Land-Use and Alternative Bioenergy Pathways for Waste Biomass

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Rapid escalation in biofuels consumption may lead to a trade regime that favors exports of food-based biofuels from tropical developing countries to developed countries. There is growing interest in mitigating the land-use impacts of these potential biofuels exports by converting biorefinery waste streams into cellulosic ethanol, potentially reducing the amount of land needed to meet production goals. This increased land-use efficiency for ethanol production may lower the land-use greenhouse gas emissions of ethanol but would come at the expense of converting the wastes into bioelectricity which may offset fossil fuel-based electricity and could provide a vital source of domestic electricity in developing countries. Here we compare these alternative uses of wastes with respect to environmental and energy security outcomes considering a range of electricity production efficiencies, ethanol yields, land-use scenarios, and energy offset assumptions. For a given amount of waste biomass, we found that using bioelectricity production to offset natural gas achieves 58% greater greenhouse gas reductions than using cellulosic ethanol to offset gasoline but similar emissions when cellulosic ethanol is used to offset the need for more sugar cane ethanol. If bioelectricity offsets low-carbon energy sources such as nuclear power then the liquid fuels pathway is preferred. Exports of cellulosic ethanol may have a small impact on the energy security of importing nations while bioelectricity production may have relatively large impacts on the energy security in developing countries.

1. Introduction

Global bioenergy consumption has expanded rapidly in response to rising fossil fuel prices, interest in supporting agriculture economies, and environmental concerns over anthropogenic greenhouse gas (GHG) emissions. Over 70% of the growth in biofuels consumption between 2003 and 2007 has been in the U.S. and Europe and continued growth is forecasted due to ambitious targets set by policy makers (*1*). Tropical developing countries have large biofuels resource potential and relatively low production costs, suggesting the possibility of a transition to a global trade regime favoring exports of biofuels from developing countries to developed countries (*2*). Even with current trade policies that constrain the comparative advantages of developing countries, bioenergy trade is growing rapidly, particularly with respect to liquid transportation fuels (*3*).

Biofuels trade has been challenged by ethical and environmental concerns due to the land-use impacts of feedstock production. Direct land-use impacts occur when natural lands are cleared to grow biofuels (*4*). In this case the life-cycle GHG emissions from biofuels can be larger than emissions from fossil fuels because the natural lands emit CO_2 from natural carbon pools when they are converted to croplands. Direct land-use impacts are most significant for tropical developing countries where disturbance of carbon-rich forests results in large life-cycle CO_2 emissions (*5, 6*). Indirect land-use impacts occur when existing croplands are used to grow biofuels feedstocks. When existing food croplands are used to grow biofuels feedstocks, the displaced food crops may expand onto natural lands causing the life-cycle GHG emissions from biofuels to be greater than emissions from fossil fuels (*7*). Although current global policies that promote the expansion of biofuels do not explicitly account for these land-use impacts (*8*), government agencies are considering the adoption of land-use related regulations on biofuels (*9, 10*). In both cases biofuels create a food-fuel competition for land that increases food prices and has the greatest impact on food insecure people in developing nations (*11*).

To mitigate these land-use impacts there is growing interest in increasing the land-use efficiency of ethanol production by making additional biofuels from the waste streams of food-based biofuels. Converting these largely lignocellulose wastes into ethanol is an emerging technology which has attracted significant research investment in recent years. For Brazil, the dominant exporter of biofuels, it has been argued that cellulosic ethanol conversion of refinery wastes would significantly improve the amount of ethanol produced per unit area of sugar cane cropland, thus reducing land-use impacts (*12, 13*). Cellulosic production also results in a small net production of electricity, but the primary energy output is ethanol. Sugar cane ethanol is produced by crushing sugar cane stalks to remove sugars and then fermenting the sugars into ethanol. The crushed stalks, called bagasse, are burned in a power plant to provide electricity and steam for the ethanol refinery power needs and to dispose of the wastes. The surplus bagasse that is not needed for refinery heat and electricity could be converted into ethanol if emerging cellulosic ethanol technologies become economically feasible. This additional ethanol production could increase the land-use efficiency of biofuels production, potentially lowering the land-use greenhouse gas emissions of the biofuels to help meet emerging regulations in the importing developed nations.

