

Using Cellulosic Ethanol to ‘Go Green’: What Price for Carbon?

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1. Introduction

Provisions in the Energy Independence and Security Act of 2007 (EISA) revised the Renewable Fuels Standard (RFS2) to mandate the use of 36 billion gallons of biofuel annually by 2022. Further, the Food, Energy and Conservation Act (FECA) of 2008 (or more commonly referred to as the 2008 Farm Bill) provides incentives for the production of both biomass feedstock and biofuel. What has motivated strong government intervention in the biofuel market and at what cost? The three most commonly mentioned motivations for development of the biofuel industry are: 1) energy independence from or reduced dependence on imported petroleum, especially from unstable and unfriendly national governments; 2) the future economic well-being of rural communities from the economic development opportunities provided by biofuel expansion; and 3) the potential environmental benefits associated with substituting biofuel for fossil fuels. Each of these arguments relies on the premise that government intervention is justified to correct market failure, i.e., the underproduction of biofuel relative to liquid fossil fuels.

Utilizing domestic renewable resources for biofuel production has been promoted as a way to decrease the dependency on fossil fuels and reliance on politically unstable countries, but in 2008 only 57% of US petroleum consumed was imported and approximately half of the imports came from the Western Hemisphere (EIA, 2009). More importantly, even if RFS2 biofuel mandates are reached, the potential contribution of the mandated biofuel production levels will be small relative to total liquid fuel consumption (i.e., less than 20%) and will have limited impact on energy markets and resulting energy imports.

Biofuel expansion can also benefit rural communities through increased farm income, land rents and job opportunities, but economic gains for rural areas are limited due to competition for land and biomass between livestock feed, food, and biofuel feedstock (Miranowski et al., 2009). The rural economic benefits are also sensitive to impact model assumptions. Previous studies that predicted high positive rural impacts from corn-ethanol production were found to overstate the actual impacts through generous multiplier effects or failure to account for shifting labor and resources (Swenson, 2006).

With the growing concern of climate change and an emphasis on findings ways to promote sustainable production and reduce greenhouse gas (GHG) emissions, the environmental benefits of biofuel relative to conventional fuel have provided a rationale for government

intervention in the biofuels industry. EISA revised the original RFS, which mandated 7.5 billion gallons of grain ethanol and biodiesel use by 2012, to 36 billion gallons of all biofuels by 2022. The RFS2 outlines volume standards for each year by biofuel type, including 15 billion gallons of corn-based ethanol counting toward the mandate in 2022 and a minimum of 16 billion gallons of cellulosic ethanol, 1 billion gallons of biodiesel, and 4 billion gallons from advanced biofuels to satisfy mandated use. To monitor biofuel use, each gallon of biofuel produced is given a renewable identification number (RIN) and obligated parties must provide RINs for their minimum blend requirements. In order to avoid a “produce at all costs” scenario, the RFS2 stipulates that an unlimited number of credits will be available at a price of \$1.56 per gallon. This creates a cap on the cost of meeting the mandate. The RFS2 also sets a minimum greenhouse reduction standard for each biofuel type relative to 2005 gasoline or diesel [EPA, 2010]. In addition to the RFS2 mandates, the 2008 Farm Bill provides a \$1.01 per gallon tax credit to cellulosic ethanol blenders and a temporary (two-year) biomass production incentive up to \$45 per ton of feedstock for biomass collection, harvest, storage, and transportation (CHST).³

Despite legislative efforts to support biofuel production, the biofuel industry still faces several challenges. One challenge, specifically for the biomass ethanol industry, will be the “blending wall” or the regulatory limit on the amount of ethanol that can be blended with gasoline and supplied through traditional gasoline pumps. According to Nuernberg (2009), the current regulatory cap of 10 percent will limit ethanol blending to 14 billion gallons per year, well below the future mandate levels. E85 has the potential to partially alleviate this constraint, but lack of refueling infrastructure has created limited demand for E85 relative to the flex-fueled fleet below the supply potential of the ethanol industry. The corn ethanol industry currently has the capacity to produce over 12 billion gallons annually and is already suffering narrow gross margins due to the blend wall. We will focus on the feasibility of cellulosic ethanol in the absence of the blending wall constraint but acknowledge that this may be another limiting factor to future biofuel market development. For exposition purposes in this paper, we attribute current policy intervention, especially beyond corn ethanol into cellulosic and advanced biofuel, as primarily motivated by the environmental benefits from GHG emission reductions in the transportation system.

³ For a more detailed background on ethanol policies see Duffield et al. (2008) and Tyner (2008).

The new legislation mandates that cellulosic biofuels be part of the liquid transportation fuel mix and contribute to reducing our carbon footprint. Unfortunately, since no commercial cellulosic biorefinery exists and cellulosic biomass production is typically smaller scale than conventional crop production, the Congress had very limited knowledge of the actual costs of producing cellulosic biomass and converting it to cellulosic ethanol. Understanding of the implications of RFS2 requires a better understanding of the economics of producing cellulosic ethanol.

We use the Biofuel Breakeven model (BIOBREAK), a simple long run breakeven model that represents the feedstock supply system and biofuel refining process, along with estimates of the potential reduction in carbon emissions from biofuels relative to conventional fuels, to derive the implicit carbon price (or carbon credit) needed to sustain a biomass market and cellulosic ethanol industry under different oil prices, the RFS2 mandate, and with and without other biofuel incentives. Because cellulosic ethanol is in the early stages of industry development, this analysis focuses on research estimates of the costs and benefits of cellulosic ethanol production using six alternative cellulosic feedstocks (corn-stover, switchgrass, *Miscanthus*, wheat straw, prairie grass, and woody biomass) grown under different climatic and environmental conditions.

