Investigation of thermochemical biorefinery sizing and environmental sustainability impacts for conventional supply system and distributed pre-processing supply system designs

David J. Muth Jr, Praxik, LLC, Ames, IA, USA
Matthew H. Langholtz, Oak Ridge National Laboratory, Oak Ridge, TN, USA
Eric C.D. Tan, National Renewable Energy Laboratory, Golden, CO, USA
Jacob J. Jacobson, Idaho National Laboratory, Idaho Falls, ID, USA
Amy Schwab, National Renewable Energy Laboratory, Washington DC, USA
May M. Wu, Argonne National Laboratory, Argonne, IL, USA
Andrew Argo, Sundrop Fuels, Longmont, CO, USA
Craig C. Brandt, Oak Ridge National Laboratory, Oak Ridge, TN, USA
Kara G. Cafferty, Idaho National Laboratory, Idaho Falls, ID, USA
Yi-Wen Chiu, Argonne National Laboratory, Argonne, IL, USA
Abhijit Dutta, National Renewable Energy Laboratory, Golden, CO, USA
Laurence M. Eaton, Oak Ridge National Laboratory, Oak Ridge, TN, USA
Erin M. Searcy, Idaho National Laboratory, Idaho Falls, ID, USA

Abstract: The *2011 US Billion-Ton Update* estimates that by 2030 there will be enough agricultural and forest resources to sustainably provide at least one billion dry tons of biomass annually, enough to displace approximately 30% of the country's current petroleum consumption. A portion of these resources are inaccessible at current cost targets with conventional feedstock supply systems because of their remoteness or low yields. Reliable analyses and projections of US biofuels production depend on assumptions about the supply system and biorefinery capacity, which, in turn, depend upon economic value, feedstock logistics, and sustainability. A cross-functional team has examined combinations of advances in feedstock supply systems and biorefinery capacities with rigorous design information, improved crop yield and agronomic practices, and improved estimates of sustainable

Correspondence to: Jacob Jacobson, Idaho National Laboratory, 2525 N Fremont Ave, Idaho Falls ID, 83415, USA.
E-mail: jacob.jacobson@inl.gov

biomass availability. A previous report on biochemical refinery capacity noted that under advanced feedstock logistic supply systems that include depots and pre-processing operations there are cost advantages that support larger biorefineries up to 10 000 DMT/day facilities compared to the smaller 2000 DMT/day facilities. This report focuses on analyzing conventional versus advanced depot biomass supply systems for a thermochemical conversion and refinery sizing based on woody biomass. The results of this analysis demonstrate that the economies of scale enabled by advanced logistics offsets much of the added logistics costs from additional depot processing and transportation, resulting in a small overall increase to the minimum ethanol selling price compared to the conventional logistic supply system. While the overall costs do increase slightly for the advanced logistic supply systems, the ability to mitigate moisture and ash in the system will improve the storage and conversion processes. In addition, being able to draw on feedstocks from further distances will decrease the risk of biomass supply to the conversion facility. © 2014 The Authors. *Biofuels, Bioproducts, Biorefining* published by Society of Chemical Industry and John Wiley & Sons, Ltd.

Keywords: biofuel; thermochemical conversion; biorefinery size; cost analysis

Introduction

Biofuels have the potential to reduce dependence on fossil fuels, enhance energy security, provide environmental benefits, and stimulate rural economies.[1,2] In the United States, these objectives are supported by the Energy Independence and Security Act of 2007 (EISA), with the goal of producing and using 136 billion liters (36 billion gallons) of renewable fuels by 2022.

To commercialize biofuels, significant tradeoffs are acknowledged between improved economies of scale associated with increased biorefinery size, and higher feedstock price that may be associated with supply chains needed to satisfy increased feedstock demand. Advanced feedstock supply chain strategies can potentially play a key role in optimizing biorefinery size. An earlier study reported the influence of biorefinery size and biomass logistics supply system design on process economics and environmental sustainability metrics for herbaceous biomass (corn stover and switchgrass) converted to ethanol in a biochemical process.[3] This analysis was applied to two logistics scenarios: a conventional-bale logistics system, and an advanced supply system design that involved pre-processing biomass into a high-density, aerobically stable, easily transportable form that could be traded and transported as a commodity. The results from the previous study determined that increasing biorefinery size (up to 10 000 dry metric tonnes day^{-1}) can achieve lower minimum ethanol selling prices (MESP). This proved true even after accounting for increased delivered feedstock cost associated with additional pre-processing operations required to achieve commodity feedstock characteristics.

The previous study did not consider woody biomass supply systems, account for variability in biomass ash content throughout the supply chain, or look at biorefinery scale impacts for thermochemical conversion processes.

In this paper, we analyze the influences of biorefinery size, biomass supply system designs, and feedstock specifications on process economics and environmental sustainability metrics for southeastern (SE) US woody feedstocks converted into ethanol through a thermochemical process. The woody feedstocks include logging residues, which are low cost at the forest landing (i.e. roadside after harvest, chipping, and loading on a truck), but because of ash, may not be the least expensive for the conversion process. Because of this difference, this report also analyzes the impact of costs incurred between landing and the throat of the conversion system ('reactor throat'), including the costs of feedstock pre-processing. The analyses compared options of performing pre-processing operations at the landing or depot, such as ash removal, or letting the conversion process handle the upgrading of the material. The analyses support upgrading the material near the point of extraction rather than allowing the conversion facilities to handle the upgrades.

Illustrative cases

The SE USA is projected to be highly productive for the emerging biorefinery industry.[4] One potential challenge with developing supply chains in the SE (Fig. 1) is that the resource base is made up of various types of herbaceous and woody biomass resources. Table 1 shows the primary biomass categories and potentially available quantities

Figure 1. Area of interest including eleven Southeast US states, and two sites selected for Conventional scenarios, including Rankin, MS (high-production region) and Aiken, SC (low-production region). (Courtesy ORNL, 2013)

for the SE US as projected for the year 2022 in the *US Billion-Ton Update*.[5] Each of the biomass resources in Table 1 has unique physical and chemical characteristics that impact how they must be handled throughout a supply chain. These different resource types also have significantly different procurement costs and value to biorefinery conversion processes. Because of this, the analysis described in this study develops supply chain scenarios that account for feedstock-specific procurement prices and material characteristics, such as moisture and ash content.

Three illustrative cases are developed that simulate the supply chain for thermochemical conversion processes; thus, woody resources are the focus of this study and include all the resources identified in Table 1. Available resource quantities are based on projections for woody feedstock supply in the SE USA in 2022 as assessed in the *US Billion-Ton Update*.[5]

Conventional and advanced supply system logistics design concepts are represented in three distinct cases:

Conventional supply system (Conventional) design

This design implements current state of technology woody biomass supply chain equipment in evaluations of

Table 1. Projected feedstock availability[1] for eleven SE US states shown in Fig. 1[5].

Feedstock type	Base-case scenario	High-yield scenario[2]
	Dry tonnes (millions)	
Agricultural residues	32.0	34.0
Annual energy crops	2.0	4.0
Forest thinnings	11.0	11.0
Logging residues	28.7	28.7
Perennial grasses	35.4	55.4
Pulpwood to energy	1.1	1.1
Short-rotation woody crops	31.4	50.0
Total	141.6	184.2

[1]Assumes projections to 2022 at a farmgate price of $66 dry tonne⁻¹. Other resources such as mill residues, construction and demolition debris, and manure are also projected to be available but are not included here. Potential resources from federal lands are excluded.
[2]Scenario changes only apply to agricultural resources and short-rotation woody crops, which are assumed limited to agricultural land.

individual biorefineries at two specified SE locations, one representing a low-production region and the other representing a high-production region.

- Case 1: Conventional low production region – Woody biomass is collected using a Conventional system and evaluated for biorefinery capacities ranging from 500 to 5000 dry tonnes day^{-1} (quantities are assumed dry throughout unless otherwise specified) for our low production region in Aiken, South Carolina. Aiken was selected as the low production site for two reasons: (i) forecasts project this site to have lower biomass productivity potential than many other SE sites, and (ii) significant ongoing research collaborations near this site can provide supporting data.

- Case 2: Conventional high production region – Woody biomass is collected using a Conventional system and evaluated for biorefinery capacities ranging from 500 to 5000 dry tonnes day^{-1} for our high production region in Rankin County, Mississippi. Rankin County was selected because forecasting models project Rankin County to be among the highest productivity areas in the SE.

(Advanced) Distributed pre-processing supply system (Depot) design

This design delivers the entire woody biomass resource base identified in the SE to biorefineries.

- Case 3: Depot All WBR – Woody biomass feedstock collected using a Depot and evaluated for biorefinery capacities ranging from 500 to 10 000 dry tonnes day^{-1}. In this case, a specific biorefinery site location and adjacent feedstock resource was not investigated, but instead we used a generalized biorefinery site drawing on all the woody biomass resources (WBR) available in eleven SE states in the USA (Fig. 1).

Both the Conventional and Advanced Depot concepts are modeled using the Biomass Logistics Model (BLM) developed at Idaho National Laboratory (INL).[6] All three cases use a thermochemical ethanol-conversion biorefinery that is based on a published design.[7]

Feedstock-specific costs and availability are calculated at the county scale. Supplies and costs for each feedstock type from each county are determined at the forest landing. The total cost of the feedstocks at the reactor throat is then determined by adding the forest-landing costs to the additional costs associated with the feedstock-specific engineered supply chain.

In each of the three cases, we consider engineered biomass supply chain scenarios with and without ash management unit operations. Additionally, we consider each case with either high moisture (50% as harvested) or low

moisture (30% field dried). Thus, each case considers four different feedstock quality specification scenarios, which are identified as follows:

- HA50 – High ash and high moisture content
- HA30 – High ash and low moisture content
- LA50 – Low ash and high moisture content
- LA30 – Low ash and low moisture content

The biorefinery design is modified to accommodate the feedstock composition change for each of these different feedstock qualities.

Feedstock supply

The feedstock production and supply scenario is calculated using the methodology employed in the *US Billion-Ton Update*.[5] The SE US woody feedstocks for this study include whole-tree forest thinnings; logging residues; dedicated, short-rotation woody energy crops (SRWC); and pulpwood. Table 1 shows the available supply of each of these resources projected for 2022, assuming a landing price of $66 dry tonnes^{-1}.

However, availability is a function of price, with higher prices incentivizing increased supply. Additional feedstock supplies that are available at higher price increments are projected for each county. County level supply estimates were summarized over the SE region and from that summary a supply curve of forest landing prices for the woody feedstocks was developed (Fig. 2). The following discussion describes how the case-specific supply curves are generated and used for this analysis.

