Project 001(B) Alternative Jet Fuel Supply Chain Analysis

Massachusetts Institute of Technology

Project Lead Investigators

Steven Barrett
Associate Professor
Department of Aeronautics and Astronautics
Massachusetts Institute of Technology
77 Massachusetts Avenue, 33-322, Cambridge, MA 02139
+1 (617) 452-2550
sbarrett@mit.edu

Robert Malina
Research Scientist
Associate Director, Laboratory for Aviation and the Environment
Massachusetts Institute of Technology
77 Massachusetts Avenue, 33-322, Cambridge, MA 02139
+1 (617) 253-1516
rmalina@mit.edu

University Participants

Massachusetts Institute of Technology

- P.I.(s): Professor Steven Barrett, Professor Robert Malina
- FAA Award Number: 13-C-AJFE-MIT, Amendment Nos. 003, 012, and 016
- Period of performance: August. 1,2014 to August. 31, 2016 (reporting here with the exception of FAA funding and cost share for August 1, 2014 to August 31, 2015)
- Tasks:
    - Task 1: Calculate screening-level lifecycle GHG emissions for additional feedstock to fuel pathways and quantify differences in lifecycle GHG emissions calculations in different regulatory frameworks for (aviation) biofuels
    - Task 2: Develop ranges for GHG reductions per unit of aviation biofuel use
    - Task 3: Estimate future bioenergy energy / aviation biofuel potential
    - Task 4: Support FAA in their decision-making for ICAO CAEP AFTF
    - Task 5: Work with Purdue University on the development and application of stochastic techno-economic models for aviation biofuel pathways
    - Task 6: Develop proposal for methodology for calculation of CO2 emissions
    - Task 7: Calculate lifecycle CO2 emissions

Project Funding Level

$735,000 FAA funding and $735,000 matching funds. Sources of match are approximately $147,000 from MIT, plus 3rd party in-kind contributions of $326,000 from Byogy Renewables, Inc and $262,000 from Oliver Wyman Group.

Investigation Team

Principal Investigator: Prof. Steven Barrett (MIT)
Co-Principal Investigator: Dr. Robert Malina (MIT)
Co-Investigator: Dr. Raymond Speth (MIT), Task 1
Postdoctoral Associate: Dr. Pooya Azadi (alternative jet fuels life cycle analysis), Task 1

Graduate Students: Pooja Suresh (alternative jet fuels life cycle analysis and AFTF), Tasks 1-7, Mark Staples (supporting FAA at ICAO AFTF and stochastic analysis, Tasks 2-4,5-7)

Project Overview

Alternative jet fuels offer the potential to mitigate the net environmental impacts resulting from aviation-related emissions while diversifying energy supplies and thereby reducing the economic impacts of volatility in the price of oil and enhancing U.S. energy security. As a result, alternative fuels are receiving considerable attention from policy-makers, industry and academia. To evaluate various alternative jet fuels, a consistent set of metrics should be used to measure their impact on, among other things, climate change, air quality, land usage, and production costs. Such metrics have been examined by MIT in previous efforts under PARTNER Project 28 ("Environmental cost benefit analysis of alternative jet fuels"), under the FAA CLEEN Program and in an ongoing effort under PARTNER Project 47 ("Alternative aviation fuel sustainability") for different fuels that are compatible with the existing aircraft fleet. Considerable progress has been made through this work especially in fostering the understanding of lifecycle analysis in general (Stratton, 2010), and of the economic and environmental properties of jet fuel produced from hydroprocessed esters and fatty acids (HEFA) (Stratton et al., 2010 Pearlson, 2011, Pearlson et al., 2013, Olcay et al., 2013, Seber et al., 2014), from Fischer-Tropsch (F-T) pathways (Stratton et al., 2010 and Carter et al, 2011) and from biomass-derived simple sugars using a variety of chemical and biological techniques (Bond et al. 2014, Staples et al. 2014). The MIT team has also contributed to a wider understanding of the water footprint of aviation biofuels and of trade-offs between water and land requirements (Staples et al., 2013), as well as to understanding the impact of biogeophysical climate effects of land-use change induced by biofuel production (Caiazzo et al., 2014).

In a previous effort under Project 47, the MIT team has started to advise the International Civil Aviation Organization Committee on Aviation Environmental Protection's Alternative Fuels Task Force (ICAO CAEP AFTF) on scenarios for future alternative fuel production and associated GHG emission savings.

The overall objectives of COE Project 2014-1 are (1) to derive information on regional supply chains to create scenarios for future alternative jet fuel production and (2) to identify the key supply chain-related obstacles that must be overcome to produce 1 billion gallons of alternative jet fuel by 2018 and an order of magnitude larger production in the longer term.

After the original grant narrative was approved, the ICAO Committee on Aviation Environmental Protection (CAEP) Steering Group assigned a new task to the ICAO Alternative Fuels Task Force (AFTF) on the development of a methodology to assess lifecycle CO_2 emissions from alternative fuels for use in a system of market-based measures as currently discussed at ICAO, that was not covered under the original proposal. MIT committed to supporting FAA in this additional AFTF task and submitted a supplement to the original project grant narrative. The development of a methodology for assessing lifecycle CO_2 emissions from different fuels and feedstocks needs to address several key items. First, criteria for data quality will be needed such that the inputs to the calculation of lifecycle emissions are sound. Second, an accounting method will be needed that clearly defines the system boundaries (including the treatment of emissions from land-use change) and properly assigns emissions among the various products being produced. Third, a mechanism will be needed that describes who will compute the lifecycle emissions using the agreed-upon methodology. Fourth, a decision needs to be made on how frequently the calculations need to be revised over time.

In October 2014, AFTF decided to introduce a new task group (TG) that will develop the methodology for calculating lifecycle CO_2 emissions. Three members of the MIT team are members of the new TG.

Under this background, the objectives of the MIT proposal are (1) to develop long-run scenarios for future alternative jet fuel production and associated savings in GHG emissions attributable to aviation, (2) calculate lifecycle greenhouse gas emissions for alternative jet fuel pathways, (3) to contribute to developing and applying stochastic techno-economic models for assessing risk in conversion pathways as one key barrier for alternative jet fuel deployment and (4) to support FAA in the development of a methodology for lifecycle CO2 emissions of alternative jet fuels for use in the market based measures scheme currently under discussion at the International Civil Aviation Organization (ICAO).

The project consists of 7 tasks, the last two of which are part of the supplement to the original grant narrative:

- Task 1: Calculate screening-level lifecycle GHG emissions for additional feedstock to fuel pathways and quantify differences in lifecycle GHG emissions calculations in different regulatory frameworks for (aviation) biofuels
- Task 2: Develop ranges for GHG reductions per unit of aviation biofuel use

- Task 3: Estimate future bioenergy energy / aviation biofuel potential
- Task 4: Support FAA in their decision-making for ICAO CAEP AFTF
- Task 5: Work with Purdue University on the development and application of stochastic techno-economic models for aviation biofuel pathways
- Task 6: Develop proposal for methodology for calculation of CO_2 emissions
- Task 7: Calculate lifecycle CO_2 emissions under different methodological draft proposals developed by AFTF for select feedstock-to-fuel pathways

Objective(s)

The objectives, as outlined above are:

(1) to develop long-run scenarios for future alternative jet fuel production and associated savings in GHG emissions attributable to aviation,

(2) to calculate lifecycle greenhouse gas emissions for alternative jet fuel pathways,

(3) to contribute to developing and applying stochastic techno-economic models for assessing risk in conversion pathways as one key barrier for alternative jet fuel deployment and

(4) to support FAA in the development of a methodology for lifecycle CO_2 emissions of alternative jet fuels for use in the market based measures scheme currently under discussion at the International Civil Aviation Organization (ICAO).

Research Approach

The research approach is detailed under major accomplishments for each task separately.

Milestone(s)

Month	**Milestone**
October 2014	MS 1: High-level methodology developed for bioenergy potential and lifecycle GHG calculations
February 2015	MS 2: White paper on quantitative differences in policy frameworks for (aviation) biofuels available for FAA review
March 2015	MS 3: Future bioenergy potential results available for AFTF discussions
April 30th, 2015	MS 4: Results on savings in GHG emissions through alternative jet fuel in 2050 available for AFTF discussion
May 31st, 2015	MS Supplement 1: Presentation of methodological proposal at ICAO CAEP AFTF meeting in Brazil
August 31st, 2015	MS 5: Stochastic techno-economic study available for FAA review MS 6:

	Screening-Level lifecycle GHG emission estimates for additional feedstock-to-fuel pathways available MS Supplement 2: Preparation of papers for CAEP steering group meeting finished

Major Accomplishments

Task 1

The US generated an average of 4.38 lbs/person/day of municipal solid waste (MSW) in 2012, as reported by the EPA. Excluding the portions of the generated MSW that were recycled and composted, the remaining discards that were sent to landfill or combusted translated to 330 billion pounds of MSW in 2012. Converting this to fuels could potentially satisfy 15% of the annual US transportation demand for middle distillate fuel, making MSW a significant energy resource in the US. From an environmental and economic perspective, producing transportation fuels from MSW can offer several advantages.

The major environmental advantage is that conversion of MSW to fuel displaces the existing waste management strategy, which is primarily landfilling. 53.8% of the generated MSW was discarded in landfills in 2012. Replacing landfills, the third-largest anthropogenic source of methane emissions in the US, can give MSW-derived fuels a greenhouse gas emissions credit. Since a fraction of the MSW feedstock is biogenic, the direct emissions during fuel combustion are lower than that of conventional fossil fuels. Additionally, unlike conventional crop-based biofuels, using MSW as a feedstock implies no direct competition with food production and no additional land and water use.

The economics of using MSW as a feedstock are potentially favorable. Relative to conventional biomass with positive feedstock costs, there is currently zero cost associated with MSW and many municipalities pay to dispose of MSW in landfills. The average landfill tipping fees in the US is $50/ton. This may translate to a negative feedstock cost or source of revenue for MSW-derived fuels and may offset high fuel production costs. Additionally, waste management infrastructure for collection and sorting of MSW already exists and can be utilized, reducing the net production costs.

However, MSW-derived middle distillate fuels have not yet been produced at an industrial scale because significant challenges remain to be resolved, primarily the heterogeneity of the feedstock (requiring expensive pretreatment) and the lack of maturity of the conversion technologies (low efficiency and yields). As a result of these remaining challenges, it is not yet known empirically how these technologies will develop and perform commercially. Though there is some existing work in the area of evaluating the environmental and economic performance of MSW-derived middle distillate fuels, a large research gap remains to be bridged.

