Project 001(F) Alternative Jet Fuel Supply Chain Analysis

Massachusetts Institute of Technology

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- P.I.(s): Steven R.H. Barrett, Professor
- FAA Award Number: 13-C-AJFE-MIT, Amendment Nos. 003, 012, 016, 028, and 033
- Period of Performance: [August 1, 2014 to August 31, 2018]
- Tasks (note that the tasks listed here are relevant only to the reporting period, 10/01/2016 – 09/31/2017):
    1. LCA methodology development and default core LCA emissions value calculation for use under CORSIA
    2. Regionalized assessment of AJF from MSW production technologies
    3. Assessment of long term potential for AJF production in the US
    4. Time- and path-dependence of AJF technologies, including the effects of learning-by-doing on production costs and environmental performance
    5. Assessment of the impact of policies on the economic viability of AJF in the context of AFTF
    6. Additional support of FAA in the context of AFTF
    7. Collaborate with ASCENT 21 to capture non-CO_2 lifecycle emissions in APMT-IC
    8. Collaborate with WSU to facilitate development of Aspen HEFA model

Hasselt University (sub-award from MIT)

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Project Funding Level

$1,660,000 FAA funding and $1,660,000 matching funds. Sources of match are approximately $296,000 from MIT, plus 3rd party in-kind contributions of $326,000 from Byogy Renewables, Inc. and $1,038,000 from Oliver Wyman Group.

Investigation Team

Principal Investigator: Prof. Steven Barrett (MIT)
Co-Principal Investigator: Dr. Raymond Speth (MIT)
Co-Investigators: Dr. Mark Staples, Dr. Florian Allroggen (MIT)
Graduate Research Assistants: Timothy Galligan, Cassandra Rosen, Paula do Vale Pereira, Juju Wang (MIT)

The research will partly be conducted through a sub-award with Hasselt University (Belgium), led by Prof. Robert Malina, and Hasselt University post-doctoral researchers Marieke Franck and Hakan Olcay.

Project Overview

The overall objectives of ASCENT Project 1 for the reporting period October 1, 2016 to September 30, 2017 are to derive information on regional supply chains to create scenarios for future alternative jet fuel (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.

Following these overall objectives, MIT's work under ASCENT Project 1 during AY 2016/2017 (from 09/01/2016 to 08/31/2017), as defined in the Grant Proposal Narrative for that period, was focused on: 1) supporting US participation in the International Civil Aviation Organization Committee for Aviation Environmental Protection Alternative Fuels Task Force (ICAO CAEP AFTF) to develop a methodology for appropriate accounting of AJF life cycle greenhouse gas (GHG) emissions under the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA); 2) to support FAA assessment of policy options for AJF in the context of AFTF; 3) build upon and extend previous work to estimate the economic production costs and life cycle GHG benefits of AJF production from MSW; 4) assess the long term potential for AJF production in the US; 5) and explore the time- and path-dependent characteristics of AJF technologies, including the effects of learning-by-doing on production costs and environmental performance.

MIT's work under ASCENT 1 during AY 2017/2018 (from 09/01/2017 to 08/31/2018), as defined in the Grant Proposal Narrative for that period, is focused on: 1) supporting US participation in ICAO CAEP AFTF by applying the developed LCA methodology to calculate default core LCA GHG emissions values for use under CORSIA; 2) support FAA work to calculate induced land use change (ILUC) emissions of AJF and assess sustainability certification schemes for potential inclusion under CORSIA; 3) quantify and assess the impact of various policy options on the financial viability of AJF to provide guidance to States that are party to CORSIA; 4) collaborate with ASCENT Project 21 to capture the climate impacts of non-CO_2 lifecycle emission from petroleum jet fuels and AJF in the Aviation environmental Portfolio Management Tool - Impacts Climate (APMT-IC); 5) collaborate with Washington State University (WSU) to facilitate development of an Aspen model of the hydroprocessed esters and fatty acids (HEFA) fuel production process; 6) and to provide additional (including in-person) support to FAA for decision-making in the context of AFTF.

In order to capture work that occurred during the reporting period (from 10/01/2016 to 09/30/2017) and overlaps with both funding periods, MIT's work under ASCENT Project 1 is described here under the following eight task categories:

1. AY 2016/2017 Task 1 & AY 2017/2018 Task 1 – LCA methodology development and default core LCA emissions value calculation for use under CORSIA

2. AY 2016/2017 Task 3 – Regionalized assessment of AJF from MSW production technologies

3. AY 2016/2017 Task 4 – Assessment of long term potential for AJF production in the US

4. AY 2016/2017 Task 5 – Time- and path-dependence of AJF technologies, including the effects of learning-by-doing on production costs and environmental performance

5. AY 2016/2017 Task 2 & AY 2017/2018 Task 3 – Assessment of the impact of policies on the economic viability of AJF in the context of AFTF

6. AY 2017/2018 Tasks 2 & 6 – Additional support of FAA in the context of AFTF

7. AY 2017/2018 Task 4 – Collaborate with ASCENT 21 to capture non-CO_2 lifecycle emissions in APMT-IC

8. AY 2017/2018 Task 5 - Collaborate with WSU to facilitate development of Aspen HEFA model

Because 11 of the 12 months of the reporting period correspond to AY 2016/2017, the bulk of this annual report focuses on work accomplished during that period of time. The plan to accomplish the remaining tasks under ASCENT 1 for AY 2017/2018 is also summarized.

Task #1: LCA Methodology Development and Default Core LCA Emissions Value Calculation for Use under CORSIA

Massachusetts Institute of Technology

Objective(s)

The overall objective of this task is to provide support to the FAA for its engagement with ICAO CAEP AFTF, specifically on the development of a methodology for appropriate accounting of AJF lifecycle GHG emissions under CORSIA, and applying the method to calculate AJF default core LCA emissions values for use under CORSIA.

Research Approach

During this reporting period, significant progress has been made on the work of the core LCA Task Group of AFTF. The MIT ASCENT Project 1 team has been key to this progress in terms of development of the methodology to calculated LCA values, and the application of the method been instrumental in that work. These two task items are described below.

Core LCA Methodology Development

Guidance document

In preparation for the AFTF/2 meeting in October 2016, the MIT ASCENT Project 1 team prepared a guidance document. The purpose of this document was to summarize the agreed-upon core LCA methodology of CORSIA for those wishing to participate in the calculation and submission of default values to AFTF. Although the LCA methodology had already been documented in a number of information papers (IPs), these documents could not be distributed beyond technical experts nominated to AFTF. In addition, the guidance document defines the relevance, adequacy, quality, transparency and accessibility requirements of LCA data submitted to AFTF, in order for it to be considered in the calculation of core LCA values.

At the AFTF/2 meeting, feedback on this document was elicited from AFTF, and the feedback was incorporated to generate a final draft of the guidance document following the meeting. Coming to agreement on the guidance document was a key step towards calculating default core LCA values for use in CORSIA, as it defined the rules by which the analysis would be carried out.

Geographical aggregation study

During AY 2016/2017, the MIT ASCENT Project 1 team carried out an analysis to quantify the sensitivity of core LCA results to regional specificity, in order to inform the level of geographical aggregation to which default LCA values should be calculated.

The sensitivity analysis of LCA results to geographic variation was carried out by altering regionally specific parameters. The starting point for calculations were USA default values in GREET. This USA-specific data was then replaced with parameters relevant for different geographic regions, to generate LCA results for the same pathway in different world regions, and compared to each other. Data for different regions were collected from publically available and region-specific models, government documents, and peer-reviewed literature.

The parameters modified within each pathway varied based on the feedstock and conversion technology of interest. However, generally speaking, the primary drivers of emissions were identified to be agricultural productivity, process efficiencies, and the emission factors associated with utility inputs, as documented in CAEP/11-AFTF/01-IP/7. The parameters affecting the agricultural productivity include crop yield, nutrient application rates, and farming energy demand. Process efficiency includes both pre-processing of feedstock and fuel production process. Emissions factors were relevant for inputs such as electricity, hydrogen, and natural gas.

Several conclusions were drawn from the regional sensitivity analyses. First, regional variation was shown to have a relatively minor impact on LCA emissions within each specific pathway. For waste HEFA pathways, where no emissions are associated with feedstock production, the regional differences resulted in a total range of variability in LCA emissions of less than 1.2 gCO_2e/MJ. For oil crop HEFA pathways, LCA emissions varied less than 4.7 gCO_2e/MJ due to regional-specificity. The geographic variation in the LCA results for oil crop HEFA pathways showed up primarily in the feedstock production step however, because emissions from feedstock-to-fuel conversion dominate overall emissions and are relatively constant between pathways, little geographic variation was observed in the overall LCA emissions. For the FT pathways, where electricity and heat demand is met within the process through co-generation, regional-specificity resulted in variability of LCA emission of less than 3.6 gCO_2e/MJ. Compared to the 89 gCO_2e/MJ baseline for petroleum jet fuel, the sensitivity to regional variation observed for the HEFA and FT pathways was relatively small. These results are shown in Figure 1.

