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An Economic Evaluation of US Biofuel Expansion Using the Biofuel Breakeven Program with GHG Accounting

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We present results from an application of the Biofuel Breakeven program (BioBreak) to 14 US cellulosic ethanol markets that vary by feedstock and location. BioBreak estimates the economic costs of cellulosic biofuel production for each market and identifies the necessary conditions to sustain long-run markets. Based on current market conditions, our results suggest that long-run cellulosic ethanol production is not sustainable without significant government intervention or high long-run oil prices ($135-170 per barrel). Using life-cycle analysis for cellulosic ethanol and conventional gasoline, we extend the BioBreak program results to derive an implicit value of reduced greenhouse gas emissions embodied in cellulosic ethanol. For the markets considered in our analysis, sustaining cellulosic ethanol production is equivalent to valuing the reduction in CO_2 equivalents between $141 and $282 per metric ton.

Key words: biofuel, biofuel policies, biomass, carbon tax, cellulosic ethanol, greenhouse gas emissions, life-cycle analysis, renewable fuel standard.

Introduction

Unstable energy prices and concern regarding the environmental impacts of growing greenhouse gas (GHG) emissions have increased interest in finding alternative sources of energy. The use of biomass, a renewable and potentially GHG-reducing energy source, has gained significant attention in the United States. In this article, we consider one type of bioenergy—cellulosic biofuel. Along with allocating federal funds to biofuel research projects, the United States has imposed mandates and implemented market-based incentives to stimulate the development of cellulosic biofuel markets. The revised Renewable Fuels Standard (RFS2) took effect in July 2010 and mandates a minimum contribution from cellulosic biofuel to the US transportation fuel mix through 2022. At the same time, the 2008 Farm Bill provides tax credits to cellulosic biofuel producers and subsidy payments to biomass suppliers. Even with mandated production and market-based incentives, the industry has been slow to develop; cellulosic biofuel production has been limited to research labs and pilot plants. Without a commercial-scale cellulosic biorefinery or biomass supply system, knowledge is limited regarding the costs and environmental impacts of supplying and converting cellulosic biofuel at the scale needed to meet current and future mandate levels. Consequently, economists and environmentalists have been asked to evaluate the potential economic and environmental implications of biofuel expansion, and more specifically, the impacts of meeting the ambitious RFS2 mandates.

Yet, to understand the economic implications of biofuel expansion first requires an understanding of the economics of cellulosic biofuel production. For instance, can the production of cellulosic biofuel be a long-run breakeven proposition given available technology and market conditions? If not, what are the costs or market conditions needed to sustain a cellulosic biofuel market? These are the main questions addressed by the Biofuel Breakeven program (BioBreak). BioBreak is a simple and flexible program developed to evaluate the long-run economic sustainability of local biofuel markets using breakeven models of the local feedstock supply system and biofuel refining process. A local biofuel market can exist only if the biofuel processor can obtain sufficient feedstock and the local biomass market can deliver sufficient feedstock at a market price that allows both parties to break even in the long-run. Given expected local market conditions, BioBreak calculates the supplier and processor long-run breakeven values for biomass. Further, BioBreak derives the difference—or "price gap"—between the estimated supplier and processor breakeven prices. If the price gap is zero or negative, the local biofuel market is economically sustainable in the long-run, and if positive, the price gap represents the market incentive needed to sustain the local market.

In this article, we provide an overview of the BioBreak program and present results from an application to 14 cellulosic ethanol markets that vary by feedstock and location. In addition, we use our BioBreak results in conjunction with GHG emissions reductions derived from life-cycle analysis (LCA) to identify the carbon price needed to sustain local cellulosic ethanol markets in the long-run. This carbon price can be considered an implicit CO_2-equivalent (CO_2-eq) price embodied in cellulosic biofuel policies (i.e., mandates).

Overview of the BioBreak Program

The BioBreak program is based on breakeven models for local feedstock supply systems and the biofuel refining process. The separation of the economic analysis into biomass production and biomass processing is based on the assumption that the biorefinery will outsource biomass production to several local producers.