The paper proceeds as follows. The next section provides the economic framework for BIOBREAK and resulting analysis. Section 3 briefly describes BIOBREAK and the model assumptions. Data and simulation techniques are presented in Section 4 and Section 5 discusses results and implications from policy runs of the simulation model. The paper concludes with a brief summary and policy implications.

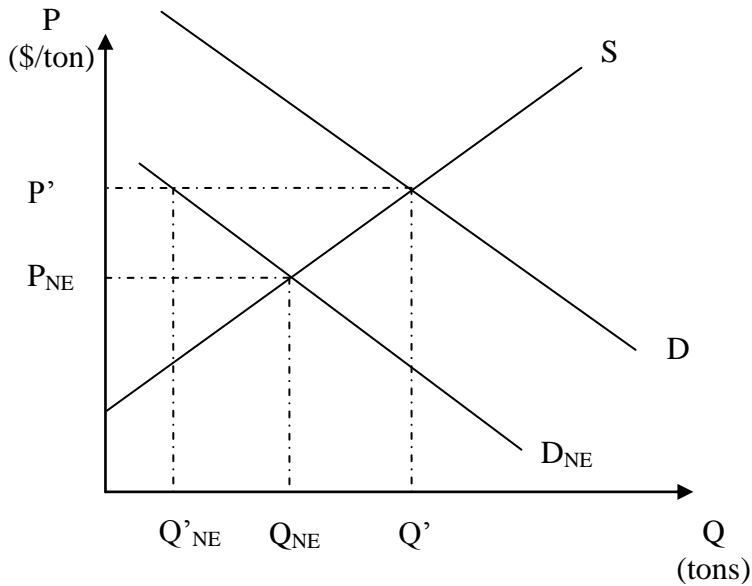
2. Economic Framework

In this section, we provide the basic economic framework for our analysis using simple supply and demand relationships. Figure 1 depicts a perfectly competitive biomass market without government intervention where D_{NE} is non-ethanol demand for biomass and S is biomass supply. Without biomass demand for ethanol, the price for biomass is P_{NE} and the equilibrium quantity of biomass produced for non-ethanol purposes is Q_{NE} . Biomass demand for ethanol production shifts the demand curve out to D to a new equilibrium biomass price of P' .⁴ At the

⁴ Figures 1-3 do not account for the RIN price cap, which places a ceiling on the biomass price needed to meet the mandate.

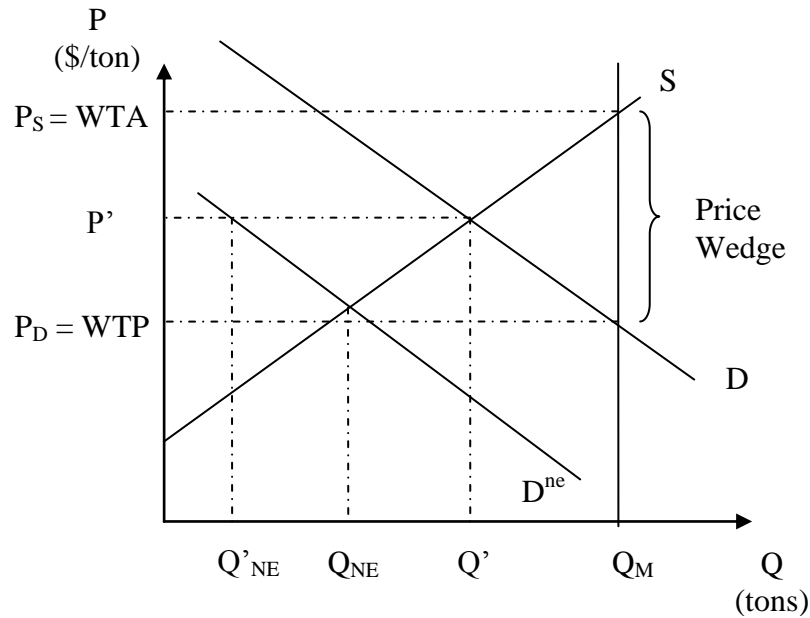
new equilibrium, Q'_{NE} tons of biomass are produced for non-ethanol purposes and $Q' - Q'_{NE}$ tons of biomass are converted to ethanol.

Figure 1. Biomass Market without Government Intervention



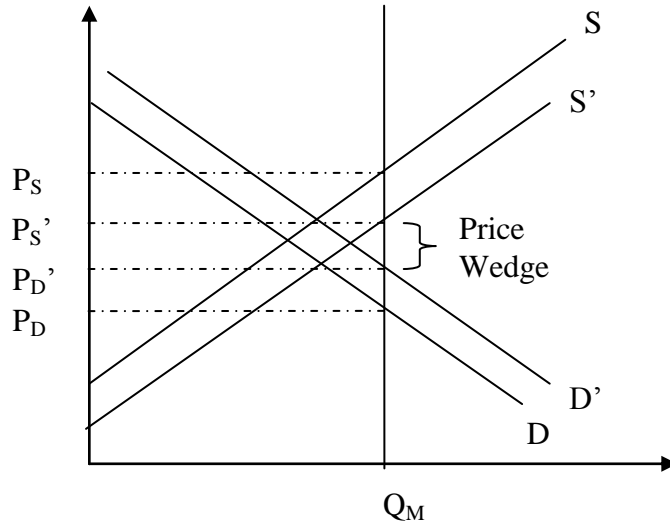
The RFS2 mandates annual cellulosic ethanol use and therefore mandates a minimum quantity of biomass converted to ethanol. Assuming the amount of biomass needed to meet the mandate (Q_M) is greater than the equilibrium quantity of biomass converted to ethanol in Figure 1 ($Q' - Q'_{NE}$), the mandated quantity of biomass for ethanol will place a wedge between the biomass supply and demand curves, as shown in Figure 2. The mandated quantity of biomass (Q_M) creates a wedge between the price the supplier is willing to accept (WTA) and the price the processor is willing to pay (WTP) for the marginal unit of biomass equal to $P_S - P_D$.