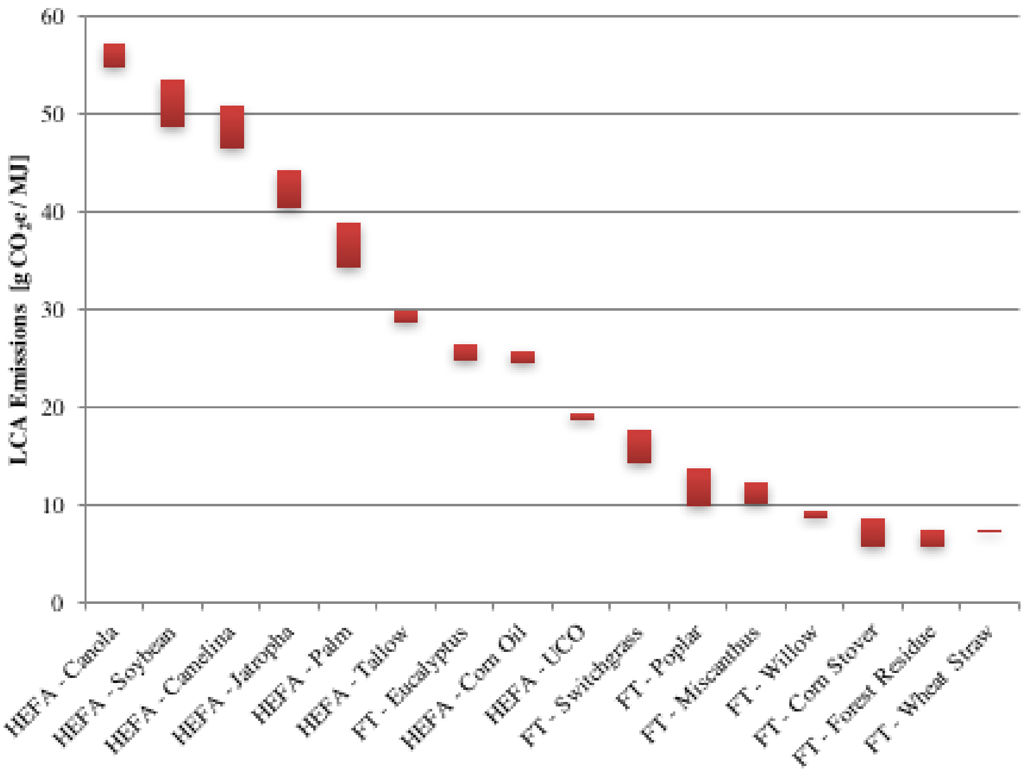

Figure 1: LCA emissions of HEFA and FT pathways. The whiskers indicate variability due to regional specificity for each feedstock-to-fuel pathway.

One the basis of this analysis, it was determined by AFTF that a single global value would be calculated for the default core LCA value of different feedstock-to-fuel pathways.

Calculation of Default Core LCA Emissions Values

Based on the agreed core LCA methodology, and the use of a single global value for default core LCA emissions of different feedstock-to-fuel pathways, significant progress was made during AY 2016/2017 on the calculation of default LCA values for different AJF pathways under CORSIA.

In advance of the AFTF/4 meeting in June 2017, the Core LCA Task Group carried out analysis according to the following agreed upon principles:

- Core default LCA values are calculated at a global level of resolution
- A pathway is defined as a feedstock and conversion technology pairing for which emissions vary by <10% of the conventional jet fuel baseline (8.9 gCO_2e/MJ)

- Default values are calculated as the mid-point of the range of results for a given pathway

Under the leadership of the MIT ASCENT Project 1 team, a number of institutions contributed to the work on the Task Group on this analysis, including the European Union Joint Research Centre, Argonne National Laboratory, and the University of Toronto. Analysis efforts focused first on waste and residue pathways, because these do not require ILUC values to be completed and included in the Standards and Recommended Practices (SARP) document. Institutions volunteered to act as lead and verifying analysts on the identified waste and residue pathways, as indicated in Table 1.

Table 1: List of first priority feedstock-to-fuel pathways for development of core LCA default values and responsible AFTF member organizations

Technology	Feedstock	Lead	Verifier
FT	Herbaceous energy crops	MIT/JRC	ANL
	Short rotation wood crops		
	Agricultural residues		
	Forest residues		
	MSW	MIT	
HEFA	Tallow	MIT/JRC	ANL
	UCO		
	PFAD	ANL	U Toronto
	Corn oil		
	Tall oil	JRC	ANL
ATJ	Agricultural residues	MIT	JRC
	Forest residues		

Two models were used for LCA calculations. The GREET® (the Greenhouse gasses, Regulated Emissions, and Energy use in Transportation) (Argonne National Laboratory, 2015) model has been used for the analyses by ANL, MIT and University of Toronto. GREET is a peer-reviewed, publicly available, and editable software. JRC used the E3 Database model for their calculations (Ludwig-Bolkow Systemtechnik GMBH, 2006). Over the course of the analysis performed for AFTF, the original database was reviewed and updated to respond to AFTF-specific requirements. Lifecycle inventory datasets for the various AJF pathways were inputs for these LCA models, and were put together collaboratively based on information from the different experts within the Modelling Subgroup. This data is documented in detail in CAEP/11-AFTF/4-IP/4. The functional unit was defined as one mega joule (MJ) of delivered jet fuel energy (lower heating value), and the LCA results are presented in terms of the amount of GHG emissions for each functional unit (gCO_2e/MJ).

The process of calculating the default core LCA values proceeded as follows. Immediately following the AFTF/3 meeting in February 2017, the lead institutions started their calculations. In March 2017, the verifying institutions reviewed the calculations of the lead organizations. In April 2017, discrepancies between lead and verifying calculations were discussed and reconciled by the Core LCA Modelling Subgroup. The results of the analysis are summarized in Table 2, which are the default core LCA values agreed to by AFTF and submitted to Steering Group for approval in September 2017.

Table 2: Default core LCA values for selected AJF pathways [gCO2e/MJ]

Technology	Feedstock	Sub-feedstock type		Data source	Model	Data points	Mid-point value
FT	Herbaceous energy crops	Switchgrass		MIT	GREET	12.7	10.4
				JRC	GREET	12.7	
				JRC	E3	11.3	
		Miscanthus		MIT	GREET	10.7	
				JRC	GREET	8.0	
	Short rotation woody crops	Poplar		MIT	GREET	9.9	12.2
				JRC	GREET	13.0	
				JRC	E3	16.5	
		Willow		MIT	GREET	7.8	
				JRC	GREET	9.7	
		Eucalyptus		MIT/ANL	GREET	9.1	
				JRC	E3	16.6	
	Agricultural residues	Corn stover (without nutrient replacement)		MIT	GREET	6.5	7.7
				JRC	GREET	5.4	
				JRC	E3	9.7	
		Wheat straw (without nutrient replacement)		MIT	GREET	6.6	
				JRC	GREET	10.0	
				JRC	E3	5.5	
	Forest residues			MIT	GREET	6.1	8.3
				JRC	GREET	7.1	
				JRC	E3	10.5	
	MSW	Non-biogenic C content	NBC = 0%	MIT	GREET data implemented in Suresh (2016) model	5.2	**5.2**
			NBC > 0%			NBC*170.5+5.2	**NBC*170.5+5.2**
HEFA	Tallow	Boundary starts at tallow rendering		MIT	GREET	25.3	22.5
				JRC	E3	19.8	
	UCO			MIT	GREET	14.8	13.9
				JRC	E3	13.0	
	PFAD	Boundary starts at PFAD production		ANL	GREET	24.3	20.7
				JRC	GREET	21.8	
				JRC/ANL	E3/GREET	17.0	
	Corn oil	Boundary starts at corn oil production		ANL	GREET	17.5	17.2
				JRC	GREET	16.8	
ATJ	Agricultural residues	Corn stover (without nutrient replacement)		MIT	GREET	31.9	29.3
				JRC	E3	25.9	
				JRC	GREET	30.0	
	Forest Residues			MIT	GREET	24.7	23.8
				JRC	E3	22.8	

Milestone(s)

The work described above on this task represents the achievement of MS 1, 2 and 3 as defined in the AY 2016/2017 Grant Proposal. The revised guidance document on calculation of core LCA values for AJF under CORSIA was submitted to AFTF, and the status and progress on core LCA default value calculations was presented to AFTF at meetings in October 2016, February 2017, and June 2017.

Major Accomplishments

The major accomplishments during this period of performance was the submission of a finalized guidance document to AFTF, outlining the methodology for the calculation of core LCA values under CORSIA. In addition, as of June 2017, the MIT-led core LCA Task Group had agreed upon core LCA values for 11 feedstock-to-fuel AJF production pathways. This progress will enable the inclusion and use of these fuels as soon as CORSIA goes into effect.

