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Techno-Economic Evaluation of Cellulosic Ethanol Production Based on Pilot Biorefinery Data: a Case Study of Sweet Sorghum Bagasse Processed via L+SScF

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Abstract

Replacing fossil fuels with renewable fuels derived from lignocellulosic biomass can contribute to the mitigation of global warming and the economic development of rural communities. This will require lignocellulosic biofuels to become price competitive with fossil fuels. Techno-economic analyses can provide insights into which parts of the biofuel production process need to be optimized to reduce cost or energy use. We used data obtained from a pilot biorefinery to model a commercial-scale biorefinery that processes lignocellulosic biomass to ethanol, with a focus on the minimum ethanol selling price (MESP). The process utilizes a phosphoric acid-catalyzed pre-treatment of sweet sorghum bagasse followed by liquefaction and simultaneous saccharification and co-fermentation (L+SScF) of hexose and pentose sugars by an engineered *Escherichia coli* strain. After validating a techno-economic model developed with the SuperPro Designer software for the conversion of sugarcane bagasse to ethanol by comparing it to a published Aspen Plus model, six different scenarios were modeled for sweet sorghum bagasse Under the most optimistic scenario, the ethanol can be produced at a cost close to the energy-equivalent price of gasoline. Aside from an increase in the price of gasoline, the gap between ethanol and gasoline prices could also be bridged by either a decrease in the cost of cellulolytic enzymes or development of value-added products from lignin.

Keywords Biofuel · MESP · Sorghum · Sugarcane · Sensitivity analysis

Introduction

The increasing demand for energy, fueled by a growing global population and an increasing standard of living in many developing countries, puts considerable strain on the environment. Combustion of fossil fuels contributes significantly to air pollution and smog, as well as greenhouse gas emissions [1] with negative impacts on the global climate. Sustainable alternatives to generate electricity, such as wind and solar power, are already being deployed on a large scale [2]. While the share of electric vehicles is currently increasing, and hydrogen vehicles are expected to become available in the future, liquid fuel is expected to still represent 80% of the transportation energy in 2050 and 50% in 2075 [3]. As the transportation sector currently contributes 20% to the global carbon dioxide emissions, and is growing faster than any other sector [4], increasing the proportion of liquid fuel generated from sustainable resources is expected to limit the net increase in CO_2 concentration resulting from burning fuel.

Lignocellulosic biomass is an attractive renewable resource, as it is abundant, inexpensive and does not compete directly with food production [5]. Lignocellulosic biomass consists mainly of cellulose, hemicellulosic polysaccharides and lignin. Cellulose is a linear polymer of 1,4-beta-linked D-glucose molecules [6], whereas hemicellulosic polysaccharides vary in

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composition depending on the species and developmental stage, and can contain both hexoses and pentoses [7]. Lignin is an aromatic polymer formed from the oxidative coupling of monolignols that is deposited in the plant secondary cell wall to provide mechanical strength and a water-impermeable coating of water-conducting xylem vessels [8]. The challenge with the use of lignocellulosic biomass is that its use as a feedstock is considerably more expensive than the use of starch- or sugar-based feedstocks currently providing fermentable sugars for biofuel production. This is largely due to the cost associated with thermo-chemical pre-treatment and cellulolytic enzymes necessary to hydrolyze polysaccharides to monomeric sugars that can be fermented by microbes [9]. Due to the complex structure of plant cell walls, a substantial amount of energy and hazardous chemicals is required [5]. The pre-treatment utilizes either shear forces or dissolves one or more of the cell wall constituents. A typical shear force pre-treatment is steam explosion, which utilizes the shear force of rapidly evaporating water due to a release of pressure [10]. Alkaline, dilute acid, and organosolv pre-treatments solubilize the hemicellulose and/or lignin fractions of the biomass [11, 12].

Current commercially used lignocellulosic feedstocks include wheat straw, corn stover, and giant reed [13]. Other lignocellulosic feedstocks that are likely to become available in large volumes are woody biomass and, especially along the US coast of the Gulf of Mexico and in Brazil, sugarcane and sweet sorghum bagasse. Sugarcane bagasse is an agro-industrial residue generated during the processing of sugarcane (*Saccharum* spp.) for the production of crystalline table sugar (sucrose). Sugarcane bagasse is currently used by sugar mills as boiler fuel, but utilizing sugarcane bagasse as a lignocellulosic feedstock for ethanol production could improve energy efficiency as well as the overall process economics [14]. Sweet sorghum (*Sorghum bicolor* (L.) Moench) is a tall annual grass that accumulates large amounts of soluble sugars in the juice present in its stems [15–17]. It is anticipated to be cultivated primarily as a dedicated energy crop, either as a complement to sugarcane or as a dedicated bioenergy crop on land that is not suitable for the production of food crops in areas that are too cold for sugarcane, or on land where limits on the volume of irrigation water and/or amount of fertilizer restrict the cultivation of other crops, such as sugarcane and maize [18, 19]. The juice from sweet sorghum yields readily fermentable sugars that can be used for the production of ethanol, similar to how ethanol is produced from sugarcane juice in Brazil, or for the production of chemical feedstocks for biodegradable plastics [20, 21]. The sweet sorghum bagasse that remains can then subsequently be used as a lignocellulosic feedstock. As a diploid, seed-propagated, annual species, the prospects of modifying sorghum biomass composition via genetic approaches to enhance the efficiency of enzymatic saccharification of bagasse are excellent [22, 23].

