Project 001(F) Alternative Jet Fuel Supply Chain Analysis

Massachusetts Institute of Technology

Project Lead Investigator

PI: Steven R. H. Barrett
Raymond L. Bisplinghoff Professor of Aeronautics and Astronautics
Director, Laboratory for Aviation and the Environment
Massachusetts Institute of Technology
77 Massachusetts Ave, Building 33-322, Cambridge, MA 02139
+1 (617) 253-2727
sbarrett@mit.edu

Co-PI: Dr. Mark D. Staples
Research Scientist
Laboratory for Aviation and the Environment
Massachusetts Institute of Technology
77 Massachusetts Ave, Building 33-322, Cambridge, MA 02139
+1 (617) 253-7422
mstaples@mit.edu

University Participants

Massachusetts Institute of Technology

- P.I.: Professor Steven R. H. Barrett
- FAA award number: 13-C-AJFE-MIT, amendment nos. 003, 012, 016, 028, 033, 040, 048, and 055
- Period of Performance: August 1, 2014 to April 30, 2020 (via no-cost extension)
- Tasks (tasks listed here are for the reporting period, October 1, 2018 to September 31, 2019):
    1. Support U.S. participation in the International Civil Aviation Organization (ICAO) Committee on Aviation Environmental Protection (CAEP) by calculating default core life-cycle greenhouse gas (GHG) emissions associated with alternative jet fuel (AJF) use under the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA);
    2. Support U.S. participation in ICAO CAEP by providing guidance on the economic impacts of potential policies on AJF financial viability;
    3. Support U.S. participation in ICAO CAEP by developing tools and resources to assess the ramp-up of AJF production under CORSIA;
    4. Carry out environmental and economic assessment of co-processing of renewable lipids in petroleum refineries;
    5. Support coordination across all A01 universities' work on AJF supply-chain analyses.

Hasselt University (subaward from MIT)

- P.I.: Robert Malina
- Period of Performance: August 1, 2014 to April 30, 2020 (via no-cost extension)
- Tasks (relevant only to the reporting period, October 1, 2018 to September 31, 2019):
    1. Support U.S. participation in ICAO CAEP by calculating default core life-cycle GHG emissions associated with AJF use under CORSIA;
    2. Support U.S. participation in ICAO by providing guidance to CAEP on the economic effects of potential policies on AJF financial viability;
    3. Support U.S. participation in ICAO by developing tools and resources to assess the ramp-up of AJF production under CORSIA.

Project Funding Level

$2,235,000 FAA funding and $2,235,000 matching funds. Sources of match are approximately $388,000 from Massachusetts Institute of Technology (MIT), plus third-party in-kind contributions of $809,000 from Byogy Renewables, Inc. and $1,038,000 from Oliver Wyman Group.

Investigation Team

Principal Investigator: Prof. Steven Barrett (MIT) (all MIT tasks)
Co-Principal Investigator: Dr. Mark Staples (MIT) (all MIT tasks)
Co-Investigators: Dr. Raymond Speth (MIT, Tasks 1 and 4) and Dr. Florian Allroggen (MIT, Tasks 2 and 4))
Graduate Research Assistants: Juju Wang (MIT, Tasks 1, 2, and 5), Uyiosa Oriakhi (MIT, Tasks 1 and 4), and Tae Joong Park (MIT, Task 4)

Part of the research will be conducted through a subaward with Hasselt University (Belgium), led by Prof. Robert Malina, and Hasselt University post-doctoral researcher Hakan Olcay.

Project Overview

The overall objectives of ASCENT Project 1 for the reporting period were to derive information on regional supply chains for creating scenarios for future AJF production, to identify the key supply-chain-related obstacles that must be overcome for commercial-scale production of AJF in the near term, and to achieve large-scale replacement of conventional jet fuel with AJF in the longer term.

According to these overall objectives, MIT's work under ASCENT Project 1 during the assessment year (AY) 2018–2019 (from October 1, 2018 to September 31,2019) focused on the following: (a) participation in ICAO CAEP to calculate default LCA GHG-emission values associated with AJF use under CORSIA; providing quantitative guidance to CAEP on (b) the economic impacts of potential AJF policies and (c) the effect of policy options, including CORSIA, on AJF production ramp-up; (d) quantification of the life-cycle GHG emissions and costs of production of AJF from the co-processing of renewable lipids with petroleum; and (5) providing support for coordination of the A01 team.

Task 1- Default Core LCA Emission Value Calculation, Documentation, and LCA Methodology Development for Use under CORSIA

Massachusetts Institute of Technology and Hasselt University

Objective

The overall objective of this task is to provide support to the FAA in its engagement with the ICAO CAEP Alternative Fuels Task Force (AFTF) (during CAEP/11) and the Fuels Task Group (FTG) (during CAEP/12). The specific focus of the work during this period was to develop the method for appropriate accounting of AJF life-cycle GHG emissions under CORSIA, apply the methods to calculate AJF default core LCA emission values for use under CORSIA, and document this work for communication to the relevant stakeholders.

Research Approach

Introduction

In this reporting period, progress has been made on the work of the CLCA Task Groups of AFTF (CAEP/11) and FTG (CAEP/12). The MIT ASCENT Project 1 team (including a subaward to Hasselt University) has been key in this progress. In particular, the MIT ASCENT team had a leading role on the following tasks: (a) calculating the default core life-cycle emission value for four additional feedstock-to-fuel AJF pathways; (b) writing a technical report documenting the default core LCA analysis performed by AFTF during CAEP/11; (c) developing the reporting requirements for airlines wishing to use "actual" LCA values under CORSIA; (d) defining categories for feedstock classification under CORSIA; and (e) continued development of methods to account for avoided landfill emission credits (LECs) and recycling emission credits (RECs) associated with municipal solid waste (MSW)-derived fuel under CORSIA.

Default core LCA-value calculation

During the reporting period, the MIT ASCENT 1 team performed core LCA analyses for four additional feedstock-to-fuel pathways for inclusion with default values under CORSIA. The analysis procedure and results for each of these pathways are summarized below and documented in detail in CAEP/11-WP/44.

Corn-grain iso-butanol (iBuOH) ATJ

Two independent analyses were compared for this pathway to determine an appropriate default core LCA value: one performed by MIT and the other performed by the European Union Joint Research Centre (JRC). The LCA values from MIT and JRC are compared in Table 1. The presented values reflect initial reconciliation of inconsistencies in the results.

Table 1. Comparison of default core LCA values for corn-grain iBuOH ATJ from MIT and JRC

Conversion technology	Data source	Model	Cultivation	Feedstock transp.	Fermentation and upgrading	Jet fuel transp	Total emissions [gCO$_{2e}$/MJ]	Midpoint value [gCO$_{2e}$/MJ]
Corn grain iBuOH ATJ	MIT	GREET	15.9	0.9	38.8	0.4	56.0	55.8
	JRC	E3db	22.5	0.6	32.1	0.3	55.5	

The remaining differences in the LCA data presented here stem from differences in the underlying life-cycle inventories used: E3db assumes a corn-grain yield of 7.1 t/ha, as opposed to a yield of 10.4 t/ha in the Greenhouse Gases, Regulated Emissions, and Energy use in Transportation (GREET) 2017 data; a distiller's dried grains with solubles yield of 0.31 $kg/kg_{corn\ grain}$ in E3db versus 0.28 $kg/kg_{corn\ grain}$ in GREET 2017; and differing feedstock and fuel transportation distances and energy intensities leading to small differences in transportation emissions. Despite the remaining differences, the results from the two models are within the 8.9 grams of carbon dioxide equivalent per megajoule of jet fuel produced (gCO_2e/MJ) definition of a pathway for CORSIA. Therefore, the default core LCA value for the corn-grain iBuOH ATJ pathway was determined to be 55.8 gCO_2e/MJ.

Herbaceous lignocellulosic iBuOH ATJ

Three separate analyses were compared for this pathway to determine an appropriate default core LCA value. MIT modeled the switchgrass (*Panicum virgatum*) and miscanthus (*Miscanthus sinensis*) iBuOH ATJ pathways, and JRC independently modeled the switchgrass iBuOH ATJ pathway. The LCA values from the MIT and JRC analyses, which reflect an initial reconciliation of inconsistencies in results, are compared in Table 2. These results are within the 8.9 gCO_2e/MJ definition of a pathway for CORSIA. Therefore, the default core LCA value for the herbaceous lignocellulosic iBuOH ATJ pathway was determined to be 43.4 gCO_2e/MJ.

Table 2. Comparison of default core LCA results for herbaceous lignocellulosic iBuOH AJT from MIT and JRC

Conversion technology	Data source	Model	Cultivation	Feedstock transp.	Fermentation and upgrading	Jet fuel transp	Total emissions [gCO$_{2e}$/MJ]	Midpoint value [gCO$_{2e}$/MJ]
Miscanthus iBuOH ATJ	MIT	GREET	12.5	1.4	27.7	0.4	42.1	43.4
Switchgrass iBuOH ATJ	MIT	GREET	14.9	2.1	27.0	0.4	44.5	
	JRC	E3db	9.9	3.1	31.4	0.3	44.7	

Molasses iBuOH ATJ

Molasses iBuOH ATJ was included as one of the new pathways, as agreed upon by the CAEP Steering Group in March 2018, for which the default core LCA value needed to be calculated by AFTF. This pathway is based on, and consistent with, the sugarcane (*Saccharum officinarum*) iBuOH ATJ pathway, for which default core LCA values had already been agreed upon by AFTF: the fuel production is from sugar-derived iBuOH, which is subsequently converted to drop-in fuel via dehydration, oligomerization, and hydrotreating. Data from both MIT and JRC were compared for this pathway. The results for the MIT analysis on the molasses iBuOH AJT pathway are shown below in Table 3 and are compared with the data proposed by JRC. These data are within the definition of a pathway of 8.9 gCO$_2$e/MJ for CORSIA, and therefore the default core LCA value for the molasses iBuOH ATJ pathway was determined to be 27.0 gCO$_2$e/MJ.

