Supplementary Data for

Can Ethanol Alone Meet California's Low Carbon Fuel Standard?

An Evaluation of Feedstock and Conversion Alternatives

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1. Ethanol production from lignocellulosic feedstocks

In this section we provide information on key assumptions used in the modeling of the ethanol pathways not included in CA-GREET 1.8b (CARB 2009). All pathways we develop in this work are implemented in CA-GREET 1.8b.

Direct energy use for collecting agricultural residues (Midwest corn stover and California agricultural residues) is estimated using equations originally developed by Sheehan et al. (2002). We use rice straw to represent California agricultural residue. Corn stover and rice straw are collected in a second pass after the grain is harvested. We assume additional fertilizers are required to compensate for nutrient losses due to the removal of the agricultural residues. The replacement rates of N, P, and K-fertilizer are taken from Sheehan et al. (2002) and Dobermann and Fairhurst (2002) for corn stover and rice straw, respectively (Table SI-1). A biochemical process utilizing dilute acid pretreatment followed by enzymatic hydrolysis (Aden et al. 2002) is assumed for converting agricultural residues to ethanol. Ethanol yields from corn stover and rice straw are estimated based on corn stover and rice straw compositions (Aden et al. 2002, Kadam et al. 2000). The conversion rates of cellulose (glucan) and hemicellulose (xylan, mannan, arabinan, and galactan) to their corresponding monomeric sugars are assumed at 90% (Aden et al. 2002). The conversion rate of glucose to ethanol is 95% while that of hemicellulosic sugars (xylose, mannose, arabinose, and galactose) to ethanol is 85%. The ethanol plants are assumed to use the lignin portion of the feedstock and unconverted sugars as fuels to generate steam and electricity for the process. The estimated excess electricity from the corn stover ethanol plant is 0.60 kWh/L (2.28 kWh/gal) (Aden et al. 2002). The excess electricity is assumed to displace the Midwest average electricity mix. For the rice straw ethanol plant, the energy input (lignin, unconverted sugars, anerobic biogas) to the boiler is estimated at 633 GJ/h for an ethanol plant processing 2000 dry metric tons (t) of straw per day. The process steam and electricity requirements are about 380 GJ/h and 11.7 MWh/h (Aden et al. 2002). At a boiler efficiency of 68% and a steam to electricity conversion efficiency of 85%, the plant is still energy self-sufficient, however, it has virtually no excess electricity (0.3 MWh/h) to sell to the grid.

Direct energy use for harvesting forest residues differs depending on the types of wood residues harvested (limbs and tops from merchantable trees, small trees from forest thinning, etc.) and the equipment used for harvesting. Data on diesel use for harvesting forest residue is taken from CA-GREET (CARB 2009). It is estimated that about 10 L of diesel are required for harvesting 1 t of forest residues. The average moisture content of forest residue is assumed at 50%. No additional fertilizer is used for making up nutrient losses due to forest residue removal (default assumption in the CA-GREET model). A biochemical process is assumed for converting hardwood forest residues to ethanol. We use white oak to represent hardwood to estimate ethanol yield and excess electricity credit, following the approach described above for rice straw. The composition of white oak is taken from CEC
The estimated ethanol yield from hardwood residue is 390 L/dry t, with excess electricity of 1.2 kWh/L (4.4 kWh/gal). The excess electricity is assumed to displace the average California electricity mix.

The energy used for harvesting softwood forest residues is assumed to be the same as that for harvesting hardwood forest residues. The thermochemical process developed by NREL (Phillips et al, 2007) is assumed to be utilized to convert softwood residues to ethanol. The ethanol plant is energy self-sufficient; 28% of the syngas is diverted so that the process steam and electricity requirements can be exactly met. The ethanol yield is estimated at 334 L/dry t. No excess electricity is sold to the grid. However, the plant produces mixed alcohols as co-products, which contain ethanol, propanol, butanol and pentanol. The yields of ethanol, propanol, butanol and pentanol in mixed alcohols are estimated to be 3.4, 46.7, 5.8, and 0.8 L/dry t of biomass, respectively. Since there is no specific product which can be directly displaced by the co-products (mixed alcohols), an energy value based approach is used to allocate energy use and emissions between the main product (ethanol) and co-products (mixed alcohols).