Publications

Peer reviewed publications

Staples, M.D., R. Malina, P. Suresh, J.I. Hileman, S.R.H. Barrett (*in revision*) "Aviation CO_2 emission reductions from the use of alternative jet fuels." *Energy Policy*.

Written reports

CAEP/11-AFTF/4-IP/04, Calculation of core default LCA values for selected pathways under CORSIA, presented at AFTF/4, June 2017, Montreal, Canada

CAEP/11-AFTF/4-WP/02, Progress update on core LCA task, presented at AFTF/4, June 2017 Montreal, Canada.

CAEP/11-AFTF/3-IP/02, Core LCA Task Group – study of pathway aggregation, February 2017, Montreal, Canada.

CAEP/11-AFTF/3-WP/02, Progress update on core LCA task group, February 2017, Montreal, Canada.

CAEP/11-AFTF/2-IP/04, Core LCA Task Group – study of pathway aggregation, October 2016 Montreal, Canada.

CAEP/11-AFTF/2-WP/02, Report on Core LCA Task, October 2016, Montreal, Canada.

CAEP/11-AFTF/2-IP/03, Guidance Document for Calculation and Submission of Alternative Jet Fuel Lifecycle Analysis Data for Default Values under the Global Market-based Measure, October, 2016, Montreal, Canada.

Outreach Efforts

Progress on these tasks were communicated during weekly briefing calls with the FAA and other US delegation members to AFTF, numerous AFTF teleconferences between in-person meetings, as well as at in-person meetings of AFTF in October 2016, February 2017, and June 2017. In addition, MIT presented this work to ASCENT in a poster at the April 2017 biannual meeting, and in a presentation at the September 2017 biannual meeting. MIT also briefed the entire A001 team on these topics on the January 9 and 23, 2017 ASCENT Project 1 teleconferences.

Awards

None.

Student Involvement

During the reporting period of AY 2016/2017, the majority of the analysis work was carried out by Cassandra Rosen, who finished her Masters at MIT in June 2017. Going forward, the MIT graduate students involved in this task will be Paula do Vale Pereira and Juju Wang, both funded under ASCENT Project 1.

Plans for Next Period

In the coming year, the MIT ASCENT Project 1 team will continue its work in AFTF. Default core LCA values will be calculated and proposed for additional pathways, and the results will be presented at AFTF/5 and AFTF/6 in October 2017 and April 2018, respectively. In addition, Prof. Robert Malina from Hasselt University will continue to lead the core LCA Task Group, and Dr. Mark Staples will lead a small group responsible for defining a methodology for assigning landfilling and recycling emissions credits to fuels derived from MSW feedstocks. The work of the core LCA Task Group will be summarized in a draft technical report delivered to the Steering Group 3 meeting in June 2018, and MIT will take the lead in writing this report.

References

Argonne National Laboratory. (2015) Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) Model. [Online]. http://greet.es.anl.gov/

Ludwig-Bolkow Systemtechnik GMBH. (2006) E3 Database. [Online]. http://www.e3database.com/

Task #3: Regionalized Assessment of AJF from MSW Production Technologies

Massachusetts Institute of Technology

Objective(s)

The objective of this task is to build upon previous work, in order to quantify the performance of AJF derived from MSW as a function of geographical location.

Research Approach

Introduction

Over the previous two years of ASCENT Project 1, a model was developed that quantifies the US-average costs of production and lifecycle GHG emissions of several pathways for MSW conversion into liquid transportation fuels, accounting for parameter uncertainty with a Monte Carlo framework (Suresh 2016). This previous analysis focused on three thermochemical conversion pathways: conventional gasification and Fischer-Tropsch (FT MD), plasma gasification and Fischer-Tropsch (Plasma FT MD) and conventional gasification, catalytic alcohol synthesis and alcohol- to-jet-upgrading (ATJ MD). These conversion pathways were chosen as they are well-suited to deal with the heterogeneous composition of MSW feedstock.

All three technology pathways demonstrate significant environmental potential, even when accounting for the foregone landfill gas recovery when discarded MSW is used as a feedstock: all of the conversion pathways considered are expected to have lower lifecycle GHG emissions compared to conventional middle distillate (MD) fuels.

The estimated probability of a positive NPV ranges from 0.1 to 14% in the Suresh (2016) analysis. Sensitivity analysis revealed that the results are sensitive to changes in the MSW composition, the waste management strategy that is displaced, plant scale and fuel yield, co-product allocation method, and transportation distance. It should be noted that these conversion pathways are not yet commercialized, which means that the calculated probability of a positive NPV may represent an underestimation of the commercialized version of the technology. Moreover, the possibility of a positive NPV when taking a societal perspective (societal opportunity cost of capital, social cost of GHG emissions) ranges between 67 to 93%. As mentioned before, this model was US-average specific and the estimated probabilities are sensitive to changes in the parameters. It is therefore highly relevant to allow for spatial variation within the US. The next section describes how the original modeling tool was adapted to reflect geographical variation within the US.

Methods

A state specific model was developed, based on the US average model, in order to estimate the GHG emissions (gCO_2eq/MJ) resulting from the production of ATJ MD from MSW as a function of lovation. Spatial variation between the US states was introduced in the following parameters: pre-processed and dried MSW characteristics (carbon content, non-biogenic portion carbon content) and GHG emissions factors (replaced waste management strategy credit, recycling credit, average grid electricity). During the analysis, it became apparent that not all states could be assessed due to lack of data. Therefore, for the states/regions/counties that do report on their MSW data, one specific state/region/county was carefully selected per NERC region.

The most recent published report on MSW from EPA dates from 2014, therefore 2014 has been chosen to serve as the base year for the analysis. When further breakdown of the data is unavailable, 2014 national averages for MSW generation[1] have been used to estimate the landfilled values (e.g. to calculate the share of PET in landfilled plastic bottles or films). When selecting a specific state/region/county to represent a certain NERC region, the following items were taken into account:

- Data from 2014 has been chosen to minimize efforts to estimate the composition for that year
- When data is unavailable for the year 2014, the most recent data to that year was selected and adjusted (this process is described below)
- Statewide data has been favored over data from any other region
- When data appeared to be unreliable or of poor quality, the state/region was not considered

As can be seen in Table 3[2], this selection method resulted in 8 states/regions/counties that were included in the analysis out of a pool of 27. The following states have been selected: Texas, Florida, Minnesota, Vermont, Michigan, Missouri, Kansas and California (indicated in bold in Table 3). As mentioned before, each of them represent a different NERC region.

Table 3. The US regions for which the MSW data has been collected. Bold rows indicate those used for this analysis.

No.	NERC Region	State	Data Year
1	**ERCOT**	**Texas[1]**	**2014**
2	**FRCC**	**Florida**	**2014**
3	MRO	Iowa	2011
4	**MRO**	**Minnesota**	**2012**
5	MRO	Nebraska[1]	2014
6	MRO	Wisconsin	2009
7	NPCC	Connecticut	2009
8	NPCC	Maine	2011
9	NPCC	Massachusetts	2013
10	NPCC	New York[1]	2013
11	**NPCC**	**Vermont**	**2012**
12	RFC	D.C.	2007
13	RFC	Delaware	2016
14	RFC	Indiana	2009
15	RFC	Maryland[1]	2012
16	**RFC**	**Michigan**	**2014**
17	SERC	Arkansas	2010
18	SERC	Georgia	2004
19	SERC	Illinois[1]	2014
20	**SERC**	**Missouri**	**2008**
21	SERC	North Carolina[1]	2010
22	SERC	Tennessee	2005
23	**SPP**	**Kansas**	**2012**
24	**WECC**	**California**	**2014**
25	WECC	Colorado[1]	2016
26	WECC	Oregon	2010
27	WECC	Washington	2016

[1]Data available for a county, region or city.

Next, the following approach was applied to adjust MSW quantities from a different year into 2014 data, when data specific to 2014 was unavailable. The equations make use of real GDP per capita data (rGDP/c) and MSW quantities for both the state/region/county and the US.

[1] Generation data was used as it offered a more complete data breakdown than reported national landfilled values. Note that the previous MSW analysis by MIT was based on the national averages reported for the year 2013.
[2] Table 3 is based on the survey conducted in 2011 by the Earth Engineering Center (Shin, 2014) as this survey resulted in a collection of MSW characterization information from 27 U.S. regions, most of which represent states.

