Scale Sensitivity of Ethanol Production via Consolidated Bioprocessing with Consideration of Feedstock Cost

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ABSTRACT

We examine feedstock cost and minimum selling price for ethanol production from corn stover as a function of scale, stover yield and participation rate, and price incentives for two conversion technologies: a conventional Base Case featuring thermochemical pretreatment and added cellulase and an Advanced Case featuring consolidated bioprocessing with cotreatment. Delivered feedstock cost ranged from $85/Mg at small (10 million gallons/year) scale with high yield and participation rates to $124/Mg at large scale (60 million gallons/year) and low yield and participation rates. The minimum ethanol selling price (MESP) was approximately 2-fold lower for the Advanced Case compared to the Base Case. Payback period was several-fold lower for the Advanced Case compared to the Base Case, with increasing disparity at smaller scales, and was highly sensitive to ethanol price supports. For both C-CBP and the conventional processing paradigm, MESP decreased with increasing scale, indicating that the cost penalty due to higher feedstock transport distances is more than outweighed by lower capital costs. However, the cost penalty for operation at small scale, expressed in $/gallon ethanol, is lower for C-CBP than for the conventional paradigm by roughly 2-fold. Particularly for initial applications of C-CBP, we speculate that this cost penalty will likely be modest compared to anticipated benefits of small-scale operation such as increased opportunity to use existing infrastructure, easier plant siting and supply chain establishment, and lower total investment required.

INTRODUCTION:

Biologically-mediated events associated with lignocellulose conversion to ethanol – production of saccharolytic enzymes, feedstock deconstruction yielding soluble carbohydrates, fermentation of six-carbon sugars and fermentation of five-carbon sugars – can be implemented in a variety of configurations (Lynd et al., 2002). In consolidated bioprocessing (CBP), these steps occur in one integrated unit operation. Thermophilic, lignocellulose-fermenting bacteria have received the most attention for use in CBP and are substantially more effective than commercial cellulase at biomass deconstruction under controlled conditions ((Paye et al., 2016); (Lynd et al., 2022); (Holwerda et al., 2019)). Combined with milling during fermentation (cotreatment), consolidated bioprocessing with cotreatment, C-CBP, has potential to markedly reduce costs compared to the conventional processing paradigm (Lynd et al. 2017). Comparing an Advanced Case featuring C-CBP to a Base Case featuring thermochemical pretreatment and added fungal cellulase, Lynd et al. project C-CBP to have 8-fold shorter payback period and economic feasibility at 10-fold smaller scale ((Lynd et al., 2017); (Lynd et al., 2022)). Research-driven advances are, however, required to realize the cost reduction potential of C-CBP.

Prior work has considered higher feedstock costs due to increased transport distances in the form of delivered feedstock cost curves (Breechbill 2011, Haque 2014). Argo (2013) assessed the inclusion of feedstock logistics on the economics of cellulosic ethanol production using a conventional processing paradigm based on thermochemical pretreatment and fungal cellulase, resulting in the decrease of MESP with increasing scale. Motivated by the observation of Lynd et al. (2017) that the economic penalty for operation at decreasing scale is much smaller for C-CBP compared to the conventional processing paradigm, we report here analysis aimed at further exploring the scale dependence of C-CBP economics. Whereas the prior work of Lynd et al. (2017) analyzed the economies of scale for C-CBP assuming constant feedstock costs, here modify the Advanced Case of Lynd et al. (2017) to include scale-dependent feedstock costs and evaluate the extent to which this mitigates the cost penalty for small-scale operation. Comparison is made to the Base Case defined by Lynd et al., and results are presented in terms of the minimum ethanol selling price assuming both 100% equity or debt/equity financing.