Since the production of ethanol from lignocellulosic biomass has to compete with the still dominant petroleum industry, and given that the shift towards renewable resources will be more likely to take place if it is more economically attractive than the current fossil resources, either *per se* or via standards or subsidies [24], it is critical to consider the cost of producing ethanol. At the moment, there are only a few commercial lignocellulosic biomass-based biofuel plants in operation [25] despite the implementation of the revised Renewable Fuel Standard in the USA [26]. Even though several economic analyses have been performed on different biorefinery systems, the economic implications of these analyses are not consistent, as evident from the range in the minimum ethanol selling price (MESP) from US$0.89 to US$4.58 per US gallon of ethanol as projected in a number of studies [27–35]. The MESP is the price at which the ethanol must be sold in order for the net present value (NPV) to be equal to zero [28, 31]. The NPV is an indicator of the present value of the cash flow at the required rate of return of the project compared to the original investment. The difference in MESP reported in the different studies [27–35] is in part the result of different biorefinery systems using different pre-treatments and/or feedstocks, but also due to different economic assumptions, which can affect the outcome significantly. In the different analyses, a wide range in the values of several parameter estimates is observed, even when the same process design methods and feedstocks are taken into account. A meta-analysis of a number of techno-economic analyses indicated that the assumptions with the greatest impact on MESP are feedstock price, ethanol yield, and enzyme cost [9]. The significant range in the cost of feedstocks and enzymes points to a high degree of uncertainty over the exact cost, exacerbated by the fact that the estimates are sometimes only available based on small-scale crop production systems or lab-scale biomass conversion systems. In general, these techno-economic analyses indicate that the production of biofuels from lignocellulosic feedstock is technically feasible, but that the MESP is too high to compete with fossil fuels [36].

Using production statistics of a pilot biorefinery can reduce the uncertainty resulting from the difficulty of predicting the performance of a full-scale bioprocessing facility based on small-scale analyses. The University of Florida operates a pilot-scale biorefinery, the Stan Mayfield Biorefinery Pilot Plant, located in Perry, Florida, with a maximum capacity of 100,000 US gallons (380,000 L) per year. The biorefinery utilizes a phosphoric acid-catalyzed steam explosion pre-treatment [37] combined with enzymatic liquefaction and fermentation with an engineered *Escherichia coli* that co-ferments both glucose and xylose efficiently [38, 39]. This process is referred to as liquefaction plus simultaneous saccharification and co-fermentation (L+SScF), which has the benefit of eliminating the need for aseptic liquid/solid separation and separate fermentations [38].

A techno-economic evaluation of commercial-level production of ethanol (20–60 million gallons per year; 76–227 million liter per year) from sugarcane bagasse was recently performed by Gubicza et al. [40] using data generated from the Stan Mayfield Biorefinery Pilot Plant and the Aspen Plus software. In the present study, we used a different software package, SuperPro Designer, to compare ethanol production from sugarcane and sweet sorghum bagasse using a common base case scenario. In addition to comparing the two feedstocks and the two software packages, this study also aimed to determine which factor(s) would be most effective at reducing the MESP in the case of sweet sorghum bagasse. This was accomplished by analyzing different scenarios in which enzyme dosage, conversion efficiency, solids loading, and biomass throughput were varied and by calculating at which price point products from the residue stream can make up any gaps between the MESP and the price of gasoline. Based on these analyses, we show that by increasing the scale and enhancing the production process parameters, it will be feasible to produce ethanol at a cost close the current price of gasoline.

Materials and Methods

Software

To determine the design, economics and scaling up of the process, SuperPro Designer software, version 9, build 9, made by Intelligen, Inc. (Scotch Plains, NJ) was used. SuperPro Designer is a process simulation software package, capable of analyzing the economics, sustainability, and performance of a designed process. This software enables the comparison of different pre-treatments and substrates, in terms of the performance, economics and sustainability.

To determine the sensitivity of the process to specific price changes, a sensitivity analysis was performed, in which the Component Object Model (COM) interface was used to remotely control SuperPro Designer's operations. The COM interface allows the use of Visual Basic for Applications (VBA), a computer programming language developed by Microsoft, which can be used to enable Microsoft Excel and SuperPro Designer to communicate with each other, with Excel providing input values to SuperPro, which subsequently calculates mass and energy balances, and executes the economic calculations, after which the desired economic indices are communicated back to Excel.

The model of the process used for the techno-economic analysis is based directly on the Stan Mayfield Biorefinery Pilot Plant as represented in Fig. 1 and further described in the text as follows.

Biomass Processing Parameters

The biomass used at the Stan Mayfield Biorefinery Pilot Plant was either sugarcane or sweet sorghum bagasse. The sugarcane bagasse was kindly provided by Florida Crystals (West Palm Beach, FL). A recently developed sweet sorghum cultivar developed at the University of Florida, referred to as "UF15" [17], was cultivated on a commercial farm near Memphis, TN in the summer of 2015. Mature stems were harvested as 20-cm billets in September 2015 and transported to the facilities of Delta BioRenewables, LLC, a commercial sweet sorghum syrup producer located in Memphis, TN. The billets were subjected to two passes through a three-roll mechanical tension sugarcane mill (Laurel Machine and Foundry; Laurel, MS) with a wash-step (water) in between. The resulting bagasse was dried with warm air and transported by truck to the UF Stan Mayfield pilot biorefinery in Perry, FL. As shown in Table 1, the composition of the sugarcane and sweet sorghum bagasse, determined via the procedure of Sluiter et al. [41], is overall very similar and for practical purposes the same biomass conversion parameters were used.

The biomass was fed into the pre-treatment reactor, where it was mixed with 0.5% (*w*/*v*) phosphoric acid and exposed to steam (190 °C, 1.35 MPa). After a residence time of 15 min, the pressure was released, causing the water to evaporate rapidly, leading to high shear forces, thereby disrupting the cell wall structure. During this pre-treatment, part of the lignin is solubilized and most of the hemicellulosic polysaccharides are hydrolyzed to monomeric sugars, predominantly the pentose xylose, since the main hemicellulosic polysaccharide in sugarcane and sweet sorghum bagasse is glucuronoarabinoxylan. After the pre-treatment, this mixture was passed through a screw press, and a fraction of the recovered liquid (10%) was used for seed culture propagation. Seed propagation utilizes the pentose sugars generated in the pre-treatment step as a carbon source for the ethanologenic *E. coli* strain SL100 used in the main fermentation [39]. The seed propagation consisted of three consecutive stages, each with a tenfold increase in volume.

