NREL model to produce a biorefinery model that adequately represents the various Centralia biorefinery scenarios.

A techno-economic analysis will then be performed on each Centralia biorefinery case. The goal of this techno-economic analysis is to determine the absolute cost of ethanol produced by this biorefinery, which can be used to assess its performance in the marketplace or to compare process design considerations for ethanol cost reductions.

4.3.1 CASE ANALYSIS

This techno-economic analysis was performed on four cases of the Centralia Biorefinery. Each case is described in Table 4.1. And the resultant minimum ethanol selling price (MESP) for each case was identified for comparison in the results. Unit-operations, stream flows, and feedstock costs are dependent on the case selected. Processing mixed poplar, rather than dedicated poplar, was reflected in this analysis by a change in the cost of the feedstock and yield of the biorefinery. The feedstock cost was determined through the poplar supply curves in Section 4.1.2.2. Constructing a co-located biorefinery was reflected in this analysis by replacing the combustor, boiler, turbogenerator, and wastewater treatment sections with a multi-effect evaporator.

Table 4.1 Centralia biorefinery scenarios

Case Name	Feedstock	Biorefinery
Dedicated Poplar, Stand-Alone Biorefinery	Dedicated Poplar	Stand-alone
Mixed Poplar, Stand-Alone Biorefinery	Mixed Poplar	Stand-alone
Dedicated Poplar, Integrated Biorefinery	Dedicated Poplar	Co-located
Mixed Poplar, Integrated Biorefinery	Mixed Poplar	Co-located

4.3.2 DESIGN BASIS

The first step in converting NREL's technoeconomic analysis was to modify the time, scale, and yield of the biorefinery. The Centralia biorefinery operates on a smaller scale, therefore process streams and equipment were scaled down to match that of the Centralia Biorefinery. NREL assumed an ethanol yield of 79 gallons of ethanol per oven dry ton (ODT) of biomass. The assumed ethanol yield for the Centralia Biorefinery was based on previous poplar conversion research and amounts to 71 gallons of ethanol per ODT [34]. The design basis for each biorefinery is compared in Table 4.2.

Table 4.2 Biorefinery design parameters [69]

Model	NREL	Centralia
Year	2011	2018
Capacity (ODT/year)	773,000	250,000
Ethanol Yield (gal/ODT)	79	71
Ethanol Production (MMgal/year)	61	18

4.3.3 FEEDSTOCK COMPOSITION

A significant difference among the NREL and Centralia models was the choice of feedstock for the biorefinery. In the NREL design, corn stover was the feedstock. In contrast, hardwood biomass (mostly poplar) was the chosen feedstock for the Centralia biorefinery. The processing differences in feedstocks were accounted for in the lower yield conversion of hardwood biomass. Poplar and corn stover have similar chemical compositions, which are compared in Figure 4.11. As shown in Figure 4.11, corn stover and hybrid poplar have comparable total carbohydrate compositions; however, hybrid poplar contains more lignin. Based on the total carbohydrates, both feedstocks should have similar theoretical ethanol yields. At the same time, the greater presence of lignin in hybrid poplar could contribute to higher recalcitrance and a lower ethanol yield. This difference was reflected in the assumed ethanol yield of the Centralia Biorefinery, which was lower than the ethanol yield of NREL Biorefinery.

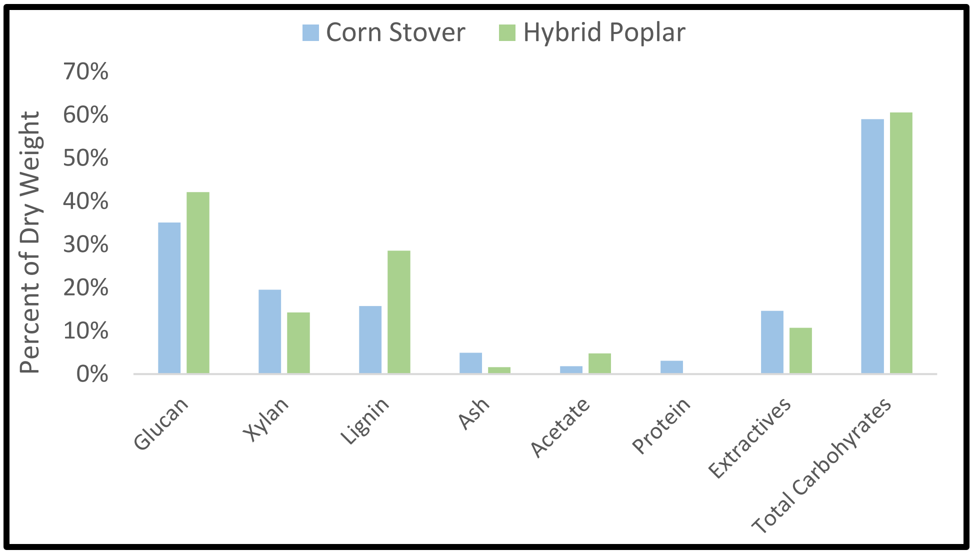


Figure 4.11 Feedstock composition comparison [21]

Another difference between the two processes was that the Centralia biorefinery did not utilize a central supply depot for preprocessing biomass and instead delivered the biomass directly from the farm-gate. Although the biomass in the Centralia biorefinery scenario is not preprocessed at a central supply depot, it was assumed that poplar necessitated minimal storage and handling at the biorefinery. This assumption was based on the difference in harvest cycles for each of the crops. Corn is harvested once per year; therefore, the biomass must be stored at a supply depot. At the supply depot, the corn is preprocessed to increase shelf life. Hybrid poplar can be harvested year-round, this means that poplar will not be harvested until it is ready to be accepted to the biorefinery. This alternate design simplifies the biomass supply chain by removing preprocessing steps and supply depot stockpiling. This design consideration was assumed to pose minimal impact on the downstream processes in the biorefinery.

4.3.4 Process Economics

This analysis was developed from a detailed process design and simulation model to estimate the economics of ethanol production. This analysis first determined the total capital investment (TCI) from equipment and installation costs [69]. Next, variable operating costs were determined through process stream flows. And finally, the fixed operating costs were calculated from employment statistics and maintenance, insurance, and tax assumptions [69]. Capital and operating costs were scaled to reflect the size of the biorefinery, and a time-shift was performed to reflect the current prices of equipment, raw materials, and labor.

4.3.4.1 SCALING

Capital costs were estimated though baseline equipment costs. Equipment costs are dependent on the size of the biorefinery. An exponential scaling expression was used to calculate the new cost of equipment based on the quoted cost of the original equipment size [69]. The equation shown below was used to scale equipment to the desired size. In Equation 4.1, equipment can be scaled to determine its *New Cost*. The *Base Cost* of the equipment was quoted in NREL's report. The *New Size* and *Old Size* of the equipment was based on the ethanol production rate of the biorefinery. In this case, *New Size* was the production rate of the Centralia Biorefinery and *Old Size* was the production rate of the NREL Biorefinery. The term *n* is a scaling exponent, which was given in NREL's report and is specific to each individual piece of equipment.

$$New\ Cost = (Base\ Cost)\left(\frac{New\ Size}{Base\ Size}\right)^{n}$$

Equation 4.1 Equipment scaling [69]

Variable operating costs were estimated through stream flows of raw materials in the bioconversion process. Stream flows are dependent on the scale of the biorefinery; therefore, they were scaled accordingly. In this analysis, stream flows were scaled linearly with the ethanol production rate of each biorefinery. Equation 4.2 displays the expression used to derive the *New*

Flow Rate for raw material streams in this analysis. The *Base Flow Rate* represents the flow rate of the stream in NREL's model, which was linearly scaled by the ratio of the *New Size*, ethanol production rate of the Centralia Biorefinery, over the *Base Size*, ethanol production rate of the NREL Biorefinery.

$$New\ Flow\ Rate = (Base\ Flow\ Rate)\left(\frac{New\ Size}{Base\ Size}\right)$$

Equation 4.2 Stream flow scaling [69]

Fixed operating costs were divided into employment, maintenance, and property insurance and tax costs. Employment costs were not scaled according to the size of the biorefinery under the assumption that the number of employees needed in a biorefinery is weakly dependent on the scale of the biorefinery. Maintenance and property insurance/tax were scaled with respect to the capital costs of the biorefinery.

4.3.4.2 COST-YEAR INDICES

Equipment, raw material, and employment costs were relative to the time frame of construction and operation of the biorefinery [69]. This section describes the techniques used to reflect the differences in time frames in the costs of the biorefinery. The cost-year of the Centralia Biorefinery is 2018. The following equation, along with cost indices, were used to estimate the cost of materials and equipment in the 2018 cost-year.

$$2018\ Cost = (Base\ Cost)\left(\frac{2018\ Cost\ Index}{Base\ Year\ Index}\right)$$

Equation 4.3 Time-shift [69]

Equipment costs in the NREL model were assigned a purchase cost that is based on a quote made in a specified year [69]. The equipment cost was then adjusted with the Equation 4.3 and the Plant Cost Index for the specified year. The Plant Cost Index was provided by the *Chemical*

Engineering Magazine [69]. For fixed operating costs, NREL determined employee salaries, which experienced a time-shift to the 2018 cost-year with labor indices from the United States Department of Labor Bureau [69]. The plant cost, inorganic chemical, and labor indices are shown in Table 4.3. Most raw material streams were time-shifted to the 2018 cost-year through Inorganic Chemical Indices [46]. However, some raw material streams, such as the glucose, water, and electricity were determined through literature. And feedstock costs were determined in Section 4.1.2.2.

Table 4.3 Cost-year indices [44]

Plant Cost Index	
Year	Index
1990	357.6
1991	361.3
1992	358.2
1993	359.2
1994	368.1
1995	381.1
1996	381.7
1997	386.5
1998	389.5
1999	390.6
2000	394.1
2001	394.3
2002	395.6
2003	402
2004	444.2
2005	468.2
2006	499.6
2007	525.4
2008	575.4
2009	521.9
2010	550.8
2011	585.7
2012	584.6
2013	567.3
2014	576.1
2018	567.5

Inorganic Chemical Index	
Year	Index
1980	89
1981	98.4
1982	100
1983	100.3
1984	102.9
1985	103.7
1986	102.6
1987	106.4
1988	116.3
1989	123
1990	123.6
1991	125.6
1992	125.9
1993	128.2
1994	132.1
1995	139.5
1996	142.1
1997	147.1
1998	148.7
1999	149.7
2000	156.7
2001	158.4
2002	157.3
2003	164.6
2004	172.8
2005	187.3
2006	196.8
2007	203.3
2008	228.2
2009	224.7
2010	233.7
2011	252.1
2012	260.3
2013	263.9
2014	269.2
2018	312.6

Labor Index	
Year	Index
1990	12.85
1991	13.3
1992	13.7
1993	13.97
1994	14.33
1995	14.86
1996	15.37
1997	15.78
1998	16.23
1999	16.4
2000	17.09
2001	17.57
2002	17.97
2003	18.5
2004	19.17
2005	19.67
2006	19.6
2007	19.55
2008	19.5
2009	20.3
2010	21.07
2011	21.45
2012	21.45
2013	21.4
2014	21.49
2018	25.21

4.3.5 CAPITAL EQUIPMENT COSTS

This section elaborates on the details of estimating capital equipment costs for the stand-alone and integrated biorefinery cases. Equipment costs were not affected by feedstock cost reductions; therefore, this section focuses on the differences between the stand-alone and integrated biorefinery models. The following tables show the scaling and time-shift operations performed on each piece of equipment in the biorefinery to reflect the Centralia biorefinery cases in this analysis.

The first section of the biorefinery, feedstock handling, remained unchanged with regards to the stand-alone and integrated models. The capital equipment costs for the feedstock handling section for both the stand-alone and integrated biorefinery are shown in Table 4.4.

