Techno-economic Analysis for the Biochemical Conversion of *Miscanthus x giganteus* into Bioethanol

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ABSTRACT

This study assessed the economic viability of using *Miscanthus x giganteus* as a feedstock for the production of bioethanol based on plant designs and models by the National Renewable Energy Laboratory. In 2007 dollars, the total cost of installed equipment for a plant with an annual feedstock requirement of 701 million kg/year was

\$281 million, with the single largest component, cost of feedstock, contributing approximately 40% to the total. The total capital investment needed for the plant was \$464 million, or \$2.01 per annual liters of ethanol. The variable operating cost of the plant varied between \$79 and \$93 million per year, depending on the cost of feedstock. The minimum ethanol-selling price (MESP) was calculated from discount cash flow rate analysis. Changing the feedstock cost from \$0.08/kg to \$0.10/kg increased the MESP from \$0.65/L to \$0.71/L. The analysis estimated the sensitivity of the MESP to variations in the percentage of equity financing (from 0 to 100%), internal rate of return (from 10% to 20%) and federal corporate taxes (from 30% to 60%). The results of the study allow a direct comparison of the MESP for *Miscanthus* as opposed to corn-stover, grass straw and hybrid poplar, and provide a benchmark for future studies of economic feasibility of alternative lignocellulosic feedstocks against each other as well as against conventional gasoline and diesel fuels.

Keywords:

Techno-economic analysis

Biofuels

Miscanthus x giganteus

Lignocellulosic bioethanol

Minimum ethanol selling price (MESP)

1. Introduction

The technology for the conversion of lignocellulosic biomass to ethanol has developed rapidly. Advancements such as optimization of enzyme usage including high specific activity and thermal stability, lower end-product inhibition, improvements in raw materials such as engineered biomass, and effective pretreatment techniques, have led to demonstration, commercial-scale plants constructed in the United States, Canada and some European countries, with operational capacities of several million liters per annum [1].

Despite the advantageous and promising nature of producing ethanol from lignocellulosic biomass and substantial research efforts, significant technical and economic challenges remain. The complexities of different technological steps such as pretreatment, detoxification, hydrolysis, and fermentation contribute to economical non-competitiveness of the conversion process under present conditions. Techno-economic analyses of the complete conversion process could identify the potential areas of technological improvement and/or economic conditions under which production can move beyond bench-scale and demonstration plants toward commercial viability [2]–[6].

Techno-economic analyses of bioethanol production based on spruce, salix and corn stover [7], rice straw [8], aspen, corn stover and hybrid poplar/switchgrass [9], sugarcane bagasse, coffee cut-stems, rice husk and empty fruit bunches [10], kraft pulp [11], olive-stone [12], sugarcane-bagasse [13][10], switchgrass [15], and wood-based products [16], point to the need for further improvements of the technology such as rigorous and innovative pretreatment of feedstock, lowering the cost of enzymes, the

development of more robust industrial strains and alternative approaches for enzymatic hydrolysis and fermentation, and reducing capital costs associated with complex processes [17]. We contribute to this discussion with the techno-economic analysis of the lignocellulosic feedstock which has gained attention for its biomass and potential energy yields, *Miscanthus x giganteus* [18]–[20].

Multiple technological aspects of bioethanol production from *Miscanthus* have been studied in the recent literature, including improving pretreatment methods [21]–[26], enhancing enzymatic hydrolysis and microbial fermentation [24], [27], [28], boosting energy efficiency of the process [29], and understanding the chemical compositions of *Miscanthus* for better processing [30]–[32]. Economics literature on bioenergy from *Miscanthus* has focused on the costs of the feedstock production and delivery to processing plants [20], [33], [34], as well as the implications of large-scale *Miscanthus* production for markets and land use [35]–[38]. However, to the best of our knowledge, no techno-economic analysis has been conducted on *Miscanthus x giganteus* ethanol production process.