		Year	
		20xx	2014
Region	rGDP/c	G_{R1}	G_{R2}
	MSW Quantity	Q_{R1}	Q_{R2}
US average	rGDP/c	G_{U1}	G_{U2}
	MSW Quantity	Q_{U1}	Q_{U2}

$$\frac{R_2}{R_1} = \frac{U_2}{U_1}$$

where,

$$R_1 = \frac{Q_{R1}}{G_{R1}}\ R_2 = \frac{Q_{R2}}{G_{R2}}$$

$$U_1 = \frac{Q_{U1}}{G_{U1}}\ U_2 = \frac{Q_{U2}}{G_{U2}}$$

When data from a state is to be used to represent a NERC region (e.g, in the case of Texas), the compositions are assumed for the region that the state belongs to, and the quantities have been estimated for the state based on the relative total landfilled MSW amounts. This, however, does not affect the calculated GHG emissions results.

These categories, which represent one of the ways the EPA breaks down the MSW, are defined as follows:

- Paper and paperboard
- Glass
- Metals
- Plastics
- Rubber and leather
- Textiles
- Wood
- Other materials
- Food wastes
- Yard trimmings
- Miscellaneous inorganic wastes

These categories are further broken down as shown in Table 4. MSW characterization has been reported by the authorities in many different categories that do not necessarily line up with the ones shown in this table. Hence, a careful consideration has been taken to re-group all the data into these categories.

The reported data typically includes information about the MSW quantity generated, composted, recycled, combusted and landfilled. The reported combusted data indicates the amount of MSW that is utilized in waste-to-energy facilities. There is also a part of MSW which is used as process fuel in the recycling plants, which is included in the recycled and/or combusted MSW datasets. Therefore, these two sources of potential feedstocks could be considered unavailable for fuel production. However, to be consistent with the previous analysis by MIT on MSW, the combusted MSW data has been taken into account in this analysis as a potentially available feedstock, along with the landfilled quantities, for conversion into MD fuels. This assumption plays an important role in the calculation of the avoided landfill credits. On the other hand, any other MSW combustion process is not accounted for explicitly in the official reports, and they are assumed to have been reported as part of the landfilled data.

When composition of combusted and landfilled MSW is not provided separately (which has been the case for all the 8 states chosen here), aggregate composition has been assumed to be the same. Typically, composition data is available for the disposed/discarded MSW, which includes the combusted (if any[3]) and landfilled quantities, along with an overall ratio defining how much is combusted and how much is landfilled. (Note that, however, even though the compositions are kept the same, as mentioned above, whether the feedstock scope is expanded to include the combusted MSW or not will still affect the GHG results through combustion and recycling credits.) When this ratio is not explicit, total combusted MSW quantities estimated for the year 2011 by Shin (2014) have been considered, which are then extrapolated to 2014 using the relations described above.

Note also that the MSW reported under construction and demolition (C&D) has been excluded from the data used for this analysis, as this was the case in the EPA reports.

[3] Some states don't have any waste-to-energy facilities, e.g. Kansas, Missouri, Texas and Vermont. Their reported disposal data then represents the landfilled quantities.

Table 4: Categories utilized to re-group reported MSW data for consistency.

Material	**Breakdown level I**	**Breakdown level II**
Paper and paperboard	Newsprint Paper Containers & Packaging	
Glass		
Metals	Ferrous (iron and steel)	Steel cans and packaging Steel ingot
	Aluminum	Aluminum cans and packaging Aluminum ingot (durable goods) Aluminum (nondurable)
	Other nonferrous	Lead Other nonferrous metals
Plastics	PET HDPE PVC LDPE/LLDPE PLA PP PS Other resins	
Rubber and leather	Rubber Leather	*Partial breakdown below**
Textiles Wood Other materials Food wastes Yard trimmings Miscellaneous inorganic wastes Mixed MSW		

*Carpet and rugs	*As a whole included in Rubber and leather*
*Rubber in tires	*Only rubber content is included in Rubber and leather*

As mentioned above, the carbon footprint of electricity has also been varied throughout the NERC regions in the calculations. For this, NERC region-specific data have been extracted out of the ECOINVENT database. Avoided landfill credits and recycling credits have been calculated using EPA's WARM model for the year 2014 (v14). For comparison purposes among the NERC regions and with the US average, the calculations have been calculated for a single feedstock-to-jet fuel pathway, instead of all three: conventional gasification, catalytic alcohol synthesis and alcohol-to-jet upgrading (ATJ MD).

Results

Table 5 represents the assumed MSW composition for the 8 states/NERC regions that were selected for this report.

Table 5: Landfilled MSW characterization (tons) and combusted-to-landfilled ratio for the states/NERC regions in consideration.

	California WECC	Florida FRCC	Kansas SPP	Michigan RFC	Minnesota MRO	Missouri SERC	Texas ERCOT	Vermont NPCC
Paper and paperboard	5170	3570	1580	1620	400	850	4660	100
Glass	740	440	180	160	40	180	800	10
Metals	920	1230	220	280	80	240	880	10
Plastics	3100	1260	900	1050	300	660	2630	50
Rubber and leather	1210	120	90	680	80	20	300	10
Textiles	1190	590	190	270	70	210	590	30
Wood	510	0	40	390	90	40	310	0
Other materials	1080	120	280	300	150	220	2280	70
Food wastes	5380	1530	830	1010	300	670	5290	60
Yard trimmings	2060	1150	310	550	40	100	1350	20
Miscellaneous inorganic wastes	2460	1800	190	1160	10	190	960	10
Total	23800	11800	4800	7500	1600	3400	20100	400
Combusted-to-Landfilled	4%	30%	0%	19%	82%	0%	0%	0%

Table 6 presents the preliminary results for each NERC region compared to the US average. The calculations include a Monte Carlo analysis, therefore the results are displayed by a mean value accompanied by a percent standard deviation. Moreover, these preliminary results are displayed for two different allocation methods. Energy allocation refers to the calculations where emissions of producing all the co-products are allocated based on the relative energy content of each product. Displacement, on the other hand, refers to the system expansion technique applied for the electricity and higher alcohol co-products, where excess generated electricity is assumed to displace US average grid electricity, and higher alcohols are assumed to displace virgin higher alcohol production from fossil energy.

The results range from 12.1 to 54.6 gCO_2e/MJ for when an energy allocation is applied for all the co-products. The values that involve system expansion, on the other hand, do not differ much from these results. The fact that all the values for the NERC regions except for SERC (Missouri) have come below the US average indicates that some, if not all, of the 8 states chosen are not representative of the respective NERC region average.

Table 6. Preliminary lifecycle GHG emissions (gCO_2eq/MJ) for producing ATJ MD fuels from disposed MSW in the NERC regions. Results are provided using two different allocation methods. See text for details.

	Energy allocation		Displacement	
	Mean	**%Std. Dev.**	**Mean**	**%Std. Dev.**
California-WECC	35.2	15.3	34.4	15.3
Florida-FRCC	12.1	12.1	11.5	12.2
Kansas-SPP	42.8	10.7	41.8	10.5
Michigan-RFC	45.3	19.9	44.4	19.8
Minnesota-MRO	49.7	13.3	48.6	13.1
Missouri-SERC	54.6	11.6	53.9	11.3
Texas-ERCOT	31.9	11.5	31.1	11.5
Vermont-NPCC	23.5	10.6	22.5	10.6
US	52.8	13.3	52.0	13.1

Milestone(s)
This analysis, and it's documentation in this report, represents completion of MS 6 from the AY 2016/2017 Grant Proposal Narrative.

Major Accomplishments
This work has quantified the regionalized lifecycle GHG emissions for MSW-derived drop-in MD fuels, in 8 NERC regions around the US. The variation between the analyzed regions (e.g. Florida-FRCC at 12.1 gCO_2e/MJ vs. Missouri-SERC at 54.6 gCO_2e/MJ) demonstrates the importance of region specificity in assessing the emissions from this pathway.

Publications
None.

Outreach Efforts
None.

Awards
None.

Student Involvement
This work was carried out by Marieke Franck and Hakan Olcay, both post-doctoral researchers at Hasselt University, and was supervisor by Prof. Robert Malina of Hasselt University.

Plans for Next Period
The analysis described here represents completion of the work on this task for ASCENT Project 1.

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Task #4: Assessment of Long Term Potential for AJF Production in the US
Massachusetts Institute of Technology

Objective(s)
For AY 2016/2017 Task 4, the objective of the funded work is to assess the long-term production potential of AJF in the US. The analysis leverages the modeling framework developed for the Fuel Production Assessment carried out by MIT in the context of AFTF during CAEP/10. Estimates of GHG emissions reductions associated with different scenarios of AJF deployment are provided, with the tradeoffs between increased AJF production and increased fuel emissions quantified.

Research Approach

Introduction
Air travel accounts for approximately 3% of total GHG emissions within the United States (US), and the Federal Aviation Administration (FAA) expects continued growth at a 2.6% annual rate over the next 20 years (Federal Aviation Administration, 2015; OAR,OTAQ US EPA, n.d.). Emissions from petroleum jet fuel into the atmosphere contribute to global warming, and therefore replacement of petroleum jet fuel with AJF has been identified by the EPA as a primary area of focus for abatement of aviation GHG emissions (OA US EPA, n.d.).