Biofuel Processing

Since a commercial-scale biorefinery is not currently available, the model of the biofuel refining process reflects a profit-maximizing biofuel processor deciding whether to build a proposed biorefinery. The processor will only build the proposed biorefinery if he expects the biorefinery to break even in long-run equilibrium. As a result, the maximum amount the biofuel processor can pay for feedstock in long-run equilibrium will be the long-run breakeven price given biorefinery technology and expected market conditions (e.g., output and input prices). Equation 1 outlines a simplified version of the equation used in the BioBreak program to calculate the processor's long-run breakeven price or derived demand (DD) per ton of feedstock.

$$DD = \{P_{CF} \times EV + G_P + V_C + V_O - C_I - C_O\} \times Y_E \quad (1)$$

The processor's derived demand equals total expected revenues per ton of feedstock converted to biofuel less non-feedstock costs. The expected market price of biofuel is calculated as the energy equivalent price of conventional fuel, that is, the price fuel blenders would be willing to pay in a competitive market. In Equation 1, P_{CF} denotes per-gallon price of conventional fuel and E_V denotes the energy equivalent factor of conventional fuel to biofuel. Within BioBreak, the price of conventional fuel is a user-specified function of the price of oil (P_{oil}).[1] Beyond returns from the sale of each gallon of biofuel, the processor may also receive revenues from government incentives (G_P), e.g., tax credits, coproduct production (V_C), and octane benefits (V_O) per gallon of processed biofuel. Non-feedstock biorefinery costs per gallon include amortized investment costs (C_I) and operating costs (C_O). The calculation within brackets in Equation 1 provides the net return per gallon of biofuel above all non-feedstock costs. The conversion ratio of gallons of biofuel produced per dry ton of biomass (Y_E) converts per-gallon net return prior to feedstock costs into the processor's DD per dry ton of feedstock.

The general format of Equation 1 allows BioBreak to accommodate most biofuel platforms by categorizing platform-specific costs into the appropriate model parameters. In our application of BioBreak to the cellulosic ethanol industry, we use data for a proposed biorefinery using a biochemical process (co-current dilute acid prehydrolysis and enzymatic hydrolysis). A distinguishing characteristic of a biochemical process is the use of enzymes to break down cellulose into simple sugars. As a result, enzyme costs are included in the operating costs for our analysis. Similarly, we use investment costs, other operating costs, and coproduct value (electricity) consistent with a biochemical processing facility. Biorefineries utilizing other conversion platforms, such as a gasification or fast pyrolysis design, can be analyzed within the BioBreak program with minor adjustments to the interpretation and values included in each cost component.[2]

Biomass Supply

Since the biorefinery will contract with several local suppliers to acquire sufficient biomass for commercial-scale production, the model of biomass supply underlying BioBreak evaluates the long-run per-ton feedstock cost faced by the biorefinery in a competitive local biomass market. With a competitive market, the biorefinery cannot price discriminate and the price paid to all suppliers will be the price paid for the marginal unit. The minimum payment a supplier of the marginal unit would accept is the value at which the supplier breaks even in the long run. The long-run breakeven price for the marginal unit will depend on all costs incurred, including land and biomass opportunity costs, to produce, store, and transport biomass to the biorefinery in the long run

1. *In our application to the cellulosic ethanol market we assume the price of conventional gasoline is a constant fraction of the price of oil, $P_{gas} = P_{Oil}/29$ based on historical trends (Elobeid, Tokogz, Hayes, Babcock, & Hart, 2006), but this relationship is flexible within BioBreak.*
2. *Coefficients for biomass gasification, fast pyrolysis, and biochemical processes can be obtained from Swanson, Satrio, Brown, Platon, & Hsu (2009), Wright, Satrio, Brown, Daugaard, & Hsu (2009), and Kazi et al. (2010), respectively.*

and any government incentives received for biomass supply (G_s , e.g., production subsidies). Equation 2 outlines a simplified version of the equation used in the BioBreak program to estimate the long-run supply cost (SC) for the last ton of biomass to the biorefinery.

$$SC = \{C_{ES} + C_{Opp} + C_{HM} + SF + C_{NR} + C_S + DFC + DVC \times D\} - G_S \quad (2)$$

Depending on biomass feedstock, costs per dry ton include establishment and seeding (C_{ES}),[3] land and biomass opportunity costs (C_{Opp}), harvest and maintenance (C_{HM}), stumpage fees (*SF*), nutrient replacement (C_{NR}), biomass storage (C_S), transportation fixed costs (*DFC*), and variable transportation costs calculated as the variable cost per mile (*DVC*) multiplied by the average hauling distance to the biorefinery (*D*). Average hauling distance is a function of the annual biorefinery biomass demand, annual biomass yield, and biomass density, and is calculated using the formulation by French (1960) for a circular supply area with a square road grid. Costs reported per acre are converted into per-ton costs using the annual biomass yield per acre.