While converting wastes from food-based biofuels into cellulosic ethanol could reduce land-use impacts, this comes at the expense of converting wastes into surplus bioelectricity and biogas for domestic consumption in developing countries. Food-based biofuel refineries with significant waste streams, such as sugar cane ethanol plants, are increasingly being viewed as a vital source of domestic electricity (*14−17*). Both the cellulosic ethanol and bioelectricity options have the potential to reduce GHG emissions. Even in Brazil where hydropower provides most of the electricity production, the marginal electricity production is increasingly supplied by natural gas which can be offset by bioelectricity. Both options also have the potential to influence energy security in the exporting and importing nations. Liquid fuels are a critical energy security issue in the importing developed nations. The primary energy security concern in the tropical developing countries that export liquid fuels in some cases may be electricity.

At present there is relatively little evidence of economically competitive approaches to either cellulosic ethanol or biomass gasification at commercial scales. However, Brazilian

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investment in both of these emerging technologies suggests that both technologies could play an important role in near-term and midterm energy production (*16, 18, 19*). Brazil in particular may become the technological frontier for either of these technologies due to the low costs of biomass in Brazil (*18*).

As developing countries expand their biofuels production and developed countries expand their biofuels imports these countries will be faced with a strategic choice with respect to the optimal use of waste streams. Although a portion of the biomass wastes may be needed as soil amendments (*20*), some component of the waste stream, particularly biorefinery wastes such as bagasse, are attractive candidates for bioenergy. Previous work suggests that conversion of bagasse may have significant climate forcing and environmental pollution advantages relative to conversion to ethanol (*21*). Comparisons of dedicated crops achieve greater GHG reductions than ethanol when bioelectricity is coupled with electric vehicles to offset gasoline (*22*) and when bioelectricity offsets fossil fuel-based electricity production (*23*). However, it is uncertain how these alternative energy choices compare for a range of offset possibilities, the magnitude of GHG savings associated with the enhanced land-use efficiency, and the relationship between energy security benefits in the exporting developing countries and the importing developed countries.

Here we compare the cellulosic ethanol and bioelectricity options for refinery wastes using a life-cycle assessment of net GHG emissions and energy production. We assess performance metrics across a range of electricity production efficiencies, ethanol yields, land-use scenarios, and energy offset assumptions. The focus of this analysis is on Brazilian sugar cane wastes due to Brazil's current role as the leading ethanol exporter, its prospects to be the dominant future exporter, the significant waste streams that result from sugar cane ethanol production, and the growing importance of natural gas in Brazilian marginal electricity production. Since the amount of available waste biomass may vary beyond the surplus bagasse considered here (e.g., increased biomass availability as field burning is phased out), our analysis is best suited for a comparison of cellulosic ethanol and bioelectricity.

2. Materials and Methods

2.1. Energy Offset. Emissions for alternative energy sources are used to determine the GHG offsets achieved by substituting bioelectricity for marginal electricity production in Brazil and ethanol for U.S. transportation fuels consumption. Life-cycle emissions are taken from the GREET model for bioelectricity offsetting marginal electricity production from natural gas in Brazil (596 g CO_2-e per kWh of electricity at the plug) (*24*) and for ethanol offsetting U.S. gasoline (94 g CO_2-e per MJ) (*25*). In recent years, consumption of natural gas has grown faster than production forcing Brazil to import natural gas, and most of the forecasted growth in imports is liquefied natural gas (LNG) (*26*). The fuel-cycle emissions of LNG are higher than domestic and pipeline-imported natural gas due to additional energy requirement for processing, liquefacation, dedicated LNG tankers, and regasification, resulting in a 28% increase in life-cycle emissions (*27*). Based on this LNG factor and the GREET natural gas emissions rate, we estimate life-cycle emissions for Brazilian electricity produced from LNG as 763 g CO_2-e per kWh of electricity at the plug. We also consider a range of efficiencies for natural gas electricity production in Brazil. While the efficiency of Brazilian marginal electricity in GREET was 40% (industry mix of gas turbine and combined cycle power plants) we allow for potentially higher efficiency production from natural gas combined-cycle power plants with a GREET efficiency of 53%.