Ethanol plants utilizing municipal solid waste (MSW) as feedstocks are assumed to be located close to landfills. We do not allocate energy use to MSW collection and transportation because these activities are required regardless of whether MSW is used for ethanol production. A gravity pressure vessel (GPV) process is assumed for converting MSW to ethanol. MSW is classified and the lignocellulosic components are sent to pretreatment for ethanol production. The plant uses purchased electricity (from California’s grid) and natural gas to meet its process energy requirements. Data on energy use (electricity and natural gas) and ethanol yield are derived from Kalogo et al. (2007). A few co-products (e.g., furfural, CO₂) are generated during the ethanol production, however, no credit is allocated to these co-products due to the uncertainty of co-product markets. Ten percent of MSW, which cannot be used for ethanol production or recycling, is eventually sent to landfills. Unlike the process modeled by Chester and Martin (2009), the GPV process modeled in this study neither utilizes lignin to produce process energy nor exports excess electricity to the grid because the majority of MSW (such as paper, textiles, food) contains very low lignin component. Instead, the GPV process needs to purchase electricity and natural gas to meet process energy requirement, and the lignin residue from processing MSW is disposed of in landfills.

In estimating GHG emissions from the MSW-ethanol pathway, we assume that MSW as a waste material has no feedstock production related GHG emissions. Our approach is consistent with prior studies (Chester and Martin 2009) and practice under Chicago Climate Exchange protocols, and also with CA-GREET estimation procedures for forest residues (CARB 2009). However, as Kalogo et al. (2007) and Christensen et al. (2009) discuss, avoided feedstock GHG emissions for waste materials can vary depending on assumed disposal alternatives. Since a number of disposal alternatives such as recycling, landfilling with or without landfill gas recovery either for
flaring or electricity generation, are available for various components of MSW (e.g. paper, food waste, wood waste), for simplicity and to avoid having a number of potential GHG values for a single pathway, we assume MSW is a biomass resource similar to forest residue without considering various disposal alternatives of MSW. More research is needed in the future to quantify the net GHG emissions benefits of using MSW for ethanol production for different disposal alternatives of MSW. Table SI-1 summarizes the key assumptions for modeling the lignocellulosic ethanol pathways in our study.

Table SI-1. Key assumptions for lignocellulosic ethanol pathways for 2020.

| Feedstock collection energy use (kJ/dry t) | CA agricultural residue | CA hardwood residue | CA softwood residue | CA MSW |
|------------------------------------------|-------------------------|---------------------|---------------------|--------|
| Feedstock transportation                  | 80 km by truck from field to plant | 130 km by truck from field to plant | 130 km by truck from removal site to plant | 130 km by truck from removal site to plant |
| Ethanol yield (L/dry t)                   | 374                     | 366                 | 390                 | 334    | 85 (L/t of MSW) |
| Source of process thermal energy and electricity | On site steam and power generation from lignin | On site steam and power generation from lignin | On site steam and power generation from lignin | 28% of total unconditioned syngas |
| Co-product credit (kWh/L)                 | 0.6 (replacing Midwest electricity) | 0 | 1.2 (replacing CA electricity) | Mixed alcohols | Not included |
| Ethanol transportation and distribution   | 65 km by truck from ethanol plant to rail, 2250 km by rail from Midwest to CA; 130 km by truck from rail to bulk terminal and then refueling station | 130 km from ethanol plant to bulk terminal and then refueling station | 130 km from ethanol plant to bulk terminal and then refueling station |

a Midwest electricity mix: natural gas (1.0%), coal (73.0%), nuclear (16.0%), biomass (1.0%), other renewable (9.0%).
bCalifornia electricity mix: natural gas (43.1%), coal (15.4%), nuclear power (14.8%), biomass (1.1%), other renewable (25.5%).
2 California biomass inventory

Table SI-2 details the amount of California in-state lignocellulosic biomass feedstock, which is considered to be available for ethanol production by 2020.