Biofuel Market Feasibility

A local biofuel market can exist only if the biofuel processor can obtain sufficient feedstock and the local biomass market can deliver sufficient feedstock at a market price that allows both parties to break even in the long run. Therefore, without cellulosic biofuel mandates, economic sustainability of cellulosic biofuel markets depends on the relationship between the long-run price the local biomass producers will accept for biomass (*SC*) and the long-run price the biofuel processor can pay for biomass (*DD*). Given market conditions, BioBreak provides the difference or "price gap" between the biomass supply price and processor DD. If the price gap is zero or negative, the local biofuel market is economically sustainable in the long-run, and if positive, the price gap represents the gap that needs to be closed to sustain the local biofuel market.

BioBreak does not estimate complete biomass demand and supply curves but rather derives point estimates of the SC and DD values and the price gap between them for a fixed plant capacity and local feedstock market. Figure 1 provides a graphical depiction of the price gap derived by BioBreak. Although illustrated as a horizontal line, the DD for feedstock calculated by the BioBreak program is a point estimate at A—that is, the price that the processing plant can pay per ton of feedstock if operating at capacity *Q*. Otherwise, the plant will not operate in the long run. Consider the two upward sloping biomass supply curves in Figure 1. First, SC_1 intersects the DD curve but at a feedstock quantity less than necessary to operate the biofuel plant at capacity and still break even in the long run. For a biomass market with SC_1, the BioBreak program would calculate the price gap = $(P - P_E) > 0$ at feedstock quantity *Q*. Alternatively, if SC_2 was the supply curve for the biomass market which intersects DD at point A, then the price gap = $(P - P_E) = 0$ at quantity *Q*.

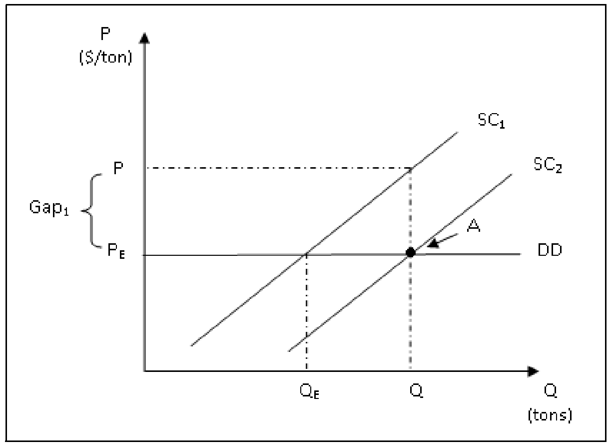

Figure 1. Price gap estimated by the BioBreak program.

Simplifying Assumptions

The BioBreak estimates are based on a number of assumptions. A brief discussion of key assumptions is warranted. Here, we address three assumptions; a full discussion can be found in Miranowski and Rosburg (2010a, 2010b).

First, BioBreak assumes a fixed relationship between gasoline and ethanol based on the energy equivalence of ethanol to gasoline. A fixed relationship presumes that gasoline and ethanol are perfectly substitutable in consumption and that ethanol does not require an extra marketing cost. De Gorter and Just (2009a, 2009b) argue that perfect consumption substitutability between ethanol and gasoline is a realistic assumption for low-level blends of ethanol (such as 10 or 15%) and for E85 in flex fuel vehicles but may not be a valid assumption for differentiated products or in the presence of the "blending wall" (i.e., the regulatory limit on the

3. *For perennial crops, the establishment and seeding cost is amortized over the expected life of the crop.*

amount of ethanol that can be blended with gasoline and supplied through traditional pumps). BioBreak evaluates the economic feasibility of cellulosic biofuel markets in the absence of the blending wall constraint, but we acknowledge the blending wall may be another limiting factor to future biofuel market development.

Second, BioBreak does not incorporate policy uncertainty. In its current form, BioBreak is not capable of analyzing short-run or temporary program impacts. In our application, we consider the impacts of policy incentives but assume the incentives would be provided for the life of the plant. Perhaps of greater concern is uncertainty regarding enforcement of RFS2 mandates. Since the EPA conducts an annual evaluation of the cellulosic ethanol industry and provides revised mandates if deemed necessary, potential biofuel processors face uncertainty regarding the future biofuel market (i.e., mandated demand). The biofuel processor may require a minimum biorefinery return, or a "risk premium," to induce investment. We do not consider a risk premium in our application of the BioBreak program, but a minimum biorefinery return could be incorporated into the model without difficulty.

Third, the BioBreak program does not consider the impact of energy price uncertainty on biofuel investment. If potential investors require a risk premium due to uncertainty in long-run energy markets, the actual DD will be lower and price gap higher than the estimates provided by the BioBreak program. Further, with energy market uncertainty, a price gap estimate below zero will satisfy a necessary condition for development of a cellulosic biofuel market (i.e., both biomass supplier and processor break even in the long-run), but may not be sufficient to induce investment.