Figure 2. Biomass Market with Mandated Cellulosic Ethanol Production



The BIOBREAK model, which will be described in detail in the next section, estimates the potential gap between the supplier's WTA and processor's WTP for the marginal unit in order to determine the additional price needed to sustain the biofuel market. BIOBREAK does not estimate complete biomass demand and supply curves, but rather a point estimate of the supplier's WTA and processor's WTP for the marginal unit. The flexible model structure allows sensitivity analysis of key parameters including current and potential policy shocks and incentives. Figure 3 depicts the effects of both supplier and processor policy incentives. A supplier policy incentive, such as the CHST payment, shifts down the biomass supply curve (or marginal cost curve). Similarly, a cellulosic ethanol policy incentive shifts up the biomass demand curve. One and/or both of these types of incentives will shrink the gap between the processor and supplier breakeven values, and depending on the magnitude of the incentives, may eliminate the gap.

Figure 3. Biomass Market with Mandated Cellulosic Ethanol Production



3. BIOBREAK Model

We use the Biofuel Breakeven model (BIOBREAK), a simple and flexible breakeven model that represents the feedstock supply system and biofuel refining process, to evaluate the feasibility of a cellulosic ethanol market (Miranowski and Rosburg, 2010). BIOBREAK estimates the breakeven price that biofuel refiners could pay for biomass feedstock and the breakeven price that biomass producers would be willing to accept for producing and delivering feedstock to the biomass processing plant. Feasibility of a biofuel market is determined by the relationship between the biofuel processor's and biomass supplier's breakeven values for the last unit of biomass supplied to the biorefinery.⁵ The difference or gap between what the biofuel producer is willing to pay (WTP) for feedstock and what the feedstock supplier is willing to accept (WTA) indicates the potential price gap or shortfall that would need to be closed to sustain a cellulosic biofuel market for biomass-specific feedstock.

BIOBREAK uses equation (1) to derive the processor's WTP, or the derived demand, for the marginal dry ton of delivered biomass. The maximum amount the processor can pay for delivered biomass is total returns less the cost of non-feedstock inputs.

$$WTP = \{P_{gas} * E_V + T + V_{BP} + V_O - C_I - C_O\} * Y_E \quad (1)$$

⁵ The breakeven value is evaluated at the last unit of biomass supplied (i.e. marginal unit) since the biofuel processor must pay the same price for all purchased units.

In equation (1), the market price of biofuel (or revenue per unit of output) is calculated as the energy equivalent price of conventional transportation fuels (i.e. gasoline in our analysis) where P_{gas} denotes the per gallon price of gasoline (calculated as a constant fraction of the price of oil, $P_{\text{gas}} = P_{\text{Oil}}/29$)⁶ and E_V denotes the energy equivalent factor of biofuel to conventional fuel. Beyond direct biofuel sales, the processor also receives revenues from tax credits (T), byproduct production (V_{BP}) and octane benefits (V_{O}) per gallon of processed biofuel. Biorefinery costs are separated into two components: investment costs (C_I) and operating (C_O) costs per gallon. The calculation within brackets in Equation (1) provides the net returns per gallon of biofuel above all non-feedstock costs. A conversion ratio for gallons of biofuel produced per dry ton of biomass (Y_E) is used to derive the processor's maximum WTP per dry ton of feedstock. Therefore, Equation (1) provides the maximum amount the processor can pay for the last dry ton of biomass delivered to the biorefinery and still breakeven.

In BIOBREAK, the biomass supplier's WTA or marginal cost for the last unit of delivered feedstock is equal to the total economic cost, including opportunity cost, which the supplier incurs in sustainably producing, harvesting, storing, and transporting the biomass to the processing plant, minus government incentives received (G) (e.g. tax credits, production subsidies). Equation (2) details the WTA calculation.

$$WTA = \left\{ (C_{ES} + C_{Opp}) / Y_B + C_{HM} + SF + C_{NR} + C_S + DFC + DVC * D \right\} - G \quad (2)$$

Depending on the type of biomass feedstock, costs include establishment and seeding (C_{ES}), land/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).⁷ Establishment and seeding cost and land/biomass opportunity cost are most commonly reported per acre and the biomass yield per acre (Y_B) is used to convert the per acre costs into per ton costs. Therefore, Equation (2) provides the

⁶ The relationship between the price of oil and the price of gasoline is based on historical trends and may be subject to change (Elobeid et al., 2006).

⁷ The average hauling distance from the farm or storage area to the biorefinery is calculated as a function of the annual biorefinery biomass demand (BD), annual biomass yield (Y_B), and biomass density (B) using the formulation by French (1960) for a circular supply area with a square road grid.

minimum amount the supplier can accept for the last dry ton of biomass delivered to the biorefinery and still breakeven.

Biofuel market existence depends on the ability of the biorefinery and supplier to find an agreeable price. For a market-clearing price to exist, the maximum price the biorefinery can pay for the biomass must be at least as large as the minimum price the supplier is willing to accept for the marginal unit delivered, where both supplier and buyer are at or above their breakeven values (i.e. $WTP \geq WTA$ or $WTP - WTA \geq 0$). If the difference between the processor's WTP and supplier's WTA is at or above zero for a given feedstock, the biomass supplier and biofuel producer are able to find an agreeable price where they both at least breakeven and a biomass-based ethanol market is feasible. If the difference is negative for a given feedstock, the supplier and producer cannot find an agreeable price and the feedstock market cannot be sustained under the assumed market conditions and available technology.

