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Economics and Uncertainty of Lignocellulosic Biofuel Production from Energy Cane and Sweet Sorghum in South Texas

Juan J. Monge, Luis A. Ribera, John L. Jifon, Jorge A. da Silva, and James W. Richardson

Government support uncertainty, scarce yield information, and the inherent risk in bioeconomic phenomena are some of the deterrents faced by investors in the nascent cellulosic biofuel industry. A financial probabilistic model was developed to contrast the economic feasibility of producing cellulosic biofuels from energy cane and sweet sorghum using three technologies: hydrolysis, pyrolysis, and gasification. Hydrolysis and pyrolysis proved feasible (showed possibilities of a positive net present value) without government support and conditioned to stochastic feedstock yields and biofuel prices. Gasification was feasible with government support. Improved feedstock and biofuel productivity would considerably raise the feasibility probabilities for hydrolysis and pyrolysis without government support.

Key Words: cellulosic biofuel, energy cane, gasification, hydrolysis, Monte Carlo simulation, net present value, pyrolysis, sweet sorghum

JEL Classifications: G17, Q16, Q48

The new Renewable Fuel Standard (RFS2) mandate published by the U.S. Environmental Protection Agency (EPA) established that 36 billion gallons of biofuels have to be blended by 2022, of which 16 billion gallons have to be cellulosic biofuels. Cellulosic biofuels must reduce lifecycle greenhouse gas (GHG) emissions by at least 60% relative to conventional fuels (i.e., petroleum-based fuels) to qualify. With the current surge of cellulosic biomass sources and conversion processes spurred by the RFS2, there is a lot of speculation within the biofuel industry concerning their economic feasibility at the farm and plant levels.

This speculation results from the uncertainty reigning a nascent industry and the lack of a successful story among all of its new investors. According to the U.S. EPA (2013a), the cellulosic biofuel industry will keep transitioning from pilot to commercial-scale facilities well into 2014 because only two companies produced cellulosic Renewable Identification Numbers (RINs) in 2013 (i.e., KiOR and INEOS Bio) and three more are expected to produce in 2014 (i.e.,

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Abengoa, DuPont, and Poet).[1] Considering the uncertainty present in the industry, the EPA has forecasted a likely production range of 8 to 30 million gallons of cellulosic biofuels for 2014. To forecast this production range, the EPA considered scarce production information of the different cellulosic feedstocks under variable climatic, agronomic, and edaphic environments; variation in expected facility startup times; facility production capacities and plans as well as the skepticism surrounding the fate of RFS2 mandate (U.S. EPA, 2013a).

The U.S. Congress has recently begun to consider a number of bills either modifying or repealing the RFS2 as a result of a constant opposition from petroleum-related companies among others (Slating and Kesan, 2013). The opposition to cellulosic biofuels originates from the companies' stance that the annual cellulosic Renewable Volume Obligations (RVOs) are unattainable considering current technological status. This pressure resulted in the modification of the RFS2 in late 2013 decreasing the cellulosic biofuel standard by 1.73 billion gallons.[2] This cellulosic standard reduction will likely result in lower RIN prices in 2014, hence hampering the investment impetus developed in 2013 as a result of high RIN prices.[3]

As a result of the uncertainties outlined, there is extensive literature on economic feasibility studies of new dedicated energy crops processed with different conversion technologies. Most of these studies rely on mathematical programming approaches to determine the cheapest harvesting methodology, transportation alternatives, crop combinations, logistical arrangements, and optimal plant location among others (Haque and Epplin, 2012; Kaylen et al., 2000; Tembo, Epplin, and Huhnke, 2003; Wu, Sperow, and Wang, 2010; You et al., 2011; Zhang et al., 2010). The other large share of the literature on feasibility is a number of techno-economic studies undertaken by engineers (mainly chemical) and developing simple economic analyses assuming deterministic prices for every stage of production (Dutta et al., 2011; Hamelinck, van Hooijdonk, and Faaij, 2005; Humbird et al., 2011; Jones and Zhu, 2009; Manganaro and Lawal, 2012; Phillips et al., 2011; Swanson et al., 2010; Wright et al., 2010). Although these studies model the different stages of the supply chain in detail and are helpful as a starting point, they fail to consider the prevailing uncertainty implicit in the biological and economic processes reflected in yield and price variabilities, respectively.

The combination of capital budgeting and risk modeling has proven to be a very powerful tool in business valuation in recent years as the result of the wide availability of simulation software (e.g., Simetar, @Risk, Crystal Ball, etc.) (Jahangirian et al., 2010; Kwak and Ingall, 2007). The capital budgeting literature lists several methodologies to define the feasibility of a project such as the net present value and real options. Studies using the latter approach (e.g., Schmit, Luo, and Conrad, 2011, Schmit, Luo, and Tauer, 2009; Song, Zhao, and Swinton, 2011) have proven to be more complex and have taken advantage of the value of flexibility in a project appraisal ignored by the net present value. However, the assumptions underlying the real options model do not necessarily apply to projects with high investment barriers and unknown volatilities (Wang and Hallal, 2010). Hence, the net present value, used for years in feasibility studies, is considered to be a much simpler and intuitive approach for lay investors. A more holistic strategy that combines the net present value approach, the Monte Carlo simulation method, and the underlying probability distributions of stochastic biological and economic phenomena (yields and prices) has proven to be a robust

[1] A RIN is a serial number assigned to a biofuel consignment to track its production, use, and commercialization as demanded by the RFS. Obligated parties must either accumulate or buy RINs from the market to comply with the RFS.

[2] The 1.73-billion-gallon reduction of the cellulosic biofuel standard (from the proposed 1.75 billion to 17 million gallons) is part of a larger 2.94-billion-gallon reduction of the 2014 total renewable fuel mandate proposed by the EPA. The reduction motivations are mainly the ethanol "blend wall" and the industry's capacity to produce sufficient volumes of cellulosic biofuels.

[3] The RIN premium is a price mechanism that ensures the compliance of the RFS by obligated parties (i.e., refiners, importers, and blenders). When the market-clearing quantity of biofuels is lower (higher) than the RFS, RIN prices increase (decrease).

alternative for project appraisal in the renewable fuel industry (Outlaw et al., 2007; Palma et al., 2011; Richardson et al., 2007a, 2007b).

Identifying the adequate underlying probability distribution is critical in estimating the chances of success based on a positive-net–present-value criterion. However, estimation of probability distributions in the infant cellulosic industry has been rather difficult as a result of limited or nonexistent historical data on productivity of new dedicated crops. Hence, the consideration and estimation of parametric and nonparametric distributions based on a limited amount of data are fundamental in these circumstances.

There are a handful of feasibility studies that consider risk in some way or the other. However, these studies do not include the holistic financial metrics that encapsulate the annual performance of the project into a set of probabilistic indices such as the net present value (e.g., Linton et al., 2011). They also do not consider the conversion stage (e.g., Song, Zhao, and Swinton, 2011) or differences among conversion technologies currently available (e.g., Palma et al., 2011; Richardson et al., 2007a, 2007b; Schmit, Luo, and Conrad, 2011; Schmidt, Luo, and Tauer, 2009). Analyses that take these factors into account, incorporating probabilistic estimates, would enable investors to identify alternative outcomes with different technologies and allow them to make informed investment decisions.

This study contributes to the literature by developing a probabilistic financial model, based on the Monte Carlo simulation approach, to assess the economic feasibility of cellulosic biofuel production using energy cane and sweet sorghum as feedstocks for three conversion technologies, namely hydrolysis, pyrolysis, and gasification. By simulating conventional pro forma statements, the model generated probabilistic results of unknown financial variables such as the net present value subject to variable feedstock yields and biofuel prices. The study also applied two widely used parametric and nonparametric distribution functions to simulate feedstock yields using historical yields with varying extents of data limitations and to simulate correlated biofuel prices using externally validated price forecasts. Because the short-term existence of the government's support is uncertain, feasibility was assessed based on incentives. Because of the paucity of information on feedstock production costs, biofuel yields, and varying biofuel price forecasts, sensitivity analyses were performed to assess the impacts on the project's chances of success. The model's economic modules are explicitly described allowing users to include additional stochastic variables, policy parameters, and sensitivity scenarios.

Although any dedicated energy crop could be accommodated with the model developed in this study, it will be applied to two promising C4 grasses (namely energy cane and sweet sorghum) and their conversion into biofuels using the three aforementioned conversion pathways. Some of the most promising biofuel feedstock species are C4 grasses resulting from their high biomass production potentials, high resource-use efficiencies, and genetic diversity (van der Weijde et al., 2013). Energy canes have received special attention from the biofuel industry as a result of their high yield potentials, even on marginal lands, high fiber content, and noncompetitive nature with food, feed, or fiber crops (McCutchen, Avant, and Baltensperger, 2008; van der Weijde et al., 2013). Sweet sorghum is attractive as an energy feedstock as a result of its conversion versatility to starch-based, sugar-based, or cellulosic biofuels; its drought tolerance; fast growth cycle (three to five months); and broad genetic diversity (Serna-Saldivar et al., 2012). Furthermore, the U.S. Southeast and Gulf Coast present major competitive advantages for potential commercial production of both energy crops such as long growing seasons with suitable climatic, edaphic, and logistic conditions.

Hence, by assessing the economic feasibility of the aforementioned cellulosic conversion technologies in south Texas using the two promising energy crops as feedstocks, we identified hydrolysis and pyrolysis to be feasible under a reference scenario and without any support from the government considering the possibility of a positive net present value as the feasibility criterion. By moderately increasing feedstock and conversion yields, hydrolysis is the technology closest to becoming an economic success in the near future by presenting a positive net present value 95% of the time.

The following sections of the article will describe: 1) the estimation of the probability distributions for feedstock yields, biofuels, and byproduct prices; 2) the technical and economic data used as parameters linking the feedstock and biofuel production stages; 3) the details of model development for the financial pro forma statements; 4) the results obtained for a reference scenario; and 5) the results for a set of sensitivity scenarios obtained by altering expected feedstock yields and forecasted biofuel prices.

Analytical Framework

Stochastic Variables

The two crops considered in the model were simulated independently and have varying extents of data limitations. They were simulated independently because there are currently no established markets for any of them and also because there is not enough historical data to estimate a correlation among them. Thirty yield observations for energy cane were used in this study and obtained from large experimental field plots (i.e., over an acre) for plant cane and first rattoon for 2010, 2011, and 2012 in Weslaco, Texas (latitude 26°09′45″ N, longitude 97°57′24″ W; elevation 65 feet) managed by the Texas A&M AgriLife Research and Extension Center. Because energy cane feedstock breeding is still in its infancy, yield data across locations and years are limited. However, as a result of the very close similarity between energy cane and sugarcane, it is assumed that variability in energy cane yields will be similar to that of existing commercial sugarcane cultivars. The mean yield of 17 dry short tons (dST) per acre obtained in Weslaco and reported in this study is similar to those reported in other regions such as Louisiana (Salassi et al., 2013a, 2013b) and the Imperial Valley of California (Brummels, 2014). As a result of the well-established sugarcane industry and vast local knowledge on production and logistics in Weslaco, the energy cane yields obtained there were considered reasonable, and perhaps conservative, estimates of what potential investors should expect. The Weslaco data were obtained from fields using agronomic practices similar to those for sugarcane production, thus ensuring that yield variability is representative of an average year for sugarcane. It is, therefore, expected that the impacts from truly stochastic factors (e.g., weather and pests) on yields would resemble those of sugarcane varieties. The high yield potentials of current and future energy cane varieties are expected to buffer any potential spatial and temporal variations. Energy canes are bred for high fiber and low moisture/soluble sugar contents compared with commercial sugar cane. Average yields of energy canes are also much higher with longer rattoons (four to seven years) compared with sugarcane and other feedstocks. Studies are underway to directly compare the performance of potential biofuel feedstock crops under different regions, climate, and field conditions.