The remainder of the pre-treatment mixture was fed into the liquefaction tank, where ammonium hydroxide was added to increase the pH to 5.0, so that cellulases (Cellic CTec3® from Novozymes (Franklinton, NC)), can hydrolyze the cellulose to glucose at 50 °C. At an enzyme loading of 2.5% of the bagasse dry weight, the residence time for this step was 6 h, enabling 68% of the cellulose to be converted to soluble sugars. The pH of the hydrolysate was then adjusted to 6.3 with ammonium hydroxide and fed into the fermenter. The fermentation time was 94 h, during which time 65% of the glucose and 60% of the pentoses were fermented to ethanol. The fermentation was operated in continuous mode, meaning that the fermenter is continuously fed with the mixture coming from the pre-treatment and the seed propagation tank. During

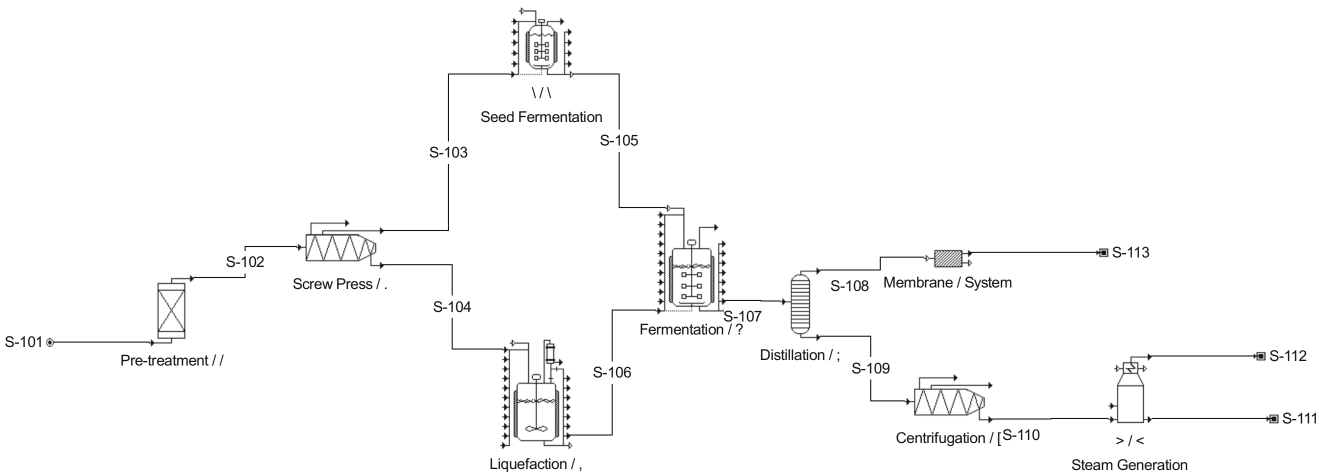

Fig. 1 Schematic representation of lignocellulosic ethanol production at the UF Stan Mayfield pilot biorefinery

the downstream processing, the fermentation broth was first distilled, resulting in ethanol as the main product, which was further purified in the membrane pervaporation system. The remaining fermentation broth was then fed into the decanter. The solid fraction was combusted to generate heat and power in the combined heat and power generator (CHP), and the phosphate-rich liquid fraction could be sold as a fertilizer.

Assumptions for a Biorefinery with a 300,000-MT Year^{-1} Capacity

For the design of the scaled-up process, several assumptions were made as outlined in this section. The desired throughput of the biorefinery was initially set at 300,000 MT of dry matter sugarcane or sweet sorghum bagasse per year. This capacity takes into consideration the limited availability of venture capital in the absence of a strong mandate for cellulosic ethanol and the need to acquire the feedstock from an area near the biorefinery.

Processing parameters were based on the operation of the pilot biorefinery, with the amount of phosphoric acid added for the steam explosion pre-treatment being 0.5% (*w*/*w*) on a dry matter basis. The amount of ammonium hydroxide added

Table 1 The biomass composition of sugarcane and sweet sorghum bagasse as determined using the procedure of Sluiter et al. [41]

Component	Sugarcane bagasse [g kg^{-1}]	Sweet sorghum bagasse [g kg^{-1}]
Cellulose	432	457
Hemicellulosic polysaccharides	271	256
Lignin	244	234
Ash	53	53

was 1 and 2% (*w*/*w*) on dry matter basis for the liquefaction and fermentation, respectively. The amount of enzyme added in the liquefaction ranged from 1.25 to 5% (*w*/*w*) on a dry matter basis, which represented a 50% reduction or twofold increase relative to the experimental conditions used at the pilot biorefinery. The enzymatic saccharification was assumed to result in a maximum of 90% conversion of cellulose to glucose based on extrapolation of recent increases in the performance of cellulolytic enzymes [42–44]. The fermentation time ranged from 48 to 72 h, and the yield of C_6 and C_5 sugar conversion was modeled to reach a maximum of 90%, based on anticipated improvements in microbial strains, extrapolated from gains made in the recent decade due to, for example, greater tolerance to inhibitors generated during the thermochemical pre-treatment [38, 45–47].