In order to have a simple, yet flexible model (BIOBREAK), we make several simplifying assumptions. First, the model ignores the supply and price relationship between gasoline and biofuel and potential import impacts of ethanol or feedstock. Second, the price of ethanol is assumed to have a fixed relationship with gasoline based on the energy equivalence of ethanol to gasoline. A fixed relationship between gasoline and ethanol presumes that gasoline and ethanol are perfectly substitutable in consumption and that ethanol does not require an extra marketing cost.⁸ 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 percent, and for E85 in flex fuel vehicles but may not be a logical assumption for differentiated products. Third, we do not estimate complete supply curves for each feedstock but rather derive a point estimate of the supplier's WTA and processor's WTP for the marginal unit. Yet, given potential biomass availability, a stepwise supply curve for all feedstock could be constructed given our model estimates in a similar manner to the supply curves provided in the ALTF report (2009). Finally, we use GREET 1.8c to derive the relative GHG savings from biofuel relative to conventional fuels. GREET only accounts for direct emissions impacts and does not incorporate indirect emissions impacts such indirect land use change.⁹

⁸ Aukayanagul and Miranowski (2010) found that a fixed relationship between gasoline and ethanol did exist in the 2006-2008 period when oil prices were high and mandates were non-binding.

⁹ The **Greenhouse gases, Regulated Emissions, and Energy use in Transportation** model ("GREET") is an Excel-based program developed by the Center for Transportation Research at Argonne National Laboratory. Depending

Given these limiting assumptions, we derive the difference between the processor's WTP and supplier's WTA, or the price increment needed to sustain the biofuel market using feedstock-specific cellulosic biomass. Simultaneously, BIOBREAK uses GREET estimates to calculate GHG savings per ton of feedstock. This price gap or increment divided by GHG savings per ton is the minimum carbon credit or carbon price necessary to sustain a feedstock-specific cellulosic ethanol market. If the initial difference between WTP and WTA is positive for any feedstock, then the feedstock market will be sustainable, realize short run profits, and expand to the point where feedstock suppliers and processors breakeven in long run equilibrium.

4. Data and Simulation

A commercial-scale cellulosic biorefinery and feedstock supply system do not currently exist, and therefore industry values are not available from existing markets on which to establish the biorefinery's derived demand curve for biomass (WTP) or the biomass supplier's marginal cost curve (WTA). To calculate the processor and supplier breakeven values and to account for the large variability in the research estimates for major parameters within the model, BIOBREAK uses Monte Carlo simulations.¹⁰ Distributional assumptions for each parameter are based on actual research data updated to 2007 values and verified with industry information when available.¹¹ Consequently, the feasibility analysis is derived from a range of published estimates. For complete distributional assumptions and a review of the literature used to develop distributional assumptions for our analysis see Miranowski and Rosburg (2010).

To estimate emission impacts from advanced cellulosic biofuel and vehicle technology, we use GREET 1.8c. For our analysis, GREET provides the total greenhouse gas (GHG) emissions per mile from both conventional gasoline and cellulosic ethanol. The change in emissions from ethanol relative to gasoline along with ethanol yield (gallons per ton) and fuel efficiency (miles per gallon) provide the necessary information to determine GHG savings per ton of feedstock. To provide a cohesive analysis, we adjust the default assumptions in GREET to be consistent with our model assumptions.

on the fuel feedstock, GREET provides a "well-to-wheels" or "field-to-wheels" analysis of transportation fuel production (Wang, 2007 Presentation).

¹⁰ For the Monte Carlo simulations, we use the Oracle's spreadsheet-based program Crystal Ball®.

¹¹ Costs were updated using USDA NASS Agricultural prices from 1999-2007 (NASSa, 2007; NASSb, 2007).

To account for regional variation in climate and agronomic characteristics, we evaluate the breakeven value for switchgrass in three regions: Midwest (“MW”: ND, SD, NE, KS, IA, IL, IN), South-Central (“SC”: OK, TX, AR, LA), and Appalachian (“App”: TN, KY, NC, VA, WV, PA). *Miscanthus* is evaluated in the Midwest and Appalachian regions while corn-stover and wheat straw are assumed to be produced on cropland used for production in the Midwest and Pacific Northwest regions (WA, ID, OR), respectively. Implicit carbon prices will be constructed for two types of woody biomass: farmed wood and forest residue. Farmed wood is assumed to be harvested from the South-Southeast United States, while no regional specific assumptions are made for wood residue/slash.

Due to variability in the published estimates for certain model parameters and in order to test the sensitivity of our model assumptions to our distributional assumptions, we evaluate select scenarios. The price of oil is highly variable and a large determinant of ethanol revenue for the processor.¹² Rather than simulating or specifying a single price for oil, we evaluate the processor’s breakeven value and the difference between WTP and WTA at three oil prices: \$60 per barrel (low), \$75 per barrel (baseline), and \$90 per barrel (high). Similarly, technological uncertainty of cellulosic ethanol production provides a wide range of estimates for the ethanol conversion (Miranowski and Rosburg, 2010). Based on these estimates, we assume a biomass to ethanol conversion ratio with a mean value of 70 gallons per ton as representative of current and near future technology (2009) and a mean of 80 gallons per ton as representative of the long-run conversion ratio (2020).¹³

Since the timing of cellulosic ethanol market development is indeterminate, emissions impacts from GREET are estimated under both 2009 and 2020 technology and varying ethanol fuel efficiency. Tables summarizing the GREET model assumptions for each feedstock and the GHG emissions savings relative to conventional gasoline are available from the authors upon request.