| Table SI-2. California biomass inventory. | Gross a (million dry t/yr) | Technically available b (million dry t/yr) | Current use | Amount considered to be available for ethanol production c (million dry t/yr) |
|------------------------------------------|----------------------------|--------------------------------------------|-------------|--------------------------------------------------------------------------|
| **Agricultural residues**                |                            |                                            |             |                                                                          |
| Field crops                              | 4.5                        | 2.2                                        |             |                                                                          |
| Some residues are incorporated into the soil. The excess residues virtually have no use except for a very small amount of residues used as animal bedding and feed. |                                                                        |
| Orchard and vine                         | 2.4                        | 1.6                                        |             |                                                                          |
| About 0.9 million t/yr are used by power plants, generally blended with forest residues and urban wood. |                                                                        |
| Vegetable crops                          | 1.1                        | 0.1                                        |             |                                                                          |
| Residues are currently incorporated into the soil. Not generally considered for off-field utilization. |                                                                        |
| Food processing                          | 0.9                        | 0.7                                        |             |                                                                          |
| About 0.3 million t/yr are utilized for power generation. |                                                                        |
| Subtotal of agricultural residues        | 8.9                        | 4.6                                        | 1.3         | 1.6                                                                      |
| Forest residues                          |                            |                                            |             |                                                                          |
| Mill residues                            | 5.6                        | 3.0                                        | 1.1 million t/yr have been utilized for energy production (power and steam). | 0.9          |
| Forest thinnings                         | 7.0                        | 3.7                                        | Current forest thinning is not a common practice in CA, but thinning is likely to increase, due to new federal legislation and increasing public concerns over the risk from wildfire. There is no data on current use of biomass from forest thinning. | 1.8          |
| Logging slash                            | 7.3                        | 3.9                                        | Not currently utilized | 2.0          |
| Shrub (or chaparral)                     | 4.5                        | 2.4                                        | Not currently utilized | 1.2          |
| Subtotal of hardwood forest residues d   | 9.8                        | 5.2                                        | 0.4         | 2.4                                                                      |
| Subtotal of softwood forest residues d   | 14.6                       | 7.8                                        | 0.7         | 3.5                                                                      |
| Municipal solid waste (MSW)              |                            |                                            |             |                                                                          |
| Disposed MSW                             | 42.5                       | Disposed at landfills (paper and organic waste diverted for recycling and composting are not included) | 17.0        |                                                                          |

Numbers may not add due to rounding.

a Gross amounts of agricultural and forest residues are adapted from CEC (2005). However, we do not include animal manure in agricultural residues. Gross amount of MSW is estimated based on projected population in 2020 and MSW disposal rate per capita.

b Technically available amounts of agricultural and forest residues are taken from CEC (2005).
For agricultural and forest residues, the amount considered to be available for ethanol production = (technically available amount – current use) ×50%. For MSW, the amount considered to be available for ethanol production = landfilled MSW ×40%.

Waddell and Barrett (2005) indicate that hardwood forests cover 40% of forest land in California. We assume that softwood and hardwood residues account for 60% and 40% of California’s forest residues, respectively.

3. Estimation of minimum ethanol selling prices

Table SI-3 presents the financial parameters used in the discounted cash flow analysis for estimating the minimum ethanol selling prices (MESPs).

| Table SI-3. Financial parameters used in discounted cash flow analysis. |
|-----------------------------------------------------------------------|
| Debt/equity ratio | 100% equity |
| Return on investment | 12% after tax |
| Economic life | 20 years |
| Construction time | 1.5 years for ethanol plants using corn, sugarcane and MSW as feedstocks; 2.5 years for ethanol plants using corn stover, agricultural residues, softwood and hardwood forest residues |
| Federal tax | For ethanol plants in the U.S.: 39% For ethanol plants in Brazil: 24% plus an additional tax of 10% on profits exceeding 240,000 Brazilian Real (IBFC 2005) |
| Depreciation period | 20 years |
| Depreciation method | Straight-line |

Table SI-4 summarizes plant capacities, capital costs, feedstock costs, operating and maintenance (O&M) costs, and co-product revenues for ethanol plants using different feedstocks. Capital cost includes installed equipment costs, and indirect costs such as field expenses, construction fee, and project contingency, etc. The O&M costs are disaggregated into variable and fixed O&M costs. Variable O&M costs include costs of all the chemicals, enzymes, yeasts, utilities (electricity, water, etc.), waste disposal, and replacement of system components (e.g., baghouse bags, catalysts). Fixed O&M costs include the costs of personnel and supplies to operate and maintain the facility plus expenses for the plant’s administration, insurance and maintenance. All costs are converted to 2007 US$ using the Chemical Engineering Plant Cost Index (Chemical Engineering 2008) or U.S. Producer Price Index.