Table 4.4 Feedstock handling equipment costs for the stand-alone and integrated Centralia biorefinery

Area	Equipment Title	Number Required	Purchased Cost in Quoted Year	Year of Quote	Flow Rate of NREL Equipment	Flow Rate Units	Scaling Exponent	Installation Factor	NREL Production Rate (MMgal/year)	UW Production Rate (Mmgal/year)	Scaled Purchase Cost	Purchased Cost in Projected Year	Installed Cost in Projected Year
Feedstock Handling	Transfer Conveyor	2	$5,400,000	2009	100,000	kg/hr	0.6	1.7	61	17.69	$2,700,000	$3,000,000	$5,000,000
	Dome Reclaim System	2	$3,000,000	2009	100,000	kg/hr	0.6	1.7	61	17.69	$1,500,000	$1,700,000	$2,800,000
	Truck Dumper	2	$480,000	2009	100,000	kg/hr	0.6	1.7	61	17.69	$240,000	$270,000	$450,000
	Truck Dumper Hopper	2	$500,000	2009	100,000	kg/hr	0.6	1.7	61	17.69	$250,000	$280,000	$470,000
	Concrete Feedstock Storage Dome	2	$3,500,000	2009	100,000	kg/hr	0.6	1.7	61	17.69	$1,800,000	$1,900,000	$3,300,000
	Belt Scale	2	$11,000	2009	100,000	kg/hr	0.6	1.7	61	17.69	$5,400	$5,900	$10,000
	Dust Collection System	6	$280,000	2009	100,000	kg/hr	0.6	1.7	61	17.69	$140,000	$150,000	$260,000
										Feedstock Handling Totals	$6,700,000	$7,200,000	$12,000,000

The pretreatment and conditioning section also had identical equipment costs for the stand-alone and integrated biorefinery. The capital equipment costs for the pretreatment and conditioning section in both the stand-alone and integrated biorefinery are shown in Table 4.5.

Table 4.5 Pretreatment and conditioning equipment costs for the stand-alone and integrated Centralia Biorefinery

Area	Equipment Title	Number Required	Purchased Cost in Quoted Year	Year of Quote	Flow Rate of NREL Equipment	Flow Rate Units	Scaling Exponent	Installation Factor	NREL Production Rate (MMgal/year)	UW Production Rate (Mmgal/year)	Scaled Purchase Cost	Purchased Cost in Projected Year	Installed Cost in Projected Year
Pretreatment and Conditioning	In-line Sulfuric Acid Mixer	1	$6,000	2009	39,000	kg/hr	0.5	1	61	17.69	$1,700	$1,900	$1,900
	Flash Tank Agitator	3	$90,000	2009	280,000	kg/hr	0.5	1.5	61	17.69	$51,000	$55,000	$83,000
	Oligomer Hold Tank Agitator	3	$90,000	2009	290,000	kg/hr	0.5	1.5	61	17.69	$51,000	$55,000	$83,000
	Ammonia Addition Tank Agitator	1	$22,000	2009	430,000	kg/hr	0.5	1.5	61	17.69	$12,000	$13,000	$20,000
	Ammonia Static Mixer	1	$5,000	2009	150,000	kg/hr	0.5	1	61	17.69	$2,600	$2,900	$2,900
	Pretreatment Water Heater	1	$92,000	2010	-9	Gcal/hr	0.7	2.2	61	17.69	$43,000	$44,000	$97,000
	Waste Vapor Condenser	1	$34,000	2009	7	Gcal/hr	0.7	2.2	61	17.69	$37,000	$41,000	$90,000
	Pretreatment Reactor	3	$20,000,000	2009	83,000	kg/hr	0.6	1.5	61	17.69	$9,400,000	$10,000,000	$15,000,000
	Sulfuric Acid Pump	1	$8,000	2009	2,000	kg/hr	0.8	2.3	61	17.69	$1,800	$2,000	$4,500
	Blowdown Tank Discharge Pump	1	$26,000	2010	290,000	kg/hr	0.8	2.3	61	17.69	$9,500	$9,800	$23,000
	Flash Tank Discharge Pump	1	$30,000	2009	280,000	kg/hr	0.8	2.3	61	17.69	$14,000	$16,000	$36,000
	Oligomer Hold Tank Discharge	1	$17,000	2010	290,000	kg/hr	0.8	2.3	61	17.69	$6,500	$6,700	$15,000
	Hydrolyzate Pump	1	$23,000	2009	430,000	kg/hr	0.8	2.3	61	17.69	$8,800	$9,600	$22,000
	Sulfuric Acid Tank	1	$6,200	2010	2,000	kg/hr	0.7	3	61	17.69	$2,600	$2,700	$8,100
	Flash Tank	1	$510,000	2009	290,000	kg/hr	0.7	2	61	17.69	$230,000	$250,000	$500,000
	Oligomer Conversion Tank	1	$200,000	2009	290,000	kg/hr	0.7	2	61	17.69	$92,000	$100,000	$200,000
	Ammonia Addition Tank	1	$240,000	2009	430,000	kg/hr	0.7	2	61	17.69	$100,000	$110,000	$220,000
	Pretreatment and Conditioning Totals										**$10,000,000**	**$11,000,000**	**$17,000,000**

The enzymatic hydrolysis and fermentation section of both the stand-alone and integrated biorefinery were the same; therefore, the capital equipment costs of this section remained the same for each case. Table 4.6 shows the capital equipment costs for enzymatic hydrolysis and fermentation for both the stand-alone and integrated biorefinery.

Table 4.6 Enzymatic hydrolysis and fermentation equipment costs for the stand-alone and integrated Centralia biorefinery

Area	Equipment Title	Number Required	Purchased Cost in Quoted Year	Year of Quote	Flow Rate of NREL Equipment	Flow Rate Units	Scaling Exponent	Installation Factor	NREL Production Rate (MMgal/year)	UW Production Rate (Mmgal/year)	Scaled Purchase Cost	Purchased Cost in Projected Year	Installed Cost in Projected Year
Enzymatic Hydrolysis and Fermentation	Ethanol Fermentor Agitator	1	$53,000	2009	12	ea	1.0	1.5	61	17.69	$180,000	$200,000	$300,000
	Seed Hold Tank Agitator	1	$32,000	2009	43,000	kg/hr	0.5	1.5	61	17.69	$18,000	$19,000	$29,000
	4th Seed Vessel Agitator	2	$26,000	2009	2	ea	0.5	1.5	61	17.69	$14,000	$15,000	$23,000
	5th Seed Vessel Agitator	2	$43,000	2009	2	ea	0.5	1.5	61	17.69	$23,000	$25,000	$38,000
	Beer Surge Tank Agitator	2	$68,000	2009	450,000	kg/hr	0.5	1.5	61	17.69	$38,000	$41,000	$62,000
	Enzyme-Hydrolysate Mixer	1	$110,000	2009	440,000	kg/hr	0.5	1.7	61	17.69	$63,000	$69,000	$120,000
	Ethanol Fermentor	12	$10,000,000	2009	12	ea	1.0	1.5	61	17.69	$2,900,000	$3,200,000	$4,800,000
	1st Seed Fermentor	2	$75,000	2009	2	ea	0.7	1.8	61	17.69	$32,000	$34,000	$62,000
	2nd Seed Fermentor	2	$120,000	2009	2	ea	0.7	1.8	61	17.69	$49,000	$53,000	$96,000
	3rd Seed Fermentor	2	$160,000	2009	2	ea	0.7	1.8	61	17.69	$66,000	$72,000	$130,000
	4th Seed Fermentor	2	$350,000	2009	2	ea	0.7	2.0	61	17.69	$150,000	$160,000	$320,000
	5th Seed Fermentor	2	$1,200,000	2009	2	ea	0.7	2.0	61	17.69	$500,000	$540,000	$1,100,000
	Fermentation Cooler	12	$87,000	2009	12	ea	1.0	2.2	61	17.69	$25,000	$27,000	$60,000
	Hydrolyzate Cooler	1	$85,000	2010	11	Gcal/hr	0.7	2.2	61	17.69	$43,000	$44,000	$97,000
	Fermentor Batch Cooler	1	$24,000	2009	6	Gcal/hr	0.7	1.8	61	17.69	$11,000	$12,000	$21,000
	Fermentation Recirc/Transfer Pump	5	$47,000	2009	12	ea	0.8	2.3	61	17.69	$18,000	$19,000	$44,000
	Seed Hold Transfer Pump	1	$8,200	2009	43,000	kg/hr	0.8	2.3	61	17.69	$3,000	$3,300	$7,500
	Seed Transfer Pump	2	$24,000	2009	43,000	kg/hr	0.8	2.3	61	17.69	$8,900	$9,700	$22,000
	Beer Transfer Pump	1	$27,000	2009	450,000	kg/hr	0.8	2.3	61	17.69	$9,300	$10,000	$23,000
	Saccharification Transfer Pump	5	$47,000	2009	440,000	kg/hr	0.8	2.3	61	17.69	$18,000	$20,000	$46,000
	Seed Hold Tank	1	$440,000	2009	43,000	kg/hr	0.7	1.8	61	17.69	$190,000	$210,000	$380,000
	Beer Storage Tank	1	$640,000	2009	450,000	kg/hr	0.7	1.8	61	17.69	$280,000	$300,000	$540,000
	Saccharification Tank	8	$3,800,000	2009	440,000	kg/hr	0.7	2.0	61	17.69	$1,700,000	$1,800,000	$3,600,000
	Enzymatic Hydrolysis and Fermentation Totals										**$6,300,000**	**$6,900,000**	**$12,000,000**

The cellulase enzyme production section of the biorefinery was identical for both the stand-alone and integrated biorefinery. The stand-alone and integrated models both possess the same cellulase enzyme production equipment costs, which are shown in Table 4.7.

Table 4.7 Cellulase enzyme production equipment costs for the stand-alone and integrated Centralia biorefinery

Area	Equipment Title	Number Required	Purchased Cost in Quoted Year	Year of Quote	Flow Rate of NREL Equipment	Flow Rate Units	Scaling Exponent	Installation Factor	NREL Production Rate (MMgal/year)	UW Production Rate (Mmgal/year)	Scaled Purchase Cost	Purchased Cost in Projected Year	Installed Cost in Projected Year
Cellulase Enzyme Production	Cellulase Fermentor Agitators	1	$580,000	2009	9	ea	1.0	1.5	61	17.69	$1,500,000	$1,600,000	$2,500,000
	Cellulase Fermentor Agitators	1	$3,400	2009	4	ea	1.0	1.5	61	17.69	$4,000	$4,300	$6,500
	Cellulase Fermentor Agitators	1	$63,000	2009	4	ea	1.0	1.5	61	17.69	$73,000	$79,000	$120,000
	Cellulase Fermentor Agitators	1	$11,000	2009	4	ea	1.0	1.5	61	17.69	$13,000	$14,000	$21,000
	Media-Prep Tank Agitator	1	$8,500	2009	16,000	kg/hr	0.5	1.5	61	17.69	$5,200	$5,700	$8,500
	Cellulase Nutrient Mix Tank Agitator	1	$4,800	2009	220	kg/hr	0.5	1.6	61	17.69	$2,900	$3,200	$5,100
	Cellulase Hold Tank Agitator	1	$27,000	2009	14,000	kg/hr	0.5	1.5	61	17.69	$16,000	$18,000	$27,000
	Cellulase Fermentor	1	$400,000	2009	9	ea	1.0	2.0	61	17.69	$1,000,000	$1,100,000	$2,300,000
	1st Cellulase Seed Fermentor	1	$46,000	2009	4	ea	1.0	1.8	61	17.69	$53,000	$58,000	$100,000
	2nd Cellulase Seed Fermentor	1	$58,000	2009	4	ea	1.0	1.8	61	17.69	$67,000	$73,000	$130,000
	3rd Cellulase Seed Fermentor	1	$95,000	2009	4	ea	1.0	1.8	61	17.69	$110,000	$120,000	$220,000
	Fermenter Air Compressor Package	2	$350,000	2009	33,000	kg/hr	0.6	1.6	61	17.69	$160,000	$180,000	$290,000
	Cellulase Transfer Pump	1	$7,400	2010	14,000	kg/hr	0.8	2.3	61	17.69	$2,800	$2,900	$6,600
	Cellulase Seed Pump	4	$30,000	2010	770	kg/hr	0.8	2.3	61	17.69	$12,000	$13,000	$29,000
	Media Pump	1	$7,400	2010	16,000	kg/hr	0.8	2.3	61	17.69	$3,000	$3,000	$7,000
	Cellulase Nutrient Transfer Pump	1	$1,500	2009	220	kg/hr	0.8	2.3	61	17.69	$320	$340	$790
	Cellulase Feed Pump	1	$1,500	2009	14,000	kg/hr	0.8	2.3	61	17.69	$1,700	$1,900	$4,300
	Anti-foam Pump	1	$1,500	2009	13	kg/hr	0.8	2.3	61	17.69	$670	$730	$1,700
	Media-Prep Tank	1	$180,000	2009	16,000	kg/hr	0.7	1.8	61	17.69	$88,000	$96,000	$170,000
	Cellulase Nutrient Mix Tank	1	$9,000	2010	220	kg/hr	0.7	3.0	61	17.69	$3,800	$3,900	$12,000
	Cellulase Hold Tank	1	$250,000	2009	14,000	kg/hr	0.7	1.8	61	17.69	$120,000	$130,000	$240,000
										Cellulase Enzyme Production Totals	**$3,300,000**	**$3,600,000**	**$6,100,000**