We base our analysis on the conceptual model of a cellulosic ethanol plant. We use one of the most comprehensive setups that has been developed by National Renewable Energy Laboratory (NREL) [3], for our analysis. The ethanol plant model has previously been applied to multiple feedstocks including corn stover, grass straw, hybrid poplar and bagasse, alternative pretreatments and various processing methods [39]–[45]. This paper specifically calculates the minimum-ethanol selling price (MESP) of bioethanol produced from *Miscanthus x giganteus* using experimentally generated biomass composition data

89 and considering variations in feedstock costs and further examining how changes in
90 economic parameters such as interest rates, equity financing and corporate taxes affect
91 MESP. The MESP can be used to assess the cost-competitiveness and market penetration
92 potential of cellulosic ethanol in comparison with petroleum-derived fuels and starch- or
93 sugar-based ethanol [41].

94 Most of the techno-economic analyses of the lignocellulosic feedstock that did not
95 employ the NREL model did not aim to estimate an absolute ethanol-selling price but
96 rather curtailed their analysis at the ethanol production cost. The extensive process design
97 and economic analysis conducted by NREL considered an entire cellulosic ethanol
98 manufacturing process and plant assumptions consistent with applicable best practices in
99 engineering, construction and operation [3], [40] .

100 Our study incorporates the data on *Miscanthus* biomass composition documented in
101 the analyses of recently completed field trials in North Carolina. From the agronomic
102 perspective, *Miscanthus* is especially suitable for U.S. Southeast growing conditions [20],
103 [37], [38]. Specifically for North Carolina, climatic conditions including a maximum
104 monthly average temperature of 32 °C and annual precipitation of between 102 and 140 cm
105 [46], make the location favorable for *Miscanthus* cultivation. Moreover, a recent study
106 found *Miscanthus* to be most productive among bioenergy grasses in the state [47].
107 Additional agronomic and environmental advantages of *Miscanthus*, when compared to
108 other lignocellulosic feedstocks, include its cold tolerance, low levels of nitrogen needed,
109 and the associated benefits of reduced nitrate losses to water bodies [19], [48], [49].

The results of the study allow a direct comparison of the MESP for *Miscanthus* as opposed to corn-stover, grass straw and hybrid poplar, and provide a benchmark for future studies of economic feasibility of alternative lignocellulosic feedstocks against each other as well as against conventional gasoline and diesel fuels.

2. Materials and Methods

This study uses the process design and ASPEN modelling information generated using an ASPEN plus V7.2 (Aspen Technology, Burlington, MA; <http://www.aspentech.com/products/engineering/aspen-plus/>), publicly available from NREL [3]. The feedstock considered for the analysis was *Miscanthus x giganteus*.

2.1 Process description and assumptions

The cellulosic ethanol plant model on which this analysis is based was adapted from that used for the NREL 2011 design report [3]. **Figure 1 shows a schematic diagram of the proposed plant outlining some of the major streams associated with material and energy flows in and out of the various sections of the biorefinery plant.** The model was selected for analysis because it exemplifies a typical lignocellulosic ethanol technology globally, and the technical and economic data surrounding the process is easily accessible in a series of publications containing details of the process design [40].

The model plant comprises of 9 sections, including a feed storage and handling area (Area A100), pretreatment and conditioning area (Area B200), enzymatic hydrolysis and fermentation area (Area C300), cellulase enzyme production area (Area D400),

product, solid and water recovery area (Area E500), wastewater treatment area (Area F600), product and feed storage area (Area G700), combustor, boiler and turbogenerator area (Area H800) and a utilities area (Area I900) [40]. The modeled process uses co-current dilute acid pretreatment of lignocellulosic biomass (*Miscanthus*), followed by enzymatic hydrolysis (saccharification) of the remaining cellulose, and by fermentation of the resulting glucose and xylose to ethanol using *Zymomonas mobilis* as the fermenting organism [3].

Based on previous applications of the model, a plant size of 2 million kg/day (2,000 metric tonne/day) was assumed for analysis, with expected operating hours of 8,410 per year (96% uptime), resulting in an annual feedstock requirement of 701 million kg/year [3], [4]. Feedstock is assumed to be delivered to the plant from a satellite storage and processing facility similar to the pioneer uniform-format facility described by Idaho National Laboratory [3]. This uniform-format vision feedstock supply system could potentially incorporate many species and types of biomass making the processing of these feedstocks essentially the same [50]. The feedstock supply system assures that the biomass is received preprocessed and homogenized to a degree, so that the biorefinery receives feedstock with known, uniform-format specifications including particle size distribution (0.004 - 0.006 m), moisture content (20%) and bulk density (144 - 176 kg/m³) [3]. The composition of the *Miscanthus* feedstock used for the analysis was adapted from previous literature based on field trials in North Carolina as 63.7 wt% cellulose, 49.1 wt% hemicellulose and 22.1 wt% lignin, with a moisture content of 20% [51], [52].

