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Feasibility analysis of a hybrid poplar-based biorefinery in southwestern Washington

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A thesis

submitted in partial fulfillment of the
requirements for the degree of

Master of Science

University of Washington

2018

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Abstract

Feasibility analysis of a hybrid poplar-based biorefinery in southwestern Washington

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To mitigate climate change, reduce greenhouse gas (GHG) and particulate emissions, contribute towards energy independence and security, and promote sustainable economic development in the United States (U.S.), cellulosic biofuels have been considered as potential replacement fuels for petroleum-derived fuels. While biofuels offer many environmental and socioeconomic benefits, commercial scale biorefineries are not prominent in the U.S. High feedstock costs and capital investment costs are two of the biggest challenges prohibiting the advancement of commercial scale biofuel production. This study reduced feedstock costs to supply a 250 Gg feedstock capacity cellulosic ethanol biorefinery in western Washington by 22% by incorporating local, low-cost hardwood sawmill residues and hybrid poplar from treated wastewater management ecosystem service with the traditional method of supplying biomass (hybrid poplar) from purpose-grown plantations. The proposed biorefinery is modeled producing 75 megaliters of cellulosic ethanol annually. The proposed biorefinery design, referred to as the

Integrated design case, assumes co-location with an adjacent power plant, eliminating the need for an in-house boiler/turbogenerator and wastewater treatment system by using a multi-effect evaporator to evaporate waste streams into combustible syrup for steam production. Two additional design cases are further evaluated for comparison: (1) Non-integrated design case producing 75 megaliters of ethanol annually, and (2) Integrated, Increased Production design case producing 189 megaliters of ethanol annually. Under the Integrated design case, total capital investment is reduced by 38%, installed equipment costs are reduced by 43%, and electricity use is decreased by 64% as compared to the Non-integrated design case. A 38% reduction in total capital investment per liter can be realized by scaling biorefinery ethanol production up to 189 megaliters per year using the integrated design approach. Discounted cash flow rate of return analysis is used to evaluate economic performance and ethanol minimum selling price. Under the most realistic financing scenario, 40% loan and 15% discount rate, the Integrated, Increased Production design case incorporating integrated approaches, including using mixed feedstock supply sources, achieves the lowest minimum ethanol selling price of \$0.67/liter, resulting in a 31% reduction in ethanol minimum selling price compared to the Non-integrated design case and a 19% reduction compared to the Integrated design case. Life cycle carbon analysis (quantifying global warming potential (GWP) contribution in CO₂ eq. MJ⁻¹) of the Integrated design case is conducted, yielding a 52% reduction in GWP as compared to 2005 gasoline production and use. This study provides a framework for incorporating integrated approaches into biorefinery design using local context to realize economic and environmental gains.

Contents

1. Thesis Introduction	8
1.1. Local context: Lewis County, WA.....	10
1.2. Thesis objectives	12
2. Utilizing hybrid poplar-based ecosystem service and local residues to reduce biorefinery feedstock cost: A quantitative biomass assessment and case study in southwestern Washington	13
2.1. Abstract	13
2.2. Paper objective	14
2.3. Methods.....	14
2.3.1. Purpose-grown hybrid poplar plantations.....	14
2.3.2. Wastewater management ecosystem service derived hybrid poplar biomass	19
2.3.3. Hardwood sawmill residues.....	24
2.3.4. Hardwood forest harvest residues.....	25
2.3.5. Agricultural residues.....	26
2.4. Results	26
2.4.1. Purpose-grown hybrid poplar plantations.....	26
2.4.2. Wastewater management ecosystem service derived hybrid poplar biomass	31
2.4.3. Hardwood sawmill residues.....	35
2.4.4. Hardwood forest harvest residues.....	37
2.4.5. Agricultural residues.....	37
2.4.6. Mixed feedstock scenarios and cost reductions.....	38
2.5. Discussion	41
2.6. Conclusion.....	44
3. Techno-economic and life cycle carbon analysis of an integrated cellulosic ethanol biorefinery.....	45
3.1. Abstract	45
3.2. Background	46
3.3. Results	49
3.3.1. Integrated Process design	49
3.3.2. Economic modeling.....	51
3.3.2.1. Capital Expenses.....	51
3.3.2.2. Variable operating expenses	54
3.3.2.3. Fixed operating expenses.....	57
3.3.2.4. Discounted cash flow analysis.....	59
3.3.3. Carbon life cycle analysis.....	61

3.4.	Discussion and conclusion	64
3.5.	Methods.....	68
3.5.1.	Biorefinery process modeling.....	68
3.5.2.	Economic modeling.....	71
3.5.2.1.	Capital expenses.....	72
3.5.2.2.	Capital equipment costs	72
3.5.2.3.	Variable operating costs.....	74
3.5.2.4.	Fixed operating costs	75
3.5.2.5.	Discounted cash flow rate of return analysis	76
3.5.2.6.	Design case scenarios	78
3.5.3.	Life cycle carbon analysis	80
3.6.	Thesis Conclusion	82
4.	Recommended future work.....	84
5.	References.....	85

List of Figures

Figure 2.1	Suitable land for hybrid poplar cultivation.....	15
Figure 2.2	Transport Cost Contribution.....	18
Figure 2.3	Land availability for hybrid poplar wastewater management ecosystem service	20
Figure 2.4	Hardwood forest harvest parcels; yellow dot = Centralia, WA	25
Figure 2.5	Total potential suitable land area across all land types under varying land conversion rate assumption (biomass \leq \$121/bone dry Mg delivered and within 100km)	27
Figure 2.6	Total potential hybrid poplar biomass supply across all land types under varying land conversion rate assumption (biomass \leq \$121/bone dry Mg delivered and within 100km).....	28
Figure 2.7	Pastureland, purpose-grown, hybrid poplar supply curve	29
Figure 2.8	Irrigated cropland, purpose-grown, hybrid poplar supply curve	30
Figure 2.9	Non-irrigated cropland, purpose-grown, hybrid poplar supply curve	31
Figure 2.10	Wastewater management ecosystem service feedstock cost reductions	35
Figure 2.11	Projected hardwood sawmill residues (excluding chips) by county	36
Figure 3.1	Minimum ethanol selling prices under various biorefinery designs and production capacities with 0% loan	60
Figure 3.2	Minimum ethanol selling prices under various biorefinery designs and production capacities with 40% loan	61
Figure 3.3	Global warming potential (g CO ₂ eq. per MJ fuel) of 2 cellulosic ethanol biorefinery designs and gasoline	63
Figure 3.4	Process flow diagram for the Integrated and Non-integrated biorefinery process designs.....	68

List of Tables

Table 2.1 Pixel data summary: Total associated acreage and average pixel yield	19
Table 2.2 Plant material, crop care, and harvest costs (adapted from Greenwood Resources Production Cost Calculator).....	22
Table 2.3 Other plantation expenses (adapted from Greenwood Resources Production Cost Calculator).....	23
Table 2.4 Wastewater management ecosystem service derived hybrid poplar biomass summary table.....	32
Table 2.5 Forest harvest residues over 5-year period (bone dry Gg/year).....	37
Table 2.6 Annual agricultural residues by county (dry Mg/year).....	38
Table 2.7 Feedstock scenarios and plant-gate cost savings (250 Gg/year feedstock capacity)....	40
Table 2.8 Feedstock scenarios and plant-gate cost savings (630 Gg/year feedstock capacity)....	42
<i>Table 3.1 Biorefinery unit operation annual steam use and electricity use by design case</i>	<i>50</i>
Table 3.2 Capital and operating expenses for three cellulosic ethanol biorefinery design cases .	52
Table 3.3 Variable operating expenses for an integrated and non-integrated 75 megaliters per year cellulosic ethanol biorefinery	55
Table 3.4 Fixed operating expenses for two cellulosic ethanol biorefineries under three production capacity and design cases	57
Table 3.5 Pretreatment reactor conditions	69
Table 3.6 Biorefinery unit operation breakdown.....	73
Table 3.7 8-effect multi-evaporator parameters.....	74
Table 3.8 Summary of financing options.....	76
Table 3.9 Discounted cash flow analysis parameters	77
Table 3.10 Sensitivity cases description	79

List of Equations

Equation 3.1 Exponential scaling expression for re-costing capital equipment	73
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Funding Statement

This research is a part of Advanced Hardwood Biofuels Northwest (AHB), a research consortium initiative supported by the U.S. Department of Agriculture National Institute of Food and Agriculture (USDA-NIFA).

1. Thesis Introduction

United States (U.S.) legislative acts enacted over the past two decades, such as the Energy Policy Act of 2005 and the Energy Independence and Security Act of 2007 (EISA), which house the Renewable Fuel Standard, have significantly launched the use and production of liquid transportation biofuels to the forefront in an unprecedented way. Biofuels offer an extensive list of social, economic, and environmental benefits such as providing value added service from biomass cultivation (ecosystem service) or residue utilization, contributing towards energy independence and security, reducing greenhouse gas (GHG) and particulate emissions, and promoting economic development, especially in rural communities ¹.

Biofuels offer a pathway towards climate change mitigation since feedstock cultivated for biofuel production can sequester significant amounts of CO₂, offsetting process emissions, as oppose to solely emitting CO₂ in the case of petroleum-derived fuels. When GHG emissions can be offset or reduced by employing cost-effective design and approaches, biofuels offer the opportunity to displace petroleum-derived fuels in a sustainable manner.

While biofuels have a potentially significant contributory role in climate change mitigation strategy and offer many other socioeconomic benefits, to overcome key challenges, such as the “food vs. fuel” debate and negative impacts of land use change, second generation biofuels and use of agricultural residues will need to be heavily incorporated in deployment plans². Second generation biofuels are derived from non-food crops and can be grouped by cultivation method including the following: (1) short rotation coppice (SRC) (e.g. short rotation coppice *Salix* (willow) or *Populus* (poplar)), (2) perennial grasses (e.g. *Miscanthus* (silvergrass), *Panicum* (switchgrass), etc.), and (3) short rotation forestry (SRF) (e.g. poplar, *Alnus* (alder), *Betula* (birch), *Fagus* (beech), etc.)³. Hybrid poplar, which can be cultivated via SRC is often referred to

as a short rotation woody crop (SRWC). Hybrid poplar is particularly attractive as a feedstock source for biofuel production due to its' ability to rapidly re-sprout from coppice, support a short (2-5 years) and continual harvest cycle, and thrive in minimal climatic conditions on marginal, idle, or less productive lands⁴.

Volume standards mandated by the Renewable Fuel Standard require annual production of 32 gigaliters (32.2 hm³) of cellulosic biofuels in 2019 with increases to 61 gigaliters (60.6 hm³) in 2022⁵. Although there are many benefits associated with biofuels, as well as identified feedstock sources capable of supporting new industry, there are challenges to meeting annual production targets. Commercial-scale biofuel production is still insignificant compared to that of fossil fuels. The high capital cost of startup biorefineries is one of the greatest barriers towards building a viable biofuels industry in the U.S., thus making it near impossible to obtain competitive minimum selling prices of second generation, lignocellulosic fuels without incorporating cost reduction strategies^{6,7}. Combusting residual biomass to produce energy for sale to the electric grid or for reuse in-house, selling intermediary products or co-products, and reducing feedstock costs are typical methods explored to reduce capital or operational costs. The cost of feedstock is a major component of total costs and factor in economic viability¹. Methods for reducing feedstock costs are continually explored and include utilizing waste resources, diversifying feedstock supply⁸, developing and incorporating technical processing improvements⁹, and minimizing transportation costs¹⁰.

While feedstock cost reduction strategies can provide a pathway for reducing overall biorefinery startup costs, effective supply and implementation is dependent on local conditions and circumstances. Localized biomass assessments can be used to quantify available biomass, associated costs and proximity, and opportunities for value added services like ecosystem

services. Techno-economic modeling and discounted cash flow analysis can be used to evaluate economic outcomes of various biorefinery design options. To measure the environmental impact of biofuel production and use, life cycle assessment can be used to model CO₂ and other GHG emissions of biorefinery process designs. Case studies using these methods with local context provide an effective way to assess the potential for feedstock cost reduction strategies and biorefinery design approaches to provide mutual social, economic, and environmental benefits.

1.1. Local context: Lewis County, WA

The concept for the biorefinery described in this study involves integration with a co-located power plant and collaboration with local community stakeholders and partners to provide socioeconomic and environmental benefit to the region, while reducing capital investment costs to make construction attainable. Advanced Hardwood Biofuels Northwest (AHB), a research consortium initiative supported by the U.S. Department of Agriculture National Institute of Food and Agriculture (USDA-NIFA), developed integrated modeling frameworks for assessing the feasibility of a hybrid poplar-based biofuels and biochemicals industry in the U.S. Pacific Northwest (PNW). Part of this research involved identifying potential sites for startup biorefineries. Results from the Geospatial Bioenergy Systems Model (GBSM, <https://hardwoodbiofuels.org/sustainability/economics/geospatial-model/>), which provides insight on the most profitable potential locations and scale for a biorefinery based on several profit optimization factors, showed a large cluster of potential sites in western Oregon and Washington, including Newburg, OR, Aumsville, OR, and Centralia, WA (located in Lewis County). These sites were favorable primarily due to ample, low-cost pastureland availability, favorable climatic conditions (sufficient rainfall, eliminating the need for crop irrigation), and access to product markets.

Also located in Centralia, WA is TransAlta's coal-fired power plant, set to be phased out by 2025 under the TransAlta Energy Transition Bill. There is an effort, however, to transition the power plant to natural gas and to extend its operation beyond 2025^{11,12}. If the coal-fired power plant were to be converted to a natural gas power plant, there is an opportunity to co-locate the biorefinery adjacent to the converted power plant and retain employment in the local region. Co-locating a potential biorefinery with a power plant offers the opportunity for the biorefinery to eliminate the in-house boiler/turbogenerator by utilizing the power plant's excess boiler capacity for combusting by-products of the production process to produce steam and consequently, electricity, by sending resultant steam through the power plant's turbines. NREL's installed capital equipment cost breakdown shows that eliminating the boiler/turbogenerator reduces installed capital equipment costs by about 34%¹³. The wastewater treatment system could also be eliminated by sending concentrated waste from a multi-effect evaporator system to the power plant's boiler for steam production, saving an additional 3% of installed capital equipment costs¹³.

Additionally, Lewis County is primarily a rural community that could benefit from new industry and job creation. Lewis County's per capita income for years 2012-2016 trended 23% lower than the national average¹⁴. Mean household income, \$44,526, is also lower than the national average and poverty percentage, 15%, is higher than the national average for years 2012-2016¹⁴. Particularly, Lewis County has faced tough challenges in the agricultural industry, such as lack of infrastructure and markets, catastrophic flooding, housing development, and aging landowners¹⁵, resulting in significant need for economic growth and development.

The case for a biorefinery in Lewis County becomes increasingly attractive when the potential for hybrid poplar plantations to provide ecosystem service is considered. The Chehalis

Regional Water Reclamation Facility, located in Lewis County, currently utilizes a 101 ha (1.01 km²) poplar plantation to dispose of treated wastewater during times of low flow in the Chehalis River (<28.3 m³ s⁻¹) and provides a good model for extrapolating this service within the region.

Lewis County is also the largest producer of hardwood sawmill residuals (hog fuel and sawdust) of all its surrounding counties. Access to this supply of hardwood sawmill residues could provide opportunity for an immediate supply of affordable biomass, though limited in quantity.

For these reasons, a proposed bioconversion facility located in Lewis County, WA was selected to conduct this case study applying the integrated/co-located approach. Due to the bioconversion process, only hardwoods and other easily fractionated biomass (such as agricultural residues) are acceptable. Hybrid poplar, as a hardwood, does not display the same recalcitrant properties as softwoods¹⁶ and can be fractionated without extensive pretreatment¹⁷, making it an optimal feedstock choice. To evaluate performance of a small to moderately sized production scale start-up biorefinery (based on the production scale reference of 94.6 megaliters based on Iowa's Project LIBERTY cellulosic ethanol biorefinery¹⁸), an annual cellulosic ethanol production of 75 megaliters was chosen. Considering an ethanol yield of 300 liters/Mg, 250,000 Mg (250 Gg) of biomass would be required to supply the bioconversion facility annually. Based on the potential quantity of available biomass within the region, 250,000 Mg of biomass per year is considered feasible.

1.2. Thesis objectives

The first objective of this thesis is to conduct a biomass assessment in the region of the proposed biorefinery (Lewis County, WA) in effort to quantify available biomass and associated costs. The second objective of this thesis is to evaluate the economic outcomes, including capital

investment and ethanol minimum selling price, of an integrated biorefinery approach and compare results to a traditional biorefinery design and an increased production biorefinery design. The third objective of this thesis is to quantify the life cycle carbon emissions (GWP contribution in CO₂ eq. MJ⁻¹ of fuel) of the proposed integrated biorefinery design producing 75 megaliters of cellulosic ethanol annually from hybrid poplar feedstock and compare results to 2005 gasoline production and use.

The biomass assessment portion of the thesis will be submitted for publication in the scientific journal, *Biomass and Bioenergy*. The techno-economic modeling and life cycle carbon analysis portion of the thesis will be submitted for publication in the scientific journal, *Biotechnology for Biofuels*. Both publications have been drafted and are going through review iterations.

The content of this thesis includes a thesis introduction, the draft for the *Biomass and Bioenergy* publication, the draft for the *Biotechnology for Biofuels* publication, a thesis conclusion, future work, and references.

2. Utilizing hybrid poplar-based ecosystem service and local residues to reduce biorefinery feedstock cost: A quantitative biomass assessment and case study in southwestern Washington

2.1. Abstract

To mitigate climate change, reduce greenhouse gas (GHG) and particulate emissions, contribute towards energy independence and security, and promote sustainable economic development in the United States (U.S.), cellulosic biofuels have been considered as potential replacement fuels for petroleum-derived fuels. While biofuels offer many environmental and socioeconomic benefits, commercial scale biorefineries are not prominent in the U.S. High

feedstock costs and capital investment costs are two of the biggest challenges prohibiting the advancement of commercial scale biofuel production. This study reduced feedstock costs to supply a 250 Gg feedstock capacity cellulosic ethanol biorefinery in western Washington by 22% by incorporating local, low-cost hardwood sawmill residues and hybrid poplar from treated wastewater management ecosystem service with the traditional method of supplying biomass (hybrid poplar) from purpose-grown plantations. This study provides a framework for incorporating local, low-cost feedstock sources into biorefinery feedstock supply to realize cost savings.

2.2. Paper objective

This assessment provides a framework and identifies regional resources to quantify the potential of various sources of hardwood and agricultural residue biomass, including hybrid poplar and agricultural residues, in primarily southwestern Washington to supply a proposed ethanol-producing biorefinery located in Lewis County, WA with reduced-cost feedstock options. The goal of this case study is to estimate the quantity, availability, and cost of several local biomass sources including (1) hybrid poplar from purpose-grown plantations, (2) hybrid poplar from treated wastewater management ecosystem service, (3) hardwood sawmill residues, (4) hardwood forest harvest residues, and (5) agricultural residues to assess the implications of these biomass sources on biorefinery production size and potential feedstock cost savings.

2.3. Methods

2.3.1. Purpose-grown hybrid poplar plantations

Hybrid poplar biomass from purpose-grown plantations was chosen as the foundational feedstock choice for supply of this conceptualized biorefinery producing cellulosic ethanol. Researchers under AHB developed a suite of models to determine the feasibility of growing and

the potential supply and cost of hybrid poplar biomass in the PNW. Figure 2.1 shows suitable land parcels within 100km of the proposed biorefinery site.

