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2013 feedstock supply and price projections and sensitivity analysis*

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Abstract: Farmgate prices (i.e. price delivered roadside ready for loading and transport) for biomass feedstocks directly influence biofuel prices. Using the latest available data, marginal (i.e. price for the last ton) farmgate prices of \$51, \$63, and \$67 dry ton^{-1} (\$2011) are projected as necessary to provide 21 billion gallons of biofuels from about 250 million dry tons of terrestrial feedstocks in 2022 under price-run deterministic, demand-run deterministic, and stochastic simulations, respectively. Sources of uncertainty in these feedstock supply and price projections include conversion efficiency, global market impacts on crop price projections, crop yields, no-till adoption, and climate. Under a set of low, high, and reference assumptions, these variables introduce an average of +/– \$11 dry ton^{-1} (~15%) uncertainty of feedstock prices needed to meet EISA targets of 21 billion gallons of biofuels produced with 250 million dry tons of biomass in 2022. Market uncertainty justifies the need for fairly frequent (i.e. annual or biennial) re-assessment of feedstock price projections to inform strategies toward commercialization of biofuels. Published in 2014 by John Wiley & Sons, Ltd

Keywords: biomass; resource assessment; economic availability; bioenergy feedstocks; sensitivity analysis

Introduction

Second-generation (advanced) biofuels are expected to make an important volumetric contribution to the energy mix in the USA and internationally over the next 8–10 years. Advanced biofuels can displace non-renewable liquid transportation fuels and provide both environmental and economic benefits, such as job creation. Research and development currently aims to produce advanced biofuels that are cost-competitive with conventional fossil fuels on a gallon of gasoline equivalent (GGE) basis. This research evaluates feedstock farmgate[†] price[‡] as a component of total delivered cost of cellulosic biofuels.

Essential to the success of the nascent bioenergy industry is the development of a profitable, yet cost-competitive, biofuels industry. A \$3 GGE^{-1} (\$2011) biofuels wholesale price target will be needed to make biofuels cost-

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[†] The forest landing or farmgate price mentioned throughout this paper is a basic feedstock price that includes cultivation (or acquisition), harvest, and delivery of biomass to the field edge or roadside. It excludes on-road transport, storage, and delivery to an end user. For grasses and residues, this price includes baling. For forest residues and woody crops, this includes minimal communition (e.g. chipping).

[‡] We use the term ‘price’ to indicate that profit is in included, while ‘cost’ covers operational expenses but not profit margin. ‘Farmgate price’ thus includes both payments to the grower, including profit needed to incentivize production, and harvest costs.

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competitive with conventional fuels in the future, and this target has been adopted by the Bioenergy Technologies Office (BETO) of the US Department of Energy (USDOE) Office of Energy Efficiency and Renewable Energy (EERE) for planning purposes. Langholtz *et al.*[1] projected biomass feedstock farmgate prices of about \$50–\$60 would likely be needed to procure enough feedstock to meet EISA targets in 2022. Assuming a biofuels yield of 85 gallons of ethanol equivalent dry ton^{-1}, this means about \$0.60 to \$0.70 gallon^{-1} of biofuels, or about 20–25% of the \$3 gallon^{-1} price target, would be spent on feedstock alone, at the farmgate and before additional haul, storage, and preprocessing costs are added. As a result, the final fraction of biofuel cost attributable to feedstocks may approach one-third (i.e. \$1) of the \$3 GGE^{-1} target biofuel cost, and possibly even more. Considering inherent uncertainty in projecting agricultural prices in the future, this significant cost component warrants monitoring as strategies towards commercialization of biofuels are developed. Here we show revised 2013 feedstock supply and price projections (FSPPs) and present highlights of a sensitivity analysis of key modeling variables on projected prices for feedstocks anticipated to be required to meet EISA biofuel targets.

Background

BETO administers research and development efforts across industry, academic institutions, and national laboratories. BETO aims to foster the sustainable development of a bioenergy industry in the USA that will enhance US energy security, reduce dependence on petroleum, provide environmental benefits, and create economic opportunities. The program supports the Energy Independence and Security Act of 2007 (EISA), with the goal of producing and using 136 billion liters (36 billion gallons) of renewable fuels by 2022. This ramp-up of biofuels use includes second-generation cellulosic and algal biofuels, including ethanol, drop-in biofuels that can be blended with petroleum-derived gasoline, diesel, and jet fuels.

Significant advancements have been made toward evaluating biomass feedstock supplies and prices in the USA. Perlack *et al.*[2] estimated that upwards of 1 billion dry tons per year of biomass are potentially sustainably available in the USA by year 2030; the USDOE in its US Billion-Ton Update Report (referred to here as BT2)[3] evaluated the economic availability of these resources, reporting resource supplies as a function of price and year. Langholtz *et al.*[1] projected biomass feedstock farmgate prices of up to \$53 and \$62 would likely be needed to procure enough feedstock to meet EISA targets in 2022 under constant-price and demand-based price scenarios, respectively. However, given market dynamics and ongoing innovation, there is inherent uncertainty associated with feedstock price projections. Quantification of this uncertainty in the literature is rare.

The global economic climate is influenced by population growth, economic development, consumer preferences, resource availability, technological innovation, climate, currency valuation, national and international policies, and other uncertainties. These variables necessitate the annual re-evaluation of projections of agriculture commodities,[4] and energy resources.[5] Similarly, lignocellulosic biomass is produced within the context of competing market opportunities (e.g. other crops, urbanization) and fluctuating input costs (e.g. fertilizers, fuels). Thus, biomass supply and price projections must be revised to reflect market trends and technological advancements if they are to remain relevant to biofuels-related commercialization strategies. For example, an index of world crop prices has spiked six times since 1970, approximately once every 6–8 years. Further, historic spikes have been seen in 2008 and 2011 (Fig. 1). This historic volatility immediately before and after the release of the BT2[3] adds considerable uncertainty to feedstock price projections. This is because the economic competitiveness of cellulosic crops is impacted by the profitability of conventional crops as well as agronomic input costs, such as fuel and fertilizer. Thus, macroeconomic forces impact USDA Agricultural Baseline Projections (ABPs), which in turn influence FSPPs. To help inform biofuels commercialization strategies, this report shows revised 2013 FSPPs and illustrates the impacts of a sensitivity analysis around key modeling variables on said prices.