Table 3. Summary of core LCA results for the molasses iBuOH ATJ pathway

Conversion technology	Data source	Model	Cultivation	Feedstock transp.	Fermentation and upgrading	Jet fuel transp	Total emissions [gCO$_{2e}$/MJ]	Midpoint value [gCO$_{2e}$/MJ]
Molasses iBuOH ATJ	JRC	E3db	17.7	1.6	7.7	0.3	27.3	27.0
	MIT	GREET	17.8	2.1	6.4	0.3	26.6	

Sugarbeet synthesized iso-parrafin (SIP)

The sugarbeet SIP pathway was modeled in a manner consistent with the sugarcane SIP pathway, as approved by CAEP SG in June 2018. Both processes are based on the fermentation of sugars to hydrocarbon intermediates and subsequent hydrotreating to drop-in jet fuel. The results for the JRC and MIT analyses of the sugarbeet SIP pathway are shown below in Table 4. Several factors contribute to the remaining discrepancy between the data: the two analyses rely on differing data sources for sugarbeet cultivation; MIT assumes a lower sugar yield from sugarbeet, resulting in a 21%-lower energetic yield of farnesene per unit feedstock; and assumptions differ regarding the biogas yield from sugarbeet pulp and electricity and heat co-generation efficiencies.

Despite the differing assumptions, these data are within the definition of a pathway of 8.9 gCO$_2$e/MJ for CORSIA, and therefore the default core LCA value for the sugarbeet SIP pathway was determined to be 32.4 gCO$_2$e/MJ.

Table 4. Default core LCA results for sugarbeet SIP

Conversion technology	Data source	Model	Cultivation	Feedstock transp.	SIP production	Jet fuel transp	Total emissions [gCO$_{2e}$/MJ]	Midpoint value [gCO$_{2e}$/MJ]
SIP from sugarbeet	JRC	E3db	11.0	0.9	16.6	0.3	28.8	32.4
	MIT	GREET	23.4	1.4	10.8	0.4	36.0	

Summary

During this reporting period, the MIT ASCENT 1 team led the default core LCA analysis for four additional pathways (results summarized in Table 5).

Table 5. Pathway (column 1), data source (column 2), model (column 3), core LCA modeling results (column 4), default core LCA values agreed upon in this reporting period (column 5).

Conversion technology	Data source	Model	Core LCA results [gCO2e/MJ]	Proposed default core LCA value [gCO_{2e}/MJ]
Corn grain iBuOH ATJ	MIT	GREET	56.0	55.8
	JRC	E3db	55.5	
Herbaceous lignocellulosic iBuOH ATJ	MIT	GREET	42.1	43.4
	MIT	GREET	44.5	
	JRC	E3db	44.7	
Molasses iBuOH ATJ	JRC	E3db	27.3	27.0
	MIT	GREET	26.6	
Sugarbeet SIP	JRC	E3db	28.8	32.4
	MIT	GREET	36.0	

Technical report of the default core LCA calculation for CORSIA

To document the default core LCA calculations that occurred during the CAEP/11 cycle, MIT wrote a technical report, which is included as an appendix to Working Paper (WP) 45 from the February 2019 CAEP/11 meeting. This report is publicly available on the ICAO website and will also be available as part of the CAEP/11 report (ICAO Document 10126, 2019).

The purpose of this report is to present the methodology and calculation of default core LCA values for different sustainable alternative fuels (SAF), which can be used to reduce aircraft operators' offsetting obligations under CORSIA.

Methods

Chapter 1 of the report explains the methodology and steps agreed upon by AFTF to calculate default core LCA values to be used under CORSIA. This process includes an attributional approach using energy-based allocation, encompassing the following life-cycle stages:

- feedstock cultivation;
- feedstock harvesting, collection, and recovery;
- feedstock processing and extraction;
- feedstock transportation to processing and fuel-production facilities;
- feedstock-to-fuel conversion processes;
- fuel transportation and distribution; and
- fuel combustion in an aircraft engine.

Waste, residue, and by-product feedstocks are assumed to incur zero GHG emissions during the feedstock-production step of the life cycle; however, emissions generated during their collection, recovery, and extraction, as well as the processing of wastes, residues, and by-products are included.

Emissions are quantified in terms of 100-year global-warming potential (GWP) carbon dioxide equivalent (CO_2e) emissions of CO_2, CH_4 and N_2O from well-to-pump activities, and CO_2 emissions from pump-to-wake fuel combustion. The 100-year GWP was calculated by using the CO_2e values for CH_4 and N_2O from the Intergovernmental Panel on Climate Change (IPCC-AR5) (28 and 265, respectively) (Intergovernmental Panel on Climate Change (IPCC), 2014). Biogenic CO_2 emissions from fuel production or combustion are not included in the calculation, per the IPCC Fifth Assessment Report 100-year global warming potentials (IPCC, 2014). The functional unit selected for the LCA results is gCO_2e/MJ_{jet}, considering combustion in an aircraft engine using the lower heating value for characterizing fuel energy content. A single global value is used to represent life-cycle emissions from petroleum-derived jet fuel and aviation gasoline: 89.0 gCO$_2$e/MJ and 95.0 gCO$_2$e/MJ, respectively.

Each pathway evaluation has been led by a single institution and verified by the other institution. The results of the calculations often diverged, as a result of differences in feedstock yields, process inputs, and other parametric assumptions. Therefore, a procedure was implemented to reach agreement on a single default core LCA value. A threshold equal to 10% of the jet-fuel baseline (i.e., 8.9 gCO$_2$e/MJ) was defined; if the difference between two analyses for the same pathway fell within this threshold, the midpoint between the results was taken as the default value. If the difference between two analyses was greater than 8.9 gCO$_2$e/MJ, harmonization of the parametric assumptions was undertaken, or the pathway was split into two to better represent physically different systems.

Analysis

Chapters 2–5 of the technical report document the data sources and results for 26 unique feedstock-to-fuel SAF pathways for which default core LCA values were calculated. The pathways are summarized in Table 6. Because feedstock type influences the results, we highlight classifications for each specific case. A color code is used to describe the feedstock classification: green for residues, wastes, and by-products [R,W,B]; orange for co-products [C]; and blue for main products [M].

Table 6. List of pathways included in the CAEP/11 technical report

Conversion process	Feedstock	Type of feedstock
Fisher-Tropsch (FT)	Agricultural residues	[R]
	Forestry residues	[R]
	Short-rotation woody crops	[M]
	Herbaceous energy crops	[M]
	MSW, 0% NBC	[W]
	MSW, NBC as % of total C	[W]
Hydro-processed esters and fatty acids (HEFA)	Tallow	[B]
	Used cooking oil	[W]
	Palm fatty acid distillate	[B]
	Corn oil	[B]
	Soybean	[M]
	Rapeseed/canola	[M]
	Camelina	[M]
	Palm oil - closed pond	[M]
	Palm oil - open pond	[M]
	Brassica carinata	[M]
Synthesized Iso-Paraffins (SIP)	Sugarcane	[M]
	Sugarbeet	[M]
Iso-butanol Alcohol-to-jet (ATJ)	Sugarcane	[M]
	Agricultural residues	[R]
	Forestry residues	[R]
	Corn grain	[M]
	Herbaceous energy crops	[M]
	Molasses	[C]
Ethanol Alcohol-to-jet (ATJ)	Sugarcane	[M]
	Corn grain	[M]

For a detailed review of the pathway-specific data and analysis associated with each of these pathways, please refer to CAEP/11 WP45, the CAEP/11 report, or the version of the technical report to be posted on the ICAO website[1].

---

[1] https://www.icao.int/environmental-protection/CORSIA/Documents/CORSIA%20Supporting%20Document_CORSIA%20Eligible%20Fuels_LCA%20Methodology.pdf

Results

Chapter 6 of the technical report documents all default core LCA values for CORSIA calculated during CAEP/11. These results are summarized in Table 7.

Table 7. Summary of default core LCA values calculated during CAEP/11

Conversion process	Feedstock	Default core LCA value [$gCO_{2}e/MJ$]
Fisher-Tropsch (FT)	Agricultural residues	7.7
	Forestry residues	8.3
	MSW, 0% NBC	5.2
	MSW, NBC as % of total C	NBC*170.5+5.2
	Short-rotation woody crops	12.2
	Herbaceous energy crops	10.4
Hydro-processed esters and fatty acids (HEFA)	Tallow	22.5
	Used cooking oil	13.9
	Palm fatty acid distillate	20.7
	Corn oil	17.2
	Soybean	40.4
	Rapeseed/canola	47.4
	Camelina	42
	Palm oil - closed pond	37.4
	Palm oil - open pond	60
	Brassica carinata	34.4
Synthesized Iso-Paraffins (SIP)	Sugarcane	32.8
	Sugarbeet	32.4
Iso-butanol alcohol-to-jet (ATJ)	Sugarcane	24.0
	Agricultural residues	29.3
	Forestry residues	23.8
	Corn grain	55.8
	Herbaceous energy crops	43.4
	Molasses	27.0
Ethanol Alcohol-to-jet (ATJ)	Sugarcane	24.1
	Corn grain	65.7

Reporting requirements for 'actual' core LCA values

CORSIA allows airlines to use an actual LCA value if the producer of the fuel can demonstrate, with certification from a sustainability certification scheme (SCS), that their fuel has an LCA value differing from the default core LCA value (a so-called "actual" core LCA value). Under the leadership of the MIT ASCENT 1 team, AFTF agreed to a set of reporting requirements, including chain-of-custody aspects, needed for use of actual LCA values. The details of these requirements are given in CAEP/11-WP/44.