Application of the BioBreak Program

We apply BioBreak to estimate the feasibility of cellulosic ethanol markets using a biochemical refining process (dilute acid prehydrolysis with saccharification and cofermentation) and seven potential feedstocks (corn stover, switchgrass, *Miscanthus*, wheat straw, alfalfa, farmed tress, and forest residue). Corn stover is evaluated for land in continuous corn production (CC) and land in a corn/soybean rotation (CS).[4] We also consider a four-year corn stover/alfalfa rotation with two years in each crop (i.e., CCAA). Switchgrass is evaluated in three markets with characteristics considered representative of three regions: Midwest ("MW"), South-Central ("S-C"), and Appalachian ("App"). *Miscanthus* is evaluated for the Midwest and Appalachian regions, while corn stover and wheat straw are assumed to be produced on current cropland base in the Midwest and Pacific Northwest ("PNW") regions, respectively. To account for the heterogeneity in Midwest land quality, we evaluate perennial grass feedstocks (switchgrass and *Miscanthus*) from biomass markets with high quality (HQ) and low quality (LQ) Midwest cropland. In total, we consider 14 biomass feedstock/market regions.

The biorefinery technology and costs used in our application are based on the techno-economic analysis by Kazi et al. (2010) for a 54-million-gallon-per-year (mmgy) biorefinery. Although we do not consider larger or smaller biorefineries in our application, a brief discussion of the relationship between biorefinery capacity and production costs is warranted. Cellulosic biofuel production faces an economic tradeoff between biorefinery economies of scale and biomass transportation. As the long-run biorefinery capacity increases, biorefinery economies of scale result in decreasing average processing costs per gallon at least up to a point. At the same time, the increase in feedstock demand for a larger biorefinery requires feedstock to be transported from more distant locations resulting in an increase in average feedstock cost per gallon. Given the complexity of the relationship between economies of scale and diseconomies of transportation, an analysis of alternative biorefinery capacities is beyond the scope of the BioBreak model presented here. The tradeoff between processing economies and transportation diseconomies is an extension we are planning to pursue.[5]

Without data from a commercial-scale biorefinery or biomass supply system, uncertainty exists regarding input values for the BioBreak program. BioBreak provides the option to estimate breakeven values with fixed parameters or with stochastic simulation based on user-specified parameter distributions.[6] For our analysis, we

4. *Continuous corn production is less profitable then corn/soybean rotation with and without stover harvest because of the yield penalty associated with continuous corn (Iowa State University Extension, 2010; Purdue University Cooperative Extension Service, 2009). Yet, continuous corn means higher stover density in a given local market over two years and lowers biomass transportation costs.*

5. *See Wright and Brown (2007), Searcy and Flynn (2009), and Leboreiro and Hilaly (2011) for further discussion on the tradeoff between biorefinery economies of scale and diseconomies of transportation.*

6. *BioBreak uses Oracle's spreadsheet-based program Crystal Ball for stochastic simulation. Stochastic simulation allows for parameter variability, parameter correlation, and sensitivity testing not available in the fixed-parameter specification.*

utilize the stochastic simulation feature and create distributions for model parameters using observed values in published literature which exhibit significant variation.[7] The program results discussed in the following section are based on the mean values from stochastic simulation.

For the long-run price of oil, we chose to evaluate scenarios rather than specify a distribution or a single value. The price of oil is variable and determines the price of ethanol in BioBreak. In July 2008, the price of oil escalated to $145 per barrel but dropped to $30 per barrel in December 2008. For our analysis, we consider three long-run oil price scenarios: $50 per barrel, $100 per barrel, and $150 per barrel. Similarly, technological uncertainty of cellulosic ethanol production provides a range of estimates for the ethanol conversion ratio. Based on the range of conversion ratios reported in Miranowski and Rosburg (2010a), we assume a biomass-to-ethanol conversion ratio with a mean value of 70 gallons per dry ton to be representative of current and near future technology. At the assumed baseline conversion rate of 70 gallons per dry ton and an annual capacity of 54 mmgy, the biorefinery will process approximately 771,000 tons of feedstock per year or 2,200 dry tons per day assuming an online time of 350 days per year. In our sensitivity analysis, we consider the impact of an increase in the mean conversion ratio to 80 gallons per dry ton.

For comparison purposes, we specify a "baseline" scenario and provide sensitivity results relative to the baseline scenario. The baseline scenario consists of no fiscal policy incentives for biofuel production (i.e., no tax credits or payment programs), a long-run oil price of $100 per barrel, and a conversion rate of 70 gallons per dry ton of feedstock.