Only two published studies (Niziolek et al., 2015 and Pressley et al. 2014) have attempted to quantify the environmental performance of MSW-derived middle distillate fuels in terms of lifecycle greenhouse gas emissions. These examine only one conversion pathway and exclude some critical components of the lifecycle such as the displaced waste management strategy or fuel combustion emissions. Niziolek et al. estimate the overall production costs but do not perform a comprehensive techno-economic analysis. One academic thesis (Motycka, 2013) conducts a techno-economic assessment of a different MSW-to-middle distillate fuel pathway. However, it considers only a single optimized scenario and does not account for the wide range of conversion efficiencies available from other literature.

It must be noted that there are numerous published academic papers on LCA and TEA studies of waste to energy and waste to ethanol pathways. This literature has been utilized but needs to be supplemented to extend the analysis to production of middle distillate fuel from MSW. Lastly, the existing studies do not comprehensively account for the significant uncertainty and variability in each pathway. Stochastic analyses and sensitivity analyses are required for both environmental and economic performance evaluations to facilitate better-informed decision-making. Therefore, the project task's focus is to comprehensively analyze the environmental and economic performance of middle distillate fuel derived from MSW compared to that of conventional, petroleum derived middle distillate fuel, with stochastic modeling and scenario-based sensitivity analyses. The overall approach is shown in Figure 1.

In the last year, the environmental performance in terms of lifecycle greenhouse gas emissions for three thermochemical technologies was studied. The three thermochemical technologies that have been considered are:

1. Conventional gasification + Fischer-Tropsch (FT) synthesis
2. Plasma gasification + Fischer-Tropsch synthesis
3. Conventional gasification + Alcohol synthesis + Alcohol-to-jet conversion (ATJ)

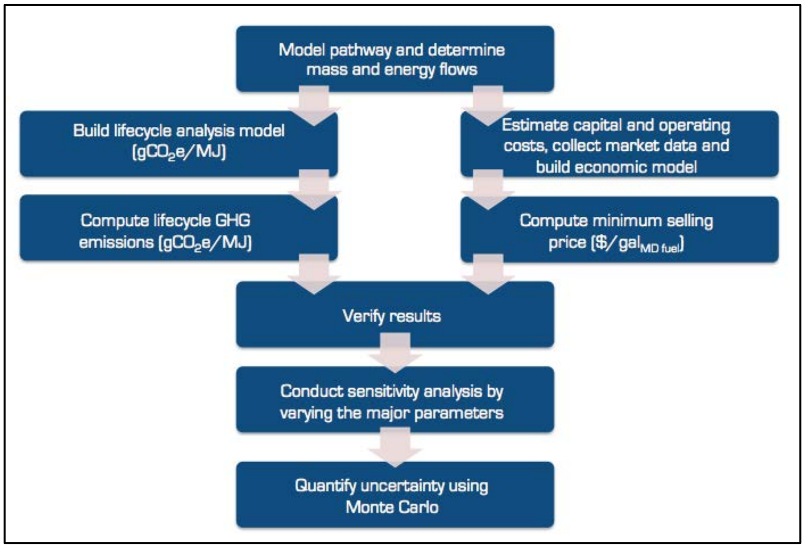

Figure 1: Overall research approach

Following the approach in Figure 1, the first step was to model these pathways. A brief description of the general pathway model and some important data sources are given below:

- The analysis excludes curbside collection, transportation and initial sorting, which must take place regardless of the waste management strategy. Only the MSW discards that remain after recycling and compost enter the LCA. The MSW discards' composition used for the analysis was obtained from the US 2012 MSW data presented by EPA, 2014.

- The pathway replaces the existing waste management strategies for these discards (landfill and combustion). This replacement results in a GHG credit because of the methane and CO_2 emissions that are offset. This credit is calculated from the EPA WARM model and accounts for energy recovery from landfill gas and combustion.

- The feedstock is transported to the biorefinery. At the biorefinery, further sorting is required in most scenarios to adjust the feedstock composition that enters the gasifier. Metals, glass and other inorganics are removed and some of it is recycled. This again results in a GHG credit that is calculated using the EPA WARM model and is included within the system boundary in the baseline case. The emissions related to energy consumption for the sorting process are also accounted for using simulation model data from academic literature.

- Note that the rejects and ash are sent to landfill but since these tend to be inorganic or non-biogenic in nature, they do not contribute to anthropogenic methane emissions; only the emissions from transportation and use of landfill machinery are included.

- The feedstock is then converted to jet and diesel fuel via one of the three thermochemical technologies. The direct GHG emissions from these processes are accounted for. The primary co-products include naphtha (reformed to gasoline in some cases), higher alcohols and excess electricity. Energy allocation is employed to allocate the emissions for fuel and alcohol co-products, whereas the excess electricity is assumed to displace the US national average grid electricity. Secondary co-products such as slag material for construction aggregates and elemental sulfur have also been included in the analysis but were found to have negligible impact.

- The middle distillate fuels are then transported and distributed to their end-use destinations. The emissions from this step are obtained from the GREET 2014 model.

- Finally, only the end-of-life combustion emissions due to the non-biogenic portions of the MSW are included in the LCA (40% non biogenic for the US EPA 2012 data based on the methodology from EIA, 2007).

The deterministic, baseline results that were computed for the three pathways in terms of lifecycle GHG emissions are shown in Figure 2. The credits from the replaced waste management strategy and recycling are the same for each of the three technologies on the basis of per ton of input MSW but vary when they are divided over the energy of the output fuels (MJ). The highest conversion efficiency to fuels (almost 60%) and hence, highest energy output in the form of fuels, is achieved by the conventional gasification + FT pathway when comparing the three baseline cases. Primarily due to this, this pathway also has the lowest lifecycle GHG emissions footprint (~ 24 gCO_2e/MJ).

The other two pathways have lower fuel yields, implying that more of the non-biogenic carbon in the MSW feedstock is emitted as CO_2 directly during the process and therefore, the emissions per MJ of middle distillate fuel are higher. In the plasma gasification pathway, less than 40% of the energy in the feedstock is converted to fuels. Fossil fuel inputs such as petroleum coke and natural gas further increase the direct emissions. Though the plasma gasification process produces a large amount of electricity, plasma power requirements are high and the excess electricity that is returned to the grid is not sufficient to balance the process emissions. In the case of the third pathway, conventional gasification + alcohol synthesis + alcohol-to-jet conversion, the fuel yields are the lowest. Due to high conversion losses, less than 25% of the energy in the feedstock is converted to middle distillate fuels and the excess electricity generation is very low (less than 1% of the feedstock energy as compared to 3% in the first pathway and 12% in the second pathway). Therefore, the third pathway had the largest lifecycle GHG emissions footprint (~ 45 gCO_2e/MJ).

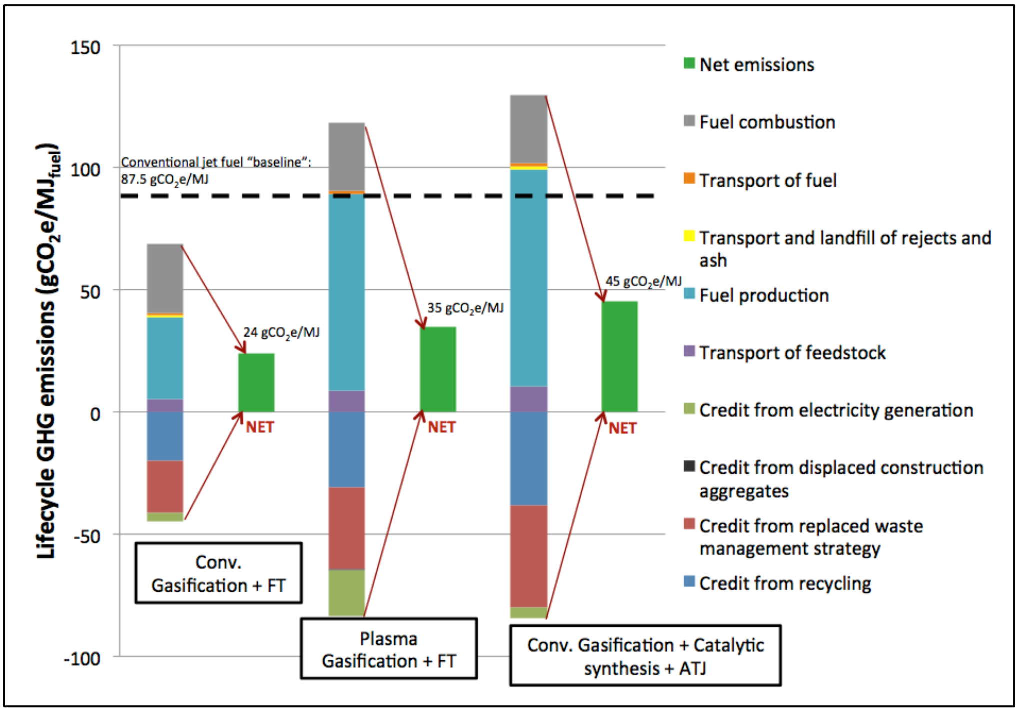

Figure 2: Lifecycle GHG results for three pathways that convert MSW to middle distillate fuel

These results were verified, whenever possible, by comparing to available literature. Some aspects of the pathway were compared to the earlier mentioned publications as well as other academic papers that study MSW conversion to ethanol, waste management strategies including waste-to-energy strategies and conversion of biomass to middle-distillate fuels. The next step was sensitivity analysis. An example of a preliminary sensitivity analysis for the conventional gasification + FT pathway is shown in Figure 3. The variables are on the left and the baseline assumptions are listed on the right. The graph shows the baseline scenario and the two extreme scenarios for each parameter.