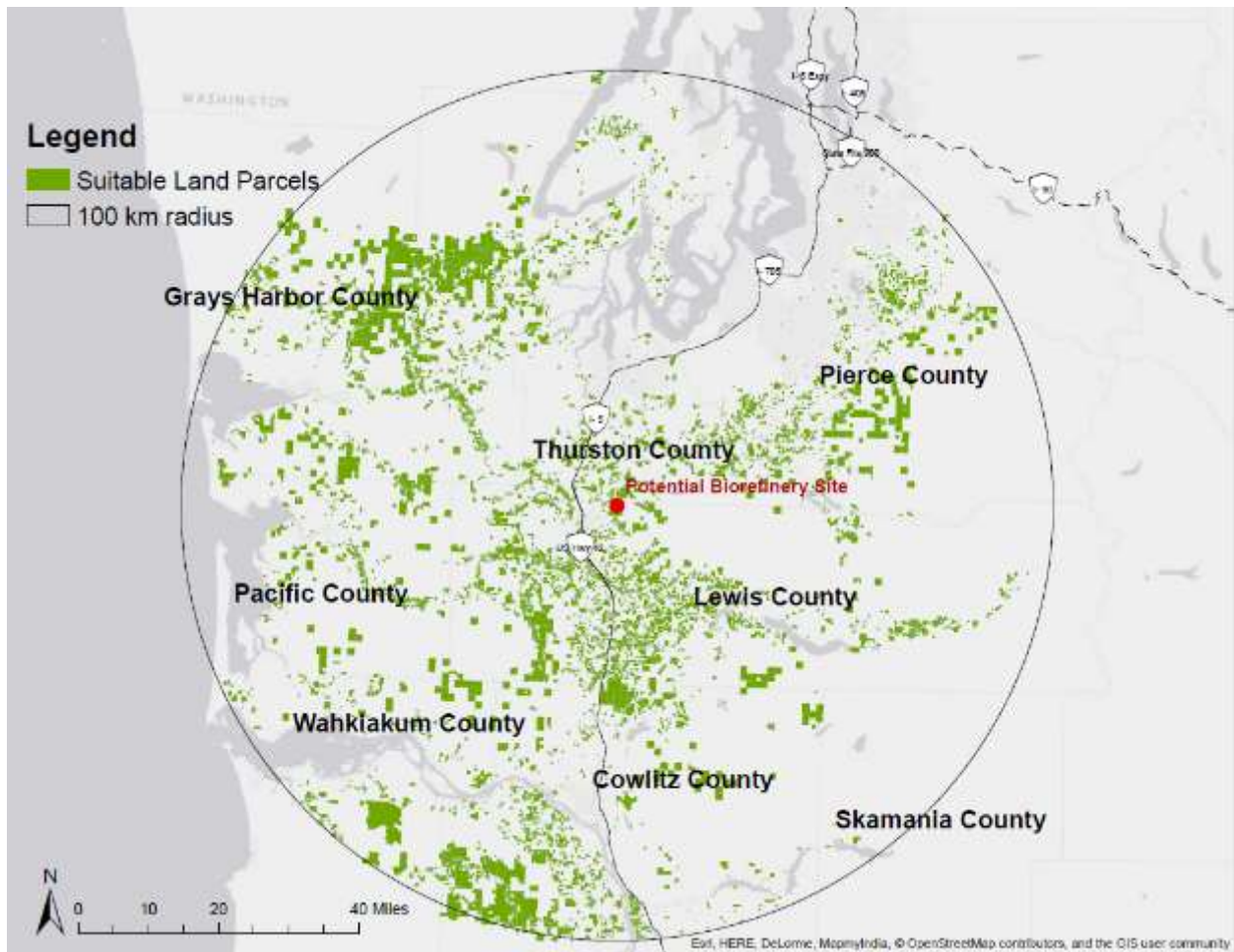


Figure 2.1 Suitable land for hybrid poplar cultivation

To determine suitable land, a set of land suitability factors were applied to USDA land cover data (<http://datagateway.nrcs.usda.gov>) to extract the qualifying rangelands (hereafter referred to as pastureland) and croplands. The land suitability criteria for hybrid poplar cultivation include 1) non-federal lands, 2) non-forestland, 3) soils with slope < 15%, 4) pH between 4.5 and 8.0, 5) soil salinity < 4.0 ds/m, and 6) soil and water depth > 50.8 cm¹⁹. Suitable lands were then categorized as pastureland (non-irrigated), irrigated cropland (IRR), or non-irrigated (NIRR) cropland using the 2015 USDA Cropland Data Layer (CDL), which informs the

crop type occupied by a parcel utilizing the maximum crop type. The Physiological Principles Predicting Growth (3PG) model (<http://3pg.forestry.ubc.ca/>) estimates biomass yields for suitable lands based on specific characteristics of hybrid poplar species and regional soil and climate data. Biomass yields for hybrid poplar were estimated using the 3PG-Coppice growth model²⁰. The biomass yield model provides estimates for each pixel within an 8km grid overlay. This grid defined the spatially distinct pixels that are used in representing the land base. Within each pixel, suitable land areas were summed for each of the land uses; irrigated cropland, non-irrigated cropland and pastureland. These pixels were used to model potential biomass production from hybrid poplar plantations grown and harvested on the land parcels within the pixels.

To determine the farm-gate or total biomass cost without transportation to the biorefinery, the breakeven cost was calculated for each pixel and land-use combination. The breakeven cost accounts for hybrid poplar yields, the cost of production, and opportunity cost of displacing the incumbent crop or value of pastureland. The cost of production was calculated using pixel-specific values for hybrid poplar biomass yield, land rent cost, irrigation requirement, irrigation cost, fixed production cost, and variable production costs. Production costs come from a budget provided for growing poplars in irrigated and non-irrigated conditions that is documented in the Farm Budgets tool (farmbudgets.org). These costs include establishment, annual crop care, coppice harvesting, and restoration. The plantations are assumed to have seven harvests over the course of the twenty-year life of the plantation. Due to the perennial nature of hybrid poplars the production costs are amortized over the life of the plantation with an 8% required return on investment. The opportunity cost for pastureland-derived hybrid poplar is calculated from estimates of net revenues based on county-level revenues for hay. Only pixels

with plant-gate costs up to \$121/bone dry Mg were included in this analysis; this eliminates extreme outliers falling far outside of biorefinery affordability ranges.

Transportation routing was determined using the Open Source Routing Machine (OSRM) (<http://project-osrm.org/>) powered by OpenStreetMap data to find the shortest route (using road miles) from each pixel to the biorefinery location (adjusted from Centralia, WA). Truck transport costs were assumed to cost \$0.13/GST (green short ton)/mile (\$4 per loaded mile at 30 GST per load) or \$89/green Gg/km or \$0.03 green Mg/km and 57% moisture content during transport²¹. A factor of 1.5 was applied to the final transport cost to account for variable backhaul (Dr. Eric L. Jessup, personal communication, August 22, 2018). For any missing transport data, a pixel was assigned the same transportation cost as the next nearest pixel with the most significant portion of its parcels closest to the parcels of the reference pixel. Land areas east of the biorefinery site were matched with like pixels and the same for pixels west of the biorefinery site. Added, the farm-gate cost and transportation cost equate to the plant-gate cost or delivered biomass cost. Biomass transportation costs generally increase as distance increases and in this region, can comprise upwards of 30% of the plant-gate cost at about 100km as shown in Figure 2.2. Only suitable pixels within 100km of the sited biorefinery location were considered in this study to limit transportation contribution to the plant-gate cost.

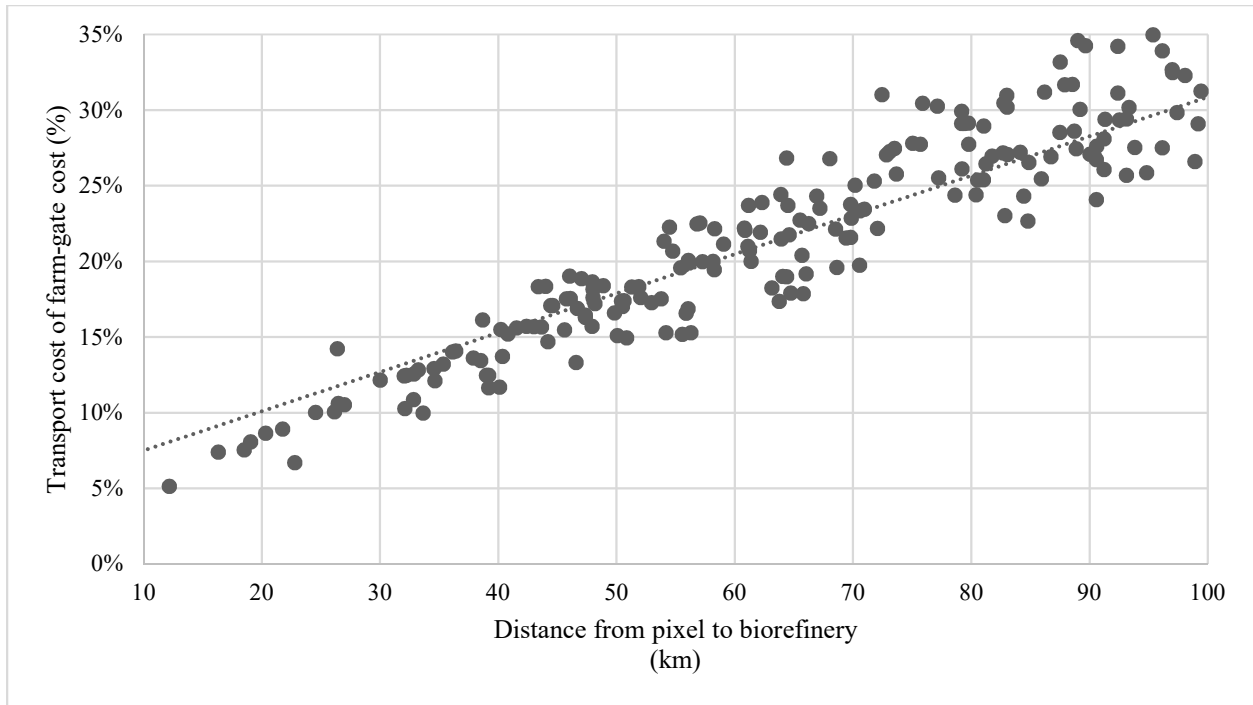


Figure 2.2 Transport Cost Contribution

Potential land availability, or the likelihood of a landowner to convert their land for hybrid poplar cultivation, is modeled as four subjective land conversion rates, 25%, 50%, 75%, and 100%. The conversion rates were applied to the total acreage available within each pixel as opposed to applied randomly across pixels. A review of literature conducting surveys of U.S. farmer willingness to adopt bioenergy crops revealed potential land conversion rates vary extensively by crop type and geographic region but typically do not exceed 76%²²⁻²⁹ and was noted as low as 5% in one study³⁰. A more region relevant survey revealed 51% of landowners are somewhat willing or willing to switch to a bioenergy crop³¹. In this study, a 50% land conversion rate was used to build feedstock scenarios. Table 2.1 shows the assumed land availability of each land type and their respective yields.

Table 2.1 Pixel data summary: Total associated acreage and average pixel yield

	Total Associated Land Area (km ²)		
	Pastureland	IRR Cropland	NIRR Cropland
50% converted land assumption	324,925	42,385	43,882
¹ Average pixel yield (bone dry kg/m ² /year)	1.7	1.9	1.7

2.3.2. Wastewater management ecosystem service derived hybrid poplar biomass

Hybrid poplar plantations were assessed as ecosystem service providers serving as disposal sites for treated wastewater during times of low river flow, thus limiting discharge to rivers under the Environmental Protection Agency’s (EPA) Clean Water Act. This is assumed to be a steady 90-day period during the summer months of June to August based on a case study conducted on AHB hybrid poplar trees at the Hayden Area Regional Sewer Board (HARSB). However, actual disposal need varies from one individual publicly owned treatment works (POTW) to the next. Biomass derived from this ecosystem service serves two primary functions: (1) serve as a reduced-cost feedstock source to the biorefinery and (2) provide a designated ecosystem service.

A data query from the EPA ICIS (Integrated Compliance Information System) National Pollutant Discharge Elimination System (NPDES) provided a list of POTWs under NPDES regulation in California, Idaho, Oregon, and Washington. Provided information included NPDES ID, state code, facility name, facility type indicator (POTW for all), total actual average flow, total application design flow, and latitude and longitude coordinates. For instances where total actual average flow data was missing, POTWs were contacted directly to retrieve this information. In the case that a POTW could not be reached, half of the total application design flow was used as an estimate (Karen Burgess - EPA, personal communication, August 1, 2017).

The list of POTWs was then limited to those within 100km of the biorefinery. Some POTWs that are already utilizing poplar plantations or currently do not have discharge issues were still included in this analysis in order to capture the region’s maximum potential biomass supply assuming full participation of all qualifying POTWs.

To determine potential biomass supply and corresponding yield characteristics surrounding each POTW that could house hybrid poplar plantations, four proximity scenarios were investigated using suitable land data described in Section 2.3.1. Figure 2.3 shows suitable land and qualifying POTWs within 100km of the proposed biorefinery site.

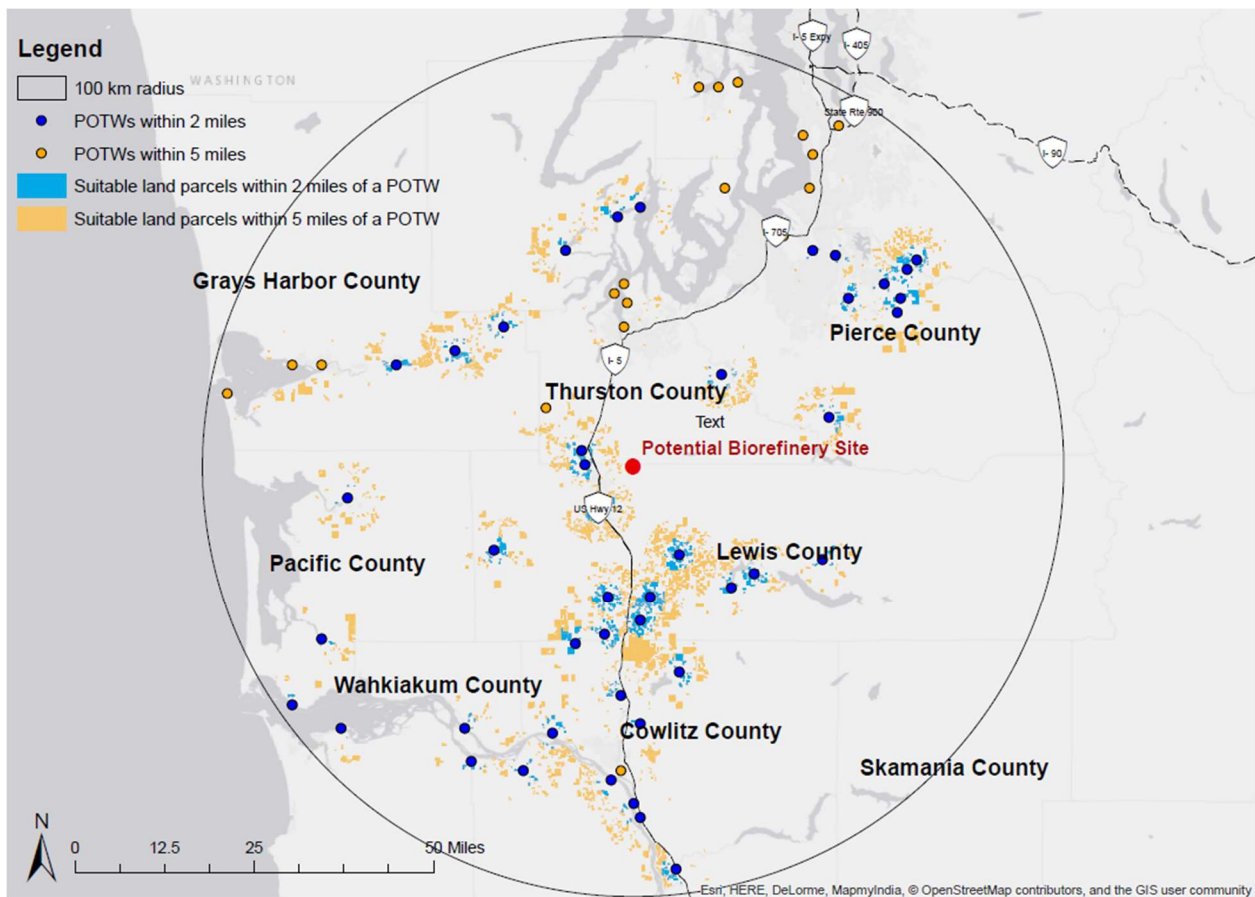


Figure 2.3 Land availability for hybrid poplar wastewater management ecosystem service

POTWs were grouped as being adjacent or intersecting (2 total), within 0.4 km or ¼ mile (15 total), within 3.2 km or 2 miles (44 total), or within 8.1 km or 5 miles (62 total) of suitable

land for growing hybrid poplar. The limiting factor affecting maximum allowed distance between a POTW and its supporting hybrid poplar plantation was cost of construction for piping for the water pumping system. Through an industry survey of PNW POTWs (6 total) currently using poplar plantations in some capacity with a pumping system, it was determined that 8.1 km was a reasonable maximum distance to consider, with 1.6-3.2 km being typical.

Since this study assumes that hybrid poplar plantations would only be utilized as disposal sites during the 90-day summer period, the average flow rate, in $\text{m}^3 \text{s}^{-1}$, was calculated to determine the effluent disposal need for each POTW over this period. Two effluent application rates were considered over the 90-day summer period: (1) to represent a high recycled water application rate with low land use ($141 \text{ m}^3/\text{day}/\text{hm}^2$ or $0.002 \text{ m}^3/\text{s}/\text{hm}^2$) and (2) to represent a low recycled water application rate with high land use ($45 \text{ m}^3/\text{day}/\text{hm}^2$ or $0.001 \text{ m}^3/\text{s}/\text{hm}^2$). The acreage required to handle the estimated discharge load from each POTW was determined by dividing the disposal need over the 90-day summer period ($\text{m}^3 \text{ s}^{-1}$), or the flow rate, for each POTW by the respective effluent application rate over the 90-day summer period ($\text{m}^3/\text{day}/\text{hm}^2$).

To determine the total required land area for each hybrid poplar plantation, 8% additional headway land area to allow space for equipment, maintenance, and access was added to the calculated required land area. Biomass supplied from each participating POTW was determined by multiplying the calculated required acreage (not including headway acreage) to handle the estimated discharge load and the associated biomass yield of the pixel housing the POTW and its corresponding hybrid poplar plantation land. Biomass quantities from wastewater management ecosystem service are calculated based on 100% participation from all qualifying POTWs in order to capture the maximum potential of the study area.

Two shared cost scenarios were evaluated to calculate feedstock costs from this source. The first scenario, Free Land, is on the basis that the POTW provides the land for the poplar plantation at no cost, and the biorefinery is responsible to manage all biomass cultivation, harvest, and shipment activities. The second scenario, Harvest and Ship, is on the basis that the POTW provides the land for the poplar plantation at no cost and manages all biomass cultivation activities; the biorefinery manages only the harvest and shipment activities. Hybrid poplar production costs include a 2-year establishment cycle, six 3-year coppice cycles, and a 1-year restoration cycle, representing a 22-year total plantation life cycle based on Greenwood Resources. Table 2.2 shows plantation production costs for an AHB hybrid poplar demonstration plantation located near Pilchuck WA.

Table 2.2 Plant material, crop care, and harvest costs (adapted from Greenwood Resources Production Cost Calculator)

	Site Prep, Planting Stock, Establishment (crop year 0) (\$/m ² /year)	Two-year Establishment Cycle (Crop Years 1 and 2) (\$/m ² /year)		Three-year Coppice Cycle (Crop Years 3, 4 and 5...) (\$/m ² /year)		Restoration Cycle (Crop Year 6) (\$/m ² /year)
		Crop Care	Harvest	Crop Care	Harvest	
Crop year	0	1,2	2	3,4,5...	5...	22
Pilchuck Site costs	\$0.09	\$0.03	\$0.08	\$0.05	\$0.15	\$0.02

These costs were used to estimate production costs for qualifying pixels (pixels which meet the criteria for housing hybrid poplar plantations for wastewater management ecosystem

service) due to the similarity in climatic conditions with Lewis County, WA. Annual operational, administrative, and property management expenses were also included as shown in Table 2.3.

Table 2.3 Other plantation expenses (adapted from Greenwood Resources Production Cost Calculator)

	Cost (\$/m ² /year)	Frequency
Operational expenses	\$0.004	Annually
Administrative expenses	\$0.001	Annually
Property management	\$0.012	Annually

Rent and transportation costs were the same as determined for each pixel under purpose-grown hybrid poplar plantations. Establishment cycle yields are estimated as half that of other cycles. Farm-gate cost for qualifying pixels was determined by dividing the pixel-level 22-year total plantation life cycle cost by the total biomass yield for that pixel over the 22-year life cycle. Under the Free Land scenario, all rent costs are removed from the biorefinery’s shared cost portion. Under the Harvest and Ship scenario, only harvest and transportation costs are considered as the biorefinery’s shared cost portion. Feedstock cost savings were calculated by taking the difference between the average plant-gate price for all qualifying pixels under the purpose-grown hybrid poplar plantation method by land type and the biorefinery portion of the calculated shared cost for all qualifying pixels by land type (referred to as the biorefinery average plant-gate shared cost). The biorefinery average plant-gate shared cost is calculated based on all qualifying pixels, and not selected pixels, since the actual participation of POTWs is unknown.