Cost data for corn ethanol are mainly taken from a model developed by USDA (2007), which uses ASPEN Plus to generate stream flowrates, equipment sizes, and material and energy balances for a state-of-the-art dry mill with a capacity of 150 million L of ethanol/yr. This model is used directly to estimate ethanol cost from dry mills, which produce only dry DGS. We modify the capital and O&M costs for dry mills, which produce only wet DGS; the natural gas ring dryer is removed and the natural gas consumption is lower compared to those which produce only dry DGS. The corn price is assumed at $157/t ($4/bu), which was the US average corn price in 2007. The delivered corn costs are estimated at $170/t ($4.24/bu) and $202/t ($5.14/bu) for dry mills in the Midwest and in
California, respectively. The shipping cost of corn is estimated based on a rate of $0.02 and $0.15/tonne·km for rail and truck, respectively (Morrow 2006). DGS is sold at a price of $116/t of dry matter.

Cost data on ethanol produced from agricultural and hardwood forest residues are adapted from a model developed by the National Renewable Energy Laboratory (NREL) for a biochemical process utilizing dilute acid pre-treatment followed by enzymatic hydrolysis (Aden et al. 2002). The process design first develops a set of process flow diagrams, and then uses ASPEN Plus to generate stream flowrates, equipment sizes, and material and energy balances for an ethanol plant, which has a capacity of processing 2000 dry t of corn stover per day. Since the original model is developed for corn stover, modifications are made to the capital cost and O&M costs for plants which utilize California agricultural and hardwood forest residues, to reflect changes in annual ethanol and electricity outputs due to differences in biomass composition. Excess electricity (if any) is sold to the grid at a price of $0.04/kWh. The corn stover price is estimated based on Walsh (2008), which indicates that 85% of collectible corn stover can be available at a farm-gate price of $51/dry t. The estimated delivered corn stover cost is $64.2/dry t, assuming the corn stover (15% moisture content) is shipped 80 km by truck to the ethanol plants. The farm-gate price of California agricultural residues is assumed to be the same as that of corn stover. The estimated delivered cost of California agricultural residues is about $73.6/dry t, assuming the residues (15% moisture content) are shipped 130 km by truck to ethanol plants. The forest residue price is estimated based on Walsh (2008), which indicates that 80% of forest residues (logging residues and removals from forest thinning, etc.) can be available at a price of $51/dry t. The delivered forest residue cost is estimated at $89.4/dry t, assuming the forest residues (50% moisture content) are shipped 130 km by truck to ethanol plants.

Cost data on ethanol produced from softwood forest residues are taken from a model developed by NREL for a thermochemical process utilizing indirect gasification and mixed alcohol synthesis (Phillips et al. 2007). The design uses ASPEN Plus to generate stream flowrates, equipment sizes, and material and energy balances for an ethanol plant, which has a capacity of 2000 dry t of forest biomass (hybrid poplar) per day. No modifications are made to the capital and O&M costs. The delivered biomass cost for softwood forest residue is assumed to be the same as that for hardwood forest residue. The co-products, mixed alcohols, are assumed to be sold to market as a product similar to residual fuel oil (Phillips et al. 2007). The price of residual fuel oil was $0.37/L in 2007. The estimated price of the mixed alcohols is $0.24/L (adjusted for mixed alcohols’ lower heating value).

Cost data on ethanol produced from California MSW are taken from Sakamoto (2004). Unlike cost estimates discussed above for ethanol derived from corn, agricultural and forest residues, cost estimates for ethanol from MSW were originally provided by GeneSyst Inc. for a gravity pressure vessel process. The plant processes 450 t of MSW per day. We assume the ethanol plant charges a disposal (tipping) fee of $38.6/t for delivered MSW,
which is the typical tipping fee paid to waste-to-energy facilities in California (Farrell and Sperling 2007). The estimated revenue from selling recovered materials including plastics, aluminum and ferrous scrap is about $9.1 for each t of MSW treated.