The cost of sugarcane bagasse and sweet sorghum bagasse delivered to the biorefinery from within an assumed radius of 50 mi (80 km) was set at US$44 and US$60 BDMT^{-1} (bone dry metric tons), respectively. The cost for the sugarcane bagasse was selected to match the cost used by Gubicza et al. [40], enabling direct comparison of results for sugarcane processing between the current study and theirs. This value is consistent with the feedstock cost for the Gulf Coast area reported in the Billion Ton Study commissioned by the US Department of Energy [48]. The latter study was also the source for the feedstock cost of the sweet sorghum bagasse. Both feedstock costs also fall within the range reported by Graham et al. [49]. The cost for the other process chemicals and enzymes was based on the actual cost at the pilot biorefinery and was as follows: cellulases US$1.00 kg^{-1}; phosphoric acid US$0.80 kg^{-1}; ammonia US$0.68 kg^{-1}; and trace metals US$0.10 kg^{-1}. Labor needs were estimated by extrapolation based on labor needed for the pilot biorefinery operation, and amounted to 60 FTE year^{-1}, with an average annual salary and fringe of US$60,000, resulting in an annual labor cost of US$3,600,000. The depreciation time was set to be 15 years, and the discount rate for the net present value calculation was set to be 11%. The corporate income tax was set to 35% [50]. The cost for the biorefinery equipment was based on the SuperPro Designer database (2015 prices), and the cost of the pre-treatment equipment was US$14,000,000 as quoted by an engineering firm familiar with this equipment for use at this scale. The range of dry matter percentage required for each of the different unit operations was determined by Nieves et al. [51]. The process produced enough heat and power to be self-sustainable in terms of energy inputs, so only water was needed for cooling purposes at US$0.022 MT^{-1} of cooling water. The power generation was more than sufficient to be self-sustainable, and the excess power was modeled to be sold to the grid at US$0.08 kWh^{-1} [2].

A Comparison Between Aspen Plus and SuperPro Designer for the Sugarcane Bagasse Base Case Scenario

The base case scenario is a realistic prediction of the conditions that will be possible for an n^{th} generation plant, based on available experimental data and conditions anticipated to be realistic in the near future. In order to enable a direct comparison with the techno-economic model from Gubicza et al. [40], which was based on data obtained from the Stan Mayfield Biorefinery Pilot for sugarcane bagasse and which was generated in the Aspen Plus software (Aspen Technology, Inc., Bedford, MA), we analyzed the base case scenario for sugarcane bagasse in SuperPro Designer. In order to make the comparisons as meaningful as possible, the SuperPro Designer model was adjusted to the extent possible to match the assumptions made by Gubicza et al. [40], while trying to keep its specific program characteristics intact.

The Base Case and Six Scenarios Based on Anticipated Improvements in the Bioprocessing of Sweet Sorghum Bagasse

Several scenarios for the processing of sweet sorghum bagasse were analyzed as listed in Table 2. The experimental scenario used data generated under laboratory conditions and at the UF Stan Mayfield pilot biorefinery to model the process and formed the basis for the base case scenario.

The other scenarios (1–6) represent further improvements that can be implemented pending technological advances that include increases in the efficiency of cellulolytic enzymes, the development of enhanced microbial biocatalysts, and the improvements in process technology [52]. Specifically, increasing the solids loading in the fermentation (scenario 1) decreases the amount of water added, thereby reducing the energy usage as well as reducing reactor volume. Decreasing the amount of enzyme added (scenario 2) results in operational savings due to decreased enzyme costs. This assumption depends on the future availability of improved enzymes capable of the same conversion yields at reduced titer and without negative impact on price. In scenario 3, we combined the improvements of scenarios 1 and 2. In case the assumptions regarding the improvements in enzyme technology could not be met, scenario 4 included doubling the enzyme dosage relative to the base case in order to enhance the rate of conversion and yield of glucose (due to a higher proportion of active enzymes) and therefore to a higher rate of production and yield of ethanol. Scenario 5 combined the higher solids loading with greater glucose yield due to improved enzymes. Scenario 6 is an optimal case scenario, which combines the higher solids loading with an even greater glucose yield, while at the same time the capacity of the biorefinery is doubled to benefit from the economy of scale.

Definitions, Formulas, and Assumptions Associated with the Operation of the Biorefinery

The total capital investment, the amount of capital needed to build and start up the facility, is calculated by applying a certain cost factor to the total equipment costs:

$$\text{Total equipment purchase cost (PC)} \\ = \text{listed equipment cost} + \text{unlisted equipment cost}$$

where listed equipment cost represents the equipment visible in the process design, unlisted equipment cost (equipment generally not shown; for example, pumps and heating equipment) is defined as 20% of the listed equipment cost.

The direct fixed capital, the capital needed to build the biorefinery, consists of the direct cost, indirect cost, and other cost, defined as follows:

$$\text{Direct fixed capital} = \text{direct cost} + \text{indirect cost} + \text{other cost}$$

The calculation of the direct cost, indirect cost, and other cost is based on the approach developed by Peters et al. [53], using cost factors that depend on the total equipment purchase cost, as listed in Table 3. The Lang factor, which provides an estimate of the total capital investment based on the equipment cost, has been set to 3.2, which is considered a feasible value for a bioethanol facility using a process that has been tested extensively in a pilot facility.

The total capital investment is then calculated as follows:

$$\text{Total capital investment} = \text{direct fixed capital} + \text{working capital} \\ + \text{startup costs}$$

The working capital is estimated to cover 30 days of operation, and the startup costs are estimated as 5% of the direct fixed capital, standard values set in SuperPro Designer.

