

Life-Cycle Assessment for the Production of Bioethanol from Willow Biomass Crops via Biochemical Conversion*

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Abstract

We conducted a life-cycle assessment (LCA) of ethanol production via bioconversion of willow biomass crop feedstock. Willow crop data were used to assess feedstock production impacts. The bioconversion process was modeled with an Aspen simulation that predicts an overall conversion yield of 310 liters of ethanol per tonne of feedstock (74 gal per US short ton). Vehicle combustion impacts were assessed using Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) models. We compared the impacts of bioconversion-produced ethanol with those of gasoline on an equivalent energy basis. We found that the life-cycle global warming potential of ethanol was slightly negative. Carbon emissions from ethanol production and use were balanced by carbon absorption in the growing willow feedstock and the displacement of fossil fuel-produced electricity with renewable electricity produced in the bioconversion process. The fossil fuel input required for producing 1 MJ of energy from ethanol was 141 percent less than that from gasoline. More water was needed to produce 1 MJ of ethanol fuel than 1 MJ of gasoline. The life-cycle water use for ethanol was 169 percent greater than for gasoline. The largest contributors to water use were the conversion process itself and the production of chemicals and materials used in the process, such as enzymes and sulfuric acid.

The Energy Independence and Security Act (EISA) mandates that at least 16 billion gallons (61 billion liters) per year of cellulosic fuel be in production by the year 2022 (EISA 2007). To meet this ambitious goal, many feedstocks, with appropriate conversion technologies, will be required for fuel production. Woody biomass will play an important role in supplying feedstock for biofuels production. The National Academy of Sciences (NAS 2009) projects that

124 million dry tons (112 million tonnes) per year of woody biomass will be available for use by 2020, without compromising the environment. The Consortium for Research on Renewable Industrial Materials (CORRIM) has comprehensively assessed the life-cycle impacts of solid wood products. The current work by CORRIM expands that research portfolio to investigate production of fuels from woody biomass. In this project, the production of ethanol

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* This article is part of a series of nine articles addressing many of the environmental performance and life-cycle issues related to the use of wood as a feedstock for bioenergy. The research reported in these articles was coordinated by the Consortium for Research on Renewable Industrial Materials (CORRIM; <http://www.corrim.org>). All nine articles are published in this issue of the *Forest Products Journal* (Vol. 62, No. 4).

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Forest Prod. J. 62(4):305–313.

using bioconversion is investigated with willow biomass as the feedstock. Willow is considered a good bioconversion feedstock because the carbohydrates can be recovered with good yields without extensive pretreatment (Sassner et al. 2005). Companion CORRIM biofuels investigations reported in this issue of the *Forest Products Journal* use softwood residual feedstocks. Hardwood feedstocks were chosen for this study because they do not exhibit the recalcitrance reported for softwoods (Mansfield et al. 1999). Other benefits of using willow as a feedstock include high biomass production, suitability for cultivation on marginal land, ease of vegetative propagation from dormant hardwood cuttings, broad genetic base and ease of breeding, and ability to resprout after multiple harvests (Keoleian and Volk 2005).

Life-cycle assessment (LCA) of ethanol produced by bioconversion of willow has been investigated for Europe using the information of feedstock production available in literature from the United Kingdom (Stephenson et al. 2010). In this study, the impacts associated with conversion were estimated using the Aspen model developed by the National Renewable Energy Laboratory (NREL; Aden et al. 2002), and emissions from vehicle use were estimated using data from the Conservation of Clean Air and Water in Europe and the European Council for Automotive Research and Development (Stephenson et al. 2010). Environmental impacts were calculated using Environment Development of Industrial Products methodology. Stephenson found that ethanol produced using bioconversion reduced life-cycle greenhouse gas (GHG) emissions and fossil energy requirements by 90 and 83 percent, respectively, compared with gasoline. There have also been LCA studies for production of ethanol using bioconversion of poplar feedstocks (González-García et al. 2010). Poplar is similar to willow in terms of growth, harvesting, and biomass composition. Results from these LCAs should be similar to those using willow. In the González-García study, feedstock data were obtained from the literature on poplar crops grown and harvested in Spain. They used the Aspen model (Aden et al. 2002) to assess the impacts of the bioconversion process and used available literature to estimate emissions associated with vehicle usage. The Institute of Environmental Studies (CML), a European LCA impact indicator method, was used for impact characterization. González-García et al. (2010) found that compared with gasoline, the life-cycle GHG emissions for bioconversion ethanol (E100) were 80 percent lower than those for gasoline, and fossil fuel use was decreased by 78 percent. This life-cycle GHG emission that was smaller than that reported by Stephenson et al. (2010) could be explained by González-García et al. (2010) not accounting for the impact of excess electricity production on the life-cycle impacts.