Because the number of observations was not enough to fit a parametric distribution, the available observations were used to develop a non-parametrical univariate empirical (UVE) probability distribution and to simulate stochastic energy cane yields following the procedure developed by Richardson (2010) and described in Appendix A. As a result of the limited information on sweet sorghum yields in the area of interest, the GRKS distribution developed by Richardson (2010) was used to simulate yields using 7.5, 10, and 12.5 dST per acre as the assumed minimum, expected, and maximum yields as described in Appendix A, respectively.[4] The assumed yield parameters for sweet sorghum were obtained from Morris (2008) and Turnhollow, Webb, and Downing (2010) for south Texas.

The biofuels (i.e., ethanol and renewable diesel) and byproducts prices (excess electricity) were simulated with the Multivariate

[4] The GRKS is a parametric, two-piece normal distribution that has been widely used in renewable fuels feasibility studies (e.g., Palma et al., 2011; Richardson et al., 2007a, 2007b) and, similar to the triangular distribution, it is fully characterized by a minimum, expected, and maximum value. However, the assumed minimum and maximum values in the GRKS represent the 2.5% and 97.5% quantiles, respectively, whereas for the triangular distribution, they represent the lower and upper bounds of the domain. Hence, in contrast to the triangular distribution, the GRKS allows the stochastic variable to take on values below and above the assumed minimum and maximum, respectively, with low probabilities of occurrence.

Empirical (MVE) distribution developed by Richardson, Klose, and Gray (2000) and briefly described in Appendix A. The historical diesel and electricity prices used to simulate the MVE were obtained from the U.S. Energy Information Agency (EIA) (2012b) for the last 16 years. Historical ethanol prices were obtained from Hart Energy Publishing (2012) for the last 16 years as well. A set of forecasted wholesale prices was obtained from the Annual Energy Outlook (AEO) published by the EIA from 2013 to 2021.[5] The EIA's 2013 AEO presents different economic scenarios of which three were used in this study: the reference, high oil, and low oil price cases as shown in Figure A.2 in the appendix. The average price differential in the reference scenario shown in panel c of Figure A.2 reflects diesel's higher energy content than ethanol and will affect the feasibility of the different technologies.

Feedstock and Biofuel Production Parameters

As a result of seasonal and agronomic limitations in the production of both energy crops, it was assumed that energy cane could potentially supply feedstock from September to May or approximately 70% of the total scheduled supply and the rest would come from sweet sorghum. Because energy canes are relatively new crops, there are currently no robust production costs in the literature. Hence, for this study, energy cane production costs were assumed to be the same as for sugarcane and were obtained from the regional budgets for plant ($936/acre) and rattoon cane ($532/acre) for District 12 in Texas on a per-acre basis (Texas A&M AgriLife Extension, 2012). These costs were averaged out for a plant and four rattoon crops to $613 per acre including variable, fixed, and land rent expenses, not including harvest costs.[6] Sweet sorghum production costs were obtained from the budgets developed for Willacy County in a Texas A&M University's feasibility study (Morris, 2008) on a per-acre basis. All feedstock production costs include cash rents. Besides the feedstock production costs, a return to the farmer was considered as an incentive to switch from any incumbent crop to the new energy crops and was modeled as a percent over production costs. A 20% return was considered to be competitive with the crops currently grown in the region.

Fixed and variable harvest and hauling costs for sugarcane were supplied by the Rio Grande Valley Sugar Growers (RGVSG) (2012). The 30-mile radius considered by the RGVSG for the harvest and hauling costs is large enough to cover the harvested area considered in this study for both energy crops. Relying on previous literature (e.g., Linton et al., 2011), the harvest and hauling costs for sweet sorghum were assumed to be the same as for sugarcane. As a result of the harvesting flexibility offered by energy cane and sweet sorghum, a just-in-time delivery system was assumed in this study (i.e., no storage costs). Both energy crops were assumed to be harvested and transported as silage to the conversion facilities. All production, harvest, and hauling costs have been inflated from their original values to 2012 dollars using the Producer's Price Index (PPI). Table 1 lists the yields and costs considered for each feedstock.

The technical and economic parameters considered for the different conversion technologies, in Table 2, were obtained from the most updated techno-economic studies developed by the National Renewable Energy Laboratory (NREL) and Pacific Northwest National Laboratory (PNNL): Humbird et al. (2011) for hydrolysis; Jones et al. (2009) for pyrolysis; and gasification's high temperature scenario from Swanson et al. (2010). Fixed expenses include employees' salaries, benefits, general overhead, maintenance, insurance, and taxes. The plant's operating expenses include chemicals, waste disposal, and utilities. Because the operating and capital expenses were reported in 2007 dollars in the NREL and PNNL studies, the Chemical Engineering Plant Cost Index (CEPCI) was used to convert them

[5] Wholesale prices for diesel were estimated from EIA's retail price projections by considering a 5-year average wholesale share (75%) of retail prices.

[6] Contrasting the Texas A&M AgriLife sugarcane production costs to LSU AgCenter's, the latter estimated a 2013 cost of $745.87 per acre considering only variable, fixed, and land rent expenses (no harvest costs) for one plant and four rattoon crops (Salassi and Deliberto, 2013).

Table 1. Feedstock Production and Harvest Costs

	Units	Energy Cane	Sweet Sorghum
Production share	Percent	70	30
Production cost	\$/acre	613[a]	390[b]
Return to producer	Percent	10–30	10–30
Fixed harvest and hauling cost[c]	\$/acre	92	92
Variable harvest and hauling cost[c]	\$/dST	10	10

[a] Obtained from Texas A&M AgriLife Extension (2012).
[b] Obtained from Morris (2008).
[c] Obtained from Rio Grande Valley Sugar Growers, (2012) considering a 30-mile radius. Anything within that radius would have the same cost.

to 2012 dollars (Chemical Week Associates, 2012). The numerical relationships using the data just described and linking the feedstock and biofuel production stages of the supply chain are described in detail in Appendix B.

Probabilistic Financial Indices

All the technical and economic random variables estimated in the first two parts were used to develop pro forma statements for a 10-year planning horizon and subsequently to estimate a stochastic net present value variable, as shown in equation (1), that was simulated to obtain the probabilities of investing in a feasible project under different scenarios. The probability distributions of the annual net cash income, ending cash and net worth were also estimated from the pro forma statements and helped to determine the solvency, liquidity, and capital growth under each technology. All of the following formulas were estimated for the different technologies considered in this study; hence, they will not contain the technology subscript (*tech*) for conciseness.

The net present value was estimated by adding the capital generated by the project, reflected by the discounted final year's ($t = T = 10$) net worth (*EndNetWorth*) and total dividends (*TotDividend*) and then subtracting the starting capital (*BegNetWorth*) and the financial expenses incurred in the construction period (*TotConsInt*). The ending net worth, total dividends, and construction interests were brought to the present ($t = 0$) at a specific discount rate (*DiscRate*) as shown in equations (2), (3), and (5), respectively.[7] The discount rate used in the NREL and PNNL studies was 10% as suggested by Short, Packey, and Holt (1995) for conservation and renewable energy investments. Other feasibility studies of biofuel plants used discount rates of 8% (e.g., Schmit, Luo, and Conrad, 2011) and 7.5% (e.g., Richardson et al., 2007a). Hence, as a result of the importance of the discount rate on the estimation of the net present value, different interest rates were considered: 7%, 8%, and 9%. The estimation of the dividends (*Dividend*), beginning assets (*BegAsset*), beginning liabilities (*BegLiab*), and construction period interests (*ConsInt*) is described in Appendix C. The net worth (*NetWorth*) was obtained from the balance sheet explained later. Starting here, variables with a "$\sim$" on top denote stochastic variables.

$$(1)\quad \widetilde{NPV} = \widetilde{EndNetWorth} + \widetilde{TotDividend} - BegNetWorth - TotConstInt,$$

$$(2)\quad \widetilde{EndNetWorth} = \frac{\widetilde{NetWorth_T}}{(1 + DiscRate)^T},$$

$$(3)\quad \widetilde{TotDividend} = \sum_t^T \frac{\widetilde{Dividend_t}}{(1 + DiscRate)^t},$$

$$(4)\quad BegNetWorth = BegAsset - BegLiab,$$

$$(5)\quad TotConstInt = \sum_c (ConstInt_{t-c} \cdot 1 + DiscRate)^{-(t-c)} \quad where \quad t = 0.$$

The annual forecasted net worth (*NetWorth*) was obtained from the pro forma balance sheet and is a function of the stochastic value of assets and liabilities as shown in equation (6). As formulated in equation (7), the annual value of assets (*Asset*) is estimated from the cash reserves (*CashReserve*), the value of land (*LandVal*), and the value of the conversion and steam plants (*PlantVal*) all described in detail

[7] The future value of the construction interests were estimated and aggregated for the first year of operations. This is equivalent to considering the first year of construction as the beginning of the project.

Table 2. Technical and Economic Parameters of the Three Conversion Technologies

	Units	Hydrolysis[a]	Pyrolysis[b]	Gasification[c]
Biofuel		Ethanol	Diesel	Diesel
By-product		Electricity		Electricity
Annual production	Million MBTU (million gallons)	4.6 (61)	9.3 (76)	5.1 (42)
Biofuel yield	MBTU/dST (gal/dST)	5–7 (70–90)	7–9 (55–75)	6–9 (50–70)
Operating expenses	\$/MBTU (\$/gal)	6.5 (0.5)	6.0 (0.7)	2.5 (0.3)
Fixed expenses	Million \$/year	12	19	16
Tax credit[d]	\$/MBTU (\$/gal)	13.2 (1.01)	8.2 (1.01)	8.2 (1.01)
RIN credit[e]	\$/MBTU (\$/gal)	9.4 (0.72)	9.9 (1.22)	9.9 (1.22)
Investment				
Conversion plant	Million \$	378	342	544
Steam plant	Million \$	75		51
Land	Million \$	2	20	10

[a] Obtained from Humbird et al. (2011).
[b] Obtained from Jones et al. (2009).
[c] Obtained from Swanson et al. (2010).
[d] Obtained from FAPRI (2013).
[e] Obtained from FAPRI (2012).

in Appendix C.[8] As shown in equation (8), the annual value of liabilities (*Liab*) was derived from the total payment of a deficit loan (*DefLoan*) and the plant loan balance (*PlantLoan*), all described in detail in Appendix C.

$$\widetilde{NetWorth_t} = \widetilde{Asset_t} - \widetilde{Liab_t}, \tag{6}$$

$$\widetilde{Asset_t} = \widetilde{CashReserve_t} + LandVal_t + \sum_{type} PlantVal_{type,t} \tag{7}$$

$$\widetilde{Liab_t} = \widetilde{DefLoan_t} + PlantLoan_t. \tag{8}$$

The aforementioned ending cash (*EndCash*) was obtained from the pro forma cash flow statement and is a function of the cash inflows and outflows as formulated in equation (9). As shown in equation (10), the cash inflows (*Inflow*) are estimated with the net cash income (*NetCashInc*) resulting from the income statement, beginning cash (*BegCash*), and the interest earned (*IntResEarn*) on the positive cash reserves from the previous year, all described in detail in Appendix C. As shown in equation (11), the cash outflows (*Outflow*) are estimated with the principal payments of the plant loan (*PlantPrinc*), the payment in full of the previous year's deficit loan (*DefLoan*), dividends (*Dividend*), and the income tax (*IncTax*), all described in Appendix C.

$$\widetilde{EndCash_t} = \widetilde{Inflow_t} - \widetilde{Outflow_t}, \tag{9}$$

$$\widetilde{Inflow_t} = \widetilde{NetCashInc_t} + \widetilde{BegCash_t} + \widetilde{IntResEarn_t}, \tag{10}$$

$$\widetilde{Outflow_t} = PlantPrinc_t + \widetilde{DefLoan_{t-1}} + \widetilde{Dividend_t} + \widetilde{IncTax_t}. \tag{11}$$

The aforementioned net cash income (*NetCashInc*) comes from the pro forma income statement and is estimated with the annual revenues and expenditures as formulated in equation (12). The revenues (*Rev*) were estimated from the annual biofuel and by-product production (*FuelPrd*), forecasted stochastic series of prices (*Price*), regional price adjustment factors (*RegAdj*), the second-generation biofuel producer tax credit (*TaxCred*), and the RIN premium (*RINprem*) as formulated in equation (13). The regional adjustment factors, listed in Table C.1 in the appendix, were estimated by subtracting the 2012 average national prices from the 2012 average regional prices

[8] Accounting for depreciation in the annual plant values, there are two types of plants (*type*) depending on the technology: conversion and steam plant. The waste produced by digestion processes is burned in the steam plant generating steam and electricity to be used in the conversion plant or sold to the grid as excess electricity. Hydrolysis and gasification include a steam plant.