Methodology

Feedstock supply analyses

Feedstock supply analyses were performed using the POLYSYS model, which operates as a mathematical displacement model and is tied to historical agricultural-production and land-use patterns. The regional crop supply module in POLYSYS consists of 3,110 independent linear programming regional models that correspond to county boundaries. Each county is characterized by homogeneous production for all cropland area by crop type and tillage. The purpose of the crop supply module is to allocate land at the county level to the model crops, given baseline information on county cropland area, regional enterprise budgets of each crop, prices from the previous year, and a set of allocation rules. County-level acreages of various crops are provided assuming a 3-year average of observed cropland production by the National Agricultural
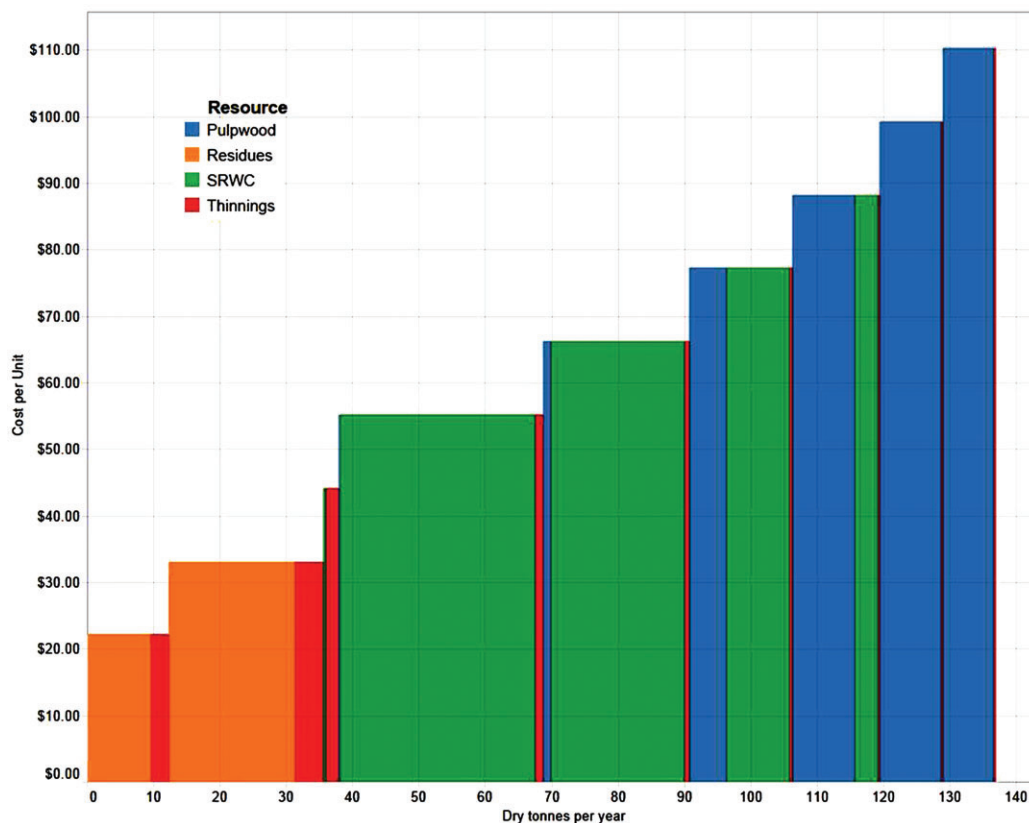
Figure 2. Supply curve of woody feedstock resources for the eleven SE US states[5].

Statistics Service (NASS), which tracks 126 million hectares (311 million acres) of national cropland. Conventional crops currently considered in POLYSYS include corn, grain sorghum, oats, barley, wheat, soybeans, cotton, rice, and hay. POLYSYS also considers cellulosic biomass resources for bioenergy including annual and perennial herbaceous energy crops, coppice and non-coppice woody crops, and agricultural and forest residues.

Biomass crops are allocated to agricultural land based on relative profitability to conventional major crops. Residues are collected when they are able to generate a profit. More information about POLYSYS assumptions and operations is available from English.[8,9] Further documentation regarding the application of POLYSYS to biomass crops is available in the appendix[5,8].

Biorefinery siting

The Site Characterization Model (SCM) was used to identify (i) a potential biorefinery site in a high production region (Rankin County, Mississippi) and (ii) the geospatial source of feedstock supply for a refinery site preselected in a low production region (Aiken, South Carolina). SCM

builds upon previous systems and analyses developed over the last several years.[10–14] SCM is a geographically based modeling system for locating biorefineries and predicting the associated supplies (price and quantity) of bioenergy feedstocks. SCM combines geographic estimates of feedstock supply with a transportation network to either select optimal locations for biorefineries or to identify the lowest-cost feedstock supplies for a set of predefined locations. Although SCM can use fine-scale (e.g. 0.5 km^2) feedstock locations, we chose to allocate all of the county-level POLYSYS estimates to the centroid of the county. This significantly reduced the computational burden of the analysis while still providing a level of geospatial resolution that was sufficient for the objectives of this study.

For the low production region analysis (Aiken, South Carolina), SCM calculated the optimal feedstock supply for this location by iteratively selecting those feedstocks and county centroid combinations (i.e. combined farmgate price and transportation cost) that minimized the delivered feedstock cost.

The high production region analysis (Rankin County, Mississippi) was based on selection of a location that minimized the marginal cost of growing, harvesting, and

transporting the feedstock to the candidate site. SCM coupled the county-centroid feedstock supply estimates with a road transportation network to calculate the total marginal price of supplying a candidate site. The analysis was iterated to generate a set of possible refinery locations ordered by increasing marginal cost. The site with the lowest marginal cost was selected as the location for further characterization.

Application

With unspecified conversion facility locations, previous applications of POLYSYS[5] (e.g. Perlack, 2011) have presented supply curves (i.e. supply as a function of price) at the farm-gate that exclude transportation costs. In this study transportation and pre-processing costs are quantified under the feedstock supply system. Thus, we present feedstock costs and supplies at the reactor throat by combining the farm-gate price with feedstock logistics costs. In the Conventional cases, this is simulated for both the low and high production sites. In the Advanced case, all identified SE US woody biomass resources (All WBR) are simulated to be supplied into a hypothetical commodity exchange facility.[5] The transportation distance(s) between exchange points are simulated using mathematical representations based on the geographic production density for each individual resource.

For the Conventional cases, we use the following calculation to determine the price of the feedstock as delivered to reactor infeed:

$$P_c^F = LP_c^F + FL_c^F \qquad (1)$$

where:

P_c^F = total delivered feedstock cost for each feedstock (*F*) from each county (*C*).

LP_c^F = landing price for each feedstock type (*F*) from each county (*C*).

FL_c^F = feedstock logistics cost for each feedstock type (*F*) and county (*C*).

$$FL_c^F = \sum_{i=1}^{n} TC_{Ci}^F + \sum_{i=1}^{n} PC_{Ci}^F \qquad (2)$$

where:

TC_{Ci}^F = transportation cost for each feedstock type (*F*) from each county centroid (*C*) for each pre-processing unit operation (*i*).

PC_{Ci}^F = Pre-processing cost for each feedstock type (*F*) from each county (*C*) for each pre-processing unit operation (*i*).

Applying a unique set of PC_{Ci}^F unit operations allows the opportunity for a more holistic feedstock cost to be considered. For example, logging residues, while less

expensive at the forest landing, may require a pre-processing operation to reduce ash content and thus add cost to the delivered product. Conversely, SRWC and pulpwood, while more expensive to purchase, may have lower ash content and lower associated pre-processing costs (Table 2).

This methodology provides quantities of biomass for different landing prices (LP_c^F), ranging from \$20 to \$120 dry tonnes^{-1}, in \$5 dry tonnes^{-1} price increments. Unique transportation costs (TC_c^F) and pre-processing costs (PC^F) for each feedstock type from each county are added to LP_c^F to provide total delivered price (P_c^F) for each feedstock type from each county. TC_c^F and PC_c^F are calculated using the supply system engineering methodology described later. By sorting from lowest to highest total delivered price (P_c^F) for each feedstock type from each county, additional supplies available at each price increment are used to produce the supply curves shown later.

This study includes the feedstocks modeled in POLYSYS that are best suited for thermochemical conversion technologies, which prefers woody feedstocks; thus, herbaceous dedicated feedstocks are excluded. From forestlands, these feedstocks include hardwood and softwood logging residues, thinnings, and pulpwood available at certain prices for bioenergy.[5] Federal lands may provide additional feedstocks but were excluded from this analysis due to uncertainty of policies on federal lands. From agricultural lands, these feedstocks include SRWCs. In the SE USA, SRWC could refer to various species (e.g. eucalyptus, poplar), but for this study, loblolly pine (*Pinus taeda*) is assumed.

Feedstock logistics

In this analysis, feedstock logistics includes all of the unit operations that handle the biomass from the point of standing in the field/forest to the reactor infeed. The process steps included in feedstock logistics are harvest, collection, storage, pre-processing, and transportation. Figure 3 shows the unit operations in the Conventional designs for both

Table 2. Farmgate/landing price, assumed ash contents and associated pre-treatment costs.

Feedstock type	Farmgate/landing price range (\$ dry tonnes^{-1})	Assumed landing ash content
Logging residues	\$20–\$35	15%
Forest thinnings	\$20–\$65	10%
Pulpwood for bioenergy	\$65–\$115	5%
Short-rotation woody crops	\$55–\$90	5%

low and high production sites for pulpwood as configured for the LA30 scenarios. Field drying techniques are used to reduce the feedstock moisture to 30%. Ash is actively managed by including a debarking unit operation.

Figure 4 shows the unit operations for the Advanced Depot design (Case 3) for pulpwood. Unit operations are located at distributed pre-processing depots to actively manage each of the critical biomass quality characteristics (moisture, ash, particle size, density, etc.). For this analysis, depots have a throughput of 5–20 dry tonnes hr^{-1}, and are sized and replicated based on the feedstock supply density for the county where they are located. Biomass is transported 25 km or less to a depot, and depots are configured to process multiple woody resource types. Feedstock material leaving a depot is considered aerobically stable with handling properties that are compatible with existing solids handling infrastructure (i.e. grain).