¹² In July 2008, oil escalated to \$145 per barrel but dropped to \$60-\$70 per barrel in later months. Elobeid et al. (2006) assumed a baseline price of \$60 per barrel in their ethanol cost analysis.

¹³ Ethanol yields vary by feedstock but Miranowski and Rosburg (2010) were unable to find consistent yield patterns across studies, especially given the lack of commercial cellulosic ethanol plant yield information. Even though woody biomass has a higher lignin yield, some studies also assign a relatively high ethanol yield. With a wide range of estimates for both herbaceous crops and woody biomass and the lack of commercial yield estimates, we chose a conservative approach by assuming the same yield for all feedstock, similar to the ALTF Report (2009). We have estimated results where we allow the ethanol yield to vary by feedstock. These results are available upon request.

Finally, for government incentives we consider three alternative policy scenarios. First, we determine the carbon price needed to sustain each feedstock market given no government intervention. Next, we evaluate how the necessary carbon price changes if blenders are provided the tax credit outlined in the 2008 Farm Bill (i.e. blender's tax credit only). In the final policy scenario, we determine the carbon price needed to sustain feedstock markets given both the blender's tax credit and supplier CHST payment.¹⁴

For consistency, we specify a "baseline" scenario and provide sensitivity results relative to the baseline scenario. The baseline scenario consists of no current policy incentives, an oil price of \$75 per barrel, 70 gallon per ton biomass to ethanol conversion rate, 23 MPG fuel efficiency for fuel-celled vehicles, and 2009 technology.

5. Simulation results and analysis

Given the distributional assumptions, no feedstock market exists in the baseline scenario. As can be seen in Table 1, the estimated mean and 90% confidence interval for the difference between the processor's WTP and supplier's WTA are strictly negative (i.e. no market existence) for all region-specific feedstock when there are no policy incentives in place. The mean difference between the processor and supplier breakeven values ranges between \$56 per ton (wheat straw) and \$126 per ton (Midwest switchgrass). This gap is equivalent to a cost of \$0.80 to \$1.80 per gallon of ethanol. In this case, prairie grass and switchgrass or *Miscanthus* grown in the Midwest would not be converted into ethanol since the cost of conversion exceeds the \$1.56 RIN price cap outlined in the RFS2. Therefore, depending on the available supply of lower cost feedstock, mandated cellulosic ethanol will either be met with ethanol from lower cost feedstock or a combination of low cost feedstock ethanol and the purchase of RINs at the cap price.

¹⁴ The parameter draws and calculations were repeated one thousand times for each scenario resulting in one thousand values for WTP, WTA, and the difference value (WTP-WTA) at each oil price, technology, and policy scenario.

Table 1 – Simulated Mean Difference with no Blender’s Credit or CHST Payment
(Baseline Oil Price and 70 gal per ton Conversion Rate)

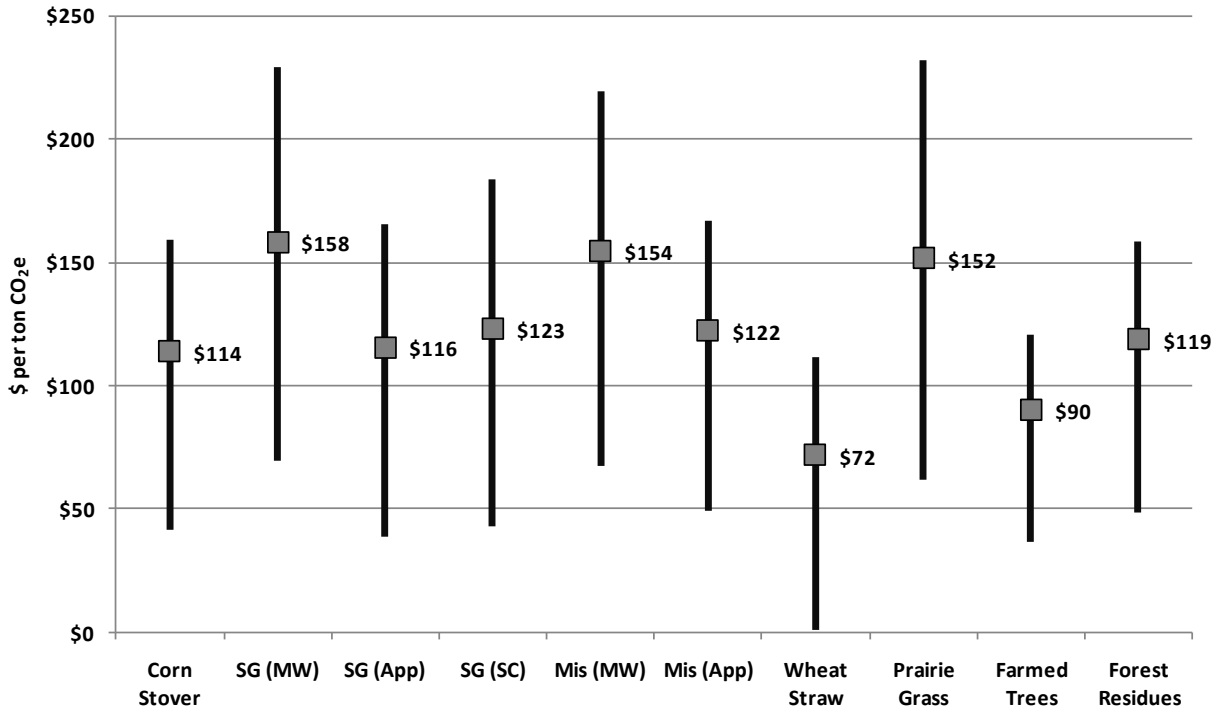
	WTP-WTA (per ton)
Corn Stover	-\$96 (-134, -61)
Switchgrass (MW)	-\$126 (-183, -81)
Switchgrass (App)	-\$92 (-132, -57)
Switchgrass (SC)	-\$98 (-146, -60)
Miscanthus (MW)	-\$123 (-175, -78)
Miscanthus (App)	-\$98 (-133, -65)
Wheat Straw	-\$56 (-88, -26)
Prairie Grass	-\$121 (-184, -74)
Woody Biomass	-\$99 (-132, -66)