The marginal electricity offset from bagasse-based electricity may be largely natural gas (*28*) but we also consider a range of other electricity offset possibilities that may form a large component of marginal electricity. For hydropower we use a range of 3−120 g CO_2^-e kWh^{-1} (*29*) though some studies suggest the potential for much higher emissions rates (*30*). Electricity emissions from fuel oil, nuclear, and coal life-cycles were 657−866 g CO_2^-e kWh^{-1}, 3−40 g CO_2^-e kWh^{-1}, and 823−1085 g CO_2^-e kWh^{-1}, respectively (*29*). Furthermore it has been suggested that bagasse-based ethanol might be used to offset sugar cane ethanol rather than gasoline (*12, 13*). For sugar cane ethanol we use life-cycle emissions of 34.5 kg CO_2e/Mg sugar cane (fossil fuel inputs, emissions from field burning, and soil N_2O emissions) as well as a range of land-use change emissions (see Supporting Information).

2.2. Cellulosic Ethanol. Cellulosic ethanol production from surplus bagasse was calculated for an assumed average yield of 6.34 MJ ethanol/kg dry bagasse and a range of 5.91 MJ ethanol/kg to 6.96 MJ ethanol/kg (*13*). Life-cycle components included emissions from building the cellulosic refinery (29 g CO_2-e/l ethanol) and emissions offsets from electricity coproducts from the lignin component of the waste (0.57 kWh/gallon ethanol) (*25*). The transportation and distribution of ethanol has estimated emissions of 69 g CO_2-e/l ethanol (*31*). The agriculture and pretreatment phase emissions (e.g., fertilizer, pesticide, drying) were not accounted to avoid double counting with the sugar cane ethanol. While assigning a portion of the agriculture emissions to the waste coproducts is an alternative approach, both methods would result in the same impact on cellulosic ethanol and bioelectricity.

2.3. Bioelectricity. The production of electricity from surplus bagasse was compared with cellulosic ethanol. We used biomass gasification as the bioelectricity technology rather than conventional combustion because both gasification and cellulosic ethanol are emerging, highly efficient technologies (*15, 33, 34*). The expected efficiency for electricity production from biomass gasification at small B-IGCC power plants (5−50 MWe) is reported to range from 36% to 45% (*34*), 24% to 45% (*14*), and 44% to 45% (*35*). We use an average of 40% based on these ranges but also consider the full range of possibilities. This efficiency is consistent with GREET's biomass gasification efficiency of 40%. Emissions associated with the capital costs of the biomass gasification power plant were 12 g CO_2-e/kWh (*36*). The heating value of bagasse is 17 MJ/kg on a dry basis and 7.5 MJ/kg bagasse on a delivered basis (50% moisture). While the biogas is assumed to be converted on site, opportunities have also been discussed to cofire biogas with natural gas (*17, 37*).

2.5. Scope and System Boundaries. The comparison of using bagasse for electricity or ethanol is considered for two different systems, the first for a fixed amount of bagasse and the second for a fixed amount of ethanol (see flowcharts in the supporting online material). For both systems we consider the net GHG emissions and energy production. The first system has a functional unit of one kg bagasse (dry basis). For this system the upstream agriculture phase emissions (land-use, field burning, harvesting, etc.) are not included because these emissions have been allocated to sugar cane ethanol in previous work (*38*).

The second system has a functional unit of 102 billion liters of ethanol. This functional unit is useful for considering recent studies that argue that Brazil could meet 5% of 2025 gasoline demand (*12, 13*). Furthermore, these studies argues that the land-use emissions associated with 102 billion liters of sugar cane ethanol production could be reduced if the surplus bagasse was converted into ethanol, requiring less land to meet the production goal. In addition to these two energy alternatives (sugar cane ethanol or sugar cane ethanol + bagasse ethanol), a third case would be to produce the 102

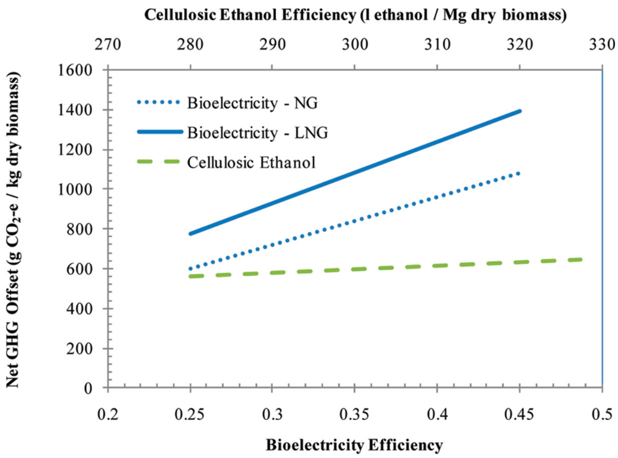

FIGURE 1. Net GHG offsets for cellulosic ethanol and bioelectricity for a range of conversion efficiencies. Bioelectricity is assumed to offset marginal electricity production from natural gas (NG, dotted line) or liquefied natural gas (LNG, solid line). Cellulosic ethanol is assumed to offset gasoline.