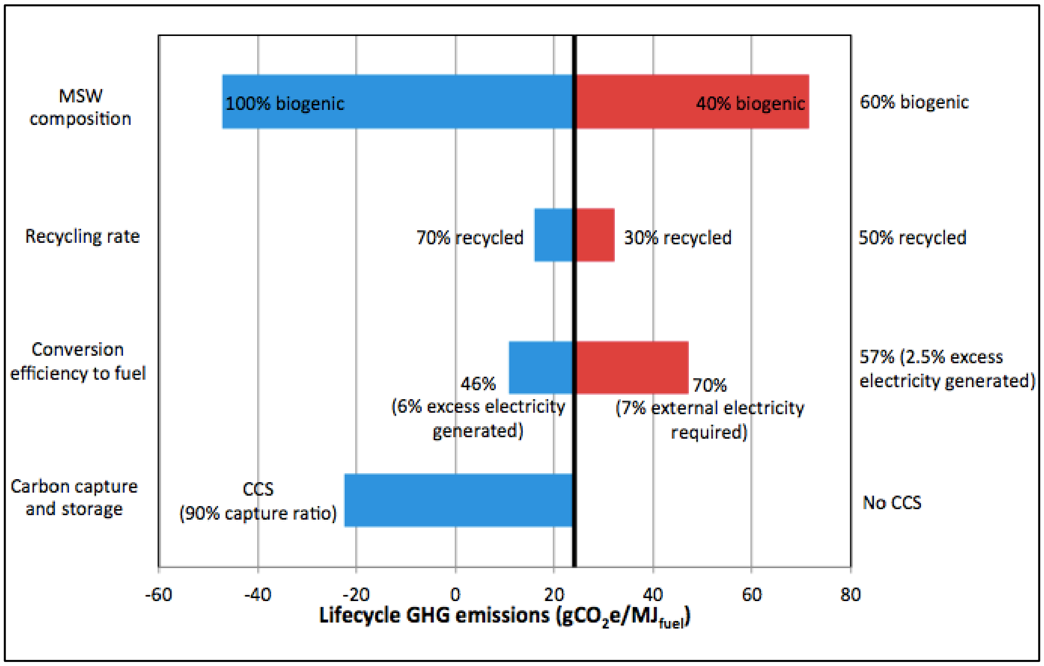

Figure 3: Preliminary sensitivity analysis for the conventional gasification + FT pathway

The major parameter is the MSW composition, particularly the biogenic vs. non-biogenic content ratio. The 100% biogenic case requires more energy for sorting to separate out all the plastics and thereby requires external electricity. Removing the plastics reduces the energy content of the feedstock and as a result, produces lower quantity of fuel. However, since there are no direct non-biogenic emissions, the credits per MJ are high. The resulting lifecycle GHG footprint is -47 gCO_2e/MJ. It must be noted that this is accompanied by a significant reduction in the amount of middle distillate fuel that can be produced (by more than 50%). The 40% biogenic case also requires additional sorting to remove the food waste, yard wastes and wood. Removing these biogenic wastes and sending them as rejects to landfill has a significant negative impact because of the high methane emissions from these biodegradable components. Also, the non-biogenic CO_2 emissions from both fuel production and combustion increase. The resulting lifecycle GHG footprint is 71 gCO_2e/MJ.

Varying the recycling rate proportionally changes the GHG credit from recycling. The effect is an increase of 8 gCO_2e/MJ when the recycling rate is reduced to 30% (from 50%) and a decrease of 8 gCO_2e/MJ when the recycling rate is increased to 70%. The data derived from academic literature showed that as more of the feedstock energy is converted to fuel (70%) and less electricity, the generated electricity cannot satisfy the energy demands of the process and an external electricity requirement arises. This increases emissions. On the other hand, because of displacement allocation, generating more excess electricity reduces the net emissions. The effect of the two scenarios is shown under the conversion efficiency parameter in Figure 3. Implementing carbon capture and storage by capturing 90% of the carbon that is released as CO_2 directly during the fuel production process is another scenario that reduces the net emissions significantly.

In the second year of the project that began this fall, the economic performance is being quantified by conducting techno-economic analysis to determine the minimum selling price of middle distillate fuels from the three pathways. The pathway model is the same as that used for the environmental analysis with some modifications. The major assumptions and methods are briefly described below:

- For the techno-economic analysis, the replaced waste management strategy affects the feedstock cost or revenue. Replacing existing or new landfills may allow the biorefinery to charge similar tipping fees for the MSW feedstock.

However, this may result in feedbacks to the system and in the long run, result in a positive associated cost. Therefore, the analysis assumes a zero cost for the MSW feedstock in the deterministic baseline case but will vary this parameter to account for current landfill tipping fees during sensitivity analysis.

- The mass and energy balances from the environmental analysis are carried over to the techno-economic analysis to build the biorefinery economic model. The revenue streams are middle distillate fuels, naphtha or gasoline, higher alcohols, excess electricity, scrap metals and glass from the further recycling step, sulfur and construction aggregates. Variable operational costs arise from process inputs such as electricity, natural gas, water, petroleum coke, limestone, catalysts and other chemicals.

- The prices of these revenue streams and operational inputs are based on 5-year historical market data from sources such as Bloomberg and EIA, governmental and international agencies such as USGS, EPA and OECD, and academic techno-economic studies for biomass conversion to fuels.

- Capital investment costs are estimated from a variety of academic techno-economic studies, few of which are relevant to MSW and the majority are related to biomass conversion to fuel. Some of the papers rely on chemical engineering models in Aspen to arrive at equipment factor estimates and some employ general cost-curve estimations.

- Fixed operational costs are estimated from capital expenses, based on heuristics in the literature. These expenses include insurance, taxes, maintenance and plant staff salaries.

- All of the above mentioned costs, revenues and material and energy balances are input into a Discounted Cash Flow Rate of Return (DCFROR) model based on Pearlson et al., 2013. The model is solved for the minimum selling price defined as the middle distillate price at which the net present value of the project cash flow equals zero at given internal rate of return. The minimum selling price is estimated for n-th plant operations at commercial scale.

- Most of the baseline assumptions are derived from Pearlson et al., 2013. These include 80%/20% debt to equity ratio, internal rate of return of 15%, loan interest rate of 5.5%, loan term of 10 years, income tax rate of 40% and a plant valuation life of 20 years. Capital expenses during construction are spread over three years and distributed as 8%, 60%, and 32% of the total project investment, respectively. Depreciation is scheduled over 10 years, and based on the variable declining balance method.

- The fuel transport and combustion stages are not included in the techno-economic analysis. The minimum selling price is estimated as the gate price that the biorefinery would sell the fuel at.

The minimum selling price is sensitive to the scale of the facility, which impacts the conversion efficiency and outputs and reduces capital costs per unit of output by taking advantage of economies of scale. It is also very sensitive to the assumed internal rate of return as well as the prices of the fuel products and scrap metals. Many of these critical inputs are stochastic in behavior, including the prices of products that are used to create the fuels, prices that finished products are sold for, and the capital costs associated with construction of the biorefinery. It is also important to note that many of the critical inputs for the lifecycle GHG emissions analysis have significant uncertainty margins, including conversion efficiency data, GHG intensities of utility inputs, waste management emission factors and MSW composition. Therefore, when the deterministic techno-economic analysis is completed for all three pathways, stochastic and scenario-based analyses will be performed to evaluate uncertainty and variability of the environmental and economic performance results.

In addition, MIT also provided an outline of the core differences in the approach for calculating lifecycle greenhouse gas (GHG) emissions in current legislation in the European Union (EU RES, EU FQD) and the United States (US EISA, US RFS 2). They are summarize below:

1. Allocation rules

EU legislation mandates that GHG emissions shall be divided between the fuel or its inter- mediate product and the co-products relative to their energy content (EU RES, Annex V, C.18; EU FQD, Annex IV, C.18) If excess electricity is being produced from cogeneration in the biofuel pathway, then emissions credits are to be assigned to the biofuel according to the emissions being avoided through the biomass-derived electricity generation. (EU RES, Annex V, C.16; EU FQD, Annex IV, C.16) In the US, emissions are calculated using energy-based allocation among co-products that can qualify under RFS 2 (transportation fuels), and system expansion for all other products. This choice can significantly impact on reported GHG emission values. For example, in case of the camelina HEFA pathway, Olcay et al. (2013) calculate lifecycle GHG emissions of ~31gCO2e /MJ if emissions are allocated among all co-products using energy-based allocation, and ~52gCO2e /MJ if system expansion is used at the camelina oil and camelina meal step, and energy-based allocation is used to attribute emissions among the transportation fuels being produced. [1]

2. System boundary

A core difference for system boundary for the calculation of lifecycle GHG emissions exists in the extent to which emissions from land-use change are included. Whereas the US RFS 2 mandates the inclusion of emissions from both direct and indirect change of land use due to biofuel production (US EISA, Title II, Subtitle A, Section 201 definitions) European legislation currently only includes emissions from direct land-use change (EU RES, Annex V, C.7; EU FQD, Annex IV, C.7). However, following provisions contained in EU RES and EU FQD the EU commission investigated a potential inclusion of emissions from indirect land-use change (ILUC) in EU regulation and recommended ILUC emission factors in a proposed revision of EU RES and EU FQD (EU COM(2012) 595). This proposal is currently under negotiation at the EU institutions.

3. Annualization of emissions from land-use change

In EU, emissions from carbon stock changes caused by land-use change are ann 7.; EU FQD, Annex IV, C.7), whereas they are annualized over 30 years in the U.S (US RFS 2, p. 14679). The choice of time horizon for annualization can significantly alter the reported results. For example, US EPA reports emissions from land-use change of ~32 gCO2e per MJ of soybean biodiesel (reported as 34 kg CO2e / mmbtu) (US EPA TABLE V.C–2), which - if emissions from land-use change were annualized over 20 years instead of 30 years - would translate into emissions of ~48gCO2e /MJ of soybean biodiesel.

4. Geographical scope of sustainability criteria

While it does not directly affect emissions calculations, there is an important difference in the application of sustainability criteria between the US and EU rules. The US sustainability criteria apply only to biofuels produced in the U.S (US RFS 2 Section II.B.4; US EISA, Title II, Subtitle A, Section 201), whereas EU sustainability criteria apply globally (EU RES Art. 17 (1)), EU FQD Art. 7b (1)). Thus, according to E. U. sustainability criteria, sensitive lands anywhere in the world do not count towards EU biofuels production targets (EU RES Art. 5(1)) and are not eligible for support schemes in the EU (EU RES Art. 17(1). These restrictions do not apply under the US regulation.

Tasks 2-4

The research approach for quantifying the CO_2 benefit of alternative fuels in aviation is two-fold: 1) develop and use ranges for life cycle GHG emissions estimates of alternative jet fuels in the short- and long-run, and 2) assess the potential alternative jet fuel production in the short- and long-run. The short-run is defined as 2020, and the long-run is defined as 2050. The final step in the research is to combine the LCA efforts (task 1) and the fuel production assessment (task 2).