METHODS:

Delivered Feedstock Cost

A Python model was developed to estimate the corn stover supply area and the costs for harvest, storage, and transport operations, which comprise feedstock cost. The model considered impacts of stover yield and grower participation rate to evaluate impacts of supply density on cost, as well as the inclusion of grower repayments to compensate for nutrient lost during stover harvest. A two-pass harvesting process of shredding then baling was used as considered in the 2016 Billion-ton report. (M. H. Langholtz et al., 2016) Three scenarios presented in Table 1 are intended to define reasonable low, medium, and high-density supply areas. Stover yield varied between 2 mg ha^{-1} (Scenario 1) and 6 mg ha^{-1} (Scenario 3), based on typical low and high harvest rates of corn stover field studies ((K. J. Shinners et al., 2007), (K. J. Shinners et al., 2012)). Assuming a location in central Iowa, the land area engaged in growing corn was 37.4 percent. The corn stover participation rate, defined as the percent of corn growers who also participate in harvesting corn stover was 30, 50, and 70% for scenarios 1, 2, and 3 respectively. The corn stover supply area, obtained by multiplying the corn production area times the corn stover participation, varied from 11 to 26 percent.

Table 1. Regional stover supply scenarios.

Scenario	Yield (Mg Ha^{-1})	Corn Production Area	Corn Stover Participation	Corn Stover Supply Area
(1) Low Yield Low Participation	2	37.4 %	30%	11.2%
(2) Medium Yield Medium Participation	4	37.4 %	50%	18.7%
(3) High Yield High Participation	6	37.4 %	70%	26.2%

The costs involved in harvesting, transporting, and processing corn stover, derived from prior studies, are shown in Table 2. The harvesting cost is a function of yield, and it is based on a two-pass harvesting system ((M. Langholtz et al., 2019); (K. J. Shinners et al., 2012)) where the first pass rakes the corn stover into windrows and the second pass bales the feedstock. The long-term storage cost was set at $14.83 per dry mg with an overall dry matter loss of 3 percent (D. Stauffer, personal communication, 2022). We assumed a hybrid storage system consisting of both pole barns to store half of the annual harvest and tarps to store the other half of the harvest. This requires temporary storage before grinding as well as material handling. The costs for unloading, temporary storage, and grinding have been estimated at $2.23, $2.16, and $19.29 per dry mg ((M. H. Langholtz et al., 2016)).

Table 2. Costs for stover harvest, storage and grinding.

Data	Value
Harvest cost at 2 Mg per Ha (a)	$35.29
Harvest cost at 4 Mg per Ha (a)	$19.55
Harvest cost at 6 Mg per Ha (a)	$13.84
Grower payment to farmer for nutrient replacement (per dry mg) (b)	$ 27.38
Storage cost using hybrid storage (per dry mg) (c)	$14.83
DML in storage (c)	3%
Unloading at refinery cost (per dry mg) (a)	$2.23
Temporary storage cost at refinery (per dry Mg) (a)	$2.16
Grinding cost (per dry Mg) (a)	$19.29

a) (M. H. Langholtz et al., 2016)
b) (Roni et al., 2019)
c) (D. Stauffer, personal communication, 2022)

The transport process was modeled using crews consisting of semi-trucks with flatbed trailers and loaders. The loader would be field side loading the trucks while the trucks are transporting the feedstock from the field to the storage facility. We assumed a crew configuration of 3.5 trucks per loader to minimize the trucks waiting on the loader at the field and the loader waiting on trucks returning from the storage area. The loaders at the storage area unloading the trucks were included in the cost of storage (D. Stauffer, personal communication, 2022). The hourly cost of the semi, trailer and loader was $78.28, $5.80 and $59.27 respectively as shown in Table 3.

Table 3. Transport equipment cost model parameter assumptions

Equipment Characteristics	Value
Semi Truck	
List price[b]	$120,000
Annual Usage	2,000 hours
Wage rate[a]	21.55

Benefit Rate[a]	29.6%
Mpg[b]	6.5
Fuel[c]	\$3.28 per gallon
Truck to loader ratio	3.5
Hourly rate (\$/h)	\$78.28
Flatbed Trailer	
List price[b]	\$42,500
Annual Usage	2,000 hours
Hourly rate (\$/h)	\$5.80
Loader (JD 304L FOUR WHEEL DRIVE LOADER)	
List price[d]	\$108,646
Annual Usage	2,000 hours
Wage rate[a]	\$16.54
Benefit Rate[a]	29.6% (2)
Hourly rate (\$/h)	\$59.27

a. (*Bureau of Labor Statistics*, 2021)
b. (Williams, n.d.)
c. (*Gasoline and Diesel Fuel Update*, 2021)
d. (John Deere, 2022)

As shown in Table 4, corn stover bales were assumed to have a moisture content of 20% (John Deere, n.d.) and a density of 175 kg m^{-3} (Sokhansanj et al., 2014). With a load of 36 bales, trailer capacity was 18.5 dry mg. We assumed a loading time at the field and unloading time at the storage facility of 12.5 minutes and average highway speed of the truck to be 45 miles per hour. The winding factor was assumed to be 1.4.