(i.e., in Texas), all obtained from Hart's Oxy Fuel News and EIA as previously mentioned. The second-generation biofuel producer tax credit is a federal provision of $1.01/gallon for biofuels that comply with the 60% reduction requirement specified in the RFS2 and renewed every year. The RIN premium is earned by obligated parties when selling the surplus RINs in the market, after complying with their RVOs, and directly translates into a price premium for biofuel producers. Although few cellulosic RINs were produced in 2013, the RIN price included in this study is the average RIN price for advanced biofuels (code D5) for 2012–2013 obtained from FAPRI (2012) and listed in Table 2.[9] As shown in equation (14), expenditures (*Exp*) include delivered feedstock cost (*FeedDlvCost*), total operating (*OpExp*) and fixed expenses (*FixExp*) (all inflated) as well as interest expenses (*IntExp*) estimated in Appendix C. The assumed inflation rate (*InfRate*) was obtained from FAPRI (2013) and Richardson et al. (2013).

$$\widetilde{NetCashInc}_t = \widetilde{Rev}_t - \widetilde{Exp}_t, \tag{12}$$

$$\widetilde{Rev}_t = \sum_{fuel} \widetilde{FuelPrd}_{fuel} \cdot \big(\widetilde{Price}_{fuel,t} + RegAdj_{fuel} + TaxCred_{fuel} + RINprem_{fuel}\big) \tag{13}$$

$$\widetilde{Exp}_t = \left[\sum_{crop} \big(\widetilde{FeedDlvCost}_{crop} + OpExp \cdot \widetilde{FuelPrd}\big) + FixExp\right] \cdot InfRate_t + \widetilde{IntExp}_t. \tag{14}$$

The model also considers a startup period, in months, once the plant is already built and operating. Because the conversion plant does not run at its full capacity during this startup period, revenues, variable costs, and fixed costs are assumed to be percentages of full-capacity operations as listed in Table C.1 in the appendix.

[9] Cellulosic diesel (code D7) and biofuel (D3) RINs can be used to meet the standard for advanced biofuels, which also include biomass-based diesel (D4) and advanced biofuel (D5). RIN prices exist for D4 and D5. The prices reported take ethanol as a reference, whereas a 1.7 ratio is considered for renewable diesel.

Results

Stochastic Feedstock Yields

The probability density functions (PDFs) shown in Figure A.1 in the appendix were obtained by simulating yields 500 times using the aforementioned UVE and GRKS distributions for energy cane and sweet sorghum, respectively. The mean and standard deviation of energy cane were 16.83 and 2.95 dST per acre, respectively. The mean and standard deviation of sweet sorghum were 10 and 1.25 dST per acre, respectively. The probabilities of obtaining yields higher than the mean were 52% and 50% for energy cane and sweet sorghum, respectively.

Stochastic Biofuel Prices

As previously mentioned, ethanol, diesel, and electricity prices were considered stochastic and simulated with an MVE distribution over a 10-year horizon using EIA's scenarios as the forecasted means. Panels A and B in Figure A.3 in the appendix illustrate the annual variation, represented by percentiles, around EIA's reference case forecasted means for ethanol and diesel prices, respectively. Contrasting both fan graphs, the price distribution for diesel is more skewed to the left (i.e., longer right tail) than for ethanol meaning that there is a higher probability (61% in average) that the annual price of diesel will be less than that of its mean annual price compared with ethanol (56% in average). These price distributions will directly affect annual revenues and, hence, annual net cash income as formulated in equation (12) and depicted in Figure D.1 in the appendix. The fan graphs of the net cash income for the three technologies show the same variation patterns as their respective biofuels' price distributions illustrated in Figure A.3 in the appendix.

Expected Cost Structure

By considering mean feedstock yields and biofuel prices, panel A of Figure 1 shows the breakdown of the annual cash costs of each technology for the second year of plant operations. The annual cash costs include the expenses

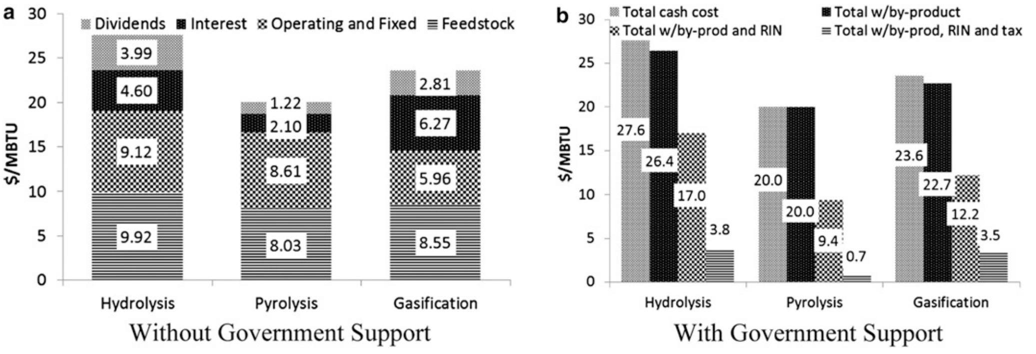

Figure 1. Expected Annual Cash Costs for Conversion Technologies in $ per MBTU

included in the income statement as formulated in equation (14) plus the dividends paid to the investors.[10] From these figures it is evident that the largest annual cash cost shares by technology are taken by feedstock costs for hydrolysis (36%); operating and fixed expenses for pyrolysis (43%); and the expenses incurred from the capital borrowed (dividends and interests) for gasification (50%). Evidence of the high capital requirements for gasification is the high investment-to-nameplate ratio for gasification (14) compared with hydrolysis (7) and pyrolysis (5).

Panel B of Figure 1 shows the mean annual cash costs for the three different technologies with and without the byproduct (electricity), RIN premium, and tax credits in place for the second year of plant operations. Although the premium and credit were included in equation (13) as revenue additions, they are included as cost reductions in Figure 1 to give the reader a clear idea of the economic support provided by the federal government through the tax credit and the beneficial outcome from the creation of the RIN market by the RFS2. The annual cash cost could be lower because the actual cellulosic RIN price (D3 or D7) will probably be higher than the conservative advanced RIN used in this study. Because the tax credit and RIN premium benefit only cellulosic biofuel producers and blenders (and not the other RFS2 categories), the emission-reduction compliance, determined through life cycle analysis, would be of significant importance. According to the U.S. EPA (2010b, 2013b), energy cane-based biofuels produced from hydrolysis, pyrolysis, and gasification qualify for cellulosic D7 RINs by emitting 112%, 60%, and 84% less GHGs (without land-use change emissions) than its petroleum-based counterparts, respectively.[11] The graphs depicted in Figure 1 are listed on a per-gallon basis in Figure E.1 in appendix E.

Because the feedstock cost in the entire biofuel supply chain is anticipated to be a significant cost component (McCutchen, Avant, and Baltensperger, 2008), the U.S. Department of Energy (DOE) has proposed a delivered

[10] Because interests are the financial costs from using borrowed capital (i.e., loan), dividends were considered annual cash costs because they represent the financial cost from using the capital obtained from public sources (i.e., investors).

[11] Energy cane production and pyrolysis emissions were obtained from the U.S. EPA (2013b). Hydrolysis and gasification emissions were obtained from the U.S. EPA (2010b). Hydrolysis, pyrolysis, and gasification produce approximately –12, 40, and 15 kg of CO_2 equivalent per MBTU, respectively, without considering emissions from land-use change. These were compared with the 98 and 97 kg of CO_2 equivalent per MBTU emitted by petroleum-based gasoline and diesel in 2005, respectively. Because there are no official studies treating land-use change GHG emissions from energy cane production, a close approximate would be the domestic and international emissions estimated for switchgrass by the U.S. EPA (2010a) of –2.5 kg and 15 kg of CO_2 equivalent per MBTU, respectively. By considering these figures, the biofuels produced from hydrolysis and gasification would still qualify for the cellulosic RFS. The biofuels produced through pyrolysis would not qualify when adding the land-use change figures but it is worth stressing that no by-product has been considered for this technology in the present study and this would definitely reduce its emissions.

feedstock cost in the range of \$30 to \$40 per dST to hold down the overall cost of biofuels. Panel B of Figure E.2 in appendix E shows that at current production, harvest, and hauling costs, and for a 20% (over production costs) return to the farmers, DOE's goal is quite close to the observed delivered feedstock cost range of \$48–80 per dST. With high probabilities of obtaining yields above the average for energy cane in Weslaco (17 dST per acre) as shown in Figure A.1 in the appendix, there are high probabilities (60%) of reducing the feedstock standing cost to less than its average of \$45 per dST as shown in panel A of Figure E.2 and the delivered cost to less than \$62 per dST (60%) as shown in panel B of Figure E.2. The previous cost reductions do not include possible reductions to the farmers' return, which would lower the delivered feedstock cost even further.

Feasibility in Reference Scenario

With the stochastic delivered feedstock costs depicted in panel B of Figure E.2 and the correlated stochastic prices, the net present value, net cash income, ending cash, and net worth were simulated 500 times using the results from all of the pro forma statements and were summarized as distribution functions of key output variables. The level of detail considered when creating the financial model allows the estimation of several important financial metrics from the pro forma statements. However, as a result of their holistic representation of a project's performance, and for brevity, the aforementioned metrics were the only ones used in this study to contrast the feasibility of the different conversion technologies. Furthermore, the net present value was assessed under current circumstances (reference scenario) and under probable short-term and long-term future scenarios. The reference scenario considers the crop yield distributions shown in Figure A.1 in the appendix and assumes a 20% return to farmers; current biofuel yields of 6.11, 7.50, and 7.99 MBTU per dST for hydrolysis, gasification, and pyrolysis, respectively; a discount rate of 8%; and no government incentives (tax credit and RIN premium). It also uses the EIA's 2013 reference case as the price forecast.