Methodology

Modeling framework

Consistent with the BT2,[3] Langholtz *et al.*,[1] De La Torre *et al.*,[7] and ongoing resource analysis performed at Oak Ridge National Laboratory, FSPPs were generated using the Policy Analysis System (POLYSYS) model, an agronomic market simulation linear program that solves for the most profitable allocation of agricultural lands to meet future demands for food, feed, and fiber, with the addition of cellulosic feedstocks. POLYSYS solves at the county level for the contiguous 48 U.S. states. Feedstocks include biomass from agricultural and forest residues, dedicated herbaceous crops (perennial and annual), short-rotation woody crops, and under certain economic conditions, mill residues and small-diameter trees. (Because of price uncertainty, algal feedstocks are excluded from FSPPs presented here. However,

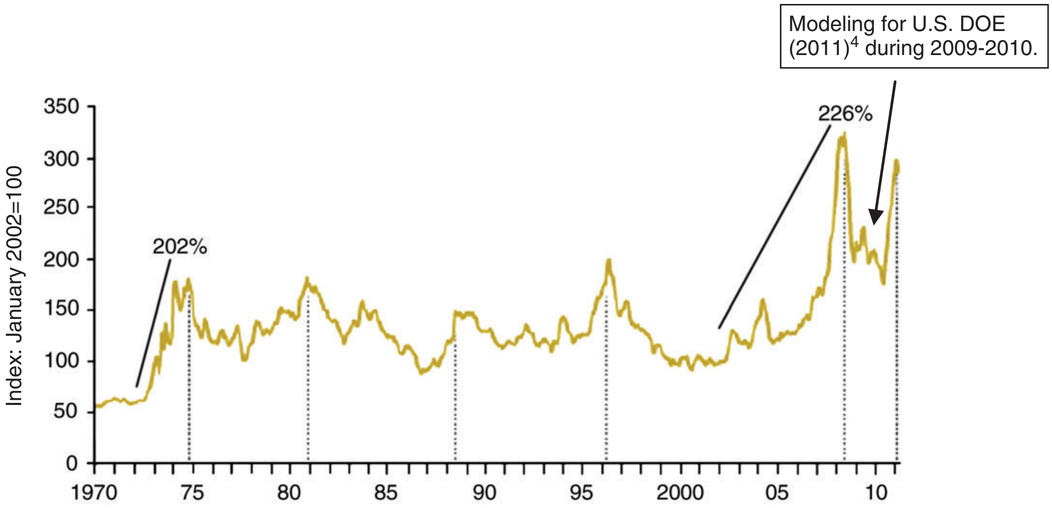

Figure 1. World crop prices since 1970: Index: January 2002=100. Index of monthly wheat, rice, corn, and soybean prices weighted by global trade shares. Source: Trostle (2011)[6] using International Monetary Fund nominal prices and weights. Vertical lines indicate six peaks since 1970, two of which occurred in close succession during development of the Billion-Ton Update.[3]

results by Wigmosta[8] and Venteris[9] suggest that adequate land and water are available to meet a significant portion of the US renewable fuel goals with algae. Algal biofuels prices are estimated at $12 per gallon,[10] with projected cost reductions to $3.27 GGE^{-1} by 2022.[11]) Detailed discussion of this modeling framework is available from De la Torre and Ray[7] and Ray *et al.*[12] Application of POLYSYS to modeling biomass feedstocks is described in the BT2[3] and Langholtz *et al.*[1] County-level FSPPs from the BT2 are available from the Bioenergy KDF.[13]

To generate FSPPs, POLYSYS can now be run in three different modes:

1. *Price-run scenario, deterministic.* In price-run, supply is reported as a function of feedstock price. The user can select feedstock farmgate prices in POLYSYS and determine what farmgate price is needed to procure the desired supply. The price-run scenario has a price fixed for all years, reflecting potential long-term contracting conditions, where biomass consumers lock land into production for specific facilities. The price established in the contract is simulated as a nominal average price that is received throughout the life of the contract (in the case of energy crops, the lifetime of the stand) until expiration. The price run simulation is considered 'policy agnostic' as it does not specify volumetric targets. This is the same application of the model in the BT2. Each price modeled represents a simulation independent of other price points. However, to elucidate potential marginal supplies (i.e. additional supply at a given price change) at price increments and to contrast marginal prices (i.e. price of the last ton at a given level of supply) with national average prices that might be realized across resource- and location-specific prices, here we disaggregate supplies in $10 increments.
2. *Demand-run scenario, deterministic.* In demand-run, the user inputs in POLSYSYS the supplies required and runs the model to determine what farmgate prices are necessary to procure the national feedstock demand. The demand-run scenario can simulate a gradual increase in demand, and in turn, feedstock price, over time. In this mode, demand can be increased by specifying volumetric biofuels targets by year to simulate policies (e.g. EISA).
3. *Stochastic climate (price-run or demand-run scenarios).* Stochastic POLYSYS runs a Monte-Carlo simulation reflecting historic variability of county-level yields as influenced by climate and associated factors. For each year in a POLYSYS projection, a random draw is taken from the years 1970 and 2008, and for each county, the deviation from the mean yield over that period is observed for both hay and corn, adjusted for continuous improvement over time. Units are in tons acre^{-1} year^{-1} and bushels acre^{-1} year^{-1} for hay and corn, respectively. This variability is subsequently applied to projected yields of commodity crops and dedicated cellulosic feedstocks. For example, for each county and each year, corn yield variability is applied

to corn stover expected yields, while hay variability is applied to switchgrass expected yields. The simulation is run 100 times, allowing for statistical distribution of biomass supply and price projections. In this analysis, stochastic POLYSYS is applied in demand run-mode to simulate EISA requirements.

Following this methodology, we show feedstock price projections under simulations of EISA, and illustrate sensitivities to key modeling assumptions.