Table 4. Transport equipment model parameter assumptions

Data	Value
Moisture[a]	20%
Bale density (kg per M^3)[b]	175
Bales per load	36
Trailer capacity (dry mg per load)	18.54
Average truck speed (mph)	45
Time to load at field (minutes)	12.5
Time to unload at storage (minutes)	12.5
Winding factor	1.4

a) (M. H. Langholtz et al., 2016)

b) (Sokhansanj et al., 2014)

The radius of the circular supply shed and the average distance to the fields was calculated using an algorithm described in (Clark & Webb, 2024). This provided a means to estimate the total equipment hours required and total cost of transport Based as a function of the feedstock yield and supply density, resulting in the feedstock cost curves in Figure 2.

Implementation of Feedstock Cost Curves into Process Scenarios

Economic models for both the Base and Advanced Case process scenarios, used in Lynd 2017, were updated to reflect current ethanol process and results are presented in 2021 dollars. Biorefinery scale and corresponding calculated feedstock costs were used as inputs to the respective process models used to estimate minimum ethanol selling price (MESP) and payback period (PBP). The financial assumptions of each process scenario are listed in Table 5. The breakdown of the capital investment costs used for the Base and Advanced Case can be found in Lynd 2017.

Table 5: Summary of Financial Assumptions

Parameter	Assumption
Discount Rate (100% equity)	15%
Discount Rate (40% equity, 8% interest)	10%
Project Life (years)	20
Cost Year	2021
Income Tax Rate	35%
Construction Period (years)	3
% Spent in Year -2	8%
% Spent in Year -1	60%
% Spent in Year 0	32%
Startup time (years)	0.25
EtOH production/feedstock use (% of normal)	50%
Variable Costs (% of normal)	75%
Fixed Cost (% of normal)	100%

RESULTS AND DISCUSSION:

Results of the inclusion of the feedstock cost curves into the techno-economic process models are presented below. Figure 1 shows that total capital investment (TCI) for the Advanced Case is lower compared to the Base Case for all biorefinery scales assessed. Additionally, the difference in TCI between the two process scenarios increases as scale increases.