billion liters with sugar cane ethanol and use the surplus bagasse to produce electricity. Here, we consider these three possible cases, each producing 102 billion liters of ethanol (Supporting Information Table S1).

3. Results and Discussion

First we consider the system where the functional unit is 1 kg of surplus bagasse (dry basis). The GHG reduction for bioelectricity offsetting marginal natural gas was 58% greater than for cellulosic ethanol offsetting gasoline. The base case bioelectricity offset was 958 g CO_2e/kg dry biomass while the offset for the LNG case was 1230 g CO_2e/kg dry biomass. The average cellulosic ethanol case with a production efficiency of 6.44 MJ ethanol/kg dry bagasse achieved an offset of 607 g CO_2e/kg dry biomass. While the cellulosic ethanol offset included accounting of the coproduct electricity production (lignin combustion), this was small relative to the bioelectricity case because the production rates were 0.05 kWh/kg dry biomass and 2.0 kWh/kg dry biomass for the cellulosic ethanol electricity coproduct and bioelectricity cases, respectively. For a range of possible conversion efficiencies in Figure 1, the lowest bioelectricity efficiencies result in similar GHG offsets as the full range of cellulosic efficiencies. The bioelectricity was assumed to offset the average marginal electricity based on GREET efficiencies (40% efficient). Considering a high-efficiency case for Brazilian marginal electricity (natural gas combined cycle) and bioelectricity from combined cycle (45%), the net GHG offset would be 825 g CO_2e/kg dry biomass.

While bioelectricity offsetting natural gas and ethanol offsetting gasoline are typical offset targets (*31*), we also considered the potential for a range of alternative offsets. In Figure 2, the net GHG offset per unit kg of surplus bagasse is summarized for the bioelectricity offsets described above as well as offsets to hydropower, fuel oil, nuclear power, and coal. The net offsets are much lower for bioelectricity offsetting nuclear and hydropower than the other carbon-rich energy sources, though some studies suggest the potential for much higher emissions from hydropower (*30*).

Previous work has also argued that bagasse-based ethanol may offset other sources of ethanol rather than gasoline (*12, 13*). If bagasse-based ethanol offsets sugar cane ethanol then the emissions offset would range from 200 g CO_2e/kg dry bagasse to 1276 g CO_2e/kg dry bagasse for sugar cane associated with land-use change on grasslands and forestlands, respectively. One land-use model suggests that 67% of the total land-use change associated with sugar cane expansion would be on forestlands. Using this percentage to weight the grassland and forestland emissions gives a bagassed-based ethanol offset of 917 g CO_2e/kg dry bagasse which is similar to the 958 g CO_2e/kg dry bagasse offset achieved by using bagasse-based electricity to offset natural gas. The bagasse-based ethanol emissions offsets would be much smaller given scenarios of crop and pasture intensification in which increased sugar cane ethanol is associated with very low land-use emissions (*6, 13*).

The energy security impacts of the cellulosic ethanol and bioelectricity alternatives will have unique impacts on the exporting developing countries and importing developed countries. While many developed countries are focused on petroleum as a critical energy security issue, developing countries that become exporters of biofuels may have other primary energy security concerns. In Brazil, petroleum and biofuels production provide domestic and diversified liquid fuels. However, electricity remains a challenge for energy security due to the lack of diversification (85% of 2006 Brazilian electricity generation was hydropower). For the functional unit of 1 kg bagasse, the bioelectricity case produces 1.67 kWh (40% efficiency) and the cellulosic ethanol base case produces 0.305 L ethanol. Scaling the available surplus bagasse from a kg basis to the entire 2006 sugar cane crop (assuming 8% of bagasse is surplus) results in 1.79×10^{10} kWh from bioelectricity or 4.3% of Brazil's 2006 electricity demand. The same amount of biomass would produce 3.26×10^9 l of ethanol or 0.37% of U.S. 2006 gasoline demand. This suggests that cellulosic ethanol exports may have a small impact on the energy security of importing nations and that bioelectricity may have a relatively significant impact on the energy security of the exporting developing nations.

