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Lifecycle greenhouse gas footprint and minimum selling price of renewable diesel and jet fuel from fermentation and advanced fermentation production technologies

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Fermentation and advanced fermentation (AF) biofuel production technologies may offer a means to reduce the greenhouse gas (GHG) intensity of transportation by providing renewable drop-in alternatives to conventional middle distillate (MD) fuels, including diesel and jet fuel. To the best of our knowledge, this is the first peer-reviewed study of the environmental and economic feasibility of AF technologies. We find that the attributional lifecycle GHG footprint of AF MD from sugar cane, corn grain and switchgrass ranges from -27.0 to 19.7, 47.5 to 117.5, and 11.7 to 89.8 gCO_2e/MJ_{MD}, respectively, compared to 90.0 gCO_2e/MJ_{MD} for conventional MD. These results are most sensitive to the co-product allocation method used, the efficiency and utility requirements of feedstock-to-fuel conversion, and the co-generation technology employed. We also calculate the minimum selling price (MSP) of MD fuel produced from sugar cane, corn grain and switchgrass AF as a range from 0.61 to 2.63, 0.84 to 3.65, and 1.09 to 6.30 $/liter, respectively, compared to the current price of conventional MD in the United States of approximately 0.80 $/liter. The MSP results are most sensitive to feedstock-to-fuel conversion efficiency, feedstock costs, and capital costs. Finally, we demonstrate that emissions from land use change (LUC) directly attributable to the growth of biomass for AF fuel could dominate the GHG footprint of AF MD fuels.

1 Introduction

Transportation is an energy and greenhouse gas (GHG) intense activity, which predominately relies upon the use of fossil fuels. In 2011 the transportation sector accounted for approximately 109 exajoules, or 20%, of global primary energy consumption.[1] Furthermore, 13% of global GHG emissions were from the transportation sector in 2010.[2] In order to address the GHG footprint of transportation, and its dependence on fossil fuels, a number of jurisdictions have enacted policies that encourage the production and use of biofuels. For example, two such policies in the United States (US) are the Energy Independence and Security Act (EISA) of 2007, and the Renewable Fuels Standard 2 (RFS2) of 2010. Historically, ethanol and biodiesel have made up the vast majority of biofuel production: in 2012 92% and 7% of renewable fuel volumes reported under RFS2 were classified as ethanol and biodiesel, respectively.[3]

Diesel and jet, collectively referred to as middle distillate (MD) fuels, make up approximately 36% of global liquid fuel consumption,[4] and this demand is not likely to be offset by the production of ethanol and biodiesel. Blending of conventional MD fuel with ethanol results in higher vapor pressure and increased risk of fire or explosion,[5] and the use of biodiesel in aviation is limited by its poor thermal stability and high freezing point.[6] Therefore, renewable drop-in fuels or blendstock, chemically similar to petroleum-derived MD fuels, are of particular interest. Renewable drop-in diesel should be compatible with existing diesel trucks, automobiles, railroad locomotives and agricultural machinery, and renewable drop-in jet should be compatible with turbojet and turboprop aircraft engines.[6,7] Renewable drop-in MD fuel or blendstock, should also be compatible with existing fuel transportation and re-fuelling infrastructure. Furthermore, production of renewable drop-in MD fuels is expected to grow: the US Federal Aviation Administration (FAA) has a goal of 1 billion gallons of alternative fuel consumption by 2018,[8] and 21 of the 36 billion gallons of alternative fuel production mandated by RFS2 in 2022 could be renewable MD.[9]

One class of proposed technologies for the production of renewable MD fuels involves the microorganic metabolism, or fermentation, of biomass-derived sugars. Typically, polymer sugars are extracted from a biomass feedstock and decomposed to monomer sugars using mechanical, chemical or biological means. The monomer sugars are metabolized by a microorganism to produce energy carrying platform molecules, which are then chemically upgraded to a drop-in MD fuel or blendstock specification. This class of production technologies is referred to as fermentation and advanced fermentation (AF). AF production technologies make up a subset of techniques for the valorization of biomass resources, specifically those defined as submerged fermentation (SmF) and anaerobic fermentation (AnF) by ElMekawy et al.[10,11] A number of private corporations are in varied stages of commercialization of technologies that could be categorized as AF, such as LS9, Inc., Solazyme, Inc., Amyris, Inc., Byogy Renewables, Inc., and Gevo, Inc. Despite commercial interest in AF technologies, the environmental and economic feasibility of AF MD fuels have not been comprehensively addressed in the peer-reviewed literature.