Techno-economic analyses for feedstock logistics are performed using the Biomass Logistics Model (BLM) developed by INL. The BLM simulates delivered feedstock cost and energy consumed for feedstock supply systems. The model structure for the BLM is shown in Fig. 5. The BLM incorporates information from a number of databases that provide (i) engineering performance data for equipment systems, (ii) spatially explicit labor cost datasets, and (iii) local tax and regulation data. The BLM analytic engine is built using Powersim^{TM}, a systems dynamics software package. The BLM accommodates a range of cellulosic biomass types (herbaceous residues, dedicated short-rotation woody and herbaceous energy crops, woody residues, algae, etc.). The BLM simulates the flow of biomass through the supply chain, tracking changes in feedstock characteristics (i.e. moisture content, dry matter, ash content, and dry bulk density)
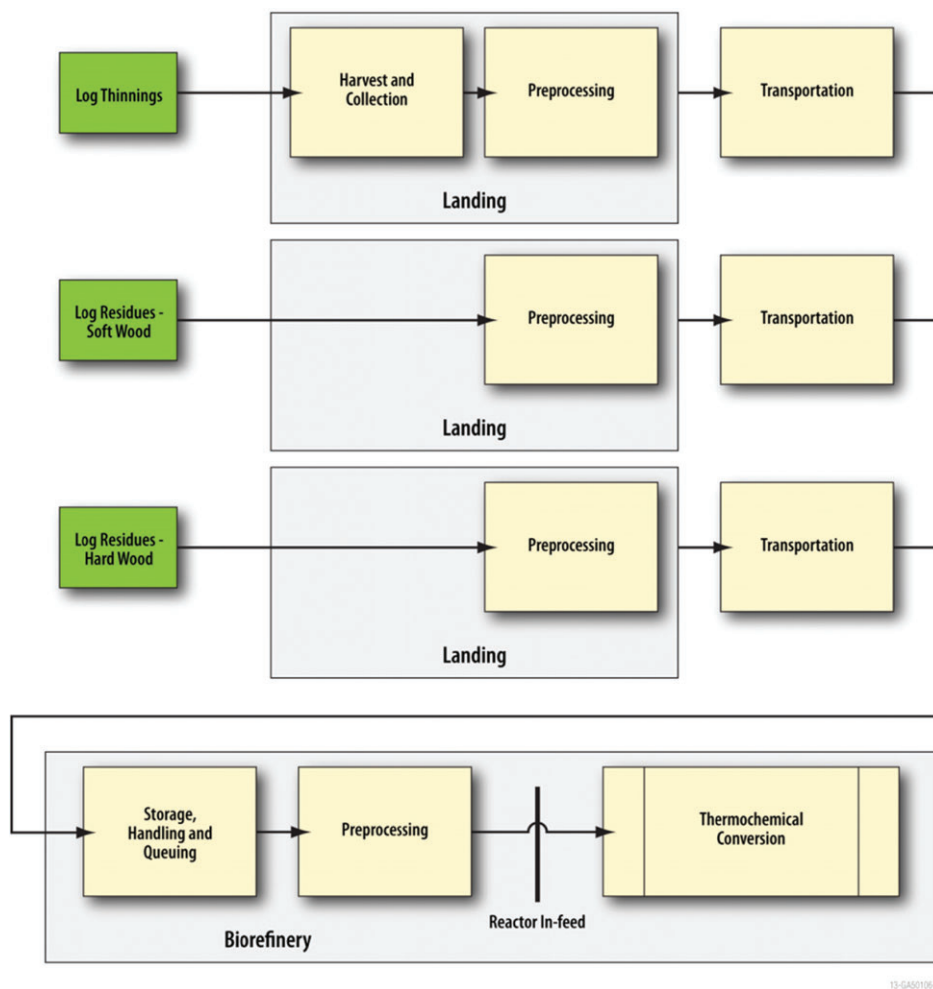

Figure 3. Conventional Supply System (Conventional) unit operation design. (Courtesy INL, 2013)
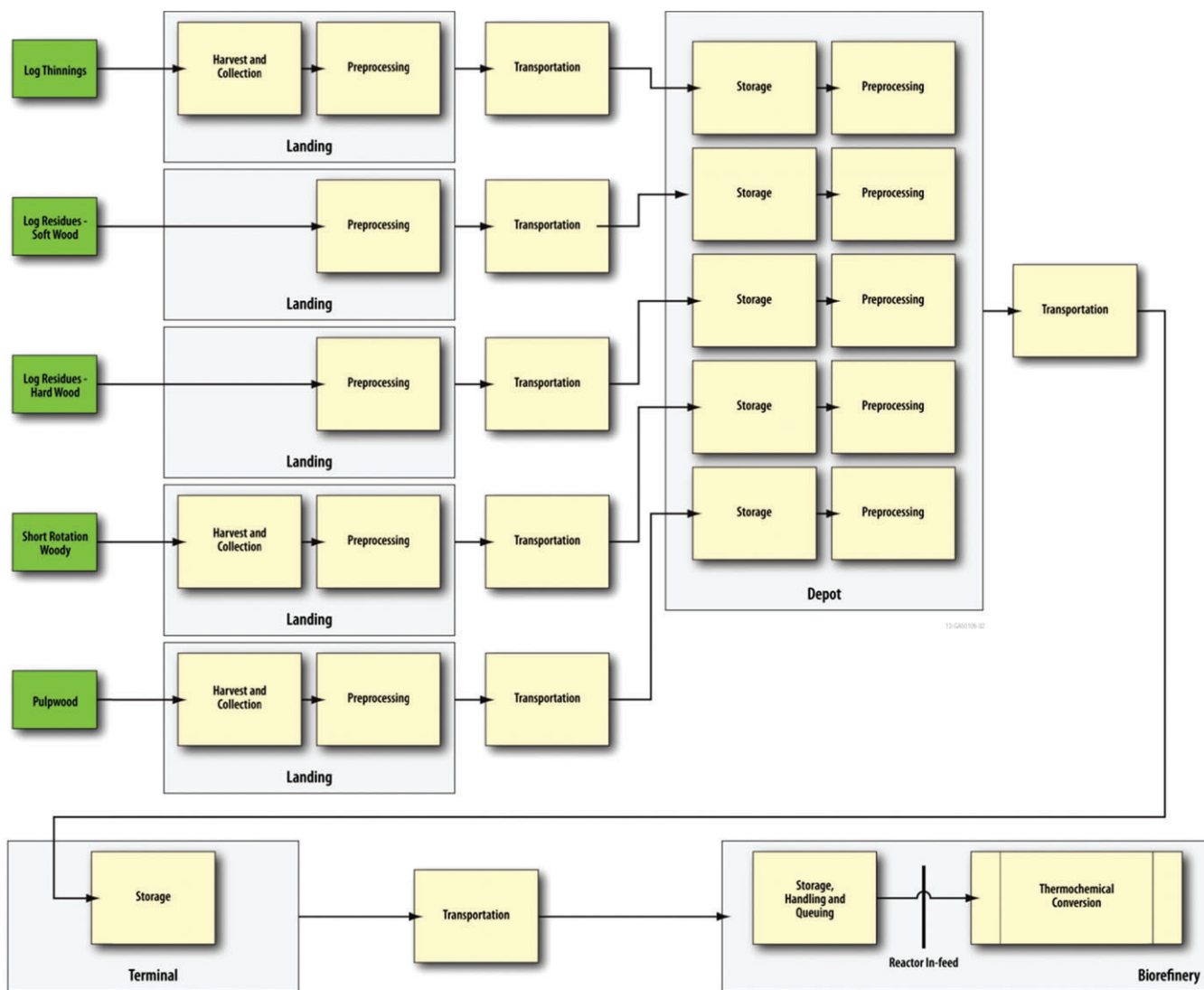
Figure 4. Depot Preprocessing Supply System (Depot) unit operation design. (Courtesy INL, 2013)

as influenced by the unit operations in the supply chain. By accounting for all of the equipment that comes into contact with biomass between the field and the reactor infeed, along with interim changes in feedstock characteristics, the BLM evaluates economic performance of the engineered system, as well as determines energy consumption and greenhouse gas (GHG) performance of the design.

Table 3 provides the modeled logistics system costs for each Conventional unit operation for each feedstock type, residues and thinnings for the LPR case for a biorefinery size of 2000 tonnes day^{-1}. Using the methodology described in Section 3, the feedstock mix for this scenario includes only the lower cost resources, logging residues, and forest thinnings. Logging residues are assumed to be

piled at the forest landing and are not allocated harvest and collection costs. Landing pre-processing costs include size reduction to 5-cm chips and loading onto a truck. In the LA scenarios, landing pre-processing costs also include a screening operation to separate external ash and high-ash biomass fractions. Transportation to the biorefinery is by truck, where the chips are unloaded and stored in a chip pile. Pre-processing at the biorefinery includes the final size-reduction steps, drying using conversion process waste heat, and insertion into reactor infeed.

Table 4 provides the modeled logistics system costs for unit operation in Case 3 (Advanced Depot). These costs represent the production characteristics in the high production region, and the unit operation costs are modeled for LA30 for all feedstocks investigated in the study.
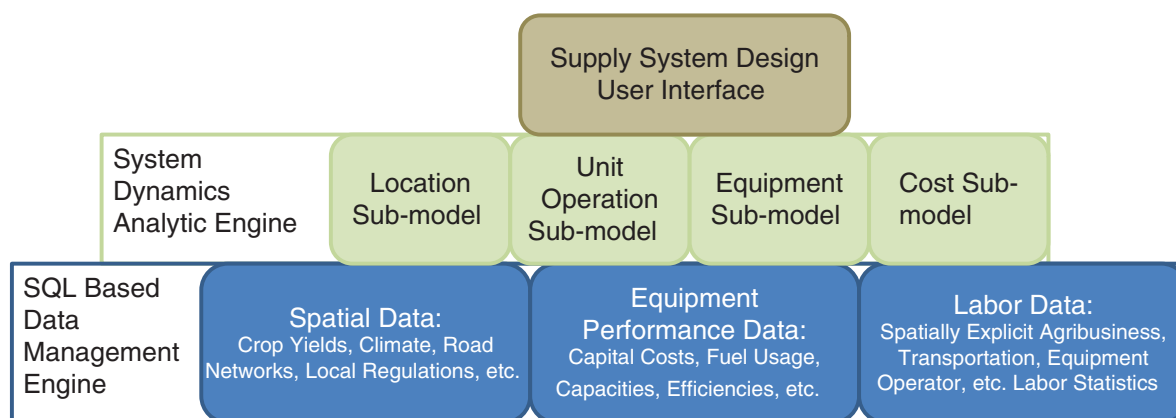
Figure 5. BLM framework.

