Perspective

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Strategic supply system design – a holistic evaluation of operational and production cost for a biorefinery supply chain

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Abstract: Pioneer cellulosic biorefineries across the United States rely on a conventional feedstock supply system based on one-year contracts with local growers, who harvest, locally store, and deliver feedstock in low-density format to the conversion facility. While the conventional system is designed for high biomass yield areas, pilot scale operations have experienced feedstock supply shortages and price volatilities due to reduced harvests and competition from other industries. Regional supply dependency and the inability to actively manage feedstock stability and quality, provide operational risks to the biorefinery, which translate into higher investment risk. The advanced feedstock supply system based on a network of depots can mitigate many of these risks and enable wider supply system benefits. This paper compares the two concepts from a system-level perspective beyond mere logistic costs. It shows that while processing operations at the depot increase feedstock supply costs initially, they enable wider system benefits including supply risk reduction (leading to lower interest rates on loans), industry scale-up, conversion yield improvements, and reduced handling equipment and storage costs at the biorefinery. When translating these benefits into cost reductions per liter of gasoline equivalent (LGE), we find that total cost reductions between –$0.46 to –$0.21 per LGE for biochemical and –$0.32 to –$0.12 per LGE for thermochemical conversion pathways are possible. Naturally, these system level benefits will differ between individual actors along the feedstock supply chain. Further research is required with respect to depot sizing, location, and ownership structures. Published 2015. This article is a U.S. Government work and is in the public domain in the USA. Biofuels, Bioproducts and Biorefining published by Society of Industrial Chemistry and John Wiley & Sons Ltd.

Supporting information may be found in the online version of this article.

Keywords: biorefinery; feedstock logistics; depot; bioeconomy; biofuel; advanced feedstock supply system

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Introduction

The United States (US) promote advanced biofuel production via several initiatives, such as the Renewable Fuel Standard (RFS2) and the US Department of Agriculture's Biorefinery Assistance Program.[1] Yet the industry has not experienced substantial growth. In 2014, three new biorefineries (POET in Emmetsburg, Iowa; DuPont in Nevada, Iowa; Abengoa in Hugoton, Kansas) started operation, using herbaceous residue materials as their primary feedstock. Even with these new additions, cellulosic biofuel production has lagged significantly behind predictions and the US Environmental Protection Agency (EPA) has reduced the volume of cellulosic biofuel required for compliance with the RFS2 every year to date.[2] The question that begs to be answered is: 'What is holding back the industry?'

Currently, the cellulosic biofuel industry relies on a vertically integrated feedstock supply system, hereafter referred to as the conventional system, where feedstock is procured through contracts with local growers, harvested, locally stored, and delivered in low-density format to the nearby conversion facility (Fig. 1). These conventional systems were designed to support traditional agricultural and forestry industries. It is worth noting that the cellulosic biofuel industry is in its infancy, currently producing fewer than 1 million gallons of cellulosic ethanol per year, and current practice may not represent that of a fully evolved industry. The conventional system has been demonstrated to work in a local supply context within high yield regions (e.g., the US Corn Belt or southeast forest lands). However, scaling up the biorefinery industry will require increasing feedstock volumes at decreasing costs. The strategic goal of the US Department of Energy's Bioenergy Technologies Office (BETO) is to meet a US$88 dry metric tonne^{-1} (DMT) delivered on-spec feedstock cost at the throat of the conversion facility (including grower payment and logistics) in support of reaching a $0.79* per liter of gasoline equivalent (LGE) delivered fuel target by 2022.[3] Targets are generally iterated between advancements in feedstock logistics and the development of more robust conversion systems. But it remains unclear if a conventional system will allow for the current goal to be met.

Different analyses[4-7] have shown that the conventional system fails to meet this supply cost target outside of highly productive regions and could encounter issues even in highly productive regions in some years due to inclement weather (e.g., drought, flood, heavy moisture during harvest, etc.). These supply uncertainties increase risks, which could limit the biorefinery concept from being broadly implemented.

*If not otherwise mentioned, all currency is in US$$_{2011}$$.