The LCA work was led by the European Commissions' Joint Research Centre (EU JRC) and Argonne National Laboratory (ANL), and the fuel production assessment and final integration of the two analyses was led by MIT and the International Air Transport Association (IATA). Therefore, this report addresses MIT's work on the fuel production assessment, and the integration of the LCA and fuel production analyses to generate final results for the CAEP 10 trends assessment.

Fuel production assessment for 2020

The methodology used for projecting alternative jet fuel production in 2020 consists of four successive steps. First, a database was built, collecting all the announcements made by alternative fuel producers regarding the development of their technology, the construction of demonstration and commercial plants, and their short-term production plans. Announcements by States (or group of States) were also collected. In a second step, the credibility of the collected announcements was evaluated according to a set of criteria established by the subgroup. Third, different sets of assumptions, constituting scenarios, were defined in order to explore a range of possible developments corresponding to increasingly optimistic assumptions regarding the achievement of the industry's announcements. Last, quantitative projections were derived from the announcements according to the credibility evaluation and the scenarios' assumptions.

[1] Reported values are for a system in which the share of jet fuel in the product slate is maximized.

Fuel production assessment for 2050

For the 2050 fuel production assessment, the methodology is designed to capture a range of future production potentials, dependent upon assumptions regarding global socio-economic evolution, future energy and environmental policies, and other factors. For that purpose, a three-step scenario approach was adopted. The three steps, as well as the major groupings of assumptions that define the outcomes of each step, are shown in Figure 4.

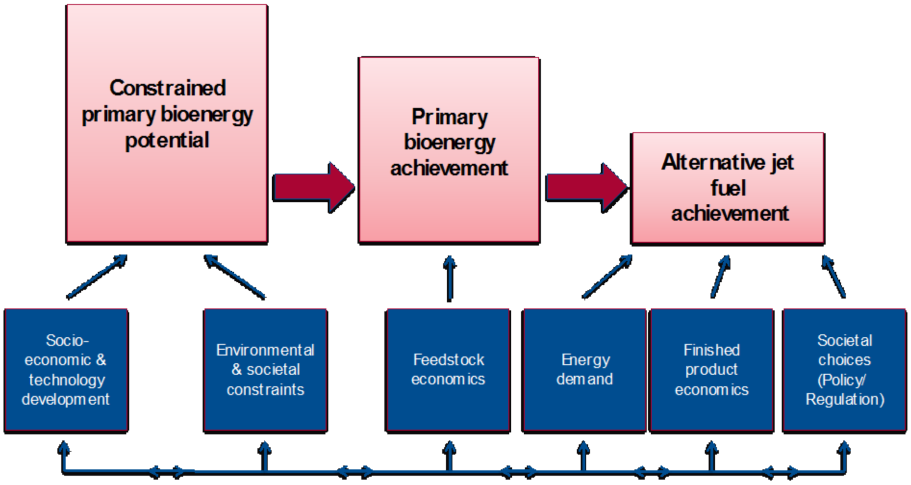

Figure 4: Analysis steps in the 2050 fuel production assessment for ICAO-CAEP

In the first step, constrained primary bioenergy potential is calculated. This is the total bioenergy potential from available land and biomass resources, subject to assumed sustainability constraints, socio-economic conditions (such as world population, GDP, etc.), possible future environmental policies, and other variables. The result is a set of constrained primary bioenergy potential scenarios.

In the second step, primary bioenergy achievement is calculated from constrained primary bioenergy potential. Achievement scenarios are constructed to reflect possible future feedstock prices and energy policies that favor or discourage the production of bioenergy, and the primary bioenergy achievement is defined as the proportion of constrained technical potential anticipated to actually be produced under different scenario assumptions.

In the third step, alternative jet fuel achievement is calculated from primary bioenergy achievement. Alternative jet fuel achievement is defined as the proportion of bioenergy achievement that is assumed to be converted to alternative jet fuel. Calculating alternative jet fuel achievement requires estimating the proportion of achieved primary bioenergy potential that is dedicated to alternative jet fuel production, as opposed to other uses, and estimating the efficiencies associated with primary energy to jet fuel conversion processes.

Integration of LCA and fuel production assessment analyses

The integration of the LCA and fuel production assessment analyses is a matter of multiplying the agreed upon fuel-grouping-specific LCA emissions factors (the outputs of work by EU JURC and ANL), by the calculated potential fuel production volumes (the outputs of work by MIT and IATA). This was carried out for 2020 and 2050, and the results are reported here in a number of different ways, in order to provide insight into the consequences of the findings for the CAEP 10 trends assessment.

The work was carried out iteratively by bringing together the AFTF experts in face-to-face and teleconference meetings:

- **Early October 2014:** Two teleconferences were held, hosted by MIT, to make a proposal to AFTF for the methodology to be used for the 2050 fuel production assessment. This proposal focused on the constrained primary bioenergy potential step of the analysis.
- **Late October 2014:** AFTF convened its second face-to-face meeting in Madrid. At this meeting a revised methodology for the 2050 fuel production assessment was presented by MIT, and key aspects were agreed upon.

- **December 2014:** A first iteration of the methodology information paper (IP) for the 2050 fuel production assessment was circulated to the group for comments by MIT. A teleconference was held shortly thereafter, hosted by MIT, to present the IP and garner comments on the document so far.
- **March 2015:** A second iteration of the 2050 fuel production assessment IP, which incorporated comments on iteration 1, was sent to AFTF by MIT. Again, a teleconference was hosted by MIT in order to present and explain the IP document, and to receive feedback from AFTF members on the state of the methodology.
- **Early May 2015:** A third iteration of the 2050 fuel production assessment IP, incorporating comments received on iteration 2, was circulated to AFTF in preparation for the meeting in Brasilia by MIT.
- **Mid-May 2015:** AFTF convened its third face-to-face meeting in Brasilia. The third iteration of the IP, and preliminary results for the 2050 fuel production assessment, were presented by MIT. The proposed methodology and preliminary results for the 2020 fuel production assessment were presented by Philippe Novelli of ICAO, the analysis for which MIT had participated in.
- **June 2015:** A final, agreed upon iteration of the 2050 fuel production assessment methodology IP was sent to AFTF by MIT. This final version reflected the input of AFTF members during the meeting in Brasilia.
- **August 2015:** An iteration of the final results IP, ultimately intended for use by the ICAO-CAEP Modeling & Data Group (MDG) in the CAEP 10 trends assessment, was sent to AFTF for comments. The results contained in this document represent the combination of results from the 2020 and 2050 LCA analyses (led by EU JRC and ANL) and the 2020 and 2050 fuel production assessment analyses (led by MIT and IATA).

During this period, MIT worked together with other AFTF members to develop a methodology for the assessment for alternative jet fuel production in 2020. The final methodology, summarized above and explained in detail in CAEP-SH/2015-IP/14, was presented to the CAEP Steering Group in September 2015.

The 2020 fuel production assessment resulted in 6 scenarios, which are presented in Table 1.

Table 1: Alternative jet fuel availability in 2020, in [Mt/yr] and [EJ/yr]

	Without green diesel		Including green diesel	
Scenario	[Mt/yr]	[EJ/yr]	[Mt/yr]	[EJ/yr]
Low	0.06	0.00	3.84	0.17
Medium	1.19	0.05	5.83	0.26
High	2.37	0.10	6.49	0.29

During this period, MIT developed, proposed, revised and finalized the methodology for the 2050 fuel production assessment for the CAEP-10 trends assessment. This involved an iterative process of proposing a methodological approach to the members of AFTF, receiving comments and adjusting the methodology. This process came to a conclusion in June 2014. The agreed upon methodology is summarized above, and explained in detail in CAEP-SQ/20153-IP/12, presented to the CAEP Steering Group in September 2015.

Having finalized the methodology, MIT proceeded to generate the results for the 2050 fuel production assessment. The generation of these results represents the culmination of a full year of analysis effort on the part of MIT. A summary of results is presented here. The first step of the analysis determined that 41-510 EJ/yr of primary bioenergy is potentially available in 2050. Results are disaggregated by feedstock type, world region, and associated land-use. The results of step 1, broken out by feedstock type, are shown in Figure 5. As a point of reference, total global primary energy demand was approximately 549.1 EJ in 2011.

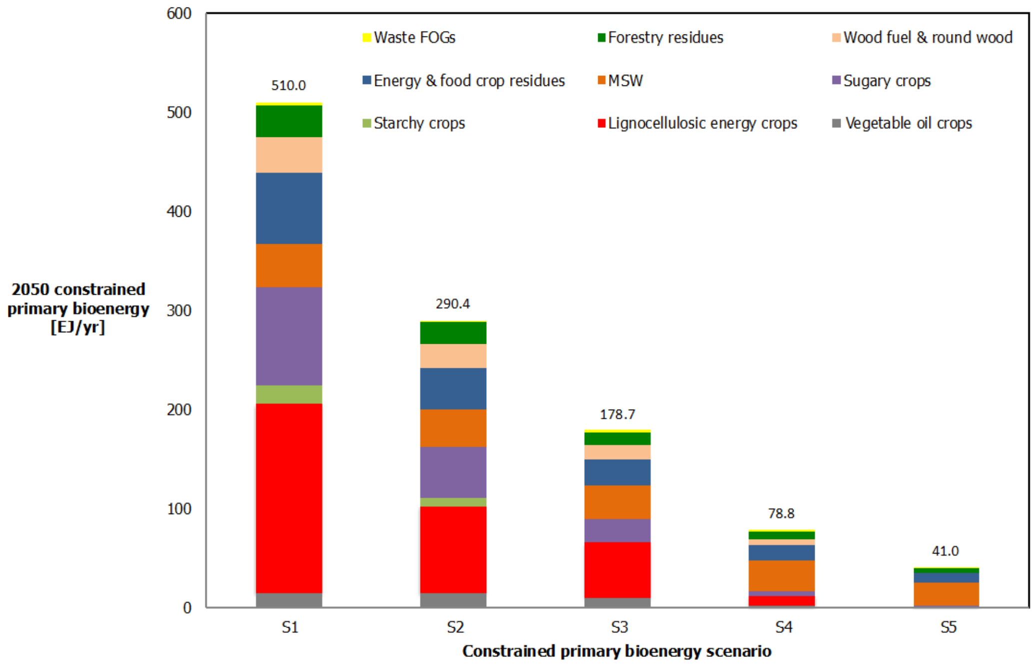

Figure 5: 2050 constrained primary bioenergy potential scenario results, broken out by feedstock type

In step 2 of the 2050 fuel production assessment, various feedstock price assumptions were tested to quantify the proportion of 2050 constrained primary bioenergy potential that might actually be produced in 2050. These results are disaggregated by feedstock type, world region, and associated land-use. The results of step 2, ranging between 16-369 EJ/yr, are shown broken out by feedstock type in Figure 6.