Figures D.1, D.2, and D.3 in appendix D show the annual progression of the forecasted net cash income, ending cash, and net worth and their inherent risk. As shown in Figure D.1 in the appendix, the high probabilities of a positive annual net cash income for all technologies are the result of mean biofuel prices being higher than annual cash costs (not including the dividends). However, the high principal payments of the plant and deficit loans reduce the probabilities of positive annual ending cash for pyrolysis and gasification. Evidence of this is Figure D.2 in the appendix showing most of the 50th and 75th percentiles of pyrolysis' and gasification's annual probability distributions on the negative side, respectively. The probabilities are higher for pyrolysis because the average ending cash becomes positive in six years compared with a negative and decreasing average for gasification as shown in panel C of Figure D.2 in the appendix. The negative ending cash balances result in zero cash reserves (assets) and increasing deficit loans (liabilities), hence decreasing the annual ending net worth for gasification as shown in panel C of Figure D.3 in the appendix. As depicted in panel B in Figure D.3, the probabilities of a positive annual net worth are higher for pyrolysis than for gasification as a result of the positive average ending net worth starting in year nine.

Figure 2 shows the CDFs created to contrast the feasibility probabilities of the three technologies under the reference scenario using the net present value. The probabilities of the project not being feasible (net present value <0) can be identified in the graph where the sigmoidal curves intercept the vertical axis. Therefore, the probabilities of the project being feasible (net present value > 0) are estimated by subtracting the intercept from one or: $prob(NPV > 0) = 1 - prob(NPV < 0)$.

As shown in Figure 2, under the reference scenario, hydrolysis is the technology with the highest probabilities of being economically feasible (67%) with a mean net present value of \$33 million and a standard deviation of \$87 million. Although pyrolysis results in a negative mean net present value of \$35 million, its high standard deviation (\$164 million) gives the project a low probability of being feasible

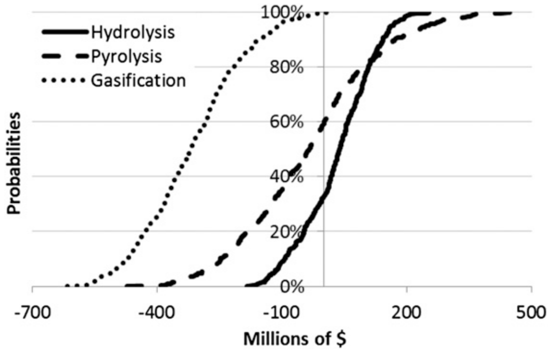

Figure 2. Cumulative Density Function Approximation of the Net Present Value for Three Different Cellulosic Conversion Technologies without Credits

(41%). Gasification is the only technology that, under current circumstances, is not feasible at all with a negative mean net present value of $317 million and a standard deviation of $122 million.

The disparity of feasibility probabilities among technologies can be explained by the constant price differential and the relative cost breakdown previously shown in panel A of Figure 1. The high chances of hydrolysis being feasible are the result of the higher forecasted ethanol prices compared with diesel, which is the biofuel produced by pyrolysis and gasification. Feedstock cost, being hydrolysis' highest cost, and its high probabilities (60%) of being less than average ($62/dST), as shown in panel B Figure E.2, also explain hydrolysis' high feasibility chances. The lower diesel prices, compared with ethanol, result in lower feasibility probabilities for pyrolysis and gasification. Furthermore, as shown in panel A of Figure 1, gasification shows the highest annual capital cash costs (interest and dividends) among the three technologies resulting in infeasibility in the near term.

Economic Success and Sensitivity Analyses

As previously stated, a technology is considered feasible when the probabilities of a positive net present value are higher than zero. However, an investor might adopt a more stringent criterion to consider a technology feasible by avoiding the chances of a negative net present value as much as possible. For example, Richardson, Johnson, and Outlaw (2012) established that a project is considered an "economic success" if the chances of a positive net present value are 95% or higher. Under the "economic success" premise, several sensitivity analyses were performed on multiple parameters to assess their implications on the chances of success for the different technologies.

The reason behind simulating yields and prices using stochastic percent deviations as formulated in equations (A.6) and (A.11) in Appendix A was to perform the sensitivity analyses by altering their means and trends, respectively. Hence, forecasted price trends were altered to account for the different economic scenarios considered in EIA's 2013 forecasts with and without the tax credit and RIN premium as shown in Table 3. As expected, as oil prices increase, the feasibility probabilities of the technologies that produce renewable diesel increase. The relationship between oil prices and the feasibility of hydrolysis is not as straightforward because, according to EIA's forecast shown in panel A of Figure A.2 in the appendix, ethanol prices are higher in the reference scenario than in the other scenarios in some instances. Although no technology can be considered an economic success without the credits, all show different degrees of feasibility (even gasification) with high oil prices, pyrolysis becoming the most feasible one. With the current tax credit and RIN premium in place, hydrolysis and pyrolysis become economically successful. Gasification becomes an economic success only with government incentives and high oil prices.

Sensitivity from Operating and Capital Expenses

However, with the ephemeral nature of the tax credit (annually renewed) and disapproval of the RFS by the oil industry, the economic incentives that would benefit cellulosic biofuel producers might not exist in the short run. Hence, it would be economically objective and appropriate to identify the parameters and magnitudes that would make the three technologies feasible, or economically successful, without the credit incentives. For example, Table 4 shows the implications of capital and operating expense

Table 3. Probabilities of Obtaining a Positive Net Present Value with and without Credit Incentives for Three Forecast Scenarios from the U.S. Energy Information Administration's 2013 Annual Economic Outlook

Tax and RIN Credits	Annual Energy Outlook forecasts	Cellulosic Biofuel Technologies		
		Hydrolysis	Pyrolysis	Gasification
No credits	Low oil prices	56%	9%	0%
	Reference	67%	41%	0%
	High oil prices	66%	84%	8%
Credits	Low oil prices	100%	100%	61%
	Reference	100%	100%	82%
	High oil prices	100%	100%	95%

reductions on the technologies' feasibility chances without the credits in place. Reductions of 25% are considered possible in the short term, whereas 50% reductions are considered long-term scenarios. Hence, under all of the assumptions considered in the reference scenario, hydrolysis and pyrolysis would become economically successful in the short and long term, respectively. Although gasification would not be considered economically successful even in the long term by reducing its expenses by half, its feasibility chances increase to 71%.

Sensitivity from Yields and Discount Rate

Because the NREL and PNNL studies considered different feedstock types, the yields were not representative for energy cane and sweet sorghum.[12] Hence, sensitivity analyses were performed by altering the biofuel conversion yield as listed on the different rows of panels A–C in Table 5. To address the uncertainty on energy cane production costs and possible genetic improvements, the energy cane yields were also altered, leaving the historic percent deviations (i.e., risk) intact, to assess their impacts on the plant's feasibility as listed in the columns of panels A–C in Table 5. The discount rate was also modified as a result of its high impact on the net present value computations.

As shown in panel A of Table 5, assuming discount rates of 7% and 8%, hydrolysis would become economically successful if energy cane and ethanol yields were to increase to 20 dST per acre and 6.9 MBTU per dST (90 gal/dST), respectively. The net present value for pyrolysis is somewhat sensitive to the discount rate and yields to the extent of increasing its feasibility chances from 41% in the reference to 75% with a discount rate of 7% and increased yields as listed in panel B of Table 5. By considering additional sensitivity scenarios (not shown in the tables), pyrolysis would become a successful alternative by combining several possible short-run scenarios such as a joint reduction of its operating and fixed expenses by 25% and capital expenses by 10%, reducing returns to farmers to 15%, high yields for feedstock (20 dST/acre) and biofuel (9.22 MBTU/dST), and a low discount rate of 7%. The net present value for gasification is not sensitive enough to the discount rate and yields to substantially increase its feasibility chances to become an economic success as shown in panel C of Table 5.

Energy cane yields were considered as low as 10 dST per acre to reflect current regional sugarcane yields and to demonstrate the low feasibility chances obtained when considering sugarcane (instead of energy cane) as the main feedstock under the three different technologies. This is the main reason why cellulosic ethanol from sugarcane is not currently produced.

Sensitivity analyses were also performed on the return that farmers should receive to switch from incumbent crops to dedicated energy crops. Presented in Appendix F, this analysis

[12] Although corn stover and hybrid poplar were the feedstocks used in the NREL and PNNL studies, it was assumed in this study that energy cane and sweet sorghum could also be converted with the same technological specifications.

Table 4. Probabilities of Obtaining a Positive Net Present Value by Reducing the Capital and Operating Expenses by Different Percentages and without Credit Incentives

Operating and Fixed Expenses Reduction	Capital Expenses Reduction								
	Hydrolysis			Pyrolysis			Gasification		
	0%	25%	50%	0%	25%	50%	0%	25%	50%
0%	67%	92%	100%	41%	61%	80%	0%	8%	41%
25%	79%	99%	100%	62%	80%	95%	1%	12%	56%
50%	89%	100%	100%	81%	95%	99%	3%	20%	71%

is useful for estimating the price that the conversion plant should pay for feedstocks at the field and gate level without compromising profitability.

Conclusions

A Monte Carlo-based probabilistic financial model was developed to assess and contrast the chances of economic feasibility for cellulosic biofuels production (i.e., ethanol and diesel) from two promising energy crops (i.e., energy cane and sweet sorghum) under three different conversion technologies: hydrolysis, gasification, and pyrolysis. The stochastic variables considered were feedstock yields and biofuel prices. Feedstock yields were simulated independently using the UVE and GRKS distribution functions for energy cane and sweet sorghum, respectively. An MVE distribution function was used to simulate biofuel prices and correlate their inherent risk. The feasibility chances were assessed and contrasted under current technological and economic circumstances and under possible short- and long-run scenarios. By explicitly describing the model's technological and economic relationships, this study provides analysts with enough versatility to include additional policy parameters, stochastic variables (assuming appropriate distribution functions), and perform additional sensitivity analyses creating near-term future scenarios.

In the reference scenario, the probabilities of reducing the delivered energy cane costs below average ($61 per dST) are high (60%) as a result of the high probabilities (52%) of obtaining above average (17 dST per acre) yields. The combination of high forecasted ethanol prices (compared with diesel) and probable low delivered feedstock costs result in hydrolysis being the technology with the highest feasibility chances (77%) without considering government incentives. Although hydrolysis is not considered an economic success (net present value is not greater than zero 95% of the time) under current circumstances and no government incentives, it would become a successful alternative in the short run either by reducing its expenses (25%) or increasing energy cane (18%) and ethanol yields (13%). Ethanol yields higher that the one assumed for the reference scenario might already be attainable in the industry; however, there are no known records in the literature with such estimates for energy cane and sweet sorghum. Advances in feedstock breeding and cropping systems indicate that energy cane yields of 20 dST per acre are feasible in the near future. If this is the case and by keeping the production, harvesting and transportation costs at the same levels as incurred for commercial sugarcane, hydrolysis would be the alternative that offers the greatest potential in the U.S. Southeast and Gulf Coast regions without any plant expense reductions and government incentives.

Although low forecasted diesel prices (compared with ethanol) explain the lower feasibility chances of the other two conversion alternatives compared with hydrolysis, the high capital expenses required for gasification also made this technology infeasible in the short term. The three technologies become economically successful when considering the economic incentives provided by the government (tax credit and RIN premium) and high oil prices. However, these economic incentives might not exist in the near future as a result of their annual renewal frequency (tax credit) and latest criticism to the RFS2 by some sectors in the economy and government (RIN prices).