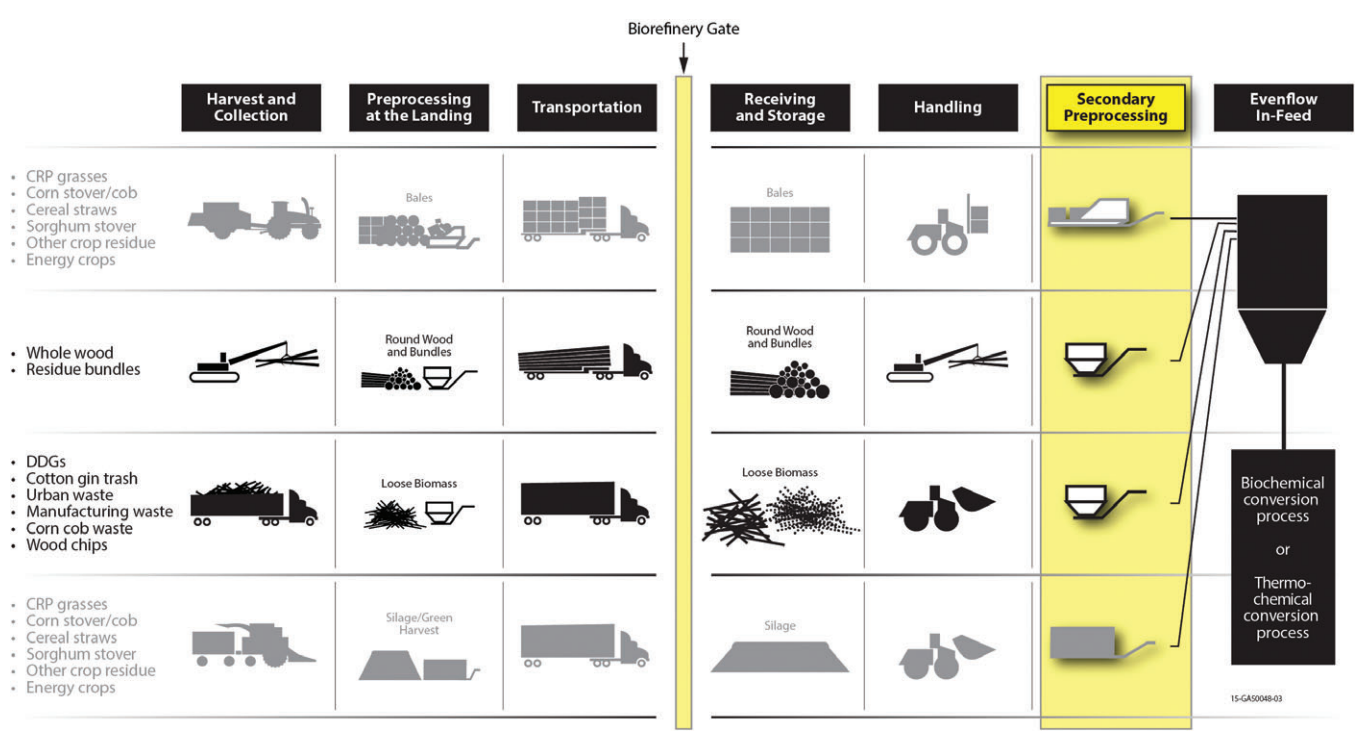

Figure 1. Schematic design of the conventional feedstock supply system.

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The advanced uniform feedstock design system,[5] hereinafter referred to as the advanced system, introduces methods to reduce feedstock quantity, price, and quality supply uncertainties. It is based on a network of distributed biomass processing centers, so-called depots, which use one or several biomass types to generate uniform format feedstock 'commodities' (Fig. 2). These 'commodities' are intermediates with consistent physical and chemical characteristics that meet conversion quality targets and at the same time leverage the spatial and temporal variability in supply quantity and costs by improving flowability, transportability (bulk density), and stability/storability (dry matter loss reduction).

A fundamental difference between the two supply systems is that the conventional system relies on existing technologies and agri-business systems to supply biomass feedstocks to pioneer biorefineries and requires biorefineries to adapt to the diversity of the feedstock. On the other hand, the advanced system emulates the current grain commodity supply system, which manages crop diversity at the point of harvest and at the storage elevator, allowing subsequent supply system infrastructure to be similar for all biomass resources.[5,8]

Previous comparisons between the two supply systems were focused on logistic costs.[4,7] They concluded that the higher initial investments into processing costs (depots) and more transportation activities increase average logistic costs, making a conventional system appear more beneficial. At the same time, they also acknowledged that advanced systems entail lower cost variability and would enable other benefits, e.g., economies of scale at the biorefinery.

Building on these analyses, the goal of this paper is to compare the two supply systems from a system level perspective, i.e., beyond mere logistic costs, and quantify the risks and benefits of each system with respect to the biorefinery's biofuel production costs. The paper does not look into the impact of inconsistent federal policies or overall market risk. The comparison explicitly addresses four major cost reductions that can be achieved across the value chain by applying the depot concept: feedstock supply risk mitigation, biorefinery economies of scale, biorefinery conversion yield improvements, and biorefinery equipment reduction (i.e., capital and operational costs reductions).

Methods and scenarios

This analysis calculates and compares the full costs of a conventional system against an advanced supply system. All comparisons are translated into an LGE basis to reflect the impact on the BETO target of $0.79 per LGE. The paper integrates the work of two US national laboratories specializing in techno-economic analyses of feedstock logistics (Idaho National Laboratory - INL) and