In this analysis we present a calculation of the lifecycle GHG footprint and minimum selling price (MSP) of AF MD fuels. AF MD fuels have not yet been produced at industrial scale because significant technical challenges remain to be resolved. These include: variable feedstock composition and quality; the recalcitrance of lignocellulosic biomass; and the efficiency and costs of sugar extraction, hydrolysis and fermentation processes.[10,12] As a result of these remaining challenges, it is not yet known empirically how these technologies will develop and perform commercially. In order to capture the spectrum of potential outcomes, we consider a wide range of feedstock-to-fuel conversion technology parameters. Sugar cane, corn grain and switchgrass feedstocks, as well as a number of feedstock-to-fuel conversion pathways, are examined to estimate the mass and energy balances associated with production of AF MD fuels. The results are used in conjunction with the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model, developed by Argonne National Laboratory, to estimate the attributional GHG footprint of the fuels produced.[13,14] In addition, we use the calculated mass and energy balances for AF MD fuel production, together with petroleum industry heuristics and empirical biofuel industry data, in a discounted cash flow rate of return (DCFROR) model to calculate the MSP of AF MD fuels. Sensitivity analysis is carried out on the GHG footprint and MSP results in order to quantify the importance of critical engineering parameters. The goal of this analysis is to evaluate the potential of AF MD fuels to reduce the GHG footprint of transportation, and to evaluate their economic viability.

2 Methods and Materials

2.1 Lifecycle GHG footprint methodology

The methodological challenges associated with the calculation of the lifecycle GHG footprint of renewable fuels are addressed extensively in the literature. For example, Limayem & Ricke[12] and Singh *et al.*[15,16] identify the major issues as functional unit definition, system boundary definition, spatial and temporal variability, data availability and quality, and co-product allocation.

We employ a lifecycle GHG analysis framework consistent with Stratton *et al.*,[17] which uses a functional unit of gCO_2e/MJ_{MD} and a system boundary including: biomass feedstock cultivation, recovery and transportation; feedstock-to-fuel conversion; transportation and distribution of finished MD; and MD fuel combustion. Low, baseline and high lifecycle GHG scenarios are defined in order to capture spatial, temporal and data quality variability. This is achieved by identifying key parameters affecting lifecycle GHG footprint, and then combining a survey of the academic and technical literature with the engineering judgement of the authors. In particular we consider a broad range of feedstock-to-fuel conversion AF technologies. The assumptions that result in the low, baseline and high attributional lifecycle GHG results are summarized in Table 1, and we discuss these assumptions in detail in the following sections.

The calculated mass and energy balances are integrated into the GREET model (.NET v1.0.0.8377). In order to allocate emissions among fuel and non-fuel co-products, we use market-based allocation: at the point where the fuel-destined product stream is physically separated from the non-fuel stream, emissions are allocated amongst the process streams in proportion to their relative market values.[18,19] We also explore the sensitivity of results to the emissions accounting method by calculating selected results using the displacement, or system expansion, method.[20] This is done because although the issue has been discussed extensively, the appropriate choice of allocation method remains largely unresolved in the literature.[21,22] Emissions are further allocated amongst all finished fuel products according to their relative energy contents.[18]

2.1.1 Sugar cane feedstock pretreatment

In order to extract sucrose from raw sugar cane, the feedstock is cleaned, chopped, shredded and crushed, and the resulting juice is concentrated and sterilized. The mass and energy balances of these processes are calculated based on Lobo *et al.*,[23] which compares conventional and optimized milling technologies, and Dias *et al*.[24] The lower heating value (LHV) of the bagasse remaining after juice extraction (7.54 MJ/kg, 50% moisture content) is taken from Ensinas *et al*.[25] We consider incineration and gasification technologies for the co-generation of heat and power to meet the utility requirements of the biorefinery, using LHV-to-process heat and electricity conversion efficiencies estimated from Murphy & McKeogh.[26]

2.1.2 Corn grain feedstock pretreatment

Starch is typically extracted from corn grain using the dry mill process (approximately 80% of corn ethanol plants in the US use dry milling, as opposed to wet milling[27]), during which corn kernels are fed to electric-powered hammermills that grind corn into a flour. The corn flour is liquefied by slurrying with process water and is exposed to high pressure steam to break down starches and kill bacteria. The starch extraction efficiency, utility requirements, and co-production of distiller dry grains and solubles (DDGS) from the corn grain milling and liquefaction processes are estimated from Wang *et al.*,[28] Mei,[29] Shapouri *et al.*,[30] Mueller,[31] Kwiatkowski *et al.*,[32] and Phillips *et al.*[33]

2.1.3 Switchgrass feedstock pretreatment

Finally, a number of emerging biological, thermal and chemical pretreatment technologies to extract polymeric sugars from lignocellulosic biomass are considered, including dilute acid, ammonia fiber explosion (AFEX), aqueous ammonia, hot water, dilute alkali and steam explosion. The achievable yields of cellulose and hemicellulose from switchgrass were estimated from Kumar & Murthy,[34] Tao *et al.*,[35] and Wyman *et al.*,[36] and utility requirements were estimated from Aden *et al.*,[37] Humbird *et al.*,[38] and Kumar & Murthy.[34] We assume that the biomass remaining after sugar extraction and fermentation is co-fired to meet the utility requirements of the biorefinery, with a LHV of 10.50 MJ/kg (50% moisture content).[26,39,40]

2.1.4 Simultaneous saccharification and fermentation

Following extraction from sugar cane, corn grain and switchgrass, respectively, sugars in the form of sucrose, starch and 5-carbon and 6-carbon sugar oligomers must be broken down to monomeric sugars via the process of saccharification. We assume that conversion of sugars to glucose and fructose (from sucrose, starch and 6-carbon oligomers), and xylose (from 5-carbon oligomers) is achieved via enzymatic hydrolysis, with efficiencies approaching the theoretical maximum.