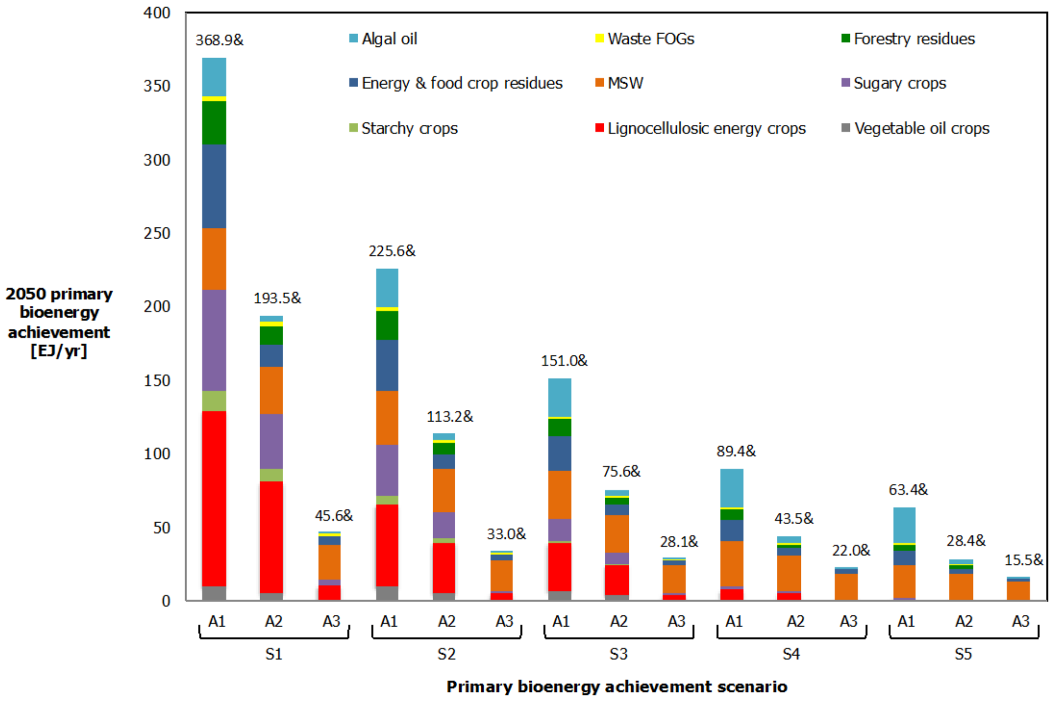

Figure 6: 2050 primary bioenergy achievement results.

In step 3 of the 2050 fuel production assessment, different scenarios are explored to quantify the volume of alternative jet fuel that could be produced from 2050 primary bioenergy achievement, given competing uses for biomass resources and feedstock-to-jet fuel conversion efficiencies. Again, the results are disaggregated by feedstock type, world region, and associated land-use. The results of step 3, ranging between 1-203 EJ/yr, are shown broken out by feedstock type in Figure 7.

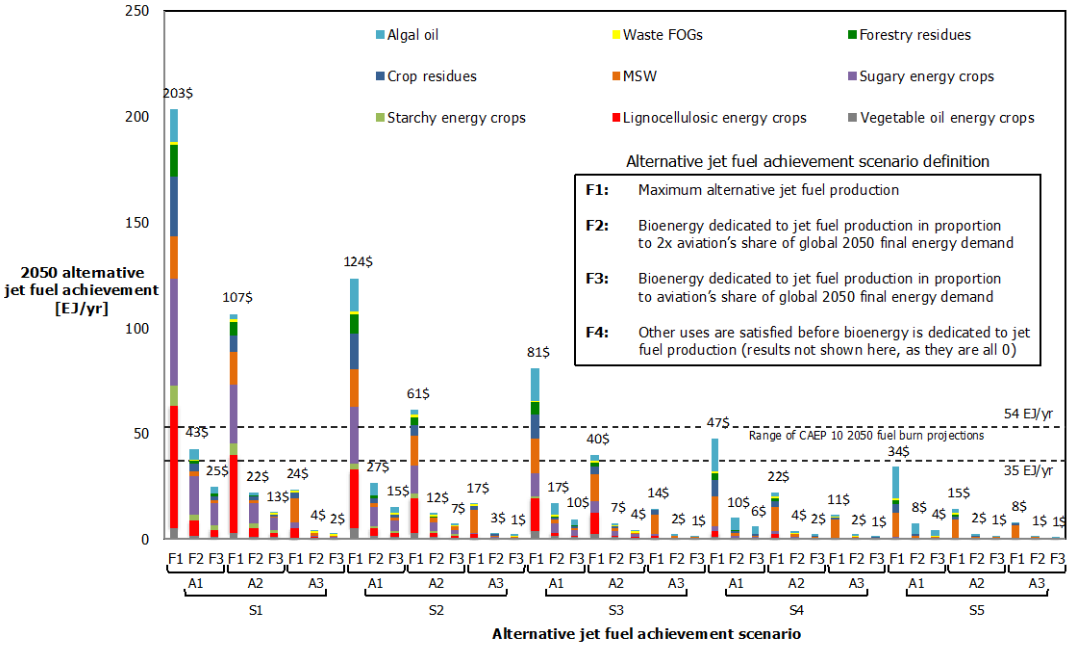

Figure 7: Alternative jet fuel achievement results. The range of CAEP-10 fuel burn projections are shown by the dashed lines for reference.

Final results for potential for alternative jet fuels to reduce the aviation CO_2 emissions to 2050

MIT combined the results of the 2020 and 2050 fuel production assessment analyses with the LCA emissions factors agreed upon by the sub-group led by EU JRC and ANL. These results were delivered to AFTF in CAEP-SQ/20153-IP/12, and are summarized for below. Figure 8 indicates that alternative jet fuel could reduce 0-1.2% of aviation CO_2e emissions in 2020, and Figure 9 indicates that alternative jet fuel could reduce 0-51.0% of aviation CO_2e emissions in 2050.

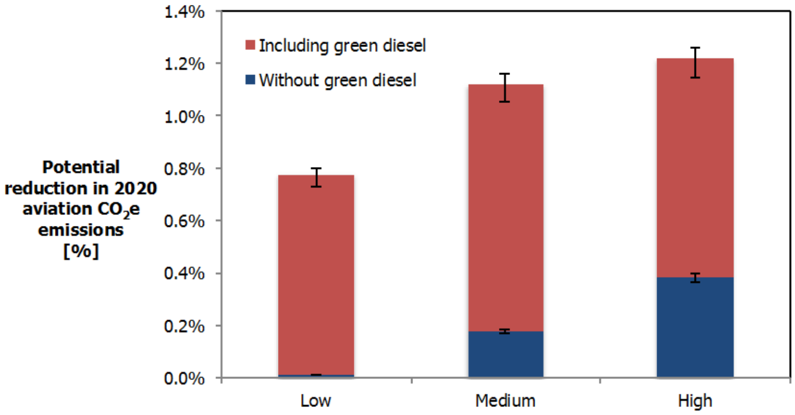

Figure 8: Potential reduction in 2020 aviation lifecycle CO_2e emissions using the low LCA emission factor case, compared to 100% petroleum-derived jet fuel baseline. Variability bars reflect different CAEP 10 fuel projections for 2020. Reduction is zero for all production scenarios under the high LCA emission factor case.

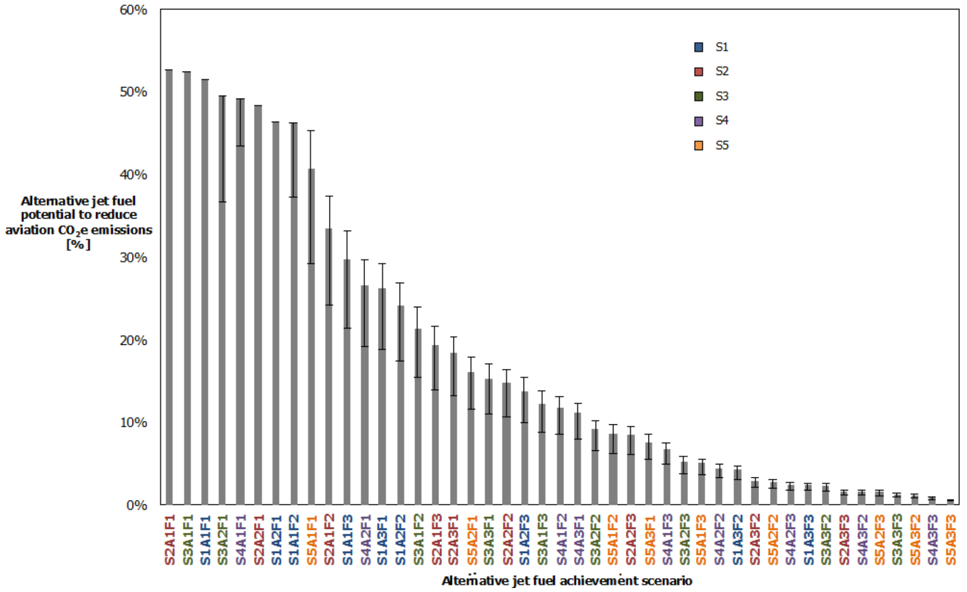

Figure 9: Potential percentage reduction in life cycle CO_2e emissions from aviation in 2050 [Mt CO_2e/yr], due to the use of alternative fuels. The grey bars indicate aviation life cycle CO_2e emissions reductions in 2050 from a 100% petroleum-derived jet fuel base case. The whiskers indicate the change in percentage of potential offset due to the range of CAEP 10 2050 fuel burn projections.

Task 5 (with Purdue University)

We conducted a stochastic techno-economic assessment of the Alcohol-To-Jet (ATJ) pathway for three different biomass feedstocks that advances existing techno-economic approaches in collaboration with Purdue University. First, we quantify the impact of technical uncertainty on the production costs of the fuel by econometrically linking process inputs and outputs to random draws on conversion efficiency. Second, we account for uncertainty in future prices of inputs and outputs through time-series estimation. Third, we develop and apply a method to estimate breakeven price distributions for the ATJ fuels under consideration. The point of departure for this research is previous analysis by Staples et al. (2014) funded under the PARTNER Center of Excellence on renewable diesel and jet fuel production via fermentation and advanced fermentation technologies. We extend this work by including stochasticity as described above.