For the pretreatment and conditioning, the hydrolysis reactions were assumed to be catalyzed using dilute sulfuric acid and heat from steam generated from the plant [42]. The pretreatment reactor system includes a feedstock receiving system, followed by a vertical vessel with a long residence time for steam heating and potential acid impregnation of the biomass followed by a horizontal pretreatment reactor, which operates at a higher pressure and shorter residence time [3]. Ammonia is employed for pH control in this process. The process also assumed 90% conversion of xylan to monomeric xylose with 5% loss to degradation products, which is consistent with previously obtained experimental results [51].

A 5-day batch fermentation process, based on separate hydrolysis and fermentation (SHF) using *Z. mobilis* at a temperature of 48 °C was assumed for this design [3]. For enzymatic hydrolysis, a cellulase loading of 20 mg enzyme protein/g cellulose was used to achieve a 90% conversion to glucose. Cellulase for this plant is produced using *Trichoderma reesei*, a filamentous fungus that secretes high levels of cellulase enzymes when grown aerobically in the presence of cellulose or other cellulase inducers [53]. Enzymatic hydrolysis and fermentation experiments are typically “integrated” with pretreatment, meaning that a single large batch of pretreated material is used to perform many hydrolysis and fermentation experiments [54].

Other auxiliary sections added to enhance the commercial feasibility of this plant include the wastewater treatment plant, and the combustor, boiler, and turbogenerator plant, which uses solids from the wastewater treatment plant among others to produce steam for electricity production and process heat [3]. The purpose of the combustor, boiler,

and turbogenerator subsystem is to burn various organic by-product streams to produce steam and electricity [54]. It is assumed that approximately 68% of the electricity generated by the boiler is used throughout the plant to power pumps, agitators, compressors, etc., with the surplus sold to the grid for credits [3].

The original NREL study [3] considered only one production process configuration and did not investigate how sensitive production costs are to alternative technological or economic assumptions. Our study is in line with the applications of the NREL base plant design to analyses that compared the implications of varying economic conditions under alternative pretreatment types and/or feedstocks [39], [42]–[45], [55]. To complement and extend these studies, we apply the plant design of [3], to conduct the first such techno-economic analysis of *Miscanthus x. giganteus* ethanol production process.

2.2 Process economic analysis and assumptions

An “nth plant” economic assumption was made for this analysis. This means that the analysis does not describe a pioneer plant. Instead, it is assumed that several plants using the same technology have already been built and are operational, indicating a mature future in which a successful industry of multiple plants has been established [3]. Similar assumptions have been made in [7], [39], [40], [42], [43], [55].

In the process economic analysis, the total capital investment (TCI) was first computed from the total equipment cost, after which the variable and fixed costs were determined [3], [41], [42], [55]. With these costs, a discounted cash flow analysis was used to determine the MESP, which is defined as the ethanol price required to obtain a zero net

present value (NPV) with a finite internal rate of return (IRR). The analysis did not take into consideration any policy factors such as subsidies, mandates or carbon credits [3].

Year 2007 costs and prices were used for the analysis. This is in line with the Department of Energy's 2012 cellulosic ethanol performance cost goals for the period through 2017, allowing for comparison of future feedstocks, conversion technologies and cellulosic biofuels [56].

The estimates of the cost of most of the equipment were obtained from vendor quotes from previous studies conducted by NREL [3], [4], [55]. These quotations were mainly for 2009 and 2010, with some equipment cost quotes as recent as 2015. Employee salaries were obtained for 2009, with the cost of chemicals obtained for the years from 1999 to 2000.

The individual equipment costs were scaled based on the equipment size for the original price quote, using scaling exponents appropriate for each type of equipment [3], [55]. This is because the purchased cost of a given equipment reflects a baseline equipment size. As such, the cost of the equipment based on the size of that equipment derived from the Aspen simulation is calculated using an exponential scaling expression (Equation 1) [4].

$$New\ Cost = (Base\ Cost) \left(\frac{New\ Size}{Base\ Size} \right)^n \quad (Equation\ 1)$$

where n is a characteristic scaling exponent based upon some characteristic of the equipment related to production capacity such as flow or heat duty. The scaling exponents for the specific equipment come from [3] and are listed in the Supporting Information (Table S1).