Note: 90% confidence intervals are in parenthesis

We derive the minimum carbon credit or carbon price necessary to sustain a cellulosic ethanol market for each feedstock based on the difference between the processor’s WTP and supplier’s WTA divided by the GHG savings per ton of feedstock. The carbon price when no policy incentives are in place (i.e. no blender’s credit or CHST payment), which can be interpreted as the carbon price needed to sustain cellulosic ethanol production if carbon credits for GHG reductions were the only policy incentive, ranges from \$72 to \$158 per ton of CO₂e. Yet, given that producers would opt to purchase RINs at the cap price rather than produce ethanol from prairie grass or Midwest switchgrass or *Miscanthus*, the carbon price would range between \$72 and \$123 per ton of CO₂e. Figure 4 provides a visual depiction of the carbon price needed to sustain each feedstock-specific ethanol market, along with the 90% confidence interval for the carbon price.¹⁵ Given the baseline scenario assumptions, the 90% confidence interval is strictly positive for all feedstock.

¹⁵ Figure 4 includes prairie grass, MW switchgrass, and MW *Miscanthus* even though the producer would not convert these feedstocks into ethanol given the outside option to purchase RINs at a lower cost. The carbon price values for these feedstocks represent the potential carbon price needed to sustain the market if the RIN cap were removed.

Figure 4 – Carbon Price Needed for Cellulosic Ethanol Market and 90% Confidence Interval
 (No policy incentives; \$70 per barrel oil; 70 gallon per ton conversion rate)



Sensitivity of Implicit Carbon Price

To demonstrate the sensitivity of our results to model assumptions and key parameters, we present sensitivity results relative to the baseline scenario. We consider the sensitivity of our results to current and potential policy shocks and incentives, the price of oil, regional differences, technological improvement, and parameter variability assumptions. Sensitivity results for alternative scenarios are available upon request.

Policy Incentives

For government incentives we consider two alternative policy scenarios. First, we evaluate how the necessary carbon price changes if blenders receive the production tax credit provided in the 2008 Farm Bill. Second, we determine the carbon price needed to sustain feedstock markets given both the blender's tax credit and feedstock supplier CHST payment. Even though the CHST payment program is currently a short-term program, we consider the potential carbon price effects if this program was to become a long-term program for biomass suppliers.

In the blender's tax credit only scenario, wheat straw is the only feasible market without carbon credits or pricing.¹⁶ All other feedstock markets are not viable given the estimated mean difference value, but the 90% confidence intervals capture positive values (i.e. market existence) for corn stover, Appalachian and South Central switchgrass, *Miscanthus* from the Appalachian region, prairie grass, and woody biomass. With the blender's tax credit in place, the cost of cellulosic ethanol production is less than the cost of purchasing the RIN at the cap price for all feedstock. Therefore, the RIN price cap is not triggered in this scenario and the RFS2 could be met with cellulosic ethanol production.

When both the blender's tax credit and the CHST payment are in place, a feedstock market exists for corn stover, switchgrass grown in the Appalachian region, South-Central switchgrass and *Miscanthus*, wheat straw, and woody biomass. On average, a market does not exist for prairie grass or switchgrass and *Miscanthus* grown on high opportunity cost Midwest cropland, but a positive difference value falls within the 90% confidence interval for each feedstock.¹⁷

As depicted in Figure 5, the introduction of policy incentives significantly reduces the carbon price needed to sustain feedstock markets relative to the baseline scenario.¹⁸ Recall that the carbon price when no policy incentives are in place, which can be interpreted as the carbon price needed to sustain cellulosic ethanol production if carbon credits for GHG reductions were the only policy incentive, ranges from \$72 per ton of CO₂e (wheat straw) to \$158 per ton of CO₂e (Midwest switchgrass). With the blender's tax credit, a wheat straw market would be sustained without a carbon price. For remaining feedstock, a carbon price of \$25 to \$70 per ton of CO₂e is required for market existence. When both the blender's tax credit and CHST payment are in place, most feedstock is viable without carbon pricing (negative value in Figure 5) and only feedstock