Table 3. Conventional logistics cost by unit operation and feedstock type for a biorefinery size of 5000 tonnes day^{-1}.[5]								
Scenario	LA50		HA50		HA30		LA30	
	($ dry tonnes^{-1})							
Feedstock Type	Logging Residues	Forest Thinnings	Logging Residues	Forest Thinnings	Logging Residues	Forest Thinnings	Logging Residues	Forest Thinnings
Harvest and Collection	0.00	17.45	0.00	17.42	0.00	17.40	0.00	17.42
Landing Pre-processing	24.14	16.82	17.24	9.36	10.42	2.38	17.45	9.60
Transportation	4.86	4.87	5.30	5.31	4.79	4.80	4.35	4.36
Storage, Handling & Queuing (Biorefinery)	4.32	5.98	4.68	5.79	3.99	4.64	3.57	4.40
Pre-processing (Biorefinery)	10.12	10.13	10.11	10.12	10.10	10.11	10.10	10.12
Total	43.44	55.25	37.33	48.00	29.3	39.33	35.48	45.90

In Case 3 (Advanced Depot), pulpwood and SRWC are debarked at the landing, and no additional ash reduction is required. For logging residues and forest thinnings, ash-reduction operations are located at the pre-processing depot. Ash reduction processes could include running the biomass through trommel screens and washing operations based on the level of ash. The feedstock is transported to the depot in a 5-cm-chip format. Advanced Depot pre-processing includes ash reduction (as needed), additional size reduction, and densification operations.

Delivered feedstock cost

The total delivered feedstock cost at the conversion reactor infeed is calculated by feedstock type and county using

Eqn (1). Feedstock supplies (e.g. total dry tonnes) are identified by feedstock type and incremental price for each county. The logistics system design and analysis is executed for each feedstock type in each county for the identified supply systems (Figs 3 and 4). Transportation costs are established for each feedstock type and county of origin based on distance from the hypothetically located biorefinery.

In the Conventional scenarios, the feedstocks with the lowest cost are selected and delivered to the biorefinery. This creates a tradeoff situation where the landing cost, material quality, and associated pre-processing costs to get the material to conversion process specifications are analyzed. For each of the Conventional scenarios, the lower-cost resources, logging residues, and forest thinnings

Table 4. Advanced Depot logistics cost by unit operation and feedstock type for the low ash low moisture case.[5]

| Scenario	LA30 Cost Table ($ dry tonnes^{-1})			
Feedstock Type	Logging Residues	Forest Thinnings	Pulpwood	Short Rotation Woody
Harvest and Collection	0.00	17.42	16.37	16.37
Landing Pre-processing	10.42	2.38	19.58	19.58
Transportation to Depot	2.60	2.61	2.60	2.60
Depot Storage	1.21	1.21	1.21	1.21
Depot Pre-processing	28.54	28.54	19.80	19.80
Transportation to Terminal	6.43	6.43	6.43	6.43
Terminal Storage	1.21	1.21	1.21	1.21
Transportation to Biorefinery	1.79	1.79	1.79	1.79
Biorefinery Handling & Queuing	2.23	2.23	2.23	2.23
Total	54.43	63.82	71.22	71.22
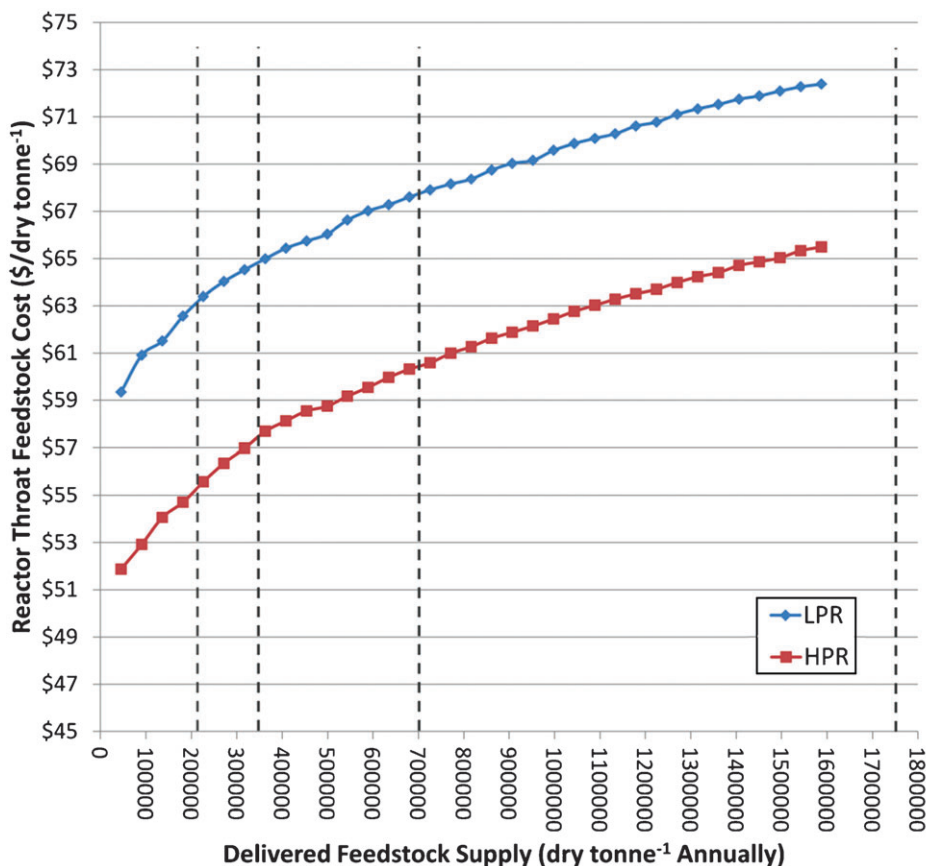
Figure 6. Reactor throat supply curve for Conventional, low moisture low ash scenarios for the high production and low production sites. Reactor throat feedstock costs include all the costs to get the biomass from standing in the forest to the throat of the conversion reactor.[5]

(Table 2) can be collected and preprocessed to conversion specifications at a lower delivered feedstock cost than higher-quality, higher landing price materials (e.g. pulpwood and SRWCs). Figure 6 shows delivered feedstock cost curve for the LA30 scenarios of both Conventional cases. The delivered feedstock for the LA30 scenarios of

Table 5. Depot tonnage weighted average reactor throat feedstock cost for entire SE region.

Depot Reactor Throat Feedstock Costs ($ dry tonnes^{-1})	
Low Ash, High Moisture	122.25
High Ash, High Moisture	120.45
Low Ash, Low Moisture	110.00
High Ash, Low Moisture	104.32

both cases includes only logging residues and forest thinnings. The biorefinery sizes investigated in this analysis are noted by vertical dashed lines in Fig. 6.

Because the Case 3 (Advanced Depot) scenarios deliver all identified resources in the SE USA to biorefineries, transportation costs are calculated using mathematical representations for movement to a depot, a terminal, and a biorefinery. The cost of transport to the nearest depot is calculated based on the local density of feedstock production (dry tonnes km^{-2}). Similarly, the transportation distance from the depot to the terminal is calculated based on regional feedstock density. Transportation from the terminals to the biorefineries was assumed at a constant average of 200 km via rail. Table 5 provides the tonnage weighted average delivered feedstock costs for each of the Advanced Depot scenarios.

Conversion to ethanol and technoeconomic analysis

Conversion methods

Techno-economic analyses of the thermochemical process for making ethanol from woody biomass via gasification were performed by scaling the process design as detailed in a report developed at the National Renewable Energy Laboratory (NREL) in collaboration with The Dow Chemical Company and INL.[7] The process steps include: (i) indirect gasification of woody biomass to produce

syngas, (ii) syngas conditioning and cleaning through tar and hydrocarbons reforming and scrubbing, followed by syngas compression, (iii) the production of ethanol and higher alcohols via the catalytic conversion of syngas, and (iv) product separation as shown in Fig. 7. The process design was adjusted to accommodate different feedstock moisture and ash contents. The biorefinery was scaled using equipment-specific scaling factors; and when there was an upper limit on size (as was the case for the gasifier and alcohol synthesis reactor), multiple process units were used. The yield was assumed to be independent of biorefinery size. The MESPs were calculated using a standard discounted cash flow rate-of-return analysis.[7]

Ultimate analysis of all the post-processed feedstock types is assumed to be consistent (Table 6). For this study, we assumed that the feedstock convertibility is the same for similar feedstock types (i.e. logging residues, pulpwood, and SRWC) and for both the Conventional and Advanced Depot systems.

Results

A comparison of the mixed alcohols yields for the three cases is shown in Fig. 8. LA30 resources had higher product yields, with the moisture content exhibiting a more negative impact on the yield than the ash content for the

Table 6. Ultimate Analysis of Woody Biomass Feedstock.[7]

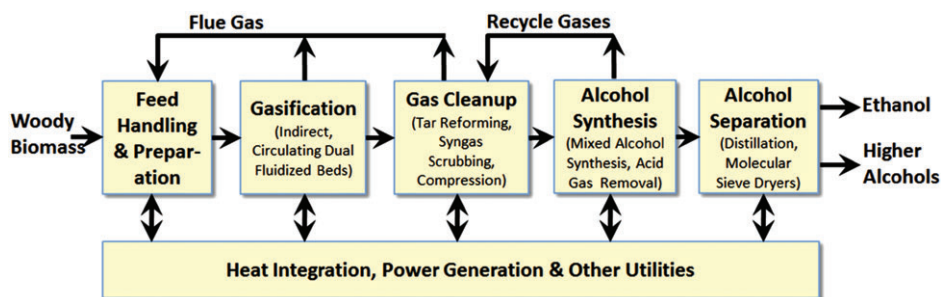| Component	Weight % (Dry Basis)	
	Low Ash	High Ash
Carbon	50.94	47.81
Hydrogen	6.04	5.67
Oxygen	41.90	39.33
Sulfur	0.03	0.03
Nitrogen	0.17	0.16
Ash	0.92	7.00