In the present work we refine and expand on the previous LCA work by using life-cycle inventory (LCI) databases developed for US data and by using actual operations data for feedstock production and harvesting. Further, we investigate life-cycle water consumption, which may have a significant environmental impact for biorefineries using a bioconversion approach.

Methods

Goal and scope

The goal of this study was to investigate the environmental impacts of using bioethanol that is produced via a

bioconversion process with willow as the feedstock. The environmental impact assessed is global warming potential (GWP). In addition, the life-cycle fossil fuel and freshwater requirements for bioethanol were assessed. All these impacts and resource demands were compared with gasoline production and use. A functional unit of 1 MJ was used in our analysis to adjust for the different heating values of ethanol and gasoline. In this study we adhered to the methodology set by the International Organization for Standardization (ISO 2006a, 2006b), such that we can compare impact assessments for producing fuels with different conversion technologies and can compare the life-cycle carbon impacts of using wood biomass to produce various products, including fuels and solid wood products.

System boundaries

System boundaries for the study are from the establishment of the site for willow crop production to the combustion of the ethanol product. The product stages in this life cycle are feedstock production and harvesting, transport to biorefinery, the conversion process, fuel distribution and use, ancillary chemicals, avoided production, and disposal of solid wastes (Fig. 1). Modules were developed in SimaPro v.7.3.0 (PRé Consultants 2011) using the US LCI (NREL 2011) and Ecoinvent (Swiss Centre for Life Cycle Inventories [SCLCI] 2009) databases for materials and processes that were not user generated. Ecoinvent was used only when no appropriate data were available from the US LCI.

Most of the data used in the analysis are national averages that are not indicative of site-specific conditions for a particular region of the country. All ethanol is assumed to be produced in the continental United States, precluding the need for imports. Electrical energy is assumed to be a coproduct from ethanol production. We anticipate that bioconversion ethanol plants will operate much like modern pulp mills, generating high-pressure steam in a boiler that is first sent to a steam turbine to produce electricity. Moderate-

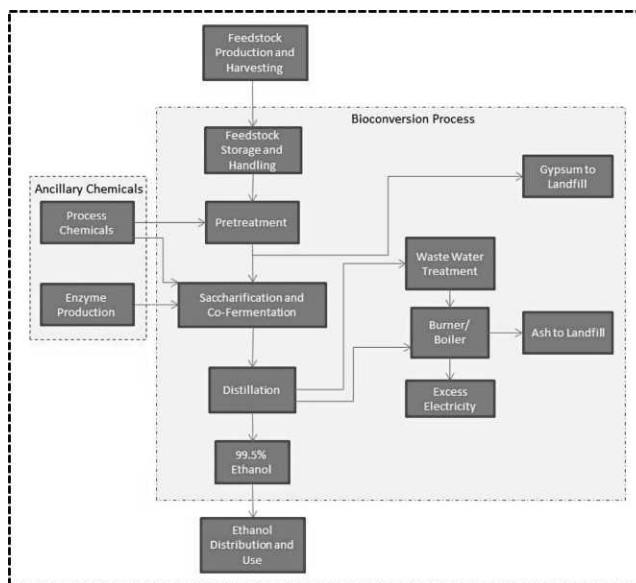


Figure 1.—Cradle-to-grave system boundaries. All process inputs and emissions associated with those areas designated in the figure are tracked within the life-cycle assessment.

Table 1.—US national electrical grid makeup (National Renewable Energy Laboratory 2011).

Fuel type	%
Coal	52
Nuclear	20
Natural gas	15
Hydroelectric	7
Residual fuel oil	3
Biomass	1.5
Other	1.1

and low-pressure steam is then withdrawn from the turbine for use as process heat. Two methods are used to analyze the impact of electricity production on global warming. The first is to treat excess electricity as an avoided product using “system expansion.” In this case, excess electricity not needed for ethanol production displaces the corresponding amount supplied by the US National Grid. US National Grid makeup is provided in the US LCI (NREL 2011), and the fuel sources that contribute to it are shown in Table 1. System expansion is commonly used in LCA studies and is the method of choice when applicable (ISO 2006b). The second method is to consider electricity as a coproduct and perform an allocation based on the ethanol’s and electricity’s respective energy content. Allocation was investigated to determine the impact of displaced national grid electricity production on life-cycle GWP.