Cost data on ethanol produced from Brazilian sugarcane are taken from van den Wall Bake (2006). As indicated by the author, no reliable data are available. Data were collected from literature and various sources (e.g., Brazilian National Economic Institute). The capital and O&M costs are estimates for a 2005 autonomous sugarcane ethanol mill of processing 10,557 t of sugarcane per day. The average sugarcane price was $15.5/t in Brazil in 2005. Since the sugarcane price paid to Brazilian sugarcane growers closely tracks the world raw sugar price (USDA 2006), we assume the average sugarcane price in 2007 was also $15.5/t given that the raw sugar price in 2005 was similar to that in 2007. The ethanol plant produces excess electricity at 0.27kWh/L, and is sold to the grid at a price of $0.05/kWh.
| Feedstock rate (per day) | Corn | Midwest corn stover | CA ag. residue | CA hw forest residue | CA sw forest residue | CA MSW | Brazilian sugarcane<sup>a</sup> |
|-------------------------|------|---------------------|----------------|---------------------|---------------------|--------|-----------------------------|
| 1,067 t                 | 2,000 dry t | 2,000 dry t | 2,000 dry t | 2,000 dry t | 450 t | 10,557 t |
| Annual ethanol production (million L/yr) | 150 | 247 | 257 | 273 | 234 | 12 | 330 |
| Delivered feedstock cost ($/unit) | 157/t (plants in Midwest); 202/t (plants in CA) | 64.2/dry t | 73.6/dry t | 89.4/dry t | 89.4/dry t | -38.6/t | 15.5/t |
| Capital cost ($ million) | 61.3 (producing dry DGS); 54.5 (producing wet DGS) | 263.5 | 254.3 | 273.2 | 214.2 | 33.7 | 69.9 |
| Variable O&M cost ($million/yr) | 14.1 (producing dry DGS); 10.9 (producing wet DGS) | 17.0<sup>b</sup> | 16.7<sup>b</sup> | 17.7<sup>b</sup> | 1.8<sup>c</sup> | 3.0 | 18.8 |
| Fixed O&M cost ($million/yr) | 4.9 (producing dry DGS); 4.6 (producing wet DGS) | 9.2 | 9.0 | 9.3 | 13.2 | 0.9 | 17.5 |
| Co-product revenue ($million/yr) | 12.6 | 6.3 | 0 | 12.7 | 9.5 | 1.3 | 4.3 |
| Ethanol T&D ($/L) | 0.04 (ethanol produced in Midwest); 0.01 (ethanol produced in CA) | 0.04 | 0.01 | 0.01 | 0.01 | 0.01 | 0.06 |

O&M = operating and maintenance, T&D = transportation and distribution, ag =agricultural, hw=hardwood, sw =softwood
<sup>a</sup> The 2005 Brazilian Real is converted to 2007 Brazilian Real using Brazilian consumer price index, and then converted to 2007 US dollar using an exchange rate of 1.93 Real to 1 US dollar. The transportation cost is estimated to be $0.05/L from Brazil to California (Tokgoz and Elobeid 2006).
<sup>b</sup> Additional $0.4 million are required every 5 years from year 1 for baghouse bags.
<sup>c</sup> Additional $0.9 million are required for olivine fill and tar reforming catalyst in the 1<sup>st</sup> year. Additional $0.8 million are required for mixed alcohol catalysts and baghouse bags every 5 years from year 1.

### 4. Potential improvements to corn and sugarcane ethanol by 2020

This section describes potential improvements to dry mill corn and sugarcane ethanol production by 2020, which are used in our sensitivity analysis.
Potential improvements to dry mill corn ethanol production

The nitrogen fertilizer application rate (kg/ha) for US corn farming remained relatively stable from 1980 to 2006 while P and K fertilizer application rates have declined slightly during the same time period (USDA 2008). The average N, P, K fertilizer application rates for the period 1980 to 2006 were 161, 60, and 76 kg/harvested ha, respectively. We assume fertilizer application rates for corn production will remain unchanged through 2020. Corn yield is projected to reach 11 t/ha (175 bu/acre) in 2018/2019 (the last year for which data are available from USDA’s projections) (USDA 2009). With projected corn yield improvement, the estimated fertilizer application rates for each t of corn harvested are shown in Table SI-5.

A recent study (The Keystone Center, 2009) indicates that energy use for producing each t of corn has been reduced by 37% from 1987 to 2007, which implies an annual reduction rate of 1.85% in energy use. If we assume this trend will continue due to potential improvements in farming equipment efficiency and less energy intensive farming practices (e.g., adoption of no till), the estimated energy use of corn production can be reduced to approximately 495 MJ/t by 2020 (compared to current farming energy use, 651MJ/t).