Table 5. Probabilities of Obtaining a Positive Net Present Value by Altering the Discount Rate, Expected Energy Cane, and Biofuel Yields without Credits

(a) Hydrolysis at Reference Prices					
Expected energy cane yield (dST/ac)		10	15	17	20
Expected production costs ($/dST)		61	41	36	31
Discount rate		Ethanol yield in MBTU (gal) /dST			
7%	5.34 (70)	2%	38%	65%	86%
	6.11 (80)	4%	54%	73%	92%
	6.87 (90)	11%	65%	79%	96%
	5.34 (70)	0%	33%	57%	82%
8%	6.11 (80)	3%	45%	67%	89%
	6.87 (90)	6%	57%	75%	95%
	5.34 (70)	0%	26%	48%	77%
9%	6.11 (80)	2%	37%	63%	85%
	6.87 (90)	3%	48%	70%	90%
(b) Pyrolysis at Reference Prices					
Expected energy cane yield (dST/ac)		10	15	17	20
Expected production costs ($/dST)		61	41	36	31
Discount rate		Diesel yield in MBTU (gal) /dST			
7%	6.76 (55)	3%	19%	28%	51%
	7.99 (65)	8%	30%	45%	64%
	9.22 (75)	11%	42%	57%	75%
	6.76 (55)	3%	17%	26%	48%
8%	7.99 (65)	7%	27%	41%	61%
	9.22 (75)	10%	39%	57%	71%
	6.76 (55)	3%	15%	24%	43%
9%	7.99 (65)	5%	25%	38%	58%
	9.22 (75)	9%	35%	51%	69%
(c) Gasification at High Oil Prices					
Expected energy cane yield (dST/ac)		10	15	17	20
Expected production costs ($/dST)		61	41	36	31
Discount rate		Diesel yield in MBTU (gal) /dST			
	6.14 (50)	0%	2%	7%	16%
7%	7.50 (61)	0%	5%	10%	24%
	8.60 (70)	0%	7%	14%	30%
	6.14 (50)	0%	2%	4%	13%
8%	7.50 (61)	0%	3%	8%	19%
	8.60 (70)	0%	5%	11%	25%
	6.14 (50)	0%	0%	3%	10%
9%	7.50 (61)	0%	2%	6%	15%
	8.60 (70)	0%	3%	8%	19%

Although high forecasted ethanol prices explain hydrolysis' high feasibility chances, the implications of the 2014 RFS modifications will definitely affect the technology's feasibility if the rule is finalized in early 2014.[13] Because the 2013 RFS required refiners to blend ethanol in excess of what the transportation fuel infrastructure could handle (10% of the gasoline volume consumed), refiners had to pay abnormally high RIN prices sparking investment on new cellulosic conversion technologies. Biofuel producers will be negatively impacted with lower RIN prices resulting from the reduced, combined ethanol volumetric mandate proposed by the EPA in the 2014 RFS. This will force ethanol coming from corn, sugarcane, and energy cane to compete for shares of a shrinking ethanol market, hence lowering RIN prices and reducing hydrolysis' feasibility chances with government support as shown in Table 3. Nevertheless, it has been demonstrated in this study that hydrolysis can become an economic success by improving certain agronomic and technological factors without any government support. Pyrolysis and gasification are not heavily affected by the 2014 RFS modifications because biomass-based diesel will stay at the same volume as the one adopted in 2013.

A critical limitation worth stressing is that all of the conclusions obtained in this study are based on the experimental plots from a single location in south Texas (i.e., Weslaco). Hence, an opportunity to further improve this study is open by including information from different locations in Texas and in the United States. Although expected yields and variability from different locations would definitely enhance the conclusions of this study, the expected yields obtained in Weslaco are comparable to the yields obtained in Louisiana and the Imperial Valley of California.

[13] It is worth mentioning that EIA's 2013 forecasts are based on market and technological conditions whereas the RFS is a flexible policy modified every year. Hence, the potential modifications to the RFS in 2014 are not reflected in EIA's 2013 forecasted ethanol wholesale prices and quantities because these are estimated using forecasted gasoline demand for E10 blends and forecasted flexible fuel vehicles consumption of E85 blends.

Another limitation worth mentioning is that the figures on life cycle emission reductions previously listed in the results section for each technology do not include emissions from domestic and international land conversion because there are no official studies treating energy cane specifically. However, according to the U.S. EPA (2013b), previous life cycle analysis performed to switchgrass can be applied to energy cane to obtain potential land-use change GHG emissions because both are perennial grasses. The potential GHG emitted by the production of energy cane would not have any adverse impacts beyond what was considered for switchgrass because energy cane offers higher yields and the crops it would displace in the southern United States (pasture, rice, commercial sod, cotton, or alfalfa) are not as widely traded as soybean or wheat (U.S. EPA, 2013b).

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Appendix A: Probability Distribution Generation for Stochastic Variables

Univariate Empirical Probability Distribution for Energy Cane Yields

The UVE, previously described in Richardson (2010), is a simpler version of the multivariate empirical (MVE) probability distribution developed by Richardson, Klose, and Gray (2000) where the random and deterministic components of the yield variable are separated as formulated in equation (A.1). In this study, the energy cane mean yield $\left(\overline{Yield}\right)$ of 17 dry short tons (dST) per acre is considered to be the deterministic component assuming that yield will not improve with time.

(A.1) $$YldDev_{crop,obs} = Yield_{crop,obs} - \overline{Yield}_{crop},$$

(A.2) $$\%YldDev_{crop,obs} = YldDev_{crop,obs} / \overline{Yield}_{crop},$$

where *crop* is the set of crops (only energy cane in this case), *obs* is the set of observations, *Yield* represents the observed energy cane yields, *YldDev* represents the random components or deviations from the mean, and *%YldDev* represents the percentage deviations from the mean. The deviations are sorted (*Sort*) from minimum to maximum in equation (A.3) and a cumulative density function (CDF) is generated for the UVE by assigning probabilities to each *Sort* as formulated in equation (A.4).

(A.3) $$Sort_{crop,obs} = Sorted\left(\%YldDev_{crop,obs} \text{ from min to max}\right),$$

(A.4) $$\begin{aligned} &P\left(Pmin_{crop}\right) = 0.0,\\ &P\left(Sort_{crop,1}\right) = \left(1/N_{crop}\right) \cdot 0.5,\\ &P\left(Sort_{crop,2}\right) = \left(1/N_{crop}\right) + P\left(Sort_{crop,1}\right),\\ &\vdots\\ &P\left(Sort_{crop,N}\right) = \left(1/N_{crop}\right) + P\left(Sort_{crop,N-1}\right),\\ &P\left(Pmax_{crop}\right) = 1.0, \end{aligned}$$

where *N* is the total number of observations and *Pmin* and *Pmax* are the pseudo-minimum and maximum values "defined to be close to the observed minimum and maximum and cause the simulated distribution to return the extreme values with approximately the same frequency as they were observed in the past" and estimated as following (Richardson, Klose, and Gray, 2000):

$$\text{(A.5)} \quad \begin{aligned} Pmin_{crop} &= Minimum\,Sort_{crop,obs} \cdot 1.0001, \\ Pmax_{crop} &= Maximum\,Sort_{crop,obs} \cdot 1.0001. \end{aligned}$$

Because any CDF maps the number in the domain to a probability between zero and one, the inverse transform is used as the pseudo-random number sampling method. Hence, a random number generator, following a uniform distribution, produced uniform standard deviates (USDs) that were mapped through the CDF to obtain random percentage deviates from the mean $(\widetilde{\%YldDev})$. The generation of USDs was performed with the Excel Add-in SIMETAR using the Latin Hypercube sampling method developed by McKay and Conover (1979) and the Mersenne Twister random number generator developed by Matsumoto and Nishimura (1998). The random variable itself $(\widetilde{Yield})$ was estimated by adding the percentage deviations to the mean as shown in equation (A.6). Starting here, variables with a "$\sim$" and "^" on top denote stochastic and estimated variables, respectively.

$$\text{(A.6)} \quad \widetilde{Yield}_{crop} = \overline{Yield}_{crop} \cdot \left(1 + \widetilde{\%YldDev}_{crop}\right).$$

GRKS Probability Distribution for Sweet Sorghum Yields

The GRKS is a parametric, two-piece normal distribution that has been widely used in feasibility studies (e.g., Palma et al., 2011; Richardson et al., 2007a, 2007b) and, similar to the triangular distribution, it is fully characterized by a minimum, expected, and maximum value. However, the assumed minimum and maximum values in the GRKS represent the 2.5% and 97.5% quantiles, respectively, whereas for the triangular distribution, they represent the lower and upper bounds of the domain. Hence, in contrast to the triangular distribution, the GRKS allows the stochastic variable to take on values below and above the assumed minimum and maximum, respectively, with low probabilities of occurrence. The inverse transform sampling method was used to simulate the sweet sorghum yields. The assumed yield parameters for sweet sorghum are listed in equation (A.7) in dST per acre.

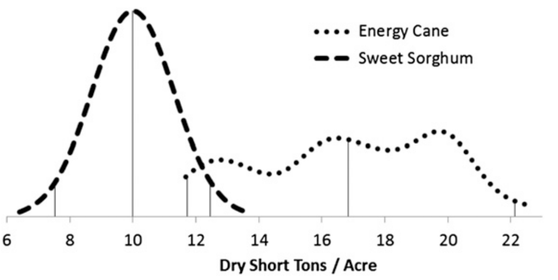


Figure A.1. Probability Density Function Approximations for Dedicated Energy Crop Yields

$$\text{(A.7)} \quad \widetilde{Yield}_{crop} \sim GRKS(7.5, 10, 12.5).$$

Multivariate Empirical Probability Distribution for Biofuel Prices

The MVE is a non-normal alternative distribution that uses limited data on historical prices for different commodities and a correlation matrix to represent intra-temporal (across commodities) and inter-temporal (across time) relationships. The MVE is equivalent to simulating the random variables using a linear copula. Generation of CDFs for each price variable was similar to the one followed for the energy cane yields with two exceptions: 1) the price deviations (*PrcDev*) are detrended as shown in equations (A.8) and (A.9); and 2) the USDs used for the inverse transform of each price variable are now correlated.

$$\text{(A.8)} \quad \widehat{Price}_{fuel,hist} = \hat{a}_{fuel} + \hat{b}_{fuel} \cdot Trend_{hist},$$

$$\text{(A.9)} \quad PrcDev_{fuel,hist} = Price_{fuel,hist} - \widehat{Price}_{fuel,hist},$$

$$\text{(A.10)} \quad \%PrcDev_{fuel,hist} = PrcDev_{fuel,hist} \Big/ \widehat{Price}_{fuel,hist},$$

where *fuel* is the set of biofuels and byproducts, *hist* is the set of historical years, *Trend* represents the trend, $\hat{a}$ represents the estimated intercepts, $\hat{b}$ represents the estimated trend parameters, $\widehat{Price}$ the estimated prices, *PrcDev* the random components, and *%PrcDev* the percent deviates. As explained in detail in Richardson, Klose, and Gray (2000), a correlation matrix was estimated and used to correlate the USDs of the different price variables using the residuals from equation (A.8). These USDs were mapped to the percentage deviates from