2.3.3. Hardwood sawmill residues

The quantity of hardwood sawmill residues available from Lewis County and its surrounding counties (Cowlitz, Grays Harbor, Thurston, Pacific, Pierce, Skamania, Wahkiakum) was determined using the 2013 Western Washington Hardwood Assessment. Yakima county also borders Lewis County but is excluded from this assessment. The modeled harvest volumes by species and county were recorded using estimates for 2010 and projections through 2030 from the report. Hardwood species categories included were *Alnus* (alder), *Acer* (maple), *Populus* (cottonwood), *Betula* (birch), and other hardwoods. Total annual hardwood logs harvested by county was calculated using the Doyle conversion assumption and an average hardwood conversion rate of 3,460 kg/m³ or 9 GST/MBF (MBF = thousand board foot). Assuming a 10% loss of biomass in transition to the mill sites, 50% moisture content for biomass, and a 20% estimated residue factor for delivered sawmill logs (David Chertudi – Washington (WA) State Mills Survey, personal communication, June 28, 2017), estimated sawmill hardwood residues by county were calculated. From this county-level data, total projected sawmill hardwood residues for years 2020, 2025, and 2030 were determined. To estimate the cost of these sawmill residues (\$/Mg) including hog fuel, sawdust, and chips, a survey was conducted collecting price quotes from local sawmills and wood product manufacturers. The weighted average cost of quoted available sawmill residues was used in building the feedstock scenarios. The WA State Mills Survey defines residue as ‘coarse’ residue that is used for pulp, boards, or other uses; this is interpreted as any biomass that is not in a merchantable log state. Therefore, chips are considered in this definition. 70% of sawmill residue volume is estimated to be chips (pulp or board) and 1% is estimated to be unused (Kristoffer Larson - WA State Mills Survey, personal communication, April 23, 2018). Assuming there is a steady pulp market for chips, chips were not considered as

available and are excluded from annual residue volumes reported. Processing facilities within 274km of the biorefinery with considerable or available residues were included when obtaining price quotes. Due to the low cost of biomass from sawmill residues, a greater search radius than 100km was applied. In the instances where undelivered biomass cost was provided, transportation costs were added according to Figure 2.2.

2.3.4. Hardwood forest harvest residues

The map in Figure 2.4 depicts the hardwood forest harvest parcels used to quantify available biomass.

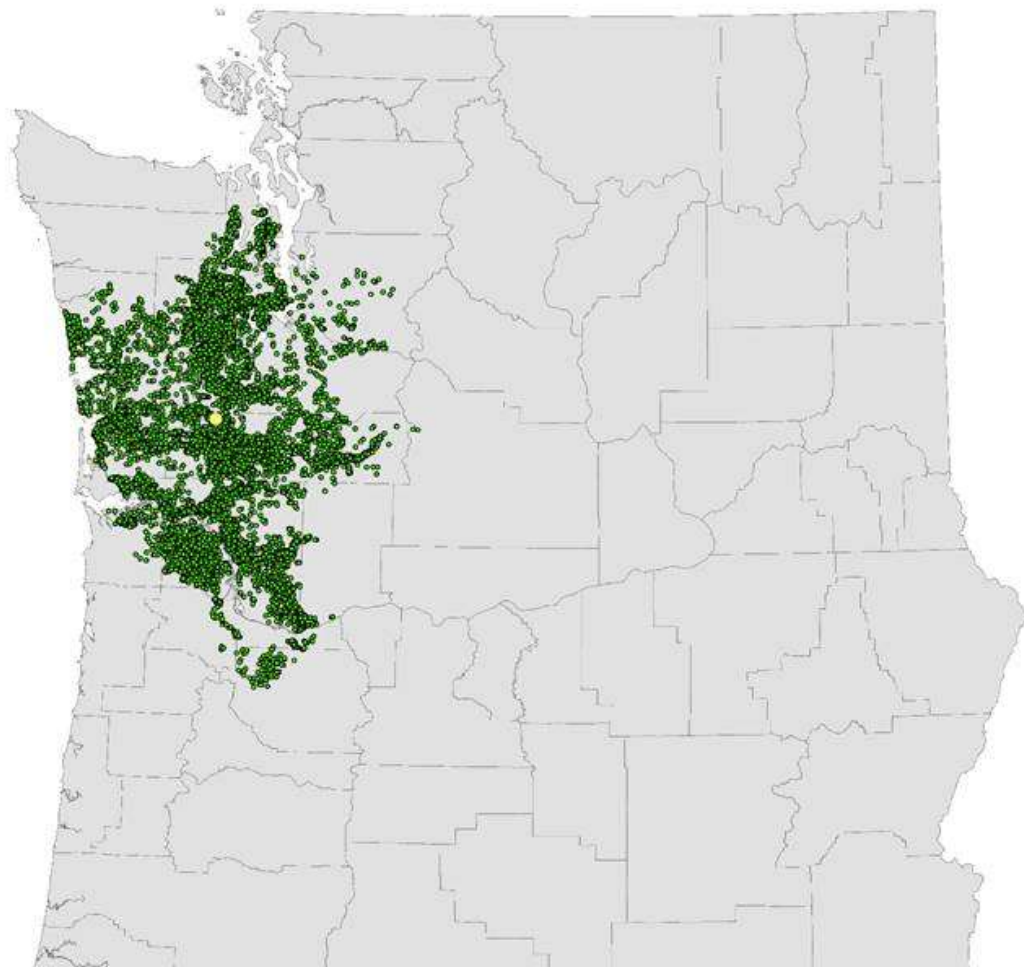


Figure 2.4 Hardwood forest harvest parcels; yellow dot = Centralia, WA

Forest harvest hardwood residue estimates were provided by the Natural Resources Spatial Informatics Group, Precision Forestry Cooperative, University of Washington (Jeffrey M. Comnick) by quantifying biomass volume of branches and tops from harvested trees within roughly 187km of Centralia, WA (located in Lewis County) over a 5-year period. Pulp logs were excluded from the available estimate assuming a market exists for this biomass. Only roadside residues were considered, and softwood harvest system/ownership recovery factors were applied.

2.3.5. Agricultural residues

Agricultural residues from Lewis County and its surrounding counties (Cowlitz, Grays Harbor, Thurston, Pacific, Pierce, Skamania, Wahkiakum) were estimated using bushel yields from the USDA 2012 Census of Agriculture, Tables 24-27. Barley straw, corn stover, wheat straw, and grass seed straw residues were considered. Other residue types were excluded because the value was 0 bushels (buckwheat, camelina, emmer & spelt, rapeseed, rye for grain, safflower, sorghum, durum wheat, mint for oil) or could not be disclosed (flaxseed, triticale, hops). Oats from grain were also excluded because this residue type was not represented in the 2005 Biomass Inventory and Bioenergy Assessment, so proper calculations could not be conducted. However, this source was minimal. Biomass conversion and residue calculation methods were taken from the 2005 Biomass Inventory and Bioenergy Assessment.

2.4. Results

2.4.1. Purpose-grown hybrid poplar plantations

Figure 2.5 and Figure 2.6 show the potential suitable land area for growing hybrid poplar and biomass supply. Considering all three land types, pastureland, irrigated cropland, and non-irrigated cropland, there is potentially 822,384 km² of suitable land area for growing hybrid

poplar and 1,398 bone dry Gg of hybrid poplar biomass priced at \$121/bone dry Mg or less available to supply a biorefinery within 100km.

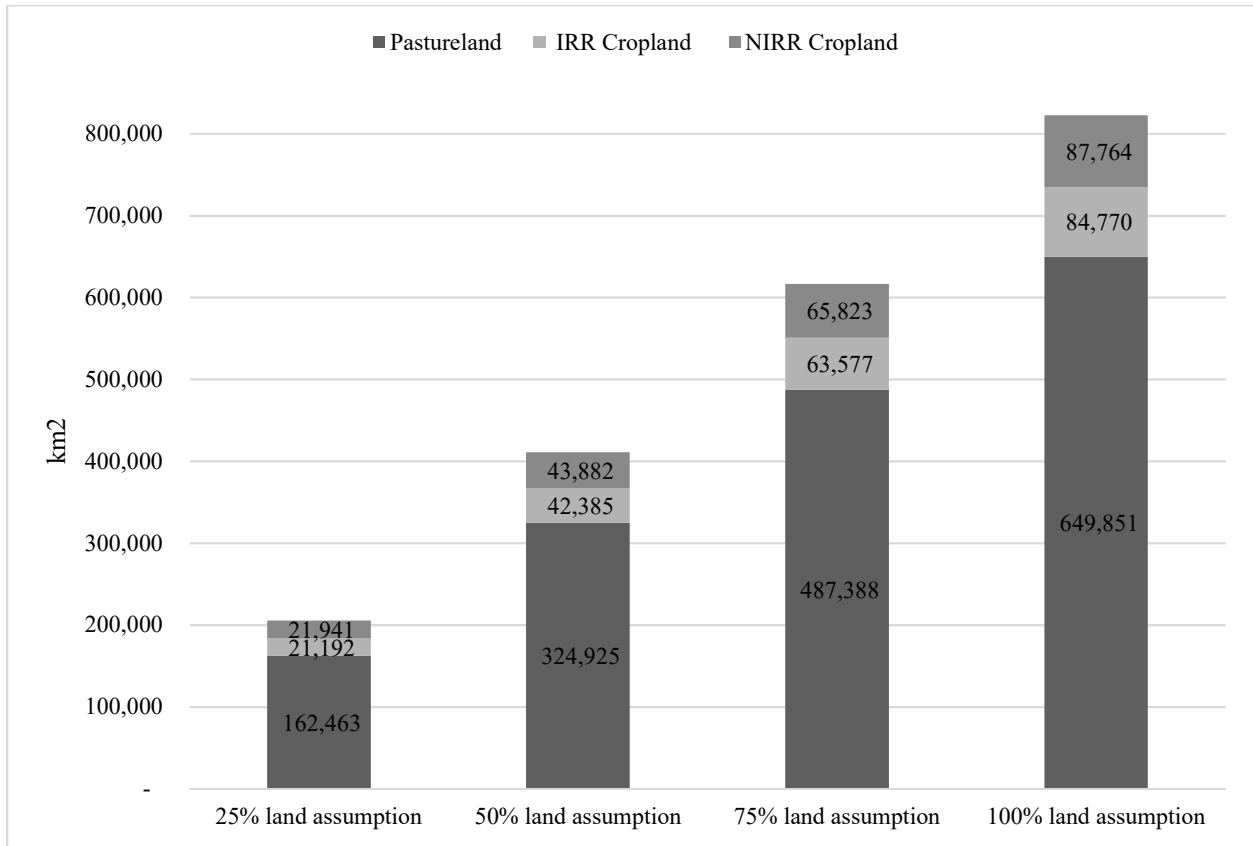


Figure 2.5 Total potential suitable land area across all land types under varying land conversion rate assumption (biomass \leq \$121/bone dry Mg delivered and within 100km)

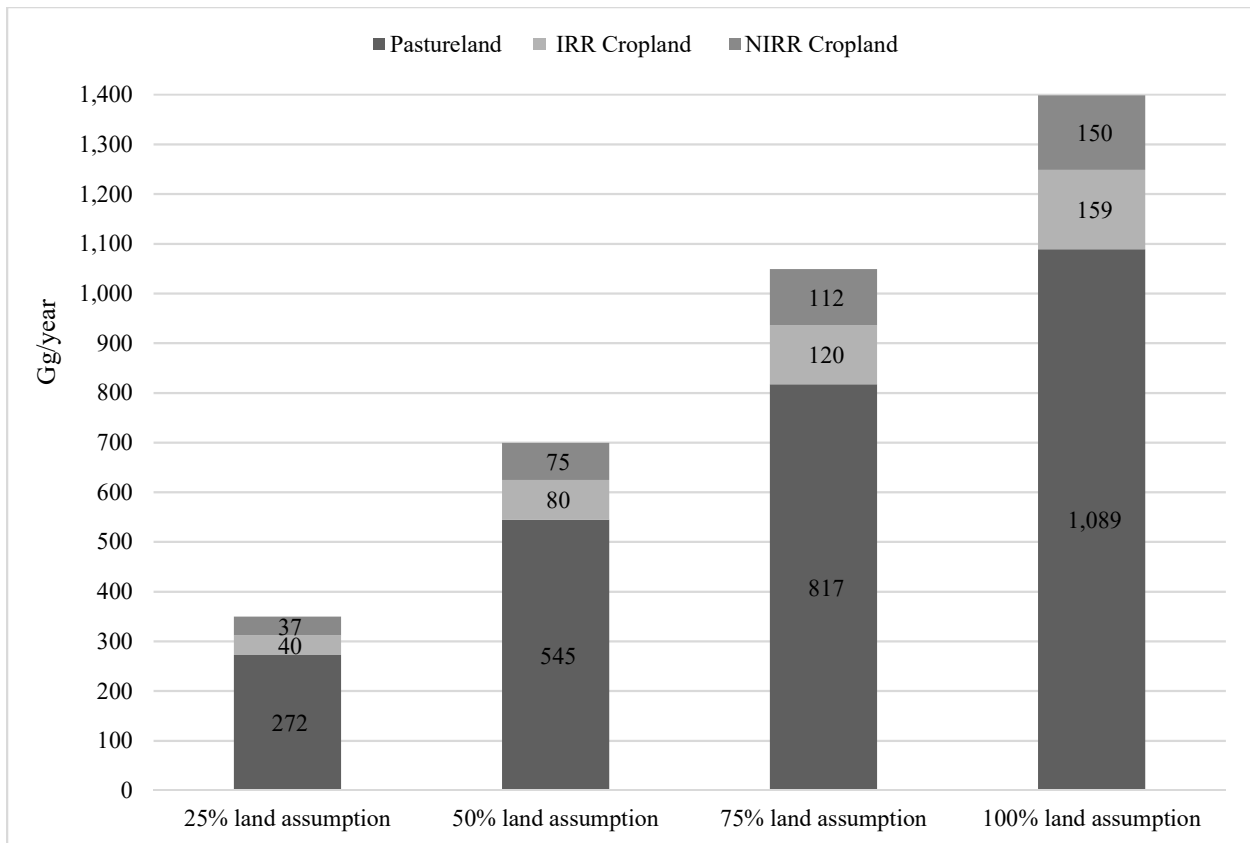


Figure 2.6 Total potential hybrid poplar biomass supply across all land types under varying land conversion rate assumption (biomass \leq \$121/bone dry Mg delivered and within 100km)

The supply curves in Figure 2.7, Figure 2.8, and Figure 2.9 show the biomass availability and associated marginal plant-gate cost by land type and land conversion rate. Non-irrigated cropland has the lowest average plant-gate cost of poplar biomass considering 100% land conversion (\$86.94/bone dry Mg), but also has the least potential supply of biomass (150 Gg/year), as compared to pastureland (\$95.19/bone dry Mg; 1,089 bone dry Gg/year) and irrigated cropland (\$105.59/bone dry Mg; 159 Gg/year). Although growing poplar on pastureland is generally less expensive due to lower land rent costs, pastureland has a higher average plant-gate cost than NIRR cropland when considering all the suitable land (100% land conversion), because there is more abundant pastureland at higher prices, driving the average price up.

Limiting the poplar biomass supply to the 1st 150 Gg/year to compare prices at the same biomass quantity levels, the average plant-gate cost by land type becomes \$76.69/bone dry Mg, \$101.85/bone dry Mg, and \$85.84/bone dry Mg for pastureland, irrigated cropland, and non-irrigated cropland respectively. In this case, biomass from pastureland assumes a lower average plant-gate cost than biomass from non-irrigated cropland since the pasturelands with relatively higher plant-gate costs are not realized at lower biomass quantities.