In summary, the use of actual core LCA values under CORSIA requires the economic operator (i.e., the fuel producer or airline) to document all relevant data in a technical report. The report is verified by an accreditation body and is made available on request to the certifying SCS, which then passes it on to ICAO on request. The relevant data include the following:

- GHG emissions by life-cycle step within the scope of certification, subdivided into GHG-emission species and aggregated in CO_2e;
- LCA inventory data by life-cycle step, including all energy and material balances;
- emission factors for calculating GHG emissions associated with energy and material inputs, including sources;
- all relevant feedstock characteristics (e.g., agricultural yield, lower heating value, and moisture content);
- quantities for all final and intermediate products, per total energy yield; and
- in the case of MSW feedstock, all relevant data required for the calculation of LEC and REC according to the MSW-crediting method agreed upon by AFTF.

The SCS is also required to report evidence that the economic operator has accurately followed the method agreed to under CORSIA, using the most recent and scientifically rigorous data available, and that the LCA calculation is complete, accurate, and transparent. The chain-of-custody system used should also be reported, and all data are to be recorded and reported to ICAO upon request in a format conducive to recalculation and verification.

The agreed-upon reporting method also requires each economic actor along the supply chain to implement a robust, transparent system to track the flow of data. Tracking should occur each time the feedstock or fuel passes through an internal processing step or changes ownership along the supply chain, and the SCS is required to implement procedures enabling verification that the economic operator used an appropriate chain-of-custody system.

Feedstock classification

Under the leadership of the MIT ASCENT 1 team, AFTF was able to reach agreement on a classification of feedstock types to be used under CORSIA. The three broad categories of feedstock include the following:

- Primary and co-products are the main products of a production process. These products have economic value and elastic supply (i.e., evidence of a causal link between feedstock prices and the quantity of feedstock being produced);
- By-products are secondary products with inelastic supply and some economic value.
- Wastes and residues are secondary products with inelastic supply and little to no economic value.

Using these definitions, AFTF further agreed to a set of feedstock definitions in an open positive list of by-products, residues, and waste feedstocks (summarized in Table 8). In addition, AFTF agreed upon a procedure for adding materials to this list (summarized in Figure 1). This work is discussed in detail in CAEP/11-WP/44.

Table 8. Positive list of materials classified as residues, wastes, or by-products

Residues
Agricultural residues:
- Bagasse
- Cobs
- Stover
- Husks
- Manure
- Nut shells
- Stalks
- Straw
Forestry residues:
- Bark
- Branches
- Cutter shavings
- Leaves
- Needles
- Pre- commercial thinnings
- Slash
- Tree tops
Processing residues:
- Crude glycerine
- Forestry processing residues
- Empty palm fruit bunches
- Palm oil mill effluent
- Sewage sludge
- Crude Tall Oil
- Tall oil pitch
Wastes
- Municipal solid waste
- Used cooking oil
By-products
- Palm Fatty Acid Distillate
- Tallow
- Technical corn oil

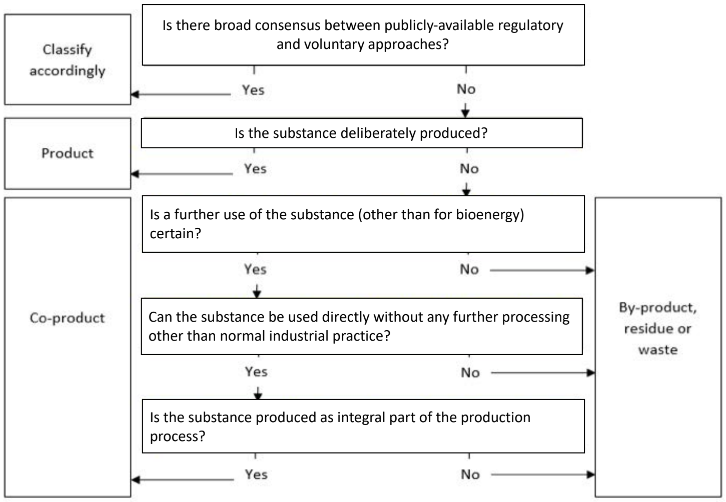

Figure 1. Guidance for inclusion of additional materials in the positive list

Method development for MSW-emission crediting

During this reporting period, the MIT ASCENT 1 team led an AFTF task group on emissions crediting. This small group addressed the following items relevant to MSW-emission credits:

- determining whether MSW-emission credits are consistent with the CAEP/10 LCA methodology;
- refining the LEC and REC methodologies previously agreed upon by AFTF; and
- evaluating the risk of double-counting emission credits, and assessing options to avoid or mitigate the risk.

This work is discussed in greater detail in CAEP/11-WP/46.

Consistency of MSW-emission credits with CAEP/10 LCA methods

The small group determined that emission credits are not consistent with the CAEP/10 LCA methodology, because AFTF had previously agreed on a process-based LCA approach for core LCA-value calculation. Emission credits imply a consequential approach distinct from the attributional approach otherwise adopted by AFTF for core LCA calculations.

To enable the inclusion of emission credits under CORSIA, the emissions-credit small group, under the leadership of the MIT ASCENT 1 team, developed rules for exceptional cases in which emission credits may be assigned to a SAF. Amended text was drafted for paragraph 12 of the CORSIA Implementation Elements (CAEP-SG/20183-WP/14) to allow for the inclusion of emission credits in these exceptional cases. This text, as currently written, strictly limits emission credits to the cases of LEC and REC calculated with the AFTF-approved methods and prohibits the issue of double issuance of emission credits.

Refinement of LEC and REC methods

During this reporting period, the emission-crediting small group (led by the MIT ASCENT 1 team) further developed the LEC and REC methods previously agreed upon by AFTF.

Specifically, the group compared the method developed by AFTF with the United Nations Framework Convention on Climate Change (UNFCCC) (UNFCC, 2018) Clean Development Mechanism (CDM) approach for crediting avoided landfilling emissions. One key reason for differences between the methods is the fundamentally different purposes of the two schemes: the CDM methodology credits ongoing behavior for a specific project, estimating avoided emissions on an annual basis, whereas the AFTF LEC methodology quantifies the emissions avoided over 100 years. The AFTF method follows diversion of MSW feedstock from a landfill and attributes it to the fuel produced from that MSW on a life-cycle basis for a unit of fuel. Other differences arise from technical details: CDM does not account for biogenic CO_2 emitted from, and sequestered in, landfills. The AFTF methodology provides guidance on estimating landfill gas collection to improve accuracy. Furthermore, the CDM includes an “uncertainty factor,” which cannot be directly applied to the AFTF method. Although the CDM method could be applied to calculate LEC instead of the approach proposed by AFTF, doing so would result in a time series of LEC emission credits, some of which could be claimed only in the years following SAF combustion. Adding this temporal index would add substantial complexity in the accounting of SAF to reduce offsetting obligations under CORSIA, including that the time series of reductions would extend past the end of CORSIA in 2035. Therefore, the emission-crediting small group proposed that AFTF continue to use the original methodological approach.

The REC methodology was also determined to need to cover only plastics and metals. This approach is appropriate because commercial operators indicated to AFTF that only plastics and metals are currently recovered, because other materials are more difficult and less lucrative to separate. Furthermore, a case study performed by the small group indicated that, even if glass were recovered, it would compose less than 3% of the total REC.

AFTF agreed on the LEC and REC methods proposed by the small group but noted that the methods should be revisited as more real-world data are collected.

Double-counting, and options to avoid and mitigate the risk of double-counting

Double-counting could occur if activities generating emission credits under CORSIA were to also result in fewer emissions being reported in another scheme, such as UNFCCC. For example, MSW-derived SAF might result in avoided landfill emissions, thus leading to a LEC. However, the state where the landfill is located might also report fewer emissions from the solid-waste-disposal sector to UNFCCC.

During this reporting period, the MIT ASCENT 1 team used the results of the CAEP/10 Fuel Production Assessment (CAEP/10-WP/44) to show that, even under conservative assumptions, the potential magnitude of double-counting of emission reductions under CORSIA is <5% of the projected international aviation CO_2 emissions in 2050. Notably, this calculation does not indicate the risk or likelihood of double-counting but instead indicates the potential magnitude of the phenomenon.