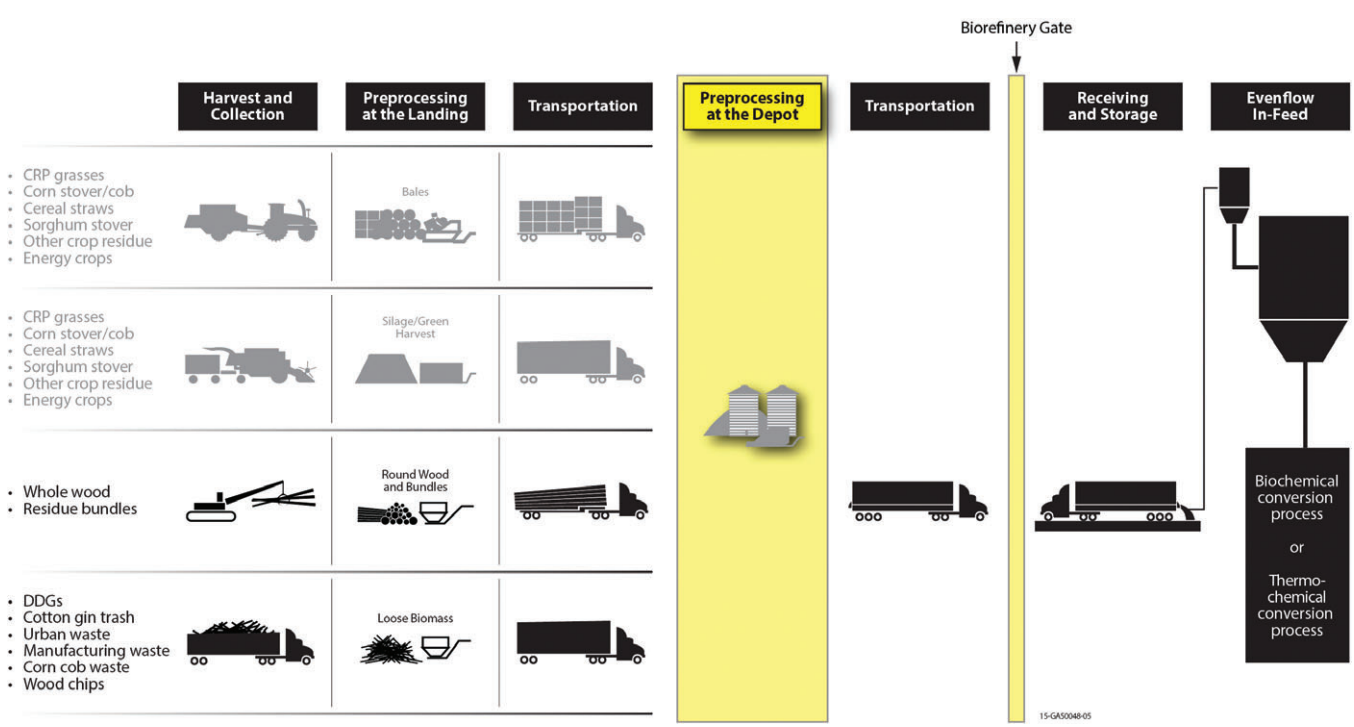

Figure 2. Schematic design of the advanced feedstock supply system.

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biorefinery conversion pathways (National Renewable Energy Laboratory - NREL). The integration provides a system-level perspective, while taking detailed specifics of each sub-system into account. INL's work builds on empirical feedstock characterization,[9] respective cost evaluations, and logistic system analyses via the Biomass Logistics Model (see Cafferty *et al.*[10] for details). NREL's techno-economic biorefinery work is based on the AspenPlus framework. Both INL's and NREL's analyses were developed under the instruction of BETO as a basis for setting technical targets and cost of production goals in order to assess technology progress toward producing and validating processes at an increasing scale and integration for biomass to biofuels/products. The analyses were based on best available information and current projections for n^{th}-plant systems.

The underlying feedstock logistics are extensively described in INL's design reports for the biochemical and thermochemical conversion pathways.[11,12] Processing in the advanced supply system has been updated with a recent techno-economic comparison of different biomass depot configurations.[13]

The conversion system baselines for biochemical and thermochemical processes are shown in Table 1. Their respective minimum fuel selling prices (MFSP) to give a 10% after-tax internal rate of return were calculated using a standard discounted cash flow rate of return analysis and the financial assumptions outlined in NREL design reports.[14,15]

Techno-economic analyses (TEA) for the biochemical process of making ethanol from corn stover were performed by scaling the biochemical process design model for corn stover that was developed at NREL.[15] For this study, we assumed that the feedstock convertibility is the same in the conventional and advanced system. All conversion data are based on those reported for corn stover, using the feedstock composition data displayed in Table 2.

Similarly, TEA for the thermochemical process of making ethanol from woody biomass were performed by scaling the thermochemical pathway by indirect gasification and mixed alcohol synthesis process design model that was developed at NREL.[14] The process design was adjusted to accommodate different feedstock moisture and ash contents. The biorefinery was scaled using equipment-specific scaling factors; when there is an upper limit on size (e.g., gasifier and alcohol synthesis reactor), multipliers were used. For this study, we assumed that the feedstock convertibility is the same for similar feedstock types (i.e., logging residues, pulpwood, and short-rotation woody crops) as well as between the feedstock supply systems. All conversion data are based on those reported for pine[14] using the feedstock composition data displayed in Table 3. In addition to differentiating between ash contents, the woody biomass selection was also distinguished by a low (30%) and high (50%) moisture level.

Results

Operational risks

Biomass is highly variable – both spatially and temporally.[9] Changing yields, inclement weather, competition, and other factors make biomass a highly vulnerable resource for a supply system that has fairly constant demand. Biomass characteristics vary as a function of field characteristics such as soil type, slope, climate, maturity, and crop management practices.[16] These resource uncertainties are

Table 1. Baseline parameters in 2011 US$ values.