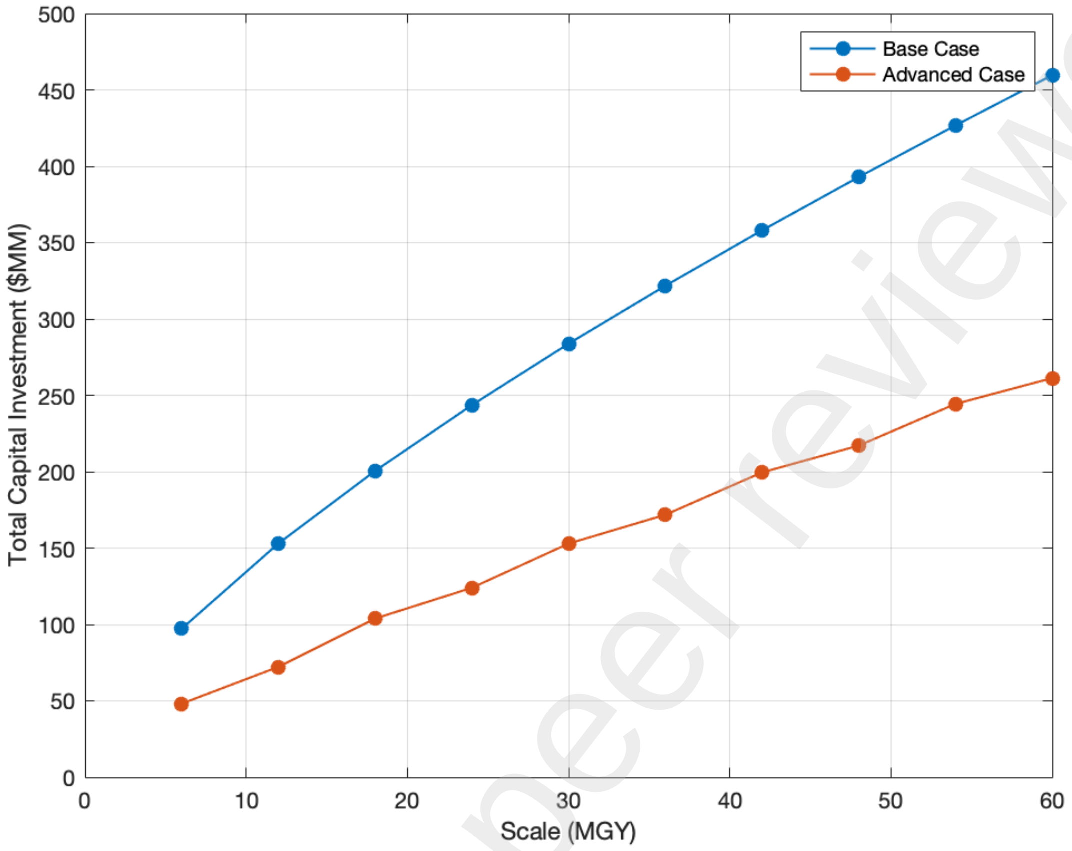

Figure 1. Total capital investment for Base and Advanced Case process scenarios versus biorefinery scale

Total delivered feedstock cost ($/dry megagram) increases with biorefinery demand as shown in Figure 2 and decreases with increasing regional supply density assuming a constant biofuel conversion rate. Here, delivered cost includes grower payment, harvest, transport, storage, and preprocessing. The low supply density scenario (yellow) is more than $25/Mg more expensive than the high supply density scenario (blue) for all biorefinery sizes. The difference between the medium (green) and high (blue) scenarios is $8 – 10/Mg across the range of refinery sizes.

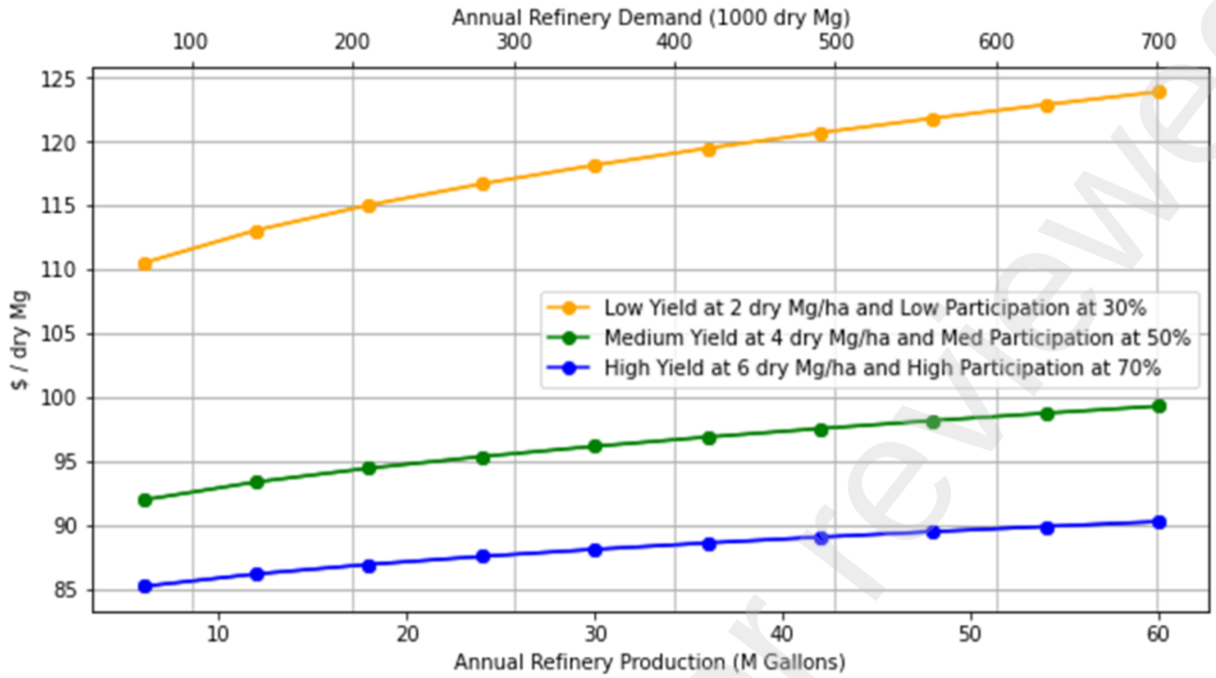

Figure 2. Total feedstock cost per dry Mg by refinery production, refinery demand, and effective yield. Total feedstock cost includes the grower payment, harvest, transport, storage, and grinding costs.