Sensitivity analysis assumptions

The assumptions made in POLYSYS runs influence FSPPs. Assumptions include agronomic practices (e.g. conventional tillage *vs.* strip tillage *vs.* no-till; irrigation *vs.* rainfed), yield assumptions (e.g. rate of annual yield increase due to genetic and/or agronomic practice improvements), harvest operations to be employed (e.g. forage harvester *vs.* baler; chips *vs.* billets), and sustainability constraints (e.g. residue retention coefficients). Major inputs to POLYSYS include agricultural land availability derived from the USDA National Agricultural Statistics Service (NASS) and projected prices for agricultural products, derived from the USDA ABPs. Other assumptions are also needed in defining scenarios in which EISA might be met. Following is a description of some key variables and the assumptions made about them in this sensitivity analysis, which are summarized in Table 1.

1. *Conversion yield (gal/dt)*: Under basic supply curve assumptions, higher prices are required for more feedstock supply, all else being equal. Thus, assumptions about biomass conversion processes that result in less biofuel product per ton of biomass will require a greater feedstock supply and, in turn, higher prices for feedstock (due to increased demand). Langholtz *et al.*[1] use a generalized assumption of 85 gallons of ethanol equivalents per dry ton. This value at commercial scale is not known with certainty, varies with feedstock quality and conversion process, and is expected to improve with time. Further, different biofuels types have different energy contents. For example, ethanol has only two-thirds of the energy content of gasoline, while advanced drop-in biofuels have higher energy densities. Current federally mandated targets of 21 billion gallons of second-generation biofuels expressed in volumes of ‘ethanol-equivalent’, and physical volume of renewable fuel used to meet the RFS2 standards may be lowered by the use of more energy-dense fuels.[14] Presumably, biofuels with higher energy content than ethanol will be produced at lower conversion efficiency yields (i.e. lower gallons per dry ton of biomass). Given the current uncertainty, this simulation assumes 85 gallons dry ton^{-1} as a reference scenario based on Langholtz *et al.*[1] and the BETO Multi-Year Program Plan.[15] Ninety-five and 75 gallons dry ton^{-1} are assumed for optimistic and pessimistic scenarios, respectively.
2. *USDA Agricultural Baseline Projection (ABP)*: The USDA Economic Research Service releases revised ABPs annually in February. As already described, ABPs include commodity price projections based on current and expected market conditions. These price projections in turn influence projections for FSPPs. For example, all else being equal, forecasts for high corn prices mean higher prices are needed to incentivize farmers to switch from production of corn to dedicated biomass feedstocks. Similarly, projections of high fuel costs drive higher harvest costs for the collection of agricultural residues and, in turn, higher farmgate prices. As illustrated in Fig. 1, historic volatility in 2008 and 2011 added uncertainty to ABPs used in the projections reported in the BT2. The 2009 ABP includes lower crop price projections than the ABPs submitted in 2011 and 2013. Thus, in this analysis we use the latest available 2013 ABP in the reference scenario, and apply the 2009 ABP, as used in the BT2, in the optimistic scenario.
3. *Crop yield (dt/ac annual improvement)*: A major variable in FSPPs is the set of assumptions regarding future crop yields. Corn yields in the USA have improved steadily from about 40 bushels per acre in the early 1900s to about 150 bushels per acre today. This yield improvement is attributable to a combination of selective breeding, genetic modification, higher inputs (e.g. fertilizers, pesticides), and improved crop production practices (e.g. pest control, crop rotation). Relatively

Table 1. Key variables and associated assumptions used in optimistic, reference, and pessimistic scenarios.

Variable	Optimistic	Reference	Pessimistic
1. Conversion Yield (gal/dt)	95	85	75
2. USDA Baseline	2009	2013	n/a
3. Crop Yield (dt/ac annual improvement)	3%	1%	n/a
4. No-till adoption rate	High (3)	Intermediate (2)	Low (1)
5. Climate		Monte Carlo	

little investment has been made to date with the goal of improving yields of dedicated cellulosic feedstocks such as switchgrass, energycane, Miscanthus, poplars, and willows, which infers that there is great potential for significant yield improvements. The High-Yield Workshop Series[16] developed base-case and more optimistic high-yield scenarios that were used in the BT2. The base-case scenario assumes 1% annual yield improvements in yields (which approximates the historical trend for corn grain yields over the last 40 years, or so), while the high-yield scenarios assume 2%, 3%, and 4% annual yield improvements. While most users of the BT2 results probably assume the more conservative base-case yield scenarios, the high-yield scenarios provide a more optimistic outlook for future feedstock supply. Following the same yield assumptions of the BT2, we apply the base-case yield assumption of 1% annual yield improvement to the reference crop scenarios, and use the high-yield 3% annual yield improvement assumption in the optimistic scenario.

4. *Reduced-till and no-till adoption rate*: Innovative agricultural practices are being evaluated for their potential to produce biomass feedstocks while improving incomes and enhancing environmental benefits. One example is no-till or reduced-till cultivation, as opposed to conventional tillage practice, which involves plowing the soil each year. Initially developed for soil conservation purposes, the lower tillage strategies involve growing crops with minimal soil disturbance and maintenance of organic cover, which in turn protects soil from erosion and enhances its physical and chemical properties. Farmers practicing low- or no-till cultivation, particularly corn growers at northern latitudes, find that a surplus of stover on the surface of the ground inhibits soil warming in the spring, which slows early-season growth and can impact grain yields. Thus, synergies may be realized by combining low- or no-till cultivation with crop residue harvest for biomass. In the BT2, no-till and reduced-till adoption rates were established as exogenous assumptions in the base-case and high-yield scenarios described above. The base case assumed continuation of observed tillage trends while the high-yield scenario assumed a larger fraction of no-till cultivation. However, modeling enhancements in POLYSYS after release of the BT2 now allow simulation of farmers' responsiveness of low- and no-till adoption to biomass price. Consistent with the BT2, in this analysis we restrict agricultural residue collection to land managed with no-till and reduced tillage operations. No-till production is assumed to produce higher crop grain and residue yields, and due to the lack of current data on tillage choices, we simulate tillage adoption as a function of residue biomass price. In this analysis we test three levels of this assumption. This responsiveness takes on three values such that between \$50–60 dry ton^{-1} for all feedstocks, the responsiveness in additional acres in no-till production is 15.2 million at the lower value, 15.6 million in the medium value, and 20.6 million at the highest value. For the reference case, the responsiveness indicator is set to the medium value.
5. *Climate*: As described earlier, a stochastic version of POLYSYS developed in 2012 captures historic county-level yield variability as impacted by climate. A statistical distribution of feedstock prices is derived from one hundred simulations. Assuming reference-scenario assumptions for variables 1–4 above (Table 1), the average derived from a Monte-Carlo simulation can deviate from the reference case price projection of the deterministic model, but still the distribution of results provides valuable insight in the expected variability in price that can be expected from future climate variability. In this analysis we show one standard deviation of price projections under stochastic climate simulation in comparison with the pessimistic, reference, and optimistic cases derived from the other variables.