Results

For the 14 feedstock/regions considered in our analysis, long-run cellulosic ethanol production is not sustainable without significant government intervention in the baseline scenario. As shown in Table 1, the long-run biomass supply cost (SC) exceeds the processor's long-run derived demand price (DD) for all markets. The difference between the supply cost and derived demand price, denoted as the price gap, ranges from $57 per ton of wheat straw in the PNW to $115 per ton of switchgrass grown on high-quality Midwest cropland. The estimated price gaps represent the costs to sustain markets and are equivalent to a per-gallon ethanol cost between $0.82 and $1.65.[8]

Table 1. Supply cost, derived demand, and price gap for a 54 mmgy biorefinery ($ per ton feedstock).

	SC	DD	Price gap
Stover (CC)	$115	$13	$102
Stover (CS)	$89	$13	$76
Stover/alfalfa	$89	$14	$75
Alfalfa	$115	$15	$100
Switchgrass (MW HQ)	$130	$15	$115
Switchgrass (MW LQ)	$124	$15	$109
Switchgrass (App)	$98	$15	$83
Switchgrass (S-C)	$95	$15	$81
***Miscanthus* (MW HQ)**	$113	$15	$98
***Miscanthus* (MW LQ)**	$117	$15	$102
***Miscanthus* (App)**	$103	$15	$89
Wheat straw	$72	$15	$57
Farmed trees	$87	$12	$75
Forest residues	$75	$12	$63

(Baseline scenario, 70 gal/dry ton, 2007 $s)
Note: Reported SC, DD, and price gap estimates are mean values from BioBreak simulation.

The breakeven values and resulting price gaps presented in Table 1 are sensitive to assumptions and parameters used in the analysis. Here, we present a sensitivity analysis relative to the baseline scenario for the price of oil, conversion technology, and current and potential policy incentives.

Oil Price

The price of oil impacts both the processor's DD price and feedstock supply cost. An increase in the energy price will increase biomass input costs but also increase the biofuel price (i.e., processor revenue). Over the range of oil prices considered in our analysis, we find that a change in the price of oil has only minimal impact on the supplier's nutrient replacement, harvest, and

7. *Published literature values were updated to 2007 using US Department of Agriculture (USDA), National Agricultural Statistics Services (NASS) Agricultural prices (2007a, 2007b) and distributional assumptions were verified with industry information when available. See Miranowski and Rosburg (2010a) for a summary of the literature on biomass production and conversion.*

8. *Although we present estimates on a per-gallon ethanol basis, other studies report estimates on a gasoline-equivalent basis. The estimated price gaps for the baseline scenario (i.e., $100 per barrel oil, 70 gallons per dry ton conversion rate, and no fiscal policy incentives) are equivalent to a cost between $1.23 and $2.47 per gallon gasoline equivalent.*

Table 2. Price gap for a 54 mmgy biroefinery by oil price, technology, and policy scenario ($ per ton feedstock).

	Baseline ($100 oil)	$50 oil	$150 oil	80 gal/ton conversion ratio	Tax credit
Stover (CC)	$102	$182	$21	$92	$31
Stover (CS)	$76	$156	0	$66	$5
Stover/alfalfa	$75	$156	0	$66	$4
Alfalfa	$100	$181	$20	$90	$29
Switchgrass (MW HQ)	$115	$196	$35	$106	$45
Switchgrass (MW LQ)	$109	$189	$28	$99	$38
Switchgrass (App)	$83	$164	$3	$74	$12
Switchgrass (S-C)	$81	$161	$0	$71	$10
***Miscanthus* (MW HQ)**	$98	$178	$17	$88	$27
***Miscanthus* (MW LQ)**	$102	$183	$22	$93	$32
***Miscanthus* (App)**	$89	$169	$8	$79	$18
Wheat straw	$57	$138	$0	$48	$0
Farmed trees	$75	$156	$0	$66	$5
Forest residues	$63	$144	$0	$54	$0

(Baseline assumptions unless noted otherwise, 2007 $s)
Note: Price gap estimates censored below at $0.

Table 3. Long-run oil price needed to sustain a biomass market for a 54 mmgy biorefinery.