The diseconomy of scale for the feedstock supply shed is driven by increasing transport distance as shown in Figure 3, which shows the supply region radius with increasing biorefinery size. The effect of low supply density increases with biorefinery size. A similar trend is seen as in Figure 2, where the difference in distance traveled to meet demand increases with refinery scale (production/demand) as well as the difference seen between the low, medium and high yield/participation scenarios.

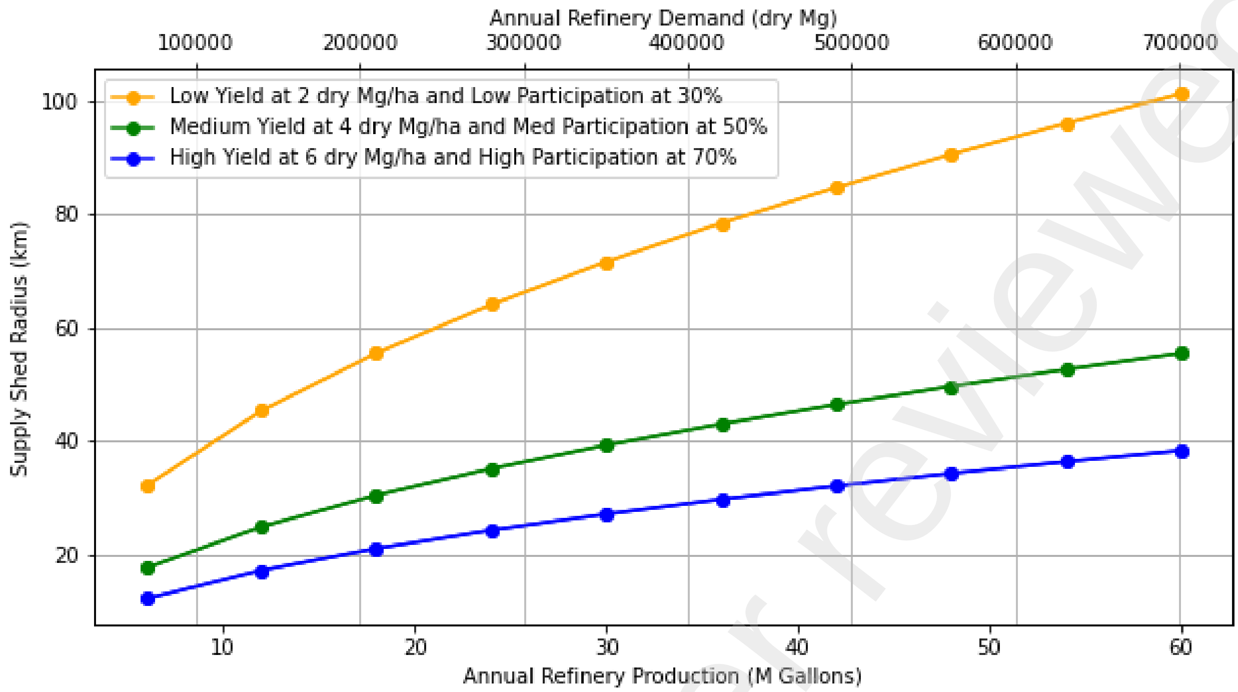

Figure 3. Supply shed radius in km by refinery production, refinery demand, and effective yield.

In Figure 4, the minimum ethanol selling price (MESP) for both the Base and Advanced Case at the different yield/participation scenarios versus biorefinery scale are shown with two different financing assumptions. For all biorefinery scales, the MESP remains higher for that of the Base Case compared to the Advanced Case. Additionally, the sensitivity of MESP to biorefinery scale is lower for the Advanced Case compared to the Base Case.