In contrast with Langholtz *et al.*[1], no additional demand was included for biopower generation. However, forest resources were constrained to only 50% of non-federally sourced wood as estimated as available in the BT2. The forest resources include supply curves of Integrated Operations (50% of available logging residues and thinnings), pulpwood for bioenergy, unused milling residues, urban wood waste, thinnings from other forestland, and residues from other operations. The largest component of this resource at \$60 dry ton^{-1} (an intermediate price point along projection period) is the combination of forest thinnings and residues equaling 17.2 of 41.7 million dry tons. The amount of cumulative material available for fuel production is further restricted to 50% at each price level to reflect the 'strandedness' of the forest resource based. For the reference EISA run, this constraint amounts to about 29.7 million tons of woody biomass in 2013, and increases to 50.7 million dry tons in 2022. This unused quantity could supply much of the 80 million tons of biomass projected as needed in 2022 for additional biopower by Langholtz *et al.*[1]

This analysis includes results from ten modeling simulations. First, feedstock supplies and prices are evaluated under two reference case scenarios:

1. One price-run simulation (\$50–100 dry ton^{-1} in \$10 increments, nominal dollars) under the reference case scenario.
2. One price-run simulation at \$63 dry ton^{-1} (nominal dollars) under the reference case scenario, which was identified as sufficient to provide 21 billion gallons of cellulosic fuels by 2022.

Additional runs for the sensitivity analysis include:

3. One demand-run EISA simulation under reference case assumptions provided in Table 1.
4. Six additional demand-run simulations holding reference assumptions and varying iteratively (i.e. changing one variable at a time) for the four optimistic assumptions and two pessimistic assumptions shown for conversion yield, USDA Baseline, crop yield, and no-till adoption rate variables shown in Table 1.
5. One stochastic-climate demand-run simulation under the reference assumptions provided in Table 1.

Results

Price-run simulation (\$50–100 in \$10 increments, nominal dollars) under the reference case scenario

Total supplies at prices between \$50 and \$100 in \$10 increments are reported under a price-run scenario. Focusing on results for 2022, here we estimate marginal supplies that could be provided at \$10 price increments. For each price point, supplies of a specified resource are subtracted from supplies of that same resource from the previous price point to quantify marginal supplies (i.e. additional supplies) at each price. In addition to marginal price (i.e., price for an additional ton at each level of supply) average prices are also calculated by dividing total cumulative supply by total cumulative price across the supply curve. This approach elucidates how much of each type of resource is projected to be available at each price, and average prices that can be realized if least-cost resources are used to meet a specified level of demand. Results are shown in tabular form in Table 2 and graphically in Fig. 2. Under this simulation, 250 million dry tons, enough to simulate EISA, could be realized with a marginal farmgate price of \$70 dry ton^{-1} and an average price of \$60 dry ton^{-1}. Figure 2 illustrates that in 2022, resources below \$70 dry ton^{-1} are mostly comprised of agricultural and forest residues, while supplies greater than \$70 dry ton^{-1} mostly include dedicated feedstocks.

Price-run simulation at \$63 (nominal, \$51 in 2011\$), reference case scenario, simulating 21 billion gallons of cellulosic fuels by 2022

In contrast with the price-run simulation illustrated, we executed a price run under the reference case assumptions adjusting price iteratively until estimated demand for EISA of about 250 million dry tons was realized in 2022. The best fit was a price run assuming a nominal \$63 dry ton^{-1} from 2013 to 2022. Forest resources were limited to 50% available to simulate integrated harvesting operations. Feedstocks in this simulation are comprised largely of corn stover and wood residues (Fig. 3).

Demand-run EISA simulation under reference case assumptions

In contrast with the price runs presented, in demand runs POLYSYS solves for prices needed to realize annual EISA volumetric targets. This initial demand run solves under the reference assumptions in Table 1 to establish the reference case in the sensitivity analysis shown in Fig. 4. Compared with price-run simulations, demand-run simulations solve for lower prices during the first half of the simulation at the cost of higher prices in the second half of the simulation, consistent with results from Langholtz *et al.*[1] This simulation solved for a marginal farmgate price of \$78 (nominal, \$63 in 2011\$) under the reference case assumptions in Table 1. As with the price-run simulations shown in Figs 2 and 3, resources from the demand-run simulation are largely comprised of residues (Fig. 5). Forest resources were limited to 50% available to simulate integrated harvesting operations.

Additional demand-run simulations varying iteratively for optimistic and pessimistic assumptions

As already described, six additional EISA demand runs were executed in the deterministic version of POLYSYS to evaluate impacts of conversion yield, USDA ABP, crop yield, and tillage adoption. Scenario results are summarized in Table 3 and Fig. 5. Following is a description of impacts on farmgate price by variable.

6. *Conversion yield (gallons dry ton^{-1})*: As a ratio, impacts are proportionally smaller as the numerator increases (i.e. improving conversion yield from 75 to 85 gallons dry ton^{-1} achieves a reduction in 3.1 lbs biomass gallon^{-1}, while an improved conversion efficiency from

Table 2. Marginal price, marginal supplies, cumulative supplies, and average prices realized in 2022 in a price-run simulation under reference-case assumptions described in Table 1 (nominal prices). Shown in bold is 250 million tons, the approximate amount needed to meet the EISA target, is available at a marginal price of $60 dry ton^{-1}, and an approximate average price of $47 dry ton^{-1}.