Next we consider the system in which the functional unit is 102 billion liters of ethanol production (5% of 2025 global gasoline demand). Recent work suggests that Brazil could meet 5% of the 2025 gasoline world demand using sugar cane ethanol or alternatively could meet this demand with lower land-use emissions using a combination of sugar cane ethanol and cellulosic ethanol from waste biomass (*13*). We also consider a third option for meeting this demand which is a combination of sugar cane ethanol and conversion of surplus bagasse to bioelectricity to offset natural gas. In Figure 3 we show the net GHG emissions associated with these three alternatives: (1) sugar cane only, (2) sugar cane ethanol and bagasse-to-ethanol, (3) sugar cane ethanol and bagasse-to-electricity. If the expansion of sugar cane occurs at the expense of grasslands, then all three cases result in a net GHG offset (GHG emissions from bioenergy are less than gasoline, Figure 3a). If the expansion of sugar cane occurs at the expense of forests, then all three cases result in a net GHG emission (GHG emissions from bioenergy are greater than gasoline, Figure 3b). For both the grassland and forest conversion scenarios, the bioelectricity option is advantageous. If bioelectricity offsets a low-carbon electricity source (e.g., nuclear rather than natural gas), then the bioelectricity case is similar to the sugar cane ethanol only case (case 1). The sugar cane ethanol only case has similar emissions to the cellulosic case with grassland conversion but 124% greater emissions than the cellulosic case with forestland conversion.

For the 102 billion liter expansion of Brazilian ethanol exports including conversion of surplus bagasse to cellulosic ethanol, the cellulosic ethanol production would yield 2.3×10^{10} liters annually. This cellulosic ethanol is equivalent to 2.7% of the 2006 U.S. gasoline consumption on an energetic basis (*39*), suggesting modest effects on the energy security of importing nations. Alternatively, the bioelectricity produced from the equivalent amount of surplus bagasse would produce 1.7×10^{11} kWh annually. This is equivalent to 40% of Brazil's electricity production suggesting a significant impact on exporting developing nations.

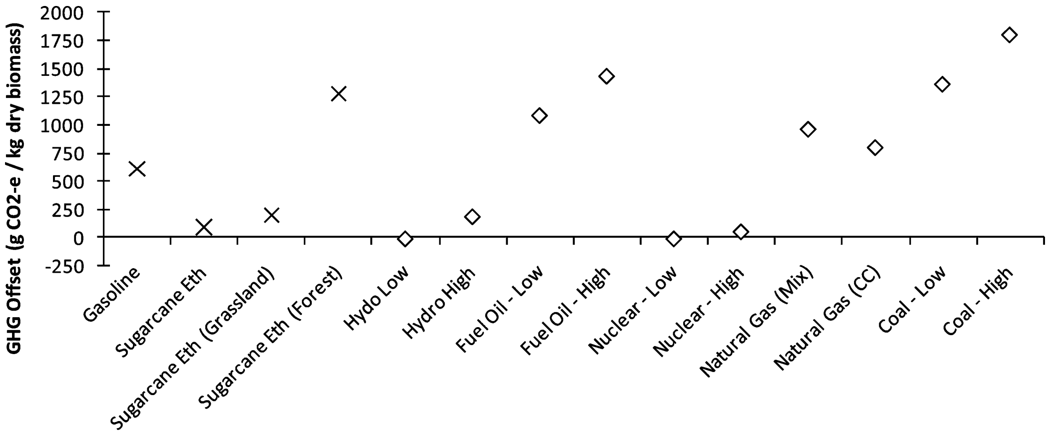

FIGURE 2. Net GHG offsets for cellulosic ethanol (cross; offsetting gasoline and sugar cane ethanol) and bioelectricity (diamonds; offsetting hydropower, fuel oil, nuclear, natural gas, and coal-fired power plants) per unit of biomass feedstock. High and low estimates of emissions for alternative energy sources are provided. For the offset to sugar cane ethanol the low and high emissions are based on sugar canes indirect land use impacts to grassland and forests, respectively.