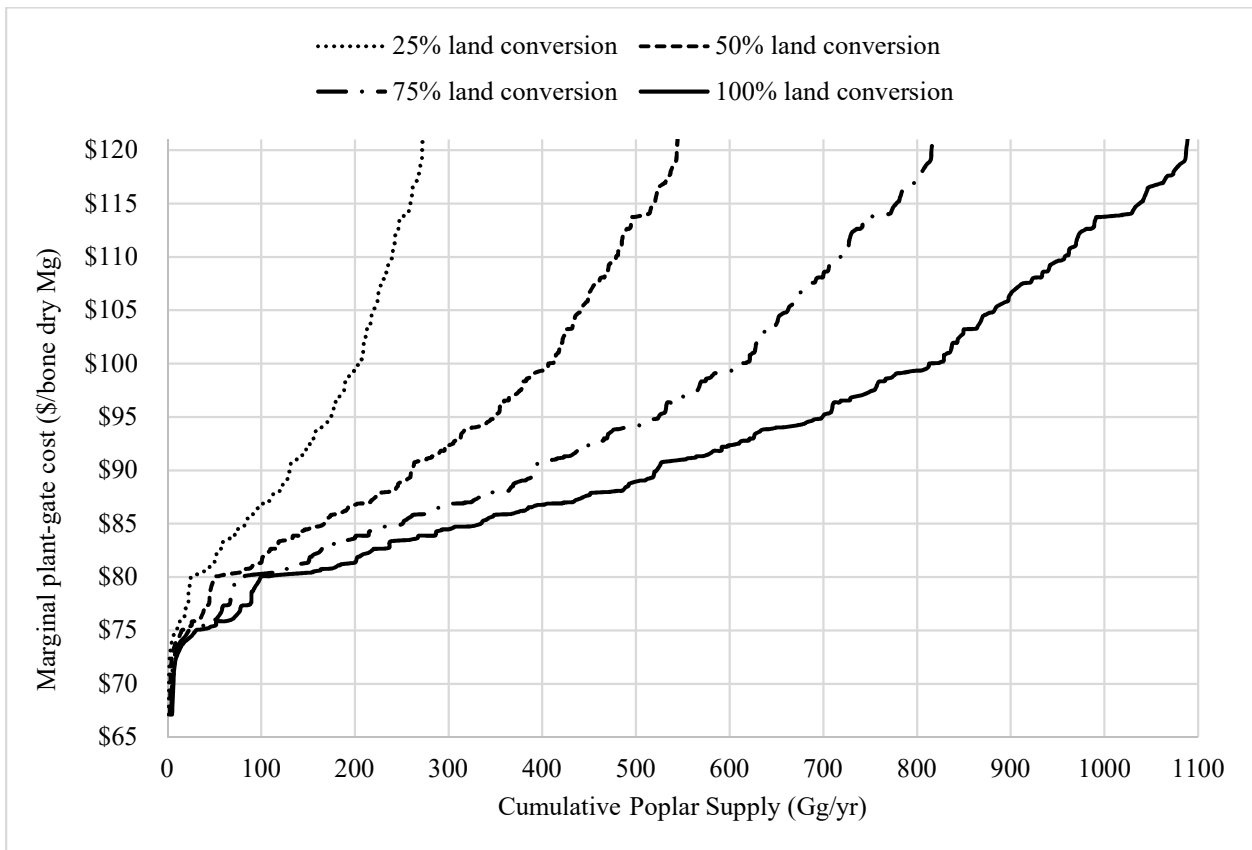


Figure 2.7 Pastureland, purpose-grown, hybrid poplar supply curve

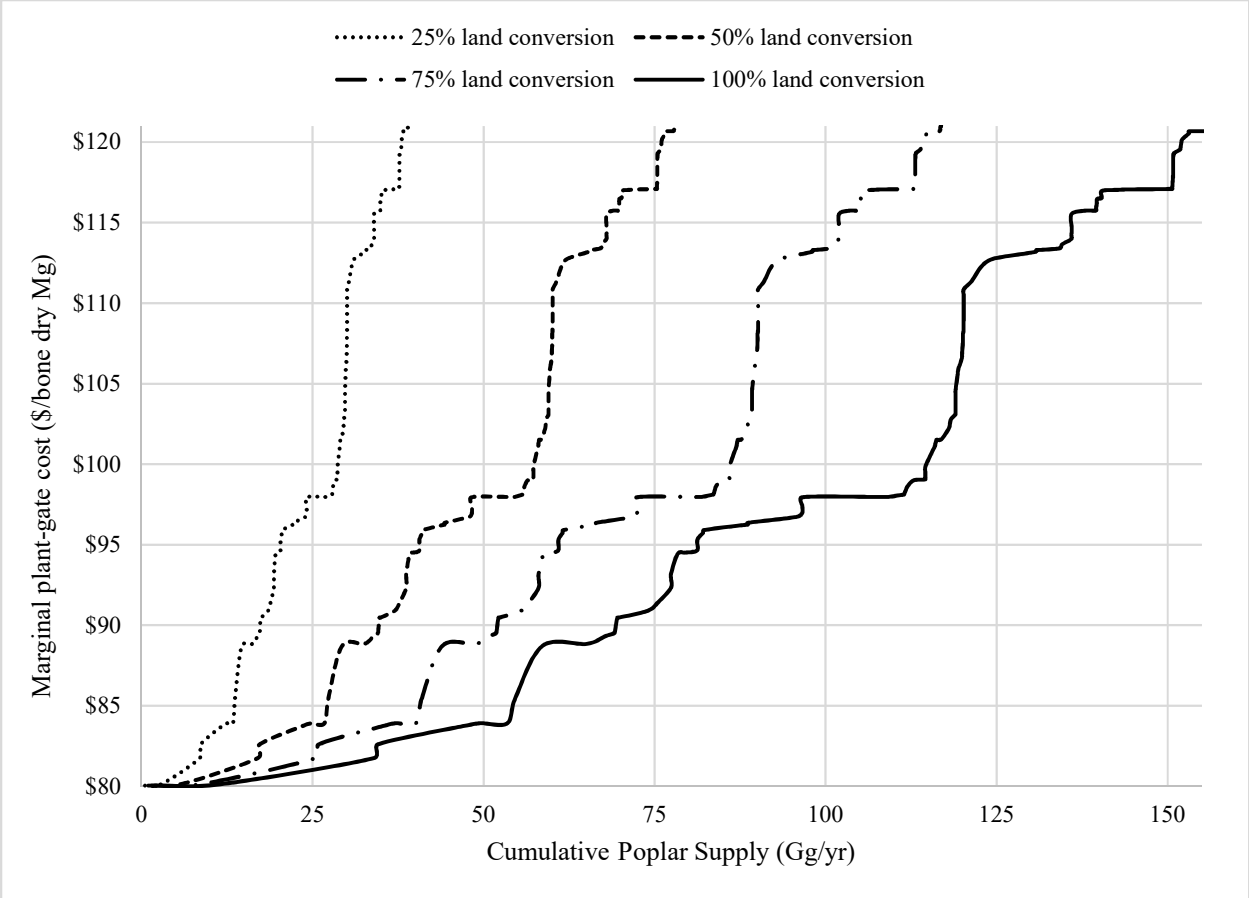


Figure 2.8 Irrigated cropland, purpose-grown, hybrid poplar supply curve

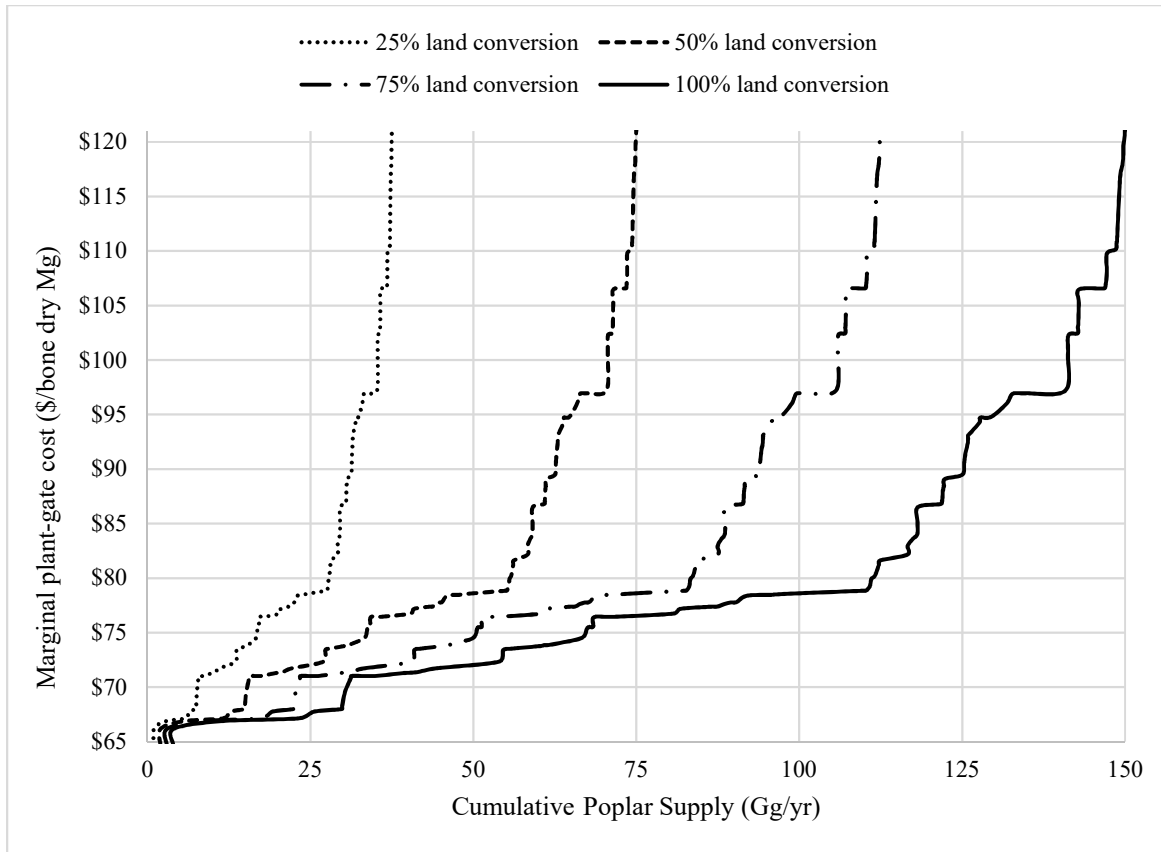


Figure 2.9 Non-irrigated cropland, purpose-grown, hybrid poplar supply curve

2.4.2. Wastewater management ecosystem service derived hybrid poplar biomass

Table 2.4 shows summary data from the wastewater management ecosystem service application by proximity scenario including POTW disposal need, required plantation area for handling the disposal need, and potential biomass supply. The maximum potential of hybrid poplar biomass available from wastewater management ecosystem service is 180 dry Gg year, considering the 45 m³/day/hm² (0.001 m³/s/hm²) application rate and 5-mile proximity scenario. The 141 m³/day/hm² (0.002 m³/s/hm²) application rate, representing the high recycled water application rate with low land use scenario, may be the more realistic scenario considering that POTW management strategy would likely desire to minimize land use and maximize application

rate to reduce land costs. Considering the 141 m³/day/hm² application rate and 5-mile proximity scenario, the maximum potential of poplar biomass is 58 Gg/year.

Table 2.4 Wastewater management ecosystem service derived hybrid poplar biomass summary table

Scenario	POTW Combined Avg. Flow Rate (m³ s⁻¹)	POTW Individual Avg. Flow Rate (m³ s⁻¹)	Disposal Need (dam³) over 90-day summer period	Available, suitable land for hybrid poplar cultivation within proximity distance (hm²)	Land area required (hm²)	Potential Biomass Supply¹ (Gg/year)
Adjacent, 52 m Gs⁻¹	0.01	0.01	101	27 (25 accounting for 8% headway space)	25 (27 with 8% headway)	0.4
Adjacent, 163 m Gs⁻¹					8 (9 with 8% headway)	
0.25 miles, 52 m Gs⁻¹	0.47	0.03	3,670	552 (508 accounting for 8% headway space)	903 (975 with 8% headway)	15
0.25 miles, 163 m Gs⁻¹					289 (312 with 8% headway)	
2 miles, 52	1.93	0.04	15,001	19,963	3,691	58

m Gs⁻¹				(18,366 accounting for 8% headway space)	(3,987 with 8% headway)	
2 miles, 163 m Gs⁻¹					1,181 (1,276 with 8% headway)	18
5 miles, 52 m Gs⁻¹	6.05	0.10	47,011	95,924 (88,250 accounting for 8% headway space)	11,568 (12,493 with 8% headway)	180
5 miles, 163 m Gs⁻¹					3,702 (3,998 with 8% headway)	58

¹Considering 100% participation from all qualifying POTWs

Plant-gate costs under the Free Land and Harvest and Ship scenarios is influenced by available acreage, yields, available biomass, and land rental costs. Although some cost parameters for the pixels under each land type may be the same (in terms of \$/m²), there is variation in the biorefinery average plant-gate shared cost by land type due to the varying amounts of acres and biomass available under each land type and their associated yields. The favorable yields of irrigated cropland over the other two land types helps to lower its biorefinery average plant-gate shared cost. Under the Free Land scenario, feedstock cost reductions from purpose grown feedstock costs are 14%, 31%, and 16% for pastureland, irrigated cropland, and non-irrigated cropland, respectively (Figure 2.10). Irrigated cropland has the greatest potential savings under this scenario. This land type also has the most expensive land rent costs and is able

to maximize on the benefit of free land provided by the POTWs for the hybrid poplar plantations. Under the Harvest and Ship scenario, feedstock cost reductions from purpose grown feedstock are 42%, 54%, and 45% for pastureland, irrigated cropland, and non-irrigated cropland, respectively (Figure 2.10). Under this scenario, transportation and harvest costs (in terms of $\$/m^2$) are the same for all three land types. The biorefinery average plant-gate shared cost varies only slightly accounting for the differences in available acres, biomass, and yields of the three land types. Irrigated cropland again has the greatest savings potential because it has the highest average purpose-grown plant-gate cost. The Harvest and Ship scenario offers the greatest feedstock cost reductions to the biorefinery and is a likely scenario since the POTWs are most interested in utilizing the land resource (poplar plantations) as disposal sites and the biorefinery is most interested in the biomass produced from these lands. Average cost of wastewater management ecosystem service derived biomass under the Harvest and Ship cost scenario across all land types for qualifying land is $\$51/\text{bone dry Mg}$. Under the Free Land scenario, average biomass cost is $\$75/\text{bone dry Mg}$ across all land types.

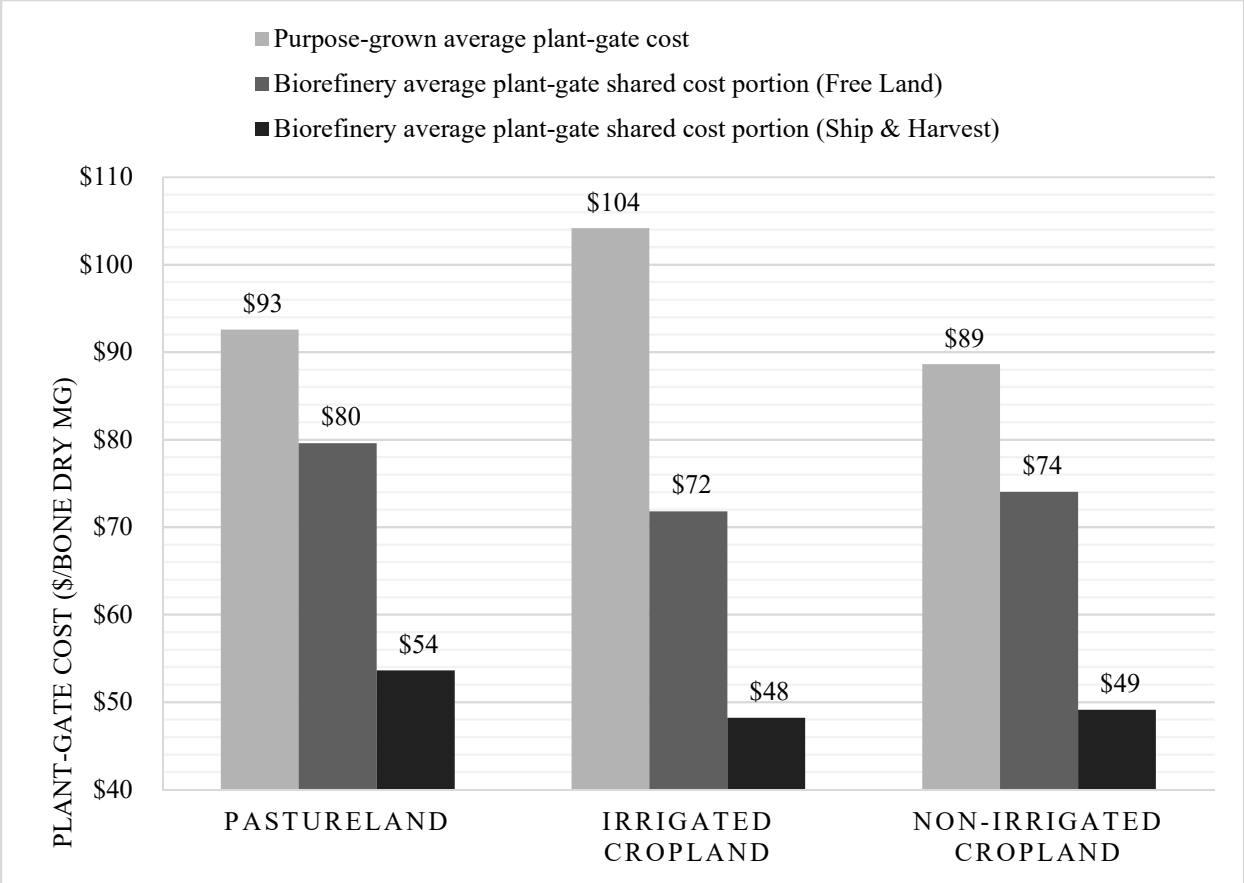


Figure 2.10 Wastewater management ecosystem service feedstock cost reductions

2.4.3. Hardwood sawmill residues

Figure 2.11 shows projected hardwood sawmill residue volumes by county in years 2020, 2025, and 2030. Hardwood sawmill residue projections average 52 Gg/year with projected annual residue volumes of 52 Gg/year in 2020, 48 Gg/year in 2025, and 57 Gg/year in 2030. Lewis County is the largest producer of the included counties. Actual residue volumes will vary with sawmill production, and availability will be a function of competitive price offering. Other factors may reduce actual biomass availability on the open market such as long-term contracts with competing customers.

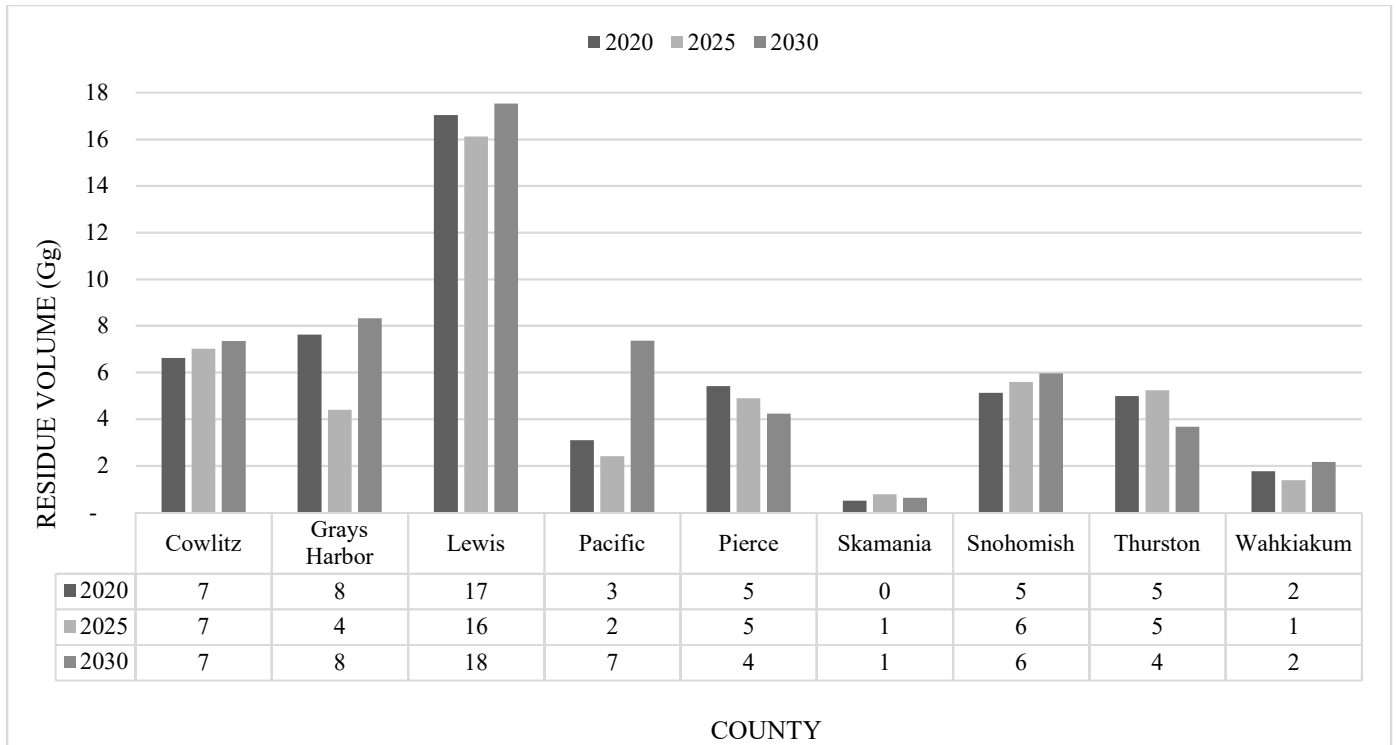


Figure 2.11 Projected hardwood sawmill residues (excluding chips) by county

The delivered price for hardwood sawmill hog fuel residues ranged from \$13-\$55/bone dry Mg, with an average price of \$28/bone dry Mg. Majority of these quoted residues are located far from the biorefinery site, driving the weighted average delivered cost up to \$46/bone dry Mg. Delivered sawdust prices ranged from \$27-\$88/bone dry Mg, with an average price of \$42/bone dry Mg. Majority of these quoted residues are located within 100km of the biorefinery site, driving the weighted average cost down to \$35/bone dry Mg. Combined, hardwood sawmill residues have an average weighted delivered cost of \$41/bone dry Mg, representing a 46% feedstock cost reduction compared to hybrid poplar from pastureland at the same quantities. Although this source of biomass has a relatively low undelivered, base cost (ranging from \$11-25/bone dry Mg for hog fuel and \$12-40/bone dry Mg for sawdust), transportation costs comprise a large portion of the total biomass cost and becomes the limiting factor in biorefinery

affordability of this source. And while sawmill residues do offer a reduced-cost feedstock option, quantities are limited.

2.4.4. Hardwood forest harvest residues

Table 2.5 shows hardwood forest harvest residues from pulp, tops, and branches within 187km of Centralia, WA (located in Lewis County). Considering only forest harvest residues from tops and branches, there is approximately 142 bone dry Gg/year of this biomass source available. Though this amount of biomass is noteworthy, it is considered unattainable and not pursued further in this study. Currently, it is not economically viable to obtain this biomass and hardwood forest residues are mixed with softwood forest residues, making this biomass unacceptable for bioconversion processes.

Table 2.5 Forest harvest residues over 5-year period (bone dry Gg/year)

Harvest System	Pulp	Tops	Branches
Ground	248	58	527
Cable	56	14	113
Total	305	72	639
Combined Tops & Branches	712		
Combined Tops & Branches per year	142		

2.4.5. Agricultural residues

Table 2.6 shows estimated annual agricultural residue volumes by county. Agricultural residues totaled 10,645 dry Mg/year (~11 Gg/year). Due to the low agricultural activity in Lewis County and surrounding counties, this biomass source was considered quantitatively trivial and not pursued further in this study. Limited local agricultural industry offers some explanation for the low-cost, ample pastureland available in the study area.