This analysis aims to determine the future availability of AJF that can be produced in the United States, limited by land use constraints and the availability of wastes and residues for conversion to AJF. The inclusion of land use change (LUC) emissions into the calculation allows for accurate determination of AJF emissions. Previous work to assess the availability of AJF in the United States has focused on economic feasibility, and climate assessments have only considered the life cycle emissions of AJF, without any consideration for the emissions associated with converting land for feedstock cultivation. This analysis assesses the maximum AJF production limit not constrained by economic limitations, and quantifies the maximum climate benefits that could be achieved by total replacement of petroleum derived jet fuel with AJF.

Methods

The analysis considers a number of feedstock resource pools for conversion to AJF. AJF production levels, using three fuel conversion pathways, are quantified for three scenarios defined in the below, and the climate impacts of each scenario are assessed.

The largest potential source of AJF is the cultivation of energy crops. The FORE-SCE model results from the US Geological Survey describe land use patterns in 2050 across the US (Sohl et al., 2014). Land uses unavailable or unsuitable for energy crop cultivation, such as cropland, developed areas, and protected areas, are not considered for energy crop production. Crop specific suitability, determined by soil and climate characteristics, is available from the Global Agro-Ecological Zone (GAEZ) model from the United Nations' Food and Agriculture Organization (FAO). A lower threshold on suitability for agriculture is applied on a crop by crop basis to eliminate areas of low productivity. Crop specific yield data from the US Department of Agriculture (USDA) is extrapolated temporally to 2050, and capped by the agro-climatically attainable rain-fed yield available from the GAEZ model (USDA, n.d.). Lignocellulosic energy crop yields from literature are used, due to an absence of historical yield data (Baskaran, Jager, Schweizer, & Srinivasan, 2010; Lewandowski, Scurlock, Lindvall, & Christou, 2003). The highest producing crop is chosen at each location, with both maximum AJF and maximum transportation fuel (AJF, diesel, and naphtha) cases considered. The combination of optimal crop choices and available land quantifies potential feedstock production levels for conversion to AJF.

Agricultural residues from different crop types, as a function of yield, are also quantified as a potential feedstock for AJF production. The energy crop production levels from the previous step are used in combination with future USDA crop estimates (USDA, 2017). From the literature, a residue yield per unit of agricultural yield is found for each crop (Lal, 2005). Sustainable residue removal rates from the literature are used to determine the portion of generated residue that can be extracted for generation of AJF (Muth, Bryden, & Nelson, 2013).

Additionally, forestry and wood processing residues are a potential source of bioenergy feedstocks for AJF production. Residue fractions for harvested wood, which includes treetops and branches left behind, and processed wood products, such as the chips and dust generated in sawmills and the production of plywood, are available from the literature (Searle & Malins, 2013; Smeets & Faaij, 2007). This literature also contains the portion of residue that is recoverable from each source. Historical production data from the US Forest Service is used to estimate lumber and engineered products production (Howard, 2016). Finally, estimates of the residues diverted for char and pellets from the literature are not considered available for AJF production (McKeever, 2004).

Waste fats, oils, and greases (FOGs) include tallow from slaughtered livestock and waste grease from food production. USDA data from 2016 is used to estimate per capita livestock production in 2050 (USDA-NASS, 2017). Waste grease availability is available from the National Renewable Energy Lab (NREL), also on a per capita basis (Wiltsee, 1998). For each analysis scenario, literature estimates of annual population growth are applied to current US population to estimate the population in 2050 (Gaffin, Rosenzweig, Xing, & Yetman, 2004). From the calculated quantity of waste FOG generation, it is assumed that 100% of tallow is collected, and that 85% of waste grease is collected, based on data from the US Department of Energy (Moore & Myers, 2010). An ECOFYS consultancy fact sheet estimates the portion of collected waste FOGs in the EU diverted for feed and oleochemical products, and it is assumed that the remainder is available for conversion to AJF (Peters, Koop, & Warmerdam, 2011).

Per capita Municipal Solid Waste (MSW) estimates from the International Energy Agency (IEA) are combined with 2050 population estimates to estimate total quantity of MSW produced (IEA, 2016). Based on EPA data, the composition of MSW and landfill rate by component are determined (USEPA, 2016). The availability of MSW for conversion to AJF is quantified using component energy content from the US Energy Information Administration (EIA) (U.S. Department of Energy, 2007).

The calculated feedstock quantities are fed into either advanced fermentation (AF), Fischer-Tropsch (FT), or hydro-processed esters and fatty acids (HEFA), fuel conversion pathways. The conversion efficiencies and product slates of these conversion technologies are well characterized in the literature (Pearlson, Wollersheim, & Hileman, 2012; Staples et al., 2014; Stratton, Wong, Hileman, & Stratton, 2011; Suresh et al., 2016). Additionally, each feedstock-fuel pathway has lifecycle emissions quantified in scientific literature; for energy crop cultivation requiring a land use change (LUC), emissions factors from the Global Trade Analysis Project (GTAP) emissions factor model are used.

Results

The potential quantity of AJF production is dependent on a number of assumptions. Three scenarios are defined in Table 7, outlining the assumptions of interest, in order to capture the range of.

Table 7: Scenarios investigated for AJF production potential in the US

Scenario	Description	Technological/ economic development	Land use decision criteria	Hay/pasture land availability	Ag. residue removal rate	Agro-climatic suitability threshold
A	Highest AJF potential	SRES B1	Max. AJF	20%	50%	Moderate
B	Baseline	SRES A2	Max. Transportation Fuel	10%	30%	Moderate
C	Lowest AJF potential	SRES A1B	Max. Transportation Fuel	0%	10%	Good

For each scenario, the total AJF production potential is shown in Figure 2, broken out by fuel pathway.

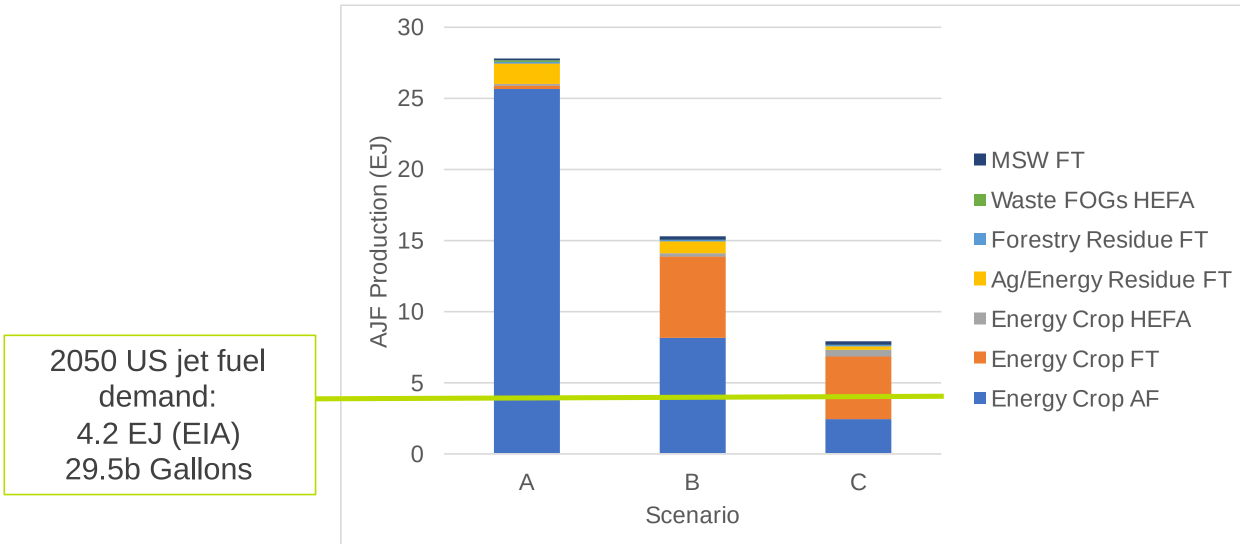

Figure 2: AJF production potential by fuel pathway for each analysis scenario

Table shows the areas required for energy crop cultivation to attain the energy crop AJF levels of Figure 1. Expected area of food crops in 2050 are provided in Table as a reference.

Table 8: Land area used for energy crop cultivation

Scenario	Energy Crop Area (10^6 ha)	Food Crop Area (10^6 ha)
A	217	130
B	188	145
C	120	150

The climate impacts of each feedstock-fuel pathway depend on lifecycle emissions and land use change emissions, for energy crops. Figure 3 presents AJF emissions on a per unit basis plotted against cumulative AJF production. These results from the baseline scenario are ordered from lowest to highest emissions; also shown are jet fuel demand and petroleum jet fuel emissions.