Figure 5 presents the difference between the MESP at the indicated scale and that at 60 million gallons per year, referred to herein as the small-scale cost penalty. The Advanced Case has a roughly half the small-scale cost penalty compared to the Base Case across all scales, with the Advanced Case having a cost penalty of ~ $0.80 at the lowest scale (6 MGY), compared to that of ~$1.60 for the Base Case. Additionally, the Advanced Case scall-scale cost penalty has a lower sensitivity to scale compared to the Base Case.

The ratio of capital costs to EBITDA has units of years and can be interpreted as payback period (PBP). Figure 6 shows the payback period for both cases as a function of biorefinery scale (MGY) for an ethanol price of $3/gallon (left) and $5/gallon (right). $5/gallon represents the projected selling price of ethanol including a $1/gallon Low Carbon Fuel Standard (LCFS) credit, $3/gallon for D3 RIN (cellulosic ethanol), and a $1/gallon ethanol fuel value that stood at the time of analysis. For both the Base Case and Advanced Case, there is a lower payback period required as plant scale increases. For all scales and ethanol selling price scenarios, PBP is shorter for the Advanced Case compared to the Base Case for all yield/participation. Additionally, the Advanced Case PBP shows a remarkably low sensitivity to scale compared to that of the Base

Case for all yield/participation scenarios. An increased ethanol selling price also significantly reduces the PBP across all scales/production scenarios.

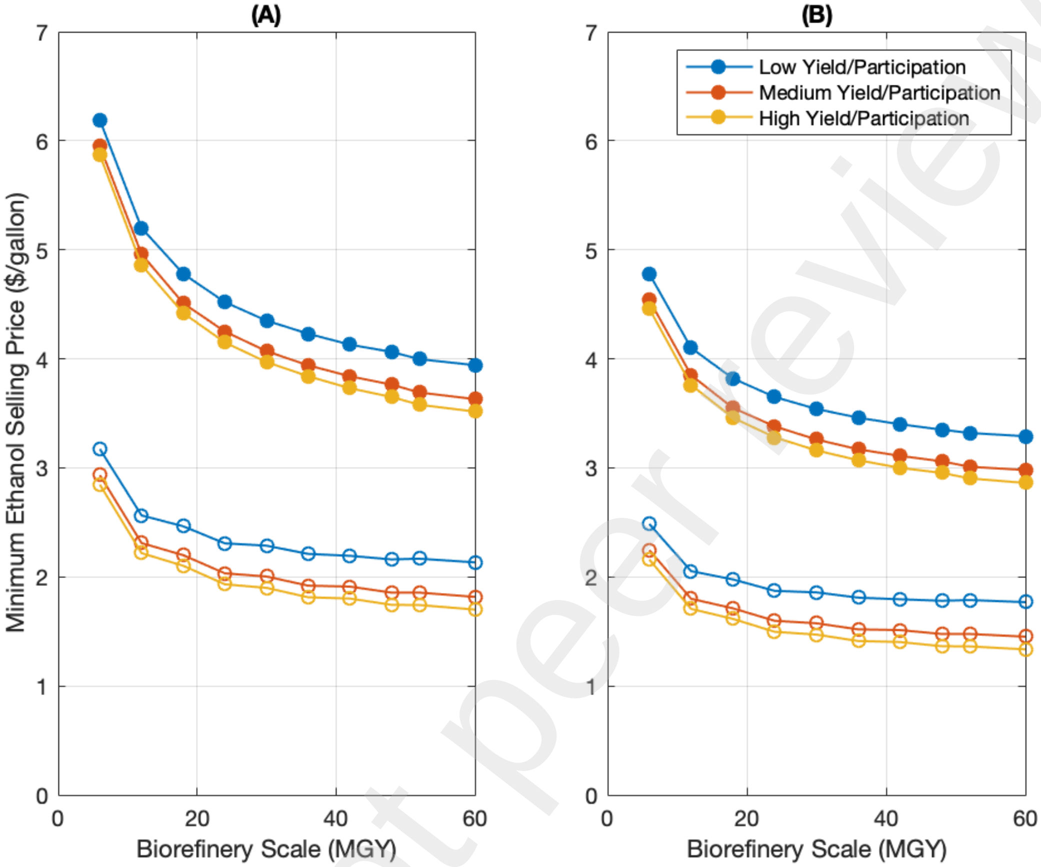

Figure 4. Minimum Ethanol Selling Price (MESP) for the Base Case (closed symbols) and Advanced Case (open symbols) at various yield scenarios versus biorefinery scale under (A) equity financing and (B) debt/equity financing