Table 2.6 Annual agricultural residues by county (dry Mg/year)

County	Barley Straw residues	Corn stover residues	Wheat Straw residues	Grass Seed Straw residues
Cowlitz	1,000	-	711	5,892
Grays Harbor	(D)	-	1,438	-
Lewis	630	-	973	(D)
Pacific	-	(D)	(D)	-
Pierce	-	1	(D)	(D)
Skamania	-	-	-	(D)
Thurston	(D)	-	-	-
Wahkiakum	-	-	-	-
Totals	1,630	1	3,122	5,892
Total				10,645

Key

(D) - withheld to avoid disclosing data for individual farms

(X) - not applicable

(-) = zero

2.4.6. Mixed feedstock scenarios and cost reductions

Potential feedstock sourcing scenarios are defined to supply a biorefinery with 250 Gg of biomass/year, representing a modest production size producing 75 megaliters (75,103 m³) of ethanol per year. Scenario objectives include: 1) minimize feedstock cost by maximizing lowest-cost sources first, 2) employ ecosystem service when appropriate, and 3) diversify feedstock source. To eliminate the concern of food vs. fuel, only purpose-grown hybrid poplar from

pastureland is considered in the defined scenarios on the basis that there is plentiful pastureland available for hybrid poplar cultivation at affordable plant-gate costs (Figure 2.7). For purpose-grown hybrid poplar, the 50% land conversion rate is considered. 100% of annual projected hardwood sawmill residues are considered available to the biorefinery to capture the maximum potential utilization of this resource; due to the low cost of this biomass, plant-gate costs fall well within biorefinery affordability ranges. The $141 \text{ m}^3/\text{day}/\text{hm}^2$ ($0.002 \text{ m}^3/\text{s}/\text{hm}^2$) application rate and 5-mile proximity scenario was used to quantify potential biomass from wastewater management ecosystem service derived hybrid poplar; the maximum potential biomass was considered assuming full participation from all qualifying POTWs. Water treatment facilities appear to be motivated to take advantage of this opportunity provided a market for the poplar is available. The average plant-gate cost for this ecosystem service derived biomass was calculated by averaging the biorefinery average plant-gate shared cost for each land type. In this case, croplands are not excluded since acceptable land (qualifying pixels) is a function of proximity to the participating POTW. Of all the qualifying suitable land for wastewater management ecosystem service, 70% is pastureland, 19% is IRR cropland, and 12% is NIRR cropland. This suggests that high displacement of cropland is not likely.

Biomass distributions and associated costs and savings for each mixed feedstock scenario are explained in Table 2.7. The Purpose-grown scenario represents the case where only hybrid poplar from purpose-grown pastureland plantations is utilized. The Purpose-grown + Residues scenario represents the case where hardwood sawmill residues are used to their maximum potential and hybrid poplar from purpose-grown pastureland plantations is then used to meet the remaining feedstock demand. The Purpose-grown + Residues + Free Land scenario represents the case where hardwood sawmill residues are used to their maximum potential, followed by

hybrid poplar from ecosystem service under the Free Land cost scenario, and hybrid poplar from purpose-grown pastureland plantations is then used to meet the remaining feedstock demand.

The Purpose-grown + Residues + Harvest and Ship scenario is the same as the Purpose-grown + Residues + Free Land scenario except hybrid poplar from ecosystem service considers the Harvest and Ship cost scenario.

With 44% of the feedstock supply coming from reduced-cost sources, the Purpose-grown + Residues + Harvest and Ship scenario offers the greatest feedstock cost savings of 22% over the Purpose-grown scenario. While the Purpose-grown + Residues + Free Land scenario offers the same biomass distribution as the Purpose-grown + Residues + Harvest and Ship scenario, savings are less, 15%, due to the higher cost of biomass under the Free Land cost scheme. There is only minimal difference in cost savings between the Purpose-grown + Residues scenario and the Purpose-grown + Residues + Free Land scenario. Although biomass quantities under the Free Land scenario comprise 23% of the biomass distribution, the biomass costs are not much lower than hybrid poplar from purpose-grown pastureland plantations (difference of \$4/bone dry Mg).

Table 2.7 Feedstock scenarios and plant-gate cost savings (250 Gg/year feedstock capacity)

Scenario		Hybrid poplar from purpose-grown pastureland plantations	Hardwood sawmill residues	Hybrid poplar from wastewater management ecosystem service (Free Land)	Hybrid poplar from wastewater management ecosystem service (Harvest and Ship)	Weighted Average plant-gate cost (\$/bone dry Mg)	Average feedstock plant-gate cost savings (%)
Purpose-grown	Gg/year	250	0	0	0	\$83	N/A
	Feedstock contribution (%)	100%	0%	0%	0%		
	Average plant-gate cost (\$/bone dry Mg)	\$83	N/A	N/A	N/A		
Purpose-grown +	Gg/year	198	52	0	0	\$73	12%

Residues	Feedstock contribution (%)	79%	21%	0%	0%		
	Average plant-gate cost (\$/bone dry Mg)	\$81	\$41	N/A	N/A		
Purpose-grown + Residues + Free Land	Gg/year	140	52	58	0	\$70	15%
	Feedstock contribution (%)	56%	21%	23%	0%		
	Average plant-gate cost (\$/bone dry Mg)	\$79	\$41	\$75	N/A		
Purpose-grown + Residues + Harvest and Ship	Gg/year	140	52	0	58	\$65	22%
	Feedstock contribution (%)	56%	21%	0%	23%		
	Average plant-gate cost (\$/bone dry Mg)	\$79	\$41	N/A	\$51		

2.5. Discussion

Availability and quantity of alternative, low-cost feedstock biomass supply options are important in driving capital cost reductions but often, actual availability is unknown, and quantities can be limited. Actual availability of biomass would be determined once contractual agreements by individual sites are reached and can vary greatly depending on individual circumstances and temporal conditions. Alternatively sourced biomass can offer up to 46% feedstock cost savings in the case of sawmill residues and up to 54% in the case of ecosystem service derived biomass at matched biomass quantities. However, biomass quantities from these sources represent only a fraction of the available biomass that is available from purpose grown hybrid poplar plantations.

Ecosystem service applications provide an opportunity to create mutual benefits between partnering entities and the community, however, participation and potential partnerships are strongly governed on prospective financial gain or savings for participants. Development and use of poplar plantations for treated wastewater effluent disposal proves to be a more cost-effective

disposal method when compared to more costly alternatives, such as pumping wastewater to another facility for disposal (Patrick Wiltzius, personal communication, November 15, 2018).

While there are good ecological opportunities with this type of application including preservation of water within its original watershed, mitigation of nitrogen leaching, and low soil disturbance compared to other land uses, there are still challenges associated with use of poplar for water reclamation including new permitting requirements, retention of water rights, and changing legislative regulations¹⁵.

As alternatively sourced biomass quantities become more limited, and biorefinery production size increases, economy of scale benefits of alternatively sourced biomass become less prevalent as the low-cost biomass is quickly depleted. Table 2.8 shows outcomes of two feedstock supply scenarios when biorefinery production size is scaled up to a feedstock capacity of 630 Gg/year (corresponding to 189 megaliters or 189,271 m³ ethanol production).

Table 2.8 Feedstock scenarios and plant-gate cost savings (630 Gg/year feedstock capacity)

		Feedstock Source				Hybrid poplar from wastewater management ecosystem service (Harvest and Ship)	Weighted Average plant-gate cost (\$/bone dry Mg)	Average feedstock plant-gate cost savings (%)
		Hybrid poplar from purpose-grown pastureland plantations	Hybrid poplar from purpose-grown non-irrigated cropland plantations	Hybrid poplar from purpose-grown irrigated cropland plantations	Hardwood sawmill residues			
Purpose-grown	Gg/year	545	75	10	0	0	\$94	N/A
	Feedstock contribution (%)	87%	12%	2%	0%	0%		
	Average plant-gate cost (\$/bone dry Mg)	\$95	\$87	\$73	N/A	N/A		
Purpose-grown + Residues + Harvest and Ship	Gg/year	520	0	0	52	58	\$86	9%
	Feedstock contribution (%)	83%	0%	0%	8%	9%		
	Average plant-gate cost (\$/bone dry Mg)	\$94	N/A	N/A	\$41	\$51		

At this production size, purpose-grown biomass availability nears its limit. Only 545 Gg/year of 50% converted pastureland derived hybrid poplar is available, but this still comprises 87% of the biomass supply. Non-irrigated cropland can be considered for meeting the rest of the demand up to 75 Gg/year at a 50% converted land assumption rate. The rest of the demand would have to be met by irrigated cropland, which is not only the most expensive of all the land types but also poses conflict regarding food crop competition. As more biomass is needed, biomass from poplar plantations farther away from the biorefinery site must be obtained, thus driving up average feedstock costs. Considering the Purpose-grown Scenario vs. the best performing scenario, Purpose-grown + Residues + Harvest and Ship, only 9% feedstock cost savings can be realized as shown in Table 2.8, signaling that ecosystem services with limited quantities of biomass only offer cost benefits at moderate scale biorefineries. Biorefinery production size is not always dependent on the notion that “bigger is better” for obtaining cost savings, rather, production size needs to reflect the local context and circumstances regarding biomass availability.

Another challenge for startup biorefineries is access to immediately available biomass. While residues can provide an immediate source, since quantities may be limited, other sources may need to be temporarily used. Sometimes these sources can be strategically sourced, as in the case of using forest harvest residues with potential improved technology. Other times, biorefineries may be able to take advantage of unpredictable opportunities, such as China’s World Trade Organization (WTO) filing of the Green Sword. The Green Sword is a recovered paper and plastic importation ban, which has created a surplus of recovered mixed paper in the U.S. with

limited means for disposal³². This surplus of recovered mixed paper presents opportunity for an unexpected, low-grade, very low-cost feedstock supply option for a bioconversion facility.

2.6. Conclusion

This case study provided a quantitative assessment, including quantity, availability, and cost, of hardwood biomass and agricultural residues available in western Washington to supply a mid-size, ethanol-producing biorefinery while providing a framework for assessing these biomass sources with regional resources. Biomass from purpose-grown hybrid poplar plantations on three land types (pastureland, irrigated cropland, and non-irrigated cropland) was evaluated. Biomass from alternative sources including hardwood sawmill residues, wastewater management ecosystem service, forest harvest residues, and agricultural residues were assessed for feedstock cost reduction potential. Forest harvest residues and agricultural residues were quantified but not further assessed due to inaccessibility and minimal availability, respectively. 822,384 km² within 100km of the proposed biorefinery site are deemed suitable for hybrid poplar cultivation. This translates to 1,398 bone dry Gg/year of hybrid poplar biomass. However, assuming a more realistic 50% land conversion factor, 699 Gg/year could be available. Average plant-gate costs for hybrid poplar by land type for the 1st 150 Gg of biomass are \$76.69/bone dry Mg for pastureland, \$101.85/bone dry Mg for irrigated cropland, and \$85.84/bone dry Mg for non-irrigated cropland. Because these feedstock costs fall out of biorefinery affordability ranges, alternative biomass from low-cost sources are needed. 58 Gg/year of hybrid poplar biomass could be available from wastewater management ecosystem service, costing on average, \$75/bone dry Mg under the Free Land shared cost scenario and \$51/bone dry Mg under the Harvest and Ship shared cost scenario. On average, 52 Gg/year of hardwood sawmill residues (hog fuel and sawdust) could be available, with an average plant-gate cost of \$41/bone dry Mg

but the actual availability for purchase would require more in-depth analysis. Using mixed feedstock scenarios, 12-22% feedstock cost savings can be realized when incorporating alternative feedstock sources to supply a 250 Gg/year capacity. These savings decline as biorefinery capacity grows, and low-cost sources are depleted. There is significant potential for incorporating residues and ecosystem service derived biomass to supply a biorefinery, and the economic benefits grow as these low-cost sources are maximized. Due to unknown participation rates, actual availability of these biomass sources is required for future feasibility studies. Valuation of additional ecological benefits from use of otherwise waste products and employment of ecosystem service should also further be investigated.

3. Techno-economic and life cycle carbon analysis of an integrated cellulosic ethanol biorefinery

3.1. Abstract

To mitigate climate change, reduce greenhouse gas (GHG) and particulate emissions, contribute towards energy independence and security, and promote sustainable economic development in the United States (U.S.), cellulosic biofuels have been considered as potential replacement fuels for petroleum-derived fuels. While biofuels offer many environmental and socioeconomic benefits, commercial scale biorefineries are not prominent in the U.S. High feedstock costs and capital investment costs are two of the biggest challenges prohibiting the advancement of commercial scale biofuel production. This study evaluated a proposed biorefinery incorporating low-cost feedstock supply options and an integrated approach assuming co-location with an adjacent power plant to reduce capital investment costs. The proposed biorefinery design, referred to as the Integrated design case, assumes co-location with an adjacent power plant, eliminating the need for an in-house boiler/turbogenerator under the

assumption the biorefinery can utilize the power plant's excess boiler capacity for combustion of waste and by-product streams. The wastewater treatment system could also be eliminated by using a multi-effect evaporator to evaporate waste streams into combustible syrup for steam production. The biorefinery produces 75 megaliters of cellulosic annually with a feedstock capacity of 250 Gg per year. Two additional design cases are further evaluated for comparison: (1) Non-integrated design case producing 75 megaliters of ethanol annually, and (2) Integrated, Increased Production design case producing 189 megaliters of ethanol annually. Under the Integrated design case, total capital investment is reduced by 38% and installed equipment costs are reduced by 43%. Discounted cash flow rate of return analysis is used to evaluate economic performance and ethanol minimum selling price. Under the most realistic financing scenario, 40% loan and 15% discount rate, the Integrated, Increased Production design case incorporating integrated approaches, including using mixed feedstock supply sources, achieves the lowest minimum ethanol selling price of \$0.67/liter, resulting in a 31% reduction in ethanol minimum selling price compared to the Non-integrated design case and a 19% reduction compared to the Integrated design case. Life cycle carbon analysis (quantifying global warming potential (GWP) contribution in CO₂ equivalents emitted per MJ⁻¹ of fuel) of the Integrated design case is conducted, yielding a 52% reduction in global GWP as compared to 2005 gasoline production and use. This study provides a framework for incorporating integrated approaches into biorefinery design using local context to realize economic and environmental gains.

3.2. Background

The concept for the biorefinery described in this study involves integration with a co-located power plant and collaboration with local community stakeholders and partners to provide socioeconomic and environmental benefit to the region, while reducing capital investment costs

to make construction attainable. Advanced Hardwood Biofuels Northwest (AHB), a research consortium initiative supported by the U.S. Department of Agriculture National Institute of Food and Agriculture (USDA-NIFA), developed integrated modeling frameworks for assessing the feasibility of a hybrid poplar-based biofuels and biochemicals industry in the U.S. Pacific Northwest (PNW). Part of this research involved identifying potential sites for startup biorefineries. Results from the Geospatial Bioenergy Systems Model (GBSM, <https://hardwoodbiofuels.org/sustainability/economics/geospacial-model/>), which provides insight on the most profitable potential locations and scale for a biorefinery based on several profit optimization factors, showed a large cluster of potential sites in western Oregon and Washington, including Newburg, OR, Aumsville, OR, and Centralia, WA (located in Lewis County). These sites were favorable primarily due to ample, low-cost pastureland availability, favorable climatic conditions (sufficient rainfall, eliminating the need for crop irrigation), and access to product markets.

Also located in Centralia, WA is TransAlta's coal-fired power plant, set to be phased out by 2025 under the TransAlta Energy Transition Bill. There is an effort, however, to transition the power plant to natural gas and to extend its operation beyond 2025^{11,12}. If the coal-fired power plant were to be converted to a natural gas power plant, there is an opportunity to co-locate the biorefinery adjacent to the converted power plant and retain employment in the local region. Co-locating a potential biorefinery with a power plant offers the opportunity for the biorefinery to eliminate the in-house boiler/turbogenerator by utilizing the power plant's excess boiler capacity for combusting by-products of the production process to produce steam and consequently, electricity, by sending resultant steam through the power plant's turbines. NREL's installed capital equipment cost breakdown shows that eliminating the boiler/turbogenerator reduces

installed capital equipment costs by about 34%¹³. The wastewater treatment system could also be eliminated by sending concentrated waste from a multi-effect evaporator system to the power plant's boiler for steam production, saving an additional 3% of installed capital equipment costs¹³.

Additionally, Lewis County is primarily a rural community that could benefit from new industry and job creation. Lewis County's per capita income for years 2012-2016 trended 23% lower than the national average¹⁴. Mean household income, \$44,526, is also lower than the national average and poverty percentage, 15%, is higher than the national average for years 2012-2016¹⁴. Particularly, Lewis County has faced tough challenges in the agricultural industry, such as lack of infrastructure and markets, catastrophic flooding, housing development, and aging landowners¹⁵, resulting in significant need for economic growth and development.

The case for a biorefinery in Lewis County becomes increasingly attractive when the potential for hybrid poplar plantations to provide ecosystem service is considered. The Chehalis Regional Water Reclamation Facility, located in Lewis County, currently utilizes a 101 ha (1.01 km²) poplar plantation to dispose of treated wastewater during times of low flow in the Chehalis River (<28.3 m³ s⁻¹) and provides a good model for extrapolating this service within the region. Lewis County is also the largest producer of hardwood sawmill residuals (hog fuel and sawdust) of all its surrounding counties, excluding Yakima. Access to this supply of hardwood sawmill residuals source could provide opportunity for an immediate supply of affordable biomass, though limited in quantity.

For these reasons, a proposed bioconversion facility located in Lewis County, WA was selected to conduct this case study applying the integrated/co-located approach. Due to the bioconversion process, only hardwoods and other easily fractionated biomass (such as

agricultural residues) are acceptable. Hybrid poplar, as a hardwood, does not display the same recalcitrant properties as softwoods¹⁶ and can be fractionated without extensive pretreatment¹⁷, making it an optimal feedstock choice. To evaluate performance of a small to moderately sized production scale start-up biorefinery (based on the production scale reference of 94.6 megaliters based on Iowa's Project LIBERTY cellulosic ethanol biorefinery¹⁸), an annual cellulosic ethanol production of 75 megaliters was chosen. Considering an ethanol yield of 300 liters/Mg, 250,000 Mg (250 Gg) of biomass would be required to supply the bioconversion facility annually. Based on the potential quantity of available biomass within the region, 250,000 Mg of biomass per year is considered feasible.

The subsequent sections describe the process design, economic modeling, and carbon life cycle outcomes of this conceptualized biorefinery, referred to as the Integrated design case.

3.3. Results

3.3.1. Integrated Process design

Analysis of process consumption and output, steam and electricity, is important for understanding the energy and heat demand for biorefinery operations and is critical for analyzing the biorefinery carbon emissions. Table 3.1 compares steam and electricity usage for the conceptualized biorefinery described in 3.5.1, representing the Integrated design case, to an equivalently sized non-integrated biorefinery, representing the Non-integrated design case. Both design cases are based on a feedstock capacity of 250,000 dry metric tons (250 Gg) of hybrid poplar chips from purpose-grown plantations per year and produce 75 megaliters of cellulosic ethanol per year using a yield of 300,434 liters of ethanol per Gg (gigagram) (or 0.3 megaliters per Gg).

Both process designs undergo the same pretreatment, hydrolysis, and fermentation steps. The major distinction of the Integrated design case is that it does not consider an in-house boiler/turbogenerator or wastewater treatment system. Instead, excess boiler capacity from a co-located power plant is used for combustion of waste and by-product streams to produce steam. Wastewater treatment is eliminated by using a multi-effect evaporator to evaporate waste streams into combustible syrup that can be sent to the co-located power plant's boiler for steam production. The biorefinery is assumed to purchase electricity from the power grid, without selling any excess electricity produced from combusting waste streams like lignin, which is likely a conservative assumption. The biorefinery produces enough steam from evaporator syrup combustion to support steam demand for all biorefinery operations. In the Non-integrated design case, streams are either sent to wastewater treatment or the in-house boiler after distillation and ethanol recovery. Solids sent to the in-house boiler are combusted to produce excess electricity, which is then sold to the power grid.

Table 3.1 Biorefinery unit operation annual steam use and electricity use by design case

Design Case	Annual steam use by unit operation		Annual electricity use by unit operation	
	Unit Operation	Use (klb)	Unit Operation	Use (GJ)
Integrated	Feedstock handling	0	Feedstock handling	8,469
	Pretreatment & Conditioning	456	Pretreatment & Conditioning	55,348
	Enzymatic hydrolysis (or saccharification) coupled with co-fermentation	0	Enzymatic hydrolysis (or saccharification) coupled with co-fermentation	17,046
	Enzyme/Bacteria Production	0	Enzyme/Bacteria Production	36,906
	Distillation and solids recovery	1955	Distillation and solids recovery	20,784
	- Syrup evaporation	- 383	- Multi-effect evaporator	- 10,306

	Storage	0	Storage	108
	Utilities	0	Utilities	55,240
	Total	2793	Total	204,208

The integrated biorefinery process requires 2793 klb (kilopounds) of steam annually. Assuming a 75% boiler efficiency rate, the Integrated biorefinery design produces 2836 klb of steam annually steam via syrup combustion. Since the biorefinery produces slightly more steam than it consumes, the biorefinery is able to meet the steam demand for all operations with steam produced from syrup combustion.