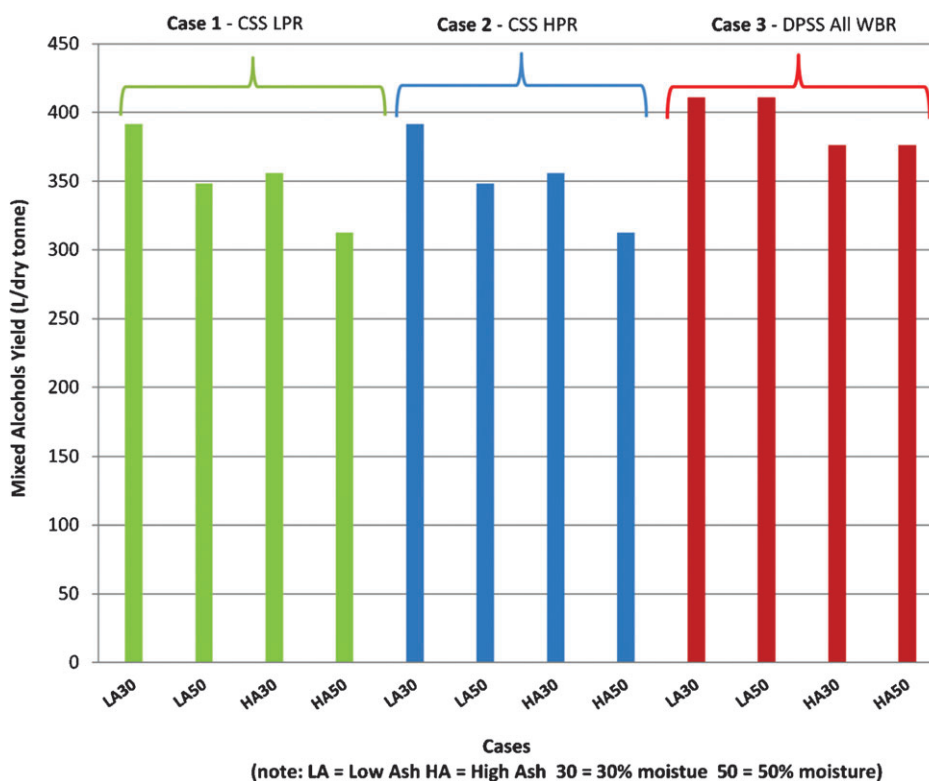Figure 7. Gasification to mixed alcohol process design.[7]

Figure 8. Ethanol costs as a function of preprocessing levels. (Courtesy NREL, 2013)

ranges evaluated. Field drying from 50% to 30% moisture content improved yield by ~43.3 L dry tonne^{-1} for the Conventional cases. Reducing ash content from 7 to 1% led to a yield increase of ~35.7 L dry tonne^{-1}.

The Advanced Depot scenarios had higher yields than the Conventional scenarios. This is primarily the result of using an engineered feedstock that already meets moisture content specifications which results in utilization of the heat which would otherwise be used for drying within the process for purposes such as supplying heat for the reboiler of the ethanol product distillation column, and preheating air for the combustors. As a result less syngas needs to be diverted to meet process heat requirements, and more of the syngas can be used for ethanol production. However, the resulting gain in yield for the Depot designs could be at the expense of additional global warming potential during feedstock pre-processing, which is discussed in Section 8.

The MESP decreases as the biorefinery size increases for all scenarios, demonstrating good economies of scale (Fig. 9). The LA30 scenarios are the least expensive, and the HA50 scenarios are the most expensive. The HA30 scenarios are generally less expensive than the LA50 scenarios, which suggest that moisture content has a greater

impact on MESP for the moisture and ash ranges used in this study. However, note that the biorefinery capacity of 5000 dry tonne day^{-1} is nearing the practical limit with conventional logistics. Biorefinery capacities in excess of 5000 dry tonne day^{-1} are only feasible with advanced logistics.[15]

For the Conventional scenarios, feedstock costs increase with increasing biorefinery scale. In addition, feedstock costs are higher in the LPR (Case 1) than the high production region (Case 2) due to increases in transportation costs. While feedstock costs are independent of the biorefinery scale for the Advanced Depot design, they are relatively higher than the Conventional design costs, due to higher logistics costs. Higher yields (tonne day^{-1}) and economies of scale are not enough to completely offset the higher feedstock costs. Figure 10 shows the ethanol production cost distribution.

Delivered feedstock cost contributes, on average, about 47% of the MESP: 40–46% for Case 1, 42–48% for Case 2, and 50–55% for Case 3. It should be noted that the advanced logistics modeled in Case 3 incur only a minor MESP increase while providing the additional advantages of reducing feedstock risk (e.g. protection from loss of feedstock from extreme weather events, supply disruption,
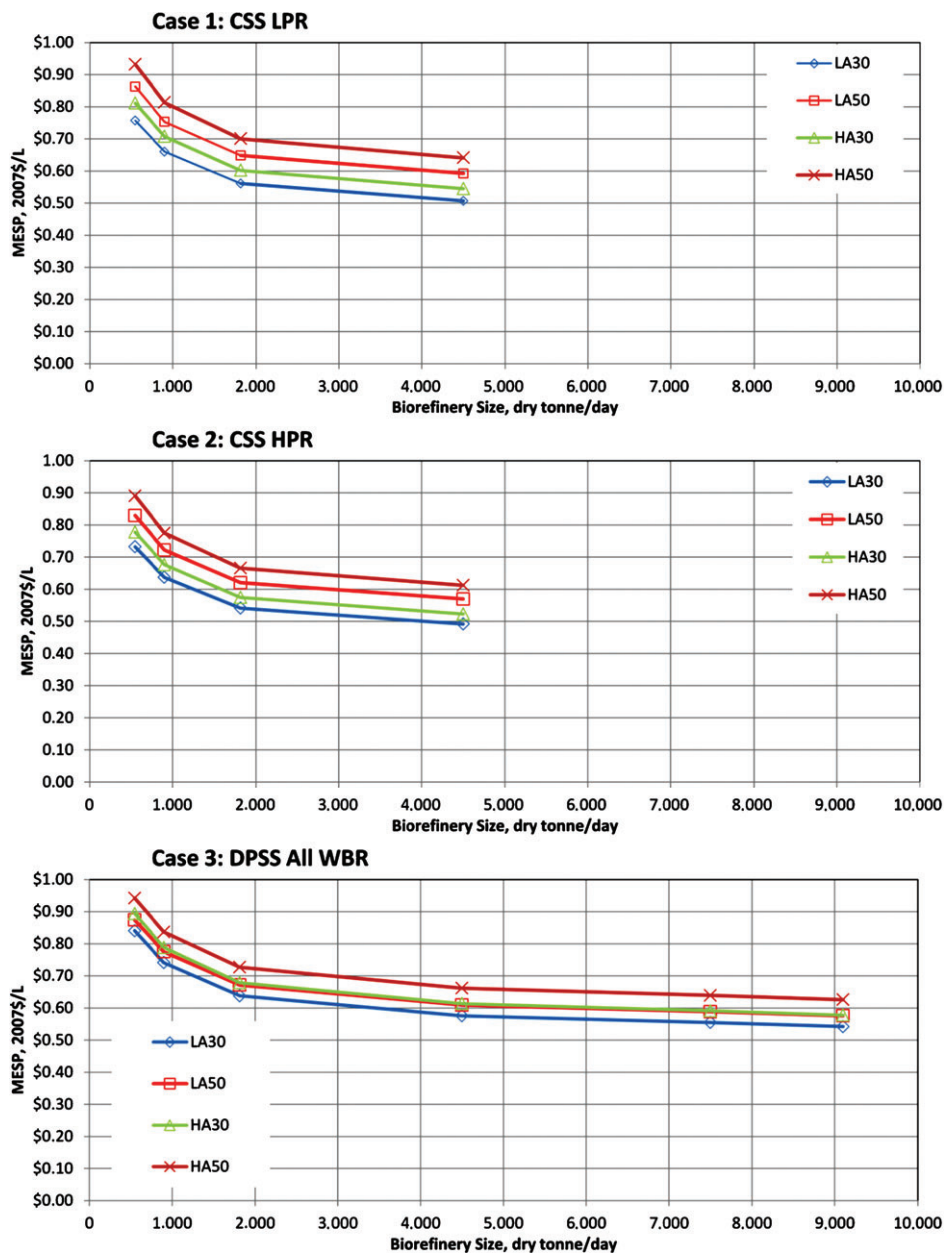
Figure 9. Ethanol costs as a function of plant size for all cases and feedstock specifications.[15]

Water

Water resources are considered in this study by presenting the water footprint (WF), which calculates blue, green, and grey water use associated with feedstock production and conversion to mixed alcohols via gasification. Green water is the consumptive use of rainfall, and blue water accounts for the consumption of surface and groundwater through the irrigation and conversion process. Grey water is employed to illustrate runoff water from fields containing nitrogen fertilizer and nitrogen in process water discharge. Detailed methodologies of the water footprint assessment are described in Chiu.[16]

Methodology and assumptions

This analysis evaluates a mixture of hardwood and softwood grown in the study region on the basis of forest
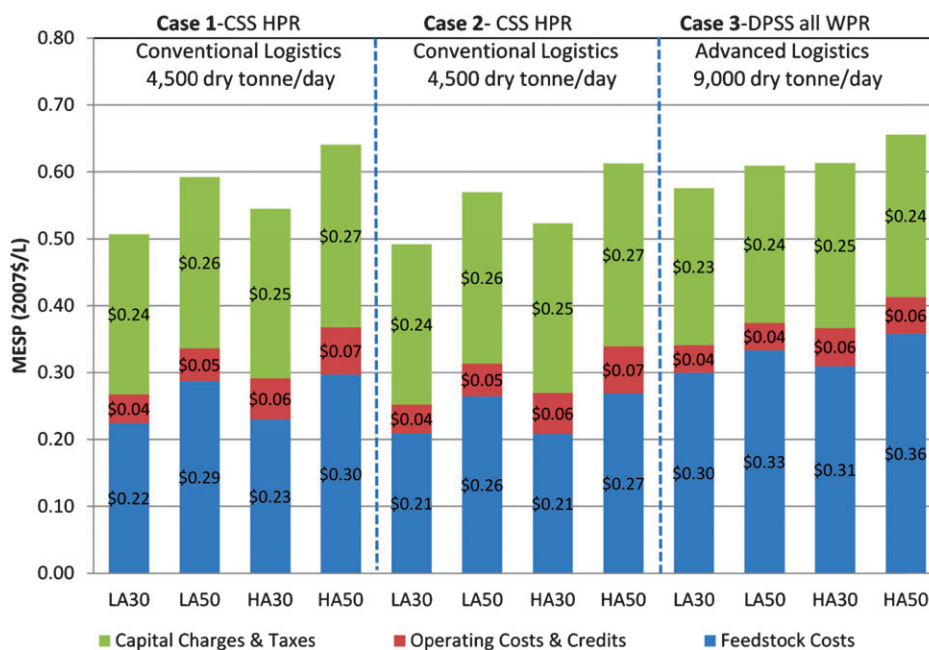
Figure 10. Ethanol product cost distribution.[15]

wood production data. The feedstock resources used include whole-tree forest thinnings, logging residues, SRWCs, and pulpwood (softwood). Loblolly and sweet-gum are selected to represent softwood and hardwood, respectively. SRWCs are assumed to be loblolly pine (*Pinus taeda*). It is assumed that only softwood receives fertilizer because, in terms of productivity, hardwood is less responsive to fertilizer than softwood in the studied region.[19,20] Because the log wood and SRWC are purposely grown for the production, they are responsible for the fertilizer input. Wood residue (thinning and log residue), in contrast, do not share the burden of grey water. The rate of nitrogen fertilizer application for softwood is estimated to be 236.0 kg ha^{-1}, and for SRWC is estimated at 201.6 kg ha^{-1} in each harvest cycle.[5,21] A fraction of 3.74% of the applied nitrogen fertilizer would be lost to streams.[21]

The analysis assumes no irrigation is required for the forest wood; therefore, no blue water is associated with the feedstock production stage. A mass-based method using USFS historical datasets is adopted to proportionally allocate the estimated volume of total green water to residue harvested for biofuel.[17,18] Consumptive water use in mixed alcohol production through the gasification process in biorefineries is generated via process simulation, which accounts for consumption in cooling towers and boilers, as well as losses through flue gas emission and wastewater treatment.