Table 2 Different bagasse processing scenarios evaluated in SuperPro Designer. Scenarios 1–6 list differences with the base case scenario

Cases	Parameters
Experimental	Based on the experimental data from the lab and pilot biorefinery
	Enzyme loading: 2.5%; glucose yield: 68% of cellulose; solids loading: 15%; fermentation yields: 65% C_6 + 60% C_5; fermentation time: 94 h
Base case scenario	Enzyme loading: 2.5%; glucose yield: 68% of cellulose; solids loading: 15%; fermentation yields: 95% C_6 + 90% C_5; fermentation time: 48 h
Scenario 1	Solids loading: 25%
Scenario 2	Enzyme loading: 1.25%
Scenario 3	Solids loading: 25% solids; enzyme loading: 1.25%
Scenario 4	Enzyme loading: 5%; glucose yield: 85% of cellulose
Scenario 5	Solids loading: 25%; glucose yield: 85% of cellulose
Scenario 6	Solids loading: 25%; glucose yield: 90% of cellulose; capacity: 600,000 MTyear^{-1}

The total operating cost, the amount of money it costs to operate the facility for 1 year, is calculated as follows:

$$\text{Total operating cost} = \text{raw material cost} + \text{labor} + \text{utilities} + \text{facility dependent cost}$$

Where the facility-dependent cost is calculated as follows:

$$\text{Facility dependent cost} = \text{maintance} + \text{depreciation} + \text{miscellaneous}$$

Maintenance is assumed to be 10% of the equipment cost. Depreciation is calculated following the straight-line method, which charges the cost of the facility evenly throughout its useful life. Miscellaneous costs include insurance, local taxes, and factory expenses, assumed to be 1, 2, and 5% of the direct fixed capital, respectively.

Table 3 Factors associated with the calculation of the direct, indirect, and other costs

Cost factor	Capital cost
Equipment	1.00 × PC
Installation	0.42 × PC
Piping	0.10 × PC
Instrumentation	0.10 × PC
Insulation	0.03 × PC
Electrical facilities	0.05 × PC
Buildings	0.15 × PC
Yard improvement	0.05 × PC
Auxiliary facilities	0.15 × PC
Direct cost (DC)	2.05 × PC
Engineering	0.15 × DC
Construction	0.25 × DC
Indirect cost (IC)	0.40 × DC
Contractor's fee	0.04 × (DC + IC)
Contingency	0.08 × (DC + IC)
Other cost	0.12 × (DC + IC)
Direct fixed capital	3.2 × PC

PC total equipment purchase cost, *DC* direct cost, *IC* indirect cost

The MESP is calculated by SuperPro Designer based on the ethanol production cost, depreciation time (15 years), and discount rate (11%), in such a way that the revenue from selling ethanol results in an NPV equal to zero. This can also be considered as the break-even price [54].

The formula for the wholesale price of E85 (transportation fuel consisting of 85% ethanol, 15% gasoline) (in US$/US gallon) is

$$\text{E85 price} = 0.85 \times \text{MESP} + 0.15 \times \text{wholesale gasoline price}$$

The energy content of E85 is 73% of that of gasoline [55]. The energy-equivalent price of E85 is, therefore

$$\text{Energy equivalent price} = \frac{\text{E85 price}}{73} \times 100$$

In the USA, the relationship between retail and wholesale price of gasoline determined by Babcock and Poulliot [56] is as follows:

$$\text{Retail price} = 0.97 \times \text{wholesale price} + 0.754$$

Results and Discussion

A Comparison of Techno-Economic Models for Processing Sugarcane Bagasse to Ethanol

In order to compare the SuperPro Designer model with the previously published Aspen Plus model from Gubicza et al. [40], sugarcane bagasse was selected as the feedstock, with a cost of US$44 BDMT^{-1}. The SuperPro Designer base case scenario, derived from the experimental pilot-scale data, and representing the situation where construction of the biorefinery would start today, was refined to accommodate continuous and batch fermentations. Table 4 displays the ethanol production costs obtained with the Aspen Plus model and the two fermentation schemes in the SuperPro Designer

Table 4 A comparison of the economic results of the model developed by Gubicza et al. [40] and the models developed in SuperPro Designer. The feedstock was sugarcane bagasse with a feedstock price of US$44 BDMT^{-1}

Cost items	Gubicza et al. [40]	SuperPro batch	SuperPro continuous
Feedstock (¢/gal)	54.8	58.7	58.7
Capital (¢/gal)	99.3	74.3	70.1
Chemicals (¢/gal)	29.9	32.9	32.9
Enzymes (¢/gal)	27.9	30.3	30.2
Utilities (¢/gal)	2.8	4.3	4.3
Other (¢/gal)	29.0	22.7	16.4
Income			
Fertilizer (¢/gal)	15.0	14.1	14.1
Electricity (¢/gal)	9.8	7.0	7.0
Ethanol production cost (¢/gal)	219.1	202.1	191.8
MESP (US$/gal)	ND	2.80	2.60

ND not determined

model. The ethanol production costs are within 10% of each other and there is general agreement between the Aspen Plus and SuperPro Designer models. Differences exist in the cost of utilities, enzymes, "other," and the generation of electricity. The most significant difference is in the capital cost calculation. The SuperPro Designer model estimates a total capital investment of US$125 million, compared to US$180 million estimated by the Aspen Plus model. This difference is difficult to break down, as it originates in the way the software operates, but is most likely due to a difference in the capital cost factor. Comparison of the two SuperPro Designer models shows that operating a continuous fermentation is more economical, as it has less downtime and allows for a decreased reactor volume.

The ethanol production cost under the Aspen Plus model [40] and the base case scenario (SuperPro Designer; batch fermentation), broken down by inputs and income is shown in Fig. 2a. The most significant difference between the two models is in the capital cost, which is 52% higher in the Aspen Plus model. The difference in other cost between the SuperPro Designer models and the Aspen Plus model [40] reflects that the latter includes maintenance and insurance, whereas these costs are included in the capital cost in SuperPro Designer. Despite these differences, the overall agreement between the two models validates both modeling approaches. Furthermore, given the similarities in feedstock composition between sugarcane and sweet sorghum bagasse (Table 1), the same parameters for the base case analysis of sweet sorghum bagasse were considered reasonable.