With 8400 annual operating hours, the integrated biorefinery’s electricity demand is 204,208 GJ (Gigajoules) per year. The Integrated biorefinery purchases electricity at a wholesale price of \$0.01/MJ³³, equating to an electricity cost of \$0.03/liter (\$25/m³) ethanol. The biorefinery proposed in this study, the Integrated design case, offers a 64% electricity use reduction when compared to the Non-integrated design case. 80% of the avoided electricity use in the Integrated design case is attributed to the boiler/turbogenerator unit operation, which is the largest electricity user of all the biorefinery process unit operations. The remaining 20% is attributed to the wastewater treatment unit operation.

3.3.2. Economic modeling

3.3.2.1. Capital Expenses

Capital expenses for three design cases are estimated as described in section 3.5.2.1 and summarized in Table 3.2. The three design cases include:

1. The Integrated design case producing 75 megaliters of ethanol annually which incorporates use of a multi-effect evaporator to replace the wastewater treatment system. The in-house

boiler/turbogenerator is also eliminated through co-location with a power plant that allows the biorefinery to use its excess boiler capacity.

2. The Non-integrated design case producing 75 megaliters of ethanol annually which has an in-house wastewater treatment system after distillation and in-house boiler for combusting waste streams.

3. The Integrated, Increased Production design case producing 189 megaliters of ethanol annually which follows the same process design as the Integrated design case producing 75 megaliters of ethanol annually.

Table 3.2 Capital and operating expenses for three cellulosic ethanol biorefinery design cases

	Integrated design case	Non-Integrated design case	Integrated, Increased Production design case
Annual ethanol production	75 megaliters, 75,109 m ³	75 megaliters, 75,109 m ³	189 megaliters, 189,271 m ³
Total Equipment Installed Cost	\$53,013,342	\$93,288,933	\$83,121,947
Feed Handling	\$296,632	\$296,632	\$516,480
Pretreatment & Conditioning	\$18,690,717	\$18,690,717	\$32,543,330
Enzymatic Hydrolysis & Co-fermentation	\$6,550,828	\$6,550,828	\$11,405,969
Distillation & Solids Recovery	\$21,999,590	\$9,610,458	\$29,122,375
Wastewater Treatment	\$0	\$3,702,631	\$0
Storage	\$1,425,295	\$1,425,295	\$2,481,652
Burner/Boiler/Turbogenerator	\$0	\$48,962,092	\$0
Utilities	\$4,050,279	\$4,050,279	\$7,052,141
Other direct costs: warehouse, site development, additional piping	\$8,267,199	\$6,099,101	\$12,787,543

Total Direct Costs (TDC)	\$61,280,541	\$99,388,034	\$95,909,490
Total Indirect Costs: proratable & field expenses, home office & construction, project contingency, start-up and permitting, etc.	\$36,768,324	\$59,632,820	\$57,545,694
Fixed Capital Investment (FCI)	\$98,048,865	\$159,020,854	\$153,455,183
Working Capital	\$4,902,443	\$7,951,043	\$7,672,759
Total Capital Investment (TCI)	\$102,951,308	\$166,971,896	\$161,127,943
TCI per m³ of ethanol production	\$1,371	\$2,223	\$851
TCI per liter of ethanol production	\$1.37	\$2.22	\$0.85

The Integrated design case total capital investment (TCI) of \$102,951,308, representing a TCI per liter of \$1.37 offers a 38% reduction from the Non-integrated design case (\$166,971,896, \$2.22). Installed equipment costs are reduced by 43%. The largest driver for the capital cost reduction is the elimination of the in-house boiler/turbogenerator and wastewater treatment system due to the integrated approach described in 3.5.1.

The distillation and solids recovery unit operation accounts for a significantly larger portion of the installed equipment costs for the Integrated design case, 42% vs. 11%, mainly due to the 8-effect multi-evaporator. The 8-effect multi-evaporator has an installed cost of \$12,389,132, representing 56% of the Distillation & Solids Recovery total capital equipment costs and is the most expensive piece of equipment in the Integrated design case. The Feed handling unit operation is <1% of the total installed equipment capital cost breakdown for either design case. This is accredited to the handling of poplar chips, which is relatively simple as compared to other feedstock options such as corn stover, which requires bale unwrapping, washing, and shredding systems and pre-production on-site storage. There are no capital equipment costs for the enzyme production unit operation in either biorefinery design since

cellulase enzymes are bought from 3rd party sources and not produced on site. Pretreatment and conditioning processes account for 35% and 21% of the total installed capital equipment cost in the Non-integrated design and Integrated design, respectively. Pretreatment and conditioning processes represent the 2nd largest cost contributor in the Integrated design case, followed by enzymatic hydrolysis and co-fermentation.

When the Integrated design case is scaled up to produce 189 megaliters (189,271 m³) of cellulosic ethanol per year, the TCI becomes \$161,127,943, with a TCI per liter of \$0.85. This represents a reduction in total TCI per liter of ethanol of 38% as compared to the Integrated design case. TCI per liter is reduced by 62% when comparing the Integrated design case with a 189 megaliters yr⁻¹ production capacity to the Non-integrated design case with a 75 megaliters yr⁻¹ production capacity.

3.3.2.2. Variable operating expenses

Variable operating costs are estimated as described in section 3.5.2.3. Table 3.3 shows the variable costs associated with the Integrated and Non-integrated design cases at an annual ethanol production capacity of 75 megaliters. The 189 megaliters design case is not shown in the results below since the process design is identical to the Integrated 75 megaliters design case and linearly scaled to meet the increased production capacity. To obtain variable costs for the 189 megaliters design case, streams can be scaled based on process flow (except for the biomass feedstock stream which is explained later in this section). Biomass feedstock costs are based on the feedstock supply case that all biomass is sourced from purpose-grown hybrid poplar plantations from pastureland with an average plant-gate cost of \$83/bone dry Mg. Total variable costs under the Integrated design case are \$0.48 per liter of ethanol and \$0.46 per liter of ethanol for the Non-integrated design case. In the Integrated design case the boiler feed water, cooling

water, wastewater treatment chemicals, and wastewater treatment polymer are eliminated. However, the costs associated with these boiler and wastewater treatment related ancillary chemicals and streams are very small, and exclusion has little effect on total variable price. Other ancillary chemicals and streams include propane, make-up water, clarifier polymer, sulfuric acid, hydrated lime, and ammonium phosphate also make up represent a small cost contribution. For the Integrated design case, electricity is purchased from the power grid at wholesale price. However, in the Non-integrated design case, sufficient electricity is produced by the biorefinery (with an in-house turbogenerator) to run all biorefinery operations, and excess electricity is sold to the grid. The financial benefit for excess electricity sold to the grid is not reflected in this analysis since this contribution is relatively small and electricity costs are low. The cost savings realized by eliminating the WWT (wastewater treatment) & boiler ancillary chemicals in the Integrated design case do not overcome the costs of purchasing electricity. However, electricity costs are low, and this has little effect on total variable costs.

Table 3.3 Variable operating expenses for an integrated and non-integrated 75 megaliters per year cellulosic ethanol biorefinery

		Integrated			Non-Integrated		
Stream	2018 Indexed Cost (\$ kg ⁻¹)	Annual usage (kg year ⁻¹)	2018 Indexed Cost (\$ year ⁻¹)	\$ per liter ethanol	Annual usage (kg year ⁻¹)	2018 Indexed Cost (\$ year ⁻¹)	\$ per liter ethanol
Biomass Feedstock	\$0.08	250,000,000	\$20,668,331	\$0.28	250,000,000	\$20,668,331	\$0.28
Corn	\$0.45	3,140,985	\$1,418,191	\$0.02	3,140,985	\$1,418,191	\$0.02

Steep Liquor							
Purchased Cellulase (enzymes)	\$0.59	16,412,008	\$9,764,089	\$0.13	16,412,008	\$9,764,089	\$0.13
Ancillary chemicals	\$7.64	458,843,235	\$1,901,152	\$0.03	458,843,235	\$1,901,152	\$0.03
WWT & boiler ancillary chemicals	\$28.52	0	\$0	\$0	146,708	\$174,786	\$0.002
Disposals of gypsum and ash	\$0.10	11,325,434	\$578,774	\$0.008	11,325,434	\$578,774	\$0.008
Wholesale Electricity (kW, \$/kWh)	\$0.04	56,724,404	\$1,985,354	\$0.03	155,617,328	\$0	0
Total Variable Costs			\$36,315,891	\$0.48		\$34,505,323	\$0.46

Variable costs are further reduced by incorporating biomass from low-cost sources as described in 3.2. Feedstock costs for the Integrated design case using only biomass from purpose-grown hybrid poplar plantations on pastureland are \$0.28 per liter of ethanol. Feedstock costs are reduced to \$0.21 per liter of ethanol, offering a cost reduction of 22%, when hardwood

sawmill residuals and ecosystem service derived hybrid poplar are incorporated along with purpose-grown hybrid poplar from pastureland. Although potentially significant feedstock savings could be realized, estimated savings from this mixed feedstock supply case are limited since low-cost biomass sources are quickly consumed. Total variable costs for the 189 megaliters ethanol production biorefinery, using low-cost mixed feedstock supply sources, are \$0.49 per liter of ethanol. This represents only a slight change (+2%) from the total variable cost for the Integrated design case using solely purpose-grown hybrid poplar and accounts for the slightly higher feedstock costs, \$0.29 per liter, from having to source biomass further from the facility to meet feedstock demand.

3.3.2.3. Fixed operating expenses

Fixed operating costs are estimated as described in section 3.5.2.4 and summarized in Table 3.4. Since there were no changes to the salaries or number of personnel between design cases, all differences in fixed costs are attributed to variations in maintenance and property insurance costs.

Table 3.4 Fixed operating expenses for two cellulosic ethanol biorefineries under three production capacity and design cases

			Non-integrated, 75 megaliters ethanol production facility	Integrated, 75 megaliters ethanol production facility	Integrated, 189 megaliters ethanol production facility
Fixed Variable	Number of Personnel	2018 Total Indexed Annual	\$ per liter ethanol	\$ per liter ethanol	\$ per liter ethanol

		Salary (\$ year⁻¹)			
Labor/Salaries	11	\$1,952,075	\$0.03	\$0.03	\$0.01
	Labor burden (annual value)		\$0.02 (\$1,756,868)	\$0.02 (\$1,756,868)	\$0.01 (\$1,756,868)
	Maintenance (annual value)		\$0.01 (\$1,045,560)	\$0.02 (\$1,417,234)	\$0.01 (\$2,192,150)
	Property insurance (annual value)		\$0.02 (\$1,113,146)	\$0.01 (\$686,342)	\$0.01 (\$1,074,186)
	Total Fixed Costs (annual value)		\$0.08 (\$5,867,649)	\$0.08 (\$5,812,519)	\$0.04 (\$6,975,279)

Total fixed cost for the Integrated design case is \$0.08 per liter of ethanol produced (\$5,812,519). Fixed costs for the Non-integrated design case are slightly higher, \$0.08 per liter of ethanol produced (\$5,867,649), due to increased property insurance costs associated with a higher FCI. Maintenance costs are slightly higher in the Integrated design case since maintenance costs are a factor of ISBL (inside battery limits) costs which includes the multi-effect evaporator (as part of the Distillation and solids recovery unit operation) but not the wastewater treatment system or the boiler per NREL's 2011 economic modeling³⁴. Labor, salaries, and maintenance costs are the same for both the Integrated and Non-integrated 75 megaliters ethanol production biorefinery designs. Fixed costs for the 189 megaliters biorefinery, \$0.04 per liter, are reduced by 53% compared to the 75 megaliters Non-integrated design case and by 52% compared to the 75 megaliters Integrated design case due to proportionately lower

labor costs per liter (no change in number of employees or salary), maintenance costs, and property insurance costs.

3.3.2.4. Discounted cash flow analysis

Minimum ethanol selling prices under two financing options, 0% loan and 40% loan, with 0%, 7%, and 15% discount rates, are depicted in Figure 3.1 and Figure 3.2 for the four biorefinery design and feedstock supply scenarios described in 3.5.2.6. The discount rate of 0% represents the cash cost of the project, 7% represents the “cost of capital”, a minimum acceptable return, and 15% represents a more realistic investment return requirement. Minimum ethanol selling prices under the 0% financing option ranged from \$0.59/liter-\$1.07/liter. The 40% financing option resulted in minimum ethanol selling prices ranging from \$0.60-\$0.98/liter. In all financing and discount rate combinations, the 189 megaliters biorefinery performs best in terms of lowest minimum ethanol selling prices (0.67/liter under the 40% loan and 15% discount rate scenario), displaying the significant impact of economy of scale. Under the 40% loan and 15% discount rate scenario, the 189 megaliters biorefinery results in a 31% reduction in ethanol minimum selling price compared to the 75 megaliters Non-integrated design case and a 19% reduction compared to the 75 megaliters Integrated design case.

Under the 40% loan financing option and 15% discount rate, the Integrated design case minimum ethanol selling price is \$0.84/liter as compared to the Non-integrated design case with a minimum selling price of \$0.98/liter, representing 15% reduction from the Non-integrated price. Although the investigated lower-cost biomass sources offer notable savings in biomass cost, biomass supplies, and thus savings, are limited. The 75 megaliters Integrated, Mixed Feedstock supply case using hardwood sawmill residues and ecosystem service-derived hybrid poplar has a \$0.78/liter minimum selling price, offering a 7% reduction in minimum selling price

compared to the Integrated design case using solely hybrid poplar from pastureland plantations, and a 21% reduction compared to the Non-integrated design case using solely hybrid poplar from pastureland plantations.

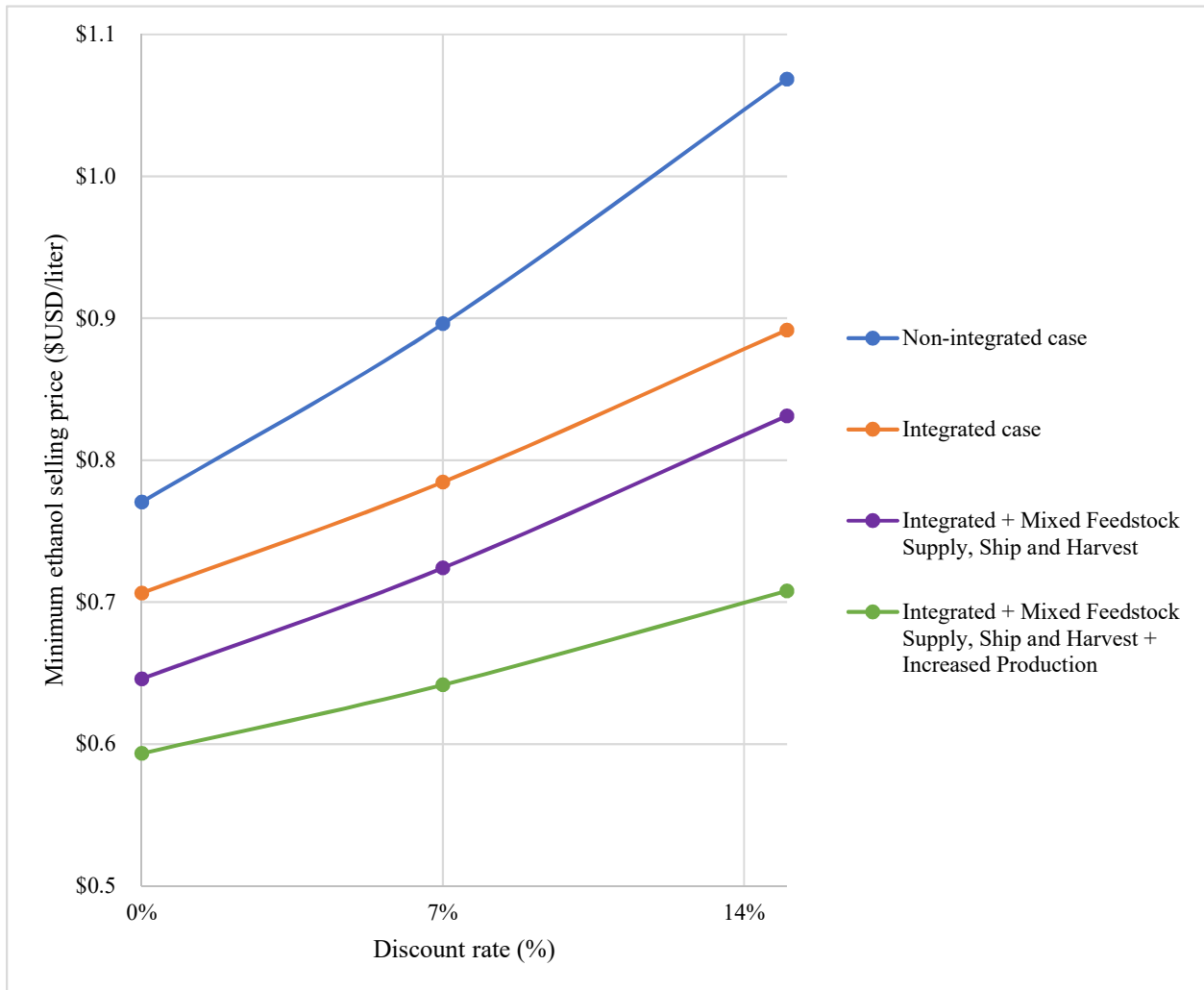


Figure 3.1 Minimum ethanol selling prices under various biorefinery designs and production capacities with 0% loan

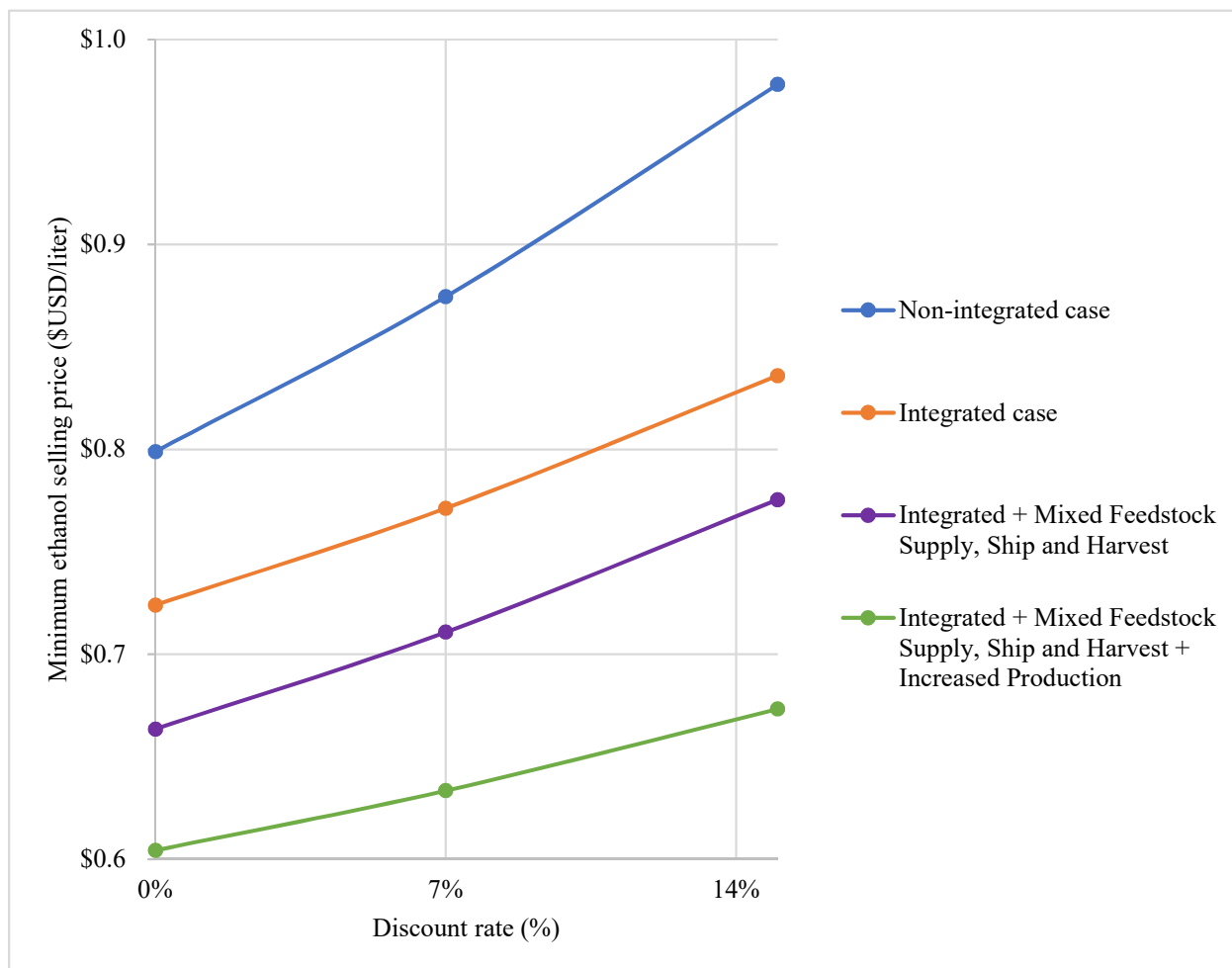


Figure 3.2 Minimum ethanol selling prices under various biorefinery designs and production capacities with 40% loan

3.3.3. Carbon life cycle analysis

GWP contributions from assessed areas of the biorefinery are presented in Figure 3.3 for the Integrated design case, Non-integrated design case³⁵, and gasoline³⁵. Ethanol fuel use, representing a GWP contribution of 67 g CO₂ eq. MJ⁻¹, refers to the use of transportation fuel combusted in an automobile over a 21-year time period. The Integrated design case incorporates a multi-effect evaporator, which evaporates processing waste streams to a syrup for combustion, producing steam for the biorefinery's use. Syrup combustion in the integrated biorefinery is the

largest CO₂ emitter in the biorefinery operations, with a GWP contribution of 175 g CO₂ eq. MJ⁻¹. No avoided production credit is awarded in the Integrated design case since the biorefinery is not assumed to sell any excess electricity to the grid. Purchased electricity to meet biorefinery demand associated emissions are accounted for in the syrup combustion since steam produced from syrup combustion would be run through the power plant's turbines. In the Non-integrated design case, GWP contributions associated with wastewater treatment aerobic digester emissions (33 g CO₂ eq. MJ⁻¹) and anaerobic digester emissions and boiler emissions (125 g CO₂ eq. MJ⁻¹) are included since the biorefinery has an in-house wastewater treatment system and boiler/turbogenerator. Transportation and ancillary chemicals GWP contributions represent minor contributions of 0.039 g CO₂ eq. MJ⁻¹ and 12.6 g CO₂ eq. MJ⁻¹, respectively. Emissions associated with poplar growth and harvesting (30 g CO₂ eq. MJ⁻¹) are relatively minimal and are the 3rd smallest GWP contributor after transportation and ancillary chemicals.