The major distinction between the stand-alone and integrated biorefinery model was in the integrated biorefinery the combustor, boiler, and turbogenerator were replaced by a pre-existent powerplant and the wastewater treatment section was replaced by a multi-effect evaporator. The purpose of the combustor, boiler, and turbogenerator section is to burn organic by-product streams from the biorefinery [69]. In the integrated biorefinery model, the organic by-product streams will be concentrated in the multi-effect evaporator and diverted to the powerplant for combustion. The purpose of the wastewater treatment section is to treat liquid waste streams from the production process. Alternatively, in the integrated biorefinery model the liquid waste streams will be concentrated in a multi-effect evaporator and the concentrated waste liquid will be sent to the powerplant for combustion. The cost and scale of the multi-effect evaporator in this model were adapted from Amira Choyuk's research. The multi-effect evaporator modeled in Chowyuk's research was installed in a biorefinery producing 19.8 million gallons of ethanol per year and the cost of the multi-effect evaporator was $12,000,000 [34]. The multi-effect evaporator was be scaled down to match the scale of the biorefinery in this research with a scaling factor of 0.6 [34]. The multi-effect evaporator had an installation factor of 1.6 [34]. These parameters were applied to the equipment cost determination for the multi-effect evaporator. The multi-effect evaporator was be placed in the product recovery section of the integrated biorefinery. Table 4.8 shows the product recovery equipment cost determination for the stand-alone biorefinery and Table 4.9 shows the product recovery equipment cost determination for the integrated biorefinery. The major difference among the two models is that the integrated model now has an additional piece of equipment, multi-effect evaporator, in the product recovery section.

Table 4.8 Product recovery equipment costs for the stand-alone Centralia biorefinery

Area	Equipment Title	Number Required	Purchased Cost in Quoted Year	Year of Quote	Flow Rate of NREL Equipment	Flow Rate Units	Scaling Exponent	Installation Factor	NREL Production Rate (MMgal/year)	UW Production Rate (Mmgal/year)	Scaled Purchase Cost	Purchased Cost in Projected Year	Installed Cost in Projected Year
Product Recovery	Filtrate Tank Agitator	1	$26,000	2009	360,000	kg/hr	0.5	1.5	61	17.69	$14,000	$16,000	$23,000
	Lignin Wet Cake Conveyor	1	$70,000	2009	37,000	kg/hr	0.8	1.7	61	17.69	$32,000	$34,000	$58,000
	Lignin Wet Cake Screw	1	$20,000	2009	37,000	kg/hr	0.8	1.7	61	17.69	$9,000	$9,800	$17,000
	Beer Column	1	$3,400,000	2009	29,000	kg/hr	0.6	2.4	61	17.69	$1,600,000	$1,700,000	$4,100,000
	Rectification Column Condenser	1	$490,000	2010	23	Gcal/hr	0.6	2.8	61	17.69	$230,000	$240,000	$670,000
	Molecular Sieve Package (9 pieces)	1	$2,600,000	2009	22,000	kg/hr	0.6	1.8	61	17.69	$1,200,000	$1,300,000	$2,400,000
	Pressure Filter Pressing Compr	1	$75,000	2009	810	kg/hr	0.6	1.6	61	17.69	$36,000	$39,000	$62,000
	Pressure Filter Drying Compr	2	$410,000	2009	12,000	kg/hr	0.6	1.6	61	17.69	$190,000	$210,000	$330,000
	Scrubber Bottoms Pump	1	$6,300	2009	27,000	kg/hr	0.8	2.3	61	17.69	$2,500	$2,800	$6,400
	Filtrate Tank Discharge Pump	1	$13,000	2010	37,000	kg/hr	0.8	2.3	61	17.69	$5,400	$5,600	$13,000
	Feed Pump	1	$18,000	2010	37,000	kg/hr	0.8	2.3	61	17.69	$7,500	$7,800	$18,000
	Manifold Flush Pump	1	$17,000	2010	37,000	kg/hr	0.8	2.3	61	17.69	$7,100	$7,300	$17,000
	Cloth Wash Pump	1	$29,000	2010	37,000	kg/hr	0.8	2.3	61	17.69	$12,000	$12,000	$29,000
	Filtrate Discharge Pump	1	$13,000	2010	37,000	kg/hr	0.8	2.3	61	17.69	$5,400	$5,600	$13,000
	Pressure Filter	2	$3,300,000	2010	37,000	kg/hr	0.8	1.7	61	17.69	$1,400,000	$1,400,000	$2,400,000
	Vent Scrubber	1	$220,000	2009	22,000	kg/hr	0.6	2.4	61	17.69	$100,000	$110,000	$260,000
	Filtrate Tank	1	$100,000	2010	37,000	kg/hr	0.7	2.0	61	17.69	$48,000	$49,000	$98,000
	Feed Tank	1	$170,000	2010	37,000	kg/hr	0.7	2.0	61	17.69	$81,000	$83,000	$170,000
	Recycled Water Tank	1	$1,500	2010	37,000	kg/hr	0.7	3.0	61	17.69	$700	$730	$2,200
	Pressing Air Compressor Receiver	1	$8,000	2010	37,000	kg/hr	0.7	3.1	61	17.69	$3,700	$3,800	$12,000
	Drying Air Compressor Receiver	2	$17,000	2010	37,000	kg/hr	0.7	3.1	61	17.69	$7,900	$8,100	$25,000
										Product recovery Totals	$5,000,000	$5,300,000	$11,000,000

Table 4.9 Product recovery equipment costs for the integrated Centralia biorefinery

Area	Equipment Title	Number Required	Purchased Cost in Quoted Year	Year of Quote	Flow Rate of NREL Equipment	Flow Rate Units	Scaling Exponent	Installation Factor	NREL Production Rate (MMgal/year)	UW Production Rate (Mmgal/year)	Scaled Purchase Cost	Purchased Cost in Projected Year	Installed Cost in Projected Year
Product Recovery	Filtrate Tank Agitator	1	$26,000	2009	360,000	kg/hr	0.5	1.5	61	17.69	$14,000	$16,000	$23,000
	Lignin Wet Cake Conveyor	1	$70,000	2009	37,000	kg/hr	0.8	1.7	61	17.69	$32,000	$34,000	$58,000
	Lignin Wet Cake Screw	1	$20,000	2009	37,000	kg/hr	0.8	1.7	61	17.69	$9,000	$9,800	$17,000
	Beer Column	1	$3,400,000	2009	29,000	kg/hr	0.6	2.4	61	17.69	$1,600,000	$1,700,000	$4,100,000
	Rectification Column Condenser	1	$490,000	2010	23	Gcal/hr	0.6	2.8	61	17.69	$230,000	$240,000	$670,000
	Molecular Sieve Package (9 pieces)	1	$2,600,000	2009	22,000	kg/hr	0.6	1.8	61	17.69	$1,200,000	$1,300,000	$2,400,000
	Pressure Filter Pressing Compr	1	$75,000	2009	810	kg/hr	0.6	1.6	61	17.69	$36,000	$39,000	$62,000
	Pressure Filter Drying Compr	2	$410,000	2009	12,000	kg/hr	0.6	1.6	61	17.69	$190,000	$210,000	$330,000
	Scrubber Bottoms Pump	1	$6,300	2009	27,000	kg/hr	0.8	2.3	61	17.69	$2,500	$2,800	$6,400
	Filtrate Tank Discharge Pump	1	$13,000	2010	37,000	kg/hr	0.8	2.3	61	17.69	$5,400	$5,600	$13,000
	Feed Pump	1	$18,000	2010	37,000	kg/hr	0.8	2.3	61	17.69	$7,500	$7,800	$18,000
	Manifold Flush Pump	1	$17,000	2010	37,000	kg/hr	0.8	2.3	61	17.69	$7,100	$7,300	$17,000
	Cloth Wash Pump	1	$29,000	2010	37,000	kg/hr	0.8	2.3	61	17.69	$12,000	$12,000	$29,000
	Filtrate Discharge Pump	1	$13,000	2010	37,000	kg/hr	0.8	2.3	61	17.69	$5,400	$5,600	$13,000
	Pressure Filter	2	$3,300,000	2010	37,000	kg/hr	0.8	1.7	61	17.69	$1,400,000	$1,400,000	$2,400,000
	Vent Scrubber	1	$220,000	2009	22,000	kg/hr	0.6	2.4	61	17.69	$100,000	$110,000	$260,000
	Filtrate Tank	1	$100,000	2010	37,000	kg/hr	0.7	2.0	61	17.69	$48,000	$49,000	$98,000
	Feed Tank	1	$170,000	2010	37,000	kg/hr	0.7	2.0	61	17.69	$81,000	$83,000	$170,000
	Recycled Water Tank	1	$1,500	2010	37,000	kg/hr	0.7	3.0	61	17.69	$700	$730	$2,200
	Pressing Air Compressor Receiver	1	$8,000	2010	37,000	kg/hr	0.7	3.1	61	17.69	$3,700	$3,800	$12,000
	Drying Air Compressor Receiver	2	$17,000	2010	37,000	kg/hr	0.7	3.1	61	17.69	$7,900	$8,100	$25,000
	8-Effect Evaporator	1	$12,000,000	2018			0.6	1.7	19.8*	17.69	$11,000,000	$11,000,000	$19,000,000
										Product recovery Totals	$16,000,000	$16,000,000	$30,000,000

**Production rate of Amira's biorefinery model*

As mentioned previously, the wastewater treatment section was omitted from the integrated Centralia biorefinery model. Therefore, the integrated model did not include a wastewater treatment equipment cost evaluation. Table 4.10 shows the wastewater treatment equipment cost evaluation for the stand-alone biorefinery model.