Results

Conventional logistics (Conventional cases)

The available resource mix drives the magnitude and spatial distribution of the WF of bioethanol produced from woody feedstock. In general, softwood is the major source in Aiken, South Carolina (LPR Case 1), whereas more hardwood is available in Rankin County, Mississippi (high production region Case 2) (Fig. 11). Green water use dominates in both areas, as there is no irrigation requirement (blue water) in practice, and comparatively, resources in Case 2 have a slightly higher green WF than those in Case 1 (Fig. 12).

On a county level, green WF ranges from 194 to 1942 liters per liter biofuel produced (L L^{-1}) with an average running between 358 to 546 L L^{-1}, depending on resource mix, location where the resource is grown, and refinery sizing assumptions. Blue WF, primarily the refinery process water use, varies slightly from 2.3 to 2.6 L L^{-1}, largely changing with the moisture content of the feedstock. On a per-liter fuel-production basis, the WF of the biofuel is more sensitive to ash content than to moisture content in the feedstock, due to their corresponding impacts on the amount of mixed alcohols produced from a unit weight of dry feedstock. A 6% decrease in ash content (7–0.9%) could result in a 10% reduction in the green WF, while an average 12% reduction in green WF requires lowering the moisture content by 20% (50–30%). The WF appears to be
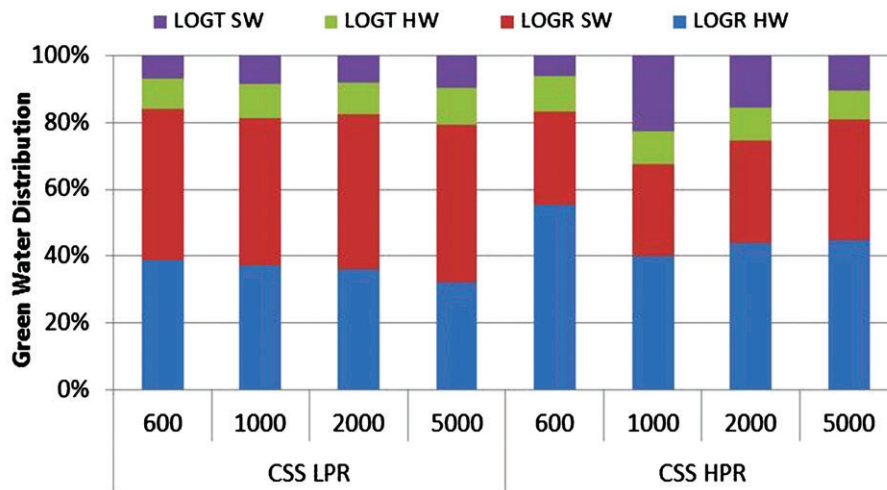
Figure 11. Partition of green water into different woody residue by biorefinery capacity (dry tonne day-1) in conventional case (moisture content 50%, ash 7%). LOGT- logging thining; LOGR – logging residue; SW – soft wood; HW – hard wood.[16]
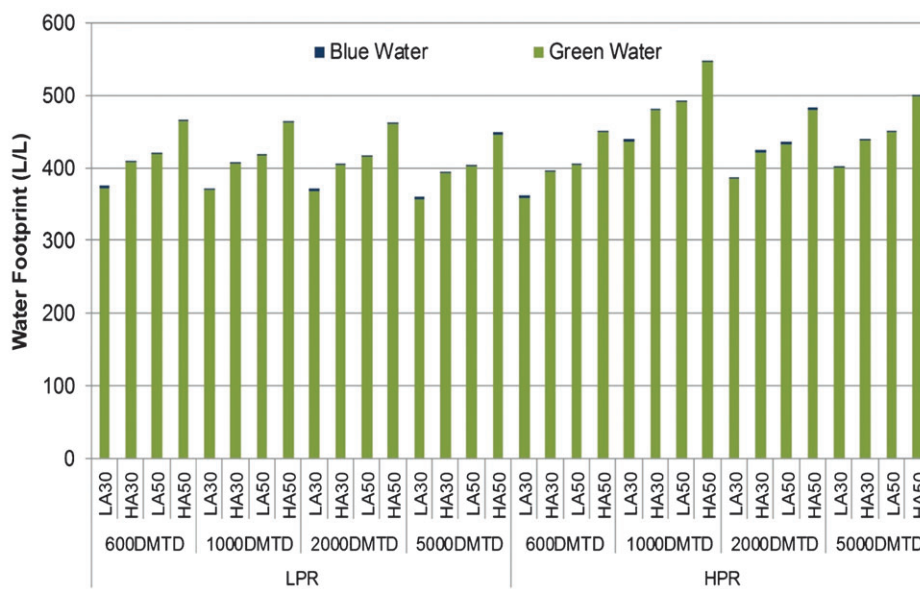

Figure 12. Blue, green, and grey water allocation in responding to different scenarios of ash and moisture contents.[15]

strongly influenced by the mix of woody feedstock and the concentration regions where the feedstock is grown. As refinery size increases, the region providing feedstock will be expanded, and available feedstock mix changes accordingly, which affects WF (Fig. 12). However, in most cases, the changes are relatively small in the studied region.

Note that the feedstock generates zero grey water as there is neither pulpwood nor SRWC involved in Conventional

cases. Therefore, green water is the dominating footprint in Conventional cases.

Advanced logistics (Depot case)

In the Case 3, SRWC plays an important role in the resource mix and therefore dominates the WF. A small portion of pulpwood is also harvested as biofuel
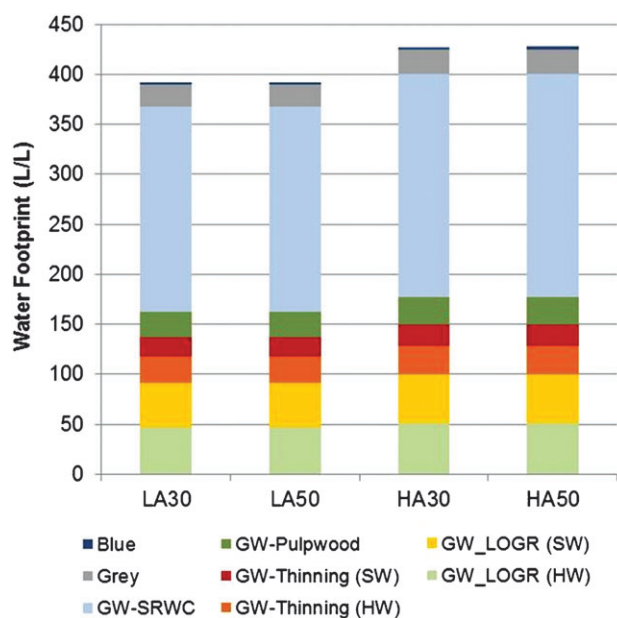
Figure 13. Green (GW), blue, and grey water allocation in responding to different scenarios of ash and moisture contents under the Depot case. The value corresponds to a plant capacity of 83 million dry tonne per year.[15]

feedstock in this case. The total green water at the studied region ranks from 367 to 400 L L^{-1} under the LA50 and HA30 scenarios, respectively (Fig. 13). This representation of green water in the WF is similar to that in the Conventional Cases 1 and 2. The regional-average gray WF in the advanced logistics Depot Case 3 is between 23 and 25 L L^{-1}. On average, the total WF from the four scenarios under Advanced Depot is regulated by feedstock ash content.

Sustainability metrics and life cycle assessment

Modeling approach and assumptions

The modeling boundary for this study is field to wheels, including embodied energy and material flows. The functional unit is 1 L of neat ethanol produced in the year 2017. SimaPro v.7.3 LCA modeling software was used to develop and link unit processes using established methods.[22] Ecoinvent v.2.0 and the US Life Cycle Inventory (LCI) processes were used to fill the data gaps.[23] The Ecoinvent processes were modified to reflect US conditions, and the US LCI processes were adapted to account for embodied emissions and energy flows. The LCI of the conversion step is based on input raw materials and outputs such

as emissions and waste as predicted by the Aspen Plus process model.

In addition to ethanol, the biorefinery also produces higher alcohols. The higher alcohols co-product can be used as a liquid fuel and the energy allocation method is applied, that is, energy use and greenhouse gas (GHG) emissions burdens are allocated among the products (i.e. ethanol and higher alcohols) according to their share of the conversion facility's energy output.[25] Energy outputs are determined using the corresponding lower heating values. Inputs to multi-year cropping systems (i.e. SRWC) are likewise annualized by the length of the cropping rotation. Impacts from direct and indirect land-use change are not considered in this study. Feedstock processing and transport are modeled according to the illustrative cases discussed earlier.

LCA modeling results

GHG emissions, also represented as global warming potential (GWP), expressed in kg CO_2-eq L^{-1} ethanol), were quantified for the production of ethanol via the present thermochemical conversion pathway. Life-cycle GWP results (i.e. feedstock contribution plus indirect impacts and waste disposal) for the Conventional LPR Case are shown in Fig. 14, which shows GWP is dominated by harvesting and pre-processing. For the Advanced Depot logistics Case 3, GWP for all scenarios is heavily dominated by feedstock production and logistics, as shown in Fig. 15. GWP for the Case 3 scenarios is more than double that of Cases 1 and 2, which is attributed to the feedstock drying in Case 3 (50–10% for the high-moisture scenarios and 30–10% for the low-moisture scenarios) that is performed in the pre-processing step, as opposed to Cases 1 and 2, where moisture reduction occurs at the biorefinery using process waste heat.

The Conventional logistics Cases 1 and 2 assume that moisture reduction at the biorefinery is achieved with heat generated from process waste heat. The Advanced Depot logistics case does drying at the depot and does not have access to waste heat and must use natural gas. However, there exist strategies that can reduce the GWP of the Advanced Depot logistics Case 3. For example, GWP ranges from 0.75 to 1.2 assuming all biomass resources are used, but excluding dedicated feedstocks reduces this range to 0.42–0.55. Further, by using a portion of the biomass to displace natural gas used in drying operation, GWP is reduced to 0.41–0.52, though this comes at a cost of reduced total biofuel production (Fig. 15).