The scaled equipment costs were then expressed in 2007 dollars and separate installation factors were used for each of the unit operations to obtain individual installed equipment cost [39], [55]. The installation cost is the cost incurred to make the unit operational, which includes wiring, piping and other materials necessary for installation. A factored approach in which multipliers were applied to the purchased equipment cost (Equation 2) was used in determining the installed cost [3].

$$\text{Installed Cost} = (\text{Purchased Equipment Cost}) \times (\text{Installation factor}) \quad (\text{Equation 2})$$

For the plant under consideration, it was assumed that the equipment was manufactured using either carbon or stainless steel with the individual installation factors reported in [39]. Table S2 in the Supporting Information lists the factors used in the study.

In adjusting the equipment cost to a common basis of 2007 dollars, the Chemical Engineering Plant Cost Index [57] for 2007, 2008, 2009, 2010 and 2014 were used (Equation 3), while the costs of chemicals for the plant were adjusted to 2007 dollars using the Industrial Inorganic Chemical Index from SRI consulting [42].

$$2007 \text{ Cost} = (\text{Base Cost}) \times \left(\frac{2007 \text{ Cost Index}}{\text{Base Year Index}} \right) \quad (\text{Equation 3})$$

In determining the TCI, other direct and indirect costs were added to the total equipment cost. Following [3], these additional types of costs included the site development and warehouse costs, and the inside-battery-limits (ISBL) equipment costs for the Areas A100, B200, C300 and D400. Project contingency, field expenses, home-office engineering and construction activities, and other costs related to construction were also added following the procedures outlined in [58]. Table S3 in the Supporting

Information summarizes these categories and additional direct and indirect costs factors used for the computation.

The variable operating costs, which include the cost of raw materials, waste handling charges and by-product credits were incurred only after the plant become operational. The cost of the biomass feedstock was determined from literature sources and the impacts of feedstock cost variability on the MESP were studied. Fixed operating costs included labor costs and various overhead items. A total of 60 employees were assumed necessary to make the plant operational [59]. A 90% labor burden was also applied to the salary total and covers items such as safety, general engineering, general plant maintenance, payroll overhead (including benefits), plant security, janitorial and similar services, phone, light, heat, and plant communications [60]. Overhead charges included maintenance (3.0% of ISBL) and property Insurance [3].

After the determination of the TCI, variable and fixed operating costs, a discounted cash flow rate of return (DCFRROR) analysis was conducted to determine the minimum selling price per liter of ethanol produced [3], [40], [42], [55]. The discounted cash flow analysis is conducted by iterating the selling cost of ethanol until the NPV is zero [61]. This analysis requires that the discount rate, depreciation method, income tax rates, plant life, and construction start-up duration be specified, and, because this plant is assumed to be equity-financed, some assumptions about the loan terms were also required [3]. Table S4 in the Supporting Information summarizes the assumptions used for the DCFRROR analysis.

3. Results and Discussion

Estimation of feedstock cost is not straightforward due to the lack of formal markets for a large part of lignocellulosic biomass and due to site-specific availability and procurement constraints [62], [20], [33], [34], [35]–[38]. Delivered costs can be calculated as the sum of farm gate costs (costs incurred in feedstock handling at farm) and transport-related costs (loading and unloading cost, costs due to transportation from farm to the plant gate, and administrative costs) [62]. The farm gate price may vary from one farm type to the other, depending on the farm size and on agricultural practices (e.g. more or less mechanization, competition between uses, competition between farms, income of farmers), and therefore has a strong spatial variability [62].

There is considerable spatial variability in the breakeven farm-gate price of *Miscanthus*. For our analysis, we consider the two extremes from [63], \$0.04/kg and \$0.06/kg. In arriving at these prices, Khanna et al. [63], used a crop-productivity model operating on GIS-based data to estimate yields of miscanthus across counties in Illinois. Spatially variable yields, together with county-specific opportunity costs of land, were used to determine the spatial variability in the breakeven farm-gate price of *Miscanthus*.