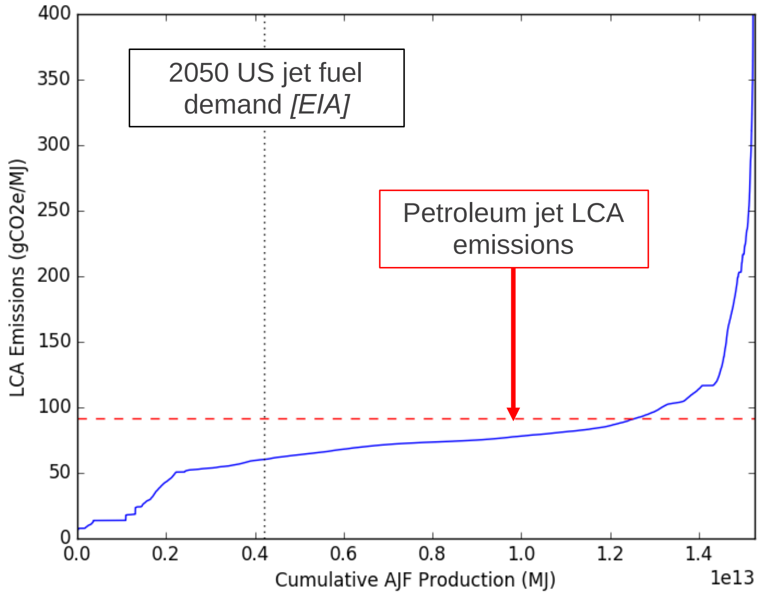

Figure 3: Fuel lifecycle emissions (including LUC emissions)

For the baseline scenario, a mixed use of all AJF feedstock-fuel pathways results in an emissions savings of 42% compared to petroleum jet fuel. Offsetting demand using the lowest emitting pathway results in the largest possible reduction of GHG emissions from jet fuel. Table presents the US aviation sector emissions savings for three levels of fuel demand replacement using the lowest emitting pathways.

Table 9: Potential aviation sector emissions savings with partial offset of petroleum fuel

2050 Jet Fuel Demand Satisfied	Potential Emissions Savings
25%	22%
50%	39%
100%	59%

AJF from wastes and residues have emissions lower than most feedstocks cultivated on converted land, due to the absence of LUC emissions. They also only require collection of existing material, rather than expanding crop area. The potential AJF production levels from wastes and residues are presented in Figure 3, broken out by feedstock.

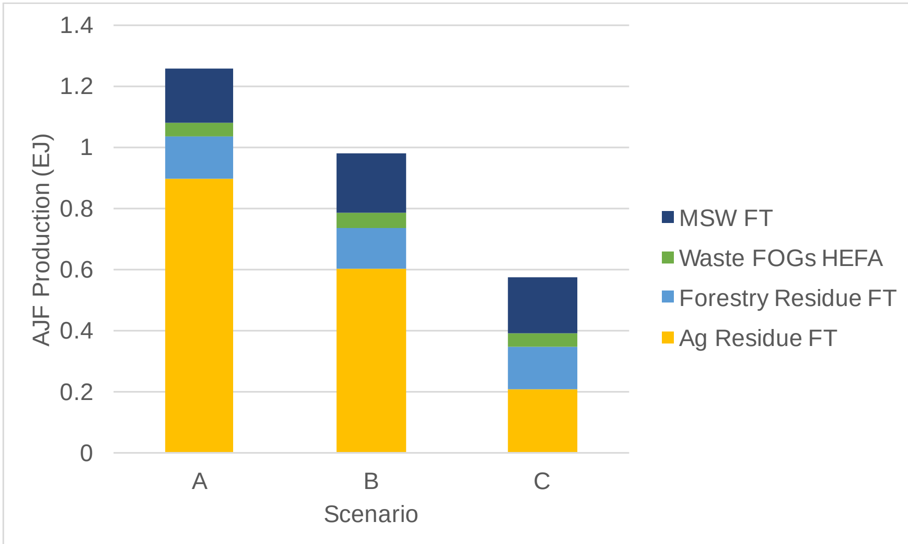

Figure 4: AJF availability from waste and residue sources for each analysis scenario

Table presents the US aviation sector emissions savings associated with complete realization of waste and residue derived AJF.

Table 10: US aviation sector emissions savings from waste and residue derived AJF

Scenario	Percent of Demand Satisfied	Sector Emissions Saved
A	30%	23%
B	23%	17%
C	14%	9%

Milestone(s)
This analysis was completed and presented to the FAA in September of 2016, and will be documented in an MIT Master's thesis to be submitted in January 2018. This represents completion of MS 4 in the AY 2016/2017 Grant Proposal Narrative.

Major Accomplishments
During this period, the production potential of AJF in 2050 in the United States has been quantified across scenarios assuming different economic, climate, and land use assumptions. The potential of AJF to reduce GHG emissions from the US aviation sector is quantified.

Publications

Peer reviewed journal publications
T. Galligan, M. Staples, R. Speth, S. Barrett. "The potential of bio- and waste- derived jet fuel to reduce US aviation sector emissions in 2050" (*in preparation*)

Written reports
T. Galligan, "The potential of bio- and waste- derived jet fuel to reduce aviation sector emissions in 2050," Master of Science thesis, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, 2017. (*in preparation*)

Outreach Efforts

Long-Term Alternative Jet Fuel Production in the United States. Presented by Mark Staples at ASCENT biannual meeting in September 2017, Alexandria, VA.

Long-Term Alternative Jet Fuel Production in the United States. Presented by Timothy Galligan on teleconference with Jim Hileman, Fabio Grandi, Dan Williams of the FAA, September 19, 2017.

Long-Term Alternative Jet Fuel Production in the United States. Presentation given on weekly ASCENT-1 teleconference, May 1, 2017.

National assessment of alternative jet fuel production potential. Poster presented at ASCENT biannual meeting in April 2017, Alexandria, VA.

Awards

None.

Student Involvement

Tim Galligan, Masters student at MIT's Department of Aeronautics and Astronautics carried out the majority of the analysis, constituting his master's thesis. He is expected to graduate in January of 2018.

Plans for Next Period

The work is being prepared for submission to a peer reviewed journal and as Tim Galligan's master's thesis. The complete work will be available on the website of the Lab for Aviation and the Environment at MIT.

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Task #5: Time- and Path-Dependent Characteristics of AJF Technologies, Including the Effects of Learning-By-Doing on Production Costs and Environmental Performance

Massachusetts Institute of Technology

Objective(s)

The purpose of this task is to carry out an assessment of AJF technologies that accounts for the time- and path-dependence of technology maturation.

Research Approach

Introduction

Anticipated growth in crude oil and conventional jet fuel prices could decrease the relative cost premium of AJF [US EIA 2015], and the societal benefits of GHG emissions mitigation are expected to grow in future years as physical and economic systems become more stressed by climate change [US IAWG 2015]. In addition, learning-by-doing, also referred to as learning curve effects, could contribute to a reduction in the production costs of AJF as experience with the technologies accumulates, as has been empirically observed in the analogous corn ethanol [Chen & Khanna 2012, Hettinga et al. 2009], sugarcane ethanol [van de Wall Bake et al 2009, Goldemberg et al. 2004] and vegetable oil biodiesel industries [Berghout 2008, Nogueira et al. 2016]. Insofar as learning-by-doing contributes to improvements in efficiency and a reduction in process input requirements, the lifecycle environmental impact of AJF fuel production may also improve over time. All of these time-dependent factors indicate that the climate damages mitigated by replacing conventional jet with AJF may exceed the additional cost premium of producing AJF at some point in the future, even if that is not the case today.

Therefore, the aim of this analysis is to test the hypothesis that the societal benefits of a policy of large-scale AJF adoption outweigh the societal costs, in terms of the climate damages and fuel production costs attributable to aviation, when changes over time are taken into account. A system dynamics approach is used to capture the time- and path-dependence of the societal climate and fuel production costs of AJF and conventional jet outlined above, as well as potential non-linearities and feedbacks associated with large-scale adoption of AJF fuels. These include the impacts of AJF feedstock demand on agricultural commodity prices and ultimately AJF production costs, the potential for CO_2 emissions from land use change (LUC), and the impact of fuel price on commercial aviation demand. The results of this cost-benefit assessment (CBA) identify the AJF production pathway characteristics that drive the balance of costs and benefits to society, in terms of climate damages and fuel production costs, attributable to aviation.

Methods

This analysis builds off of existing studies to quantify the lifecycle GHG emissions and production costs of various feedstock-to-fuel AJF technologies, both in terms of n^{th} plant performance and the potential for improvement as limited by thermodynamic and stoichiometric characteristics. The data sources for the pathways considered are summarized in Table 61. Further detail on the lifecycle emissions and production costs of these feedstock to fuel pathways assumed for n^{th} and optimal plant performance are detailed in Staples (2017).