Mueller (2007) projects the process energy source and energy system configuration of future dry mill ethanol plants based on the diffusion rates of process energy sources and energy system configurations over time. The diffusion rates are mainly estimated from the rates at which projects are announced in each category. The study projects that 65% of dry mills will use natural gas (boiler and combined heat and power) by 2020, 4% coal (combined heat and power), 20% biomass (boiler and combined heat and power), and 12% integrated biogas energy systems. As an approximation, we assume 70% of dry mills will use natural gas boiler and 30% use biomass boiler (corn stover in particular) in 2020.

In order to project future dry mill energy use, Mueller (2007) identifies process improvements and adjustments, which are expected to be adopted by dry mills through 2030. These include raw starch hydrolysis (also known as cold cooking or cold hydrolysis), corn oil extraction, and corn fractionation (removal of germ/oil at the front end). In addition, Mueller projects that efficiency improvements to energy equipment (e.g., boiler, motors) can further reduce dry mills’ energy requirement. Combining both improvements from dry mill process adjustments and energy equipment, the projected thermal energy requirement is about 7.3 MJ/L (26,326 Btu/gal) and electricity use 0.18 kWh/L (0.68 kWh/gal) for dry mills using natural gas boilers and producing 100% dry DGS in 2020. The thermal energy requirement for dry mills using biomass boilers is projected at 9.2 MJ/L (32,908 Btu/gal) and electricity use at 0.22 kWh/L (0.82 kWh/gal) in 2020. For dry mills producing wet DGS, the thermal energy requirement is estimated based on Mueller and Cuttica (2006). The thermal energy requirement of dry mills producing only wet DGS is about 4.9 MJ/L (17,900 Btu/gal) and 5.1 MJ/L (18,100 Btu/gal) for plants using
natural gas and biomass as primary process energy, respectively. The electricity requirement remains the same as for dry mills producing dry DGS.

For dry mills using biomass (corn stover in particular) as process fuel and producing dry DGS, the capital cost is estimated at $73.8 million for a plant size of 150 million L/yr (40 million gal per yr). The dry mill is assumed to employ a fluidized bed boiler, which costs about $13 million [estimated based on Cuttica and Mueller (2006) using a scaling factor of 0.75 and installation factor of 1.3] and a biomass dryer, which costs about $11.2 million. Dry mills using fluidized bed boilers do not need thermal oxidizers, which are used by natural gas fired dry mills (Cuttica and Mueller 2006). The capital cost is reduced to $62.6 million if the dry mills produce only wet DGS. The biomass is assumed to cost $56/dry t (shipped 30 km by truck to the dry mills).

Table SI-5. Improvements to corn ethanol production modeled in sensitivity analysis.

| Parameter                          | Value                                      |
|------------------------------------|--------------------------------------------|
| N fertilizer (kg/t)                | 14.6                                       |
| P fertilizer (kg/t)                | 5.5                                        |
| K fertilizer (kg/t)                | 6.9                                        |
| Farming energy use (MJ/t)          | 495                                        |
| Process fuel share                 | 70% of dry mills use natural gas, and 30% of dry mills use biomass |
| Process fuel use for dry mills producing dry DGS (MJ/L) | Natural gas: 7.3, Biomass: 9.2 |
| Process fuel use for dry mills producing wet DGS (MJ/L) | Natural gas: 4.9, Biomass: 5.1 |
| Electricity use for dry mills producing either dry DGS or wet DGS (kWh/L) | Natural gas systems: 0.18, Biomass systems: 0.22 |

Potential improvements to sugarcane ethanol production

Although no significant change is expected to agricultural operations in sugarcane cultivation in the next few years, Macedo et al. (2008) indicate that mechanical planting will be adopted to replace the separate operations of furrowing, fertilizer application and seed distribution. Taking into account opinions from different specialists, Macedo et al. developed a conservative set of conditions for 2020 sugarcane ethanol production. The sugarcane yield is expected to increase to 95 t/ha/cut (compared to the current yield of 87.1 t/ha/cut). The nitrogen fertilizer application rate is projected to decrease while P and K fertilizer use will increase (data shown in Table SI-6). Farming energy use also slightly increases due to adoption of mechanical planting.
Macedo et al. (2008) project that the sugarcane ethanol yield will increase to 92.3 L/t of sugarcane due to possible cane quality improvement (i.e., increase in sucrose in cane stalks from 14.22% to 15.25%). Macedo et al. (2008) indicate that sugarcane mills will be equipped with high-pressure steam systems and utilize more efficient equipment. In addition to using bagasse, the sugarcane ethanol plants will recover 40% of trash (leaves, tops) left on the field after cane harvest for power generation. The surplus electricity is expected to reach 1.46 kWh/L of ethanol produced for 2020.

