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Sustainability Metrics and Life Cycle Assessment for Thermochemical Conversion of Woody Biomass to Mixed Alcohols

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Abstract. This study quantifies selected sustainability metrics including the life cycle greenhouse gas (GHG) emissions for ethanol production via thermochemical conversion of biomass. Results are based on the process detailed in the National Renewable Energy Laboratory's 2011 conceptual design for mixed alcohols via indirect gasification of woody biomass. The impacts of biomass feedstock moisture and ash contents on the biofuel production efficiency and the life cycle GHG emissions are investigated. Field drying the feedstock from 50 wt% to 30 wt% moisture content lowers the life cycle GHG emissions by more than 13%. Reducing ash content in the feedstock preprocessing step from 7 wt% to 1 wt% decreases the overall GHG emissions by about 7% due to improved biofuel yield. The life cycle GHG emissions for the cases evaluated range from 39.1 to 48.7 g CO_2-equivalent (i.e., CO_{2e}) per kilometer driven or 12.4 to 15.5 g CO_{2e} per MJ. For all cases evaluated here, the GHG emissions are reduced by more than 83% compared to the baseline gasoline life cycle GHG emissions. This reduction exceeds the 60% threshold necessary to qualify as a cellulosic biofuel as specified in the U.S. Renewable Fuel Standard under the Energy Independence and Security Act of 2007.

Keywords: Biofuel, biomass, life cycle assessment, sustainability metrics, greenhouse gas reduction

1. Introduction

Aggressive renewable fuel policies will necessitate unprecedented biomass feedstock production [1] and installation of associated fuel conversion and distribution infrastructure. The U.S. cellulosic biofuels industry is currently in its nascent stages. Conversion technologies are being actively developed, and process improvements to these technologies have been investigated with the primary goal of cost optimization, thus minimizing investment risk and expediting industry learning. Expansion of the cellulosic biofuels industry at the scale needed to meet the U.S. Renewable Fuel Standard (RFS) goals [2] comes with some potential environmental impacts (e.g., [3]). In addition to process economics, sustainability elements now play critical roles in biofuels development and commercialization. The U.S. Department of Energy (DOE) Biomass Technology Program is focused on developing the resources, technologies, and systems needed to grow a sustainable biofuels industry [4]. The success of the biofuels industry depends not only on economic viability but also on more overarching concerns, such as environmental sustainability. Salient metrics and benchmarks of sustainability are needed to guide the biofuels industry toward sustainable expansion. These benchmarks will provide a framework within which biofuel conversion platforms, supply chains, producers, and products can be quantitatively assessed and compared. Such assessments can help identify and provide important information on knowledge gaps, which can direct research efforts and lead to more environmentally-optimized processes. In response to this need, we are using process engineering and life cycle assessment (LCA) to quantify resource consumption and environmental emissions at the biorefinery and to identify specific sustainability drivers, opportunities, and metrics. Key areas under investigation include greenhouse

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(GHG) emissions, consumptive water use, and select criteria air pollutant emissions, as well as energy return on investment.

To meet the intended goals of improving energy independence and mitigating climate change, biofuels will have to reduce GHG emissions compared to gasoline. The RFS, under the Energy Independence and Security Act of 2007, sets mandates for biofuel GHG emissions relative to conventional petroleum fuel emissions in 2005 [2]. For instance, qualification as a "cellulosic biofuel" requires life cycle GHG emissions to be at least 60% less than the baseline gasoline life cycle GHG emissions. The reduction threshold is 20% for renewable fuels and 50% for both advanced biofuels and biomass-based diesel. Thus, the quantification of biofuels life cycle GHG emissions from any conversion pathway is of interest not only to research laboratories and academic institutions, but also to policy makers and biofuel investment communities. It is noteworthy that the U.S. Environmental Protection Agency alone is in charge of performing LCAs of biofuels for compliance with the RFS. This study aims to quantify the life cycle GHG emissions of one of the modelled commercial ethanol production processes in DOE's ethanol conversion platforms: syngas production via indirect gasification of woody biomass followed by gas cleanup and conditioning and mixed alcohol synthesis [5]. Specifically, this study focuses on the selected sustainability metrics and GHG emissions profile associated with various moisture and ash contents of woody biomass. Life cycle GHG emissions from these cases will be compared to the 2005 gasoline baseline. Sustainability metrics for the conversion step will also be quantified for these cases.