Table 61: Feedstock-to-fuel pathway scope, data sources, and simplifying assumptions

Fuel production technology	Feedstock	TEA data source	LCA data source
HEFA	Soybean oil	Bann et al. (2017)	Stratton et al. (2011) GREET1 2015
	Rapeseed oil	Assumed equivalent to soybean oil HEFA pathway from Bann et al. (2017)*	
	Palm oil		
	Jatropha oil		
	Tallow	Bann et al. (2017)	Seber et al. (2014)
	Yellow grease		
AF	Sugarcane	Bann et al. (2017)	Staples et al. (2014) Trivedi et al. (2015)
	Corn grain		
	Herbaceous lignocellulosic crop		
	Agricultural residue	Assumed equivalent to herbaceous lignocellulosic crop AF pathway from Bann et al. (2017)*	
FT	Herbaceous lignocellulosic crop	Assumed equivalent to MSW FT pathway, plus additional feedstock cost and minus revenue from scrap, from Bann et al. (2017)*	Stratton et al. (2011) GREET1 2015
	Agricultural residue		
	Woody lignocellulosic crop		
	Forestry residue		
	MSW	Bann et al. (2017)	Suresh (2016)
FP	Agricultural residue	Bann et al. (2017)	Assumed equivalent to renewable diesel pyrolysis pathway in GREET1 2015†
	Forestry residue	Assumed equivalent to agricultural residue FP pathway from Bann et al. (2017)*	
APP	Woody lignocellulosic crop	Bann et al. (2017)	Olcay et al. (2013)
	Forestry residue		
HTL	Woody lignocellulosic crop	Bann et al. (2017)	Assumed equivalent to analogous FT pathways in GREET1 2015†
	Forestry residue		
*Denotes simplfying assumption for TEA data coverage			
†Denotes simplifying assumption for LCA data coverage			

As noted above, there may be time- and path-dependence associated with the environmental and economic performance of AJF. Therefore, this analysis uses a stochastic system dynamics model the non-linearities and feedbacks of large-scale AJF adoption, and the resulting impacts on the societal climate change and fuel production costs of commercial aviation. For example, the effect of learning-by-doing on the performance characteristics of advanced biofuel production is captured by the formulation given below, based on Vimmerstedt et al (2015) and Newes et al. (2011):

$$M = \begin{cases} 1 - (1 - M_0)\left(\frac{L^*}{E}\right)^{\left(\frac{1-PR}{ln2}\right)} & \text{for } E \geq L^* \\ M_0 & \text{otherwise} \end{cases}$$

$$L^* = \max\{L, E_0\}$$

$$m = m_{\text{early}} \cdot (1 - M) + m_{\text{minimum}} \cdot M$$

where

M	= degree of maturity, $\epsilon\,(0,1)$
M_0	= initial maturity, $\epsilon\,(0,1)$
L	= min. experience required for learning, units of cumulative production
L^*	= effective min. experience required for learning, units of cumulative production
E	= cumulative experience, units of cumulative production
E_O	= initial cumulative experience, units of production
PR	= progress ratio, percentage of maturity gap, (1-M), remaining after each doubling of cumulative production
m_{early}	= MSP or LCA characteristic of interest, n^{th} plant
m_{minimum}	= MSP or LCA characteristic of interest, minimum
m	= MSP or LCA characteristic of interest

This formulation is more meaningful than the single factor learning curve, traditionally used to model learning-by-doing of energy technologies, because a single factor learning curve implicitly has an asymptote of zero. By using the above formulation, however, the parameter m asymptotically approaches the minimum case value, which is defined by physical or practical limits on the degree to which that characteristic may improve over time.

The degree of maturity of feedstock requirements *(f)*, non-feedstock operating costs (OpEx), non-MD fuel revenue *(R)*, and lifecycle GHG emissions, are modeled as a function of cumulative production of MD fuels. In contrast, the maturity of the capital cost is modeled as a function of the cumulative number of facilities constructed, meaning that there are two parallel learning processes modeled. The n^{th} plant value of each MSP or LCA characteristic is assumed to correspond to initial maturity, M_0, of 50%, which is then used to calculate m_{early}. Initial cumulative experience, E_0, is assumed to be zero. A progress ratio *(PR)* of 90% is assumed based on a review of empirical studies of learning-by-doing for biofuel production, meaning that 90% of the gap between m and m_{minimum} remains after each doubling of cumulative production.

The minimum cumulative volume of MD fuel production required for learning-by-doing to take place is assumed to be 6.4 million metric tonnes of MD, equivalent to the annual production of approximately 30 medium-sized (5000 bpd) bio-refineries. Similarly, the minimum cumulative number of MD fuel production facilities required for learning-by-doing to begin taking place for CapEx is assumed to be 30. These values of L were selected for the two learning processes to reflect an established commercial drop-in MD fuel production industry, where the next unit of production (in terms of fuel volume or production facility) could be considered *"n^{th}"*.

In addition to learning curve effects, using a system dynamics approach enabled the inclusion of non-linear and feedback mechanisms, including: the demand elasticity of the price of agricultural commodities; the impact of incremental feedstock demand on LUC emissions; and the price elasticity of demand for aviation services. These are further documented in Staples (2017).

A simplified representation of the system dynamics model, in the form of a causal loop diagram, is given in Figure 5. This figure shows two re-enforcing loops, and two balancing loops.

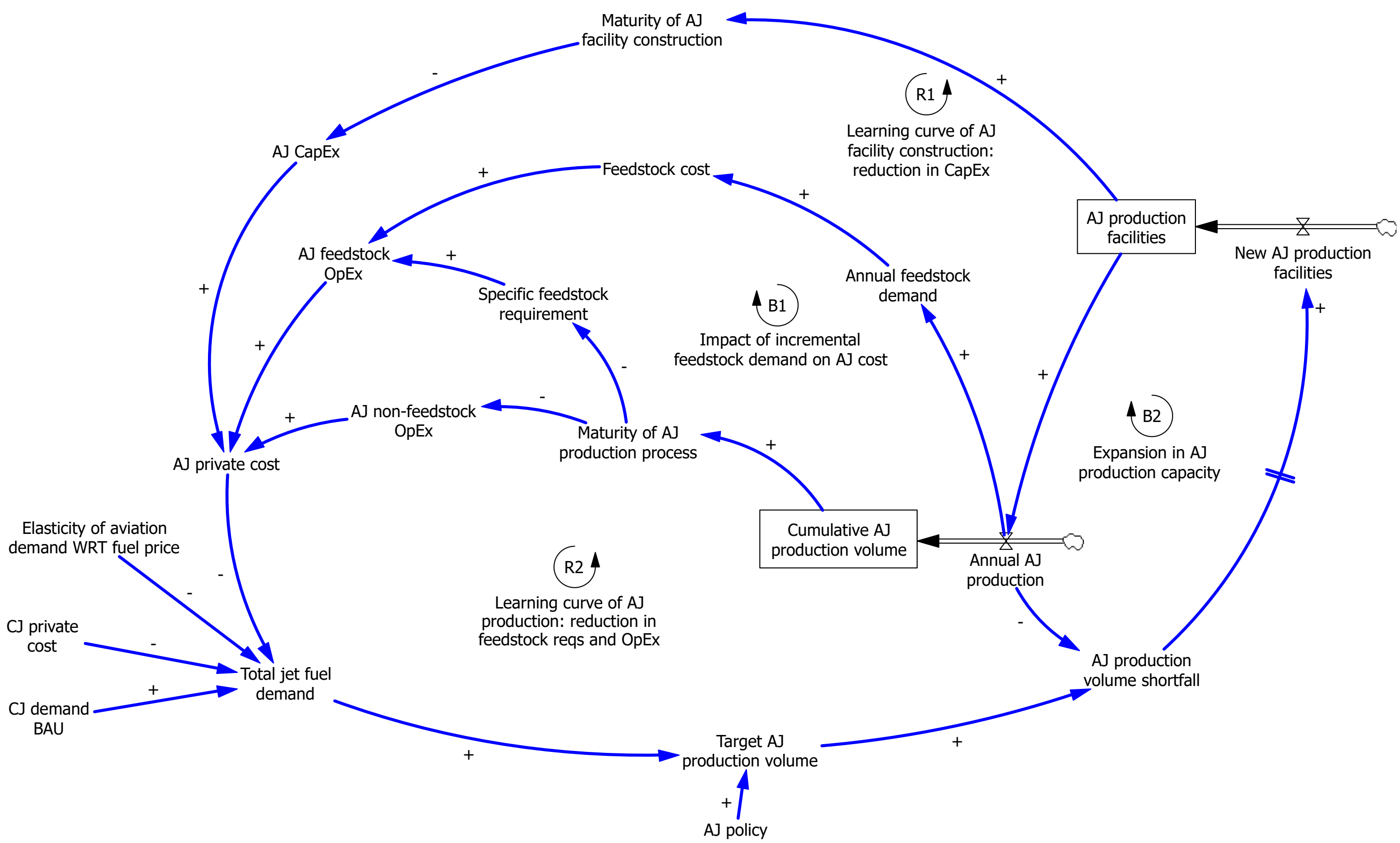

Figure 5: Simplified causal loop diagram of the system dynamics model

The resulting climate impacts of emissions from the business-as-usual and policy cases are monetized using version 23 of APMT-IC. Commodity prices and conventional jet fuel demand are modeled as Geometric Brownian Motion processes, in order to capture stochasticity in the analysis. The methods and selected analysis runs are described in greater detail in Staples (2017).