Assumptions

- The land used to grow the energy crop had previously been idle cultivated land. The impacts of indirect land use change from use of this type of land will be minimal, since it is not currently in production, and is not included in the analysis. Previous research has shown that aboveground biomass carbon loss for abandoned cropland would have a small carbon debt (6 Mg CO₂ per ha, which translates to approximately 0.0006 kg CO₂ per MJ; Fargione et al. 2008) and would not contribute significantly to the carbon accounting, because this would be a one-time emission during site preparation. Other aboveground impacts associated with preparing the land for willow growth are incorporated in the feedstock portion of the life-cycle inventory model. Belowground carbon is assumed to maintain a steady state for the crop’s lifetime. We do not account for any belowground carbon emissions as a result of disturbing the soil during site preparation or the sequestration of carbon as a result of root and stool formation. No measurable changes in soil carbon over time to a depth of 45 cm in willow plantation sites have been observed (Pacaldo et al. 2010). There may be considerable increases in belowground carbon in willow plantations because of the permanent plant parts—coarse roots and stool—as well as some allocation to fine roots, but how much of that remains as part of the soil matrix over time is not yet clear. The assumption of a neutral belowground carbon pool is believed to be a conservative estimate. Changes in biomass productivity and soil carbon may result from treatments that address nutrient deficiencies or accelerate regeneration, providing potential future alternatives of importance that are not addressed in this study.

- Higher heating value for ethanol, 29.6 MJ/kg (Oak Ridge National Laboratory 2012).
- Higher heating value for gasoline, 47.9 MJ/kg (Oak Ridge National Laboratory 2012).

Data collection

Operations data for production and harvesting of willow biomass are combined with bioconversion data generated from an Aspen-Plus (Aspen Technology Inc. 2005) simulation. The end use tailpipe emission for ethanol is modeled with Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET; Wang 2010). LCA models were developed using SimaPro 7 (PRé Consultants 2011) software. The GWP along with fossil fuel consumption from producing and using ethanol fuel from willow are assessed relative to that of a gasoline product system available in the US LCI (NREL 2011) database covering all primary products. The life-cycle impact assessments (LCIA) were performed using the Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI; Bare 2002). Water use is compared with a gasoline product system from the Ecoinvent (SCLCI 2009) database because the US LCI gasoline process does not contain data on water usage. In both databases of the gasoline, life cycles begin with extraction of crude oil in the ground, include transportation and refining, and end with combustion in a spark ignition engine.

Impacts for ethanol production are broken down by production segments to show the relative effects of each segment of the life cycle and to provide guidance on where to reduce overall environmental impact.

Feedstock production and harvesting.—Feedstock production and harvesting data were obtained from operational data for willow crops that are managed at the Woody Biomass Program at the State University of New York, Syracuse (WBP 2011). Willow is grown on seven 3-year rotations and includes 1 year of site preparation prior to planting the crop as unrooted cuttings. No irrigation is required to grow the willow crop. After the first growing season, the willow is coppiced and produces multiple stems on each plant the following spring. The willow is left to grow for 3 years and then harvested with a single pass cut and chip harvester based on a New Holland FR 9080 forage harvester and a 130FB short rotation coppice head. Chipped material is placed in a truck and ready for transport with no need of preprocessing once arriving at the biorefinery. After harvest the plants resprout and grow for another 3 years. In this model, nitrogen fertilizer is applied at the rate of 100 kg of nitrogen per ha in the spring, after each harvest (Quaye et al. 2011). Seven 3-year rotations are included in the life of the crop. Plants are killed with herbicide following the final harvest and stools are ground down (Buchholz and Volk 2011).

The carbon content of willow is assumed to be 494 g/kg of wood (Keoleian and Volk 2005) resulting in biomass CO₂ sequestration of 1.82 kg CO₂ per kg of wood. Similar values were used by González-García et al. (2010) for poplar.

Transport to the refinery.—Feedstock is transported from the tree farm to the conversion facility. The mode of transportation is assumed to be diesel truck. Distances are based on literature review. It was assumed that the willow would be transported an estimated average distance of 80 km (160 km round-trip haul; Wojnar 2010) for a large-scale

bioethanol plant operating at 1,200 dry tonnes of willow feedstock per day (1,320 dry US short ton willow per day). This category also includes the transportation of all other materials delivered to the biorefinery.

Bioconversion.—While primary LCI survey data are often collected to be representative of industrial operations, no commercial-scale cellulosic ethanol facilities are operating yet to supply processing impact data. Processing impacts were modeled in Aspen Plus software to generate conversion process LCI inputs for the SimaPro LCA model. The model is a modification of the NREL model for cornstover feedstock (Aden et al. 2002), which was altered to be suitable for willow feedstock. The composition of the willow feedstock used in the simulation is shown in Table 2 (Sassner et al. 2008). For the base case investigated in this work, it was assumed that 1,200 dry tonnes of willow would be fed to the biorefinery each day (419,000 dry tonnes/y), which results in production of 130 million liters of ethanol per y (310 liters/tonne). While the NREL model is rigorous and complete, it represents one hypothetical process out of multiple possible configurations. Future data from operating biorefineries will be necessary to develop definitive life-cycle assessments.