Virtually all biofuel currently produced is ethanol or biodiesel, which cannot be used for aviation for performance and safety reasons. Therefore, specific technologies are being developed to produce fuels that are compatible with existing aircraft and air transport infrastructure. One such technology, referred to as alcohol-to-jet (ATJ), involves the upgrading of biomass-derived alcohols to a drop-in jet fuel or blendstock specification. Typically, ATJ technologies extract polymer sugars from a biomass feedstock via mechanical, chemical or biological means. The polymer sugars are then decomposed to monomer sugars, and metabolized (or fermented) by an engineered microorganism to an alcohol platform molecule. Finally, the alcohol is dehydrated, oligomerized and hydrogenated to a final fuel product slate which includes some proportion of drop-in jet fuel or blendstock. A number of private corporations, such as Byogy Renewables, Inc. and Gevo, Inc., are pursuing ASTM certification and commercialization of ATJ technologies. The subject of this analysis is a subset of ATJ technologies that includes sugars derived from sugarcane, corn grain or switchgrass, followed by fermentation to an ethanol platform molecule. These feedstocks were selected to represent the present and future of renewable fuel production: corn grain and sugarcane are commonly used for the production of ethanol in the United States and Brazil, respectively, and herbaceous lignocellulosic crops, such as switchgrass, can be used for the production of second-generation renewable fuels such as cellulosic ethanol. A simplified schematic of the ATJ process is shown in Figure 10.

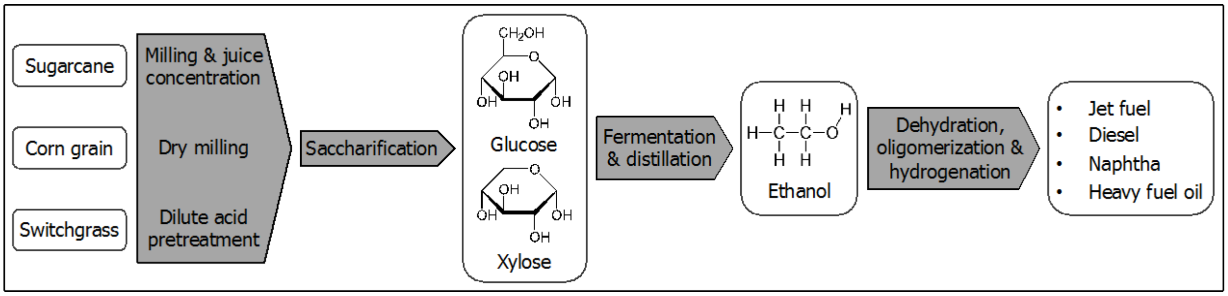

Figure 10: Alcohol-to-jet pathway description

Figure 11 presents an overview of the stochastic techno-economic analysis in this study. The arrows indicate the direction of impacts from one variable to another. ATJ first converts feedstocks to alcohol, and then converts alcohol to jet fuels. Thus, there are two conversion efficiencies subject to uncertainty. These two conversion efficiencies, in turn, drive feedstock, utility input requirement and output levels. We include uncertainty in feedstock and natural gas prices because of their high proportion in operating costs. Diesel prices are also projected with uncertainty and other fuel prices are highly correlated with diesel prices. Capital cost also is driven by capacity and feedstock quantity requirements, which are determined by conversion efficiency.

The upper left corner of Figure 11 presents the feedstock inputs and DDGS by-products and the lower right corner displays the utility requirements and by-products in the two production steps. The upper right corner shows the final fuel products. The lower-left corner is capital cost. All the uncertain input variables follow a defined distribution. Technology conversion factors, capital costs, feedstock, natural gas and diesel prices are projected through distributions represented by ovals in Figure 11. Exogenous variables are represented by parallelograms, and variables dependent on a stochastic variable are shown as rectangles. Each iteration of the Monte Carlo simulation yields output values that reflect the random draws from all the input distributions. The base case from Staples et al. (2014) is defined as the most likely or mode value in our analysis. The breakeven price distribution design is discussed in subsequent sections of the paper.

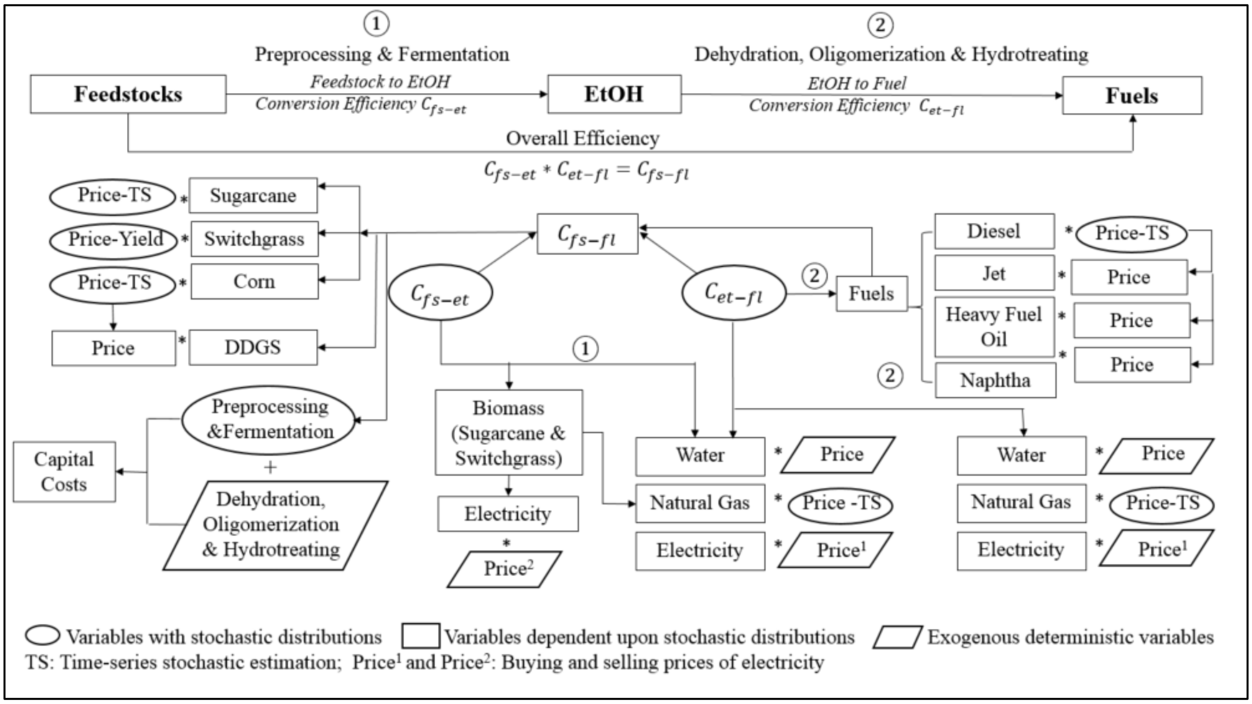

Figure 11: Schematic overview of techno-economic analysis model in this research

We first present results for net present value distributions, followed by breakeven price distributions. The summary of NPV distribution results is presented in Table 2. The mean NPV for corn grain, sugarcane and switchgrass are negative. Sugarcane has the highest NPV and smallest standard deviation, and switchgrass has the lowest NPV and largest standard deviation (Figure 12). All three feedstocks' probability of loss is higher than 85%, and there is more uncertainty in switchgrass to jet fuel production. These results imply that under current diesel, jet and feedstock prices, technology levels, and projected future product prices, incentives would be needed to stimulate investment in aviation biofuel production via ATJ.

Table 2: Stochastic NPV distribution results for corn grain, sugarcane and switchgrass

Statistics ($)	Corn Grain	Sugarcane	Switchgrass
Mean	(202,676,272)	(166,949,693)	(578,847,888)
Std Dev	123,078,088	143,503,827	239,347,128
Minimum	(610,068,151)	(829,256,428)	(1,665,733,740)
Maximum	197,763,45	319,977,497	68,609,042
Probability of Loss	95%	88%	100%

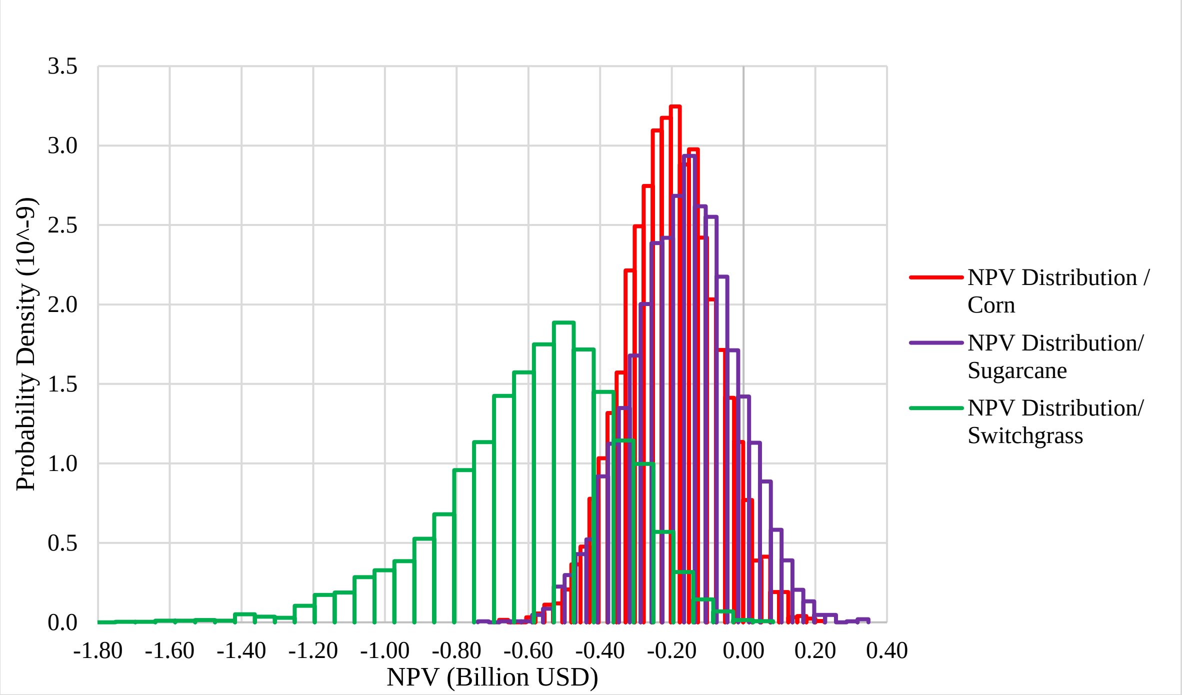

Figure 12: NPV distribution comparisons of corn grain, sugarcane and switchgrass

The NPV results show that sugarcane is the least-cost option for the ATJ pathway among the three feedstocks considered under all circumstances. Sugarcane production does not require external heat and electricity. The sugarcane bagasse produced provides more than sufficient heat and power for fuel production, and permits 167,847,524 kWh produced electricity to be exported to the grid in the base case. Although the combustion of biomass residues generated from switchgrass can also offset the heat and power requirements for fuel production, it still requires more natural gas than sugarcane, and the power generated is less than sugarcane. In addition, its conversion efficiency is lower than corn grain. In general, we find that mean NPV of the different renewable jet fuel pathways are inversely proportional to the recalcitrance of simple sugars in the raw feedstock to be converted to ethanol: switchgrass is the most recalcitrant feedstock examined (requiring greater utility, energetic and feedstock inputs per unit of monomer sugar extracted) and has the lowest NPV and, in contrast, sugarcane is the least recalcitrant feedstock (requiring fewer utility, energetic and feedstock inputs per unit of monomer sugar extracted) and has the highest mean NPV.