Several approaches to mitigate the risk of LEC/REC double-counting were evaluated by the small group. These included requiring adjustments to national inventories to account for LEC/REC credits claimed under CORSIA (which would avoid double-counting in principle but might be difficult to implement in practice); limiting the total life-cycle emissions value (LSf) value to ≥ 0 gCO_2e/MJ (which would decrease the risk of double-counting to a maximum of 2.6% of the 2050 international aviation CO_2, compared with 4.4% when LSf is allowed to be negative); and defining GHG-reporting requirements for the SCS, to allow national authorities to check for inconsistencies and make the corresponding adjustments noted above. The second of these options to mitigate the risk of double-counting, namely requiring LSf ≥ 0 gCO2e/MJ, was discussed in greater detail by AFTF, and the experts agreed that this practice could serve as an interim measure for mitigating double-counting.

Milestones

The work described above on this task represents the achievement of MS 1 as defined in the AY 2018/2019 Grant Proposal. The culmination of AFTF work on core LCA default-value calculations and emission crediting during CAEP/11 was presented to the Steering Group in February 2019. The MIT ASCENT 1 team wrote WPs 44, 45, and 46, which were presented by the FAA at this meeting, and prepared slide decks to communicate this information. In addition, the status of this work was reviewed at the first meeting of FTG for CAEP/12, during which the MIT ASCENT 1 team facilitated the drafting of a work program to continue to calculate default core LCA values for use in CORSIA during CAEP/12.

Major Accomplishments

The major accomplishments during this period of performance were the calculation of four additional default core LCA values and the writing of a comprehensive technical report documenting the calculation of default core LCA values, undertaken by AFTF during CAEP/11 for use under CORSIA. Furthermore, the MIT ASCENT 1 team led the development and agreement on methods to quantify avoided emissions from landfilling and recycling (LEC and REC), associated with MSW-derived SAFs under CORSIA. This work should enable the inclusion and use of AJF under CORSIA as soon as the policy goes into effect.

Publications

Peer-reviewed journal publications

N/A

Written reports

CAEP/11-WP/44, Core LCA values and methods, February 2019, Montreal, Canada.

CAEP/11-WP/45, Technical report outlining the methodology and calculation of default core life cycle emissions values for sustainable alternative fuels under CORSIA, February 2019, Montreal, Canada.

CAEP/11-WP/46, Emission credits from the production of CORSIA eligible fuels, February 2019, Montreal, Canada.

Outreach Efforts

Progress on these tasks was communicated during weekly briefing calls with the FAA and other U.S. delegation members to AFTF/FTG, numerous AFTF teleconferences between in-person meetings, and the first in-person meeting of FTG in May 2019. In addition, MIT presented its work under Project 1 to ASCENT at the biannual meetings in October 2018 (Alexandria, VA) and April 2019 (Atlanta, GA), in the form of a poster and presentation, respectively.

Awards

None.

Student Involvement

During the reporting period of AY 2018/2019, the MIT graduate students involved in this task were Juju Wang (graduated in the summer of 2019) and Uyiosa Oriakhi.

Plans for Next Period

In the coming year, the MIT ASCENT Project 1 team will continue its work in FTG. Default core LCA values will be calculated and proposed for additional pathways. Prof. Robert Malina from Hasselt University will continue to lead the core LCA Task Group. The work of the core LCA Task Group during CAEP/12 will be summarized in a series of working and information papers presented to FTG, and MIT will take a lead role in drafting papers.

References

CAEP/10-WP/44. (2016). Short-term and long-term alternative jet fuel production and associated GHG emissions reductions. Committee on Aviation Environmental Protection (CAEP). Montreal, Canada.

CAEP/11-WP/45. (2019). Technical report outlining the methodology and calculation of default core life cycle emissions values for sustainable alternative fuels under CORSIA. Montreal, Canada.

ICAO Document 10126. (2019). Report of the Eleventh Meeting of the Committee on Aviation Environmental Protection.

Intergovernmental Panel on Climate Change (IPCC). (2014). Climate Change 2014. Synthesis Report. https://www.ipcc.ch/pdf/assessment-report/ar5/syr/SYR_AR5_FINAL_full.pdf

United Nations Framework Convention on Climate Change (UNFCCC). (2018). AMS-III.G.: Landfill methane recovery – Version 9.0, Clean Development Mechanism. Valid from November 2014. The tool to estimate emissions from the solid waste disposal site is available at https://cdm.unfccc.int/methodologies/PAmethodologies/tools/am-tool-04-v8.0.pdf/history_view

Task 2 - Provide Guidance to CAEP on the Economic Impact of Potential Policies on AJF Financial Viability

Massachusetts Institute of Technology and Hasselt University

Objective

For AY 2018–2019 Task 2, the objective of the funded work was to quantify the impact of different policy options on the economic viability of AJF production, referred to as SAF in the ICAO context. This analysis was used to inform the work of the Policy Guidance Task Group of AFTF, by providing quantitative evidence of the effectiveness of policies that CAEP member states may be considering for supporting the deployment of AJF technologies. The analysis leverages techno-economic work and models that MIT developed previously, including the beginning of this modeling work with the Policy Guidance Task group of AFTF during AY 2017–2018. During AY 2018–2019, the stochastic techno-economic analysis (TEA) policy analysis work of AFTF was concluded for the CAEP/11 cycle.

Research Approach

Introduction

During CAEP/11, the Policy Task Group was tasked with “assessing specific industrial case studies in different world regions to extract lessons learned.” Technical experts from MIT, Purdue University, and Hasselt University volunteered to lead this analysis, by performing stochastic TEA of different SAF production pathways and quantifying the impact of potential policies on their economic viability.

The purpose of the stochastic TEA presented here is to assess the impact of policies being considered by some CAEP member states to support the deployment of SAF production technologies. The results quantify the impact of policies on the economic viability of SAF production in terms of two metrics: net present value (NPV) and minimum selling price (MSP). This work took place over the entire CAEP/11 cycle; however, it was concluded and documented in a CAEP WP during the reporting period, which was presented to the CAEP Steering Group in February 2019.

Methods

Six different SAF production pathways were selected as case studies for the stochastic TEA, as shown in Table 9. These were chosen by consensus among the Policy Task Group members to reflect SAF pathways that are close to commercialization in different world regions.

Table 9. Case studies selected for stochastic TEA policy assessment

Process	Feedstock	Region	Company example
Micro FT	Forest residues	North America	Velocys
SIP	Sugarcane	South America	Total-Amyris
HEFA	Waste tallow and yellow grease	North America/ Europe	Altair/Neste
HEFA	Palm oil/palm fatty acid distillates (PFAD)	Asia and Pacific	Pertamina
FT	Municipal solid waste	North America	Fulcrum
ATJ via iBuOH	Corn	North America	Gevo

For evaluation of economic viability, the stochastic TEA model described in Bann et al. (2017) was adapted to reflect the case studies described above. The model builds on a number of previously published studies and modeling efforts (Martinkus et al., 2017; McGarvey and Tyner, 2018; Pearlson et al., 2013; Suresh et al., 2018). The model and assumptions are described in greater detail in Sections 1 and 2 of Appendix A to CAEP/11-WP/50. The results shown here should be considered preliminary, because additional robustness checks are still required before they can be finalized.

Four different policy types were considered in this analysis: input subsidy, modeled as a percentage reduction in the feedstock cost seen by the SAF producer; capital grant, which decreases the fixed capital investment of a new SAF production facility; output-based incentive, which increases the price received by the SAF producer for fuel products; and GHG-emission-reduction-defined incentive, modeled as a revenue stream received by the SAF producer equal to the product of the fuel volume, the life-cycle emission reduction relative to petroleum-derived jet fuel, and the assumed value of emission offsets. These policy types are summarized in Table 10, and the life-cycle emission values used to determine the GHG-emission-reduction-defined incentive are given in Table 11.

Table 10. Policy type to be considered in stochastic TEA policy assessment

Policy type	**Implementation in stochastic TEA model**
Input subsidy	Reduce feedstock costs seen by fuel producer by subsidy amount
Capital grant	Reduce initial capital cost by grant amount
Output-based incentives	Increase prices received by fuel producer for products by incentive amount
GHG-emission-reduction-defined incentive	Increase prices received by fuel producer for products, as a function of GHG reduction from petroleum fuels

Table 11. LCA values used for GHG-emission-reduction policy

Pathway	**GHG emissions (gCO_2e/MJ)**
Micro FT (wood residue)	8.3
SIP (sugarcane)	50.6
HEFA (FOG)	22.5
HEFA (palm oil/palm fatty acid distillates)	20.7
FT (MSW)	40
ATJ via iBuOH (corn)	75**

**This will depend on the calculation of a land-use-change emission factor, which remains to be determined.

In addition to the baseline no-policy results, NPV and MSP distributions were generated under these policies for three cases: an equivalent total cost analysis, quantifying the impact of the four policy types at the same total policy cost; a break-even analysis, which identifies the magnitude of each individual policy required to achieve an NPV of zero for each SAF pathway; and specific policy cases reflecting policies similar to those currently existing in the real world.

Preliminary results

The preliminary results of this analysis indicate that, in the baseline no-policy case, the mean MSPs of all six SAF pathways are greater than the current market price for conventional jet fuel of approximately 0.55 USD/L (IATA jet-fuel price monitor, accessed November 2018). The lowest mean MSP is 0.67 USD/L for MSW Fischer–Tropsch (FT) fuel, and the greatest is 1.52 USD/L for wood-residue FT. The baseline results for MSP and NPV are presented in Figure 2 and Figure 3 below. The results show the reference point when no policies have been implemented. The red line shows the median value, the boxes are marked at the 25th and 75th percentiles, and the whiskers extend to the furthest data points not considered outliers. The current selling price of jet fuel of 0.55 USD/L is shown as a blue vertical line.