The main process parameters used in the bioconversion model are shown in Table 3. Pretreatment conditions and xylan recovery are those given by Sassner et al. (2006) and are similar to what has been used in our laboratory for poplar. Minor hemicellulose sugars are assumed to have the same recovery as xylan. The saccharification yield (75%) is a conservative estimate based on our experience with steam exploded hardwoods and low enzyme loadings. Fermentation conditions and yields were provided by Aden et al. (2002) for *Zymomonas mobilis*.

The bioconversion process modeled in this analysis is described as follows. Chipped willow enters the facility and undergoes sulfur dioxide catalyzed steam explosion pretreatment. Steam explosion was selected because it will result in a somewhat higher glucose yield with reduced fermentation inhibitor production than other pretreatment methods (Ewanick and Bura 2010). Endo- β -1,4-glucanase, cellobiohydrolase, and β -glucosidase are used for enzymatic hydrolysis, and *Zymomonas mobilis* is assumed to be the fermentation organism. Ethanol is distilled and dehydrated until 99.5 percent purity is obtained. Lignin, unreacted carbohydrates, and other organics are combusted in a boiler to provide process steam and electricity. In the Aspen simulation, 28,000 kg/h of combustible material is sent to the boiler. This results in 154,650 kg/h of 86 atm steam. The steam is sent to a steam turbine, which produces 28 MW of power. The bioconversion process consumes 9 MW, and 19 MW of electricity is exported to the national grid. The electricity demands of the biorefinery are quite modest,

Table 2.—Willow feedstock chemical composition (Sassner et al. 2008).

Chemical	% dry weight
Cellulose	42.5
Hemicellulose	22
Lignin	26
Ash	2
Acetate	3
Extractives	4.5

Table 3.—Parameters used in Aspen bioconversion model.

Processing step	Process parameter	Value
Pretreatment	SO ₂ charge (% wt/wt)	2
	Temperature (°C)	205
	Xylan to xylose (%)	74
Saccharification	Temperature (°C)	65
	Enzyme loading (FPU/g cellulose)	5
	Cellulose to glucose (%)	75
Cofermmentation	Temperature (°C)	41
	Glucose to ethanol (%)	95
	Xylose to ethanol (%)	85

since the power is only needed to drive moderately sized pumps. Moderate (13 atm), low (4.4 atm), and very low (1.7 atm) pressure steam is drawn off the turbine for use in the reactors, fermenters, and distillation columns. Roughly 20 percent of the incoming steam is condensed to hot water. The relatively high electricity production is a direct consequence of use of a high-pressure boiler. We note that construction of high-pressure boilers (some over 90 atm) to maximize electricity production is common in modern pulp mills (Gustafson and Raffaelli 2009). A similar approach has been taken in the proposed biorefinery configuration.

No auxiliary fuel is required for heat or power. Gypsum could be produced as a byproduct, but in this analysis it is assumed to be a solid waste material (Foust et al. 2009). Wastewater is filtered and processed in anaerobic and aerobic environments. Wastewater treatment results in clean process water, sludge, and methane. The sludge and methane are sent to the burner. The building and maintenance of required capital goods and infrastructure are outside the bounds of this study.

Process chemicals and enzymes are lumped into the “ancillary chemicals” category. The chemical production and use included in this category are sulfur dioxide, lime, sulfuric acid, diammonium phosphate, phosphoric acid, and urea. Of special interest for the LCA is the production of enzymes. There are no life-cycle data for cellulase production that can be directly applied to this study. To estimate the emissions and material (especially water) and energy demands of cellulase production we used values published by Wooley et al. (1999a, 1999b) and Sheehan et al. (2004). Using the economically viable enzyme charge of 5 filter paper units (FPU) per g of cellulose and a bioreactor productivity of 75 FPU/liter/h reported by Sheehan et al. (2004), it was possible to estimate the resource demands and emissions associated with enzymes used in our ethanol conversion process. These factors were then input to SimaPro, either as a process or a direct inventory input. Resources required for enzyme production include cellulose (modeled with dissolving pulp), corn oil, corn steep liquor, and potassium biphosphate.

Ethanol distribution and use.—Ethanol is distributed from the conversion plant to a blending terminal. This fuel is then transported to the regional storage facility. The transportation mode is assumed to be diesel truck. The total round-trip transportation distance for ethanol distribution is assumed to be 160 km (Wojnar 2010). Infrastructure needed for ethanol distribution is not included in the analysis.

The operation of a 2012 passenger vehicle is assumed to be the end use of the biofuel. LCI data for vehicle operation is derived from the GREET 1.8d model (Wang 2010).