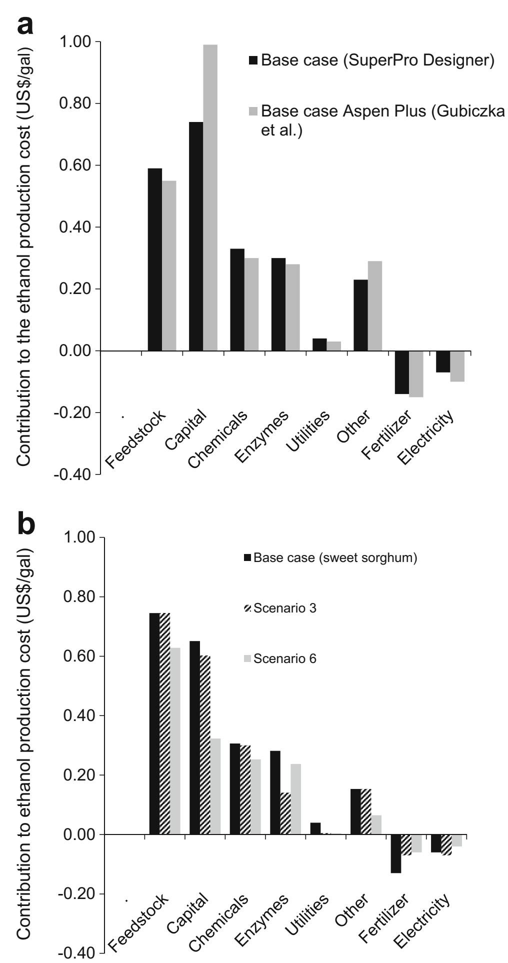

Fig. 2 **a** Comparison of the ethanol production cost of the base case scenario using a batch fermentation (SuperPro Designer) and the base case of Gubicza et al. [40] (Aspen Plus). Both models are based on sugarcane bagasse with a feedstock price of US$44 BDMT^{-1}. **b** Comparison of the ethanol production cost for the base case scenario and scenarios 3 and 6, with sweet sorghum bagasse as the feedstock at a price of US$60 BDMT^{-1}

Improvements in Bioprocessing Are Projected to Substantially Reduce the Cost of Ethanol Production from Sweet Sorghum Bagasse

The economic results obtained from modeling the different scenarios for processing sweet sorghum bagasse are summarized in Table 5. At over US$3 gal^{-1}, the ethanol production cost for the experimental scenario is high. This is due to the

Table 5 The ethanol production cost derived from the SuperPro Designer model for the different scenarios under consideration using sweet sorghum bagasse as the feedstock. "L" represents a modification of scenario 6 in which the lignin-rich stream is not burned to generate heat and electricity, but used as a feedstock for value-added products from lignin. The values listed are dollar cents per gallon (¢/gal), except for the MESP, which is in US$/gallon

Cost items	Exp.	BC	1	2	3	4	5	6	L
Feedstock (¢/gal)	110.1	74.5	74.5	74.5	74.5	65.2	65.2	62.8	62.8
Capital (¢/gal)	107.4	65.1	60.2	65.1	60.2	56.8	52.6	32.3	28.6
Chemicals (¢/gal)	45.2	30.6	30.0	30.6	30.0	26.8	26.2	25.3	25.3
Enzymes (¢/gal)	83.2	28.2	28.2	14.1	14.1	49.2	24.6	23.7	23.7
Utilities (¢/gal)	6.4	4.0	0.5	4.0	0.5	3.5	0.4	0.6	30.5
Labor (¢/gal)	22.7	15.3	15.3	15.3	15.3	13.4	13.4	6.5	6.5
Income									
Fertilizer (¢/gal)	20.1	13.2	7.3	13.2	7.3	11.6	6.4	6.2	6.2
Electricity (¢/gal)	9.6	5.5	6.6	5.6	6.6	3.7	4.7	4.4	51.1*
Ethanol production cost (¢/gal)	346.6	199.0	194.8	184.9	180.7	199.7	171.3	140.4	120.1
MESP (US$/gal)	4.45	2.40	2.31	2.21	2.12	2.35	1.96	1.50	1.29

Exp experimental, *BC* base case, *MESP* minimum ethanol selling price

*This value represents the revenue from lignin-derived products, rather than from electricity

high cost of capital, primarily because of the long fermentation time as well as the low solids loading, resulting in a low yield of ethanol. Optimizations are needed in order to reduce costs and have a more competitive product. Moving towards the base case scenario shows significant reductions in capital and enzyme cost. The decrease in fermentation time means the reactor size can be decreased, requiring less investment capital.

Comparing an increase in solids loading with a decrease in enzyme dosage under the original solids loading, as calculated in scenarios 1 and 2, respectively, shows that decreasing the enzyme dosage has a larger impact on the MESP. Combining these two improvements in scenario 3 leads to a MESP that is 12% lower than the MESP in the base case scenario. In scenario 4, the enzymatic hydrolysis yield was increased due to increased enzyme dosage. However, this did not result in a significant reduction in the MESP, as the increased revenue did not compensate for the increased enzyme cost. Scenario 5 assumes optimal conditions for a facility with a capacity of 300,000 MT year^{-1}, where an increased solid loading combined with an increased enzymatic hydrolysis yield leads to a MESP of US$1.96 per gallon. Increasing the capacity of the plant, as calculated in scenario 6, has a substantial effect on the MESP: a decrease by almost 25%. This decrease in MESP is due to the economy-of-scale effect in the capital investment, while the labor needs remain constant. This scenario results in the lowest MESP, US$1.50 per gallon of ethanol, and illustrates the utility of this techno-economic model in defining (combinations of) parameters that impact the MESP.