Feedstock moisture content impacts not only pre-processing, but also feedstock transportation. Feedstock
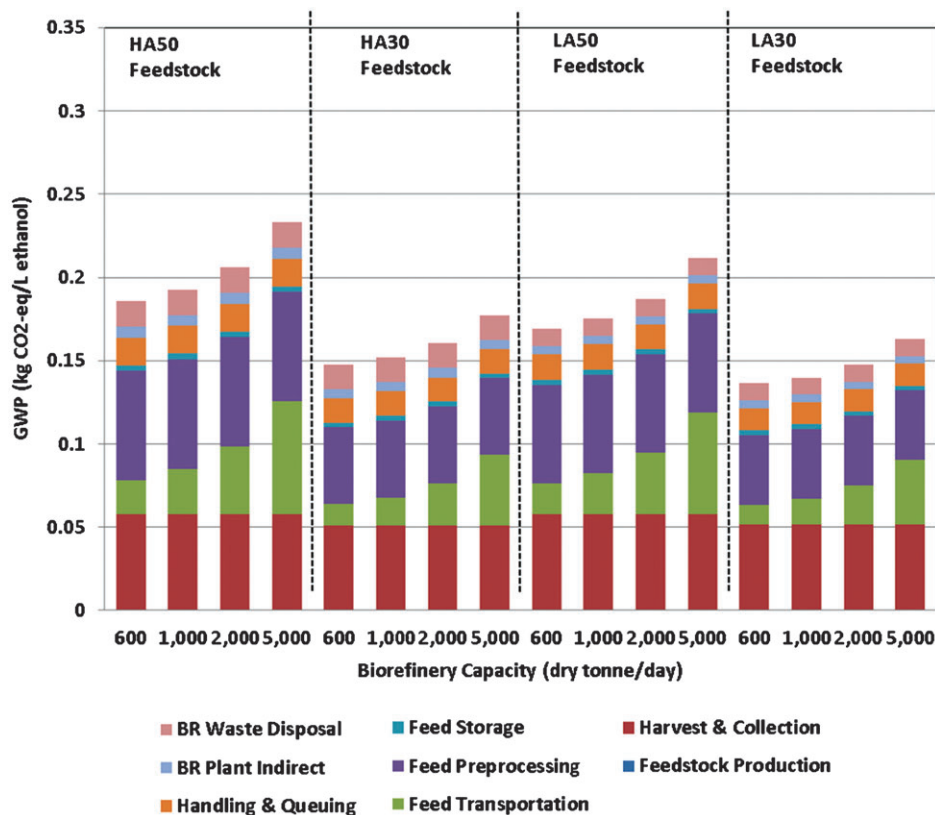
Figure 14. Global warming potential (GWP) results for Conventional LPR scenarios.[7]

with lower moisture content requires less energy for transportation. Thus, low-moisture scenarios (HA30 and LA30) have lower GWP than the high-moisture scenarios (HA50 and LA50). Additionally, compared to feedstock moisture content, feedstock ash content has a lower impact on GHG emissions associated with feedstock logistics for the ranges considered in this study.

Finally, in contrast to the Advanced Depot logistics Case 3 scenarios, GHG emissions associated with feedstock production and logistics for the Conventional logistics Cases 1 and 2 are dependent on biorefinery size, due to different scales with different feedstock mixtures and compositions. The variation of GHG emissions from feedstock production are the result of different feedstock compositions and mixtures being applied to different conversion facility sizes.

It is noteworthy that life-cycle GWP at the conversion stage is largely dictated by the indirect GHG emissions that associated with the underlying processes (e.g. catalysts and chemicals production); there is negligible direct conversion facility impact on life-cycle GWP. Direct biorefinery GHG emissions at the conversion stage (primarily resulting from char and fuel combustors) are biogenic CO_2

(i.e. CO_2 absorbed from the atmosphere and incorporated as biomass). With its biomass origin, biogenic CO_2 does not contribute to the increase of GHGs in the atmosphere and is not considered in the Intergovernmental Panel on Climate Change (IPCC) global warming methodology.[26,27] Biogenic CO_2 is typically not counted as a contributor to global warming in IPCC global warming methodology because it is assumed that the emitted CO_2 was removed from the atmosphere during the same time horizon of the GWP estimate (e.g. 100 annum, 200 annum). Hence, the GWP contribution from direct plant CO_2 emissions for the evaluated processes is zero.

It is important to emphasize that qualification as a 'cellulosic biofuel' under the Renewable Fuel Standard (RFS) requires lifecycle GHG emissions to be at least 60% less than the 2005 baseline gasoline GHG emissions.[28] Without this qualification, the biofuel would not qualify for the renewable identification number (RIN) value, which is very important to the economics of the producers. A comparison of the Conventional logistics designs (Cases 1 and 2) and Depot logistics designs (Case 3) against the 2012 Biochemical and 2012 Thermochemical State-of-Technology base cases show that Cases 1 and 2
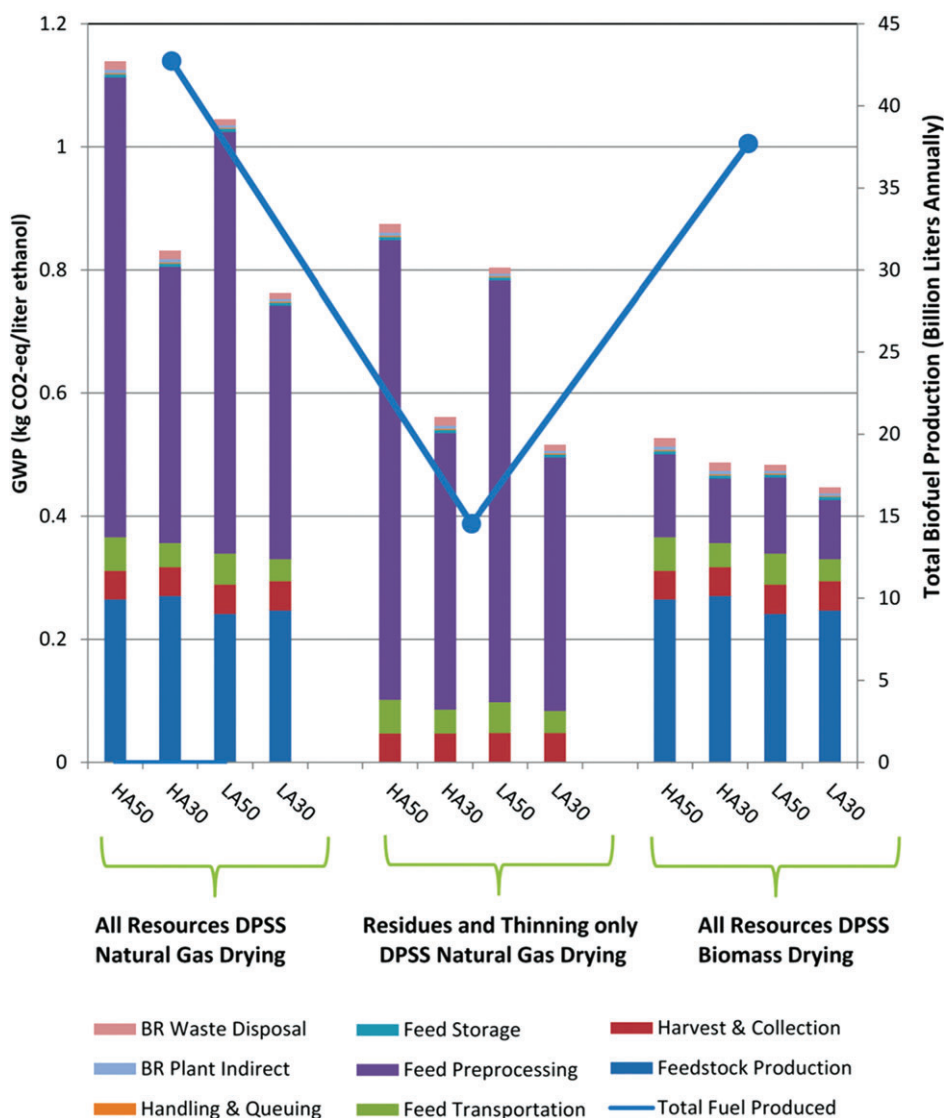
Figure 15. GWP results for Depot all WPR Case for the entire SE. (Courtesy NREL, 2013)

qualify but Case 3 does not (Fig. 16).[29,30] However, if the moisture reduction operation that occurs at the depot is performed with a dryer that uses biomass rather than natural gas, then the biofuel does, in fact, qualify as a cellulosic biofuel.

Conclusions

Feedstock specifications

In this work, we show that field-drying woody feedstock to reduce moisture content from 50% to 30% lowers the feedstock cost by $9–11 dry tonne^{-1} and $12–16 dry tonne^{-1}

for Conventional and Advanced Depot logistics, respectively, and thereby lowers the MESP for conversion in the thermochemical biorefinery by $0.07–0.10 L^{-1} and by $0.02–0.04 L^{-1}. Field-drying lowers the life-cycle GWP by 17–21% and 26% for Conventional and Advanced Depot, respectively. Additionally, field-drying reduces the water footprint (WF) by 10–12% for Conventional logistics. The field-drying effect is achieved from two mechanisms: (i) improving transportation efficiency with lower amounts of residual moisture and (ii) increasing conversion yield by lowering required drying heat.