Although hypothetical, this study considered the use of E100 in a flex-fuel spark ignition vehicle. Pure ethanol was chosen to facilitate direct comparison with pure gasoline. The 100 percent ethanol comparison with gasoline shows the direct GHG savings due to ethanol production and use. Further, direct comparison enables us to judge whether the biofuel produced here meets the GHG threshold requirement set by the EPA (US EPA 2009). Other life stages of the vehicle, such as vehicle manufacturing, servicing, and end-of-life, are not included. Vehicle operation data for ethanol fuel was generated in the GREET model primarily with default parameters. The only parameters that were specified were the feedstock type and blend ratio (100 in our case). The ethanol vehicle emissions are compared with gasoline, which is composed of GREET default market shares for 2012. For comparison, the model assumes that the gasoline is also combusted in a spark ignition vehicle.

Results

Global warming potential

A comparison of the GWP, using the system expansion model, between ethanol fuel and gasoline fuel is shown in Figure 2. The graph shows the GWP calculated in carbon dioxide equivalents per megajoule fuel equivalent. The contribution of each processing stage to the GWP as well as the overall average is shown in Figure 2. “CO₂ absorption” is presented as a separate category to show the significant effect of CO₂ sequestration in willow feedstock on GWP for the ethanol life cycle. The following stages of GWP were considered.

- CO₂ absorption: includes CO₂ absorbed during photosynthesis.
- Feedstock production and harvesting: includes all crop management and production activities from site preparation through seven harvest cycles (except photosynthesis).

- Transport to refinery: includes transport of feedstock, materials in ancillary chemicals, and product fuel.
- Ancillary chemicals: includes production of all the chemicals and enzymes required by the biorefinery.
- Conversion process: includes biochemical conversion of willow chips to ethanol.
- Avoided production: includes avoided production of grid electricity due to export of excess electricity from biorefinery to grid.
- Fuel distribution and use: includes the transportation and emissions associated with distributing the E100 fuel and its combustion in a flex-fuel vehicle.
- Disposal of solid wastes: includes disposal of gypsum waste and wood ash streams.
- Gasoline production and use: includes all process and emissions associated with the manufacturing of gasoline and its combustion in a single-injection vehicle.

GWP of willow-derived ethanol fuel is slightly negative and 120 percent less than the value of 2005 gasoline, the standard for measurement set in EISA. This result is greater but consistent with that of Stephenson et al. (2010), who found a 90 percent reduction in GWP for ethanol produced by bioconversion process. The larger percent reduction in GWP is a consequence of a lower ethanol yield and greater electricity displacement (310 liters/tonne and 1.3 kwh/liter of ethanol [74 gal/ton and 4.9 kwh/gal of ethanol]) in our model than those used by Stephenson et al. 2010 (340 liters/tonne and 0.29 kwh/liter of ethanol [81 gal/ton and 1.1 kwh/gal of ethanol]). The difference in electricity displaced has a large impact: the Stephenson et al. (2010) study is located in the United Kingdom, where the electrical grid is supplied by 29 percent coal (Department of Energy and Climate Change 2012), as compared with the US electrical grid, at 51 percent coal (NREL 2011; Table 1). The greater use of coal in the United States provides for greater GHG benefits in the displacement energy.