Some modifications to the energy systems will be needed in order to utilize sugarcane trash for electricity production. Due to a lack of data on the breakdown of capital cost for each section of the sugarcane mills, we assume a 10% increase in capital cost. The total feedstock cost increases because the ethanol plants need to purchase sugarcane trash for electricity production. No data on sugarcane trash is available in the literature. We estimate the sugarcane trash cost as a sum of collection and transportation cost and a premium paid to the farmers. The collection and transportation costs of sugarcane trash are assumed to be the same as those of sugarcane, and are estimated based on van den Wall Bake (2006). Adding a $2/t premium, the estimated cost of sugarcane trash is about $18/dry t. The revenues from excess electricity increase because more electricity is available for export to the grid.

| Table SI-6. Improvements to sugarcane ethanol production modeled in sensitivity analysis. |
|-----------------------------------------------|---|
| Parameter                     | Value |
| N fertilizer (kg/t)            | 0.6   |
| P fertilizer (kg/t)            | 0.6   |
| K fertilizer (kg/t)            | 1.5   |
| Farming energy use (MJ/t)     | 107   |
| Ethanol yield (L/t)           | 92.3  |
| Excess electricity (kWh/L)    | 1.46  |
### 5. Ethanol supply scenarios without indirect land use change

Table SI-7 summarizes ethanol demand, direct agricultural land requirement, petroleum reduction directly due to ethanol blending and average ethanol cost for each supply scenario when iLUC effects for corn and sugarcane ethanol are not included.

**Table SI-7.** Ethanol demand, direct agricultural land requirement, petroleum reduction directly due to ethanol blending and average ethanol cost for each scenario (without iLUC effects).

| Scenario          | Ethanol demand for blending ($10^9$ L/y) | Ethanol source ($10^9$ L/y) | Average vol (%) of ethanol in fuel blends | Ag. land required ($10^6$ ha/y) | Petroleum reduction directly due to ethanol blending $^a$ ($10^9$ L/y) | Weighted average ethanol cost ($/L of ethanol) |
|-------------------|------------------------------------------|------------------------------|-------------------------------------------|---------------------------------|---------------------------------------------------------------------|----------------------------------------------|
| 1A BR_sugarcane_w/o_tariff | 9.8                                      | BR sc: 9.7                   | 18                                        | 1.6                             | 5.7 (11%)                                                           | 0.37                                         |
| 1B BR_sugarcane_w_tariff     | 9.7                                      | BR sc: 9.7                   | 18                                        | 1.6                             | 5.7 (11%)                                                           | 0.51                                         |
| 1C MW_corn                  | 28.1                                     | MW corn: 28.1                | 46                                        | 7.1                             | 16.5 (32%)                                                          | 0.56                                         |
| 2A LP_w/o_tariff            | 10.2                                     | CA MSW: 1.4                  | 18                                        | 1.4                             | 6.0 (12%)                                                           | 0.37                                         |
| 2B LP_w_tariff              | 8.1                                      | CA MSW: 1.4                  | 15                                        | 0                               | 4.9 (10%)                                                           | 0.47                                         |
| 3A CA_eth_w/o_tariff        | 10.2                                     | CA MSW: 1.4                  | 18                                        | 1.1                             | 6.0 (12%)                                                           | 0.42                                         |
| 3B CA_eth_w_tariff          | 8.8                                      | CA MSW: 1.4                  | 16                                        | 0.2                             | 5.3 (10%)                                                           | 0.48                                         |

BR = Brazilian; MW = Midwest; CA = California; sc = sugarcane; MSW = municipal solid waste; hw = hardwood; sw = softwood; stover = corn stover; ag = agricultural.