Baselines	Biochemical	Thermochemical
Biorefinery capacity (daily feedstock demand)	2,000 dry tonnes	2,000 dry tonnes
Average feedstock to fuel conversion rate	329 liters/dry tonne	392 liters/dry tonne
Annual production volume	238,935,079 liters/year	284,662,832 liters/year
Total Capital Investment (TCI) (US$)	$ 458,300,000	$ 575,042,802
Loan amount (60% of TCI) (US$)	$ 274,980,000	$ 345,025,681
Equity Percent of Total Investment	40%	40%
Loan period	10 years	10 years
Annual loan interest rate	8%	8%
Internal rate of Return (after tax)	10%	10%
Break-even price ($/liter) – LGE	$ 1.07	$ 0.92
Minimum Fuel Selling Price ($/liter)	$ 0.71	$ 0.60
BETO target by 2022 ($/liter) – LGE	$ 0.79	$ 0.79

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Table 2. Corn stover compositions applied in the analysis.

	Conventional (dry wt %)	Advanced (dry wt %)
Glucan	34.50	36.85
Xylan	19.62	20.96
Lignin	15.98	17.07
Ash*	11.01	4.94
Acetate	1.24	1.32
Protein	2.12	2.27
Extractives	10.02	10.71
Arabinan	2.97	3.17
Galactan	1.60	1.71
Mannan	0.41	0.44
Sucrose	0.53	0.56
Total structural carbohydrates	**59.10**	**63.13**
Moisture (wet wt%)	26.00	9.00

* The reduction in ash in the advanced system is a result of advanced harvest and collection practices and results in a higher proportion of all other elements.

Table 3. Woody biomass composition applied in the analysis.

Component	Weight (dry wt%)	
	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

risks, which impact access to and terms of finance, creating a barrier for new biorefineries to enter the market. Investment risks increases the cost of capital as investors in bonds and equity require a greater risk premium, directly impacting the weighted average costs of capital (WACC). Feedstock quantity and price variations are commonly identified as a key sensitivity to break-even in biorefinery investments.[17]

The advanced system reduces the variability of feedstock supply by allowing wider sourcing ranges. Advanced systems mitigate supply risks associated with feedstock outages, such as those associated with local weather, pests, and diseases (Fig. 3). For example, Hansen *et al.*[18] found that extending the supply radius could reduce feedstock supply risk by as much as 58% because of the reduction in supply uncertainty. Since feedstocks are processed into commodity-type intermediates in an advanced system, the biorefinery should also be less vulnerable to price volatility and may not need to contract directly with feedstock producers. Mitigating the feedstock supply uncertainty via an advanced system will make the biorefinery investment less risky, which will be reflected in the annual interest rate for the biorefinery loan.

NREL design reports assume an 8% interest rate over the course of a 10-year loan for 60% of the total capital investment (TCI) for a biochemical or thermochemical biorefinery based on an advanced system.[14,15] Current biorefinery investments, relying on a conventional feedstock supply system, are assumed to face much higher interest rates due to the early industry stage and opportunity costs for investors (to invest in other, more lucrative endeavors).

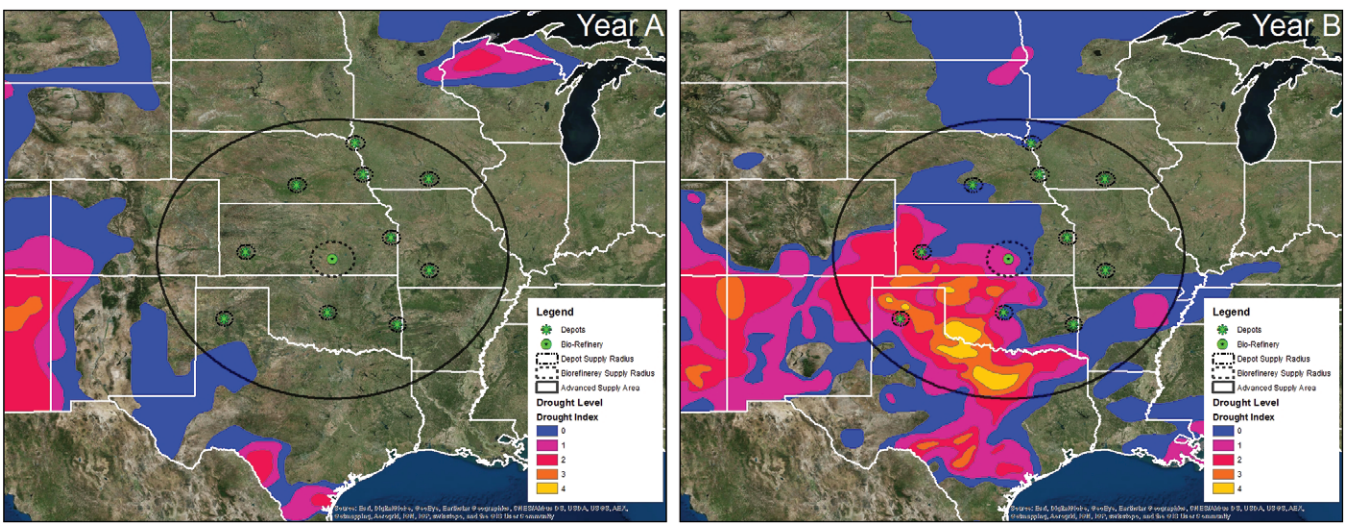

Figure 3. Impact of drought levels (from 0:low to 4:very high) on an example biorefinery sourcing radius in a conventional (dotted circle) and advanced supply system (wider circle including depot operations) over two years.[26]

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n^{th}-plant assumptions, including an 8% interest rate, are used to create a harmonized baseline for financial metrics across TEA models, but are generally seen as optimistic.[19] A mature industry, with limited feedstock supply risks due to an advanced system is likely to achieve a lower interest rate than current, conventional system based biorefinery investments. Figure 4 compares the total annual interest paid for biorefinery investments over various interest rates and the respective impact per LGE produced.