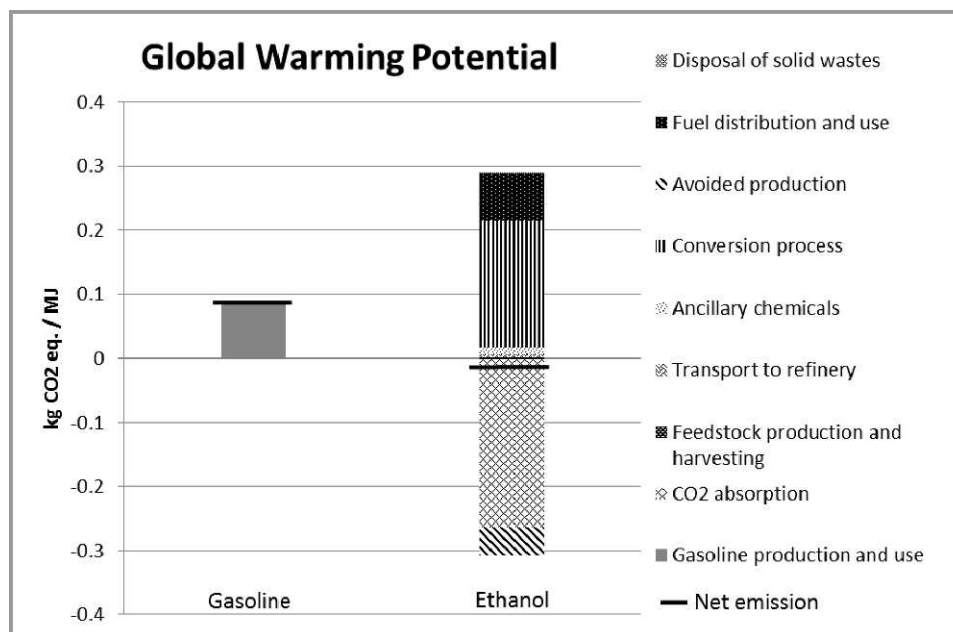


Figure 2.—Global warming potential for ethanol and gasoline fuels using the system expansion model. The net emissions are indicated with the black bar.

Ethanol GHG emissions from feedstock processing to vehicle use amount to 0.289 kg CO₂ eq per MJ. Carbon sequestration of the growing feedstock reduces emissions by 0.263 kg CO₂ eq per MJ, and displacement of fossil fuel in national grid electricity production results in an additional reduction of 0.043 kg CO₂ eq per MJ. The net result is that the life-cycle carbon emission of willow-derived ethanol product is -0.017 kg CO₂ eq per MJ fuel use. Willow-derived bioethanol is essentially carbon neutral. In contrast, there is a 0.088-kg CO₂ eq per MJ emission when gasoline is used as a transportation fuel. Substituting willow-based ethanol for gasoline reduces CO₂ equivalent emissions by 0.11 kg CO₂ eq per MJ of fuel energy used.

We investigated the impact of national grid electricity displacement on net carbon emissions by performing a comparable LCA where carbon emissions are allocated to electricity production. In our process, 0.197 MJ of excess electricity is generated and exported to the national grid for every megajoule of ethanol production. Allocating carbon emissions on energy content results in 83.5 percent of the global warming emissions being apportioned to ethanol and 16.5 percent to electricity. Applying this allocation approach yields the GWP results shown in Figure 3.

For ethanol use, the net emissions for GWP assuming coproduct allocation is 0.02 kg CO₂ eq per MJ from bioethanol. This is a 77 percent reduction compared with gasoline. This reduction in GWP is similar to studies that reported values of 78 percent (willow feedstock; Stephenson et al. 2010) and 62.4 percent (poplar feedstock; González-García et al. 2010) when not including the export of excess electricity in the results. In treating excess electricity produced on site as a coproduct and allocating the inputs and emissions based on energy content, there is a 0.038-kg CO₂ eq per MJ increase in GWP of ethanol use compared with the method using system expansion (Fig. 2). While the GWP assuming allocation does increase relative to the system expansion model, it is still a much better alternative to using gasoline.

Fossil fuel use

Life-cycle fossil fuel is monitored using the LCI generated from SimaPro. The raw fossil fuel inputs were tracked by adding up all raw material fossil fuel demand. The use of fossil fuels in ethanol production is compared with gasoline production from the US LCI database. The resulting net fossil fuel usage for ethanol and gasoline are -0.50 and 1.2 MJ of fossil fuel per MJ of fuel energy, respectively (Fig. 4). The lower net value of ethanol (141% less than gasoline) is not unexpected because the heat and power required for the bioconversion process studied in this model are fueled by the combustion of lignin and other residuals produced at the biorefinery during the conversion process. In addition, exportation of excess electricity offsets the fossil fuel demand to generate this power on the national grid. The fossil fuel use is 80 percent lower than gasoline without the credit for avoided electricity production. This value is in line with that calculated by Stephenson et al. (2010) and González-García et al. (2010).

Water use

Water use is tracked in SimaPro in the same manner as fossil fuel use. All freshwater inputs are summed per megajoule of fuel energy. The ethanol data are compared with Ecoinvent European gasoline, since there are no water data for US LCI gasoline (Fig. 5). The amount of water needed to produce 1 MJ of energy from willow-based ethanol is 169 percent greater than it is for the production of 1 MJ from gasoline: 0.49 kg of water is needed to create 1 MJ of fuel from willow-based ethanol, while 0.29 kg is needed to create 1 MJ of gasoline. Fifty-five percent of the water demand comes from the ancillary chemicals category. The processes in the ancillary chemicals category responsible for the high water demand are sulfur dioxide, enzyme, and sulfuric acid production. The conversion process accounts for 43 percent of the water demand (Fig. 5). As noted earlier, feedstock production creates little water demand, since we assumed the willow is grown without