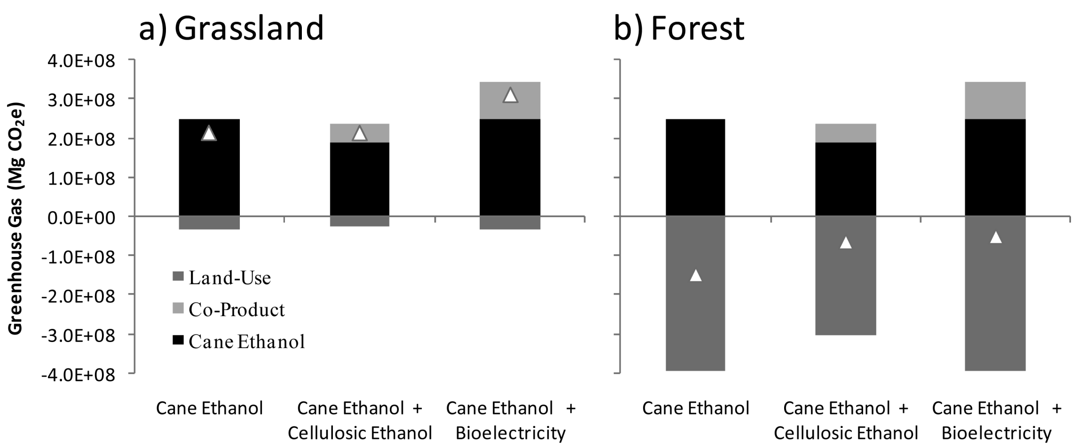

FIGURE 3. Net greenhouse gas offset for sugar cane bioenergy accounting for land-use. Greater than zero is emissions and less than zero is an offset. Triangle is sum of components. Components are land-use emission (gray), sugar cane ethanol offset to gasoline (black) and coproduct offset to fossil fuel (light gray). Land-use change is grassland (A) or forest (B). The three cases produce an equivalent amount of ethanol: (1) sugar cane ethanol, (2) sugar cane ethanol plus use of surplus bagasse for cellulosic ethanol, and (3) sugar cane ethanol with surplus bagasse used for bioelectricitiy.

The net GHG emissions show significant uncertainty in terms of the alternatives assumed for the land-use emissions, energy offsets, and functional units. For both bioelectricity and cellulosic ethanol the emissions vary by more than an order of magnitude for these different scenarios. While the net GHG emissions are highly variable across the scenarios considered, the energy security results consistently favored the bioelectricity option, regardless of the functional unit. These results may be useful for indentifying which combination of land-use and energy policies will lead to the best GHG outcomes. For example, a land-use policy that eliminates forest conversion would be best matched with an energy policy that favors conversion of surplus biomass into electricity to offset natural gas.

While cellulosic ethanol and biomass gasification are appropriate for comparison of emerging technologies, there is also potential to utilize the bagasse using technologies that are currently deployed at commercial scales. There is currently no proven cellulosic ethanol technology at commercial scale but efficient bioelectricity production is widely produced using steam-cycle power plants. Most bagasse power plants at Brazilian sugar cane refineries have low average efficiencies (16.83 kWh/ton of milled cane) (*40*). These low efficiencies result in modest electricity production which is mostly consumed by refinery energy demand. However existing steam cycle technologies and improved refinery efficiencies could increase the surplus electricity production by more than an order of magnitude (*38, 41*). For conventional technologies, efficiencies of 25% may be possible for bagasse-steam cycle and 33% for back-pressure steam turbine systems (*42*).

The comparison of uses of surplus biomass suggests that greater environmental and energy security benefits would be achieved with bioelectricity production based on energy offsets and land-use scenarios that have been considered in the past. However a broader range of offset assumptions (i.e., bioelectricity offsetting hydropower) that may be possible based on economics and energy policies also leads to results that could favor the use of bagasse to make liquid fuels. The land-use and energy offset alternatives presented here may be useful for indentifying which combination of land-use and energy policies will lead to the best GHG and energy security outcomes. In addition to the climate and energy security assessment presented here, an economic comparison of these energy pathways may be attractive in the future as data from commercial-scale cellulosic ethanol and biomass gasification plants becomes available.

Supporting Information Available

Additional information including two tables and one figure. This material is available free of charge via the Internet at http://pubs.acs.org.

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