Resource	Marginal Price ($ dt^{-1})	Marginal supply (million dt)	Cumulative supply (million dt)	Average Price ($ dt^{-1})
Mill residue, unused primary	$10	1.4	1.4	$10.00
Other removal residue	$20	4.4	5.7	$17.62
Logging residues	$20	13.0	18.7	$19.27
Simulated thinnings from forestlands	$20	3.9	22.6	$19.40
Mill residue, unused secondary	$20	6.1	28.7	$19.52
Urban wood waste, construction and demolition	$20	4.7	33.4	$19.59
Urban wood waste, municipal solid waste	$20	8.1	41.5	$19.67
Other removal residue	$30	8.1	49.6	$21.3
Logging residues	$30	28.7	78.3	$24.52
Simulated thinnings from forestlands	$30	8.6	86.8	$25.06
Urban wood waste, construction and demolition	$30	7.1	93.9	$25.44
Urban wood waste, municipal solid waste	$30	1.1	95.0	$25.49
Other removal residue	$40	0.1	95.0	$25.49
Logging residues	$40	3.3	98.4	$25.98
Simulated thinnings from forestlands	$40	6.5	104.9	$26.85
Urban wood waste, construction and demolition	$40	3.4	108.3	$27.27
Urban wood waste, municipal solid waste	$40	0.6	108.9	$27.33
Conventional wood	$50	0.1	109.0	$27.36
Simulated thinnings from forestland	$50	4.0	112.9	$28.15
Stover	$50	0.3	113.2	$28.21
Biomass Sorghum	$50	2.1	115.3	$28.60
Urban wood waste, construction and demolition	$50	8.2	123.5	$30.02
Urban wood waste, municipal solid waste	$50	1.0	124.5	$30.19
Willows	$50	0.1	124.6	$30.20
Conventional wood	$60	1.7	126.3	$30.59
Simulated thinnings from forestlands	$60	2.7	129.0	$31.21
Treatment thinnings, other forest lands	$60	1.8	130.8	$31.61
Poplars	$60	3.2	134.0	$32.28
Stover	**$60**	**151.6**	**285.6**	**$47.00**
Straw	$60	11.4	297.0	$47.50
Biomass Sorghum	$60	4.3	301.3	$47.67
Switchgrass	$60	3.6	304.9	$47.82
Willows	$60	0.6	305.5	$47.84
Conventional wood	$70	7.6	313.1	$48.38
Simulated thinnings from forestlands	$70	1.9	315.0	$48.51
Treatment thinnings, other forest lands	$70	1.8	316.8	$48.63
Poplars	$70	13.2	330.0	$49.49
Stover	$70	45.4	375.4	$51.97
Straw	$70	11.5	386.9	$52.50
Biomass Sorghum	$70	1.6	388.5	$52.58

Table 2. (Continued)

Resource	Marginal Price ($ dt^{-1})	Marginal supply (million dt)	Cumulative supply (million dt)	Average Price ($ dt^{-1})
Switchgrass	$70	19.8	408.3	$53.42
Willows	$70	0.3	408.6	$53.43
Conventional wood	$80	12.9	421.4	$54.25
Simulated thinnings from forestlands	$80	1.4	422.8	$54.33
Poplars	$80	6	428.8	$54.69
Stover	$80	12	440.8	$55.38
Straw	$80	12.5	453.3	$56.06
Switchgrass	$80	27.9	481.2	$57.44
Willows	$80	0.1	481.3	$57.45
Conventional wood	$90	13.6	494.9	$58.34
Simulated thinnings from forestlands	$90	1.1	496.0	$58.41
Poplars	$90	4.8	500.8	$58.71
Stover	$90	7.3	508.1	$59.16
Straw	$90	3	511.1	$59.35
Switchgrass	$90	24.2	535.3	$60.73
Willows	$90	0.2	535.5	$60.74
Conventional wood	$100	11.7	547.2	$61.58
Simulated thinnings from forestlands	$100	0.9	548.2	$61.65
Poplars	$100	6.2	554.4	$62.08
Stover	$100	3.6	558.0	$62.32
Straw	$100	1.2	559.2	$62.40
Boimass Sorghum	$100	1.8	561.0	$62.53
Switchgrass	$100	20.2	581.2	$63.83
Willows	$100	0.8	582.0	$63.88
Conventional wood	$110	11.0	593.0	$64.73
Simulated thinnings from forestlands	$110	0.8	593.8	$64.79
Stover	$110	2.9	596.7	$65.01
Straw	$110	1.7	598.4	$65.14
Biomass Sorghum	$110	2.9	601.3	$65.36
Conventional wood	$120	10.9	612.2	$66.33
Simulated thinnings from forestlands	$120	0.7	612.9	$66.39
Poplars	$120	1.4	614.3	$66.52
Stover	$120	1.7	616.0	$66.66
Biomass Sorghum	$120	3.5	619.5	$66.97
Switchgrass	$120	16.2	635.7	$68.32
Willows	$120	0.9	636.6	$68.39
Conventional wood	$130	11.4	648.0	$69.47
Simulated thinnings from forestlands	$130	0.6	648.6	$69.53
Poplars	$130	7.5	656.1	$70.23
Stover	$130	1.2	657.3	$70.33
Biomass Sorghum	$130	2	659.3	$70.52
Switchgrass	$130	14.5	673.8	$71.80

Table 2. (Continued)

Resource	Marginal Price ($ dt^{-1})	Marginal supply (million dt)	Cumulative supply (million dt)	Average Price ($ dt^{-1})
Willows	$130	0.8	674.6	$71.86
Conventional wood	$140	11.3	685.9	$72.98
Simulated thinnings from forestlands	$140	0.5	686.4	$73.03
Conventional wood	$150	10.3	696.7	$74.17
Simulated thinnings from forestlands	$150	0.5	697.3	$74.23
Conventional wood	$160	10.1	707.4	$75.46
Simulated thinnings from forestlands	$160	0.5	707.9	$75.51
Conventional wood	$170	9.9	717.8	$76.82
Simulated thinnings from forestlands	$170	0.4	718.2	$76.88
Conventional wood	$180	9.2	727.4	$78.18
Simulated thinnings from forestlands	$180	0.4	727.8	$78.23
Conventional wood	$190	8.1	735.8	$79.45
Simulated thinnings from forestlands	$190	0.4	736.2	$79.51
Conventional wood	$200	42.3	778.5	$86.06
Simulated thinnings from forestlands	$200	0.8	779.3	$86.18