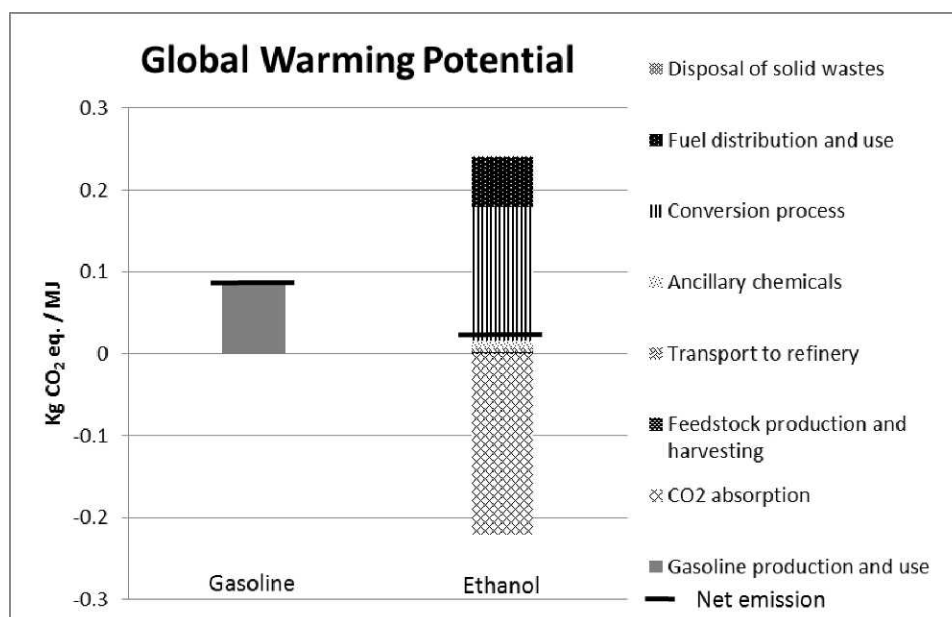


Figure 3.—Global warming potential for ethanol with allocation. The net emissions are indicated with the black bar.

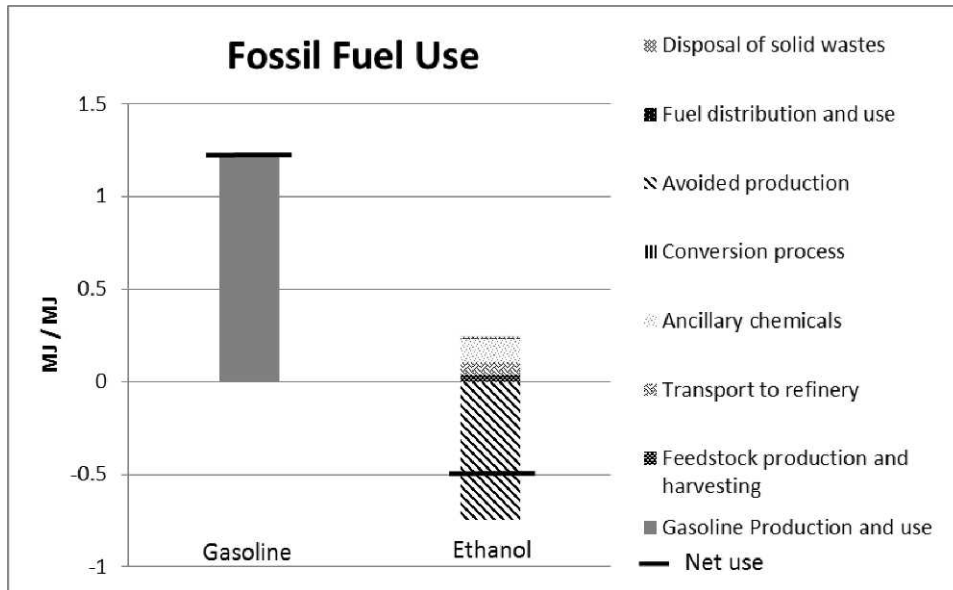


Figure 4.—Comparison of fossil fuel use to produce gasoline and willow-based ethanol.