Conversion of glucose, fructose and xylose to drop-in MD fuel is possible via a number of fermentation technologies, and we consider metabolism to five distinct platform molecules: triacylglycerides (TAGs), fatty acids, alkanes, isobutanol (iBuOH) and ethanol (EtOH). The microorganism used for metabolism defines both the species of platform molecule and the mass conversion efficiency of monomeric sugar to that molecule. We assume a range of monomer sugar-to-platform molecule mass conversion efficiencies, as a percentage of theoretical maximum. The theoretical maximum mass conversion efficiencies of monomer sugars to TAGs, fatty acids and alkanes are estimated to be 31%, 42% and 34%, respectively.[41-43] The theoretical maximum mass conversion efficiencies of monomer sugars to isobutanol and ethanol are derived from the stoichiometry to be 41% and 51%, respectively, assuming the products of metabolism are alcohols, carbon dioxide and water. A review of the metabolic conversion of monomer sugars to these and other platform molecules in is given by Dugar & Stephanopoulos.[44]

This analysis assumes simultaneous saccharification and fermentation, meaning that enzymatic hydrolysis and microorganic metabolism occur simultaneously in the same bio-reactor. The utility requirements of pumping and continuous aeration and agitation during these process operations are calculated from Najafpour[45] and Couper *et al.*,[46] under an assumption of a batch fed bio-reactor with a total residence time of 96 hours.

2.1.5 Platform molecule extraction & purification

Upon completion of the saccharification and fermentation processes, the target platform molecule species must be

Table 1: Scenario definition for low, baseline and high lifecycle GHG footprint calculations

Pathway	Case	Pretreatment	Saccharification efficiency (% of theoretical max. from polymer to monomer sugar)	Target platform molecule, theoretical max. mass conversion efficiency of sugars to platform molecules	Metabolic efficiency (% of theoretical max.)	Extraction /purification technology	Upgrading to drop-in fuel	Excess biomass co-generation technology
Sugar cane AF	Low	State-of-the-art milling [23, 24]	100%	EtOH, 51% (from stoich.) [44]	90% C6 sugars	Distillation [29, 50]	Dehydration, oligomerization and hydroprocessing [53]	Gasification [26] η_{elec}=27% , η_{heat}=24%
	Base	Conventional milling [23, 24]	97.50%	Fatty acids, 34% [43, 44]	85% C6 sugars	Centrifugation [47]	66% of hydroprocessing requirements [51]	Incineration [26] η_{elec}=15% , η_{heat}=43%
	High	Conventional milling [23, 24]	95%	TAG, 31% [41]	80% C6 sugars	Hexane [48]	100% of hydroprocessing requirements [51]	Incineration [26] η_{elec}=15% , η_{heat}=43%
Corn grain AF	Low	Dry milling [28, 29, 31]	100%	Alkanes, 34% [43, 44]	90% C6 sugars	KOH steam extraction and centrifugation [49]	33% of hydroprocessing requirements [51]	n/a
	Base	Dry milling [29, 32]	97.50%	Fatty acids, 34% [43, 44]	85% C6 sugars	Centrifugation [47]	66% of hydroprocessing requirements [51]	
	High	Dry milling [29, 30, 33]	95%	iBuOH, 41% (from stoich.) [44]	80% C6 sugars	Distillation [29, 50]	Dehydration, oligomerization and hydroprocessing [54]	
Switchgrass AF	Low	Dilute acid [36]	n/a (Saccharification efficiency is included in pretreatment references, in the form of raw feedstock to sugar monomers)	EtOH, 51% (from stoich.) [44]	90% C6 sugars 70% C5 sugars	Distillation [29, 50]	Dehydration, oligomerization and hydroprocessing [53]	Gasification [26] η_{elec}=27% , η_{heat}=24%
	Base	Dilute alkali [34]		Fatty acids, 34% [43, 44]	85% C6 sugars 60% C5 sugars	Centrifugation [47]	66% of hydroprocessing requirements [51]	Incineration [26] η_{elec}=15% , η_{heat}=43%
	High	Aq. ammonia [35]		iBuOH, 41% (from stoich.) [44]	80% C6 sugars 50% C5 sugars	Distillation [29, 50]	Dehydration, oligomerization and hydroprocessing [54]	Incineration [26] η_{elec}=15% , η_{heat}=43%

separated and purified from the fermentation beer. We consider three technologies for the separation and purification of TAGs, fatty acids and alkanes. Centrifugation may be employed to take advantage of the difference in the density of the platform molecule and the other components of the fermentation beer, and the utility requirements for the operation of centrifugal pumps are estimated from Vasudevan *et al*.[47] The utility requirements of hexane solvent extraction, which is used for extraction of vegetable oils from seed feedstocks in the production of biodiesel, are estimated based on data from Sheehan *et al*.[48] Potassium hydroxide (KOH) steam lysing, followed by centrifugation, may be required if the platform molecule is not directly secreted, but is produced intra-cellularly. The utility requirements for KOH steam lysing and centrifugation are estimated from Vaswani.[49] We assume that ethanol and isobutanol separation and purification is achieved via distillation, taking advantage of the lower boiling point of alcohols compared to the other components of the fermentation beer. The utility requirements of distillation are estimated from Mei and ethanol industry data.[29,50]