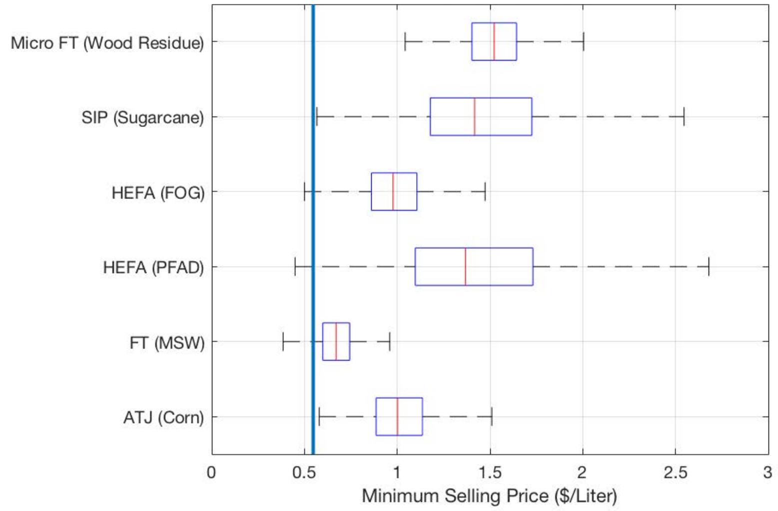

Figure 2. MSPs for the six modeled case studies

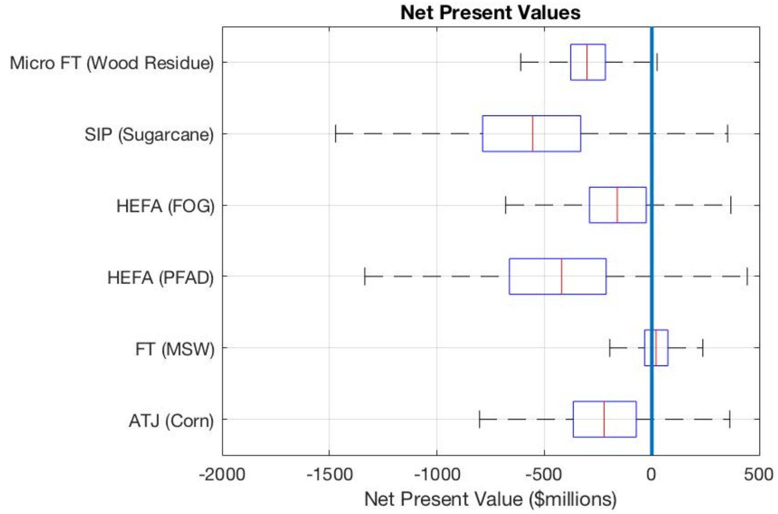

Figure 3. NPVs for the six modeled case studies

The preliminary results of the equivalent policy cost analysis indicate that different policies have different impacts on the mean and variance of SAF MSPs. For example, the capital-grant policy is found to be most effective at reducing the mean MSP at a given total policy cost, because the capital grant decreases the equity and debt required to build the SAF facility, and these benefits are not taxed in the discounted cash-flow model. In contrast, the feedstock input subsidy is shown to be more effective at reducing variance (and therefore risk) in the MSP results at an equivalent total policy cost, because variability in feedstock costs is a significant contributor to uncertainty in MSP. Because the feedstock input-subsidy policy is implemented as a percentage of total feedstock cost, the variability in feedstock costs (and the resultant uncertainty in MSP) is borne in part by the policy.

These findings indicate that policy-makers may wish to select different policy mechanisms depending on their objectives. For example, if reducing the average fuel cost of SAF is the primary policy objective, a capital grant may be a more appropriate policy. In contrast, if reducing fuel price uncertainty is the primary policy objective, a feedstock input subsidy may be a more appropriate policy. The equivalent total policy cost results are discussed in greater detail in Sections 5 and 9 of Appendix A in CAEP/11-WP/50. Example preliminary results for the equivalent policy cost analysis, as applied to the hydroprocessed ester and fatty acid (HEFA) fat, oil, and grease (FOG) pathway, are shown in Table 12.

Table 12. Policy cases for each of the four policy types, and the resulting total policy costs and effects on fuel MSP for the HEFA FOG pathway (mean values with standard deviation in brackets)

HEFA (FOG)			
Policy type	**Output subsidy**		
Policy	0.10 $/L output subsidy	0.25 $/L output subsidy	0.50 $/L output subsidy
Total policy cost ($ million) [standard deviation]	77 [3]	192 [8]	384 [15]
MSP ($/L) [standard deviation]	0.89 [0.19]	0.74 [0.19]	0.49 [0.19]
Policy type	**Input subsidy**		
Policy	14% subsidy on feedstock costs	36% subsidy on feedstock costs	71% subsidy on feedstock costs
Total policy cost ($ million) [standard deviation]	77 [19]	194 [50]	388 [102]
MSP ($/L) [standard deviation]	0.90 [0.16]	0.75 [0.13]	0.50 [0.07]
Policy type	**Capital grant**		
Policy	$77 million capital grant	$192 million capital grant*	$384 million capital grant*
Total policy cost ($ million) [standard deviation]	74 [4]	79 [9]	79 [10]
MSP ($/L) [standard deviation]	0.88 [0.19]	0.87 [0.19]	0.87 [0.19]
Policy type	**GHG-emission reduction policy**		
Policy	CO_2-reduction credit of 46 USD/t	CO_2-reduction credit of 114 USD/t	CO_2-reduction credit of 228 USD/t
Total policy cost ($ million) [standard deviation]	77 [3]	192 [8]	384 [15]
MSP ($/L) [standard deviation]	0.89 [0.19]	0.74 [0.19]	0.49 [0.19]

*The size of the capital grant in these cases is limited by total estimated CapEx: we have not considered capital grants that exceed total CapEx. For example, although the actual equivalent-cost policy to a 0.25 USD/L output subsidy would be a $192 million capital grant, in practice the total capital-grant policy cost is a mean of $79 million in this case. This is the mean estimated total CapEx of the facility, and the capital grant has not been allowed to exceed total CapEx.

The preliminary results of the break-even analysis demonstrate that each of the individual policies could be large enough to achieve an NPV of zero, with the exception of the capital grant, which was limited to being no greater than the total fixed capital investment. The magnitude of the median input subsidy required for breaking even ranges from 39% of feedstock costs for the corn-grain iBuOH ATJ pathway to 207% of feedstock costs for the wood-residue FT pathway, depending on the SAF pathway being considered. The magnitude of the output-based incentive for an NPV of zero ranges from 0.05 USD/L for the MSW FT pathway to 0.77 USD/L for the sugarcane SIP pathway. The magnitude of a GHG-based reduction incentive (applied to all fuel products) required for an NPV of zero ranges from 106 USD/t_{CO2e} for the HEFA FOG pathway to 658 USD/t_{CO2e} for the corn iBuOH ATJ pathway. These results depend on the SAF-production pathway being considered. Example preliminary results for the break-even GHG-emission-reduction-incentive policy are shown in Figure 4.

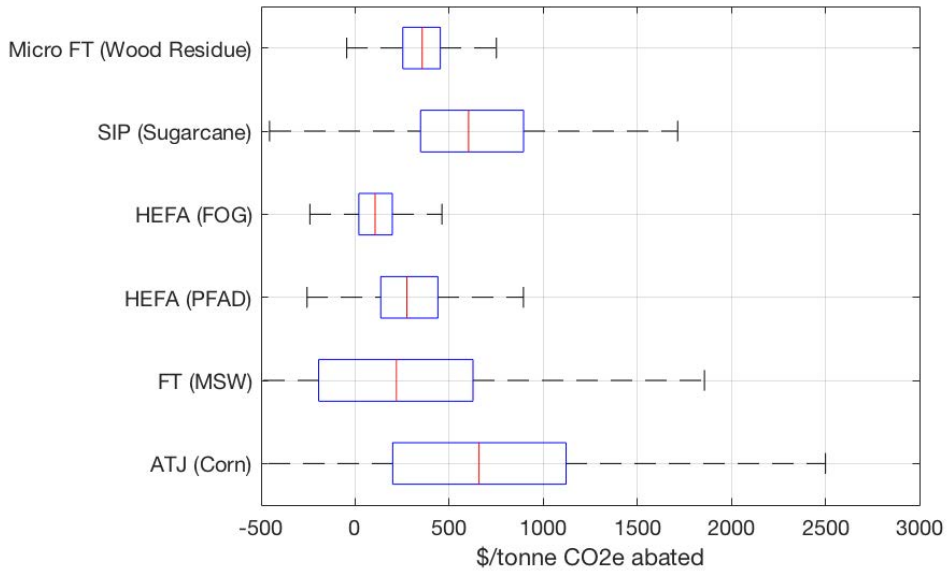

Figure 4. Break-even GHG-emission-reduction-incentive policy applied to all fuels for all pathways

Notably, in the breakeven analyses described above, each policy was considered in isolation. In practice, however, a combination of policy mechanisms from various or overlapping jurisdictions may be necessary to reach economic viability of SAF technologies. Therefore, we also considered a number of policies indicative of renewable-fuel incentives that exist in the real world and may be combined to improve the economic viability of SAF production.