For this comparison, it is less important to identify and compare exact interest rates for current, conventional *vs.* advanced systems. It is more important to observe the trend. Interest rate reductions of –2% to –15% across a range of 8% to 30% annual interest would enable cost savings per LGE between $0.01 and $0.15 (Table 4).

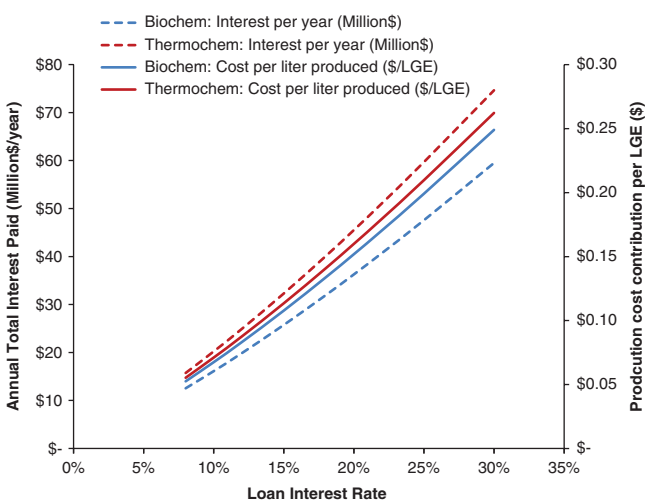

Figure 4. Annual total interest for biorefinery investments of 2,000 DMT day^{-1} facilities across varying interest rates and their respective impact on the production costs per liter of gasoline equivalent (LGE).

Table 4. Impact of interest rate reductions between calculated impacts per liter of gasoline equivalent (LGE) for interest rates in the range of 8–30% for a 10-year loan for 60% of the TCI for a biochemical or thermochemical conversion facility sized at 2,000 DMT day^{-1}.

Interest rate reduction	Reduction in unit production costs ($/LGE)
–2%	–0.02 to –0.01
–3%	–0.03 to –0.02
–5%	–0.05 to –0.04
–10%	–0.10 to –0.08
–15%	–0.15 to –0.13

Economies of scale

Biorefinery size has been an area of debate and will have a significant influence on the biofuel production costs. Aden *et al.*[20] postulated that biorefinery sizes of at least 2,000 DMT day^{-1} capacity, reflecting a collection radius of 80 km (50 miles) in a high-yield corn production area, are required to reach a competitive MFSP. More recent studies indicate that in order to achieve conversion process economics, facilities of capacities above 5,000 DMT day^{-1} are required.[4,7,21]

In the conventional system, where corn stover bales are trucked to the biorefinery, a 5,000 DMT day^{-1} facility implies a delivery of one truck every 3 min.[22] This represents a key system limitation in terms of overall truck traffic, a constriction largely linked to loading and unloading times, but also traffic congestion and potentially noise pollution. Additionally, logistic costs in the conventional system increase linearly as either biorefinery capacity or feedstock collection radius increase. With the advanced systems, the collection radius does increase costs but not as significantly as with a conventional supply system.[7] Thus, biorefineries with capacities in excess of 5,000 DMT day^{-1} are only possible with advanced systems due to transportation limitations and cost-efficient feedstock availability.[4] Table 5 compares cost reductions achieved per unit produced for scaling up biorefineries beyond 2,000 DMT daily feedstock demand, supplied via an advanced system.

Feedstock quality

Feedstock quality affects the performance of the biofuel production chain in multiple ways. Most importantly, it defines pretreatment efficacy, machine wear, contract volume, disposal, and conversion performance. For instance, moisture content, subject to a variety of components such as weather at time of harvest, influences grinding energy and equipment wear (Fig. S1). The conventional system has no methods for actively addressing moisture. In fact, dry matter loss (DML) or feedstock shrinkage is a prominent constraint to consistent feedstock quality within a conventional system. The key influencing parameters to DML are moisture content at the time of harvest and storage type.[9] Post-harvest moisture levels are typically 15–20% for the US Corn Belt region, but can reach over 50%.[5,9] Exposures to weather and temperature variations in storage drive DML[†] and feedstock ash content; which in turn influence

[†]In the conventional supply system, where corn stover bales are either 'covered on ground' or 'stacked on improved surface', DML ranges between 2.5% and 23% with an average of 13% (see Hess *et al.*[5] for details).

Table 5. Economies of scale achieved per liter of gasoline equivalent (LGE) when increasing biorefinery size beyond 2,000 DMT capacity per day.