2.1.6 Upgrading to drop-in fuel

Finally, the separated and purified platform molecules are upgraded to a drop-in MD fuel product slate. For TAGs, fatty acids and alkanes, the mass conversion efficiency and utility requirements of upgrading platform molecules to MD fuel are based on the hydro-processed esters and fatty acids (HEFA) process from Pearlson *et al*.[51] The authors describe three steps by which soybean oil (composed primarily of TAGs) is upgraded to drop-in MD fuel: de-propenation to cleave the glycerine backbone from the TAG molecule; de-oxygentation to remove oxygen and saturate double bonds; and isomerization and catalytic cracking to refine straight chain alkanes to the desired carbon chain length distribution. We assume that the TAG product of microorganic metabolism has a chemical composition similar to soybean oil (primarily carbon chain lengths of C18),[52] and that the HEFA process described in Pearlson *et al.* is an appropriate estimate of the upgrading required. Furthermore, because fatty acids do not contain a glycerine backbone, and alkanes do not contain a glycerine backbone, oxygen or double bonds, we assume that the utility requirements for upgrading of those platform molecules are approximately 66% and 33% of the Pearlson *et al.* HEFA process, respectively. We note that microorganic metabolism resulting in a carbon chain length distribution closer to MD fuel (for example, via algae or cyanobacteria synthesis to C10-C14)[52] could increase fuel yield and reduce the upgrading effort required.

In order to upgrade ethanol and isobutanol platform molecules to drop-in MD, we assume that three unit processes are required: dehydration to remove the hydroxyl functional group; oligomerization to produce longer chain alkanes; and hydroprocessing to the desired carbon chain length distribution. The mass conversion efficiencies and utility requirements of these processes are estimated based on a range of estimates from industry experts.[53,54]

2.2 Minimum selling price (MSP) calculation

We calculate the MSP of MD fuels produced using AF technology by adapting the DCFROR model from Pearlson *et al*.[51] The baseline facility size is 4000 barrels per day, and we assume the 20-year plant is built using 20% equity financing and a 10-year loan with 5.5% interest. MSP is calculated assuming an internal rate of return of 15%, income taxes of 40% and 2% inflation per year. The DCFROR model is solved under these assumptions to find the MSP of all fuel products such that the AF facility has a net present value (NPV) of zero. All prices are expressed in 2012 USD.

2.2.1 Capital cost estimation

Ethanol facility capital costs from the literature are normalized to a dollars-per-unit-mass-feedstock-processed basis, in order to estimate pre-processing and fermenter capital costs for AF facilities. For sugar cane AF, a range of \$20 to \$30 per kilogram of raw sugar cane milling and fermenter capacity is calculated from APEC[55] and Goldemberg,[56] respectively. A range of \$55 to \$95 per kilogram of corn grain dry milling and fermenter capacity is estimated from Urbanchuk[57] and Wallace *et al.*,[58] respectively, for corn grain AF. Finally, for switchgrass AF, a range of \$115 to \$215 per kilogram of switchgrass pretreatment and fermenter capacity is estimated from Bain[59] and Wallace *et al*.[58]

The additional capital costs for upgrading of TAGs, fatty acids or alkanes to drop-in MD are calculated from equipment cost estimates by Pearlson *et al*.[51] The additional capital costs of the dehydration, oligomerization and hydroprocessing equipment, required to upgrade isobutanol and ethanol to drop-in MD, is estimated from interviews with industry experts.[53,54]

2.2.2 Operating cost and commodity price estimation

Fixed operating costs, including insurance, local taxes, maintenance, miscellaneous material and labor are estimated as a function of capital cost using heuristics from the petroleum refining industry from Handwerk & Gary.[60]

Variable operating costs are based on utility, processing chemical and feedstock prices. Low, baseline and high natural gas prices are estimated using a 5-year average from 2008 to 2012, ± 2 standard deviations, as \$1.20, \$5.84 and \$10.49 per GJ, from EIA historical data.[61] We assume electric power and water prices are \$0.07 per kWh and \$0.09 per m^3, respectively. Enzyme, yeast and processing chemical costs are estimated for sugar cane,[62] corn grain[62] and switchgrass[33] on a per kilogram feedstock basis. Sugar cane prices are based on a 5-year average of historic sugar commodity prices ± 2 standard deviations,[63] and an assumed yield of 1 kg of sugar from 10 kg of raw sugar cane,[64] as \$20.74, \$45.67 and \$70.59 per tonne of sugar cane. Corn grain prices are estimated using a 5-year average of historic commodity prices, ± 2 standard deviations,[65]