The cases that we considered to be more representative of real-world policies are as follows:

- 27% feedstock cost subsidy (similar to existing feedstock subsidies in the Indonesian context)
- $5 million capital grant (similar to grants awarded by the U.S. Department of Energy and Bioenergy Technologies Office (U.S. DOE and U.S. BETO))
- GHG-reduction credit of 20 USD/t_{CO2e}, ramping up to 40 USD/t_{CO2e} by 2035 (equivalent to the high-range values used by GMTF in the CORSIA cost–benefit analysis)
- Output subsidy of 0.25 USD/L (similar to historical highs for renewable identification number (RIN) prices under the U.S. Renewable Fuels Standard (U.S. Environmental Protection Agency, 2015))

The preliminary results of these cases are presented in Section 7 of Appendix A of CAEP/11-WP/50 and are summarized in Table 13.

Table 13. Real-world policy effects on SAF MSP

Policy case	**No policy**	**27% feedstock cost subsidy**	**$5 million capital grant**	**20 USD/tonne$_{CO2}$ reduction credit (40 USD/tonne$_{CO2}$ by 2035)**	**0.25 USD/L output subsidy**	**All four policies**
Units	**MSP [$/L]**	**ΔMSP [$/L]**	**ΔMSP [$/L]**	**ΔMSP [$/L]**	**ΔMSP [$/L]**	**ΔMSP [$/L]**
Pathway						
Micro FT (wood residue)	1.53	−0.12	−0.01	−0.01	−0.46	−0.60
SIP (sugarcane)	1.49	−0.29	−0.01	−0.03	−0.22	−0.55
HEFA (FOG)	1.00	−0.19	−0.01	−0.01	−0.27	−0.48
HEFA (palm oil/palm fatty acid distillates)	1.46	−0.33	−0.01	−0.02	−0.24	−0.60
FT (MSW)	1.05	0.00	−0.01	−0.00	−0.30	−0.32
ATJ (corn)	1.02	−0.23	−0.01	−0.21	−0.01	−0.46

The preliminary results of this analysis demonstrate that the impact of each policy on the MSP is roughly linear with magnitude, and furthermore that the impacts of each policy type on MSP are independent and can be added together. Therefore, these results are useful to approximate the impacts of any combination of the four policies considered, at different magnitudes from those explicitly quantified here. This is demonstrated in the final column of Table 13: the reduction in MSP when all four policies are considered simultaneously is equal to the sum of the reduction in MSP from each of the individual policies.

Milestone

This analysis was completed and documented in CAEP/11-WP/50 and presented by the FAA to CAEP Steering Group in February 2019. It is also documented in an MIT Master's degree thesis submitted in August 2019. This represents completion of Milestone 2 in the AY 2018/2019 Grant Proposal Narrative.

Major Accomplishments

The MIT ASCENT 1 team drafted and submitted a WP to CAEP, documenting this policy analysis work and concluding the objectives of the Policy Task Group of AFTF during CAEP/11. This work also culminated in the drafting of an MIT Master's thesis, to be submitted in August 2019, and an associated journal publication.

Publications

Peer-reviewed journal publications

Z.J. Wang, M.D. Staples, W.E. Tyner, X. Zhao, R. Malina, S.R.H. Barrett. "Quantitative policy analysis for aviation biofuel production technologies" (*in preparation*)

Written reports

CAEP/11-WP/50, Summary of the work of the policy task group, February 2019, Montreal, Canada.

Outreach Efforts

Progress on these tasks was communicated during weekly briefing calls with the FAA and other U.S. delegation members to AFTF/FTG, numerous AFTF teleconferences between in-person meetings, and the first in-person meeting of FTG in May 2019. In addition, MIT presented its work under Project 1 to ASCENT at the biannual meetings in October 2018 (Alexandria, VA) and April 2019 (Atlanta, GA), in the form of a poster and presentation, respectively. Juju Wang presented the TEA analysis at the ICAO SAF stocktaking event in April 2019.

Awards

None.

Student Involvement

Juju Wang, Master's degree student at MIT's Department of Aeronautics and Astronautics performed most of the analysis, constituting her master's thesis. She graduated in August 2019.

Plans for Next Period

The work is being prepared for submission to a peer-reviewed journal. The complete work, in the form of a Master's degree thesis, will be available on the website of the Lab for Aviation and the Environment at MIT in the fall of 2019. In addition, the models and analysis described here were shared in June 2019 with other ASCENT researchers (from Purdue and Hasselt Universities) to continue to build on this work.

References

Bann, S.J., Malina, R., Staples, M.D., Suresh, P., Pearlson, M., Tyner, W.E., Hileman, J.I., Barrett, S.R.H. (2017). The costs of production of alternative jet fuel: A harmonized stochastic assessment. Bioresource Technology, Volume 227. (http://www.sciencedirect.com/science/article/pii/S0960852416316911)

Martinkus, N., Latta, G., Morgan, T. & Wolcott, M. (2017). A comparison of methodologies for estimating delivered forest residue volume and cost to a wood-based biorefinery. Biomass and Bioenergy, 106: 83-94. doi:10.1016/j.biombioe.2017.08.023 (https://www.sciencedirect.com/science/article/pii/S0961953417302672)

McGarvey, E., Tyner, W.E. (2018). A stochastic techno-economic analysis of the catalytic hydrothermolysis aviation biofuel technology. Biofuels, Bioprod. Biorefin. https://doi.org/10.1002/bbb.1863

Pearlson, M., Wollersheim, C., Hileman, J. (2013). A techno-economic review of hydroprocessed renewable esters and fatty acids for jet fuel production. Biofuels, Bioprod. Biorefin. 7, 89–96. http://dx.doi.org/10.1002/bbb.1378.

Suresh, P., R. Malina, M.D. Staples, S. Lizin, H. Olcay, D. Blazy, M.N. Pearlsonm S.R.H. Barrett, Life cycle greenhouse gas emissions and costs of production of diesel and jet fuel from municipal solid waste. (2018). Environmental Science & Technology, Volume 52. DOI: 10.1021/acs.est.7b04277

U.S. Environmental Protection Agency, 2015. A preliminary assessment of RIN Market Dynamics, RIN Prices, and their effects.

Task 3 - Develop Tools and Resources to Assess AJF Production Ramp-up under CORSIA

Massachusetts Institute of Technology and Hasselt University

Objective

The objective of this task is to develop tools and resources to assess AJF-production ramp-up under various policy options, including CORSIA offsets. This work will be used by the Technology, Production and Policy Task Group of ICAO CAEP FTG during CAEP/12.

Research Approach

At the CAEP Steering Group meeting in February 2019, a work program for FTG was agreed upon by the FTG Rapporteurs and the Secretariat. This is summarized in CAEP/12-FTG/01-WP/02 and includes Task S.09, the fuel-production evaluation. The objective of S.09 is to use data on the current offtake of CORSIA-eligible AJF, existing stochastic TEA models (as described in Section 2), and information from the CAEP/10 AFTF Fuel Production Assessment to assess AJF availability through the year 2035 on the basis of the range of estimated offset prices developed by GMTF.

When drafting the Grant Proposal Narrative for AY 2018/2019, the MIT ASCENT Project 1 team anticipated that this task would focus on the further development and use of a systems dynamics model described by Staples (2017). The strength of a dynamic modeling approach is that it captures systemic feedback occurring over time, such as learning by doing with nascent technologies, and non-linearities in land-use-change emissions due to feedstock demands. However, after the CAEP/12 work program was decided upon, it became clear that greater focus would be placed on the relationship between CORSIA offsets (and other policy incentives) and the availability of AJF volumes. This focus requires detailed economic modeling of the relationship between policy levers and AJF availability, to which a systems dynamics approach is not especially well suited.

Therefore, in preparation for the first meeting of FTG in May 2019, the MIT ASCENT 1 team reviewed and summarized the existing capabilities within AFTF/FTG that would be best suited to carrying out the Task S.09 fuel production evaluation for ICAO CAEP. This review resulted in a proposed plan for execution of this task, as documented in CAEP/12-FTG/01-WP/06 and agreed to by FTG, which uses the following tools and resources:

- Short-term AJF projection estimates developed and maintained by AFTF over the previous two CAEP cycles. This is a database of commercial AJF-production projects in various stages of development. The database will be a valuable resource in estimating the volumes of AJF in the near term as well as the feedstocks from which this fuel will be produced and can serve as a starting point for projections through 2035.

- Data from the CAEP/10 Fuel Production Assessment (FPA), which estimated the potential volume of AJF available through 2050, and the associated reduction in international aviation GHG emissions. The methods used for the FPA require several adaptations. First, the time scale of the CAEP/12 AJF availability analysis is 2035, as compared with the 2050 focus of CAEP/10 FPA. In addition, the nearer-term scope of this analysis would benefit from a narrower feedstock scope, to collect more detailed data on feedstocks likely to be commercialized by 2035. Specifically, the task could emphasize high-resolution data on waste and residue feedstocks, including (but not necessarily limited to) waste FOGs; agricultural residues; forestry residues; and MSW. The availability of these feedstocks as a function of price would be required to eventually estimate the impacts of CORSIA offset prices on AJF availability and economic viability.

- The stochastic TEA models described in Task 2 can be used to evaluate the economic viability of AJF production as a function of feedstock costs, under different CORSIA offset prices. The monetary value of CORSIA for fuel producers can be estimated by combining core LCA and ILUC values from the other task groups of CAEP/11 AFTF and FTG, together with CORSIA offsets estimates from GMTF.