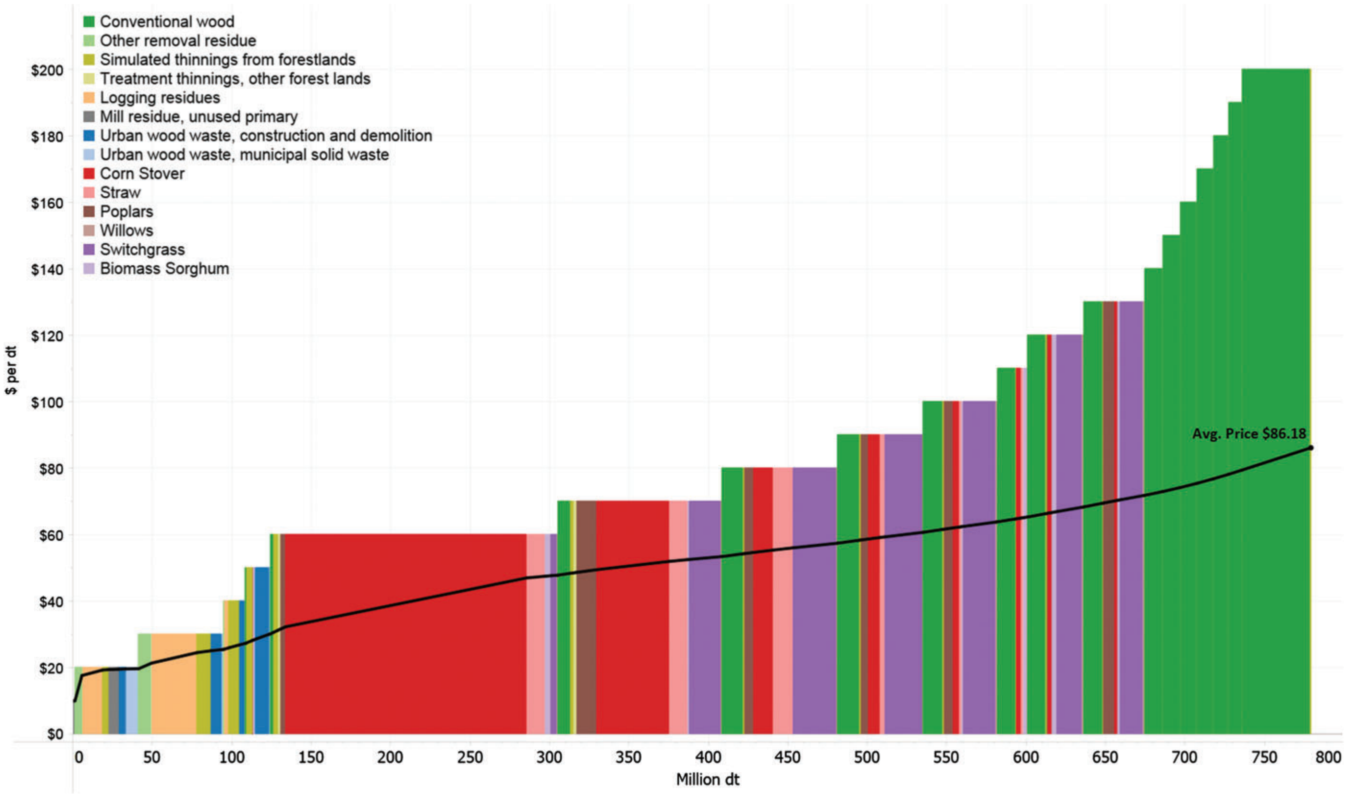

Figure 2. Step-wise supply curve indicating cellulosic supplies at prices between $50 and $100 (nominal), marginal price, and average price.

85 to 95 gallons dry ton^{-1} achieves a reduction in only 2.5 lbs biomass $gallon^{-1}$). Similarly, improving conversion yield from 75 to 85 gallons dry ton^{-1} achieves a reduction in 33 million dry tons required to produce 21 billion gallons of biofuel, while improving conversion yield from 85 to 95 gallons dry ton^{-1} achieves

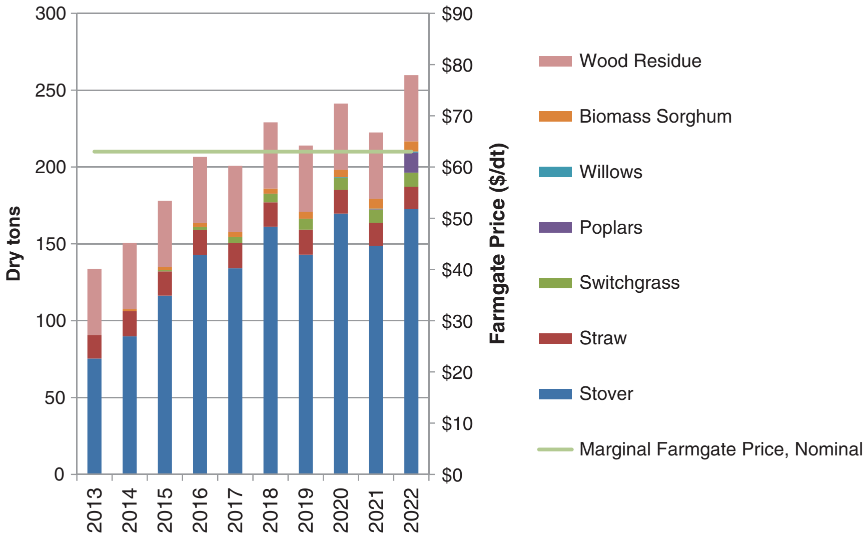

Figure 3. Resource profile of a price run at $63 dry ton^{-1}, which satisfies EISA by realizing 250 million dry tons by 2022.