Table 4.10 Wastewater treatment equipment costs for the stand-alone biorefinery

Area	Equipment Title	Number Required	Purchased Cost in Quoted Year	Year of Quote	Flow Rate of NREL Equipment	Flow Rate Units	Scaling Exponent	Installation Factor	NREL Production Rate (MMgal/year)	UW Production Rate (Mmgal/year)	Scaled Purchase Cost	Purchased Cost in Projected Year	Installed Cost in Projected Year
Wastewater Treatment	Aerobic Digester Blower	8	$1,900,000	2010	410,000	kg/hr	0.6	1	61	17.69	$950,000	$970,000	$970,000
	Aerobic Sludge Screw	1	$25,000	2010	410,000	kg/hr	0.6	1	61	17.69	$12,000	$13,000	$13,000
	Anaerobic Digestor Feed Cooler	1	$84,000	2010	410,000	kg/hr	0.6	1	61	17.69	$41,000	$42,000	$42,000
	Biogas Emergency Flare	4	$33,000	2010	410,000	kg/hr	0.6	1	61	17.69	$16,000	$17,000	$17,000
	Polymer Addition System	1	$9,300	2010	410,000	kg/hr	0.6	1	61	17.69	$4,500	$4,700	$4,700
	Caustic Feed System	3	$23,000	2010	410,000	kg/hr	0.6	1	61	17.69	$11,000	$11,000	$11,000
	Evaporator System		$3,800,000	2010	410,000	kg/hr	0.6	1	61	17.69	$1,900,000	$1,900,000	$1,900,000
	Anaerobic Reactor Feed Pump	4	$230,000	2010	410,000	kg/hr	0.6	1	61	17.69	$110,000	$120,000	$120,000
	Waste Anaerobic Sludge Pump	6	$93,000	2010	410,000	kg/hr	0.6	1	61	17.69	$46,000	$47,000	$47,000
	Aeration Basin Feed Pump	4	$84,000	2010	410,000	kg/hr	0.6	1	61	17.69	$41,000	$42,000	$42,000
	Return Activated Sludge Pump	6	$180,000	2010	410,000	kg/hr	0.6	1	61	17.69	$87,000	$89,000	$89,000
	Centrifuge Feed Pump	2	$61,000	2010	410,000	kg/hr	0.6	1	61	17.69	$30,000	$31,000	$31,000
	Centrate Pump	2	$71,000	2010	410,000	kg/hr	0.6	1	61	17.69	$35,000	$36,000	$36,000
	Membrane Bioreactor	3	$5,200,000	2010	410,000	kg/hr	0.6	1	61	17.69	$2,600,000	$2,600,000	$2,600,000
	Reverse Osmosis System	1	$2,200,000	2010	410,000	kg/hr	0.6	1	61	17.69	$1,100,000	$1,100,000	$1,100,000
	Centrifuge	3	$6,500,000	2010	410,000	kg/hr	0.6	1	61	17.69	$3,200,000	$3,300,000	$3,300,000
	Anaerobic Basin	4	$27,000,000	2010	410,000	kg/hr	0.6	1	61	17.69	$13,000,000	$14,000,000	$14,000,000
	Aeration Digester	3	$2,700,000	2010	410,000	kg/hr	0.6	1	61	17.69	$1,300,000	$1,400,000	$1,400,000
										Wastewater Treatment Totals	$25,000,000	$25,000,000	$25,000,000

Both the stand-alone and integrated models had storage sections. The storage equipment cost is identical for each model and the evaluation is shown in Table 4.11.

Table 4.11 Storage equipment costs for the stand-alone and integrated Centralia biorefinery

Area	Equipment Title	Number Required	Purchased Cost in Quoted Year	Year of Quote	Flow Rate of NREL Equipment	Flow Rate Units	Scaling Exponent	Installation Factor	NREL Production Rate (MMgal/year)	UW Production Rate (Mmgal/year)	Scaled Purchase Cost	Purchased Cost in Projected Year	Installed Cost in Projected Year
Storage	Denaturant In-line Mixer	1	$3,900	2009	22,000	kg/hr	0.5	1	61	17.69	$2,000	$2,200	$2,200
	CSL Storage Tank Agitator	1	$21,000	2009	1,300	kg/hr	0.5	1.5	61	17.69	$11,000	$12,000	$18,000
	DAP Make-up Tank Agitator	1	$9,800	2009	140	kg/hr	0.5	1.5	61	17.69	$4,900	$5,400	$8,000
	DAP Bulk Bag Unloader	1	$30,000	2009	140	kg/hr	0.6	1.7	61	17.69	$13,000	$14,000	$24,000
	Ethanol Product Pump	2	$9,200	2009	22,000	kg/hr	0.8	3.1	61	17.69	$3,300	$3,600	$11,000
	Sulfuric Acid Pump	1	$7,500	2010	2,000	kg/hr	0.8	2.3	61	17.69	$2,800	$2,900	$6,600
	Firewater Pump	1	$15,000	2009	8,000	kg/hr	0.8	3.1	61	17.69	$5,400	$5,900	$18,000
	Gasoline Pump	1	$3,000	2009	460	kg/hr	0.8	3.1	61	17.69	$1,100	$1,200	$3,700
	CSL Pump	1	$3,000	2009	1,300	kg/hr	0.8	3.1	61	17.69	$1,100	$1,200	$3,600
	DAP Pump	1	$3,000	2009	140	kg/hr	0.8	3.1	61	17.69	$1,000	$1,100	$3,400
	Ethanol Product Storage Tank	2	$1,300,000	2009	22,000	kg/hr	0.7	1.7	61	17.69	$550,000	$600,000	$1,000,000
	Sulfuric Acid Storage Tank	1	$96,000	2010	2,000	kg/hr	0.7	1.5	61	17.69	$40,000	$42,000	$62,000
	Firewater Storage Tank	1	$800,000	2009	8,000	kg/hr	0.7	1.7	61	17.69	$330,000	$360,000	$610,000
	Ammonia Storage Tank	2	$200,000	2010	1,200	kg/hr	0.7	2	61	17.69	$82,000	$85,000	$170,000
	Gasoline Storage Tank	1	$200,000	2009	460	kg/hr	0.7	1.7	61	17.69	$83,000	$90,000	$150,000
	CSL Storage Tank	1	$70,000	2009	1,300	kg/hr	0.7	2.6	61	17.69	$28,000	$31,000	$80,000
	DAP Make-up Tank	1	$100,000	2009	1,200	kg/hr	0.7	1.8	61	17.69	$34,000	$37,000	$67,000
										Storage Totals	**$1,200,000**	**$1,300,000**	**$2,300,000**

In the integrated model the combustor, boiler, and turbogenerator section was omitted because organic waste streams will be combusted in the co-located powerplant. Therefore, the integrated model did not include an equipment cost evaluation for the combustor, boiler, and turbogenerator section. Table 4.12 shows the combustor, boiler, and turbogenerator equipment costs for the stand-alone model.

Table 4.12 Combustor, boiler, and turbogenerator equipment costs for the stand-alone Centralia biorefinery

Area	Equipment Title	Number Required	Purchased Cost in Quoted Year	Year of Quote	Flow Rate of NREL Equipment	Flow Rate Units	Scaling Exponent	Installation Factor	NREL Production Rate (MMgal/year)	UW Production Rate (Mmgal/year)	Scaled Purchase Cost	Purchased Cost in Projected Year	Installed Cost in Projected Year
Burner, Boiler, Turbogenerator	Pretreatment/BFW heat recovery	1	$41,000	2009	-2	Gcal/hr	0.7	2.2	61	17.69	$17,000	$18,000	$40,000
	Boiler	1	$29,000,000	2010	230,000	kg/hr	0.6	1.8	61	17.69	$13,000,000	$14,000,000	$25,000,000
	Turbine/Generator	1	$9,500,000	2010	-41,000	kW	0.6	1.8	61	17.69	$4,500,000	$4,600,000	$8,300,000
	Hot Process Water Softener System	1	$78,000	2010	230,000	kg/hr	0.6	1.8	61	17.69	$37,000	$38,000	$69,000
	Amine Addition Pkg.	1	$40,000	2010	230,000	kg/hr	0	1.8	61	17.69	$40,000	$41,000	$74,000
	Deaerator	1	$310,000	2010	230,000	kg/hr	0.6	3	61	17.69	$140,000	$150,000	$450,000
										Burner, Boiler, Turbogenerator Totals	**$18,000,000**	**$19,000,000**	**$34,000,000**

Finally, equipment costs for the utilities section remained the same for both models. Table 4.13 shows the utilities equipment costs for both the stand-alone and integrated models.

Table 4.13 Utilities equipment costs for the stand-alone and integrated Centralia biorefinery

Area	Equipment Title	Number Required	Purchased Cost in Quoted Year	Year of Quote	Flow Rate of NREL Equipment	Flow Rate Units	Scaling Exponent	Installation Factor	NREL Production Rate (MMgal/year)	UW Production Rate (Mmgal/year)	Scaled Purchase Cost	Purchased Cost in Projected Year	Installed Cost in Projected Year
Utilities	Cooling Tower System	1	$1,400,000	2010	12,000,000	kg/hr	0.6	1.5	61	17.69	$730,000	$750,000	$1,100,000
	Plant Air Compressor	1	$28,000	2010	83,000	kg/hr	0.6	1.6	61	17.69	$13,000	$14,000	$22,000
	Chilled Water Package	1	$1,300,000	2010	13	Gcal/hr	0.6	1.6	61	17.69	$590,000	$610,000	$970,000
	CIP System	1	$420,000	2009	150	kg/hr	0.6	1.8	61	17.69	$330,000	$360,000	$650,000
	Cooling Water Pump	3	$280,000	2010	12,000,000	kg/hr	0.8	3.1	61	17.69	$110,000	$120,000	$360,000
	Make-up Water Pump	1	$6,900	2010	150,000	kg/hr	0.8	3.1	61	17.69	$2,400	$2,500	$7,800
	Process Water Circulating Pump	1	$15,000	2010	520,000	kg/hr	0.8	3.1	61	17.69	$5,700	$5,900	$18,000
	Instrument Air Dryer	1	$15,000	2009	83,000	kg/hr	0.6	1.8	61	17.69	$7,100	$7,800	$14,000
	Plant Air Receiver	1	$16,000	2009	83,000	kg/hr	0.6	3.1	61	17.69	$7,600	$8,300	$26,000
	Process Water Tank No. 1	1	$250,000	2009	520,000	kg/hr	0.7	1.7	61	17.69	$120,000	$130,000	$220,000
										Utilities Totals	$1,900,000	$2,000,000	$3,400,000

The installed capital equipment costs for the stand-alone and integrated biorefinery models are summarized in Figure 4.12. Figure 4.12 shows that the integrated model has a much lower total installed equipment cost than the stand-alone model. This is mainly due to replacement of the combustor, boiler, and turbogenerator and wastewater treatment sections with the pre-existent powerplant.

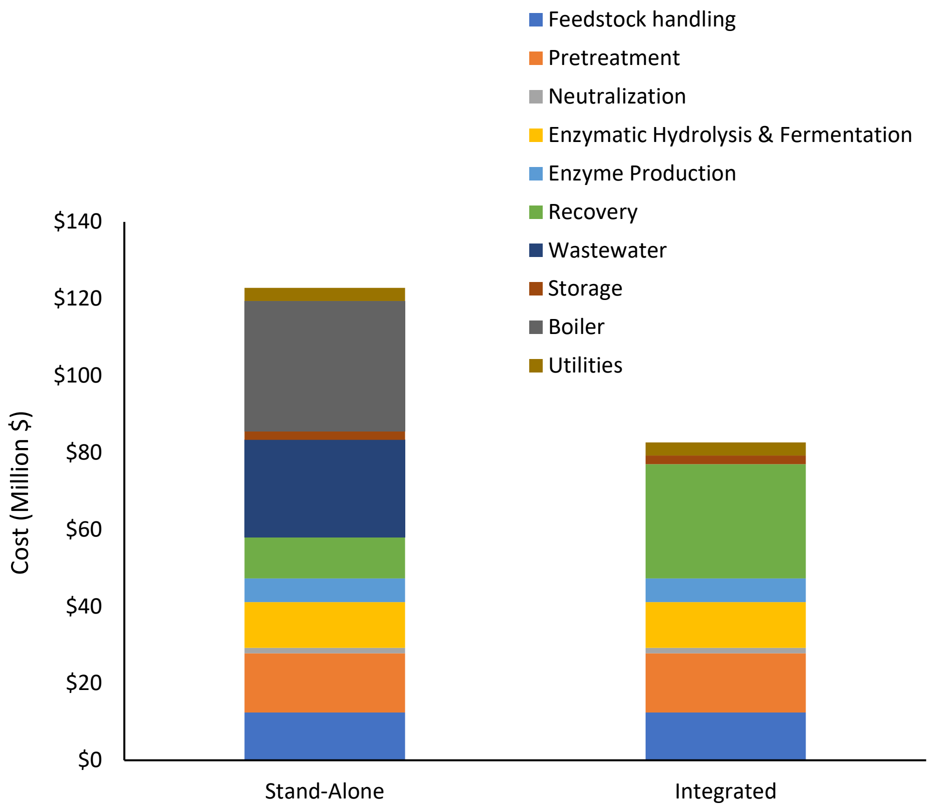


Figure 4.12 Installed capital equipment cost comparison

4.3.6 Total Capital Investment

In this section the total capital investment (TCI) for each case study was determined. Capital costs were dependent on the stand-alone and integrated scenarios or in other words, changes in feedstock costs did not affect capital cost calculations. Therefore, this section only compares the TCI for the stand-alone and integrated biorefinery models. TCI was a summation of the total indirect cost, fixed capital investment (FCI), and land cost [69]. The total indirect cost was determined through a summation of the proratable expenses, field expenses, home office and construction fee, project contingency, and other costs (start-up, permits, etc.) [69]. These costs were a function of the total direct costs (TDC). This analysis assumed that the proratable expenses, field expenses, project contingency, and other costs were 10% of the TDC and the home office and construction fee was 20% of the TDC [69]. The TDC was a summation of the total installed equipment costs (determined in Section 4.3.4), warehouse (4% of ISBL), site development (9% of ISBL), and additional piping (5% of ISBL) [69]. Land costs were determined through an assumption that the land required was 38 acres at a price of $14,000 per acre [34]. The TCI calculation for the stand-alone biorefinery model is shown in Table 4.20 and the TCI calculation for the integrated biorefinery model is shown in Table 4.21.