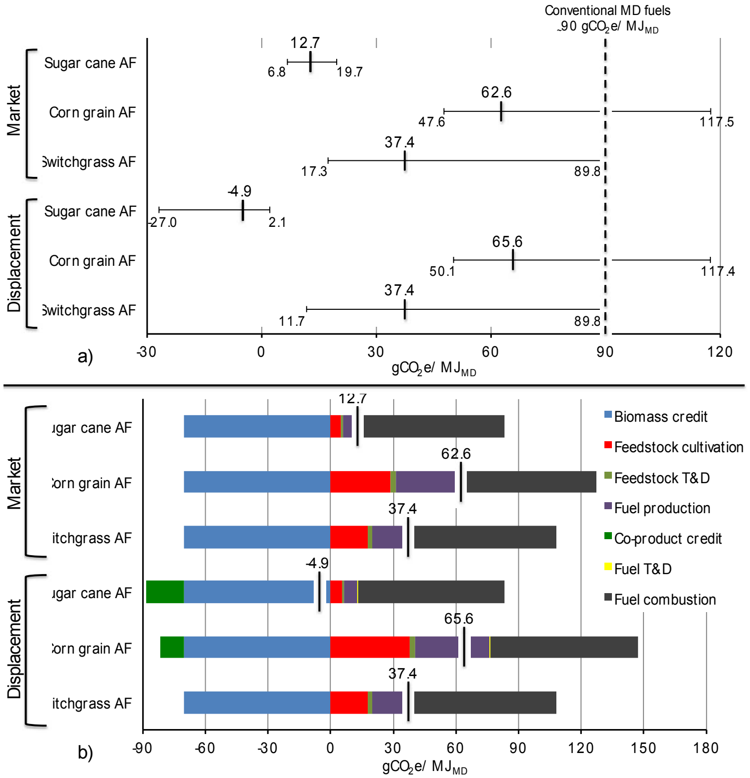

Figure 1: a) Range of lifecycle GHG footprint results under market based allocation and displacement methodologies for non-fuel co-products, and b) baseline lifecycle GHG footprint broken out by lifecycle step under market based allocation and displacement methodologies for non-fuel co-products.

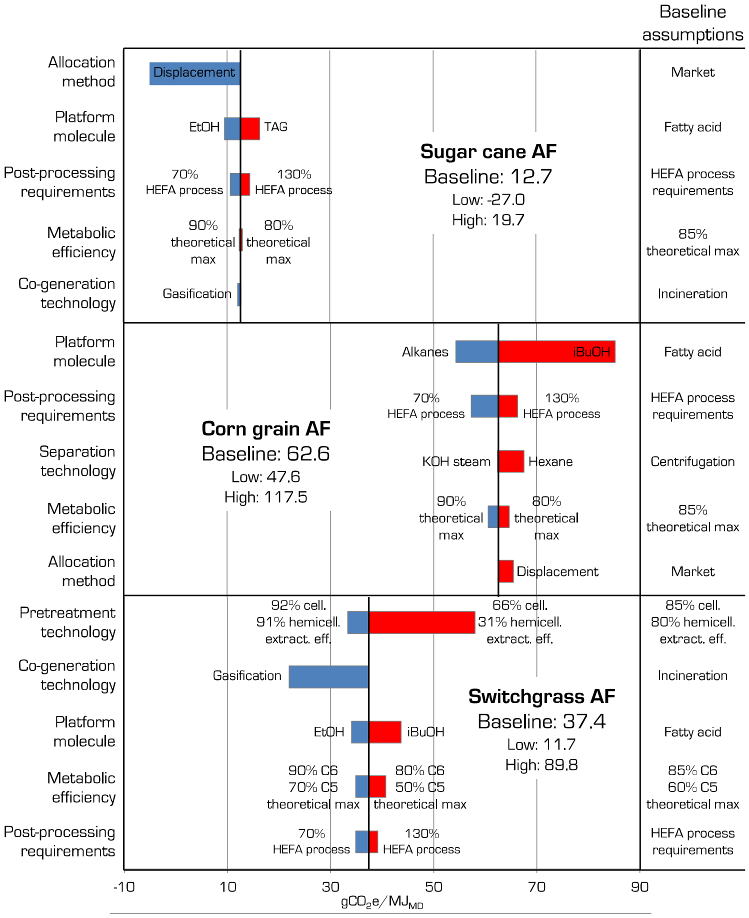

Figure 2: Lifecycle GHG footprint sensitivity analysis. The five parameters contributing to the greatest variability are shown for each pathway.

as \$3.16, \$6.17 and \$9.18 per bushel. Switchgrass prices, based on \$50 per short ton[66] ±50% to mirror variation in the other feedstock types, are estimated as \$28.67, \$57.33 and \$86.00 per tonne. Finally, the relative values of the fuel products are estimated from 5-year averages of spot prices.[67] Gasoline prices are used as a surrogate for naphtha. We note that this is a simplifying assumption, and that naphtha can be directly blended with gasoline only in limited volumes due to its low octane.

3. Results and discussion

3.1 Lifecycle GHG footprint

The range of results for the lifecycle GHG footprint of sugar cane, corn grain and switchgrass AF MD is shown in Figure 1a, broken out by two different methods of dealing with co-products of the AF fuel production process: market based allocation and displacement. Figure 1a demonstrates that, although these renewable MD production pathways have the potential to reduce attributional lifecycle GHG emissions from the conventional MD baseline of 90 gCO_2e/MJ_{MD} (low and high estimates of 82.8 and 112.5 gCO_2e/MJ_{MD}, respectively),[17] there is significant variability in the calculated results. Variability in AF technology performance, which affects the feedstock-to-fuel conversion efficiency and utility requirements, and the co-product allocation methodology employed, contribute to a range of results between -27.0 and 19.7, 47.5 and 117.5, and 11.7 and 89.8 gCO_2e/MJ_{MD} for sugar cane, corn grain and switchgrass AF, respectively.