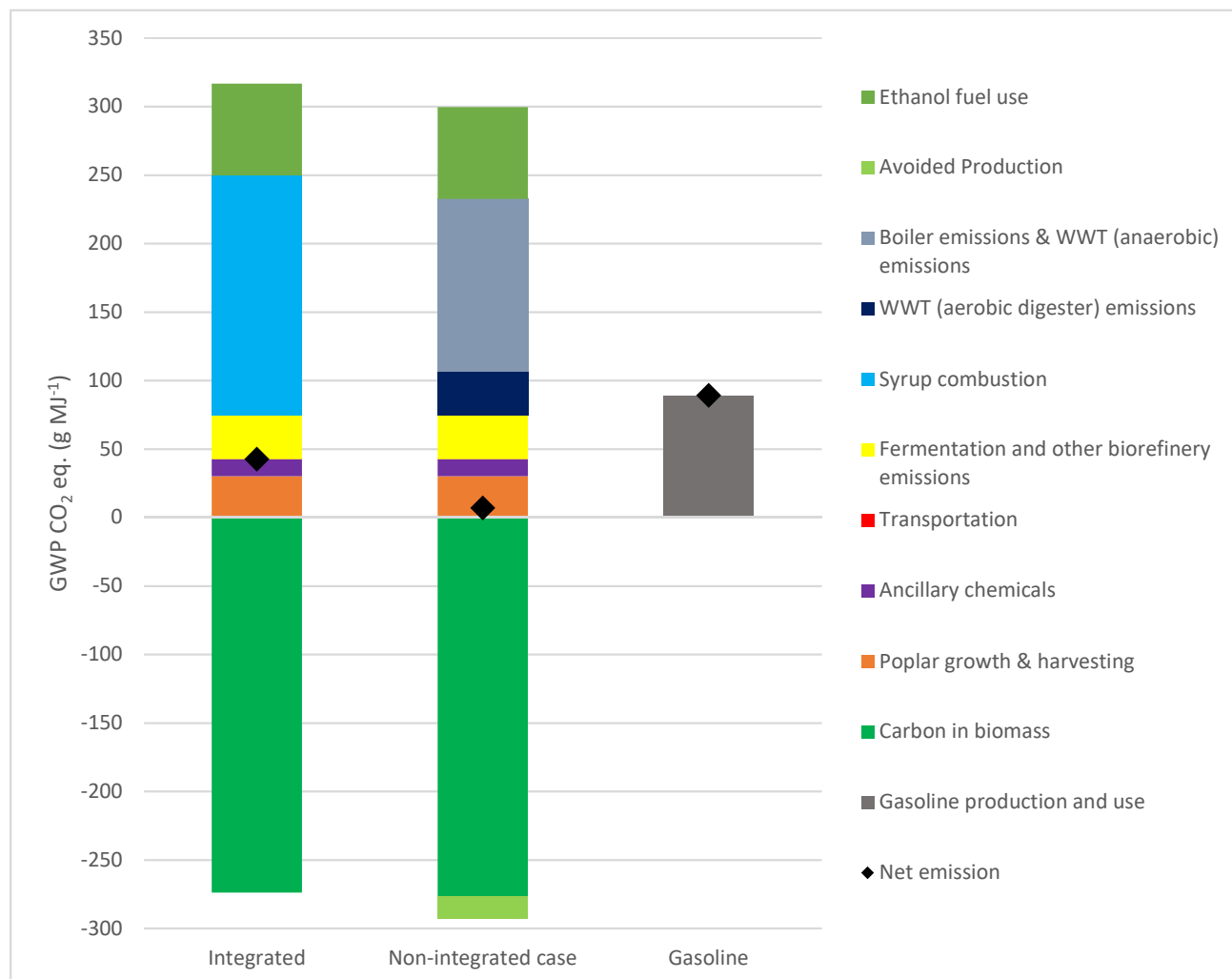


Figure 3.3 Global warming potential (g CO₂ eq. per MJ fuel) of 2 cellulosic ethanol biorefinery designs and gasoline

The Integrated case has a net GWP of 43 g CO₂ eq. MJ⁻¹, the Non-integrated design case has a net GWP of 7 g CO₂ eq. MJ⁻¹ per Budsberg et al. (2015), and 2005 gasoline production and use has a net GWP of 89 g CO₂ eq. MJ⁻¹ per Budsberg et al. (2015). Net GWP is increased in the Integrated design case as compared to the Non-integrated design case but still reduced by 52% as compared to 2005 gasoline production and use. The Non-integrated design case is credited 16 g CO₂ eq. MJ⁻¹ as avoided electricity production credit through sale of excess electricity to the power grid, which is not awarded in the Integrated design case since no excess electricity is sold.

This contributes to the lower overall emissions. The Non-integrated design case has a net reduction in GWP per MJ of fuel of 92% as compared to 2005 gasoline³⁵. CO₂ stored in harvested wood and unharvested biomass accounted for in the Integrated and Non-integrated design cases using hybrid poplar significantly offset CO₂ emitted during the ethanol production and use life cycle.

3.4. Discussion and conclusion

Biorefineries producing cellulosic fuels and renewable energy are essential towards meeting Renewable Fuel Standard production targets, yet capital investment and feedstock costs are a major obstacle towards developing the industry in the U.S. A unique biorefinery concept integrating a biorefinery with an ethanol production capacity of 75 megaliters per year with a power plant and using a biomass supply from dedicated feedstock, residuals, and those grown for treated wastewater management is investigated to quantify potential economic and environmental benefits of incorporating integrated approaches.

Elimination of an in-house boiler/turbogenerator and wastewater treatment system by co-locating with a power plant and using its excess boiler capacity results in 64% reduced electricity use, 43% reduced installed capital equipment costs, and 38% reduced total capital investment (TCI) per liter of ethanol produced. When production capacity is scaled up to 189 megaliter per year, TCI per liter is reduced by 38% as compared to the 75 megaliters biorefinery. When comparing the 189 megaliters production capacity biorefinery to the Non-integrated design case with a 75 megaliters production capacity (which includes the in-house boiler/turbogenerator and wastewater treatment system), a 62% reduction in TCI per liter is realized; highlighting the compounded effect of capital equipment resource sharing and economy of scale.

Incorporating local, low-cost biomass sources such as hybrid poplar derived from wastewater management ecosystem service and hardwood sawmill residuals (hog fuel and sawdust), reduces feedstock variable costs up to 22%. Total variable costs per liter are increased in the Integrated 189 megaliters production design by only 2% compared to the Integrated 75 megaliters production design since biomass costs are higher due to the need to source further away from the biorefinery to obtain enough feedstock to meet biorefinery demand. However, the cost effects are easily overcome due to the increased production scale.

The effects of using integrated approaches and mixed feedstock supply sources is further revealed through discount cash flow analysis where six financing and investment return scenarios are explored to calculate minimum ethanol selling prices. The scenarios are based on two financing options, 0% loan and 40% loan, in conjunction with three discount rates, 0%, 7%, and 15%. Minimum ethanol selling prices under the 0% financing option ranged from \$0.59/liter-\$1.07/liter. The 40% financing option resulted in minimum ethanol selling prices ranging from \$0.60-\$0.98/liter. Under the most realistic scenario, 40% loan and 15% discount rate, the 189 megaliters production capacity biorefinery incorporating integrated approaches, including using mixed feedstock supply sources, achieves the lowest minimum ethanol selling price of \$0.67/liter, representing a 19% reduction in minimum ethanol selling price as compared to the 75 megaliters biorefinery using solely purpose-grown hybrid poplar as feedstock. Under the 40% loan and 15% discount rate, the Integrated 75 megaliters production capacity biorefinery achieves a lower minimum ethanol selling price than the 75 megaliters Non-integrated design case (\$0.84/liter vs. \$0.98/liter), representing a 15% reduction in minimum ethanol selling price per liter.

The Integrated, Mixed Feedstock Supply case, using mixed feedstock sources, results only in a 7% reduction in ethanol minimum selling price as compared to the Integrated design case, using solely hybrid poplar from pastureland plantations, mainly due to limited biomass quantities. Although biomass cost is meaningfully lowered (by 22%), the reduction in minimal ethanol selling price is limited because low-cost biomass sources only represent a fraction of the total biomass supply.

Carbon accounting and GWP contribution analysis results show that the integrated approach of co-location with an adjacent power plant results in 52% lower life cycle CO₂ eq. emissions than gasoline production and use. The biorefinery in this study has a net GWP of 43 g MJ⁻¹, as compared to the Non-integrated design case without integration/co-location, which has a net GWP of 7 g MJ⁻¹ per Budsberg et al. (2015), and 2005 gasoline production and use, which has a net GWP of 89 g MJ⁻¹.³⁵ Net GWP is increased in the Integrated design case when compared to the Non-integrated design case and reduced by 52% as compared to 2005 gasoline. While the Non-integrated design case is able to essentially achieve CO₂ neutrality, the biorefinery represented in this study does not achieve the same significant CO₂ reductions due to the large evaporated syrup combustion emissions and conservative approach of bypassing avoided production credit from selling excess produced electricity to the power grid. This showcases the challenge of balancing economic cost reductions and environmental impact; replacement of the boiler/turbogenerator and wastewater treatment system with the evaporator and co-location approach offer notable capital cost savings but can negatively affect GWP contribution depending on assumptions made (i.e. selling excess electricity to the grid or not and assumed energy recovery assumptions). The carbon accounting results in this study are based on a

modification of a reference LCA³⁵ and are to be used as a baseline quantifying the potential for global warming potential reduction.

The results of this study show the economic and environmental impacts and tradeoffs of incorporating integrated approaches to biorefinery design concepts. Two of the biggest challenges for startup biorefineries, high capital costs and feedstock costs, can be reduced by employing equipment resource sharing (through co-location) and providing secondary services such as ecosystem services using biomass (hybrid poplar). The importance of resource sharing and sourcing low-cost biomass while providing mutual benefits to community stakeholders is emphasized by achieving positive economic and environmental outcomes.

This analysis was conducted to gain further understanding on the feasibility of introducing a sustainable bioeconomy in the PNW by constructing new biorefineries in the region. The conceptualized biorefinery to be potentially located in Lewis County, WA described in 3.5.1 provided a localized assessment of opportunities and challenges and elucidates issues that should be further investigated in greater detail. This integrated approach to biorefinery design can be adjusted and applied to other regions and facilities producing a wide range of bio-based end-products.

While there may be varying opportunities for applying integrated approaches to biorefinery design concept, it is not a research area thoroughly explored in published literature. While many studies focus on supply-chain value optimization, production of multiple and alternative end products, and waste product utilization to improve revenues and lower environmental impact, few studies report on benefits of integrated approaches⁷.

3.5. Methods

3.5.1. Biorefinery process modeling

Modeling of the bioconversion process of the proposed biorefinery was completed using Aspen Plus simulation software. The process design evaluated in this study is referred to as the Integrated design case and is shown in Figure 3.4.

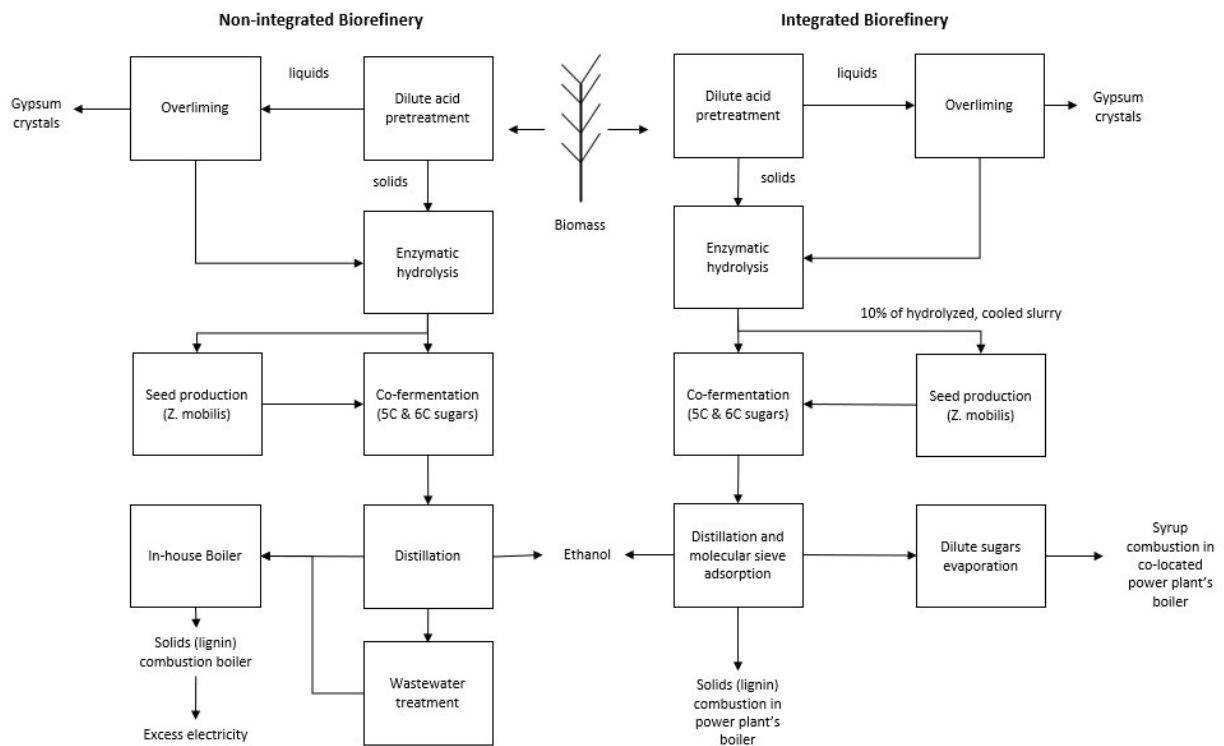


Figure 3.4 Process flow diagram for the Integrated and Non-integrated biorefinery process designs

The method used in the Integrated design case is dilute acid pretreatment with enzymatic hydrolysis and co-fermentation of the resulting glucose and xylose to produce cellulosic ethanol using hybrid poplar (*Populus spp.*) chips from purpose-grown plantations as the primary feedstock.

The model is based on a feedstock capacity of 250,000 dry metric tons (250 Gg) of hybrid poplar chips from purpose-grown plantations per year and produces 75 megaliters of

cellulosic ethanol per year using a yield of 300,434 liters of ethanol per Gg (gigagram) (or 0.3 megaliters per Gg). The composition of this biomass is presumed to be 42% cellulose, 15.3% xylan, and 25.8% lignin³⁶.

Chemical Component	Mass fraction of bone-dry poplar biomass (% dry wt.)
CELLULOSE	42
XYLAN	15.3 (HEMICELLULOSE TOTAL 22.9)
LIGNIN	25.8
ACETATE	2.86
C5SOLID	1.91
C6SOLID	5.73
EXTRACTIVES	4.5
ASH	1.91

In the pretreatment and hydrolysate conditioning step, hybrid poplar chips are steamed to 100 °C before undergoing high temperature dilute sulfuric acid pretreatment to convert most of the hemicellulose to soluble sugars. Pretreatment conditions are shown in Table 3.5.

Table 3.5 Pretreatment reactor conditions

Pretreatment Reactor Conditions	
H ₂ SO ₄ concentration	1.1% (H ₂ SO ₄ charge is 0.011 gram of acid per gram of bone-dry biomass)
Pressure	12.1 atm
Insoluble solids composition	30%
Temperature	190 °C

The stream then undergoes flash separation before liquid-solid separation via solids press. Gypsum crystals formed are filtered out via hydrocyclone and rotary drum filtration in series after overliming of the liquids stream. The filtration is assumed to remove 99.5% of the precipitated gypsum and the solids are assumed to contain 20% liquid. The resulting liquid and solid hydrolysate streams are then combined to undergo enzymatic hydrolysis at 65°C and 20% total solids loading (soluble and insoluble solids). Enzymes used for enzymatic hydrolysis are purchased externally. The hydrolyzed slurry is then cooled to 41°C before undergoing co-fermentation.

10% of the cooled, hydrolyzed slurry is sent to seed production. *Z. mobilis*, the chosen bacterium for fermentation due to its ability to simultaneously convert glucose and xylose to ethanol, is grown in a seed fermentation train of vessels with diammonium phosphate (DAP). Seed batches are scaled to support production. The seed inoculum, nutrients, and saccharified slurry then undergo fermentation. Fermentation conditions are based on NREL¹³.

During the purification step, distillation and molecular sieve adsorption are used to recover ethanol from the raw fermentation beer and produce an ethanol purity of 99.5% ethanol by mass. CO₂ scrubbers and released dissolved CO₂ is not modeled. There is a vapor overhead mixture of 92.5% wt./wt. ethanol and a bottoms composition of 0.05% wt./wt. ethanol in the rectification column. Syrup from the column bottoms is sent for combustion in the co-located power plant's boiler. Solids are separated using a pressure filter before being sent for combustion, and the resulting separated dilute sugars are evaporated to a syrup using a multiple effect evaporator before being sent for combustion.

A traditional process flow design based on Budsberg et al. (2015) is also shown in Figure 3.4. is referred to as the Non-integrated design case. In the Non-integrated design case, streams are either sent to wastewater treatment or the in-house boiler after fermentation. Solids sent to the in-house boiler are combusted to produce excess electricity which is then sold to the power grid. Methane from anaerobic digestion is also combusted.

The major distinction of the Integrated design case is that it does not consider an in-house boiler/turbogenerator or wastewater treatment system. Instead, excess boiler capacity from a co-located power plant is used for combustion of waste and by-product streams to produce steam and/or electricity. A multi-effect evaporator is used to evaporate waste streams into combustible syrup that can be sent to the co-located power plant's boiler for steam production. The biorefinery is assumed to purchase electricity from the power grid, which is likely a conservative assumption. The biorefinery produces enough steam from evaporator syrup combustion to support steam demand for all biorefinery operations.