The CAEP/10 FPA was performed at a global scale, and the analysis was led primarily by experts from the United States. However, this CAEP/12 task requires much higher-resolution feedstock data, including feedstock availability as a function of price. Therefore, the MIT ASCENT 1 team focused on world regions in which it has particular expertise, namely the United States and Europe.

Milestone

At the first meeting of the Fuels Task Group (FTG) of ICAO CAEP in May 2019, the MIT ASCENT 1 team presented a summary of tools and resources that can be used for fuel production evaluation and policy guidance to FTG during CAEP/12, as documented in CAEP/12-FTG/01-WP/06. This achievement represents the completion of Milestone 3 in the Grant Proposal Narrative for AY 2018/2019.

Major Accomplishments

The MIT ASCENT 1 team submitted and presented a WP to FTG, documenting the tools and resources available to accomplish Task S.09 fuel production evaluation for the CAEP/12 cycle.

Publications

Peer-reviewed journal publications

T.R. Galligan, M.D. Staples, R.L. Speth, S.R.H. Barrett. “Life cycle greenhouse gas emission reduction potential of aviation biofuels in the US” (*in preparation*)

Written reports

CAEP/12-FTG/01-WP/06, Discussion on the CAEP/12 workplan for the technology and production subgroup, May 2019, Montreal, Canada.

Awards

None.

Student Involvement

None.

Plans for Next Period

In the following period, the MIT team plans to support the development of methods to quantify the impacts of policy and incentives for global AJF production.

References

CAEP/12-FTG/01-WP/02, Work programme, structure and administration. (2019). Montreal, Canada.

CAEP/12-FTG/01-WP/06, Discussion on the CAEP/12 workplan for the technology and production subgroup. (2019). Montreal, Canada.

Staples, M. (2017). Bioenergy and its use to mitigate the climate impact of aviation. PhD Thesis submitted to the Massachusetts Institute of Technology.

Task 4 - Environmental and Economic Assessment of Co-processing Renewable Lipids in Petroleum Refineries

Massachusetts Institute of Technology

Objective

The objective of this task was to carry out an environmental and economic assessment of co-processing of renewable lipids in petroleum refineries. Recently, ASTM approved the addition of as much as 5% v/v lipid feedstock to petroleum-refining units, thus making this pathway important for use under CORSIA.

Research Approach

Introduction

Previous studies have considered the possibility of integrating bio-oils into the hydro-treating (Huber & Corma, 2007; Talmadge et al., 2014; Wang et al., 2012) or fluid catalytic cracking (FCC) (Bianchi et al., 2016; Graca et al., 2009; Schuurman et al., 2013) units at petroleum refineries. However, to date, no bottom-up assessment of the environmental and economic implications of lipid co-processing for AJF production has been performed.

Therefore, the approach taken to accomplish this task was to review the literature for the availability of empirical data on co-processing of biogenic feedstocks in petroleum refineries. The next step was to use the empirical data to quantify the effect of co-processing on life-cycle GHG emissions and production costs.

Methods

A review of the literature on co-processing highlighted several areas for which careful consideration will be required (Bezergianni et al., 2018). For example, in the peer-reviewed literature “co-processing of biogenic feedstocks” refers to both lipid (e.g., vegetable oils, used cooking oil, and waste grease) and bio-oil feedstocks (e.g., pyrolysis oils, or oils from other thermo-chemical processes). Furthermore, these feedstocks may be handled in either the hydro-treater or the fluid catalytic cracking (FCC) units of petroleum refineries. The simplest case is that of hydro-treating (which has less complex reaction kinetics than FCC) of vegetable oils (which are a homogenous, well-characterized feedstock). Therefore, we decided to begin the LCA and TEA analysis of the effects of co-processing there and to build up to more complicated cases.

Several methodological decisions must be considered for the LCA of co-processing. These are best discussed by using a simple example, illustrated in Figure 5. The Δ values indicate the changes in the mass and energy balances of the hydro-treater, from a business-as-usual (BAU) case (in which all Δ values equal 0), because of co-processing.

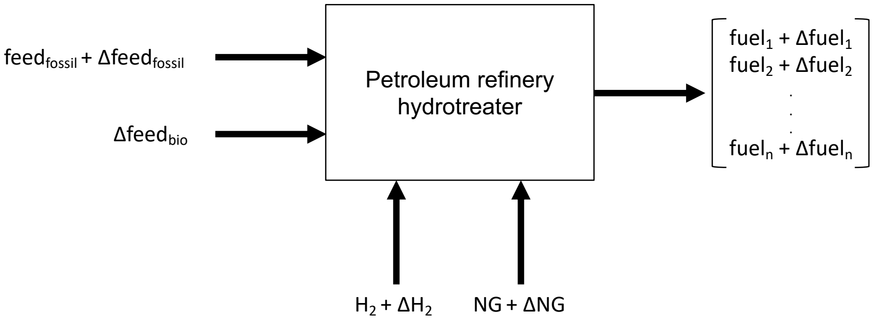

Figure 5. Example of co-processing mass and energy balance

The first methodological challenge is determining which fuel products ($fuel_1$ to $fuel_n$) will ultimately contain the carbon from the biogenic feedstock ($feed_{bio}$), and in what quantity. One means of accomplishing this task is the use of carbon-14 dating to determine the organic fraction of carbon in each fuel cut; however, ongoing testing may be required for each facility performing co-processing. Alternatively, a proportional approach may be used, in which the percentage of biogenic carbon in all fuel products is assumed to be equal to the percentage of biogenic carbon in the sum of the fossil and biogenic feedstock inputs.

A second challenge is deciding how to account for the change in life-cycle emissions due to co-processing. One option is to assume that the life-cycle emissions of all fuel products are affected in equal proportion by co-processing, relative to the BAU case. A second option is assuming that all changes in life-cycle emissions accrue to the biogenic fraction of fuel products (determined by either carbon-14 dating or a proportional approach), with the life-cycle emissions of the fossil fraction remaining the same as in the BAU case.

To illustrate the effects of these methodological decisions, the MIT ASCENT Project 1 team performed first-order analysis on the effects of co-processing on life-cycle emissions and the costs of production inputs. This analysis was based on empirical data from two peer-reviewed studies: Garrain et al. (2014), which considers soybean oil co-processed with mineral diesel in a hydro-treater, and Bezergianni et al. (2014), which considers waste cooking oil (WCO) co-processed with heavy atmospheric gas oil (HAGO) in a hydrotreater. For this analysis, a proportional approach was considered for determining the fate of biogenic carbon, owing to a lack of carbon-14 dating data.

For each data source, two methodological approaches were used. For method 1, the emission impact of co-processing (relative to a BAU case) is attributed to the entire product slate. For method 2, the emission impact is attributed only to the biogenic fraction of the fuel product, with the emissions of the fossil fraction remaining constant. The empirical mass and energy balances from that paper are used to determine the variable quantities referenced in Figure 1. The analysis assumes the BAU life-cycle emissions of the fuel products to be 89.0 gCO_2e/MJ (consistent with the CORSIA baseline) and uses life-cycle emission factors for gaseous hydrogen, natural gas as a stationary fuel in an industrial boiler, soybean oil as a biofuel feedstock, and conventional crude oil from GREET 2018 to calculate the effects on life-cycle emissions (Greenhouse Gases, Regulated Emissions, and Energy use in Transportation (GREET) Model, 2018). Two scenarios were considered: in the first scenario, life-cycle emissions were assumed to be spread across the entire fuel-product slate; and in the second scenario, the life-cycle emission impact on the biogenic fraction was calculated by assuming constant life-cycle emissions for the fossil fraction of 89.0 gCO_2e/MJ.

Unit costs for West Texas Intermediate crude oil, soybean oil, natural gas, hydrogen, and gate prices for U.S. Gulf Coast diesel were used to estimate the effects of co-processing on unit production input cost, relative to a BAU case (Energy Information Agency (EIA), 2019a; Energy Information Agency (EIA), 2019b; Macrotrends, 2019).

Results

LCA results

Under LCA method 1 (spreading emission impacts over the entire product slate), the data from both studies showed relatively moderate reductions in life-cycle emissions relative to the 89.0 gCO_2e/MJ baseline. With the data from Garrain et al. (2014), the greatest reduction in life-cycle emissions is 1.5 gCO_2e/MJ with a 12.2% soy oil/mineral diesel blend (v/v%). With the data from Bezergianni et al. (2014), the greatest reduction in life-cycle emissions is 14.4 gCO_2e/MJ with a 30% WCO/HAGO blend (v/v%).

Under LCA method 2 (in which emission impacts are attributed only to the biogenic fraction), the data from both studies showed larger emission reductions relative to the 89.0 gCO_2e/MJ baseline, but only for a (relatively small) fraction of the fuel product proportional to the volumetric fraction of biogenic feedstock. With the data from Garrain et al. (2014), the greatest reduction in life-cycle emissions is 16.7 gCO_2e/MJ with a 12.2% soy oil/mineral diesel blend (v/v%). With the data from Bezergianni et al. (2014), the greatest reduction in life cycle emissions is 58.6 gCO_2e/MJ with a 30% WCO/HAGO blend (v/v%).