4.20 Total capital investment for stand-alone Centralia biorefinery

Total Capital Investment			
Process Area		Purchased Cost	Installed Cost
Area 100: Feedstock handling*		$7,302,523	$12,414,289
Area 200: Pretreatment		$10,250,747	$15,376,120
Area 200: Neutralization		$721,349	$1,408,715
Area 300: Enzymatic Hydrolysis & Fermentation		$6,897,499	$11,924,188
Area 400: Enzyme Production		$3,592,254	$6,142,220
Area 500: Recovery		$5,284,350	$10,712,103
Area 600: Wastewater		$25,335,019	$25,335,019
Area 700: Storage		$1,287,476	$2,252,053
Area 800: Boiler		$18,705,913	$33,856,813
Area 900: Utilities		$1,992,720	$3,398,622
Totals (Excl. Area 100)		$74,067,328	$110,405,852
Warehouse	4% of ISBL		$1,822,534
Site Development	9% of ISBL		$4,100,701
Additional Piping	5% of ISBL		$2,050,351
Total Direct Costs (TDC)			$118,379,437
Prorateable Expenses	10% of TDC		$11,837,944
Field Expenses	10% of TDC		$11,837,944
Home Office & Construction Fee	20% of TDC		$23,675,887
Project Contingency	10% of TDC		$11,837,944
Other Costs (Start-Up, Permits, etc.)	10% of TDC		$11,837,944
Total Indirect Costs			$71,027,662
Fixed Capital Investment (FCI)			$189,407,099
Land			$532,000
Working Capital	5% of FCI		$9,470,355
Total Capital Investment (TCI)			$199,409,454
Inside Battery Limits (ISBL)			$45,563,345

4.21 Total capital investment for integrated Centralia biorefinery

Total Capital Investment			
Process Area		Purchased Cost	Installed Cost
Area 100: Feedstock handling*		$7,302,523	$12,414,289
Area 200: Pretreatment		$10,250,747	$15,376,120
Area 200: Neutralization		$721,349	$1,408,715
Area 300: Enzymatic Hydrolysis & Fermentation		$6,897,499	$11,924,188
Area 400: Enzyme Production		$3,592,254	$6,142,220
Area 500: Recovery		$16,473,968	$29,734,453
Area 600: Wastewater		$0	$0
Area 700: Storage		$1,287,476	$2,252,053
Area 800: Boiler		$0	$0
Area 900: Utilities		$1,992,720	$3,398,622
Totals (Excl. Area 100)		$41,216,013	$70,236,370
Warehouse	4% of ISBL		$2,583,428
Site Development	9% of ISBL		$5,812,713
Additional Piping	5% of ISBL		$2,906,356
Total Direct Costs (TDC)			$81,538,866
Prorateable Expenses	10% of TDC		$8,153,887
Field Expenses	10% of TDC		$8,153,887
Home Office & Construction Fee	20% of TDC		$16,307,773
Project Contingency	10% of TDC		$8,153,887
Other Costs (Start-Up, Permits, etc.)	10% of TDC		$8,153,887
Total Indirect Costs			$48,923,320
Fixed Capital Investment (FCI)			$130,462,186
Land			$532,000
Working Capital	5% of FCI		$6,523,109
Total Capital Investment (TCI)			$179,917,506
Inside Battery Limits (ISBL)			$64,585,695

4.3.7 VARIABLE AND FIXED OPERATING COSTS

Variable operating costs of the Centralia biorefinery were dependent on the specified case study. The stand-alone and integrated models had different variable operating costs because they possessed different stream allocations. Table 4.14 shows the variable operating costs for the dedicated poplar, stand-alone biorefinery model. Table 4.15 shows the variable operating costs for the dedicated poplar, integrated biorefinery.

Table 4.14 Variable operating costs for dedicated poplar, stand-alone biorefinery

Variable Operating Costs										
	Raw Material	NREL (kg/hr)	UW (kg/hr)	Quoted Price (cents / ton)	Year of Price Quote	2018 Cost (cents/ton)	2018 Cost ($/kg)	Cost ($/hr)	Cost (MM$/yr)	Ethanol Cost ($/gal)
Raw Materials										
	Feedstock	104,166.67	53,934.88	3,717.50	2018	3,717.50	$0.04	$2,210.17	$18.59	$1.05
Pretreatment and Conditioning	Sulfuric Acid, 93%	1,980.61	574.38	9,000.00	2009	12,520.69	$0.14	$79.27	$0.67	$0.04
	Ammonia	1,050.82	304.74	45,000.00	2009	62,603.47	$0.69	$210.29	$1.77	$0.10
Enzymatic Hydrolysis and Fermentation	Corn Steep Liquor	1,159.32	336.20	5,700.00	2009	7,929.77	$0.09	$29.39	$0.25	$0.01
	Diammonium Phosph	142.28	41.26	99,000.00	2009	137,727.64	$1.52	$62.64	$0.53	$0.03
	Sorbitol	44.37	12.87	113,000.00	2009	157,204.27	$1.73	$22.30	$0.19	$0.01
Cellulase Enzyme Production	Purchased Enzyme	0.00	0.00	0.00	2007	0.00	$0.00	$0.00	$0.00	$0.00
	Glucose	2,417.97	701.21	40,000.00	2018	40,000.00	$0.44	$309.18	$2.60	$0.15
	Corn Steep Liquor	164.49	47.70	5,700.00	2009	7,929.77	$0.09	$4.17	$0.04	$0.00
	Ammonia	114.97	33.34	45,000.00	2009	62,603.47	$0.69	$23.01	$0.19	$0.01
	Host nutrients	67.35	19.53	74,530.00	2007	114,599.50	$1.26	$24.67	$0.21	$0.01
	Sulfur Dioxide	16.42	4.76	25,400.00	2005	42,392.10	$0.47	$2.22	$0.02	$0.00
Wastewater Treatment	Caustic (as pure)	2,251.98	653.08	15,000.00	2009	20,867.82	$0.23	$150.23	$1.26	$0.07
Burner, Boiler, Turbogenerator	Boiler Chems	0.25	0.07	280,000.00	1991	696,878.98	$7.68	$0.55	$0.00	$0.00
	FGD Lime	894.45	259.39	20,000.00	2009	27,823.77	$0.31	$79.56	$0.67	$0.04
	Feedstock	0.00	0.00	3,717.50	2018	3,717.50	$0.04	$0.00	$0.00	$0.00
Utilities	Cooling Tower Chems	2.38	0.69	200,000.00	1999	417,635.27	$4.60	$3.18	$0.03	$0.00
	Makeup Water	147,136.26	42,669.52	54.00	2018	54.00	$0.00	$25.40	$0.21	$0.01
	Subtotal							$3,210.84	$27.22	$1.54
Waste Streams										
Burner, Boiler, Turbogenerator	Disposal of Ash	5724.07	1,659.98	1814	2018	1,814.00	$0.02	$33.19	$0.28	$0.02
	Subtotal							$33.19	$0.28	$0.02
Electricity		kW	kW	(cents/kWh)			$/kWh			
	Grid Electricity	12814.15	3,716.10	4	2018	4.00	0.04	$148.64	$1.25	$0.07
	Area 100 Electricity	859.48	249.25	4	2018	4.00	0.04	$9.97	$0.08	$0.00
	Subtotal							$158.61	$1.33	$0.08
Total Variable Operating Costs								**$3,085.41**	**$26.16**	**$1.63**

Table 4.15 Variable operating costs for dedicated poplar, integrated biorefinery

Variable Operating Costs										
	Raw Material	NREL (kg/hr)	UW (kg/hr)	Quoted Price (cents / ton)	Year of Price Quote	2018 Cost (cents/ton)	2018 Cost ($/kg)	Cost ($/hr)	Cost (MM$/yr)	Ethanol Cost ($/gal)
Raw Materials										
	Feedstock	104,166.67	53,934.88	3,717.50	2018	3,717.50	$0.04	$2,210.17	$18.59	$1.05
Pretreatment and Conditioning	Sulfuric Acid, 93%	1,980.61	574.38	9,000.00	2009	12,520.69	$0.14	$79.27	$0.67	$0.04
	Ammonia	1,050.82	304.74	45,000.00	2009	62,603.47	$0.69	$210.29	$1.77	$0.10
Enzymatic Hydrolysis and Fermentation	Corn Steep Liquor	1,159.32	336.20	5,700.00	2009	7,929.77	$0.09	$29.39	$0.25	$0.01
	Diammonium Phosph	142.28	41.26	99,000.00	2009	137,727.64	$1.52	$62.64	$0.53	$0.03
	Sorbitol	44.37	12.87	113,000.00	2009	157,204.27	$1.73	$22.30	$0.19	$0.01
Cellulase Enzyme Production	Purchased Enzyme	0.00	0.00	0.00	2007	0.00	$0.00	$0.00	$0.00	$0.00
	Glucose	2,417.97	701.21	40,000.00	2018	40,000.00	$0.44	$309.18	$2.60	$0.15
	Corn Steep Liquor	164.49	47.70	5,700.00	2009	7,929.77	$0.09	$4.17	$0.04	$0.00
	Ammonia	114.97	33.34	45,000.00	2009	62,603.47	$0.69	$23.01	$0.19	$0.01
	Host nutrients	67.35	19.53	74,530.00	2007	114,599.50	$1.26	$24.67	$0.21	$0.01
	Sulfur Dioxide	16.42	4.76	25,400.00	2005	42,392.10	$0.47	$2.22	$0.02	$0.00
Wastewater Treatment	Caustic (as pure)	2,251.98	0.00	15,000.00	2009	20,867.82	$0.23	$0.00	$0.00	$0.00
Burner, Boiler, Turbogenerator	Boiler Chems	0.25	0.00	280,000.00	1991	696,878.98	$7.68	$0.00	$0.00	$0.00
	FGD Lime	894.45	0.00	20,000.00	2009	27,823.77	$0.31	$0.00	$0.00	$0.00
	Feedstock	0.00	0.00	3,717.50	2018	3,717.50	$0.04	$0.00	$0.00	$0.00
Utilities	Cooling Tower Chems	2.38	0.69	200,000.00	1999	417,635.27	$4.60	$3.18	$0.03	$0.00
	Makeup Water	147,136.26	42,669.52	54.00	2018	54.00	$0.00	$25.40	$0.21	$0.01
	Subtotal							$2,980.50	$25.28	$1.43
Waste Streams										
Burner, Boiler, Turbogenerator	Disposal of Ash	5724.07	0.00	1814	2018	1,814.00	$0.02	$0.00	$0.00	$0.00
	Subtotal							$0.00	$0.00	$0.00
Electricity		kW	kW	(cents/kWh)			$/kWh			
	Grid Electricity	12814.00	9,726.23	4	2018	4.00	0.04	$389.05	$3.27	$0.18
	Area 100 Electricity	859.48	249.25	4	2018	4.00	0.04	$9.97	$0.08	$0.00
	Subtotal							$399.02	$3.36	$0.19
Total Variable Operating Costs								**$2,581.48**	**$21.92**	**$1.62**

The variable operating costs in the integrated model were altered to reflect the major design changes in the model. By comparing Table 4.14 and Table 4.15 it is apparent that the wastewater treatment and combustor, boiler, and turbogenerator raw material streams were removed to reflect the omission of these two sections in the model. Furthermore, the disposal of the ash waste stream in the integrated biorefinery was removed because this waste is now be produced in the co-located powerplant. The final difference between the two models is that an additional electricity requirement was added to the integrated model to reflect the additional electricity usage required by the multi-effect evaporator. The additional electricity usage was derived from Choyuk's multi-effect evaporator model and scaled to match this model [34].