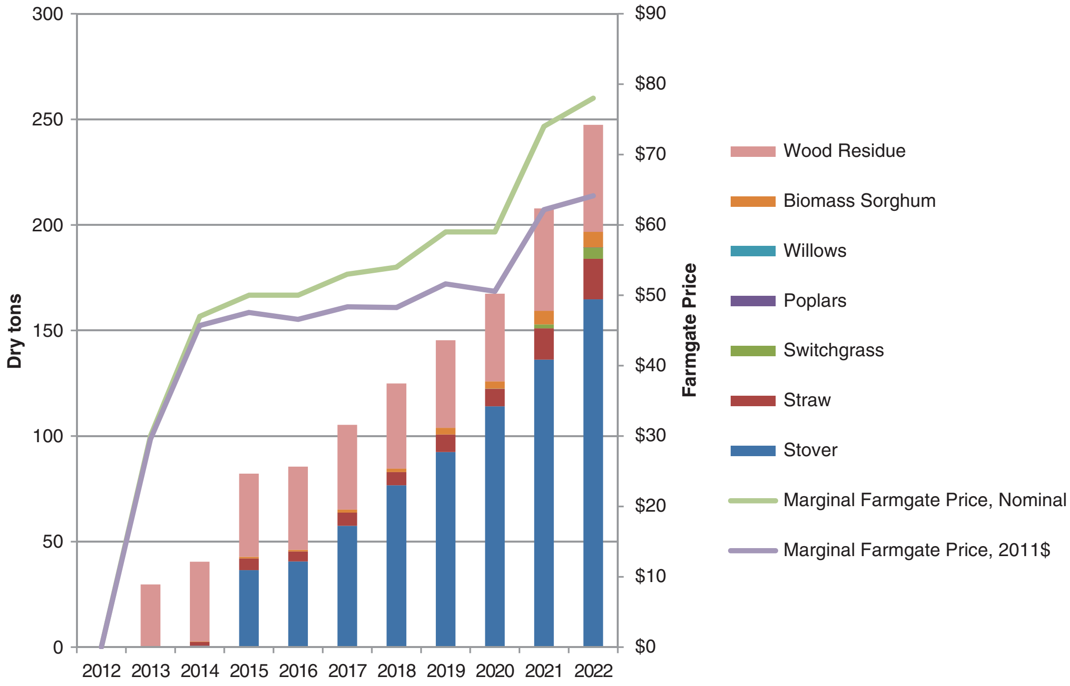

Figure 4. Resource profile of a demand run targeting annual EISA volumes under the reference case assumptions defined in Table 1.

a reduction in only 26 million dry tons required to produce the same amount of fuel. This at least in part explains why variation around the reference case in conversion efficiency is asymmetrical. The sensitivity analysis illustrates that decreasing conversion efficiency from 85 gallons dry ton^{-1} to 75 gallons dry ton^{-1} increases farmgate price[§] about $10 dry ton^{-1}, while increasing conversion efficiency from 85 gallons dry ton^{-1} to 95 gallons dry ton^{-1} decreases farmgate price about $7 dry ton^{-1}. More pessimistic conditions beyond this sensitivity analysis can be considered from

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[§] Unless otherwise specified, we report farmgate prices as marginal prices, i.e. the price of the last ton at a specified level of supply.

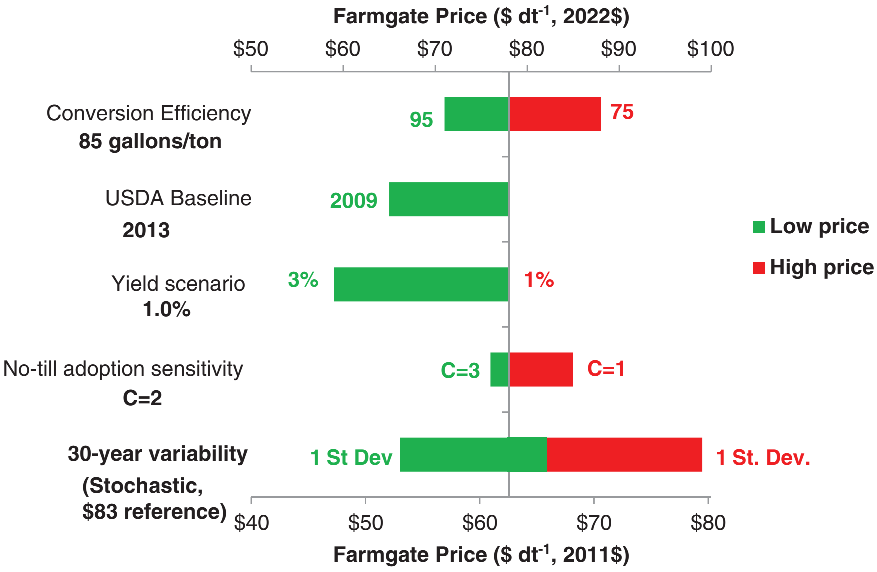

Figure 5. Marginal farmgate prices (nominal and $2011) required to meet EISA in 2022 under reference, optimistic (low price) and pessimistic (high price) assumptions from Table 1.

Table 3. Farmgate prices ($ dry ton^{-1} expressed in both $2011 and $2022) needed to meet EISA 2022 targets under the optimistic, reference, and pessimistic case assumptions described in Table 1.

Variable	Optimistic scenario	Reference case	Pessimistic scenario
	2022$ dry ton^{-1} (2011$ dry ton^{-1})		
Conversion Efficiency	$71 ($57)	$78 ($63)	$88 ($71)
USDA Baseline	$65 ($52)	$78 ($63)	N/A
Yield scenario	$59 ($48)	$78 ($63)	N/A
No-till adoption	$76 ($61)	$78 ($63)	$85 ($68)
30-year variability	$66 ($53)	$82 ($67)	$99 ($80)

the price-run scenarios show in Table 2. For example, the production of a 525 million dry tons year^{-1}, which would be required under a conversion yield of 40 gallons dry ton^{-1}, is shown supplied at a marginal farmgate price of $130 dry ton^{-1}, or an average price of $76 dry ton^{-1} (Table 2).