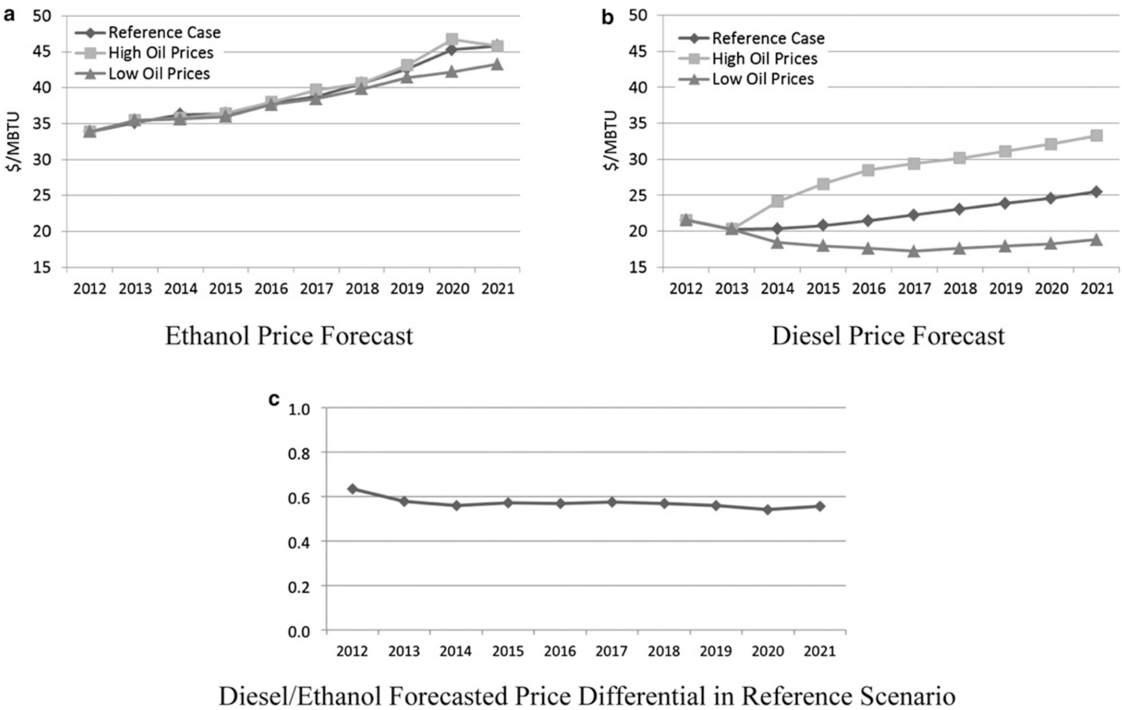


Figure A.2. Nominal Wholesale Price Forecasts for Three Economic Scenarios from the U.S. Energy Information Administration's 2013 Annual Energy Outlook

the mean $(\widetilde{\%PrcDev})$ using the different CDFs by way of the inverse transform. The random price variables $(\widetilde{Price})$ for the forecasted years (t) were estimated by adding the percentage deviations to a set of forecasted wholesale prices ($PrcFor$) as shown in equation (A.11).

$$\text{(A.11)} \quad \widetilde{Price}_{fuel,t} = PrcFor_{fuel,t} \cdot \left(1 + \widetilde{\%PrcDev}_{fuel}\right).$$

Appendix B: Feedstock and Biofuel Production Relationships

The model is built on the premise that the harvested feedstock acreage is fixed and the feedstock supply is variable as a result of stochastic yields. Harvested feedstock acreage ($HrvAcr$) is obtained as a function of the scheduled feedstock supply ($SchFeedSupply$), the share of feedstock ($FeedShr$) supplied by each energy crop ($crop$), and the expected feedstock yield ($Yield$) as formulated in equation (B.1). The scheduled

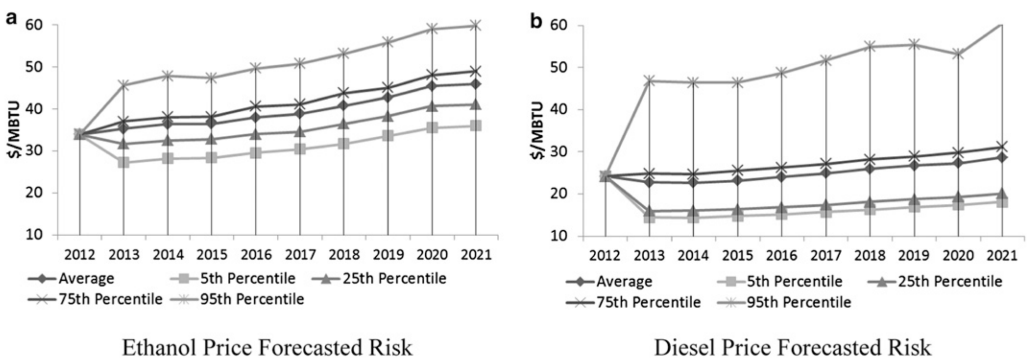


Figure A.3. Nominal Wholesale Price Forecasted Risk for the 2013 Reference Scenario from the Annual Energy Outlook feedstock supply was estimated by dividing the conversion plant's nameplate (*Nameplate*) by the biofuel yield (*FuelYld*) depending on the technology (*tech*) as shown in equation (B.2). In this study, nameplate capacity is the technical supported output an operator should expect. Hence, according to current biofuel plant manufacturers, conversion plants can be operated well over its nameplate capacity (Swain, 2006).

$$\text{(B.1)} \quad HrvAcr_{crop,tech} = \frac{SchFeedSupply_{tech} \cdot FeedShr_{crop}}{\widetilde{Yield}_{crop}},$$

$$\text{(B.2)} \quad SchFeedSupply_{tech} = \frac{Nameplate_{tech}}{FuelYld_{tech}}.$$

The cost of the feedstock delivered at the plant is comprised of the cost of feedstock standing in the field (*FeedStdCost*) in dollars per dST, a variable harvesting and hauling cost (*VarHrvCost*) in dollars per dST, a fixed harvesting and hauling cost (*FxHrvCost*) in dollars per acre, stochastic yields (*Yield*), and harvested acreage (*HrvAcr*) as shown in equation (B.3).

$$\text{(B.3)} \quad \widetilde{FeedDlvCost}_{crop,tech} = \left(\widetilde{FeedStdCost}_{crop} + VarHrvCost_{crop}\right) \cdot \widetilde{Yield}_{crop} \cdot HrvAcr_{crop,tech} + \left(FxHrvCost_{crop} \cdot HrvAcr_{crop,tech}\right).$$

The cost of feedstock standing in the field is comprised of the feedstock production cost (*FeedPrdCost*) in dollars per dST plus a return (*%Return*), expressed as a percent over production costs, the farmer receives to switch production from any incumbent crop to the new dedicated energy crops as listed in equation (B.4). Feedstock production costs (*FeedPrdCost*) are stochastic because they are a function of their per-acre counterparts (*FeedAcreCost*) and stochastic feedstock yields (*Yield*). To address the uncertainty of energy cane production costs, different production costs were considered by altering expected yields in equation (B.5).

$$\text{(B.4)} \quad \widetilde{FeedStdCost}_{crop} = \widetilde{FeedPrdCost}_{crop} \cdot \left(1 + \%Return_{crop}\right),$$

$$\text{(B.5)} \quad \widetilde{FeedPrdCost}_{crop} = FeedAcreCost_{crop} / \widetilde{Yield}_{crop}.$$

Annual fuel production (*FuelPrd*) in million British thermal units (MBTUs) is stochastic because it is a function of stochastic feedstock yield (*Yield*) in dST per acre, fixed harvested acreage (*HrvAcr*), and biofuel yield (*FuelYld*) in MBTUs per dST of feedstock for each conversion technology (*tech*) as shown in equation (B.6). MBTUs were used as a result of the inclusion of biofuels with different energy contents. The MBTU-to-gallon conversions used were the following: 0.076 for ethanol and 0.123 for renewable diesel.

$$\text{(B.6)} \quad \widetilde{FuelPrd}_{tech} = \left(\sum_{crop} HrvAcr_{crop} \cdot \widetilde{Yield}_{crop}\right) \cdot FueldYld_{tech}.$$

The plant's original nameplate, obtained from the literature, can be modified (*NameplateOrig*) to a nameplate desired by the analyst (*Nameplate*), hence adjusting the original investment, operating (*OpExpOrig*), and fixed (*FixExpOrig*) expenses. The plant's operating expenses (*OpExp*) are adjusted from the original (*OpExpOrig*) as a linear function of the plant's nameplate as shown in equation (B.7).

$$\text{(B.7)} \quad OpExp = OpExpOrig \cdot (Nameplate/NameplateOrig).$$

Fixed expenses (*FixExp*) are adjusted as a non-linear function of the plant's nameplate as shown in equation (B.8). A scaling factor (*scale*) was included to account for economies of scale and was based on engineering costs in the literature. If the scaling factor is less than one, the capital cost per unit size decreases as the equipment becomes larger (Aden et al., 2002). For this study, a scaling factor of 0.7 was used for all three technologies and was obtained from the NREL and PNNL studies.

$$\text{(B.8)} \quad FixExp = FixExpOrig \cdot (Nameplate/NameplateOrig)^{scale}.$$

The total investment in the conversion plant (*TotInv*) is composed of the investment in the infrastructure (*PlantInv*), including the cost of the equipment already installed and in the piece of land (*LandInv*) where the plant is built as formulated in equation (B.9). Both investments were estimated as a function of the plant's nameplate and scaling factor as listed in equations (B.10) and (B.11). Because this study uses the same plant nameplates as in the NREL and PNNL study, capital expenses are the same.

$$(B.9)\qquad TotInv = PlantInv + LandInv,$$

$$(B.10)\qquad PlantInv = PlantInvOrig \cdot (Nameplate/NameplateOrig)^{scale},$$

$$(B.11)\qquad LandInv = LandInvOrig \cdot (Nameplate/NameplateOrig)^{scale}.$$

Appendix C: Financial Statements Formulas

Dividends

Annual dividends (*Dividend*) are generated by a portion of the project's starting capital (*BNWDiv*) and, as a bonus, from a positive annual NCI (*NCIDiv*) as formulated in equations (C.1), (C.2), and (C.3). The percentages used (*%NCIDiv* and *%BNWDiv*) to estimate the dividends were obtained from previous feasibility studies on renewable fuels (Richardson, Johnson and Outlaw, 2012) and listed in Table C.1.

$$(C.1)\qquad \widetilde{Dividend_t} = \widetilde{NCIDiv_t} + BNWDiv,$$

$$(C.2)\qquad \widetilde{NCIDiv_t} = \begin{cases} \widetilde{NetCashInc_t} \cdot \%NCIDiv \text{ if } \\ \widetilde{NetCashInc_t} > 0, \\ 0 \text{ if } \widetilde{NetCashInc_t} \leq 0, \end{cases}$$

$$(C.3)\qquad NWDiv = BegNetWorth \cdot \%BNWDiv.$$

Plant Construction

To obtain the beginning net worth, it was assumed that the plant was built during a construction period (c) of three years before the first year of operations. The model allocates the capital investment on the plant (*PlantInv*) to every year of the construction period through a set of completion percentages (*%Const*) as shown in equation (C.4). These completion percentages were obtained from the NREL and PNNL studies and listed in Table C.1. The model assumes that a share of the initial capital needed to build and operate the plant is obtained from a loan (*%LoanInv*) and from public sources generating dividends. The loan share was assumed to be 60% for all technologies following the same specifications from the NREL studies. The PNNL study on pyrolysis did not consider any loan. However, a loan was included to keep the analysis uniform across technologies. The loan is cumulative during the construction period (*ConstLoan*), because no principal is paid, and generates interests (*ConstInt*) at a specific interest rate (*IntRate*) as shown in equations (C.5) and (C.6). The interest rate was obtained from the NREL and PNNL studies and listed in Table C.1. Land is assumed to be bought at the beginning of the construction period ($t - C$).