3.5.2. Economic modeling

Economic modeling is based on the biorefinery process design described in section 3.5.1. The Non-integrated process design, an increased production capacity, and mixed supply feedstock scenario are analyzed for comparison. Methods and parameters used for modeling are based on NREL³⁴ where capital costs are calculated using a factored approach. Total capital investment (TCI) and annual fixed and variable operating costs are developed to inform a discounted cash flow rate of return analysis. Results from the discounted cash flow rate of return analysis then reveal potential minimum ethanol selling prices under six investment scenarios with a net present value of 0 and a fixed internal rate of return (IRR), or discount rate.

3.5.2.1. Capital expenses

The fixed capital investment (FCI) is comprised of total direct and indirect costs. Total direct costs (TDC) equal the sum of the total installed equipment costs plus warehouse, site development, and additional piping costs. Warehouse costs represent 4% of the inside-battery-limits (ISBL) equipment costs, with site development and additional piping representing 9% and 4.5% of the ISBL equipment costs, respectively. ISBL equipment costs equal the installed equipment costs of the following unit operations: Pretreatment and conditioning, Enzymatic hydrolysis (or saccharification) coupled with co-fermentation, and distillation and solids recovery. Site development costs include costs for development under normal circumstances to include fencing, curbs, parking, roads, rail system, well drainage, soil borings, and pavement. Total indirect costs equal the sum of proratable expenses (fringe benefits, burdens, and construction insurance) (10% of TDC), field expenses (consumables, tool and equipment rental, field related services, and temporary facilities) (10% of TDC), home office and construction fees (20% of TDC), project contingency (10% of TDC), and other costs including start-up and permit costs (10% of TDC).

FCI plus working capital, which is 5% of FCI, equate to the total capital investment (TCI). Land costs are not factored in to TCI for this analysis.

3.5.2.2. Capital equipment costs

Capital equipment costing is based on NREL's method³⁴ but actual purchased equipment is based on NREL's 2002 process design¹³ and modified to fit the respective biorefinery design case. The inclusion or exclusion of unit operation define whether associated capital equipment costs are included. Biorefinery unit operations are broken down according to Table 3.6.

Table 3.6 Biorefinery unit operation breakdown

Unit operation
Feed handling area
Pretreatment and conditioning
Enzymatic hydrolysis (or saccharification) coupled with co-fermentation
Distillation and solids recovery
Wastewater treatment
Storage
Burner/Boiler/Turbogenerator
Utilities

Exponential scaling based on process flow was used to re-cost capital equipment using Equation 3.1:

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

Equation 3.1 Exponential scaling expression for re-costing capital equipment

where n is the scaling exponent typically in the range of 0.6 to 0.7³⁴. In this study, $n = 0.6$ for all equipment. *Base Size* is NREL's¹³ annual ethanol production of 262.3 megaliters and *New Size* is the annual ethanol production of the proposed biorefinery, 75 megaliters. The new, scaled purchase cost is then indexed to 2018 using the Chemical Engineering Plant Cost Index³⁷ (CEPCI). The indexed purchase cost is multiplied by NREL's equipment installation factors¹³ to obtain installed equipment costs.

Since the handling of poplar chips is a much different process than feedstock handling for corn stover, several equipment items are eliminated from the feed handling unit operation. The

only items from the feed handling unit operation considered in this analysis are feedstock conveyors and forklift trucks. In the distillation and solids recovery unit operation, an 8-effect multi-evaporator is manually input and scaled from a process design using a 7-effect multi-evaporator with evaporator area per effect of 27,000 ft² (2,508 m²)⁷. Scaling is based on total evaporator area per effect (ft²), where the 8-effect multi-evaporator has an evaporator area per effect of 16,200 ft² (1,505 m²). The process flow ratio used is 0.69, $n = 0.6$, and the scaling factor becomes 0.8.

Table 3.7 8-effect multi-evaporator parameters

Parameter	Value	Unit
Evaporator area per effect	1505	m ²
# of effects	8	N/A
Evaporator capacity	334.2	klb total/hr
Economy	5.22	lb/lb
WBL solids	11%	mass
SBL	69.67%	mass
Condenser press	43,300	pascal

3.5.2.3. Variable operating costs

Variable operating costs are based on NREL's method³⁴ and modified to fit the respective biorefinery design. 8400 annual operating hours are assumed. Variable streams and usage are shown in the Table 3.3. Corn steep liquor, propane, make-up water, and purchased cellulase enzymes usage is scaled from NREL¹³. Feedstock base cost is \$83/bone dry Mg; feedstock is sourced from hybrid poplar plantations on pastureland. Corn steep, propane, make-up water, clarifier polymer, sulfuric acid, hydrated lime, ammonium phosphate, and gypsum and ash

disposal base costs are based on NREL¹³. Purchased cellulase enzyme prices are 13 cents/liter⁶. Prices are indexed to 2018 using annual index values from the Producer Price Index by Commodity for Chemicals and Allied Products: Basic Inorganic Chemicals, Not Seasonally Adjusted³⁸. For the Integrated design case, electricity usage is based on NREL³⁴, eliminating electricity usage from process the wastewater treatment and boiler/turbogenerator unit operations, and scaled down based on process flow. Resultant steam from syrup combustion in the power plant's boiler is assumed to supply the biorefinery's steam demand for all operations at no cost. No excess electricity produced by the biorefinery is assumed to be sold to the grid, which is likely a conservative assumption. Wholesale electricity is bought from the grid at a price of \$0.04/kWh using Mid-C Peak wholesale data³³. In the Non-integrated design case, the biorefinery produces sufficient electricity to meet electricity demand for all biorefinery operations and excess electricity is sold to the power grid; the credit from this sold excess electricity is not expressed in the economic modeling.

3.5.2.4. Fixed operating costs

Fixed operating costs, including labor and overhead, are based on NREL's method³⁴ and modified to fit the respective biorefinery design. Yard employees for the corn stover feed handling system in the NREL method³⁴ are not included here since the feedstock of choice is hybrid poplar chips. Maintenance technicians and general shift operators were reduced by 50% due to smaller biorefinery size. Shift supervisors were limited to 3. Enzyme shift operators were reduced by 50% since only production of *Z. mobilis* occurs in-house; cellulase enzymes will be purchased from a 3rd party source. Note that salaries are based on U.S. Midwest regions. Salaries are indexed to 2018 using the Bureau of Labor Statistics Employment Cost Index: All workers, Manufacturing, Nonunion, Not seasonally adjusted. A 90% labor burden is applied to the annual

total cost of salaries for general overhead expenses such as safety, general engineering, general plant maintenance, payroll overhead (including benefits), plant security, janitorial and similar services, phone, light, heat, and plant communications³⁴. Maintenance expenses are applied at 3% of the total installed ISBL equipment cost. Property insurance is applied at 0.7% of the FCI. Total annual salaries, labor burden, maintenance, and property insurance equate to the total fixed costs.

3.5.2.5. Discounted cash flow rate of return analysis

Discounted cash flow analysis is used to model biorefinery economic performance under six investment strategies listed in Table 3.8. The discount rate of 0% represents the cash cost of the project, 7% represents a moderate investment return, and 15% represents the most realistic investment return strategy.

Table 3.8 Summary of financing options

Financing	Discount Rate
0% loan, cash cost	0%
0% loan, cash cost	7%
0% loan, cash cost	15%
40% loan	0%
40% loan	7%
40% loan	15%

Minimum ethanol selling price per gallon is determined at the point when net present project value equals 0 at a specified discount rate. The minimum ethanol selling price then represents the lowest price the ethanol could be sold at to break even with the specified discount rate. A 21% federal tax rate is assumed; no state or local tax is applied. Although there is likely

potential for federal subsidiaries or tax benefits for production of cellulosic ethanol, those are not considered in this analysis. Borrowed funds are taken out in the initial year 0. Annual depreciation costs are based on 90% of the FCI spread evenly over the modeled years.

Table 3.9 Discounted cash flow analysis parameters

Parameter	Value
Currency Year	2018
End product	Cellulosic ethanol
Production (megaliters ethanol/year)	75
Annual operating hours	8400
Feedstock capacity (Gg/year)	250
Ethanol Yield (megaliters/Gg)	0.3
Feedstock	Hybrid poplar
Discount rate	0, 7, 15%
Financing	0%, 40%
Loan interest rate, APR and duration	5%, 10 years
Federal corporate income tax rate	21%
State or local tax rate	Not considered
Plant lifetime, plant operation (years)	10 years modeled
Working capital (% of FCI)	5%
Revenues during start-up	50%
Variable costs incurred during start-up	50%
Fixed costs incurred during start-up	100%

3.5.2.6. Design case scenarios

To investigate how the ethanol minimum selling price changes based on feedstock supply, biorefinery design, and production capacity, three additional cases were developed for comparison to the Integrated design case, which produces 75 megaliters of ethanol per year using only hybrid poplar chips from purpose-grown plantations. To quantify the impact of co-locating the biorefinery with an adjacent power plant, enabling the opportunity for the biorefinery to use the power plant's excess steam and eliminate installing a boiler/turbogenerator and wastewater treatment system, a counter case, referred to as Non-integrated design case, was developed which is not co-located with an adjacent power plant and does include an in-house boiler/turbogenerator and wastewater treatment system based on NREL¹³. An additional case was applied to address the effect of reduced feedstock plant-gate cost from supplementing purpose-grown hybrid poplar with low cost, local hardwood biomass from sawmill residuals and wastewater management ecosystem service utilizing poplar plantations to receive treated water that cannot be released to rivers during times of low river flow. An analysis of hardwood sawmill residual availability (hog fuel and sawdust) found that an average of 52 Gg/year could be available at a weighted cost of \$41/bone dry Mg. Hybrid poplar sourced from wastewater treatment service is based on a shared cost scenario, Harvest and Ship. Under this scenario, the participating POTW (publicly owned treatment work) provides the land for the poplar plantation at no cost and manages all biomass cultivation activities, and the biorefinery manages only the harvest and shipment activities. This biomass has an average plant gate cost of \$51/bone dry Mg. 58 Gg of hybrid poplar could be available annually considering hybrid poplar plantations are located 5 miles or less from the POTW and an effluent application rate of $1.6E-07 \text{ m s}^{-1}$ (or 163 m Gs^{-1}). A fifth case, which scales production up to 189 megaliters of ethanol per year considers

the integrated process design and a mixed feedstock supply which maxes out hardwood sawmill residuals and hybrid poplar from wastewater management ecosystem service before using purpose-grown hybrid poplar to fill the void. The cases, representing sensitivity analysis, are shown in Table 3.10.

Table 3.10 Sensitivity cases description

Case	Feedstock Supply and Quantity (Gg)	Average Feedstock Plant-gate Cost (\$/bone dry Mg)	Ethanol Production Capacity (megaliters/ year)	Process Design
Integrated	1. Hybrid poplar chips from purpose grown plantations (250)	\$83	75	Integrated, co-location with adjacent power plant
Non-integrated	1. Hybrid poplar chips from purpose grown plantations (250)	\$83	75	Non-integrated, No co-location with power plant
Integrated + Mixed Feedstock Supply, Harvest and Ship	1. Hybrid poplar chips from purpose grown plantations (140) 2. Hardwood sawmill residuals (52) 3. Hybrid poplar from wastewater management ecosystem service under the Harvest and ship cost scenario (58)	\$65	75	Integrated, co-location with adjacent power plant
Integrated + Mixed Feedstock Supply, Harvest and Ship +	1. Hybrid poplar chips from purpose grown plantations (140) 2. Hardwood sawmill residuals (52)	\$86	189	Integrated, co-location with adjacent power plant

Increased Production	3. Hybrid poplar from wastewater management ecosystem service under the Harvest and Ship cost scenario (58)			
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3.5.3. Life cycle carbon analysis

Life Cycle Assessment (LCA) is a cradle-to-grave analysis technique used to assess environmental impacts associated with all stages of a product's life, from raw material extraction through materials processing, manufacture, distribution, and end product or service use³⁹. This study uses results based on the LCA conducted in Budsberg et al. (2015) under the ethanologen pathway and carbon accounting to quantify estimated 100-year global warming potential (GWP) in g CO₂ eq. emitted MJ⁻¹.

The biorefinery process design analyzed in this study and described in 3.5.1 assumes the same GWP contribution values as reported in Budsberg et al. (2015) for the following unit process operations: ethanol use (67 g CO₂ eq. MJ⁻¹), transportation (0.039 g CO₂ eq. MJ⁻¹) (Erik Budsberg, personal communication, September 20, 2018), ancillary chemicals (12.6 g CO₂ eq. MJ⁻¹) (Erik Budsberg, personal communication, September 20, 2018), and poplar growth and harvesting (30 g CO₂ eq. MJ⁻¹). No methane combustion was considered in the proposed biorefinery design.

The biorefinery unit process operation, representing 190 g CO₂ eq. MJ⁻¹, is further broken down into three more specific unit process operations. The 1st is fermentation and other biorefinery operations, accounting for 32 g CO₂ eq. MJ⁻¹ (Erik Budsberg, personal communication, September 20, 2018). The 2nd is the wastewater treatment aerobic digester, accounting for 33 g CO₂ eq. MJ⁻¹ and the 3rd is the boiler & wastewater treatment anaerobic digester, accounting for 125 g CO₂ eq. MJ⁻¹ (Erik Budsberg, personal communication, September

20, 2018). The proposed biorefinery design in this study assumes the same fermentation and other biorefinery operation GWP contribution as Budsberg et al. (2015) but does not have the same GWP contribution associated with the wastewater treatment aerobic digester and boiler & wastewater treatment anaerobic digester. Since, the proposed biorefinery design eliminates the in-house boiler and wastewater treatment system, emissions associated with these two unit process operations are not relevant. Instead, a multi-effect evaporator is used to evaporate stillage bottoms to a combustible syrup for burning in the co-located power plant's boiler. These emissions are accounted for in a unit process operation called syrup combustion, accounting for 175 g CO₂ eq. MJ⁻¹. This GWP was calculated from the syrup combustion emissions, which emit 307,564,824 kg of CO₂ per year (direct output from the ASPEN modeling performed and described in 3.5.1). The higher heating value (HHV) for ethanol is the same as used in Budsberg et al. (2015), 23.4 MJ L⁻¹, yielding 1,757,536,211 MJ of ethanol (equivalent to 75,108,385 liters of ethanol (or ~75 megaliters)).

In Budsberg et al. (2015), 16 g CO₂ eq. MJ⁻¹ are awarded as avoided electricity production credit since that biorefinery design considers that excess electricity produced by the biorefinery is sold to the national grid, displacing electricity produced from natural gas, representing the marginal electricity source. In the proposed biorefinery design, wholesale electricity is purchased to meet the biorefinery electricity demand, and the emission burden is captured in the syrup combustion unit process operation.

For the proposed biorefinery design, carbon in biomass, represents 274 g CO₂ eq. captured MJ⁻¹, equating to the sum of the ethanol use, fermentation and other biorefinery operations, and syrup combustion emissions. Those three unit process operations account for all the CO₂ initially in the biomass; all other emissions are associated with CO₂ from other sources.

Using the GWP contribution values noted above, the carbon in biomass in Budsberg et al. (2015) should equate to 276.64 g CO₂ eq. captured MJ⁻¹ to yield a net emission of 7.0 g CO₂ eq. MJ⁻¹. However, there is a small discrepancy of 3.64 g CO₂ eq. MJ⁻¹ between the calculated carbon in biomass 276.64 g CO₂ eq. MJ⁻¹ and the summed carbon in biomass, 273 g CO₂ eq. MJ⁻¹ (sum of ethanol use, avoided production credit, and biorefinery emissions). This discrepancy may be due to the use of rounded values in this estimated GWP analysis vs. exact actual values (i.e. net emission may not be exactly 7.0 g CO₂ eq. MJ⁻¹ as reported in Budsberg et al. (2015), but instead rounded to a reasonable number of significant figures). There may be other small differences due to energy recovery and carbon content assumptions made in either analysis. However, since the discrepancy is relatively insignificant for estimation purposes, values are left as is in this analysis.

3.6. Thesis Conclusion

Incorporating integrated approaches, such as developing partnerships with local industry to share feedstock costs by providing ecosystem services and capital equipment resource sharing through co-location, have the potential to offer meaningful feedstock cost and life cycle carbon emissions reductions.

Feedstock supply from purpose-grown hybrid poplar plantations on three land types (pastureland, irrigated cropland, and non-irrigated cropland) was evaluated. Biomass from alternative sources including hardwood sawmill residues, wastewater management ecosystem service, forest harvest residues, and agricultural residues were assessed for feedstock cost reduction potential. Forest harvest residues and agricultural residues were quantified but not further assessed due to inaccessibility and minimal availability, respectively. 822,611 km² within 100km of the proposed biorefinery site are deemed suitable for hybrid poplar cultivation. This

translates to 1,399 bone dry Gg/year of hybrid poplar biomass. However, assuming a more realistic 50% land conversion factor, 699 Gg/year could be available. Average plant-gate costs for hybrid poplar by land type are \$95.19/bone dry Mg for pastureland, \$105.04/bone dry Mg for irrigated cropland, and \$86.94/bone dry Mg for non-irrigated cropland. Because these feedstock costs fall out of biorefinery affordability ranges, alternative biomass from low-cost sources are needed. 58 Gg/year of hybrid poplar biomass could be available from wastewater management ecosystem service. Assuming two cost scenarios, Free Land and Harvest and Ship, feedstock costs can be shared between the biorefinery and the participating wastewater management facility. On average, feedstock costs under the Free Land shared cost scenario were \$75/bone dry Mg and \$51/bone dry Mg under the Harvest and Ship shared cost scenario. On average, 52 Gg/year of hardwood sawmill residues (hog fuel and sawdust) could be available, with an average plant-gate cost of \$41/bone dry Mg. Using mixed feedstock scenarios, 12-22% feedstock cost savings can be realized when incorporating alternative feedstock sources to supply a 250 Gg/year capacity biorefinery. These savings decline as biorefinery capacity grows, and low-cost sources are depleted. However, there is significant potential for incorporating residues and ecosystem service derived biomass to supply a biorefinery, and the economic benefits grow as these low-cost sources are maximized.

The proposed biorefinery in this study assumes co-location with an adjacent power plant. This co-location offers the opportunity for the biorefinery to eliminate the in-house boiler/turbogenerator by utilizing the power plant's excess boiler capacity for combusting by-products of the production process to produce steam. The wastewater treatment system could also be eliminated by sending concentrated waste from a multi-effect evaporator system to the power plant's boiler for steam production. This co-located approach of capital equipment

resource sharing results in a 64% reduced electricity use, 43% reduced installed capital equipment costs, and 38% reduced total capital investment (TCI) per liter of ethanol produced. When production capacity is scaled up to 189 megaliter per year, TCI per liter is reduced by 38% as compared to the 75 megaliters biorefinery. When comparing the 189 megaliters production capacity biorefinery to the Non-integrated design case with a 75 megaliters production capacity (which includes the in-house boiler/turbogenerator and wastewater treatment system), a 62% reduction in TCI per liter is realized; highlighting the compounded effect of capital equipment resource sharing and economy of scale.

Additionally, the co-located approach shows a 52% reduction in life cycle carbon emissions, or global warming potential (CO₂ eq. emitted MJ⁻¹ of fuel), as compared to 2005 gasoline production and use.

A framework for incorporating integrated approaches, including co-location and capital equipment resource sharing and reduced feedstock supply options through use of residues and ecosystem service, in biorefinery design is presented in this study. This approach can be adapted to model environmental and economic outcomes of cellulosic biofuel production in other regions.

4. Recommended future work

- Refine biomass assessment to determine more accurate costs and availability.
 - Develop a reasonable method for assuming purpose-grown plantation land availability within the region (this study assumed 50% of growers with qualifying land would convert their land to grow hybrid poplar for biofuel production).
 - Investigate participation rate for treated wastewater ecosystem service partnerships.

- Investigate reasonable availability of hardwood sawmill residues.
- Verify ecosystem service shared cost scenarios are reasonable.
- Identify additional local, low-cost feedstock supply options to supplement biorefinery feedstock demand.
 - Investigate the potential for other ecosystem service opportunities not evaluated in this study to supply biomass, i.e. flood mitigation, stormwater management, biosolids applications.
- Investigate the direct, indirect, and induced effects of the Integrated biorefinery design and approach to determine potential job creation and other regional economic outcomes.

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