2. Methods and Assumptions

2.1. Process Description and Assumption

The thermochemical conversion process used in this report is based on the National Renewable Energy Laboratory's 2011 design model [5]. The nth-plant thermochemical design report describes a process with syngas production via the indirect gasification of wood chips, syngas cleanup and conditioning, and subsequent fuel synthesis to produce ethanol and higher alcohols, primarily propanol, butanol, and pentanol. A simplified flow diagram for the process is shown in Fig. 1. A detailed description of the process can be found in other publications [5], [6]. The design specifies a processing capacity of 2,000 dry metric tonnes of woody biomass per day and incorporates 2012 research targets for technologies that will facilitate the future commercial production of cost-competitive ethanol. For this study the process design was adjusted to accommodate different feedstock moisture and ash contents. We further assumed that the feedstock convertibility is the same for similar feedstock types (i.e., logging residues and thinnings). All conversion data are based on the feedstock composition of pine [5].

2.2. Woody Biomass Feedstock

Woody biomass feedstock in this study includes a mixture of hardwood logging residues (48 wt%), softwood logging residues (35 wt%), and thinnings (17 wt%) from non-federal lands. Feedstocks from U.S. federal lands were not included. Additionally, short rotation woody energy crops and herbaceous feedstocks were also excluded. We developed four cases using the conventional feedstock supply format: 1) the high moisture/high ash case has 50 wt% moisture content from harvest through the plant gate and 7 wt% ash throughout the system; 2) the high moisture/low ash case has 50% moisture content from harvest through the plant gate and ash reduction at the landing, which reduces ash content from 7 wt% to 1 wt% via screening and debarking systems; 3) the low moisture/high ash case includes field drying, which reduces landing moisture content to 30 wt%, and 7 wt% ash content throughout the system; and 4) the low moisture/low ash case includes field drying, which reduces the landing moisture content to 30 wt%, and ash reduction at the landing, which reduces ash content from 7 wt% to 1 wt% via screening and debarking systems. Note that the weight percentages for ash are on a dry basis.

2.3. Modeling Approach and Assumptions

The sustainability metrics study uses two different modeling approaches and platforms: Aspen Plus process engineering software [7] and SimaPro v.7.3 life cycle assessment software [8]. Aspen Plus was used to estimate direct CO_2 emissions, consumptive water use, total fuel efficiency, and carbon-to-fuel efficiency associated with the conversion process. The boundary for all metrics is the biorefinery plant gate (conversion stage); upstream and downstream processes are not considered in this portion of the study. SimaPro v.7.3 LCA modeling software was used to develop and link unit processes using established methods [9]. In the absence of primary, publicly-available data, we used the Ecoinvent v.2.0 [10] and, to a lesser extent, the U.S. Life Cycle Inventory (LCI) [11] processes. We modified the Ecoinvent processes to reflect U.S. conditions and the U.S. LCI processes to account for embodied emissions and energy flows. The LCI of the conversion step is based on the corresponding Aspen Plus process modelling inputs and outputs. This study projects LCA GHG emissions of ethanol fuel derived from woody biomass. The modelling boundary for this study is from field to wheels, including embodied energy and material flows. The functional unit is 1 kilometer travelled by a flexible-fuel vehicle [12] operated on E100 in the year 2012. E100 contains 100% ethanol that is produced via the present process of indirect gasification and mixed alcohol synthesis of woody biomass.