	No policy incentive	Tax credit	Tax credit & CHST payment
Stover (CC)	$163	$120	$63
Stover (CS)	$147	$103	$47
Stover/alfalfa	$147	$103	$47
Alfalfa	$163	$119	$62
Switchgrass (MW HQ)	$172	$128	$72
Switchgrass (MW LQ)	$168	$124	$68
Switchgrass (App)	$152	$108	$52
Switchgrass (S-C)	$150	$106	$50
***Miscanthus* (MW HQ)**	$161	$117	$61
***Miscanthus* (MW LQ)**	$164	$120	$64
***Miscanthus* (App)**	$155	$111	$55
Wheat straw	$136	$92	$36
Farmed trees	$147	$103	$47
Forest residues	$139	$96	$39

(Baseline scenario unless noted, 70 gal/dry ton, $ per barrel in 2007 $s)

transportation costs. Compared to the baseline scenario, the low (high) oil cost scenario decreases (increases) the long-run feedstock supply cost by approximately $4 per ton. Given the small magnitude of these impacts, we focus the sensitivity analysis on the impact of the long-run price of oil on the processor's DD price.

Since the price of ethanol is tied directly to the price of oil, any increase (decrease) in the price of oil results in a decrease (increase) in the price gap. The results in Table 1 are based on a long-run oil price of $100 per barrel. If, instead, the long-run expected oil price is $50 per barrel, the price gap increases to between $138 and $196 per ton of biomass (Table 2, Column 3; $1.97-$2.80/gallon). At an oil price of $150 per barrel, cellulosic biofuel markets are sustained for stover (CS), stover/alfalfa, switchgrass (S-C), wheat straw, farmed trees, and forest residues (Table 2, Column 4).

Given long-run oil price uncertainty, we also calculate the expected long-run oil price that would be needed to sustain each biomass market (i.e., oil price which eliminates the price gap). Without government incentives, the long-run oil price needed to sustain cellulosic ethanol markets ranges between $136 per barrel for a wheat straw market in the PNW to $172 per barrel for switchgrass on Midwest cropland (Table 3, Column 2).

Conversion Technology

The baseline results assume a conversion ratio of 70 gallons per dry ton of biomass for all feedstocks, but conversion technological advances are expected to increase this ratio. An increase in the biomass conversion ratio increases the biorefinery net returns per unit of feedstock and decreases the price gap. Table 2 provides price-gap sensitivity to the higher conversion ratio of 80 gallons per dry ton. Assuming $100 per barrel of oil and the higher conversion ratio, the price gap decreases to range between $48 and $106 per ton (Table 2, Column 5).

Fiscal Policy Incentives

Policy incentives to either biomass suppliers or biofuel processors will decrease the price gap. We consider the impact of two policy incentive scenarios on our baseline model results. The first scenario maintains baseline assumptions and adds the $1.01 per-gallon tax credit provided by the 2008 Farm Bill to cellulosic biofuel producers. The second policy scenario includes the tax credit plus the biomass collection, harvest, storage, and transportation (CHST) matching payment of up to $45 per ton of biomass also provided in the 2008 Farm Bill (part of the Biomass Crop Assistance Program). Even though the CHST payment program was written as a short-term program (2 years) and the tax credit is up for renewal in December 2012, we treat the market effects as if CHST payments and tax credit were long-term policy incentives in this illustration.

With a long-run tax credit and a long-run oil price of $100 per barrel, regional biofuel markets are sustainable for wheat straw and forest residues (Table 2, Column 6). The remaining markets have a price gap between $4 and $45 per ton ($0.06-$0.64/gallon). If we compare the second and third column in Table 3, the tax credit has essentially the same impact as a $44 per-barrel long-run oil price increase. With a long-run CHST payment program in addition to the tax credit, the price gap is eliminated for all 14 markets in our baseline scenario ($100 per barrel oil).

Implicit Carbon Price

The results from the BioBreak program can also be used to calculate an implicit carbon price embodied in cellulosic biofuel. Reducing GHG emissions by substituting cellulosic biofuel for conventional fuel is frequently discussed as justification for cellulosic biofuel policies. In particular, provisions in the RFS2 outline minimum GHG reduction standards for each type of biofuel relative to 2005 gasoline or diesel. In terms of market failure theory, cellulosic biofuel creates social benefits (i.e., a positive externality) that are external to producers' and consumers' decision processes. While producers and consumers will realize the full costs of cellulosic biofuel production and consumption, they do not consider the social value of reduced GHG emissions from biofuel. As a result, biofuel production would be lower than the socially optimal level (that is, below the quantity where the added benefits equal the added costs) unless producers and consumers are forced by mandates or receive an incentive to internalize GHG benefits. The additional cost incurred to sustain cellulosic biofuel production to meet policy goals implicitly quantifies the social cost of reducing GHG emissions through cellulosic biofuel. Using life-cycle analysis, we can derive an estimate of GHG emissions reductions from cellulosic biofuel relative to conventional fuel. By combining BioBreak cost estimates with data on GHG emissions reduction, we compute the cost of GHG emissions reduction implied by mandated biofuel production.