Figure 1b shows baseline results for each pathway and emissions accounting method, disaggregated by the feedstock cultivation, feedstock transportation, fuel production, and fuel transportation and distribution steps. Off-setting fuel combustion emissions and biomass credits are displayed, as well as co-product credits in the case of the displacement method. Figure 1b shows that compared to feedstock and fuel transportation and distribution, the feedstock cultivation and fuel production steps are the major contributors to overall lifecycle GHG footprint. The difference in feedstock cultivation emissions between the pathways is largely due to N_2O emissions from fertilizer application. For example, using market based allocation, 1.3, 15.5 and 9.8 gCO_2e/MJ_{MD} are attributable to fertilizer application for sugar cane, corn grain and switchgrass AF feedstock cultivation, respectively. We note that our analysis assumes the default N_2O emissions factors associated with sugar cane, corn grain and switchgrass cultivation from GREET.

In contrast, the difference in fuel production emissions between pathways is largely due to utility requirements. For example, no external utilities are required for sugar cane AF fuel production, whereas 0.020 kWh_{elec} and 0.27 MJ_{NG}, and 0.018 kWh_{elec} are required per MJ of corn grain and switchgrass AF fuel production, respectively. (Note that these values do not include hydrogen requirements for hydroprocessing, although

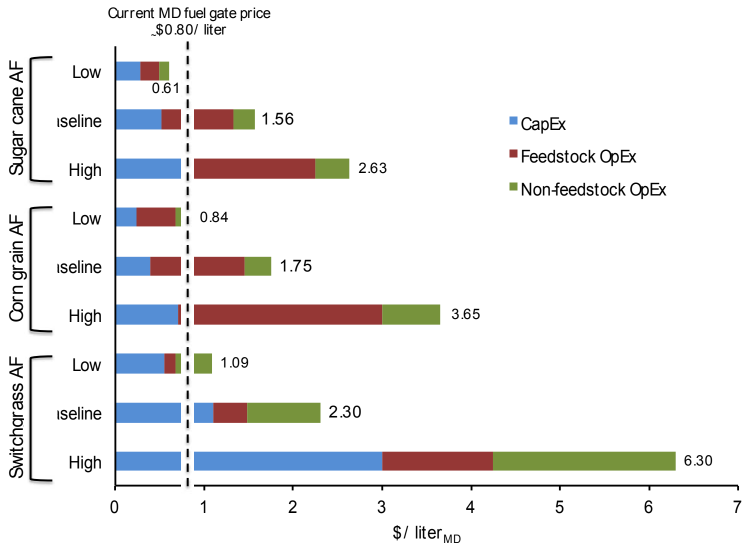

Figure 3: Low, baseline and high MSP of sugar cane, corn grain and switchgrass AF, broken out by capital cost (CapEx), feedstock operating costs (feedstock OpEx), and non-feedstock operating costs (non-feedstock OpEx).

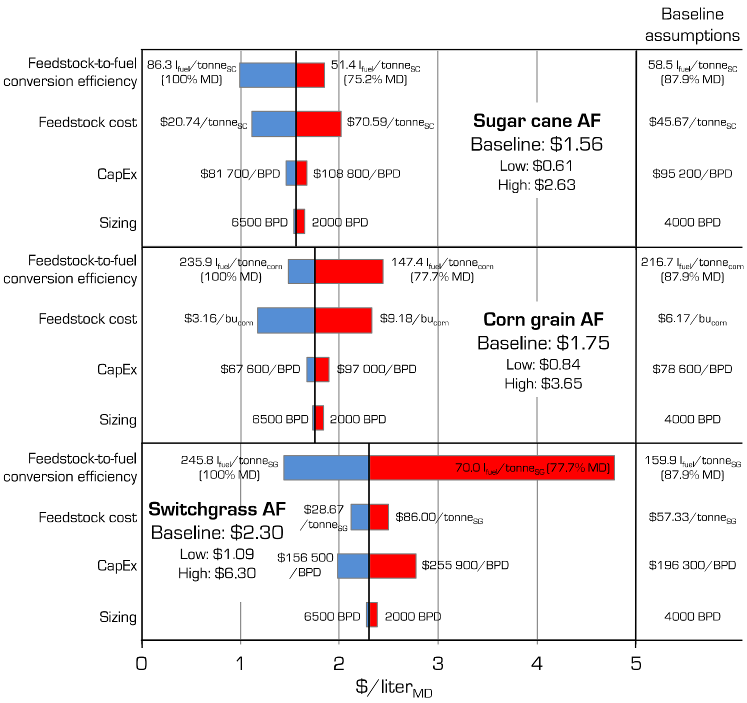

Figure 4: MSP sensitivity analysis. Variability due to feedstock-to-fuel conversion efficiency, feedstock cost, capital costs and facility size is shown for each pathway.

hydrogen requirements are included in the final GHG results.) The difference in utility requirements between pathways is due to the co-generation of heat and power from excess biomass in the sugar cane and switchgrass AF pathways. Sugar cane bagasse provides enough fuel for co-generation, such that the process heat and power requirements of sugar cane AF fuel production are satisfied and 0.029 kWh$_{elec}$ is exported to the grid per MJ$_{MD}$. Similarly, combustion of lignin and other biomass residues from switchgrass provides heat and power for fuel production, however additional external electricity must be imported.