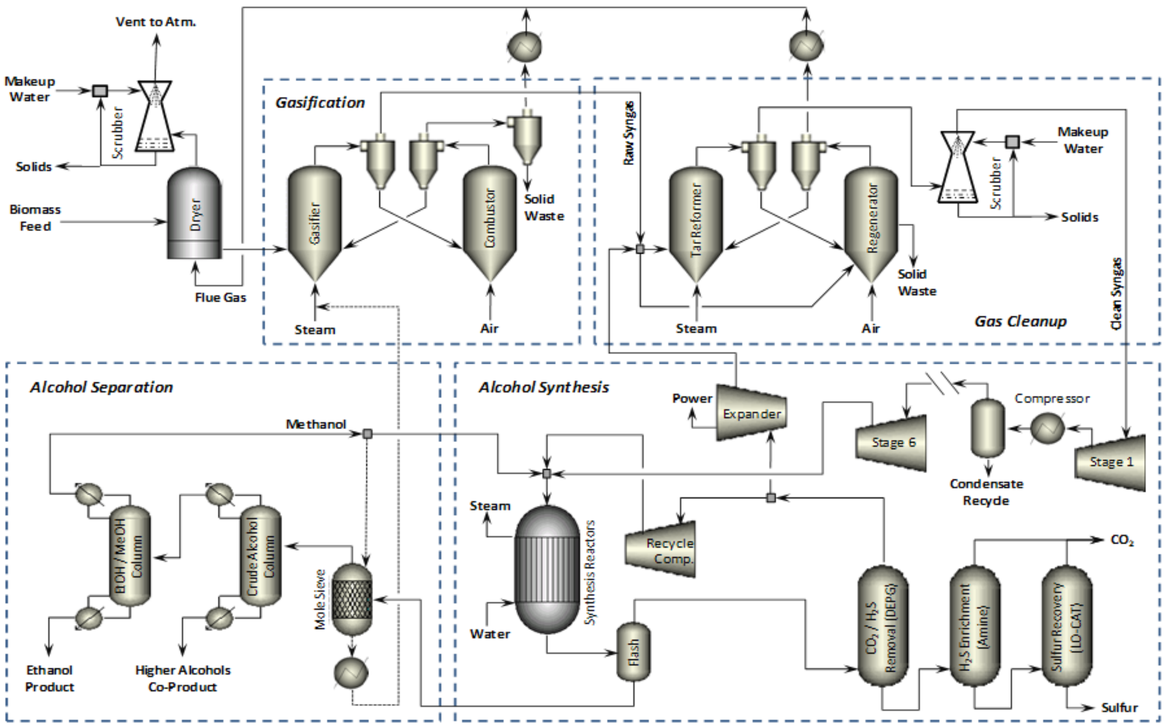

Fig. 1: Simplified process flow diagram for the thermochemical conversion process (reproduced with permission [6])

In addition to ethanol, the current thermochemical conversion pathway also produces higher alcohols as co-products. These co-products have similar properties and end uses as ethanol; they are priced at ~90% based on heating value, relative to EIA projected gasoline prices, for the calculation of minimum ethanol selling price [5]. Based on this premise, GHG emissions burdens are allocated among liquid output products (i.e., ethanol and higher alcohols) according to their energy output shares of the plant. This is accomplished by applying the direct energy allocation method [13]. Energy outputs are determined using the corresponding lower heating values.

The fuel distribution stage includes transportation of the product from the conversion facility to the pump. This step assumes trucking, rail, and barge shipping of the fuel, all of which entail fossil fuel consumption and GHG emissions. Only the E100 ethanol cases are considered in the present analysis. The ethanol fuel distribution assumptions, including the modes and respective proportions of fuel transportation and various intermediate stages between the biorefinery and the refuelling station, are based on the work by Hsu et al. [9]. Vehicle operation is the final stage of the LCA analysis. The type of vehicle used for evaluating the ethanol model pathways is the "flexible-fuel vehicle" (a passenger car) as defined in Argonne National Laboratory's GREET software [12]. The corresponding GHG emissions for the E100 ethanol flexible-fuel vehicle operation are obtained from GREET using a 2012 target year scenario. The fuel economy for E100 vehicles (year 2012) is 24 miles per gasoline gallon equivalent or 4,786 Btu/mile (3.14 MJ/km). The life cycle GHG (from well to wheels) emissions for the statutory 2005 baseline gasoline fuel defined in the Renewable Fuel Standard baseline are 98,204 g CO_{2e}/MMBtu (93 g CO_{2e}/MJ) [14].

3. Results and Discussion

The mixed alcohols yields (total fuel efficiency) are compared in Table 1. Lower ash and moisture contents lead to higher product yields, with moisture content exhibiting more negative impact on the yield than ash content. Field drying from 50% to 30% moisture content improves the total fuel efficiency by over 40 L per dry tonne. Additionally, reducing ash content from 7% to 1% also increases the yield by about 35 L per dry tonne. Table 1 also summarizes the sustainability metrics for the thermochemical conversion platform including GHG emissions, the net fossil energy consumption, consumptive water use, and carbon-to-fuel efficiency. The U.S. Geological Survey defines consumptive water use as “water that is evaporated, transpired, incorporated into products or crops, consumed by humans or livestock, or otherwise removed from an immediate water environment” [15]. Water consumption for the biorefinery plants is dominated by cooling water evaporative losses. On a liter-to-liter basis, the low ash/low moisture case exhibits the lowest consumptive water use (1.56 L/L) while the high ash/high moisture case exhibits the highest (1.84 L/L). The same impacts on the carbon-to-fuel efficiency are also found. The low ash/low moisture case achieves the highest carbon-to-fuel efficiency, 31.9%.