Capacity increase (DMT per day)	From 2,000 to 5,000	From 2,000 to 7,500	From 2,000 to 10,000
Thermochemical conversion ($/LGE)	–0.11	–0.15 to –0.14	–0.17 to –0.16
Biochemical conversion ($/LGE)	–0.13	–0.16	–0.19

conversion yields (Fig. S2). Pelleting as part of the depot concept reduces moisture content and improves storability, thus preventing DML and the build-up of ash. For the purpose of this study, DML was considered negligible in the conventional system, acknowledging that this is a very conservative approach.

Feedstock ash content typically varies between 3% and 15% but can reach up to 40% (Fig. 5). Humbird *et al.*[15] calculate biorefinery disposal costs of inherent feedstock ash at $0.01 of the $0.87 LGE, assuming a 5 wt% physiological ash[‡] content in corn stover in the biochemical design case. Kenney *et al.*[9] argue that this neglects introduced, non-physiological ash. They show that disposal costs for the biorefinery double and triple at 6.3% and 12.1% soil contamination levels, respectively. Figure 5 was derived by applying these cost calculations for ash disposal plus replacement costs for the lost material. Depot systems can reduce ash through mechanical and chemical processing. However, the key is to off-set the processing costs with improved economics at the biorefinery. Our comparison does not account for marketing removed ash, for example in products like soil amendments and fertilizers.

Ash increases the neutralization capacity of corn stover during dilute-acid pretreatment, which reduces conversion yields.[23] An increase in non-carbohydrate constituent also reduces the proportion of structural carbohydrates present. While carbohydrate content is less critical for thermochemical conversion pathways, biochemical conversion processes are particularly sensitive, specifically to the structural sugars content of the feedstock material.[9] The ratio of C5/C6 sugars and their accessibility are also relevant in the optimization of pretreatment and fermentation conditions. Evaluations of cellulosic ethanol production costs from corn stover show that ethanol yield varies linearly with structural sugar content.[24] Figure 6 shows an initial calculation of sugar carbohydrate content in relation to LGE produced (based on Kennedy *et al.*,[9] Ruth and Thomas,[24] and Templeton *et al.* [25])

As shown in Table 6, conversion yields (per unit mass feedstock) are higher for homogeneous feedstock that meets specifications over non-processed feedstock with higher ash content and therefore lower structural sugar content. All ash reduction in this study can be attributed to improved harvest and collection practices, which result in lower ash entrainment. Although there are additional

‡Feedstock ash comes in several forms including structural or physiological ash, internal to the plant, and external ash such as soil. External ash is easier to remove (e.g., via washing) and control (e.g., via biomass selection and operational improvements such as single-pass harvesting). Physiological ash requires extensive mechanical or chemical processes to remove.

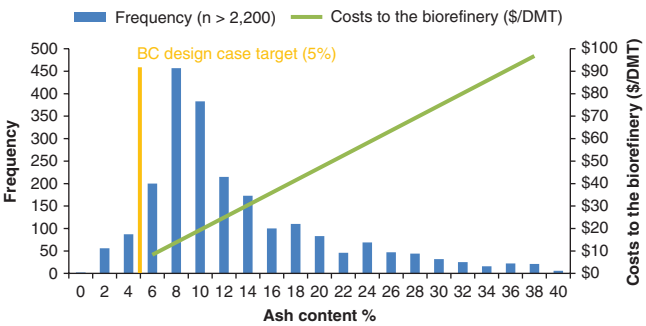

Figure 5. Ash removal, disposal, and feedstock replacement costs to the biorefinery depending on ash content. Underlying data for biomass types from Kenney *et al.*[9] Current biochemical (BC) conversion design case target is 5%. Ash costs include replacement and disposal (roughly $2.76/DMT/%ash above 5%). Costs for machine wear are not included.

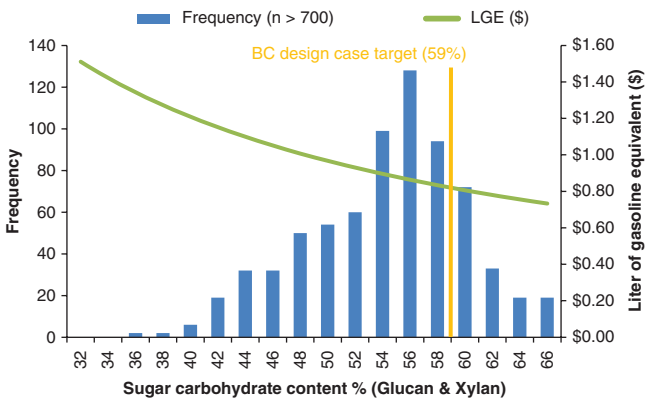

Figure 6. LGE in relation to initial sugar carbohydrate content. Current biochemical (BC) conversion design case target is 59%.

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Table 6. Mixed alcohol yields in liter per dry metric tonne (DMT) as a function of processing levels for different feedstock qualities and the respective impact per unit produced in US$ per liter of gasoline equivalent (LGE).