The cost of feedstock collection, processing, storage and transportation from farm-gate to the ethanol plant depends on multiple assumptions including those about the size of the truck, the number of trips per day, the method of loading and unloading the container and the round trip distance to be covered [63]. We use the estimate of \$0.04/kg [3], [39]. Thus, the total feedstock costs considered in this analysis were \$0.08/kg and \$0.10/kg. These boundaries are in line with the logistics cost target of \$0.09/kg for the throat of

biorefinery conversion facility (including grower payment and logistics) set by the U.S. Department of Energy's Bioenergy Technologies Office [5].

3.1 Total cost of equipment

The total purchased cost of equipment for all the sections was \$185,009,231, amounting to an installed cost of \$281,292,951. The installed cost was higher than the amount of approximately \$232.1 million estimated for a plant using corn stover as feedstock [3], but lower than the installed equipment cost of a plant using poplar and organosolv pretreatment, which was approximately \$386 million in 2007 dollars [42]. The differences in the total cost of equipment could be as a result of various factors, including the type of biomass and pretreatment method used, which may require different equipment types. Using an organosolv pretreatment which required the recovery of lignin [42], increased the total cost of equipment of that analysis compared to the present study. The ISBL total cost we estimated was \$116,667,857.

3.2 Total capital investment

The TCI was estimated as total installment cost minus the cost of feedstock and feedstock handling (AREA A100), with the latter considered in the operating cost analysis [3]. The TCI for the entire project was \$464,432,568 (Table 1), yielding a TCI per annual liters of \$2/L. Under the same assumptions, a lower TCI per annual liters of \$0.48/L was estimated for corn-stover [3], likely due to the lower cost of the feedstock and feedstock handling. Furthermore, a higher TCI per annual liter of \$3.54/L was estimated for poplar

compared to the present study due to a higher cost of equipment as a result of the organosolv pretreatment used [42].

3.3 Variable operating cost

Tables 2 and S5 summarize the variable operating costs, based on the costs of feedstock, assumed at \$0.08/kg and \$0.10/kg, respectively. Figure 2 shows the estimated positive relationship between the price of feedstock and feedstock handling and the cost of ethanol. Because biomass feedstocks can be bulky in nature and thus require a large proportion of the cost of biofuel production to be allocated to harvesting and transportation of the feedstock, the costs of producing, harvesting and delivering feedstock to the ethanol production facilities have commonly been named among the major barriers facing the commercialization of biofuel production [64].

3.4 Fixed operating costs

The fixed operating costs are normally incurred whether the plant is in full operational capacity or not. Table S6 shows the recommended number of employees necessary to run the proposed facility and their associated salaries. The number of employees needed was arrived at by considering the likely automation of each area and the number of management and support staff necessary after automation [59]. The total salaries of employees estimated in our analysis, \$2.8 million, was comparable to salaries estimated by Humbird *et al.* [3] and Kautto *et al.* [42], which were \$2.5 million and \$2.7 for corn-stover and poplar-based ethanol plants, respectively.

3.5 Total cost

Figures 3 and S1 show the percentage contributions of the various areas of the proposed plant to the total cost, which is the sum of total cost of equipment, variable operating cost, and fixed operating cost, for feedstock cost of \$0.08/kg and \$0.10/kg, respectively. Studies have shown that feedstock supply (farming and delivery) costs can be up to 35-50% of the delivered cost of ethanol, which means that ethanol supply reliability and cost competitiveness will depend significantly on feedstock production and provision [65]. Our estimation is in line with these results: we found that for the model *Miscanthus* plant, the feedstock supply costs comprise 39% of the total cost for feedstock price of \$0.08/kg (Figure 3) to 44% of the total cost for feedstock price of \$0.10/kg (Figure S1).

The analysis showed that enzyme cost is the second largest contributor (15.7%) to the overall cost, thus reinforcing the suggestion that reducing enzyme cost could lead to improved cost effective biofuels production [66]. The biofuel economy is still challenged by expensive commercial enzymes needed to convert carbohydrates into fermentable sugars, with the price of commercial cellulase from Alltech for instance, set at \$90/kg cellulase in 2004 [67].