Several aspects should be noted to properly contextualize these results. First, the ASTM standard currently limits biogenic co-processing to 5% by volume of input feedstock. Therefore, the greatest emission reductions shown here could not be achieved for commercial jet-fuel production, given the current standard. Furthermore, much smaller life-cycle-emission reductions are observed from Garrain et al. (2014) because those data show a negative effect of co-processing on total product yield, and therefore more petroleum feedstock is required per unit of fuel product. This phenomenon is not present in the Bezergianni et al. (2014) data.

The results of this analysis illustrate the potential effects of methodological decisions regarding the LCA of biogenic feedstock co-processing and identify key areas for further analysis. In particular, the results highlight the importance of the effects of co-processing on total fuel yield as a key determinant of life-cycle emissions. Further empirical data are required to clarify these effects.

TEA results

The MIT ASCENT Project 1 team also performed a first-order approximation of the effects of co-processing on process input costs per unit output. With the data from Garrain et al. (2014), each 1% increase in v/v% fraction of biogenic co-processing results an approximate 2% increase in process input costs (in terms of petroleum and biogenic feedstocks, hydrogen, and natural gas). With the Bezergianni et al. (2014) data, each 1% increase in v/v% fraction of biogenic co-processing results in an approximate 0.8% increase in process input costs.

Similarly to the LCA analysis, in this analysis, the primary cause of the discrepancy between data sources is the effect of biogenic co-processing on overall fuel yield: the data from Garrain et al. (2014) show a negative correlation between the biogenic co-processing fraction and overall product yield, whereas the data from Bezergianni et al. (2014) do not show this relationship. The greater effect on process input costs with the Garrain et al. (2014) data than the Bezergianni et al. (2014) data is primarily due to the increased requirement for petroleum feedstock per unit product.

Notably, that this analysis accounts for only the effects of co-processing on variable operating costs, namely the cost of process inputs. As a result of this simplification, for example, the baseline process input costs for the Garrain et al. (2014) data constitute 0.36 $\$/kg_{product}$, whereas the current market price for U.S. Gulf Coast diesel is 0.66 $/kg. The 0.30 $/kg difference between the two is due to factors beyond the scope of this screening-level analysis, such as refinery capital and fixed operating costs, taxes, and profit margins.

Milestone

This analysis was documented in CAEP/12-FTG/01-WP/08 presented at the first meeting of ICAO CAEP FTG, in May 2019 in Montreal, Canada. In addition, the data, analysis, and slides summarizing the findings were shared with the FAA and other members of the ASCENT Project 1 team involved in FTG in June 2019. This represents completion of Milestone 5 in the Grant Proposal Narrative for AY 2018/2019.

Major Accomplishments

The major accomplishments from this task include the first-order assessment of the environmental and economic characteristics of co-processing of biogenic lipid feedstocks in a petroleum refinery. These accomplishments resulted in the writing and presentation of CAEP/12-FTG/01-WP/08 at the first meeting of FTG. In addition, the literature review and analysis performed to date, and shared with the FAA and other ASCENT Project 1 team members, will form the basis for further analysis during the CAEP/12 cycle.

Publications

Peer-reviewed journal publications

N/A

Written reports

CAEP/12-FTG/01-WP/08, Discussion on the CAEP/12 workplan for the core LCA subgroup, May 2019, Montreal, Canada.

Outreach Efforts

The work to-date was presented in a working paper at the first meeting of FTG, in May 2019 in Montreal, Canada.

Awards

None.

Student Involvement

The MIT graduate students involved in this task were Uyiosa Oriakhi and Tae Joong Park.

Plans for Next Period

Co-processed AJF fuels will be included under CORSIA during the CAEP/12 cycle. Therefore, a robust LCA method for quantifying their life-cycle emissions should be developed for this purpose. The analysis and resources developed under this task can be leveraged in the next period to contribute to this task in the context of FTG.

References

Bezergianni, S., A. Dimitriadis, O. Kikhtyanin, D. Kubicka. (2018). Refinery co-processing of renewable feeds, Progress in Energy and Combustion Science. 68, DOI: 10.1016/j.pecs.2018.04.002

Bianchi, D; Perego, C; Capuano, F. (2016). Biomass Transformation by Thermo- and Biochemical Processes to Diesel Fuel Intermediates. in Chemicals and Fuels from Bio-Based Building Blocks, F. Cavani, S. Albonetti, F. Basile, and A. Gandini, Eds. Wiley-VCH Verlag GmbH & Co. KGaA.

Energy Information Agency (EIA), US Government, 2019a. *Petroleum & other liquids – Spot prices*, https://www.eia.gov/dnav/pet/pet_pri_spt_s1_d.htm, Accessed 05/06/2019

Energy Information Agency (EIA), US Government, 2019b. *United States natural gas industrial price,* https://www.eia.gov/dnav/ng/hist/n3035us3m.htm, Accessed 05/06/2019

Garrain, D., I. Herrara, Y. Lechon and C. Lago. (2014). Well-to-Tank environmental analysis of a renewable diesel fuel from vegetable oil through co-processing in a hydrotreatment unit, Biomass and Bioenergy. 63, DOI: 10.1016/j.biombioe.2014.01.035

Graça, I; Ramoa Ribeiro, F; Cerqueira, HS; Lam, YL; de Almeida, MBB. (2009). Catalytic cracking of mixtures of model bio-oil compounds and gasoil, Applied Catalysis B: Environmental, vol. 90, no. 3, pp. 556–563.

Greenhouse Gases, Regulated Emissions, and Energy use in Transportation (GREET) Model. (2018). http://greet.es.anl.gov/

Huber, GW; Corma, A. (2007). Synergies between bio- and oil refineries for the production of fuels from biomass. Angew. Chem. Int. Ed. Engl., vol. 46, no. 38, pp. 7184–7201.

Macrotrends. (2019). *Soybean oil prices – 45 year historical chart*, https://www.macrotrends.net/2538/soybean-oil-prices-historical-chart-data

Schuurman, Y; Fogassy, G; Mirodatos, C. (2013). Chapter 10 - Tomorrow's Biofuels: Hybrid Biogasoline by Co-processing in FCC Units, in The Role of Catalysis for the Sustainable Production of Bio-fuels and Bio-chemicals, K. S. Triantafyllidis, A. A. Lappas, and M. Stöcker, Eds. Amsterdam: Elsevier, pp. 321–349.

Talmadge, MS; Baldwin, RM; Biddy, MJ; McCormick, RL; Beckham, GT; Ferguson, GA; Czernik, S; Magrini-Bair, KA; Foust, TD;Metelski, PD; Hetrick, C; Nimlos, MR. (2014). A perspective on oxygenated species in the refinery integration of pyrolysis oil, Green Chemistry, Vol. 16, no. 2, pp. 407–453.

Wang, C; Tian, Z; Wang, L; Xu, R; Liu, Q; Qu, W; Ma, H; Wang, B. (2012). One-step hydrotreatment of vegetable oil to produce high quality diesel-range alkanes, in ChemSusChem, Vol. 5, no. 10, pp. 1974–1983.

Task 5 - Support Coordination of all A01 Universities' Work on AJF Supply-chain Analyses

Massachusetts Institute of Technology

Objective

The objective of this task is to provide support for coordination of all ASCENT Project 1 Universities' work on AJF supply-chain analysis. The sharing of method and results decreases the replication of ASCENT Project 1 Universities' work on similar topics.

Research Approach

The MIT ASCENT Project 1 team performed several functions to accomplish this task.

- Participated in the bi-weekly ASCENT Project 1 coordination teleconferences, which were used as a venue to discuss progress on various grant tasks and learn about the activities of other ASCENT Universities.
- Presented twice at the CAAFI bi-annual general meeting in December 2018 in Washington, DC. One presentation focused on core LCA analysis performed in the context of ICAO CAEP, and the other summarized an analysis to quantify the potential for AJF production in the United States. In addition, the stochastic TEA work performed by the MIT ASCENT Project 1 team was presented in a CAAFI webinar in January 2019.
- Shared a model and code with collaborators at Volpe via Dropbox, as explained during a teleconference on May 31, 2019. This model and code quantify the availability of biomass feedstocks in the United States, and the Volpe team is planning to incorporate these data into the AFTOT model.

Milestone

The MIT ASCENT Project 1 team presented two facets of its work at the CAAFI bi-annual general meeting, in December 2018 in Washington, DC. This represents completion of Milestone 6 in the AY 2018/2019 Grant Proposal Narrative.

Major Accomplishments

The major accomplishments associated with this task include participation in bi-weekly ASCENT Project 1 coordination teleconferences; presentation at the CAAFI BGM in December 2018, and in a CAAFI webinar in January 2019; and sharing of a model and code, which quantify the availability of various bio-energy feedstocks in the contiguous United States, with Volpe team members.

Publications

N/A

Outreach Efforts

Staples, M. Long-term CO_2 emissions reduction potential of aviation biofuels in the US, Presentation at the CAAFI BGM, Washington DC, December 5, 2018.

Staples, M. Life cycle GHG emissions modeling for international policy, Presentation at the CAAFI BGM, Washington DC, December 5, 2018.

Wang, J. Harmonized stochastic techno-economic assessment and policy analysis for alternative fuels, Presentation for the CAAFI SOAP-Jet webinar, January 17, 2019.

Awards

None.

Student Involvement

The MIT graduate student involved in this task was Juju Wang (graduated in the summer of 2019), funded under ASCENT Project 1.

Plans for Next Period

Continued engagement in bi-weekly teleconferences and other events to disseminate MIT's ASCENT Project 1 work.