$^a$ Petroleum refers to conventional crude oil. Numbers in parentheses indicate the percentage reductions in petroleum use relative to using 2010 baseline gasoline only.
6. Ethanol supply scenarios with potential improvements to corn and sugarcane ethanol

Sensitivity analysis is conducted in order to understand how potential improvements in corn and sugarcane ethanol production will affect the various ethanol scenarios. Table SI-8 presents the life cycle results and MESPs of corn and sugarcane ethanol with feedstock and conversion process improvements as discussed in Section 4. Tables SI-9 and SI-10 show the results for the ethanol supply scenarios with and without iLUC effects, respectively.

**Table SI-8.** Life cycle results and MESPs of corn and sugarcane ethanol with feedstock and conversion process improvements.

| Ethanol pathway                | WTW GHG emissions a (g CO₂ eq./MJ) | WTW Petroleum use (MJ/MJ) | MESP ($/L) |
|-------------------------------|-----------------------------------|---------------------------|------------|
| Midwest average corn ethanol  | 80.1(50.1)                        | 0.11                      | 0.55       |
| Brazilian sugarcane ethanol  | 60.2 (14.2)                       | 0.12                      | 0.32       |

a Values in parentheses without iLUC.

**Table SI-9.** Ethanol demand, direct agricultural land requirement, petroleum reduction directly due to ethanol blending and average ethanol cost for each supply scenario with improvements to corn and sugarcane ethanol (with iLUC).

| Scenario                | Ethanol demand for blending (10⁹ L/y) | Ethanol source (10⁹ L/y) | Average vol (%) of ethanol in fuel blends | Ag. land required (10⁶ ha/y) | Petroleum reduction directly due to ethanol blending (10⁹ L/y) | Weighted average ethanol cost ($/L of ethanol) |
|-------------------------|--------------------------------------|--------------------------|------------------------------------------|-----------------------------|-----------------------------------------------------------------|---------------------------------------------|
| 1A BR_sugarcane_w/o_tariff | 20.9                                 | BR sc: 20.9              | 35                                       | 2.9                         | 12.2 (24%)                                                      | 0.32                                         |
| 1B BR_sugarcane_w_tariff   | 20.9                                 | BR sc: 20.9              | 35                                       | 2.9                         | 12.2 (24%)                                                      | 0.46                                         |
| 1C MW_corn                | 47.2                                 | MW corn: 47.2            | 70                                       | 10.3                        | 27.9 (55%)                                                      | 0.55                                         |
| 2A LP_w/o_tariff          | Same as 1A                           |                          |                                          |                             |                                                                 |                                              |
| 2B LP_w_tariff            | 20.1                                 | CA MSW: 1.4              | 34                                       | 2.5                         | 11.9 (23%)                                                      | 0.45                                         |
| 3A CA_eth_w/o_tariff      | 16.0                                 | CA MSW: 1.4              | 28                                       | 1.7                         | 9.4 (19%)                                                       | 0.36                                         |
| 3B CA_eth_w_tariff        | Same as 3A                           |                          |                                          |                             |                                                                 | 0.46                                         |
| Scenario | Ethanol demand for blending $(10^9 \text{ L/y})$ | Ethanol source (10^9 L/y) | Average vol (%) of ethanol in fuel blends | Ag. land required $(10^6 \text{ ha/y})$ | Petroleum reduction directly due to ethanol blending $(10^9 \text{ L/y})$ | Weighted average ethanol cost ($/\text{L of ethanol}$) |
|----------|-----------------------------------------------|--------------------------|------------------------------------------|------------------------------------------|-------------------------------------------------|-----------------------------------------------|
| 1A BR_sugarcane_w/o_tariff | 9.1 | BR sc: 9.1 | 17 | 1.3 | 5.3 (11%) | 0.32 |
| 1B BR_sugarcane_w_tariff | 9.1 | BR sc: 9.1 | 17 | 1.3 | 5.3 (11%) | 0.46 |
| 1C MW_corn | 16.3 | MW corn: 16.3 | 28 | 3.6 | 9.6 (19%) | 0.55 |
| 2A LP_w/o_tariff | Same as 1A | | | | | |
| 2B LP_w_tariff | 9.6 | CA MSW: 1.4 | 17 | 1.1 | 5.7 (11%) | 0.44 |
| 3A CA_eth_w/o_tariff | 9.8 | CA MSW: 1.4 | 18 | 0.9 | 5.8 (11%) | 0.39 |
| 3B CA_eth_w_tariff | Same as 3A | | | | | 0.46 |
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