7. *USDA Agricultural Baseline Projection (ABP)*: For reasons described earlier, we use the latest available USDA ABP as the reference scenario and apply the 2009 ABP to evaluate possible impacts on farmgate price. Because crop price and production cost projections were lower in the 2009 USDA ABP as compared to the more recent 2013 USDA ABP, farmgate price needed to meet EISA in 2022 is $13 higher than the price projected using the 2009 USDA ABP. Given inherent uncertainty about the global economic market climate in the future, it is not known if the trend of increasing prices will continue.
8. *Crop yield (dry ton acre^{-1} annual improvement)*: As described, we apply the base-case yield scenario of the BT2 to our reference case and use the more optimistic 3% high-yield scenario to reflect reduced farmgate prices that might be achievable with higher yields. The difference is significant, with 3% compounding yield improvement contributing to a $19 reduction in farmgate price over the reference scenario needed to meet EISA goals in 2022. This is attributable to a combination of higher residue yields per acre, more land availability due to commodity crop demands being met on less acres, and higher yields of dedicated feedstocks translating to lower farmgate prices. All else being equal, it is doubtful that average yields would be lower than those assumed in the 1% base case scenario. Thus, we observe a potential for upside with yield improvements, with little risk of a trend of yield reductions over time. Annual yield variability, however, is inevitable and is evaluated below under the scenario of 30-year variability. Further, potential climate change impacts are currently unknown, but are under evaluation in 2014.
9. *Reduced-till and no-till adoption rate*: We restrict agricultural residue collection to land managed with no-till and reduced tillage operations. The range of simulated no-till adoption behavior introduced variability of −$2 to +$5 around the reference case value. While this

variable has the least impact of variables explored in this analysis, more research is needed to explore likely no- and reduced-till adoption rates in the future and how they might impact feedstock availability. Current efforts are underway to estimate current tillage regime allocation to replace the defunct Conservation Tillage and Information Center national survey. Additional programming is needed to allow collection of residues from conventional tillage systems where the no negative impact will result.[17]

10. *Stochastic climate demand-run simulation*. In contrast to all the other simulations in this analysis, this solution reflects a stochastic modeling simulation. As a result, the average marginal reference-case farmgate price of the stochastic model is \$83 dry ton^{-1}, as compared to the \$78 dry ton^{-1} from the determinist model. However, the \$78 dry ton^{-1} reference-case price of the deterministic model is well within the standard deviation of the stochastic model of \$83 dry ton^{-1} +/– \$16 dry ton^{-1}. This range of one standard deviation around the mean is \$66 to \$99 dry ton^{-1}, reflecting the single greatest potential source of variability in feedstock price needed to meet EISA. This price variability is not high compared conventional crops, with US corn prices ranging from \$2.54 to \$6.45 bushel^{-1} (\$2009) in 1986 and 2013, respectively.[18]

Discussion

Identifying and quantifying uncertainty is an important step toward understanding the economic availability of bioenergy feedstocks. Reference-case results suggest that nominal farmgate prices of about \$63 dt^{-1} and \$78 dt^{-1} would be needed to produce about 250 million dry tons under price-run and demand-run simulations, respectively. However, key modeling assumptions that bear inherent uncertainty.

Two potentially controllable assumptions show promise for reducing feedstock prices: conversion yield (gal dt^{-1}) i.e. reduced feedstock demand (for the same biofuels output), and yield scenario (dt ac^{-1}), i.e. increased supply. Ongoing research, development, and commercialization strategies aim to increase conversion yield, which can decrease demand, and in turn, price, needed to meet biofuels production targets. Results shown here suggest that increasing conversion yield from 85 gal to 95 gal dt^{-1} reduces demand by 26 million dry tons and, in turn, price by about \$7 dt^{-1}. On the agronomic side, crop improvement aims to increase yield per acre, which can decrease harvest costs, reduce land area in production, and meet supply targets at lower costs. The BT2 includes high-yield scenarios designed to simulate crop gains similar to those that have been achieved with conventional crops. If a combination of more productive genotypes and improved crop management can achieve yield improvements of 3% per year, then farmgate price could be reduced about \$19 dt^{-1}, achieving the single largest price reduction. The third controllable variable, no-till adoption rate, also impacts feedstock price to a lesser extent.

As with conventional agriculture, less controllable factors include climate and economic conditions as reflected in USDA Baseline Projections. One standard deviation variance associated with climate variation is plus or minus \$16 dt^{-1}, more than any other single factor. The 2012 US drought underscored the risk of extreme weather events to the agricultural sector in general, and the bioenergy supply chain in particular. However, a broad range of strategies and opportunities are available to enhance coping with climate risk across the biomass supply chain, including planting perennial and drought-tolerant crops, using advanced processing and logistics strategies, developing conversion technologies that can handle a range of feedstocks.[19] Feedstock price increases associated weather are due to decreases in supply, i.e. a liability. In contrast, feedstock price increases associated with macroeconomic conditions are due to increases in demand, a boon to producers. The modeling framework reflects that as conventional crops become more profitable, higher prices are needed to induce production of dedicated cellulosic feedstocks, a largely intractable scenario.

Conclusions and FY14 outlook

- Marginal (i.e. price of the last ton) farmgate prices \$51, \$63, and \$67 dry ton^{-1} (\$2011) are projected as necessary to provide 21 billion gallons of biofuels from about 250 million dry tons of terrestrial feedstocks in 2022 under price-run deterministic, demand-run deterministic, and stochastic simulations, respectively.
- A sensitivity analysis highlights some possible strategies directed at minimizing farmgate price:
    - Research and development in conversion efficiency and crop yield improvement may be the most controllable opportunities to reduce farmgate prices through a combination of decreased feedstock demand and/or increased supply. No- or reduced-till agronomic strategies can also contribute to increased supplies at lower prices.
    - Climate introduces uncertainty to crop yields. A stochastic analysis suggests that

  climate-associated yield variability may be greater than the other variables assessed. Thus, an emphasis should be placed on climate risk management strategies (e.g. Langholtz *et al.*, in review).
  - Economic outlook is uncontrollable and uncertain. However, the USDA ERS projects that recent trends of increasing agronomic prices are likely to flatten towards a slower upward trajectory. If true, the rate of feedstock price increases will slow, all else being equal.
- Among the independent variables evaluated here, there is an average impact of about $11 around projected feedstock prices in 2022. This means that on average, variability of feedstock farmgate (aka roadside) prices will be within the range of plus or minus $11 dry ton^{-1} out of $78 dry ton^{-1} in nominal dollars in 2022. In our view it is possible but unlikely that all parameters will collectively shift toward either worst- or best-case scenarios. Thus, it is likely that cancellation effects would be realized among changing independent variables. In sum, this analysis does not identify price variability for cellulosic feedstocks beyond what is expected for conventional commodity crops and forest products. Ongoing efforts to improve feedstock crop yields, conversion efficiencies, and logistical strategies can reduce feedstock prices and price volatility.

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