Fitted breakeven price distributions for corn grain, sugarcane and switchgrass follow a normal, a Beta General and a PERT distribution respectively. The statistics and quintiles of distributions are presented in Table 3. We find that the breakeven price distribution for switchgrass has the largest standard deviation, which is because it has higher technical uncertainty than the other two processes.

Table 3: Fitted breakeven price distribution statistics for corn, sugarcane and switchgrass ($/liter)

Feedstocks	**Corn**	**Sugarcane**	**Switchgrass**
Distribution	**Normal**	**BetaGeneral**	**Gamma**
Minimum	−∞	0.64 (2.42)	0.84 (3.17)
Maximum	∞	1.56 (5.91)	∞
Mean	1.01 (3.84)	0.97 (3.68)	1.41 (5.32)
Mode	1.01 (3.84)	0.95 (3.59)	1.32 (4.99)
Median	1.01 (3.84)	0.96 (3.65)	1.38 (5.21)
Std Dev	0.08 (0.31)	0.12 (0.44)	0.22 (0.84)
1%	0.83 (3.13)	0.74 (2.81)	1.02 (3.85)
5%	0.88 (3.34)	0.79 (3.00)	1.10 (4.15)
10%	0.91 (3.45)	0.82 (3.12)	1.15 (4.34)
15%	0.93 (3.53)	0.85 (3.21)	1.18 (4.48)
20%	0.95 (3.59)	0.87 (3.29)	1.22 (4.60)
25%	0.96 (3.64)	0.89 (3.36)	1.24 (4.71)
30%	0.97 (3.68)	0.90 (3.42)	1.27 (4.81)
35%	0.99 (3.73)	0.92 (3.48)	1.30 (4.91)
40%	1.00 (3.77)	0.94 (3.54)	1.32 (5.01)
45%	1.01 (3.81)	0.95 (3.60)	1.35 (5.11)
50%	***1.01 (3.84)***	***0.96 (3.65)***	***1.38 (5.21)***
55%	1.02 (3.88)	0.98 (3.71)	1.41 (5.32)
60%	1.04 (3.92)	1.00 (3.77)	1.43 (5.43)
65%	1.05 (3.96)	1.01 (3.83)	1.46 (5.54)
70%	1.06 (4.01)	1.03 (3.90)	1.50 (5.67)
75%	***1.07 (4.05)***	***1.05 (3.97)***	***1.53 (5.81)***
80%	1.08 (4.10)	1.07 (4.05)	1.58 (5.98)
85%	1.10 (4.16)	1.10 (4.15)	1.63 (6.18)
90%	1.12 (4.24)	1.13 (4.27)	1.70 (6.45)
95%	1.15 (4.35)	1.17 (4.44)	1.81 (6.87)
99%	1.20 (4.56)	1.25 (4.75)	1.25 (7.75)

Note: Values in parenthesis are measured in $/gallon.

The [5 percentile; mean; 95 percentile] breakeven jet prices per liter of ATJ from corn, sugarcane and switchgrass are [$0.88; $1.01, $1.15], [$0.79; $0.96; $1.17] and [$1.10; $1.38; $1.81] respectively. The mean values are at about 50% percentile distributions, which means that at this value investors have 50% probability of earning less than their threshold discount rate.

Our research investigates the economics of aviation biofuel production via the ATJ pathway from corn grain, sugarcane and switchgrass feedstocks, using stochastic TEA. Our results complement Staples et al. (2014) findings, as we can show that sugarcane is not only the least expensive ATJ pathway of the three considered, but also the least risky. However, even for sugarcane, we find that there is an 88% probability that investors won't make break even without price supports. We note, that ATJ fuel can potentially qualify for the renewable diesel category under the US Renewable Fuels Act and that price supports through RIN markets are available, which at the time of writing amount to approximately $0.20/liter ($0.75/gallon) of fuel [47], thereby reducing the required mean breakeven price of sugarcane, corn grain and switchgrass ATJ fuel to around $0.77/liter ($2.90/gallon), $0.82/liter ($3.09/gallon) and $1.18/liter ($4.46/gallon), respectively.

Tasks 6-7

MIT has also supported the work of AFTF to develop an LCA methodology for a global market-based measure (GMBM) to limit CO_2 emissions from international aviation. As the exact nature of support required by AFTF was subject to change, dependent upon the ongoing development of the negotiations, the analysis that MIT has provided has been *ad hoc*. In other words, because the GMBM negotiation process is evolving over time, MIT had prepared a number of smaller deliverables over the course of the year. These are detailed below.

Assessment of the additional carbon concept

It was proposed by ICSA that aviation biofuels should only receive a GHG emissions credit in the calculation of lifecycle GHG emissions if the CO2 sequestered from the atmosphere during biomass growth is additional to sequestration that would have occurred otherwise, without aviation biofuel production. If this credit is not assigned, a lifecycle analysis will in most cases attribute higher emissions to aviation biofuels than to conventional jet fuel, since the conversion of biomass requires more energy inputs than the conversion of crude to jet fuel. The determination of whether sequestration is additional would be done through a 'with/without' comparison; i.e. a comparison of carbon sequestration through plant growth without aviation biofuels, compared to carbon sequestration with aviation biofuels. Generally in life cycle analysis, GHG emissions are only accounted for if they are non-biogenic, that is, if they do not occur as the result of combustion or decomposition of biological materials. Biogenic CO_2 emissions occur when jet fuel from biomass is combusted, and can also occur at other steps of the fuel lifecycle such as when biomass is used to produce utilities required for feedstock conversion, or when the actual feedstock conversion process releases CO_2, as in the case of fermentation of sugars. Following ICSA's proposal, these biogenic emissions would all be accounted for in the case that the initial sequestration during feedstock growth cannot be proven to be additional to a situation without aviation biofuel production.

In order to test the implications of ICSA's proposal for MBM, MIT carried out an analysis that resulted in the following findings:

1. Consequences of ICSA's proposal for estimated lifecycle emissions

Table 4: Life cycle GHG emissions of select feedstock-to-jet fuel pathways

	Lifecycle GHG emissions (gCO2e/MJ)	
	with biomass credit	without biomass credit
Sugarcane AF-J	12.7	427.7
Corn grain AF-J	62.6	219.7
Switchgrass AF-J	37.4	332.84

Table 4 depicts an example of the consequences of not assigning a biomass credit, or in other words, accounting for all biogenic CO_2 emissions, in the lifecycle emissions for jet fuel produced using a technology known as advanced fermentation. The first column shows different feedstock-to- jet fuel-pathways, the second column shows lifecycle GHG emission results including a biomass credit as published by Staples et al. (2014), and the third column calculates emissions without a biomass credit (and therefore including biogenic emissions) as proposed by ICSA in the case that there is no proof that the biofuel producer is using additional biomass that would not have been grown without aviation biofuel. For comparison purposes we note that conventional jet fuel GHG emissions have been calculated at 87.5 gCO2e/MJ of jet fuel (Stratton et al., 2010).

In the case of advanced fermentation jet fuels, significant biogenic emissions occur at the stage of sugar fermentation, as well as fuel combustion, and – for sugarcane and switchgrass AF-J – at the stage of feedstock conversion through usage of biomass for production of utilities required in the process. The results confirm the assertion that the lack of inclusion of biomass emission credits can increase calculated emissions to a level much higher than that of conventional jet fuel. Similar trends are expected to arise for other biomass-derived jet fuels such as Fischer-Tropsch and HEFA jet fuel. For soybean HEFA, for example, including biogenic combustion emissions increase emissions from 37.0 gCO2e/MJ as reported by Stratton et al. (2010), to 107.4 gCO2e/MJ, which is ~20gCO2e/MJ higher than emissions of conventional jet fuel.

2. Additionality requirement would lead to discrimination of aviation biofuels versus other uses of biomass

The requirement of additional carbon sequestration would exclusively apply to aviation biofuels: Current mandates or incentive schemes for renewable energy (transportation fuels and electricity) such as those in the US and EU do not require biomass (and consequently CO2 sequestration from the atmosphere) to be additional to existing biomass and sequestration. Imposing an additionality requirement on aviation biofuels would increase attributed lifecycle GHG emissions for aviation biofuels. By doing so, aviation biofuels would essentially become ineligible for a credits under GMBM, whereas biomass used for other end-usages would still receive support under the respective schemes in the US and EU – whether they are using existing or additional biomass.

Given competition for biomass between different end-usages, this asymmetric regulation would put a GHG and consequently a cost-penalty on aviation biofuels compared to other usages of biomass, and would significantly decrease aviation biofuel deployment – while not contributing to ICSA's goal of increased carbon sequestration.

3. "Additionality" would need to be applied to both aviation biofuels and conventional jet fuel

ICSA proposes a "with/without" comparison to determine if aviation biofuels reduce atmospheric GHG emission levels. It would be inconsistent to apply this concept under the GMBM only to aviation biofuels - it would have to be applied to conventional jet fuel, as well. If that were the case, CO2 emissions from conventional jet fuel would only be accounted for if they lead to an increase in atmospheric GHG emissions. This would not be the case if the crude oil used for aviation were otherwise used for other purposes, such as road transportation fuels or heating. Given that the price elasticity of crude demand is non-zero, one would expect a certain fraction of this crude to be indeed used for other purposes. Consequently, applying ICSA's additionally requirement to the calculations of CO2 emissions of conventional jet fuel as necessary under GMBM would decrease lifecycle GHG emissions attributed to conventional jet fuel, and, in turn, emissions attributed to aviation in general.