The feedstock cost of each model was adjusted to reflect its respective feedstock. For example, the dedicated poplar feedstock costed $74.35/ODT and the mixed feedstock costed $48.82/ODT. The feedstock cost in the variable operating costs were altered to match the feedstock utilized in each case model. Table 4.16 shows the variable operating costs for the mixed poplar, stand-alone biorefinery and Table 4.17 shows the variable operating costs for the mixed poplar, integrated biorefinery.

Table 4.16 Variable operating costs for mixed poplar, stand-alone biorefinery

Variable Operating Costs										
	Raw Material	NREL (kg/hr)	UW (kg/hr)	Quoted Price (cents / ton)	Year of Price Quote	2018 Cost (cents/ton)	2018 Cost ($/kg)	Cost ($/hr)	Cost (MM$/yr)	Ethanol Cost ($/gal)
Raw Materials										
	Feedstock	104,166.67	53,934.88	2,441.00	2018	2,441.00	$0.03	$1,451.25	$12.20	$0.69
Pretreatment and Conditioning	Sulfuric Acid, 93%	1,980.61	574.38	9,000.00	2009	12,520.69	$0.14	$79.27	$0.67	$0.04
	Ammonia	1,050.82	304.74	45,000.00	2009	62,603.47	$0.69	$210.29	$1.77	$0.10
Enzymatic Hydrolysis and Fermentation	Corn Steep Liquor	1,159.32	336.20	5,700.00	2009	7,929.77	$0.09	$29.39	$0.25	$0.01
	Diammonium Phosph	142.28	41.26	99,000.00	2009	137,727.64	$1.52	$62.64	$0.53	$0.03
	Sorbitol	44.37	12.87	113,000.00	2009	157,204.27	$1.73	$22.30	$0.19	$0.01
Cellulase Enzyme Production	Purchased Enzyme	0.00	0.00	0.00	2007	0.00	$0.00	$0.00	$0.00	$0.00
	Glucose	2,417.97	701.21	40,000.00	2018	40,000.00	$0.44	$309.18	$2.60	$0.15
	Corn Steep Liquor	164.49	47.70	5,700.00	2009	7,929.77	$0.09	$4.17	$0.04	$0.00
	Ammonia	114.97	33.34	45,000.00	2009	62,603.47	$0.69	$23.01	$0.19	$0.01
	Host nutrients	67.35	19.53	74,530.00	2007	114,599.50	$1.26	$24.67	$0.21	$0.01
	Sulfur Dioxide	16.42	4.76	25,400.00	2005	42,392.10	$0.47	$2.22	$0.02	$0.00
Wastewater Treatment	Caustic (as pure)	2,251.98	653.08	15,000.00	2009	20,867.82	$0.23	$150.23	$1.26	$0.07
Burner, Boiler, Turbogenerator	Boiler Chems	0.25	0.07	280,000.00	1991	696,878.98	$7.68	$0.55	$0.00	$0.00
	FGD Lime	894.45	259.39	20,000.00	2009	27,823.77	$0.31	$79.56	$0.67	$0.04
	Feedstock	0.00	0.00	2,441.00	2018	2,441.00	$0.03	$0.00	$0.00	$0.00
Utilities	Cooling Tower Chems	2.38	0.69	200,000.00	1999	417,635.27	$4.60	$3.18	$0.03	$0.00
	Makeup Water	147,136.26	42,669.52	54.00	2018	54.00	$0.00	$25.40	$0.21	$0.01
	Subtotal							$2,451.92	$20.83	$1.18
Waste Streams										
Burner, Boiler, Turbogenerator	Disposal of Ash	5724.07	1,659.98	1814	2018	1,814.00	$0.02	$33.19	$0.28	$0.02
	Subtotal							$33.19	$0.28	$0.02
Electricity		kW	kW	(cents/kWh)			$/kWh			
	Grid Electricity	12814.15	3,716.10	4	2018	4.00	0.04	$148.64	$1.25	$0.07
	Area 100 Electricity	859.48	249.25	4	2018	4.00	0.04	$9.97	$0.08	$0.00
	Subtotal							$158.61	$1.33	$0.08
Total Variable Operating Costs								**$2,326.50**	**$19.78**	**$1.27**

Table 4.17 Variable operating costs for mixed poplar, integrated biorefinery

Variable Operating Costs										
	Raw Material	NREL (kg/hr)	UW (kg/hr)	Quoted Price (cents / ton)	Year of Price Quote	2018 Cost (cents/ton)	2018 Cost ($/kg)	Cost ($/hr)	Cost (MM$/yr)	Ethanol Cost ($/gal)
Raw Materials										
	Feedstock	104,166.67	53,934.88	2,441.00	2018	2,441.00	$0.03	$1,451.25	$12.20	$0.69
Pretreatment and Conditioning	Sulfuric Acid, 93%	1,980.61	574.38	9,000.00	2009	12,520.69	$0.14	$79.27	$0.67	$0.04
	Ammonia	1,050.82	304.74	45,000.00	2009	62,603.47	$0.69	$210.29	$1.77	$0.10
Enzymatic Hydrolysis and Fermentation	Corn Steep Liquor	1,159.32	336.20	5,700.00	2009	7,929.77	$0.09	$29.39	$0.25	$0.01
	Diammonium Phosph	142.28	41.26	99,000.00	2009	137,727.64	$1.52	$62.64	$0.53	$0.03
	Sorbitol	44.37	12.87	113,000.00	2009	157,204.27	$1.73	$22.30	$0.19	$0.01
Cellulase Enzyme Production	Purchased Enzyme	0.00	0.00	0.00	2007	0.00	$0.00	$0.00	$0.00	$0.00
	Glucose	2,417.97	701.21	40,000.00	2018	40,000.00	$0.44	$309.18	$2.60	$0.15
	Corn Steep Liquor	164.49	47.70	5,700.00	2009	7,929.77	$0.09	$4.17	$0.04	$0.00
	Ammonia	114.97	33.34	45,000.00	2009	62,603.47	$0.69	$23.01	$0.19	$0.01
	Host nutrients	67.35	19.53	74,530.00	2007	114,599.50	$1.26	$24.67	$0.21	$0.01
	Sulfur Dioxide	16.42	4.76	25,400.00	2005	42,392.10	$0.47	$2.22	$0.02	$0.00
Wastewater Treatment	Caustic (as pure)	2,251.98	0.00	15,000.00	2009	20,867.82	$0.23	$0.00	$0.00	$0.00
Burner, Boiler, Turbogenerator	Boiler Chems	0.25	0.00	280,000.00	1991	696,878.98	$7.68	$0.00	$0.00	$0.00
	FGD Lime	894.45	0.00	20,000.00	2009	27,823.77	$0.31	$0.00	$0.00	$0.00
	Feedstock	0.00	0.00	2,441.00	2018	2,441.00	$0.03	$0.00	$0.00	$0.00
Utilities	Cooling Tower Chems	2.38	0.69	200,000.00	1999	417,635.27	$4.60	$3.18	$0.03	$0.00
	Makeup Water	147,136.26	42,669.52	54.00	2018	54.00	$0.00	$25.40	$0.21	$0.01
	Subtotal							$2,221.59	$18.90	$1.07
Waste Streams										
Burner, Boiler, Turbogenerator	Disposal of Ash	5724.07	0.00	1814	2018	1,814.00	$0.02	$0.00	$0.00	$0.00
	Subtotal							$0.00	$0.00	$0.00
Electricity		kW	kW	(cents/kWh)			$/kWh			
	Grid Electricity	12814.00	9,726.23	4	2018	4.00	0.04	$389.05	$3.27	$0.18
	Area 100 Electricity	859.48	249.25	4	2018	4.00	0.04	$9.97	$0.08	$0.00
	Subtotal							$399.02	$3.36	$0.19
Total Variable Operating Costs								**$1,822.57**	**$15.54**	**$1.26**

Fixed operating costs included employment, maintenance, property insurance and taxes. Employment costs were assumed to be constant because the size of a biorefinery did not bear a large impact on the number of employees at the facility. Maintenance costs were defined as a function of the inside battery limit costs (ISBL), which was the sum of installed costs for the pretreatment and conditioning, enzymatic hydrolysis and fermentation, enzyme production, and product recovery sections. This analysis assumed that maintenance costs were 3.0% of the ISBL costs [69]. Property insurance and tax costs were defined as a function of the fixed capital investment (FCI), which was discussed in Section 4.3.5. This analysis assumed that property insurance and tax costs were 0.7% of the FCI [69]. Since, maintenance and property insurance and tax costs are dependent on the capital costs of the biorefinery, the integrated and stand-alone models had different fixed costs. Table 4.18 shows the fixed operating costs for the stand-alone biorefinery model. Table 4.19 shows the fixed operating costs for the integrated biorefinery model. Figure 4.13 summarizes the operating costs for the four Centralia biorefinery case studies.

Table 4.18 Fixed operating costs for stand-alone Centralia biorefinery

Fixed Operating Costs								
	Position	Salary ($/yr)	Year of salary quote	2018 Salary ($/yr)	Number Required	Total ($/yr)	Cost (MM$/yr)	Ethanol Cost ($/gal)
Labor & Supervision								
	Plant Manager	$147,000.00	2009	$182,555.17	1	$182,555.17		
	Plant Engineer	$70,000.00	2009	$86,931.03	2	$173,862.07		
	Maintenance Supr	$57,000.00	2009	$70,786.70	1	$70,786.70		
	Maintenance Tech	$40,000.00	2009	$49,674.88	12	$596,098.52		
	Lab Manager	$56,000.00	2009	$69,544.83	1	$69,544.83		
	Lab Technician	$40,000.00	2009	$49,674.88	2	$99,349.75		
	Lab Tech-Enzyme	$40,000.00	2009	$49,674.88	2	$99,349.75		
	Shift Supervisor	$48,000.00	2009	$59,609.85	4	$238,439.41		
	Shift Operators	$40,000.00	2009	$49,674.88	20	$993,497.54		
	Shift Oper-Enzyme	$40,000.00	2009	$49,674.88	8	$397,399.01		
	Yard Employees	$28,000.00	2009	$34,772.41	4	$139,089.66		
	Clerks & Secretaries	$36,000.00	2009	$44,707.39	3	$134,122.17		
	Total Salaries					$3,194,094.58	$3.19	$0.18
	Labor Burden (90%)					$2,874,685.12	$2.87	$0.16
Other Overhead								
	Maintenance	3.00%	of ISBL			$1,366,900	$1.37	$0.08
	Property Insur. & Tax	0.70%	of FCI			$1,325,850	$1.33	$0.07
Total Fixed Operating Costs							$8.76	$0.50