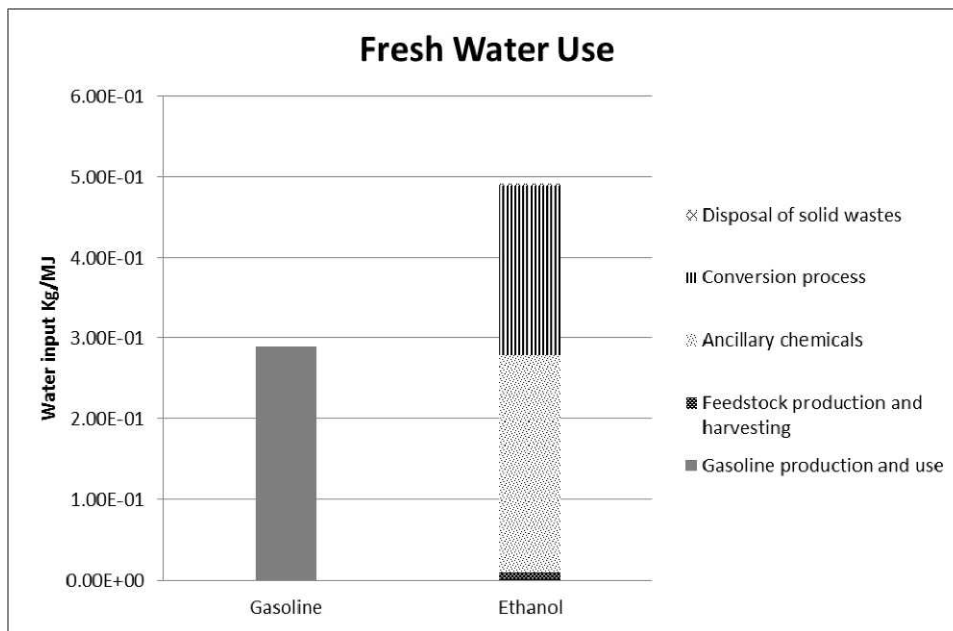


Figure 5.—Water use (kilograms) per megajoule of energy produced.

irrigation. Expressing water usage in units of liters of water used per liter of fuel produced results in 14 liters used to produce 1 liter of ethanol from willow; of this, 7.7 liters of water are used in the ancillary chemicals category and 6 liters are used in the bioconversion process itself.

A regionally specific LCA water impact analysis such as the one described by Pfister et al. (2009) was not included in this study because our analysis used US aggregated averages. LCA water impact analyses are most meaningful when done at the watershed level because of large regional differences in water availability (Pfister et al. 2009). Significant water demand is an issue if the supply is limited or constrained. A water scarcity index has been one approach to address constrained water availability in a

specific region (Berger and Finkbeiner 2010). We also made no attempt to differentiate water usage. To create consistency in water use analysis, the United Nations Environment Programme/Society of Environmental Toxicology and Chemistry recently proposed that water use be classified as in-stream or off-stream and consumptive or degradative (Bayart et al. 2010). Incorporation of regional factors and details of water usage would improve the significance of any LCA results regarding water. This level of detail would be difficult to incorporate into this LCA analysis, however, because the majority of the water usage is associated with production of materials and chemicals used in the conversion process. These materials will come from diverse sources, making it difficult to quantify regional impacts or

have good assessment of the appropriate water usage category. A future research goal of our laboratory is to develop more meaningful measures of life-cycle water impacts associated with the production of biofuels. The results in Figure 5 suggest, however, that water use to produce biofuels may be significant and should be an important environmental consideration.

Conclusions

We investigated the life-cycle impact of a hypothetical ethanol production process using short rotation willow feedstock. The bioconversion process used in the analysis produced 310 liters of ethanol per tonne of feedstock (74 gal per oven-dry US short ton). An Aspen simulation of the process was developed because there are no data from a working biorefinery. A significant feature of the modeled process is the export of 19.2 MW of electricity from the biorefinery. Life-cycle impacts of willow-based ethanol were compared with those of gasoline on a per megajoule basis. The results of the LCA show that producing and using E100 from willow in place of gasoline can reduce GHG by 120 percent. Significant carbon sequestration by fast-growing willow feedstock and the displacement of fossil fuel electricity generated on the national grid are the largest contributors to ethanol's low carbon footprint. It was found that production and use of willow-based ethanol is virtually carbon neutral. As expected, the fossil fuel inputs needed for bioethanol are 141 percent less than they are for production of 1 MJ of energy from gasoline. Minimal fossil fuel is required for bioethanol production, and the displacement of fossil fuel to produce electricity on the national grid contributes to ethanol's low usage.

The use of bioethanol from willow does require more water than needed for gasoline production and use. Producing and consuming ethanol requires 169 percent more water than is required for gasoline. Much of this water use is associated with the manufacture of enzymes and chemicals used in the bioconversion process. The life-cycle impact of water usage is complex, however, and requires further analysis before a definitive impact conclusion can be drawn.

Results of this study show that willow-based ethanol can be an excellent fuel to help our nation reach its GHG emission goals. There are some environmental categories, however, that may be exacerbated by large-scale ethanol production. Attention to these categories while designing and operating plantations and biorefineries will help avoid any unintended negative consequences with this new fuel source.

Acknowledgments

This article is one of several organized by CORRIM, a consortium of 17 research institutions, to provide life-cycle information covering biofuel collection and processing options. Funding was provided by the US Forest Service through the Forest Products Laboratory with matching funds from donors and participating institutions.

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