In order to further understand the drivers of variability within the pathways shown in Figure 1, we perform a sensitivity analysis. Figure 2 shows the five parameters for each pathway that yield the largest change in results when varied in isolation. For sugar cane AF, use of the displacement method instead of market based allocation results in a negative lifecycle GHG footprint because the excess electricity exported to the grid generates a carbon credit. We assume the grid average carbon intensity of transported US electricity from GREET, of 670.0 gCO$_2$e/kWh. The corn grain AF results are more sensitive to the type of platform molecule that is a product of fermentation than the other pathways considered. As explained above, this is because all of the utilities required for corn grain AF fuel production must be imported from the grid, while utility requirements are at least partially offset by heat and power co-generation in the other pathways, and the overall feedstock-to-fuel conversion efficiency of MD fuel production via isobutanol is lower than via fatty acids. The feedstock requirements for corn grain AF via isobutanol are 12% larger than via a fatty acid platform molecule. The switchgrass AF pathway is most sensitive to the efficiency of monomer 5-carbon and 6-carbon sugar extraction from switchgrass. This is a reflection of the large range of values that we explore for this parameter, because the efficiency of monomer sugar yield from lignocellulosic feedstocks has not yet been proven at commercial scale. In addition, assuming gasifier technology for excess biomass combustion reduces the lifecycle GHG footprint of switchgrass AF because the increased efficiency of electricity generation is enough to shift switchgrass AF fuel production from an electricity importing, to an electricity exporting process. Further lifecycle GHG footprint results data are provided in the Supplementary Information (SI).

3.2 Land use change emissions

We also explore the possibility of land use change (LUC) emissions associated with the production of AF MD fuel. Direct LUC occurs when land is converted from its original use to cultivation of biomass feedstock, causing a step change in the carbon stock of the land. Indirect LUC occurs when biomass feedstock cultivation induces LUC in some other region of the world. We do not attempt to quantify the emissions associated with indirect LUC in this analysis, and refer the interested reader to the extensive peer-reviewed literature on the subject, including Searchinger *et al.*,[68] Plevin *et al.*[69] and Lapola *et al.*[70]

We calculated the direct LUC emissions from previously uncultivated land using the carbon debt scenarios described in Fargione *et al.*[71] We estimate biomass yields for sugar cane and corn grain from NASS[72] and switchgrass from Wullschleger *et al.*[73] The low, baseline and high results are 20.2, 35.4 and 46.7, 38.4, 51.2 and 100.7, and 1.3, 2.9 and 12.2 gCO$_2$/MJ$_{fuel}$ for sugar cane, corn grain and switchgrass AF, respectively. These values are calculated based on the assumption that direct LUC emissions are amortized evenly over a 30 year period.[17] The results indicate that direct LUC emissions could significantly increase the lifecycle GHG footprint of AF MD. For example, the baseline lifecycle GHG footprints of sugar cane, corn grain and switchgrass AF increase from 12.7 to 48.1, 62.6 to 113.8, and 37.4 to 40.3 $gCO2e/MJ_{MD}$, respectively, when direct LUC is included. Direct LUC emissions calculations are provided in the SI. We note that these emissions are highly dependent upon the specific scenario in which the feedstock is grown, and should be evaluated as such.

3.3 MSP

The MSP results for production of AF MD are shown in Figure 3, broken out by capital, feedstock and non-feedstock production cost contribution to the MSP of AF MD fuel. Low, baseline and high results range from 0.61 to 2.63, 0.84 to 3.65, and 1.09 to 6.30 $\$/liter_{MD}$ for sugar cane, corn grain and switchgrass AF, respectively. Only the MSP for the low scenario for sugar cane AF is below the approximate current US price of 0.80 $\$/liter_{MD}$.[74] (We note that there is substantial uncertainty around the price of conventional MD fuels, even in the short term. For example, the US EIA projects that the price of jet fuel will be between 0.51 and 1.42 \$/liter in 2015.) Figure 3 demonstrates that there is significant variability in the MSP of each for the AF fuel pathways, and that feedstock costs are the greatest contributor to variability in the MSP of sugar cane and corn grain AF. In contrast, capital costs are the largest contributor to variability in the MSP of switchgrass AF.

In order to explore the drivers of variability within AF pathways, we conduct a sensitivity analysis of MSP to feedstock-to-fuel conversion efficiency, feedstock costs, capital costs and facility size. The results are shown in Figure 4, and are consistent with the observation from Figure 3 that feedstock costs are the largest contributor to variability for sugar cane and corn grain AF MSP, and capital costs are the largest contributor to variability for switchgrass AF MSP. MSP results are also sensitive to feedstock-to-fuel conversion efficiency, particularly in the case of switchgrass AF. Similar to the lifecycle GHG results, this sensitivity is due to our consideration of a large range of switchgrass AF conversion efficiencies, because lignocellulosic pretreatment and co-fermentation of glucose, fructose and xylose have not yet been proven at the commercial scale. The wide range of parameters considered is intended to capture variability in the way in which AF fuel production technology will be implemented at commercial scale. Further MSP results data are provided in the SI.