The overall proportionately large contributions of feedstock cost, enzyme cost, and wastewater treatment are consistent with analysis done in other works [3], [9], [39], [42]–[44]. Pretreatment methods are still considered expensive in the biofuel industry and have been likewise pointed as the area where further innovations must be implemented to make bioethanol production more cost effective [68].

3.6 Discount cash flow analysis and the MESP

From the discount cash flow analysis conducted, the impact of feedstock price variability on MESP was evaluated. Tables 3 and S7 summarize the assumptions used in the analysis at the two different feedstock prices. The MESP was \$0.65/L and \$0.71/L at feedstock pricing of \$0.08/kg and \$0.10/kg, respectively. These values were higher than the MESP calculated for corn-stover produced ethanol (\$0.57/L) by Humbird *et al.* [3], but lower than the other known MESP estimates. The MESP estimates obtained by Kazi *et al.* [39] for corn-stover ranged from \$0.90/L to \$1.19/L depending on different pretreatment methods considered. Tao *et al.* [44], calculated MESP ranging from 0.71 to 1.08 USD/L for switchgrass, while Kautto *et al.* [42] arrived at a MESP of \$0.81/L for ethanol produced from poplar. As all the studies mentioned assumed the same feedstock feed of 2 Million kg/day that we considered, the differences in MESP are attributable to a variety of factors including the type of feedstock, country of plant location and the type of pretreatment used.

Cash flow projections can serve as tools that investors rely on in their decision making process to support projects. This is because statements of cash flow show how much actual cash the company can generate over a given period. Our analysis projected consistent cash flow over the period (Figure S2), which could boost investor confidence in supporting such large biorefinery projects, making them feasible [69]. The sensitivity of MESP to the cost of feedstock is depicted in Figure 4. Figures 5 and S3 show the contributions of the various sections to MESP in monetary terms, for feedstock cost of

\$0.08/kg and \$0.10/kg, respectively. Echoing the total cost analysis, the MESP decomposition shows that the collective cost of raw materials and waste management contribute significantly to the MESP, with feedstock and its handling being the principal contributor, followed by the cost of cellulase enzyme. The internal generation of energy through the boiler/turbogenerator for the fermentation process from the lignin waste stream helps to bring the cost down as shown on figure 5.

The sensitivity of the MESP to the percentage of equity financing and the after-tax discount rate (the IRR) were also assessed. Figures 6 and S4 depicts these assessments, considering feedstock costs of \$0.08/kg and \$0.10/kg, respectively. It can be seen from Figure 6 that an increase in equity financing coupled with an increase in the IRR results in higher MESP, with a 100% equity financing and a 20% IRR resulting in a MESP of \$1.00/L at a feedstock cost of \$0.08/kg, and a MESP of \$1.07/L (Figure S4) when the feedstock price was increased to \$0.10/kg.

It is important to recognize that some equity financing is necessary to make lignocellulosic biofuels commercially competitive, because such large infrastructural projects might be too expensive or speculative to be carried on a corporate balance sheet [70]. Furthermore, apart from basic financial analysis that should be done for financing such biofuel projects, other factors require consideration by investors, including the understanding of the influence of policy and regulation on the viability of an investment, such as the legal basis and durability of any subsidies, grants, tradable certificates or tax credits [71].

Corporate tax rate has been changing over the years and, because of varying state laws, it varies across locations. Recent analysis [72] considered a federal corporate tax rate of 35% and the additional state tax rates varying from zero to 12%, implying a total corporate tax rate varying between 35% and 47%. To account for potentially wider range of the rates, we analyze the sensitivity of the MESP to corporate tax rates varying even wider, from 25% to 60% (Figures 7 and S5). When the entire range of corporate tax rates is considered, the increase in the MESP in response to an increase in the tax rate is higher for the lower feedstock price considered, both in absolute terms (\$0.42 versus \$0.23) and in relative terms (18.75% versus 8.71%). The IRR is used as a key tool in reaching investment decisions and as a measure to compare the profitability of investments [71]. Depending on the source of the fund providing equity especially in the private sector, such as venture capital funds and based on the maturity of the proposed renewable energy technology, the IRR can range from 10-500% [71]. The assumption of “nth plant economics” allowed this analysis to consider a lower IRR of 10%.