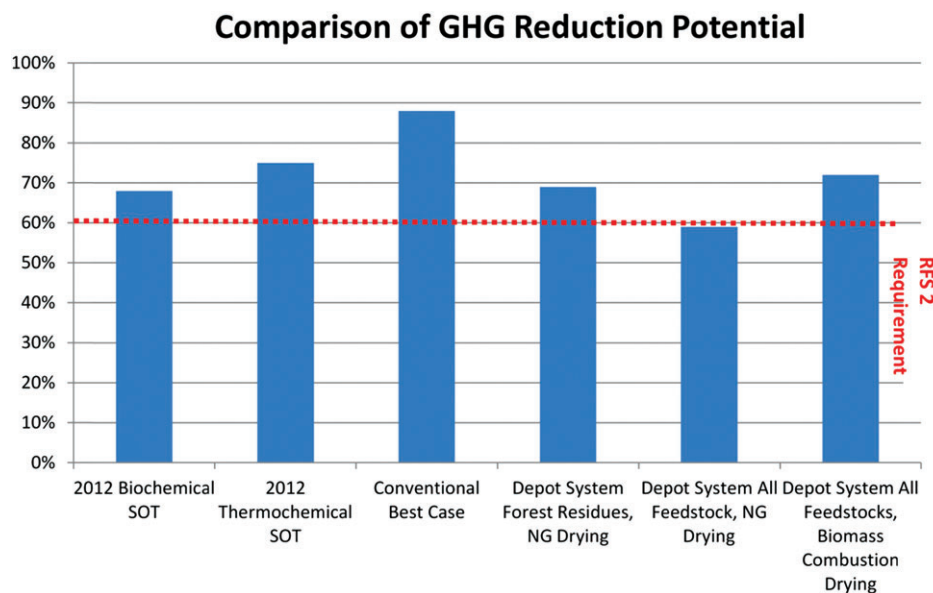Reducing the feedstock ash content from 7% to less than 1% in the supply system adds $5–7 dry tonne^{-1} and

Figure 16. GHG reduction for a selected set of scenarios from reference and the analysis developed in this paper. (Courtesy NREL, 2013)

$2–6 dry tonne^{-1} to the biorefinery feedstock cost for Conventional and Advanced Depot logistics, respectively, while lowering the overall MESP by $0.02–0.07 L^{-1} in the thermochemical biorefinery. Ash reduction in pre-processing lowers the life-cycle GWP by 8–10% and reduces the WF by 13% on average. Feedstock ash content directly affects biorefinery overall yield, demonstrating that conversion efficiency gains outweigh marginally higher feedstock pre-processing requirements.

Supply system and biorefinery size

Both Conventional and Advanced Depot logistics design concepts display good economies of scale with increasing biorefinery size; however, the conventional system cannot supply the volumes required for very large biorefineries. For the Conventional case, the life-cycle GWP increased in direct proportion to biorefinery size based solely on the increase in transportation fuel usage, whereas for the Advanced Depot case life-cycle GWP was essentially independent of biorefinery size. The WF is dependent on the mix of woody feedstock and the location where the feedstock grown, which is directly affected by refinery scale, and differences observed among the biorefinery scenarios in the studied region are relatively small.

For the current study we have limited the Conventional cases to biorefinery sizes of 5000 dry tonne day^{-1}, as these designs start to approach practical constraints, such as

limits on the number of trucks that can be unloaded in the biorefinery in each hour. The Depot results in feedstock costs that are $31–45 per dry tonne and $37–57 per dry tonne higher than those for the Conventional low production region Case 1 (Aiken, South Carolina) and Conventional high production region Case 2 (Rankin County, Mississippi) sites, respectively. At the maximum biorefinery capacities investigated in this study (5000 dry tonne day^{-1} for Conventional and 10 000 dry tonne day^{-1} for Advanced Depot), the difference in MESPs between Conventional and Depot ranged from $0.01 to 0.05 L^{-1} and from $0.01 to 0.07 L^{-1}, depending on the feedstock quality scenario, for the low production and high production sites, respectively (or from $0.03 to 0.01 L^{-1} for all SE US woody resources collected using Conventional logistics). The result indicates that the larger economy of scale possible with Depot approximately balances the added feedstock pre-processing costs in comparison to the Conventional Cases 1 and 2. Thus, at large biorefinery scales, advanced logistics Depot designs would be greatly preferred over conventional logistics Conventional designs from an economics perspective, because of consistent feedstock specifications and reduced feedstock supply risk.

In contrast to process economics, marked differences in environmental sustainability are observed between conventional logistics Conventional and advanced logistics Depot design concepts in terms of life-cycle GWP. Specifically, when using natural gas as the drying fuel for Advanced

Depot, the life-cycle GWP is approximately three times greater than that for Conventional logistics. Approximately 15% of this is attributed to differences in feedstock resources used for both Conventional and Advanced Depot case studies. Specifically, the Advanced Depot scenarios use ~50% SRWC feedstock, while Conventional does not incorporate any SRWC into the feedstock mix because demand is met by cheaper resources. The balance of the difference is attributed to the fossil-fuel-based natural gas used to dry the feedstock in Advanced Depot pre-processing. It is important to note that with modest efficiency improvements to Advanced Depot power and drying usages or by using a renewable drying fuel (such as bark), the Advanced Depot scenarios can exceed the 60% threshold for life-cycle GHG reductions, approaching an 82–87% reduction in life-cycle GHG reductions in comparison to those quantified for the Conventional scenarios. The water footprint is marginally larger for the Advanced Depot scenarios compared to the Conventional scenarios, and these differences are attributed mainly to the differences in the feedstock mixtures used in each case.

Acknowledgements

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Matthew H Langholtz

Dr. Matthew Langholtz is a Natural Resource Economist in the Bioenergy Group at Oak Ridge National Laboratory. He is principle investigator (PI) of the Resource Analysis Project of the Bioenergy Group at Oak Ridge National Lab, as well as the Short-Rotation Woody Crop Sustainability project. His research interests include biomass resource economics, short-rotation woody crops, and bioenergy from forest resources. He has worked on valuation of non-market externalities, and developed biomass supply curves for commercial projects, the South, and the United States.

Eric Tan

Dr. Eric Tan is a Senior Research Engineer in the Biorefinery Analysis Group of the National Bioenergy Center at the National Renewable National Laboratory (NREL). His research interests include the process design, economics, and sustainability for conversion of lignocellulosic biomass to biofuels with particular emphasis on the application of techno-economic analysis and life cycle assessment methods. He also has broad experience in chemically reacting flow simulation and heterogeneous catalysis.

Jacob J. Jacobson

Mr. Jacobson is a researcher from the Idaho National Laboratory. He has a diverse background in systems analysis, system dynamics, statistical consulting, software development, and project management. His work has been in the development and analysis of decision support systems to evaluate policy options and business risks of complex energy and environmental systems. His recent work has been in the area of analysis of biomass feedstock logistics.

David Muth

Dr David Muth is the Senior Vice President for Analytics at Praxik, LLC. Prior to co-founding Praxik in 2013, David led a research team at Idaho National Laboratory, working on bioenergy feedstock production and logistics analysis. He led the development of open-source environmental process modeling tools to support the design and assessment of bioenergy landscapes. These open-source tools are used by the US Department of Energy and its research partners to design sustainable and economically viable bioenergy feedstock production systems. Praxik is building upon these tools to deploy its commercial agronomic decision services products. He received his PhD in Mechanical Engineering from Iowa State University in 2012.

Amy Schwab

Ms. Schwab is the systems integration lead on assignment with the US Department of Energy's Bioenergy Technologies Office on detail from the National Renewable Energy Laboratory. She has a diverse background in agriculture, risk management, consulting, and project management. Her work has been in the design and integration of human systems to deliver breakthrough innovation and invention. Her recent work has been in the area of systems-level planning, analysis, and program integration across the bioenergy supply chain.

May Wu

Dr. May Wu leads the Water Analysis Team in Energy Systems Division, Argonne National Laboratory and PI of water sustainability analysis projects supported by Bioenergy Technologies Office at Department of Energy. Her current research interests are in the area of water use, water quality, and water availability associated with development of biofuel, conventional fuel, electricity, and emerging fuels and LCA. Dr. Wu has been leading efforts of developing spatially explicit water footprint tool and watershed modeling for Mississippi River Basin using SWAT and HSPF. Dr. Wu served as an expert advisor to the Water Working Group of the Council on Sustainable Biomass Production and supported National Biomass R&D Board's Sustainability Interagency Working Group. May has a diverse background in the area of industry water treatment, wastewater treatment, online monitoring of anaerobic biological process, microbial induced corrosion, fermentation, and membrane separation through previous appoints at Nalco and postdoctoral work at Argonne National Laboratory. Dr. Wu holds several U.S. patents, 40+ publications, and a dual Ph.D. in Environmental Engineering and Environmental Toxicology from Michigan State University.

Andrew Argo

Dr. Andrew Argo, formerly with the system integration group at the National Renewable Energy Laboratory, is a Senior Process Development Engineer at Sundrop Fuels. His work supports the development, scale up, and commercialization of advanced biofuels.

Craig C. Brandt

Mr. Brandt is a research staff member at Oak Ridge National Laboratory. He has a diverse background in data management, statistics, and software development. His research has focused on the application of advanced data analysis techniques to a variety of problems in bioremediation, biogeochemical cycling and resource analysis.

Kara G. Cafferty

Kara G. Cafferty is a Research Engineer and Analyst at the Idaho National Laboratory. Her research interests include supply system design, economics, and environmental sustainability for the delivery of biomass to produce hydrocarbon fuels. She has a diverse background in systems analysis, techno-economic analysis, geo-statistical analysis, and life cycle assessments.

Yi-Wen Chiu

Dr. Yi-Wen Chiu is a postdoctoral appointee in the Energy System Division at the Argonne National Laboratory. As an interdisciplinary scientist, her main research focus is to understand the coupling and interaction of human and natural systems by applying integrated modeling tools. She has been involved in research related to water system dynamics, water footprint and water-energy nexus with broad interests related to scenario analysis and life cycle assessment. She also participates in several studies aiming to advance biofuels by determining the feasible pathways of achieving water sustainability goals. Dr. Chiu holds a PhD degree in Water Resources Science from the University of Minnesota.

Abhijit Dutta

Mr. Dutta is a researcher at the National Renewable Energy Laboratory. His current work is focused on biorefinery analysis of the thermochemical conversion of biomass. He was previously employed at Aspen Technology and Bloom Energy where he worked in the areas of process simulation and process control.

Laurence M Eaton

Laurence Eaton is a Research Scientist at the Oak Ridge National Laboratory in the Bioenergy Resource and Engineering Systems Group of the Environmental Sciences Division. An economist by training, he conducts research to support bioenergy forecasting and analysis using economic land use models and Geographic Information Science. He participates in interdisciplinary Resource Assessment activities to support the efficient and sustainable supply of agricultural and forestry resources for commercial domestic bioenergy and bioproducts markets. He has worked in the area of applied microeconomics as it relates to bioenergy firm input decisions and the valuation of environmental goods and ecological services.

Erin Searcy

Dr. Erin Searcy is currently supporting the Department of Energy in Washington, DC as an M&O from the Idaho National Laboratory (INL). After completing her BS and MS degrees in Engineering, Erin worked as an Environmental Engineering consultant, primarily conducting environmental impact assessments and air emissions inventories. While completing her Ph. D. in Mechanical Engineering at the University of Alberta, Erin acted as a sessional professor in the Faculty of Engineering. Erin authored five peer-reviewed publications on her thesis, which studied the economics and GHG emissions related to using biomass as a feedstock for biopower and biofuels. Erin joined INL in 2008, where she worked on a variety of biomass feedstock logistics projects, primarily as a techno economic analyst.