Table 4.19 Fixed operating costs for integrated Centralia biorefinery

Fixed Operating Costs								
	Position	Salary ($/yr)	Year of salary quote	2018 Salary ($/yr)	Number Required	Total ($/yr)	Cost (MM$/yr)	Ethanol Cost ($/gal)
Labor & Supervision								
	Plant Manager	$147,000.00	2009	$182,555.17	1	$182,555.17		
	Plant Engineer	$70,000.00	2009	$86,931.03	2	$173,862.07		
	Maintenance Supr	$57,000.00	2009	$70,786.70	1	$70,786.70		
	Maintenance Tech	$40,000.00	2009	$49,674.88	12	$596,098.52		
	Lab Manager	$56,000.00	2009	$69,544.83	1	$69,544.83		
	Lab Technician	$40,000.00	2009	$49,674.88	2	$99,349.75		
	Lab Tech-Enzyme	$40,000.00	2009	$49,674.88	2	$99,349.75		
	Shift Supervisor	$48,000.00	2009	$59,609.85	4	$238,439.41		
	Shift Operators	$40,000.00	2009	$49,674.88	20	$993,497.54		
	Shift Oper-Enzyme	$40,000.00	2009	$49,674.88	8	$397,399.01		
	Yard Employees	$28,000.00	2009	$34,772.41	4	$139,089.66		
	Clerks & Secretaries	$36,000.00	2009	$44,707.39	3	$134,122.17		
	Total Salaries					$3,194,094.58	$3.19	$0.18
	Labor Burden (90%)					$2,874,685.12	$2.87	$0.16
Other Overhead								
	Maintenance	3.00%	of ISBL			$1,937,571	$1.94	$0.11
	Property Insur. & Tax	0.70%	of FCI			$913,235	$0.91	$0.05
Total Fixed Operating Costs							$8.92	$0.50

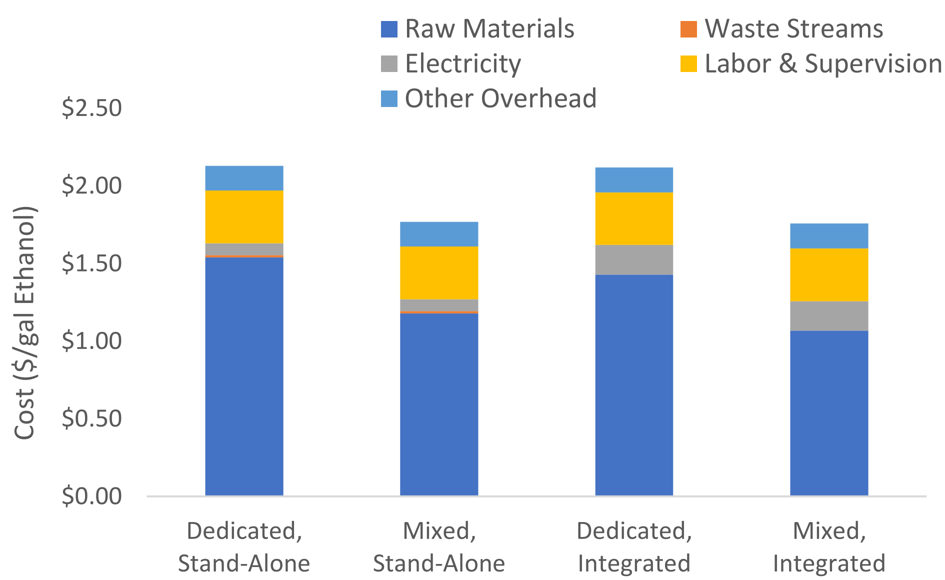


Figure 4.13 Operating cost comparison

4.3.8 DISCOUNTED CASH FLOW ANALYSIS AND MINIMUM ETHANOL SELLING PRICE

A discounted cash flow (DCF) analysis was performed to determine the minimum ethanol selling price (MESP). The DCF analysis determined the MESP by iteratively calculating the ethanol price until the net present value of the project was equal to zero [69]. The discount rate (DR) in this analysis was equal to the internal rate of return (IRR) and is set to 0%, 7%, and 15%. This economic analysis time horizon was assumed to be 10 years. The biorefinery was equity financed at 40% with an 8% interest rate for 10 years. The biorefinery was depreciated over the course of its lifetime for a total of 90% of the capital investment. Startup time for the biorefinery was one year, in which only 50% of the biorefinery capacity was utilized. Taxes and subsidies were not accounted for in this DCF because this is a new industry that may receive tax breaks and the subsidy situation remains unclear. Tables 4.22 shows an example DCF for the mixed poplar, integrated biorefinery at 15% DR. A DCF was performed for each Centralia biorefinery case-study at 0%, 7%, and 15% DR.

Table 4.22 Mixed poplar, integrated biorefinery DCF at 15% DR

Ethanol Production	17,690,000	gal/yr
Capital Cost	$130,462,186	
Dep Capital Costs	$117,415,967	
Borrowed Funds	$52,184,874	
Variable Cost	$15,541,389	
Fixed Costs	$8,919,586	
APR	5.00%	
Ethanol Price	$2.89	
Discount Rate	15%	

Year	0	1	2	3	4	5	6	7	8	9	10
Number of Units	0	8,845,000	17,690,000	17,690,000	17,690,000	17,690,000	17,690,000	17,690,000	17,690,000	17,690,000	17,690,000
Sale Price	$ 2.89	$ 2.89	$ 2.89	$ 2.89	$ 2.89	$ 2.89	$ 2.89	$ 2.89	$ 2.89	$ 2.89	$ 2.89
Ethanol Revenue	$ -	$ 25,602,719	$ 51,205,438	$ 51,205,438	$ 51,205,438	$ 51,205,438	$ 51,205,438	$ 51,205,438	$ 51,205,438	$ 51,205,438	$ 51,205,438
Net Revenue	$ -	$ 25,602,719	$ 51,205,438	$ 51,205,438	$ 51,205,438	$ 51,205,438	$ 51,205,438	$ 51,205,438	$ 51,205,438	$ 51,205,438	$ 51,205,438
Variable Costs	$ -	$ (7,770,695)	$ (15,541,389)	$ (15,541,389)	$ (15,541,389)	$ (15,541,389)	$ (15,541,389)	$ (15,541,389)	$ (15,541,389)	$ (15,541,389)	$ (15,541,389)
Fixed Costs	$ -	$ (8,919,586)	$ (8,919,586)	$ (8,919,586)	$ (8,919,586)	$ (8,919,586)	$ (8,919,586)	$ (8,919,586)	$ (8,919,586)	$ (8,919,586)	$ (8,919,586)
Gross Margin	$ -	$ 8,912,438	$ 26,744,463	$ 26,744,463	$ 26,744,463	$ 26,744,463	$ 26,744,463	$ 26,744,463	$ 26,744,463	$ 26,744,463	$ 26,744,463
Depreciation	$ -	$ (11,741,597)	$ (11,741,597)	$ (11,741,597)	$ (11,741,597)	$ (11,741,597)	$ (11,741,597)	$ (11,741,597)	$ (11,741,597)	$ (11,741,597)	$ (11,741,597)
Interest on Loan	$ -	$ (2,609,244)	$ (2,401,797)	$ (2,183,978)	$ (1,955,268)	$ (1,715,122)	$ (1,462,969)	$ (1,198,209)	$ (920,210)	$ (628,312)	$ (321,818)
Net Income	$ -	$ (5,438,402)	$ 12,601,069	$ 12,818,888	$ 13,047,598	$ 13,287,744	$ 13,539,897	$ 13,804,657	$ 14,082,656	$ 14,374,555	$ 14,681,048
Tax (21%)	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Income after Tax	$ -	$ (5,438,402)	$ 12,601,069	$ 12,818,888	$ 13,047,598	$ 13,287,744	$ 13,539,897	$ 13,804,657	$ 14,082,656	$ 14,374,555	$ 14,681,048
Net Income	$ -	$ (5,438,402)	$ 12,601,069	$ 12,818,888	$ 13,047,598	$ 13,287,744	$ 13,539,897	$ 13,804,657	$ 14,082,656	$ 14,374,555	$ 14,681,048
Depreciation	$ -	$ 11,741,597	$ 11,741,597	$ 11,741,597	$ 11,741,597	$ 11,741,597	$ 11,741,597	$ 11,741,597	$ 11,741,597	$ 11,741,597	$ 11,741,597
Fixed Capital	$ (130,462,186)	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Working Capital	$ (6,523,109)	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Borrowed Funds	$ 52,184,874	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Principle Payment	$ -	$ (4,148,936)	$ (4,356,383)	$ (4,574,202)	$ (4,802,912)	$ (5,043,058)	$ (5,295,211)	$ (5,559,971)	$ (5,837,970)	$ (6,129,868)	$ (6,436,362)
Net Cash Flow	$ (84,800,421)	$ 2,154,258	$ 19,986,283	$ 19,986,283	$ 19,986,283	$ 19,986,283	$ 19,986,283	$ 19,986,283	$ 19,986,283	$ 19,986,283	$ 19,986,283
Cash Position	$ (84,800,421)	$ (82,646,162)	$ (62,659,880)	$ (42,673,597)	$ (22,687,314)	$ (2,701,031)	$ 17,285,252	$ 37,271,534	$ 57,257,817	$ 77,244,100	$ 97,230,383

ROI	8.95%
NPV	$ -
IRR	15%

4.3.9 ETHANOL PRICE

This techno-economic analysis evaluated a biorefinery on the minimum selling price of its product, ethanol, to remain competitive and profitable. The minimum ethanol selling price (MESP) was determined for each biorefinery case-study and compared to the current ethanol price. The current ethanol price was calculated through the sum of its current market valuation and Renewable Fuel Standard (RFS) credits. Under the RFS, advanced biofuels can be issued a Renewable Identification Number (RIN) that is attached to each gallon of ethanol produced [18]. Cellulosic ethanol qualifies for issuance of a Cellulosic Waiver Credit and D5 RIN for every gallon produced [18]. The Environmental Protection Agency (EPA) has set the Cellulosic Waiver Credit at a price of $1.77 per gallon of ethanol in 2019 [18]. And according to RIN market pricing's in 2019, the D5 RIN is traded at an average of $0.44 per gallon of ethanol [18]. The ethanol market valuation of $1.44/gal, in addition to the D5 RIN and Cellulosic Waiver Credit, put the price of ethanol at $3.65 per gallon in 2019. In order to remain competitive, a biorefinery must be able to produce ethanol at a cost lower or equal to this value. Figure 4.14 shows the current ethanol price.

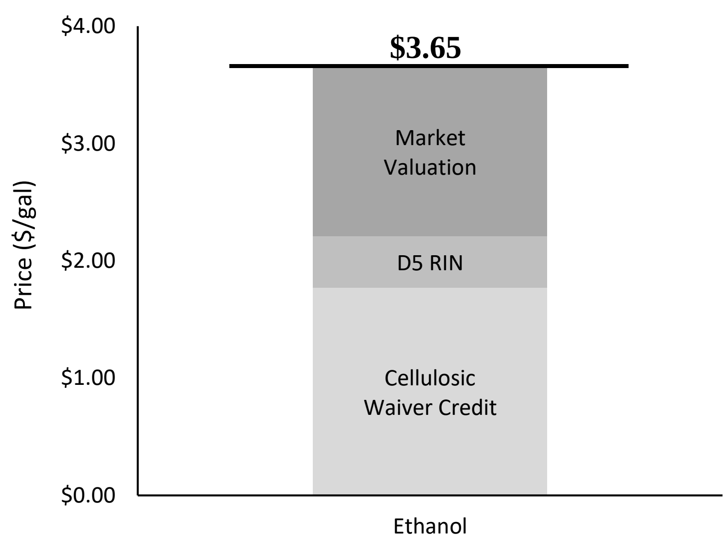


Figure 4.14 Ethanol price

4.4 RESULTS & DISCUSSION

The purpose of this techno-economic analysis was to determine the MESP for four separate biorefinery design scenarios. The MESP of each case can then be compared to determine the most profitable biorefinery design in Western Washington. Figure 4.15 shows the MESP for each of the four case-studies at discount rates 0%, 7%, and 15%. The current ethanol market price is plotted as a line to evaluate the competitive performance between cellulosic ethanol and the current ethanol price, which is calculated to be $3.65/gallon of ethanol. This techno-economic analysis has determined that a mixed poplar, integrated biorefinery is the most economically competitive biorefinery design, which has a MESP of $2.89/gallon of ethanol at a 15% discount rate. The dedicated poplar, integrated biorefinery could produce ethanol at $3.26/gallon at a 15% discount rate. The other two design scenarios, mixed poplar, stand-alone biorefinery and dedicated poplar, stand-alone biorefinery, were not economically competitive with the current market price of ethanol, these scenarios had a MESP of $3.79/gallon and $4.15/gallon at a 15% discount rate, respectively.