4. Conclusions

The techno-economic analysis of *Miscanthus x giganteus* ethanol production process contributes to the recent, growing literature on plant- rather than bench-scale techno-economic analyses of lignocellulose based bioenergy facilities. The analysis relies on experimentally determined composition of *Miscanthus x giganteus* grown in North Carolina.

In conceptualizing a plant that produces ethanol from miscanthus, an nth-plant assumption, which details a matured and proven technology, made the analysis possible

412 within the context of the factors considered. The production process described, which is
413 based on the conceptualization developed by NREL, with the use of ASPEN models,
414 allowed for a realistic sizing of the plant. The price of miscanthus feedstock has shown to
415 play a major role in the estimated MESP.

416 Comparatively, we found that the average MESP calculated for bioethanol from
417 miscanthus (\$0.65 /L and \$0.71 /L) was higher than the MESP of \$0.57/L estimated in the
418 techno-economic analysis for a U.S. corn-stover based production [2]. However, the MESP
419 that we estimated is lower than other MESP reported in the literature for bioethanol
420 produced from poplar (\$0.82/L) [42] (U.S.) and from corn stover (\$1.60/L) [40](China).

421 The choice of 2007 as a baseline allowed uniformity in prices, and the variability in
422 feedstock prices allowed several sensitivity analyses to be conducted. The results show that
423 the MESP was sensitive to the cost of feedstock, equity financing, internal rate of return on
424 loan facilities and imposition of corporate taxes, with MESP increasing (\$0.65/L to
425 \$0.71/L) with an increase in feedstock, and with a 100 % loan equity, at an IRR of 20 %
426 and a feedstock cost of \$0.10/kg, giving the highest MESP of about \$1.14/L. The findings
427 on the sensitivity to equity financing point to the need for further research on alternative
428 approaches to bioenergy production financing.

429 Multiple government policies and incentives are currently driving the biofuel
430 industry, but eventually biofuels should be able to make an impact on the energy markets
431 on its own merit. Our findings imply that there exist a significant potential to make
432 cellulosic biofuels from miscanthus commercially competitive. Lowering the costs through
433 improvement in the process itself in areas such as enzyme production (15.7% of the total

cost) and pretreatment and feedstock processing and handling (39 - 43.9 % of the total cost), can contribute positively to the rapid commercialization of bioethanol for miscanthus.

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668 Figure 1. Schematic diagram of the major streams of an ethanol biorefinery plant.

Figure 2. Impacts of feedstock price and feedstock processing on cost of ethanol.

Figure 3. Percentage contribution of the various plant areas to the total cost for feedstock price of \$0.08/kg.

Figure 4. Sensitivity of MESP to feedstock cost (40% equity and 10% IRR).

Figure 5. Monetary contribution of various sections to the MESP for feedstock prices at \$0.08/kg.

Figure 6. Sensitivity of MESP to IRR and % equity (8% interest on a 10-year loan) at a feedstock cost of \$0.08/kg.

Figure 7. Sensitivity of MESP to federal corporate tax rate (40% equity and 10% IRR) at feedstock price of \$0.08/kg.

727 Tables

728 Table 1

729 Summary of Project Cost Including Total Direct Cost and Total Capital Investment

Process Area	Purchased Cost	Installed Cost
Area B200: Pretreatment	\$ 22,064,918	\$ 33,097,377
Area B200: Neutralization	\$ 1,776,865	\$ 3,480,848
Area C300: Enzymatic Hydrolysis & Fermentation	\$ 20,481,072	\$ 34,596,863
Area D400: Enzyme Production	\$ 12,178,841	\$ 20,815,262
Area E500: Recovery	\$ 12,309,756	\$ 24,677,507
Area F600: Wastewater	\$ 53,654,259	\$ 53,654,259
Area G700: Storage	\$ 3,113,821	\$ 5,457,737
Area H800: Boiler	\$ 39,575,178	\$ 71,631,877
Area I900: Utilities	\$ 4,347,540	\$ 7,519,353
Totals	\$ 169,502,250	\$ 254,931,082
Warehouse	4.0% of ISBL	\$ 4,666,714
Site Development	9.0% of ISBL	\$ 10,500,107
Additional Piping	4.5% of ISBL	\$ 5,250,054
Total Direct Costs (TDC)		\$ 275,347,957
Prorateable Expenses	10.0% of TDC	\$ 27,534,796
Field Expenses	10.0% of TDC	\$ 27,534,796
Home Office & Construction Fee	20.0% of TDC	\$ 55,069,591
Project Contingency	10.0% of TDC	\$ 27,534,796
Other Costs (Start-Up, Permits, etc.)	10.0% of TDC	\$ 27,534,796
Total Indirect Costs (TIC)		\$ 165,208,774
Fixed Capital Investment (FCI)		\$ 440,556,732
Land		\$ 1,848,000
Working Capital	5.0% of FCI	\$ 22,027,837
Total Capital Investment (TCI)		\$ 464,432,568
TCI per annual liter		\$2.01/L