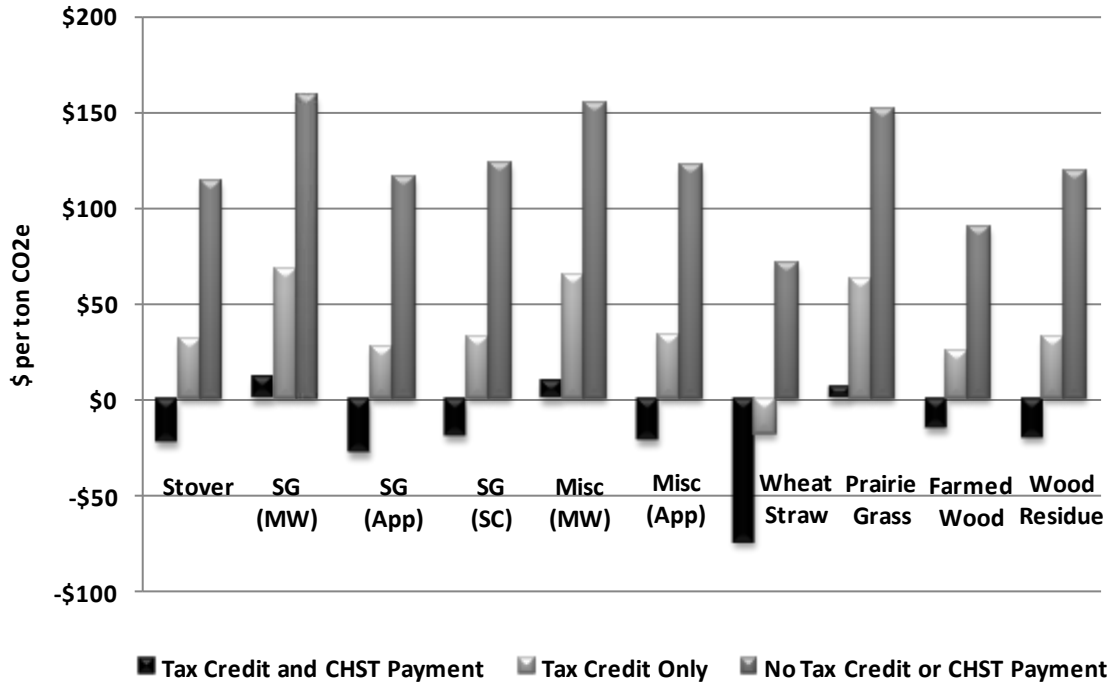
¹⁶ Relative to other feedstocks, wheat straw grown in the Pacific Northwest has very low opportunity cost and nutrient replacement cost. Wheat straw is also assumed to be supplied from previously established stands, resulting in no establishment or seeding costs.

¹⁷ The 90% confidence interval is constructed by dropping the bottom and top 5% of the simulations. With both the tax credit and biomass supplier payment, we find at least one observation that is consistent with market viability for prairie grass and Midwest switchgrass and *Miscanthus* within the remaining 90% of the simulations. This is similar to a hypothesis test for market viability where we are not able to reject potential market viability at the 10% level.

¹⁸ The values in Figure 5 are derived using the mean of the simulation results.

produced on high opportunity cost land requires a positive carbon price (around \$10 per ton of CO₂e).

Figure 5 – Carbon Price Needed for Cellulosic Ethanol Market by Policy Incentive
(\$75 per barrel oil, 23 MPG, 2009)

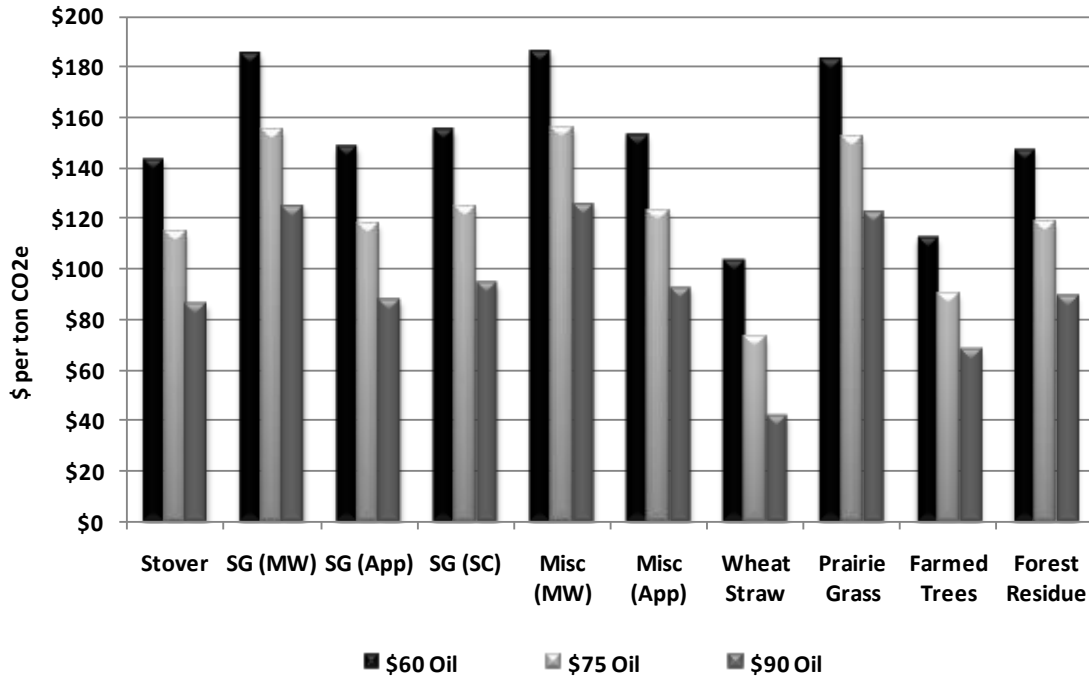


Oil Price

Since the price of ethanol is assumed to equal the energy equivalent price of gasoline and the price of gasoline is driven by the price of oil, the refiner’s revenue from ethanol production is highly dependent on the price of oil. Figure 6 shows the sensitivity of the carbon price needed for feedstock markets to exist at the three oil price levels. Recall that in the baseline scenario (i.e. \$75 per barrel oil), the carbon price needed to sustain feedstock markets ranged between \$72 (wheat straw) and \$158 (Midwest switchgrass) per ton of CO₂e. At the high oil price (\$90 per barrel), and therefore a higher ethanol price, the carbon price needed to sustain feedstock markets falls for each feedstock to between \$40 and \$125 per ton of CO₂e. Finally, when oil price drops to \$60 per barrel, the cost of producing cellulosic ethanol is greater than the RIN price cap for all feedstocks except for wheat straw. Therefore, when the price of oil is sufficiently low,

the RFS2 will be met with the purchase of RINs at the cap price in lieu of converting cellulosic feedstock.