For estimates of GHG emissions reductions we use the Greenhouse gases, Regulated Emissions, and Energy use in Transportation model (GREET 1.8d), an Excel-based program developed by the Center for Transportation Research at Argonne National Laboratory. GREET provides life-cycle GHG emissions for both conventional gasoline and feedstock-specific cellulosic biofuel (Wang, 2007). To provide a consistent analysis, we adjust the default assumptions in GREET to fit the feedstock, location, and technology assumptions used in our application of the BioBreak program.

Implicit Carbon Price Results

For a "baseline" carbon price scenario we use baseline BioBreak assumptions including $100 per barrel of oil, 70 gallons ethanol per dry ton feedstock, and no policy incentives. Further, we assume a biorefinery with 2010 technology for the GREET program. In the baseline scenario, the carbon price implied by the cost needed to sustain local cellulosic ethanol markets ranges between $141 and $280 per metric ton CO_2 equivalents (mt CO_2-eq). Table 4 provides estimates for the implicit carbon prices needed to sustain regional cellulosic ethanol production under alternative oil price and technology assumptions. At a long-run oil price of $50 per barrel, the implicit carbon price increases to between $319 and $475 per mt CO_2-eq (Table 4, Column 3). With $150 per barrel of oil, several regional cellulosic ethanol markets will be sustainable without carbon pricing, and for the other cellulosic ethanol markets, carbon prices range between $7 and $84 per mt CO_2-eq (Table 4, Column 4). Finally, with a conversion ratio of 80 gallons per ton and 2020 GREET biorefinery technology, the implicit carbon price decreases to between $99 and $216 per mt CO_2-eq (Table 4, Column 5).

Table 4. Implicit carbon price needed to sustain a biomass market for a 54 mmgy biorefinery ($ per mt CO_2-eq).

	$100 oil	$50 oil	$150 oil	80 gal/ton & 2020 biorefinery
Stover (CC)	$211	$379	$44	$165
Stover (CS)	$157	$325	$0	$119
Stover/alfalfa	$169	$349	$0	$125
Alfalfa	$246	$444	$48	$187
Switchgrass (MW HQ)	$280	$475	$84	$216
Switchgrass (MW LQ)	$264	$459	$69	$203
Switchgrass (App)	$201	$396	$7	$150
Switchgrass (S-C)	$195	$390	$0	$145
***Miscanthus* (MW HQ)**	$236	$431	$42	$180
***Miscanthus* (MW LQ)**	$247	$442	$53	$189
***Miscanthus* (App)**	$214	$409	$20	$161
Wheat straw	$141	$338	$0	$99
Farmed trees	$154	$319	$0	$117
Forest residues	$158	$359	$0	$109

(Baseline assumptions unless noted otherwise, 2007 $s)

Note: Carbon price estimates censored below at $0. Life cycle emissions for ethanol based on E85 flex-fuel vehicle and 2010 biorefinery unless noted otherwise.

Conclusions

The RFS2 requires cellulosic biofuel be part of the liquid transportation fuel mix, with a minimum annual use of 16 billion gallons of cellulosic biofuel by 2022. Available knowledge regarding costs of producing cellulosic biomass and converting it to cellulosic biofuel is largely based on engineering estimates and experimental trials. At the same time, previous literature has overlooked market conditions required for the development of second-generation biofuel markets (Babcock, Marette, & Tréguer, 2011). We use the BioBreak program to evaluate the economic feasibility of 14 regional cellulosic ethanol markets. Our results indicate that cellulosic ethanol markets are not likely to achieve long-run breakeven without significant government intervention or higher long-run oil prices. For the cellulosic ethanol markets considered in our analysis, the price gap between the supply price and derived demand price ranges from $57 to $115 per ton of feedstock, or equivalently, $0.82 to $1.65 per gallon cellulosic ethanol. If we interpret the price gap in the absence of government incentives as reflecting the cost of carbon savings associated with each gallon of cellulosic ethanol, we can derive the implicit price per unit of carbon equivalent savings from mandating cellulosic biofuel production. This approach would imply a carbon equivalent cost between $141 and $280 per metric ton, significantly higher than carbon prices discussed in the literature (America's Energy Future Panel on Alternative Liquid Transportation Fuel [ALTF], 2009; Ramseur & Parker, 2009).

References

America's Energy Future Panel on Alternative Liquid Transportation Fuel (ALTF). (2009). *Liquid transportation fuels from coal and biomass: Technological status, costs, and environmental impacts*. Washington, DC: The National Academies Press.