Table C.1. Common Technical and Economic Parameters for the Conversion Plant

Parameters	Units	Value	Parameters	Units	Value
Recovery Period[a]			Regional Adjustment[d]		
Conversion plant	Years	7	Ethanol	\$/MBTU	0.55
Steam plant	Years	20	Diesel	\$/MBTU	–0.69
Construction[a]			Electricity	\$/MBTU	–1.03
First year	Percent	8	Beginning cash	\$	0
Second year	Percent	60	Dividends[c]		
Third year	Percent	32	Beginning net worth	Percent	5
Scaling factor[a]		0.7	Net cash income	Percent	15
Investment loan[a]	Percent	60	Startup time[a]	Months	6
Loan period[a]	Years	10	Revenues[a]	Percent	50
Interest rate[a]	Percent	8	Variable costs[a]	Percent	75
Discount rate[b]	Percent	7–9	Fixed costs[a]	Percent	100
Fraction of year operating loan[c]	Percent	10			

[a] Obtained from Humbird et al., (2011), Jones et al. (2009), Swanson et al. (2010).
[b] Obtained from Richardson et al. (2007), Schmit, Luo, and Conrad (2011), Short, Packey, and Holt (1995).
[c] Obtained from Richardson, Herbst, and Outlaw (2012).
[d] Obtained from Hart Energy Publishing (2012), U.S. EIA (2012a, 2012b).

(C.4) $$Const_{t-c} = PlantInv \cdot \%Const_{t-c} \quad \text{where} \quad t = 0,$$

(C.5) $$ConstLoan_{t-c} = (Const_{t-c} + Const_{t-c-1} + LandInv_{t-C}) \cdot \%LoanInv \quad \text{where} \quad t = 0,$$

(C.6) $$ConstInt_{t-c} = ConstLoan_{t-c} \cdot IntRate \quad \text{where} \quad t = 0.$$

Beginning Net Worth

The portion of the starting capital obtained from public sources (not from a loan) is equivalent to the beginning net worth brought forward to the present using the discount rate. The beginning asset (*BegAsset*) is the sum of the beginning cash (*BegCash*) and the value of the plant and the land, contained in *Const*, brought forward to the present as formulated in equation (C.7). The beginning liability (*BegLiab*) is the accumulated value of the loan in the construction period brought forward to the present as formulated in equation (C.8).

(C.7) $$BegAsset = BegCash_t + \sum_c (Const_{t-c} \cdot 1 + DiscRate)^{-(t-c)} \quad \text{where} \quad t = 0,$$

(C.8) $$BegLiab = \sum_c ((ConstLoan_{t-c} - ConstLoan_{t-c-1}) \cdot 1 + DiscRate)^{-(t-c)} \quad \text{where} \quad t = 0.$$

Assets

Annual cash reserves (*CashReserve*) are conditional on positive ending cash coming from the cash flow statement as shown in equation (C.9). The value of land in the first year of operations is the land investment (*LandInv*) brought forward to the present using the discount rate and is appreciated in the forecasted years using the appreciation rate (*ApprecRate*), assumed to be zero in this study, as shown in equation (C.10).

(C.9) $$\widetilde{CashReserve_t} = \begin{cases} \widetilde{EndCash_t} \text{ if } \widetilde{EndCash_t} > 0, \\ 0 \text{ if } \widetilde{EndCash_t} \leq 0, \end{cases}$$

(C.10) $$LandVal_t = \begin{cases} LandInv_{t-C} \cdot (1 + DiscRate)^{-(t-C)} \text{ if } t = 0, \\ LandVal_{t-1} \cdot (1 + ApprecRate_t) \text{ if } t > 0. \end{cases}$$

Plant Depreciation

The values (*PlantVal*) of the steam plants (*type* = '*steam*') were obtained from the NREL studies and listed in Table 2; the rest of the plant investment (*PlantInv*) was allocated to the biofuel conversion plant (*type* = '*fuel*') at the beginning of the project ($t = 0$) as shown in equation (C.11). For the subsequent forecasted years, both plants are depreciated (*Deprec*) annually following the Modified Accelerated Cost Recovery System (MACRS), which is the current tax depreciation system in the United States and the one included in this model as formulated in equation (C.12). Annual depreciation is estimated by multiplying the initial value of the plant (*PlantVal*) by the annual depreciation percentages (*%MACRS*) already defined for different asset-life categories (*PlantLife*) as listed in equations (C.13) and (C.14). The model includes *%MACRS* for the following asset life categories: 3, 5, 7, 10, 15, and 20 years. The plant lives were obtained from the NREL and PNNL studies and listed in Table C.1.

(C.11) $$PlantVal_{'fuel',t=0} = PlantInv - PlantVal_{'steam',t=0},$$

(C.12) $$PlantVal_{type,t} = PlantVal_{type,t-1} - Deprec_t,$$

(C.13) $$Deprec_{type,t} = PlantVal_{type,t=0} \cdot \%MACRS_{type,t},$$

(C.14) $$\%MACRS_{type,t} = f\left(PlantLife_{type}\right).$$

Liabilities

The deficit loan is emergency funding to cover negative ending cash and, conditioned on the next year's ending cash, fully paid in the next year as formulated in equation (C.15). As previously mentioned, a share (*%LoanInv*) of the initial capital (*TotInv*) comes from a loan (*PlantLoan*) and is amortized over the project's horizon ($t = T = 10$) with an annuity (*PlantAnn*) that includes the principal (*PlantPrinc*) and interest (*PlantLoanInt*) charged at a specific interest rate (*IntRate*) as shown from equations (C.16) through (C.19).

(C.15) $$\widetilde{DefLoan_t} = \begin{cases} \widetilde{EndCash_t} \text{ if } \widetilde{EndCash_t} < 0, \\ 0 \text{ if } \widetilde{EndCash_t} \geq 0, \end{cases}$$

$$\text{(C.16)} \quad PlantLoan_t = \begin{cases} PlantLoan_{t-1} - PlantPrinc_t \text{ if } t > 0, \\ TotInv \cdot \%LoanInv \text{ if } t = 0, \end{cases}$$

$$\text{(C.17)} \quad PlantPrinc_t = PlantAnn_t - PlantLoanInt_t,$$

$$\text{(C.18)} \quad PlantAnn_t = \frac{IntRate \cdot PlantLoan_{t=0}}{1 - (1 + IntRate)^{-t}},$$

$$\text{(C.19)} \quad PlantLoanInt_t = PlantLoan_t \cdot IntRate.$$

Cash Inflows

The beginning cash at the project's start is assumed to be zero, whereas, for the forecasted period, it is equal to the previous year's positive cash reserves as formulated in equation (C.20). The positive cash reserves from the previous year earn interest (*IntResEarn*) at a forecasted savings interest rate (*SaveRate*) as shown in equation (C.21). The forecasted savings rate (*SaveRate*) was obtained from FAPRI (2013) and Richardson et al. (2013).

$$\text{(C.20)} \quad \widetilde{BegCash}_t = \begin{cases} \widetilde{CashReserve}_{t-1} \text{ if } t > 0, \\ BegCash_t \text{ if } t = 0, \end{cases}$$

$$\text{(C.21)} \quad \widetilde{IntResEarn}_t = \widetilde{CashReserve}_{t-1} \cdot SaveRate_t.$$

Income Taxes

Income taxes (*IncTax*) are estimated from a taxable income (*TaxblInc*) and a tax rate schedule obtained from the Internal Revenue Service (2012) as shown in equation (C.22). The tax schedule contains different tax rates (*TaxRate*), minimum income levels (*MinInc*), and tax base levels (*TaxBase*) depending on the taxable income as shown in equations (C.23), (C.24), and (C.25), respectively. The taxable income is estimated by subtracting the annual depreciation (*Deprec*) from the NCI (*NetCashInc*), when the former is greater than the latter or set to zero otherwise as formulated in equation (C.26).

$$\text{(C.22)} \quad \widetilde{IncTax}_t = \left[\left(\widetilde{TaxblInc}_t - \widetilde{MinInc}_t\right) \cdot \widetilde{TaxRate}_t\right] + \widetilde{TaxBase}_t,$$

$$\text{(C.23)} \quad \widetilde{TaxRate}_t = h\left(\widetilde{TaxblInc}_t\right),$$

$$\text{(C.24)} \quad \widetilde{MinInc}_t = j\left(\widetilde{TaxblInc}_t\right),$$

$$\text{(C.25)} \quad \widetilde{TaxBase}_t = g\left(\widetilde{TaxblInc}_t\right),$$

$$\text{(C.26)} \quad \widetilde{TaxblInc}_t = \begin{cases} \widetilde{NetCashInc}_t - Deprec_t \text{ if} \\ \widetilde{NetCashInc}_t > Deprec_t, \\ 0 \text{ if } \widetilde{NetCashInc}_t \le Deprec_t. \end{cases}$$

Interest Expenses

The interest expenses (*IntExp*) consist of the interest from the plant loan (*PlantLoanInt*), the interest paid for the operating loan (*OpLoanInt*), and the interest paid for any deficit loan from the previous year (*DefLoanInt*) as listed in equation (C.27). The operating loan is a short-term loan meant to provide liquidity and to cover a portion (*YearFrct*) of the inflated feedstock, operating, and fixed expenses as shown in equation (C.28). The portion of fixed operating expenses covered annually was obtained from previous feasibility studies (e.g., Richardson, Johnson and Outlaw, 2012). Both the operating loan and deficit loan create interest expenses at a forecasted interest rate series (*ChgIntRate*). The forecasted interest (*ChgIntRate*) and inflation (*InfRate*) rates were obtained from FAPRI (2013) and Richardson et al. (2013).

$$\text{(C.27)} \quad \widetilde{IntExp}_t = PlantLoanInt_t + \widetilde{OpLoanInt}_t + \widetilde{DefLoanInt}_t,$$

$$\text{(C.28)} \quad \widetilde{OpLoan}_t = \left(\widetilde{FeedDlvCost} + OpExp + FxExp\right) \cdot InfRate_t \cdot YearFrct,$$

$$\text{(C.29)} \quad \widetilde{OpLoanInt}_t = \widetilde{OpLoan}_t \cdot ChgIntRate_t,$$

$$\text{(C.30)} \quad \widetilde{DefLoanInt}_t = \widetilde{DefLoan}_{t-1} \cdot ChgIntRate_t.$$