Conventional			Advanced			Cost reduction ($/LGE)
Ash content	Moisture content	Conversion yield (liter/DMT)	Ash content	Moisture content	Conversion yield (liter/DMT)	
Thermochem						
0.92%	30%	355.29	0.92%	9%	372.74	–$0.04
0.92%	50%	316.01	0.92%	9%	372.74	–$0.12
7%	30%	322.87	7%	9%	341.47	–$0.04
7%	50%	283.59	7%	9%	341.47	–$0.13
Biochem						
5%	26%	351.72	5%	9%	379.01	–$0.06
7%	26%	344.25	5%	9%	379.01	–$0.07
9%	26%	336.82	5%	9%	379.01	–$0.09
11%	26%	329.31	5%	9%	379.01	–$0.10
13%	26%	321.84	5%	9%	379.01	–$0.12
15%	26%	314.41	5%	9%	379.01	–$0.14

technologies to reduce ash, which could be incorporated in the depot, e.g., blending/formulation, leaching, hot water or acid washing.

Handling, storage, and in-feed improvements

Depots take care of feedstock storage and processing operations that would usually need to be done at the biorefinery in a conventional system. Outsourcing these steps reduces capital and operational expenses of the biorefinery. Also, industrial operations perform best when process inputs are consistent and predictable. Uniform particle morphology (i.e., feedstock size and shape) and greater (bulk) density improves flowability and feeding properties, allowing the use of standardized, high-efficiency, high-volume handling and transport systems and equipment. Kenney *et al.*[9] estimate that feeding and handling problems due to changing and uncertain bulk solids properties can reduce plant throughputs up to 50%, significantly influencing biorefinery efficiency and economics.

Converting raw biomass into densified, flowable material will improve the storage costs, transportation costs, handling and receiving and feeding costs. Processing at the depot eliminates bale storage, handling, and grinding at the biorefinery. This also reduces the footprint and environmental impacts at the biorefinery, including fire hazards, rodent infestation, and localized odors normally associated with large-scale storage of non-aerobically stable feedstock such as corn stover bales. In situations where biorefineries source multiple feedstock types or forms, savings are even higher since the equipment for handling and processing are eliminated for all feedstock types and forms (e.g., round corn-stover bales, square wheatstraw bales, or woody biomass).

Table 7 outlines the costs associated with handling raw feedstock at the biorefinery in the conventional system (based on INL[11,12]). The total feedstock costs per pathway are translated into relative handling costs with respect to the $88/DMT cost target and the impact per LGE. The processing steps accounted for in Table 7 are associated with a common pelleting/densification depot. Additional processing to manage feedstock quality, for example with an Ammonia Fiber Expansion (AFEX™) pretreatment process, additionally eliminates the necessity

Table 7. Handling costs at the biorefinery in a conventional supply system and savings achieved by outsourcing these steps to a depot.

	Biochemical	Thermochemical
Total costs for handling at the biorefinery ($/DMT)	$48.06	$24.92
Share of total supply cost	31%	22%
In relation to US$88 per DMT supply cost target	$27.52	$19.52
Costs per gal ($/MFSP)	$0.08	$0.05
Savings ($/LGE)	–$0.13	–$0.08

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for pretreatment and neutralization/conditioning at the biorefinery, reducing biorefinery TCI of $36.8 million and achieving an LGE reduction of –$0.11.

With respect to storage, current industry practice (e.g., at POET/DSM) is to have at least a 14 day buffer of baled corn stover. A mature industry is expected to rely only on a 72-hour storage buffer at the biorefinery.[17] Table 8 compares the storage types and costs for these two configurations for a biorefinery of 2,000 DMT day^{-1} capacity. It shows that the advanced system is able to reduce costs associated with a more efficient storage (and associated handling) by $0.038 per LGE.

Comparison

Table 9 summarizes selected system benefits for the different conversion pathways (interest rate reductions are kept between –2% to –5% for illustrative purposes). We compare them to the annual depot network costs per LGE where 10 depots with an individual capacity of 200 DMT day^{-1} are required to satisfy the respective demand for a 2,000 DMT day^{-1} size biorefinery. Each depot is given a lifetime of 10 years. The depot costs are based on a techno-economic analysis comparing different concepts.[13] We see that the selected system benefits exceed the additional costs associated with the depot concept.

Table 8. Storage sizes, type, and cost comparison.

	Conventional system	Advanced system
Storage buffer	14 days	3 days
Storage type	Bale storage	Bin storage
Costs per DMT and day	$1.24	$1.60
Costs per day	$34,751	$9,585
Costs per year	$12,684,144	$3,498,456
Costs per LGE produced	$0.053	$0.015
Savings per LGE produced	n/a	–$0.038

Discussion

Whereas depots can take on many forms and sizes, the basic premise is that they will be located near the point of harvest and will involve feedstock densification and/or stabilization. Their eventual configuration and location will largely depend on the end-use market (e.g., conversion technology), region, and feedstocks available. The minimum technical requirements for a depot to achieve the outlined system benefits include particle size reduction, moisture mitigation, and densification. Additional operations, for example leaching, chemical treatment, or washing, may be added to specifically address feedstock quality requirements for improved downstream biorefinery operation.

Depots are currently not utilized by the cellulosic biofuel industry but their appearance in the system is expected to occur organically as the industry adds processing equipment and storage to existing biorefinery infrastructure to help the

Table 9. Comparison of selected supply system benefits and feedstock processing costs at the depot (in $/LGE).