4. Conclusions

In this paper, we present the first peer-reviewed environmental and economic feasibility study of AF technologies for producing renewable drop-in MD fuels. Our results show that, although their lifecycle GHG footprints are highly variable, AF MD production technologies offer the potential for improvement from conventional MD fuels. Under baseline assumptions sugar cane, corn grain and switchgrass AF provide attributional lifecycle GHG footprint reductions of 86%, 30% and 58% from conventional MD, respectively. Furthermore, lifecycle GHG footprint can be minimized by feedstock and technology selection. For example, sugar cane and switchgrass AF have relatively lower lifecycle GHG footprints than corn grain AF. For both sugar cane and switchgrass AF, lifecycle GHG footprint may be further reduced via the co-generation of process heat and power from excess biomass, the benefit of which is amplified by using more efficient technologies, such as gasification instead of incineration. Lifecycle GHG footprint may also be reduced for all of the pathways by increasing overall feedstock-to-fuel conversion efficiency. This can be achieved by increasing monomer sugar yields from the feedstock, and by increasing the efficiency of microorganic metabolism of sugars to the platform molecule.

We also demonstrate that LUC emissions are a key determinant of the lifecycle GHG footprint of AF technologies, however these results are highly dependent upon the situation in which the feedstock is cultivated. For example, if AF MD feedstock is grown on land that had not previously been cultivated, we find that inclusion of direct LUC emissions could increase the lifecycle GHG footprint of sugar cane, corn grain and switchgrass AF by 279%, 82% and 8%, respectively, under baseline assumptions. Conversely, if the feedstock is grown on land that was already being used for cultivation of that crop, there are no direct LUC emissions attributable to the fuel produced. Therefore, direct LUC emissions should be evaluated specific to the situation in which the feedstock is being produced. Indirect LUC emissions, which are generally evaluated in the context of larger-scale biofuel production goals or policies, are beyond the scope of this analysis.

The authors note that a holistic evaluation of the environmental feasibility of AF production technologies should include additional environmental criteria such as: water footprint and water availability for feedstock and biofuel production;[75],[12] the impacts of feedstock cultivation on soil nutrient removal and contaminated water runoff;[76] and non-GHG climate impacts.[77]

Similar to lifecycle GHG footprint, the MSP of AF MD fuels are highly variable. Our results show that the MSP of the AF MD production pathways considered are most sensitive to overall feedstock-to-fuel conversion efficiency, feedstock costs, and capital costs. One interesting opportunity for reducing the capital costs of AF MD fuels is to retrofit existing ethanol production facilities, instead of constructing new greenfield facilities. For example, if feedstock pre-processing and fermenter capital costs could be reduced by 50% by retro-fitting existing facilities, the baseline MSP for sugar cane, corn grain and switchgrass AF would go down to 1.30, 1.55 and 1.64 $\$/liter_{MD}$, respectively. As mentioned above, feedstock-to-fuel conversion efficiency can be improved by increasing sugar extraction and metabolic yields. These areas of improvement are especially intriguing because if feedstock-to-fuel conversion efficiency is maximized, both lifecycle GHG footprint and MSP would be reduced.

In addition to the technical and commodity price aspects captured in our sensitivity analysis, we note that the feasibility of AF technologies are subject to the prevailing economic and policy conditions. This is particularly relevant because the economic viability of AF MD fuels is evaluated with respect to conventional petroleum-derived MD fuel prices: if crude oil prices rise AF MD fuels will be more economically attractive, and if they fall AF MD fuels will struggle to compete. This means that the economic viability of AF MD fuels could be affected by the price volatility of conventional fossil fuels.

Further, policy mechanisms could determine the economic feasibility of AF MD technologies. For example, under US RFS2, advanced biofuel producers generate renewable identification numbers (RINs) that would be worth approximately 0.27 \$/liter$_{MD}$.[78] This type of policy could provide enough incentive to make AF MD fuels economically viable. Alternatively, a carbon tax or cap-and-trade policy could positively affect AF MD fuels' economic viability, given their potential for reduction in the lifecycle GHG footprint from conventional MD fuels. Because of these factors, we note that the economic viability of AF MD fuels should be considered with a regard to the relevant economic and policy conditions.

This analysis demonstrates that AF MD fuels have the potential for environmental and economic feasibility given appropriate technology selection and implementation. We note, however, that our findings hinge upon the successful technical and commercial development of these technologies, and that a number of challenges remain. Generally, these challenges originate from variability in feedstock composition and quality, and the general recalcitrance of lignocellulosic materials. Specific technical challenges include: sugar extraction and hydrolysis efficiency; enzyme separation and re-use; feedstock pre-processing costs; fermentation efficiencies, especially of 5-carbon sugars; and facility integration.[10,12,76] This analysis quantifies the impact of these aspects on environmental and economic feasibility through sensitivity analysis, and indicates that addressing these challenges will be critical to facilitating the commercial development of AF MD fuels.

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