Appendix D: Projections of Key Output Variables

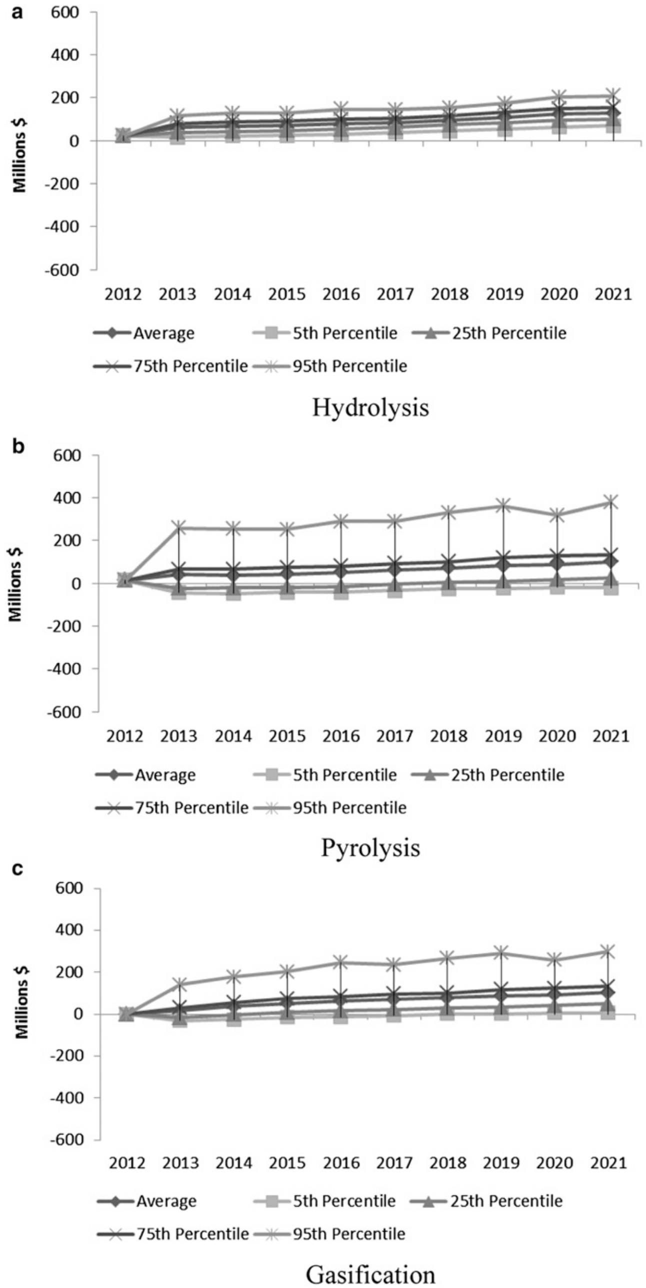
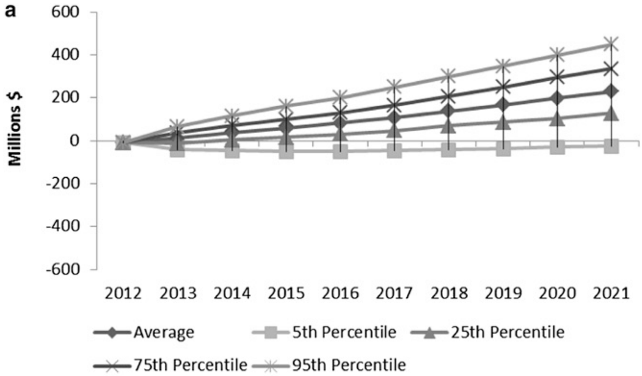
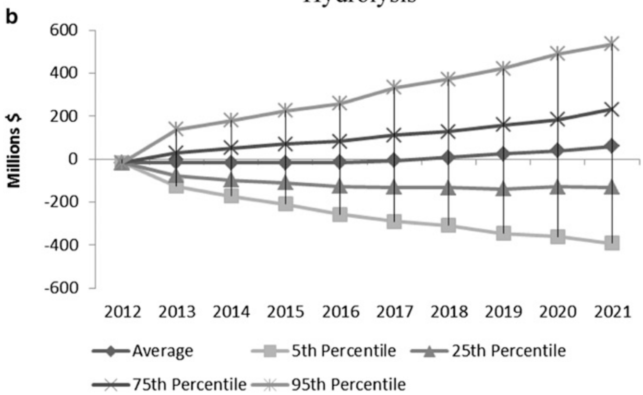


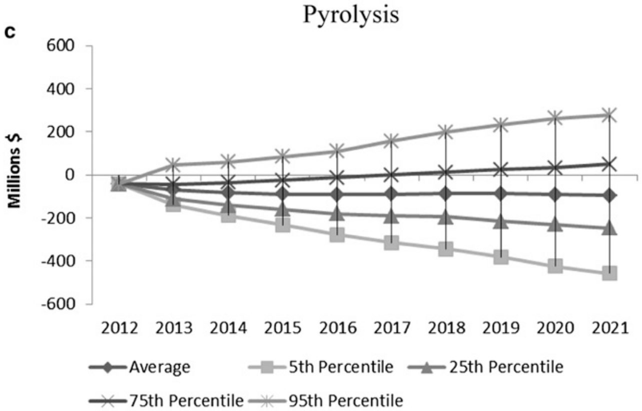
Figure D.1. Net Cash Income Projection and Related Risk in Reference Scenario



Hydrolysis

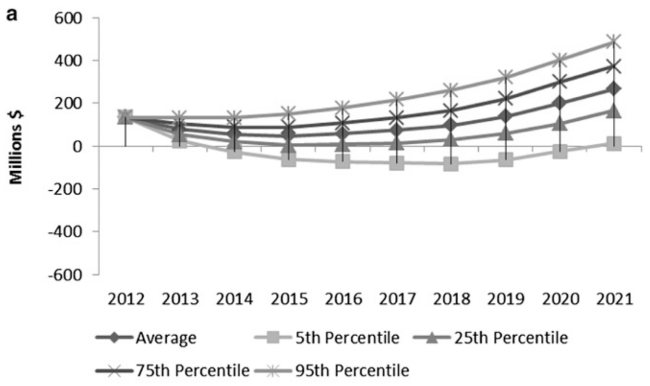


Pyrolysis

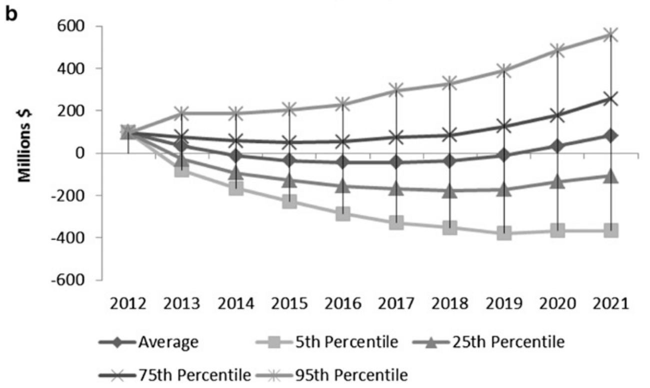


Gasification

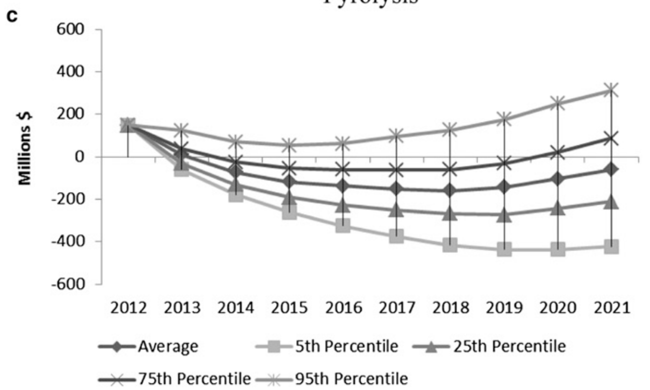
Figure D.2. Ending Cash Projection and Related Risk in Reference Scenario



Hydrolysis



Pyrolysis



(c) Gasification

Figure D.3. Net Worth Projection and Related Risk in Reference Scenario

Appendix E: Additional Graphs

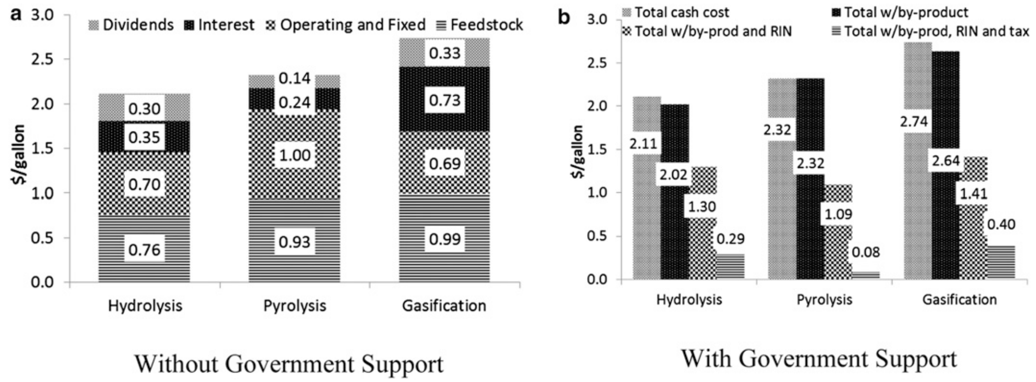


Figure E.1. Expected Annual Cash Costs for Conversion Technology in Dollars per Gallon

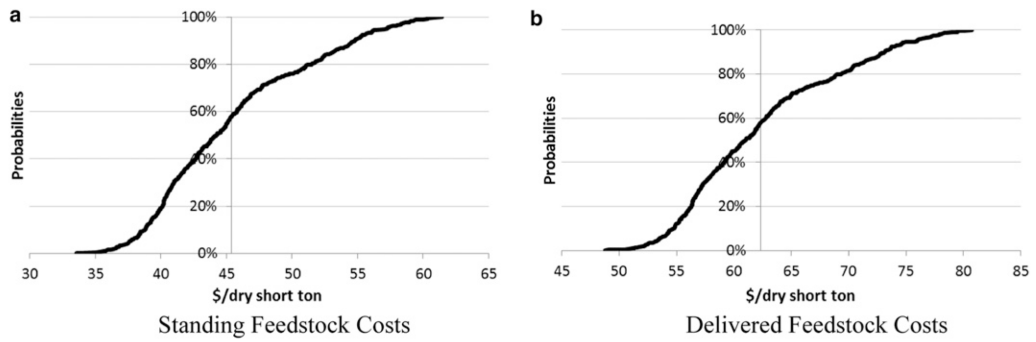


Figure E.2. Cumulative Density Function Approximations of the Standing and Delivered Feedstock Costs

Appendix F: Sensitivity on Return to Farmers

Sensitivity analyses were also performed on the return that farmers should receive to switch from incumbent crops to dedicated energy crops. These analyses are useful for different potential plant locations because the incumbent crops will vary depending on the region. Establishing the standing and delivered feedstock prices (subject to feedstock yield and biofuel price variability) helps farmers, harvesters, and freighters to either lower their inputs costs (if the price offered is low) or bargain for a higher margin (if the price offered is high) without compromising the plant's feasibility. Table F.1 shows that by decreasing the returns to the feedstock growers from the reference of 20% (over production costs) to 10%, the feasibility chances for hydrolysis would increase from 67% to 71% and the expected and delivered feedstock costs would decrease by approximately $4 per dST each. The net present value for pyrolysis is the most sensitive across technologies followed by hydrolysis and gasification. The net present value for gasification is not sensitive to the returns to the farmer across energy crops even at high oil prices.

Table F.1. Probabilities of Obtaining a Positive Net Present Value and Expected Standing and Delivered Feedstock Costs for Different Levels of Returns to Farmers without Credits

Return to Farmer (% over production cost)	Expected Standing Cost ($/dST)	Expected Delivered Cost ($/dST)	Probabilities of Feasibility		
			Hydrolysis[a]	Pyrolysis[a]	Gasification[b]
10%	41	57	71%	46%	9%
15%	42	59	69%	43%	8%
20%	44	61	67%	41%	8%
25%	46	63	66%	38%	8%
30%	48	65	64%	36%	7%

[a] The cases of hydrolysis and pyrolysis consider EIA's 2013 reference prices.

[b] The case of gasification considers EIA's 2013 high oil prices. It is not feasible otherwise.