Scenarios 3 and 6 represent processes in which several improvements have been combined, with scenario 3 representing conditions that are considered feasible within the next several years and scenario 6 representing conditions feasible in the longer term. Comparing the factors contributing to the ethanol production cost among the base case and these two improved scenarios (Fig. 2b) shows that the most substantial difference is the capital cost, due to the economy-of-scale effect. Another substantial difference is in the 'other' cost, which decreased by 58% between the base case scenario and scenario 6, because no changes occurred in labor costs, while the ethanol output more than doubled. The other reductions between the base case scenario and scenario 6 are due to the increased yield of the enzymatic hydrolysis, leading to overall better economics.

The price sensitivity of the different raw materials used in the process is shown in Fig. 3, which compares the experimental data with the base case and scenario 6. The percentages represent the increase in ethanol production cost, if the price of the raw material would increase by 10%. For the base scenario and scenario 6, the most sensitive input is the feedstock, followed at some distance by cellulases and ammonium. This is to be expected, considering the large volume of sweet sorghum bagasse needed as feedstock for the biorefinery. The price sensitivity to feedstock cost also means that an abundance of inexpensive feedstock should be considered a top priority when deciding on the location of a biorefinery. Figure 3 also shows that the sensitivity to price increases is reduced with the implementation of improvements to the process, whereby the reduction in enzyme usage has a prominent effect. An additional factor that may need to be considered for the scenarios based on processing larger volumes of feedstock is that there will likely be a feedstock cost feedback loop, whereby the increased demand for bagasse will diminish supplies and drive up cost. In this context, the ability to have a flexible operation that can accommodate multiple biomass

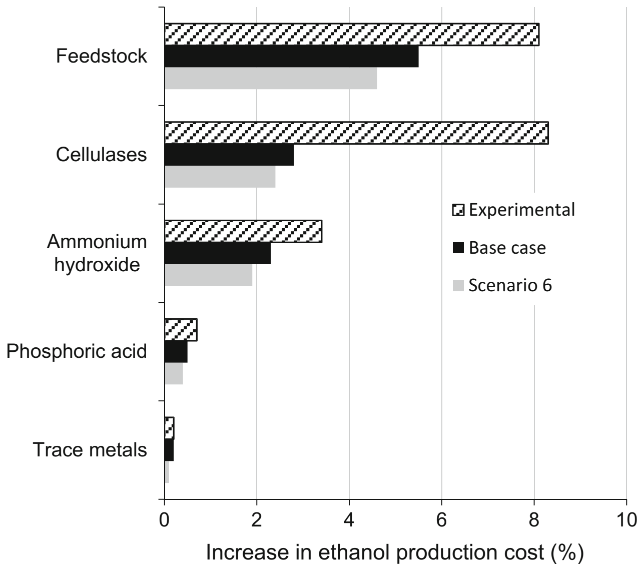

Fig. 3 Price sensitivity analysis showing the percent increase in ethanol production cost in response to a 10% increase in the price of the raw materials listed based on SuperPro Designer models derived from the experimental data, the base case and scenario 6 with sweet sorghum bagasse as the feedstock

feedstocks from the same region may be able to reduce some of this fluctuation, as has been shown for biomass supplies in the US Midwest [57]. The complementary nature of sugarcane (harvested in the winter) and sweet sorghum (harvested in the summer and fall) will also contribute to steady feedstock supplies in the US Gulf Coast area.

Making the MESP Competitive with the Price of Gasoline

In the absence of any subsidies, the MESP in most of the scenarios we evaluated were considered to be too high to be commercially competitive with the current price of gasoline (US national average of US$2.59 gal^{-1} or US$ 0.68 L^{-1} [58]). Based on our techno-economic model, a biorefinery that converts 600,000 MT per year of biomass (scenario 6) while several other improvements are implemented over the base case scenario can produce ethanol at a MESP of US$1.50 gal^{-1}. The current wholesale price of gasoline is US$1.89 gal^{-1} [56, 58], and blending this to E85 with ethanol produced under the model assumptions reported here results in a price of US$1.56 gal^{-1}. Correcting for the lower energy content, where E85 contains 73% of the energy present in gasoline [55], leads to a wholesale price of US$2.13 gal^{-1} gasoline equivalent. Converting this back to a retail price results in a price of US$2.82 gal^{-1}, which is still higher than the current average gasoline price in the USA. The MESP required for the E85 blend to be competitive with gasoline at the present time is US$1.29 gal^{-1}, which is a 14% reduction from the most favorable MESP calculated in this study.

In the current process, burning the lignin-rich residual provides so much energy that no net external energy is needed. An alternative is to use this fraction as a feedstock for aromatic chemicals or fuels, nanocarriers, or composites [59–62] that represent a higher value than boiler fuel, while contributing to a reduced dependence on fossil resources for these products. However, this is only economically viable if the added value from the lignin product is higher than the cost of generating steam and electricity. A modification of scenario 6, in which lignin was no longer burned, but turned entirely into products, impacted the ethanol production cost by slightly reducing capital expenses (no burner) from 32.3 to 28.6 ¢ gal^{-1}, while increasing the cost for utilities (electricity/gas to provide the energy for heating) from 0.4 to 30.5 ¢ gal^{-1} (Table 5). In order to reduce the MESP to US$1.29 to make ethanol competitive with gasoline, the revenue from lignin-derived products needs to be 51 ¢ gal^{-1}, which was calculated in SuperPro Designer to require a value of US$0.30 kg^{-1} lignin. This is not an unrealistic value given that depending on its purity, the current market price of lignin is between US$0.18 and 0.75 kg^{-1} [63]. A wide-scale switch from burning lignin to using lignin for other products has, however, the risk of creating an oversupply of lignin and, therefore, a reduction in value. Furthermore, having the biorefinery rely more heavily on fossil fuels for heating and electricity would also have a negative impact on the net contribution to greenhouse gas emissions.