4. Additionality requirement could be non-implementable and non-enforceable

The ICSA proposal does not cover potential implementation and enforcement of an additionality clause under GMBM. In essence, each batch of biomass would need to be 'certified' or "approved" as 'additional'. While one can imagine this being possible at non-prohibitive costs in cases where agricultural residues are being used or degraded lands are started to be farmed again, certification or approval appears to be impossible at reasonable cost levels for the third relevant case of crop yields are "actively improved (without overly increasing fertilizer emissions)" (ICSA 3.114).

Sensitivity of life cycle GHG results for alternative jet fuel to changes in market prices

In early MBM negotiations, the allocation methodology was narrowed down to two potential options: market-based allocation and energy allocation. In order to explore the differences between the two proposed approaches, MIT carried out an analysis to explore the impact of changes in market prices on life cycle GHG results. MIT assessed three different examples using the US as the geographical area of interest:

- Allocation between corn grain to AF jet fuel and distiller dry grains and solubles (DDGS)
- Allocation between soybean oil to HEFA jet fuel and soybean meal
- Allocation between soybean biodiesel, soybean meal and glycerol

The results outlined below show that, using rolling 10 year averages for relative prices of the co-products under consideration, calculated lifecycle GHG emissions only vary by ~6% in case of AF jet fuel from corn starch, and by ~4% in case of HEFA jet fuel from soybean oil.

For the notional example of a soybean biodiesel pathway that yields a chemical as a co-product we find that emissions calculated increase by ~57% over time, as glycerol prices decrease with rising production.

These results were used to guide and inform the AFTF negotiation on the appropriate allocation methodology to implement.

Generate suggestions on how to deal with LUC in the context of MBM
MIT was asked to provide some ideas on how best to include LUC emissions in MBM. There were 4 specific requests made by AFTF MBM.

1. Ideas on how to identify feedstock/land use practices that are "low risk" for LUC (include ideas on a safeguard of a periodic review mechanism that captures changing conditions, which would then result in a re-evaluation of the risk-rating)
2. Ideas on how to calculate LUC for all other feedstock/areas utilizing existing and/or new calculations to create data for the LCA
3. Ideas on how to establish safeguards to prevent the use of carbon "hot-spots"
4. Ideas on how to provide a mechanism to capture benefits of utilizing LUC-risk mitigation practices (e.g., land management practices) to reduce emissions

These issues, and the suggestions that MIT made in response to them, have been the subject of subsequent discussions within AFTF MBM.

Publications

For Tasks 2-4 and 6-7, this work is carried out in support of an international negotiation. As such, the methodology and results have not be published in scientific journals or presented at conferences, in order to respect the sensitive nature of the negotiation. The major publications associated with MIT's work on this project are the IP presented to the CAEP Steering Group:

CAEP-SG/2015-IP/14: 2020 Fuel Production Assessment Methodology
CAEP-SG/20153-IP/12: 2050 Fuel Production Assessment Methodology
CAEP-SG/20153-IP/13: 2020 and 2050 LCA Emissions Factors Methodology

An iteration of final results is presented in an information paper, which has not yet been presented to the CAEP Steering Group.

Outreach Efforts

The work described above under tasks 2-4 was discussed at length during the face-to-face meetings of AFTF in Madrid and Brasilia over the past year. Between the two meetings, approximately 32 hours (or four full days) of negotiations were dedicated to discussing the proposed methodologies and initial results.

In addition, MIT hosted 4, 2-hour long teleconferences to discuss working documents, which were previously circulated to the group, with AFTF members.

Awards

n/a

Student Involvement

Mark Staples was the primary developer of the 2050 fuel production assessment methodology. He drafted the iterations of the IP, prepared briefings for AFTF, and incorporated the requested and required changes. He also carried out the integration of the LCA and fuel production assessment analyses to generate final results, and drafted the IP that presents and explains the results. Mark also worked with Wallace Tyner and Guolin Yao of Purdue University to provide ATJ data for the work on stochastic TEA. Mark is a continuing PhD candidate.

Pooja Suresh was the primary developer of the LCA model for the three different technologies to convert MSW into jet fuel. Pooja also provided analysis support to ANL in generating LCA values for alternative fuels in 2050. Her analysis involved calculating alternative jet fuel LCA results, taking into account changes in the technologies and process inputs to 2050. Pooja prepared briefings for the LCA analysis group during teleconferences, and the entire AFTF group at the Brasilia meeting. Pooja is a continuing Masters student.

Plans for Next Period

Final results will be discussed at length during AFTF's face-to-face meeting in October 2015 in Montreal. Topics to be decided upon include:

- which of the 72 scenario results generated to provide to MDG for the CAEP 10 trends assessment
- how to connect the 2020 and 2050 results
- wording of the final results IP to aid in interpretation of the results

Once these issues are resolved, a final version of the results will be handed over to MDG for inclusion in the CAEP 10 trends assessment.

In addition, MIT will continue to support the work of AFTF in developing an LCA methodology for a global MBM for international aviation.

In terms of MSW to jet, MIT will continue work on the economics of the different pathways and incorporate stochasticity into both the environmental and economic models.

References

Bond, J., Upadhye, A., Olcay, H., Tompsett, G. Jae, J., Xing, R., Alonso, D., Wang, D., Zhang, T., Kumar, R., Foster, A., Sen, S., Maravelias, C., Malina, R., Barrett, S., Lobo, R., Wyman, C., Dumesic, J., Huber, G. Production of renewable jet fuel range alkanes and commodity chemicals from integrated catalytic processing of biomass. Energy and Environmental Science, Vol. 7 (2014).

Caiazzo, F., Malina, R., Staples, M., Wolfe, P., Yim, S., Barrett, S. Quantifying the climate impacts of albedo changes due to biofuel production: a comparison with biogeochemical effects. Environmental Research Letters Vol. 9, 024015 (2014).

EIA. Methodology for allocating municipal solid waste to biogenic and non-biogenic energy. Energy Information Administration (2007).

EPA. Municipal Solid Waste Generation, Recycling, and Disposal in the United States, Tables and Figures for 2012. U.S. Environmental Protection Agency (2014).

EU COM(2012) 595 : Proposal for a Directive amending Directive 98/70/EC relating to the quality of petrol and diesel fuels and amending Council Directive 93/12/EC and amending Directive 2009/28/EC on the promotion of the use of energy from renewable sources, COM(2012) 595, Brussels, 17.10.2012.

EU FQD: Directive 2009/30/EC of the European Parliament and of the Council of 23 April 2009 amending Directive 98/70/EC as regards the specification of petrol, diesel and gas-oil and introducing a mechanism to monitor and reduce greenhouse gas emissions and amending Council Directive 1999/32/EC as regards the specification of fuel used by inland waterway vessels and repealing Directive 93/12/EEC, Official Journal of the European Union, 5.6.2009, Official Journal of the European Union L 14/ 88–113.

EU RES: DIRECTIVE 2009/28/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC, Official Journal of the European Union, 5.6.2009, L140/1662

Motycka, S.A. Techno Economic Analysis of a Plasma Gasification Biomass to Liquids Plant. George Washington University (2013).

Niziolek, A.M., Onel, O., Hasan, M.M.F., Floudas, C.A. Municipal solid waste to liquid transportation fuels – Part II: Process synthesis and global optimization strategies. Computers & Chemical Engineering 74, pp. 184-203 (2015).

Olcay, H., Seber, G., Malina, R. Life Cycle Analysis for Fully-Synthetic Jet Fuel Production, MIT Support for Honeywell Continuous Lower Energy, Emissions and Noise (CLEEN) Technologies Development, Report to the FAA (2013).

Olcay, H., Seber, G., Malina, R.: Environmental Sustainability of Fully Synthetic Jet Fuel Production. Presentation at the FAA CLEEN consortium meeting, November 20, 2013. Available online at: http://www.faa.gov/about/office_org/headquarters_offices/apl/research/aircraft_technology/cleen/2013_consortium/media/Honeywell_CLEEN_Projects_Briefing_Nov_2013.pdf.

Pearlson, M., Wollersheim, C. & Hileman, J. A techno- economic review of hydroprocessed renewable esters and fatty acids for jet fuel production. Biofuels, Bioproducts and Biorefining 7 (1), pp.89-96 (2013).

Pressley, P.N., Aziz, T.N., DeCarolis, J.F., Barlaz, M.A., He F., Li, F., Damgaard, A. Municipal solid waste conversion to transportation fuels: a life-cycle estimation of global warming potential and energy consumption. Journal of Cleaner Production, 70, pp. 145-153 (2014).

Seber, G., Malina, R., Pearlson, M., Olcay, H., Hileman, J., Barrett, S. Environmental and economic assessment of producing hydroprocessed jet and diesel fuel from waste oils and tallow. Biomass and Bioenergy Vol. 67 (2014).

Staples, M.D., Malina, R., Olcay, H., Pearlson, M.N., Hileman, J.I., Boies, A., Barrett, S.R.H. Lifecycle Greenhouse Gas Footprint and Minimum Selling Price of Renewable Diesel and Jet Fuel from Fermentation and Advanced Fermentation Production Technologies. Energy and Environmental Science, 7, 1545 (2014).

Staples, M.D., Olcay, H., Malina, R., Trivedi, P., Pearlson, M., Strzepek, K., Paltsev, S., Wollersheim, C., Barrett, S. Water consumption footprint and land requirements of large-scale alternative diesel and jet fuel production. Environmental Science and Technology, Vol. 47 (2013).

Stratton, R. W., Wong, H. M., Hileman, J. I. Life Cycle Greenhouse Gas Emissions from Alternative Jet Fuels, PARTNER-COE-2010-001, Partnership for AiR Transportation Noise and Emissions Reduction (PARTNER) (2010).

Stratton, R.W., H.M. Wong, Hileman, J.I. Quantifying Variability in Life Cycle Greenhouse Gas Inventories of Alternative Middle Distillate Transportation Fuels Environmental Science & Technology 45 (2011).

US RFS 2: Regulation of Fuels and Fuel Additives: Changes to Renewable Fuel Standard Program. Federal Register/Vol. 75, No. 58/Friday, March 26, 2010/Rules and Regulations, 14670-14903.

US EISA: Energy Independence and Security Act of 2007.