	Biochemical conversion plus depot processing	Thermochemical conversion plus depot processing	Biochemical conversion plus AFEX pretreatment at the depot
Selected supply system benefits			
Interest rate reduction of –2% to –5%	–$0.05 to –$0.01	–$0.05 to –$0.02	–$0.05 to –$0.01
Economies of scale (>2,000 DMT day^{-1})	–$0.19 to –$0.13	–$0.17 to –$0.11	–$0.19 to –$0.13
Conversion yield improvements	–$0.14 to –$0.06	–$0.13 to –$0.04	–$0.14 to –$0.06
Reduced storage equipment at the biorefinery	–$0.04	–$0.04	–$0.04
Reduced handling equipment at the biorefinery	–$0.13	–$0.08	–$0.13
Reduced pretreatment equipment at the biorefinery	*(not applicable)*	*(not applicable)*	–$0.11
SUM benefits	**–$0.54 to –$0.36**	**–$0.47 to –$0.27**	**–$0.65 to –$0.48**
Feedstock processing costs at the depot	*$0.09 to $0.15*	*$0.15*	*$0.19*
TOTAL	**–$0.45 to –$0.21**	**–$0.32 to –$0.12**	**–$0.46 to –$0.29**

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Table 10. Overview of potential challenges and opportunities linked to the implementation of the depot concept.

Challenges/Opportunities	
Ownership	The ownership and organizational structure behind a depot directly influences the business strategy/behavior (including contractual issues between a depot and biorefineries, etc.)
Sizing and location	The initial depot concept entails distributed entities located in proximity to the biomass source; potentially followed by connections to terminals where feedstock is consolidated prior to further (bulk) distribution. Depot size will be defined by the sourcing radius and the respective biomass availability (year-round). Depot size influences economies of scale. The resulting question is whether optimal depot sizes exist and to what extent economies of scale can be utilized.
Single- *vs*. multi-feedstock	Feedstock availability/seasonality will influence the depot size and technical layout. To be operating all year, feedstock flexibility will be key. Potentially, depots may need to rely on field-storage options.
Processing intensity	The level of processing intensity at the depot depends on a number of factors including the typical markets it will sell to, size (economies of scale), feedstock availability, access to capital, business strategy, etc.
Waste streams and treatment	Depending on the involved technical processes, depots may generate waste streams/effluents that require treatment. The economic viability of a waste water treatment facility at a depot directly relates to depot size and profit. Thus, it appears that only larger, highly specialized depots would be able to compensate for such an investment. Depots as well as biorefinery feedstock reception stations will create solid waste (e.g., broken bales). Creating this organic material closer to the field creates options for reuse and reduction of transport costs to do so. Also, it may serve as a second income stream for the depot.
Permitting	The U.S. Standard Industrial Classification (SIC) for biorefineries and depots may be similar and thus permit application would need to be combined if the depots are in a relative proximity to the refinery. The permit application determines, e.g., limits for air and water emissions, etc.

biorefinery buffer supply volume and feedstock price fluctuation. The equipment would essentially be located within or close to the compounds of the biorefinery.

In terms of organizational structure, the depot would – at first – probably be owned by the biorefinery. At a later stage, it may be outsourced and become an independent business entity. At that stage, different types of ownership become possible (e.g., farmer cooperatives) and the depot will have a requirement to be a self-sufficient, cost effective business entity. In contrast to biorefineries integrating upstream, depots may also originate from the farmer side when multiple producers ban together to take advantages of economies of scale or mitigate business risks.

The location of depots will likely be driven by the ownership profile (biorefinery *vs*. farmer cooperative) as well as the existing logistical infrastructure (e.g., rail lines, shipping terminals). It is also likely that, as quality becomes more uniform, the depot will be located further away from the biorefinery. This makes decentralized locations possible, also in low-yield areas. The key depot characteristics, in our view, influencing the transition period include ownership structures, location, and sizing decisions, which relate to specialized (single-feedstock) or flexible (multi-feedstock) depots. Table 10 provides an overview of the potential challenges and opportunities linked to the implementation of the depot concept.

Conclusions

While processing operations at the depot add costs to the feedstock supply system, they address many of the supply risks associated with the conventional system and create wider system benefits. We translated several of these benefits into cost reductions per LGE for the biorefinery operation. Supply risk reduction (leading to lower interest rates on loans), economies of scale, conversion yield improvements, and reduced handling equipment and storage at the biorefinery outweigh the processing costs involved in the depot operations. We find total cost reductions per LGE between –\$0.46 and –\$0.21 for biochemical and –\$0.32 and –\$0.12 for thermochemical conversion pathways. Naturally, these cost reductions appear on a systems level and may differ per individual stakeholder across the supply chain.

Depot systems, when matched with the appropriate mode of transportation, could help reduce temporal and spatial biomass variability and allow access to greater quantities of sustainable biomass (including stranded resources) within a cost target by decoupling the biorefinery from feedstock location. Reducing profitability risks could also help leverage the reluctance from the investment community to invest in larger facilities, enabling production economies of scale. The variability of feedstock supply to biorefineries is recognized as an investment risk by financial institutions. Reducing the variability of feedstock supply will reduce

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associated project risks, which will be reflected in the annual percentage rate for financing biorefineries. Also, depots will reduce the handling equipment (for raw biomass in various formats) at the biorefinery, improve in-feed operations and thus reduce capital and operating costs. This should further reduce investment risks. While this comparison provides a first-of-a-kind holistic supply system perspective, future research is needed with respect to depot sizing, location, and ownership structures.

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