An additional factor that can help close the gap between the MESP and gasoline is policy set by local, state, and national governments. Mandates for fuel ethanol, such as stipulated by the revised Renewable Fuel Standard [26], ensure a demand that will likely attract investments in new biorefineries with improved bioprocessing technologies. This assumes the standard is enforced, which it currently is not. Alternative mechanisms to close the gap is the implementation of a carbon tax, adjusting the price of gasoline for negative impacts of combustion of fossil fuels on air quality and public health, and for the cost of military operations intended to safeguard access to petroleum [64], or subsidizing fuel ethanol, which can be accomplished in a variety of ways [24].

Comparisons with Other Techno-Economic Analyses

As mentioned earlier, there is considerable variation in MESP among different techno-economic analyses, as reviewed by Chovau et al. [9]. This reflects differences in economic assumptions as well as technical parameters [35]. Supplemental Figures 1 and 2 show that MESP values obtained for the different scenarios in this study (Table 5) match the trend reported in the comparison of different analyses [9]. The comparisons show that the calculated MESP is correlated with feedstock price and enzyme cost, which were the two most prominent factors in our sensitivity analysis. Enzyme cost estimates vary greatly among analyses. Our enzyme cost, based on pilot biorefinery data, is consistent with several other base case scenarios [29, 35, 36], but we were more conservative with the projection of improvements in enzyme performance and anticipated reductions in cost over time, especially compared to Hamelinck et al. [29].

The model developed in this study differs mostly in the MESP per capital investment when compared to the other models reviewed by Chovau et al. [9], which showed a correlation between the total capital investment and the MESP. Most of the other analyses, however, assume a biomass input of 2000 MT day^{-1}, which is significantly higher than the 800–1600 MT day^{-1} used in this study, and potentially unrealistic at the current time.

There is a notable difference in MESP depending on whether continuous or batch fermentation is implemented. Batch fermentation requires a larger tank volume due to the downtime caused by the cleaning procedure necessary between batches. The result is an increase in MESP by 5%. Another benefit of continuous fermentation is the option to reduce the volume of cooling water used in the process, by cooling down the feed containing the fermentable sugars with the exit stream of the fermenter. While this would provide the environmental benefit of water savings, the economic benefit is negligible, as the increase in capital cost associated with this set up negates the decrease in utilities cost.

A more thorough sensitivity analysis could be performed if the kinetic parameters of the fermentation process are included in the model. Exploring the relationship between fermentation time and yield to the fermentation tank cost and profitability enables the optimization of fermentation time in economic terms. The difficulty lies in the creation of an accurate kinetic model of the organism for mixed substrates, but this can be developed after conducting the necessary experiments.

The factor used to calculate the total fixed capital cost proved to have a significant impact on the MESP, as the MESP decreased by 10% when comparing the SuperPro Designer model with the Aspen Plus model [40], as shown in Table 4, whereas the most optimistic scenario 6 resulted in a 25% reduction in the MESP (Table 5). In the SuperPro Designer model, the total fixed capital cost is represented by the value of the Lang factor. Since increasing its value proportionally increases the total capital investment, an important step towards realization of a commercial biorefinery is to obtain the pertinent information from equipment vendors about the equipment and installation costs, so that the uncertainty in the value of the Lang factor can be reduced.

Conclusions

The techno-economic analysis presented here, based on experimental data from a pilot biorefinery that were used to develop a number of improved scenarios for a larger-scale commercial facility, showed that the cost of the feedstock and the size of the biorefinery are the key factors that need to be targeted to make cellulosic ethanol price competitive with gasoline. The former is evident from the sensitivity analysis, the latter from the reduction in MESP between scenarios 5 and 6. Another important factor is enzyme loading, as shown by the sensitivity analysis and the comparison of the MESP between scenarios 1, 2, and 4. Taken together, this means that current efforts towards the development of low-input, high-yielding bioenergy crops such as sweet sorghum should continue, along with technical improvements (enzyme performance, solids loading, microbial strains) and optimizations of the biorefinery operations.

When using sugarcane bagasse as the feedstock, and considering the base case scenario, the software used for the techno-economic analysis (SuperPro Designer vs. Aspen Plus) did not result in a major difference in the ultimate value of the ethanol production cost, although there were differences in the individual costs that contributed to it, notably the capital cost. The overall consistency validates the utility of these software packages for techno-economic analyses and optimizing process parameters, albeit that the underlying assumptions for calculating the capital cost need to be verified, preferably independently, for each planned operation to make sure they are realistic.

A comparison of the base case scenarios for sugarcane and sweet sorghum bagasse showed that, under the model assumptions we used, these are equivalent feedstocks for the production of lignocellulosic ethanol. There is a notable difference in feedstock cost, but this is in part due to uncertainty over the exact cost of sweet sorghum bagasse, reflecting its currently limited commercial availability, whereas sugarcane bagasse is produced as a by-product of an established industry. As a perennial crop, sugarcane needs time to establish, but biomass yields of the established crop tend to be higher than current sweet sorghum biomass yields [65]. On the other hand, sweet sorghum is more amenable to genetic improvement, including cell wall compositional traits that enhance enzymatic saccharification [23, 66] and that will help reduce the processing cost of sweet sorghum bagasse more quickly than for sugarcane bagasse.

Even though the current MESP is not competitive with the price of gasoline in the USA, given the interconnectedness of economies across the globe, the existence of geo-political tensions in areas affecting supplies of fossil fuels, an increasing global awareness of the anticipated impacts of climate change, and a need to control air pollution in large urban areas, it is within the realms of possibility that changes in policy will also contribute to making cellulosic ethanol become cost competitive with gasoline.

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