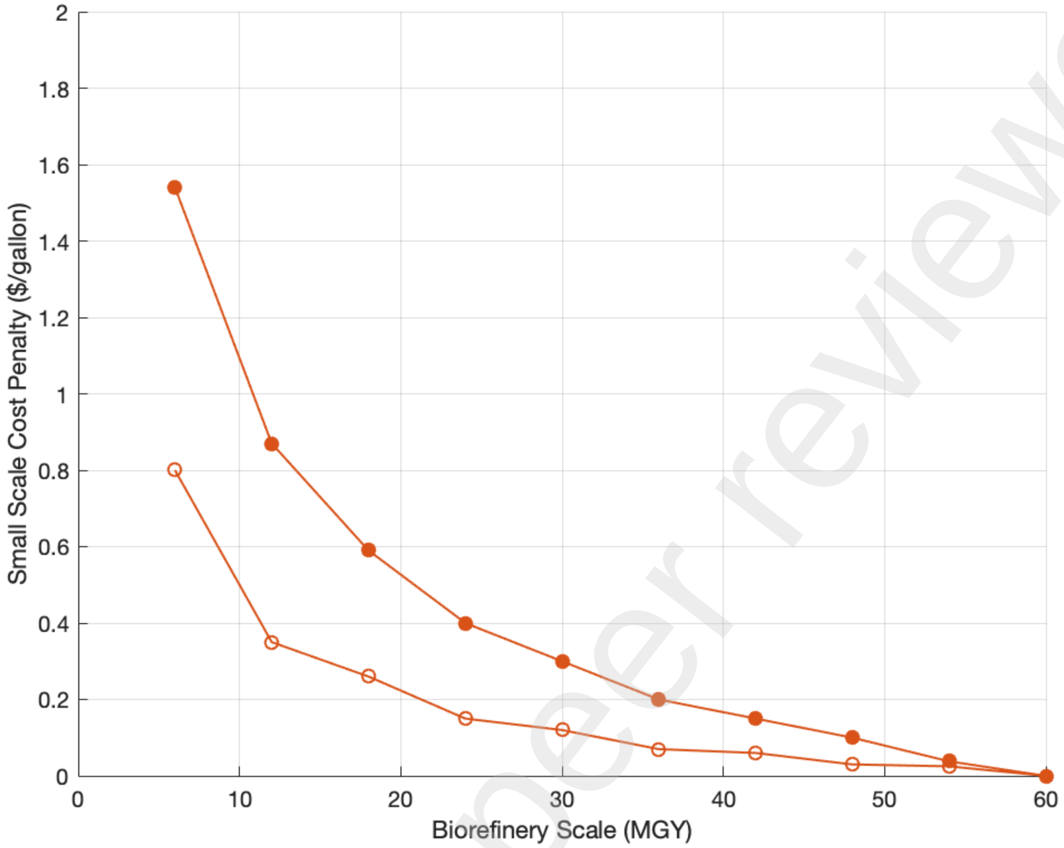

Figure 5. Minimum ethanol selling price penalty associated with smaller biorefinery scales compared with 60 MGY biorefinery (40% equity, 8% interest financing assumptions) for the medium yield/participation scenario for Base (filled circles) and Advanced Case (unfilled circles)