Table 1: Summary of sustainability metrics for the biorefinery (conversion stage)

	High Ash, High Moisture	High Ash, Low Moisture	Low Ash, High Moisture	Low Ash, Low Moisture
GHG emissions (kg CO_{2e}/GJ)	1.05	0.98	0.74	0.71
Consumptive water use (m^3/day)	1,174	1,217	1,198	1,247
Consumptive water use (L/L ethanol equivalent[1])	1.84	1.68	1.69	1.56
Total fuel efficiency (L ethanol equivalent[2]/dry metric tonne feedstock)	313	356	348	392
Carbon-to-fuel efficiency (C in ethanol equivalent[2]/C in biomass)	25.5%	29.0%	28.4%	31.9%
Net fossil energy consumption (MJ/MJ)	0.007	0.006	0.006	0.005
GHG reduction[3] (from 2005 gasoline baseline)	83.3%	85.7%	84.6%	86.6%

[1] including higher alcohols. Ethanol equivalent = Volume of Ethanol + Volume of Higher Alcohols * (HHVHigher Alcohols/HHVEthanol)

[2] including higher alcohols.

[3] "Well-to-wheels" life cycle GHG

Figure 2 presents the life cycle GHG emissions associated with the production of ethanol via the present thermochemical conversion pathway. GHG emissions for all cases are heavily dictated by feedstock production and logistics. Feedstock moisture content impacts not only the preprocessing step but also the feedstock transportation step. Feedstock with lower moisture content requires less energy for transportation. Thus, low moisture content cases have lower GHG emissions than the high moisture cases do. Additionally, compared to feedstock moisture content, feedstock ash content has a lower impact on GHG emissions associated with feedstock logistics. Direct biorefinery CO_2 emissions at the conversion stage (primarily resulting from char and fuel combustion) are biogenic CO_2 (i.e., CO_2 absorbed from the atmosphere and incorporated into biomass). With its biomass origin, biogenic CO_2 does not contribute to the increase of greenhouse gases in the atmosphere and is not considered in the IPCC global warming methodology [16].

4. Conclusions

In this work, we show that woody biomass feedstock moisture content and ash content exhibit significant impacts on the overall biofuel yield and GHG emissions. Field drying woody feedstock from 50 wt% to 30 wt% moisture content lowers the life cycle GHG emissions by more than 13%. The field drying effect is two-fold: (1) improving transportation efficiency with lower amounts of residual moisture, and (2) increasing conversion yield by lowering the heat required for drying. Reducing ash content in the feedstock preprocessing step improves the mixed alcohols product yield and this in turn decreases GHG emissions. Decreasing the ash content from 7 wt% to 1 wt% lowers the overall GHG emissions by about 7%.

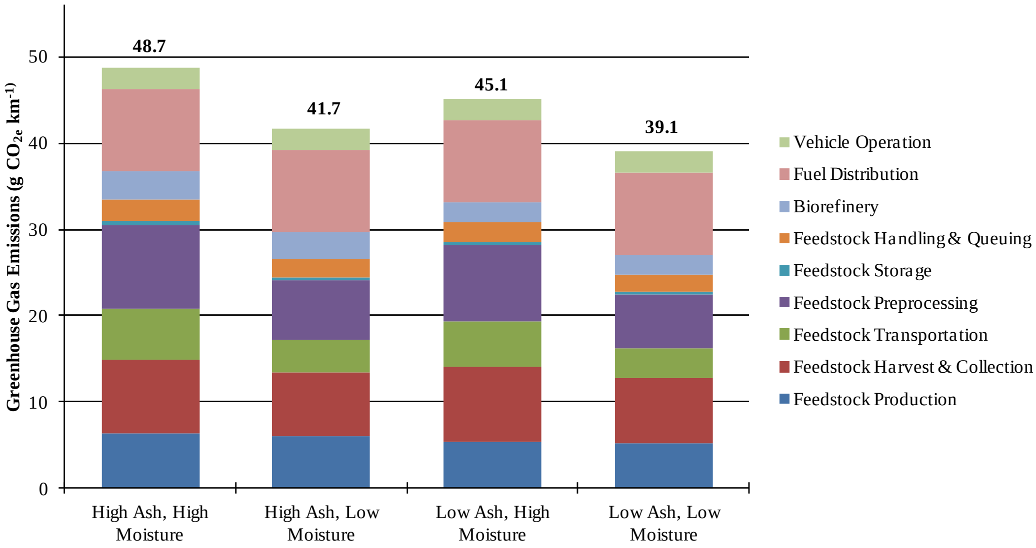

Fig. 2: “Well-to-wheels” life cycle greenhouse gas emissions comparison

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