Figure 6 – Carbon Price Needed for Cellulosic Ethanol Market by Oil Price
 (No policy incentives; 23 MPG; 2009 technology; 70 gallons per ton)



Regional Differences

To account for regional variation in climate and agronomic characteristics, the breakeven value for switchgrass suppliers was evaluated for three regions: Midwest (MW), South-Central (SC), and Appalachian (App). *Miscanthus* was also evaluated in the Midwest and Appalachian regions. Figures 4, 5 and 6 provide some indication of the sensitivity of the carbon price to regional differences. Switchgrass grown in the Midwest requires a significantly higher carbon price due to alternative land use value (cash crops) and lower biomass yields in the Midwest relative to the alternative region(s) evaluated in our analysis. The carbon price needed for a switchgrass feedstock market to exist in the Midwest is about 30% higher than the price needed for a switchgrass market in the South-Central or Appalachian regions under the assumed market conditions. The *Miscanthus* regional effects have a similar pattern.

Improved Biomass Conversion and Driving Efficiency

Technological advancement has the potential to significantly lower biomass production and biofuel processing costs. We evaluate the sensitivity of the carbon price to both fuel efficiency and improved plant technology including ethanol to biomass conversion ratio. A conversion ratio of 70 gallons of cellulosic ethanol per ton of feedstock is assumed to be representative of current and near term technology (2009), while we assume technological advancement to increase this conversion rate to 80 gallons per ton by 2020. Assuming 2009 plant technology, increasing fuel efficiency from 23 MPG to 32 MPG decreases the carbon price needed for market existence between \$13 and \$40 per ton of CO₂e. Holding fuel efficiency constant, improved plant technology between 2009 and 2020, including improved biomass to ethanol conversion, reduces the carbon price needed to sustain feedstock markets between \$4 and \$12 per ton of CO₂e.

Parameter Variability

Due to the variability in published research estimates on cellulosic ethanol production costs and technology, we fit distributions for the model parameters rather than impose point estimates. To evaluate the sensitivity of our results to the distributional assumptions used in the analysis, we tested each distributional assumption independently to determine the impact on the target value. Switchgrass, *Miscanthus*, and prairie grass are most sensitive to biomass yield and capital cost, while stover is most sensitive to capital cost and land/opportunity cost. Woody biomass is most sensitive to biorefinery capital costs and biomass harvest cost.

6. Conclusions

The revised renewable fuels standard (RFS2) mandates that cellulosic biofuels be part of the liquid transportation fuel mix, with a minimum annual use of 16 billion gallons of cellulosic ethanol by 2022. Unfortunately, since feedstock production and cellulosic ethanol conversion are not commercialized, available knowledge regarding costs of producing cellulosic biomass and converting it to cellulosic ethanol is largely based on engineering estimates and experimental trials. Therefore, it is quite difficult to estimate potential economic costs of the RFS2. Assuming that recent legislation is motivated by the environmental benefits from biofuel use relative to

conventional transportation fuels, we used the BIOBREAK model and relative GHG savings to determine the implicit price of carbon needed to sustain a cellulosic ethanol market for six potential feedstocks.

Given our baseline scenario, which assumes no blender's tax credit or biomass supplier payments, no feedstock market is viable without a positive carbon price. The carbon price needed to sustain feedstock markets ranges between \$72 and \$158 per ton of carbon equivalent. This cost is equivalent to \$0.80-\$1.80 per gallon. The high cost of feedstock such as prairie grass, Midwest switchgrass, and Midwest *Miscanthus*, will trigger the RIN price cap. Therefore, depending on the supply of low cost feedstock, the mandated cellulosic ethanol use will be met either through cellulosic ethanol production from lower cost feedstock or a combination of lower cost feedstock ethanol and the purchase of RINs at the cap price.

Incorporating the biofuel tax credit provided by EISA, only wheat straw in the PNW has the potential to develop a market under baseline conditions. Yet, given the transportation economies involved in delivering wheat straw, there is likely only sufficient wheat straw to economically supply one or two 50 million gallon per year plants in the PNW. In the blender's tax credit scenario, the RIN price cap is not triggered for any feedstock. The RFS2 will be met by ethanol production but at a cost of \$25 to \$70 per ton of CO₂e reduced relative to conventional fuel. Assuming the biofuel tax credit and the biomass CHST producer incentive provided by the 2008 Farm Bill are long-run policies, several cellulosic feedstock market alternatives exist without a carbon price. We also use the BIOBREAK Model to show that market viability for cellulosic feedstock, and therefore the carbon price to sustain the market, is sensitive to the price of oil, regional biomass productivity, technological progress, and assumed parameter variability.

Despite accounting for the large variation in research estimates in our economic accounting model, there are several other issues this analysis does not address. Transaction costs associated with contractual issues between the supplier and processor are not addressed including risk premiums necessary to induce investment and commitment to supply biomass. Closely related to transaction costs are market power issues, where one player holds more negotiating power. Biomass suppliers may hold the initial power with alternative land use opportunities, but after establishment and seeding, the biorefinery may gain some negotiating power if the farmer

has committed to a specific biomass (10 to 20 year stand). Therefore, it is likely that long-term contracts will occur between suppliers and processors.

Advancement in technology may lead to logistical and conversion changes. Custom harvesting operations or intermediate handlers (consolidators) may harvest, store and transport the biomass. Biorefineries may also become multi-feedstock facilities. Ability to convert multiple feedstocks would increase local feedstock supply and decrease transportation distance but may create logistical and enzymatic issues. Demand and supply of ethanol will also have both local and national labor impacts, which may affect input costs. Finally, model variables were assumed to vary only by feedstock and select regional differences. Additional regional differences may also affect feedstock costs from storage costs to harvesting costs. We plan to address these issues in future extensions of this analysis.

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