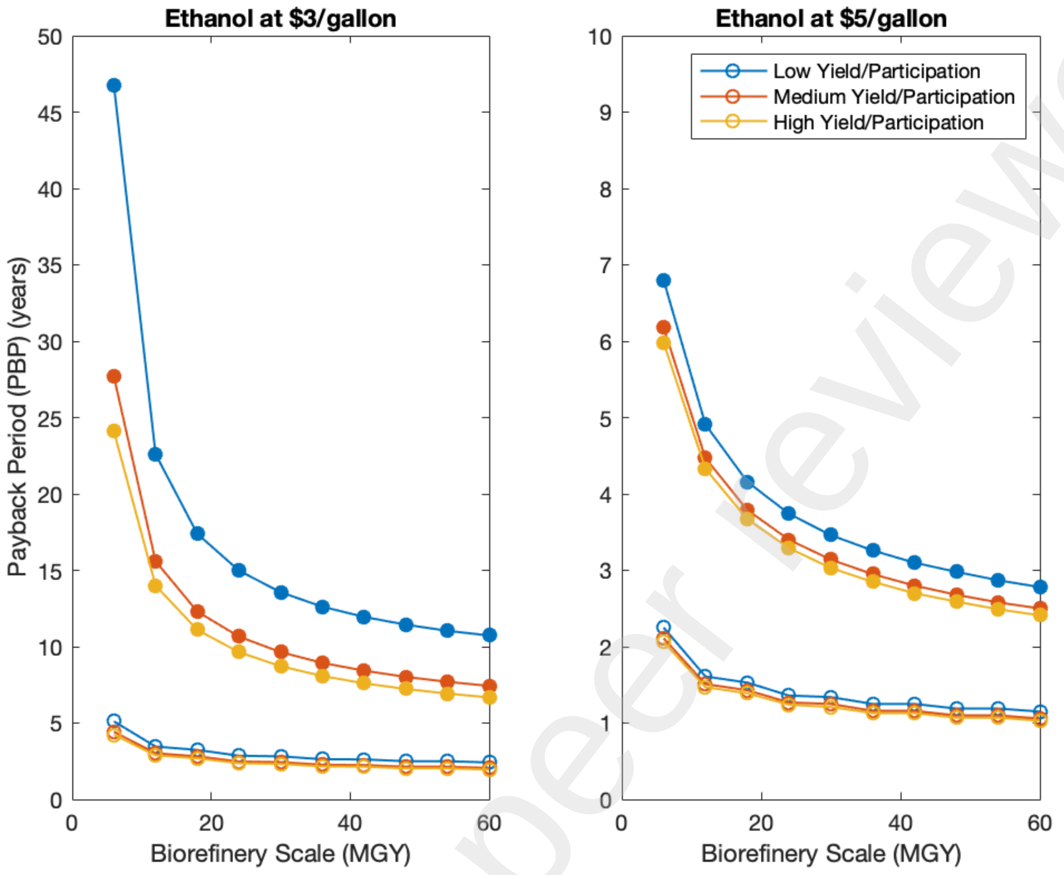

Figure 6. Payback Period (PBP, years) versus biorefinery scale for Base (filled circles) and Advanced Case (unfilled circles) at various yield scenarios using 40% equity, 8% interest financing assumptions

CONCLUSION:

Corn stover conversion to ethanol via consolidated bioprocessing with cotreatment (C-CBP) with projected research-based improvements exhibited more favorable economics across all scales in terms of both minimum ethanol selling price and payback period when compared to the conventional processing paradigm featuring thermochemical pretreatment and added fungal cellulase. For both C-CBP and the conventional processing paradigm the minimum ethanol selling price decreased with increasing scale, indicated that the cost penalty due to higher feedstock transport distances is more than outweighed by lower capital costs. However, the cost penalty for operation at small scale, expressed in $/gallon ethanol, is lower for C-CBP than for the conventional paradigm by roughly 2-fold. Relative to annual ethanol production of 60 million gallons per year, the cost penalty for operating C-CBP at smaller scales is $\leq$ 20 cents per gallon down to a scale of about 20 million gallons per year, corresponding to about 4% of the ~$5/gallon price of cellulosic ethanol with production incentives in place in the United States. Even at 10 million gallons per year, the small-scale cost penalty for C-CBP is < 10% of the cellulosic ethanol selling price. Particularly for initial applications of C-CBP, we speculate that this cost penalty will likely be modest compared to anticipated benefits of small-scale operation such as increased opportunity to use existing infrastructure, easier plant siting and supply chain establishment, and lower total investment required.

ACKNOWLEDGEMENTS

The Center for Bioenergy Innovation (CBI), which is a U.S. Department of Energy Bioenergy Research Center supported by the Office of Biological and Environmental Research in the DOE Office of Science. Oak Ridge National Laboratory is managed by UT-Battelle, LLC for the US DOE under Contract Number DE-AC05-00OR22725

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