730 FCI = TDC+TIC TCI=FCI+Land+Working Capital (5.0% of FCI)

731 Table 2

732 Variable Operating Cost with Feedstock Price of \$0.08/kg

Process Area	Steam Description	Usage (kg/h)	Cost (\$/kg)	\$/hour	MM\$/yr (2007\$)	Cent/L Ethanol (2007\$)
RAW MATERIALS						
NONE	Feedstock	104,167	0.067	6,982.50	58.72	25.42
Area B200	Sulfuric Acid, 93%	1,981	0.089	177.73	1.49	0.65
	Ammonia	1,051	0.45	471.48	3.97	1.72
Area C300	Corn Steep Liquor	1,159	0.57	65.89	0.55	0.24
	Diammonium Phosphate	142	0.99	140.44	1.18	0.51
	Sorbitol	44	1.13	49.99	0.42	0.18
Area D400	Purchased Enzyme	0	0.00	0.00	0.00	0.00
	Glucose	2,418	0.58	1,403.60	11.80	5.11
	Corn Steep Liquor	164	0.06	9.35	0.08	0.03
	Ammonia	115	0.45	51.59	0.43	0.19
	Host nutrients	67	0.82	55.34	0.47	0.20
	Sulfur Dioxide	16	0.30	4.99	0.04	0.02
Area F600	Caustic (as pure)	2,252	0.15	336.80	2.83	1.23
Area H800	Boiler Chemicals	0	4.99	1.23	0.01	0.01
	FGD Lime	894	0.20	178.36	1.50	0.65
	Feedstock	0	0.07	0.00	0.00	0.00

Area I900	Cooling Tower Chemicals	2	2.99	7.14	0.06	0.03
	Makeup Water	147,136	0	38.11	0.32	0.14
SUBTOTAL				9,936.43	83.89	36.31
WASTE STREAMS						
Area H800	Disposal of Ash	5,724	0.03	182.14	1.53	0.66
SUBTOTAL				182.14	1.53	0.66
BYPRODUCTS AND CREDITS						
	Grid Electricity	12,814kW		732.55	6.16	2.67
	Area A100 Electricity	859kW		49.13	0.41	0.18
SUBTOTAL				781.69	6.57	2.85
TOTAL VARIABLE OPERATING COST				9,386.02	78.84	38.50

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745 Table 3

746 Assumptions for DCFROR analysis for feedstock price of \$0.08/kg

Assumption	Value
<i>Fixed Capital Investment</i>	\$440,556,732
<i>Equity</i>	40%
Loan Interest	8.0%
Loan Term, years	10
Annual Loan Payment	\$39,393,567
<i>Periodic expenses</i>	
Baghouse Bags (5 yr life)	\$466,183
Working Capital (% of FCI)	5.00%
<i>Salvage Value</i>	
General Plant	0
Steam Plant	0
<i>Depreciation Period (Years)</i>	
General Plant	7
Steam/Electricity System	20
<i>Construction Period (Years)</i>	3
% Spent in Year 0	32%
% Spent in Year -1	60%
% Spent in Year -2	8%
<i>Start-up Time (Years)</i>	0.25
<i>EtOH production/Feedstock use (% of Normal)</i>	50%
<i>Variable Costs (% of Normal)</i>	75%
<i>Fixed Cost (% of Normal)</i>	100%
<i>Discount Rate (Internal Rate of Return [IRR])</i>	10.00%
<i>Income Tax Rate</i>	35.00%
<i>Ethanol Production Rate (MML/yr)</i>	231
<i>Cost Year for Analysis</i>	2007
Minimum Ethanol Selling Price (\$/L)	\$0.65/L

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