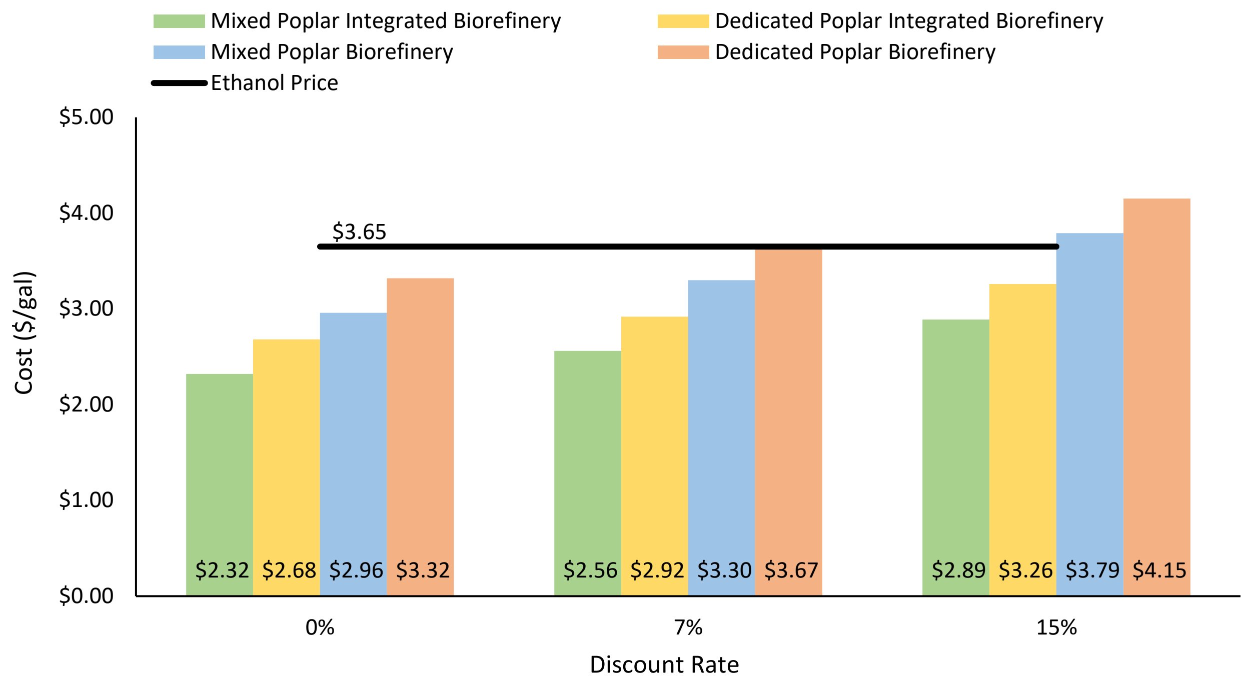


Figure 4.15 Scenario comparison for MESP

These results demonstrate that the capital costs of cellulosic ethanol production bear a larger effect on the MESP than the biomass feedstock. For example, switching the feedstock source of the biorefinery from dedicated poplar to mixed poplar sources, at a 15% DR, lowered the feedstock cost from $74.35/ODT to $48.82/ODT; however, this only lowered the MESP by $0.36/gallon. Switching to a lower-cost feedstock achieved an 18.6% annual reduction in operating costs for the biorefinery. Co-locating the biorefinery instead of building a stand-alone biorefinery, at a 15% DR, reduced the total capital investment from $199,000,000 to $178,000,000, which lowered the MESP by $0.89/gallon. Co-locating the biorefinery reduced the total capital investment by 10%. From this data, every one percent reduction in total capital investment corresponds to a $0.09/gallon reduction in MESP. Whereas, every one percent reduction in operating costs corresponds to a $0.02/gallon reduction in MESP.

The final section of this techno-economic analysis seeks to understand the economies of scale of the Centralia Biorefinery. For this section, the mixed poplar, integrated biorefinery, 15% DR scenario was analyzed at different capacities to determine how economies of scale affect the MESP. In Figure 4.16 the MESP is plotted on the primary y-axis against the capacity of the biorefinery and the feedstock cost is plotted on the secondary y-axis, also against the biorefinery capacity. Figure 4.16 shows that even when the biomass is extremely cheap, the MESP is still high. As the biorefinery capacity increases, the average cost of the feedstock increases; however, the MESP continues to decline then levels out. These results suggest that larger biorefineries are economically more favorable, until a certain threshold, due to economies of scale.

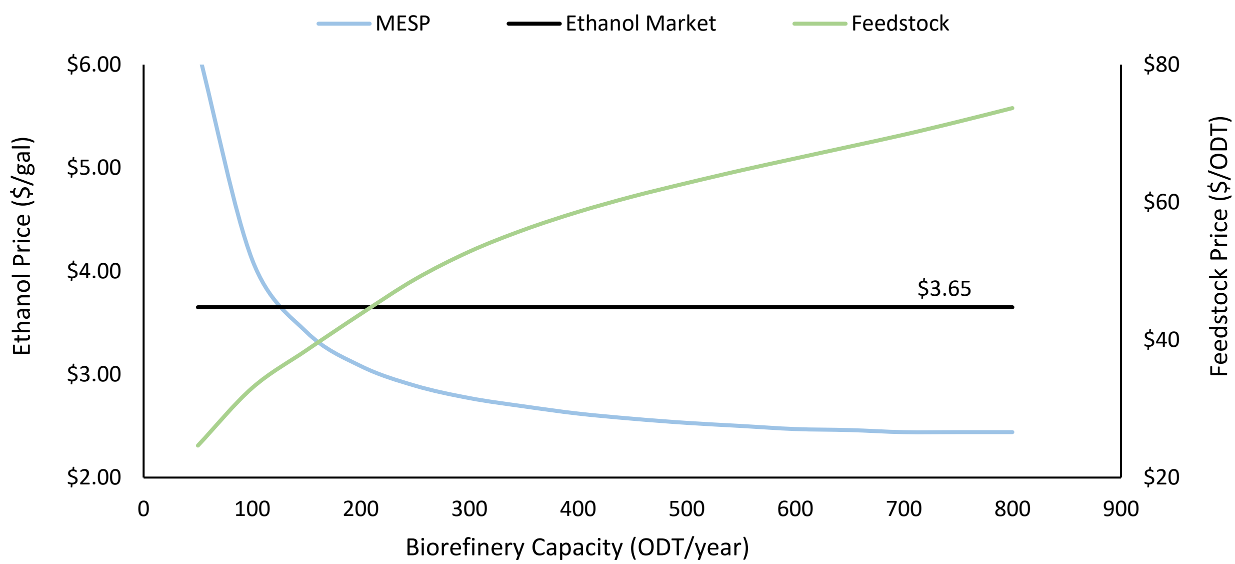


Figure 4.16 Economies of Scale

4.5 CONCLUSION & RECOMMENDATIONS

The MESP of the Centralia Biorefinery can be sufficiently reduced to make it competitive with the current ethanol market. MESP reduction is achieved through displacing high-cost dedicated poplar feedstock with low-cost poplar sources and co-locating the biorefinery with a pre-existent powerplant. These methods were able to reduce the MESP from initially $4.15/gallon to $2.89/gallon at a 15% DR; making the biorefinery's product competitive with the ethanol market price of $3.65/gallon. Co-locating a biorefinery and utilizing lower-cost feedstocks are two promising methods for constructing a profitable biorefinery in Western Washington.

5 THESIS CONCLUSION

The emerging bioeconomy can offer climate change mitigation, energy security and independence, and rural economic development. Renewable fuels, such as cellulosic ethanol, have been shown to reduce carbon emissions by restoring the carbon cycle. Through fuel blending, cellulosic ethanol can displace petroleum-derived fuels in the transportation sector, which is a leading source of GHG emissions in the United States [4]. Cellulosic ethanol has yet to become an established source of fuel production in Washington State due to economic barriers. Cellulosic ethanol biorefineries are economically hindered by complex conversion processes, which contribute to significant capital investment; and high feedstock costs, which contribute to significant operating expenses. This research sought to alleviate economic concerns with establishing a cellulosic ethanol biorefinery in Washington by exploring capital and operating cost reductions through integrated practices.

Operating costs in a cellulosic ethanol biorefinery can successfully be reduced by taking an integrated approach to resource acquisition. This research explored feedstocks that provide ecosystem services and evaluated the cost reductions associated with implementing this strategy. Roadside poplar production has the potential to supply a Washington biorefinery with a significant amount of feedstock at a lower cost than dedicated poplar production. By strategically growing roadside poplar on VFSs, they can provide an ecosystem service that benefits other vested parties in Washington. Roadside VFSs were shown to significantly reduce highway runoff pollution, which is a growing environmental concern in Washington.

Capital costs of a cellulosic ethanol biorefinery can also be reduced by taking an integrated approach. This research showed that capital costs can be reduced by constructing a biorefinery around a pre-existent powerplant, omitting the need for certain equipment to be newly constructed.

Integrated methods for operating and capital cost reductions in a cellulosic ethanol biorefinery were shown to successfully decrease the MESP for the biorefinery's product, allowing it to economically compete with traditional fuel producers.

The following list highlights major conclusions found in this research. The models in this research are based on a Centralia biorefinery that converts 250,000 ODT of poplar feedstock to ethanol per year.

- Roadside poplar production
  - Feedstocks that offer ecosystem services can be produced at a lower cost by adopting the harvest and ship model. In the harvest and ship model, a third party is incentivized to establish and maintain crops and the biorefinery is responsible for harvest and transportation of the crop.
  - 40,000 ODT/year of roadside poplar are available to the Centralia biorefinery at a lower cost than dedicated poplar.
  - Combing dedicated poplar and roadside poplar supplies can reduce a 250,000 ODT/year capacity biorefinery feedstock costs from $74.35/ODT to $69.35/ODT.
- Roadside poplar for highway runoff pollution reduction
  - Roadside poplar can be strategically grown in the form of VFSs to reduce pollution emitted through highway runoff.
  - Through VFS implementation of major roadways in Western Washington, 2 million kg/year of TSS, nearly 2000 kg/year of TP, 22,000 kg/year of TKN, 1000 kg/year of total Cu, 200 kg/year of dissolved Cu, 3500 kg/year of total Zn, 300 kg/year of dissolved Zn, 150 kg/year of total Pb, and 3 kg/year of dissolved Pb can be removed from highway runoff before it is discharged to receiving waters.

- In highly sensitive aquatic urban areas, VFS retrofits can reduce:
  - TSS, total Cu, and total Zn emissions by 25%.
  - TP and TN emissions by 10%.
  - Dissolved Cu, dissolved Zn, and total Pb by nearly 20%.
  - Dissolved Pb emissions by 15%.
- In highly sensitive aquatic rural areas, VFSs retrofits can reduce:
  - TSS, total Cu, and total Zn emissions by nearly 40%.
  - TP and TKN emissions by 15%.
  - Dissolved Cu, dissolved Zn, and total Pb emissions by nearly 30%.
  - Dissolved Pb emissions by 20%.

- Building a profitable biorefinery in Western Washington
  - An integrated approach can reduce the MESP to achieve profitability in a Centralia biorefinery.
  - Operating costs can be reduced by displacing high-cost dedicated poplar with mixed hardwood resources. Mixed hardwood resources include sawmill residues, feedstocks that provide ecosystem services, and dedicated poplar. Feedstock costs can be reduced by $74.35/ODT to $48.82/ODT, which corresponds to a decrease in the MESP by $0.39/gallon.
  - Capital costs can be reduced by co-locating the biorefinery with a pre-existent powerplant. Co-location permits the omission of the combustor, boiler, and turbogenerator and wastewater treatment sections of the biorefinery. A multi-effect evaporator must be installed to concentrate liquid waste before being transferred to the co-located powerplant. Co-location can reduce the total capital investment from

$199 million to $178 million, which corresponds to a decrease in the MESP of $0.89/gallon.

- These integrated approaches can reduce the MESP from $4.15/gallon to $2.89/gallon at a 15% DR, which is competitive with the target price of ethanol that is $3.65/gallon.

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