Babcock, B., Marette, S., & Tréguer, D. (2011). Opportunity for profitable investments in cellulosic biofuels. *Energy Policy*, *39*, 714-719.

de Gorter, H., & Just, D. (2009a). The welfare economics of a biofuel tax credit and the interaction effects with price contingent farm subsidies. *American Journal of Agricultural Economics*, *91*(2), 477-488.

de Gorter, H., & Just, D. (2009b). The economics of a blend mandate for biofuels. *American Journal of Agricultural Economics*, *91*(3), 738-750.

Elobeid, A., Tokogz, S., Hayes, D., Babcock, B., & Hart, C. (2006). *The long-run impact of corn-based ethanol on grain, oilseed, and livestock sectors: A preliminary assessment* (Briefing Paper 06-BP 49). Ames, IA: Center for Agricultural and Rural Development.

French, B. (1960). Some considerations in estimating assembly cost functions for agricultural processing operations. *Journal of Farm Economics*, *62*, 767-778.

Iowa State University Extension. (2010). *Estimated costs of crop produciton in Iowa—2010: Crop rotation summary.* Ames, IA: Author. Retrieved June 27, 2010, from http://www.extension.iastate.edu/agdm/crops/html/a1-20.html.

Leboreiro, J., & Hilaly, A. (2011). Biomass transportation model and optimum plant size for the production of ethanol. *Bioresource Technology*, *102*, 2712-2723.

Kazi, F., Forman, J., Anex, R., Kothandaraman, G., Hsu, D., Aden, A., et al. (2010). *Techno-economic analysis of biochemical scenarios for production of cellulosic ethanol* (NREL/TP-6A2-46588). Golden, CO: National Renewable Energy Laboratory.

Miranowski, J., & Rosburg, A. (2010a, February). *An economic breakeven model of cellulosic feedstock and ethanol conversion with implied carbon pricing* (Working Paper #10002). Ames: Iowa State University, Department of Economics. Available on the World Wide Web: http://www.econ.iastate.edu/research/working-papers/p10920.

Miranowski, J., & Rosburg, A. (2010b, July 25). *Using cellulosic ethanol to 'go green': What price for carbon?* Paper presented at the Agricultural and Applied Economics Association (AAEA), Canadian Agricultural Economic Society (CAES), and Western Agricultural Economics Association (WAEA) Joint Meetings, Denver, CO.

Purdue University Cooperative Extension Service. (2009). *2010 Purdue crop cost & return guide*. West Lafayette, IN: Author. Retrieved June 27, 2010, from http://www.agecon.purdue.edu/extension/pubs/id166_2010_Sept09.pdf.

Ramseur, J., & Parker, L. (2009, February). *Carbon tax and greenhouse gas control: Options and considerations for Congress* (CRS Report for Congress). Washington, DC: Congressional Research Service.

Searcy, E., & Flynn, P. (2009). The impact of biomass availability and processing cost on optimum size and processing technology selection. *Applied Biochemistry and Biotechnology*, *154*, 271-286.

Swanson, R., Satrio, J., Brown, R., Platon, A., & Hsu, D. (2009). *Techno-economic analysis of biomass gasification scenarios* (NREL/TP-6A2-46587). Golden, CO: National Renewable Energy Laboratory.

US Department of Agriculture, National Agricultural Statistics Services (NASS). (2007a, July). *Agricultural prices 2006 summary.* Washington, DC: Author. Available on the World Wide Web: http://usda01.library.cornell.edu/usda/nass/AgriPricSu//2000s/2007/AgriPricSu-07-20-2007_revision.pdf.

US Department of Agriculture, National Agricultural Statistics Service (NASS). (2007b, December). *Agricultural prices December 2007*. Washington, DC: Author. Available on the World Wide Web: http://usda01.library.cornell.edu/usda/nass/AgriPric//2000s/2007/AgriPric-12-28-2007.pdf.

Wang, M. (2007, September 19). *Well-to-wheels analysis of transportation fuels with the GREET model*. Argonne, IL: Argonne National Laboratory.

Wright, M., & Brown, R. (2007). Establishing the optimal sizes of different kinds of biorefineries. *Biofuels, Bioproducts & Biorefining*, *1*, 191-200.

Wright, M., Satrio, J., Brown, R., Daugaard, D., & Hsu, D. (2009). *Techno-economic analysis of biomass fast pyrolysis to transportation fuels* (NREL/TP-6A2-46586). Golden, CO: National Renewable Energy Laboratory.

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