Results

The results of this analysis are given in terms of the NPV of costs to society. These results are shown for three AJF pathways of interest, and are broken out in a stepwise manner to illustrate the contribution of different impacts on the change in NPV of societal climate damages and fuel production costs of aviation, over the modeled assessment period of 2015-2050. These results are shown in Figure 6.

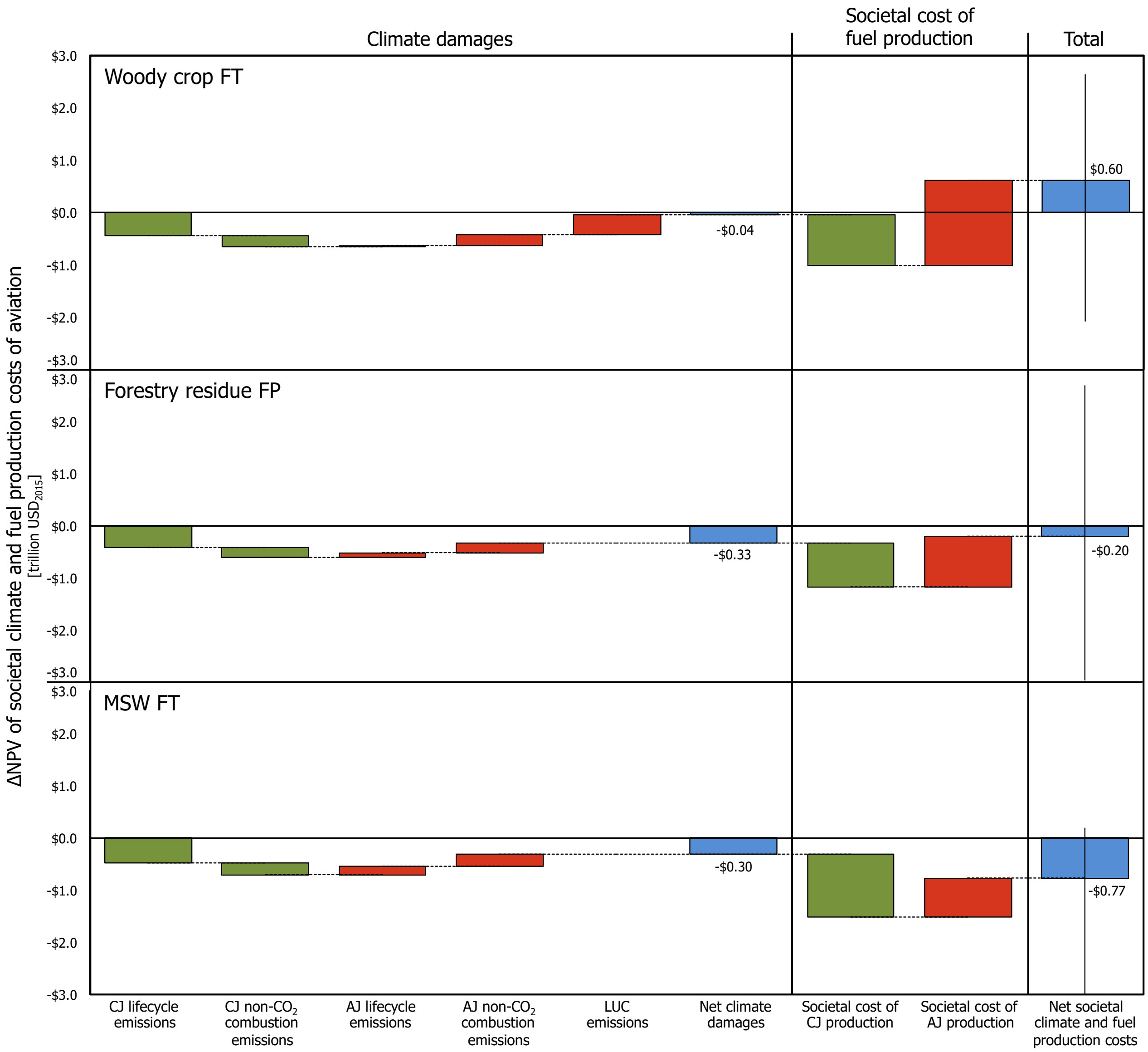

Figure 6: Change in NPV of societal climate and fuel production costs of aviation, 2015-2050. The 95% confidence interval is shown only for net results. Forestry residue FP and MSW FT 2.5th percentiles are at -3.2 and -5.6 trillion USD_{2015}, respectively, but are not shown for practical representation of the results.

Additional results are given in Staples (2017). Sensitivity analysis indicates the importance of the selected societal discount rate, the LUC emissions associated with incremental feedstock demand, and the initial feedstock price, in driving the results shown here. Therefore, a trade-space analysis of these parameters was carried out for the three pathways of interest. These results are now shown here, but are documented in Staples (2017), along with a discussion of the results.

Milestone(s)

The milestone on this task is the completion of the analysis, as described above. This work was presented in a thesis defense in December 2016, and is fully documented in an MIT PhD dissertation, available publically via MIT DSpace. Documentation of this work in the MIT dissertation constitutes completion of MS 4 from the AY 2016/2017 Grant Proposal Narrative.

Major Accomplishments
The major accomplishment on this task is completion of the analysis, and it's documentation in an accepted MIT PhD dissertation.

Publications
This work is documented in the following MIT PhD dissertation: Staples, M. Bioenergy and its use to mitigate the climate impact of aviation. PhD Dissertation submitted to the Massachusetts Institute of Technology (2017). The write-up for the dissertation is currently under revision and preparation for submission to a peer-reviewed journal.

Outreach Efforts
This work was presented at the PhD dissertation defense of Mark Staples, on December 15, 2016 at MIT. Dr. James Hileman was in attendance, as he served as a PhD committee member.

Awards
None.

Student Involvement
This work was carried out by Mark Staples, who was an MIT PhD student until January 15, 2017. As of January 16, 2017, he became research staff at MIT and continues to work on ASCENT Project 1.

Plans for Next Period
Completion of this analysis constitutes the conclusion of this task under ASCENT Project 1. The researchers who carried out this work will be moving forwards with this work to aim for peer-revied publication of the analysis.

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Task #2 & Task #3: Assessment of the Impact of Policies on the Economic Viability of AJF in the Context of AFTF

Massachusetts Institute of Technology

Objective(s)

The purpose of this task is to evaluate policies being considered to support development of AJF production by States that are party to CORSIA, in terms of the impact of the policies of interest on the economic viability of different AJF technologies.

Research Approach

Introduction

AFTF was tasked with providing guidance to CAEP on potential policies and approaches to deploy sustainable AJF. In order to fulfill this mandate, the Policy Task Group of AFTF compiled a summary of past and existing biofuels policies. This process was intended to identify policies which have been effective in developing nascent biofuels industries in the past, and to inform the design of appropriate policy measures specific to aviation in the future. In order to take the findings of this work a step further, during AY 2017/2018 the MIT ASCENT Project 1 team will carry out stochastic techno-economic analysis (TEA) on a number of specific case studies, to provide quantitative guidance to FAA and CAEP on the impact of policies to encourage AJF production.

Background

In the past, the FAA has funded TEAs for a wide set of feedstock-to-fuel pathways to convert biomass or industrial and household wastes into AJF. The resulting literature (eg. Bann et al., 2017, Yao et al., 2017; Suresh, 2016; Pearlson et al., 2013, Seber et al., 2014; Bond et al. 2014; Staples et al. 2014) shows that AJF will remain costlier to produce than conventional jet fuel in the short- to medium term. However, a number of policy measures exist that could potentially improve the economic viability of these technologies. Such measures include, for example, loan guarantees, public offtake agreements, alternative fuel production or use mandates, production or consumption subsidies, tax breaks, carbon taxation or carbon offsetting mandates. In the US, for example, support is provided to AJF production, inter alia, through the Farm to Fly Program and its associated loan guarantees and support for alternative aviation fuel R&D and pilot plant development, the Renewable Fuels Standard, and by offtake agreements of the US military. In the EU, AJF use reduces the amount of emission certificates an airline needs to surrender under the EU Emission Trading Scheme. For international aviation, the upcoming CORSIA regulation will provide an incentive for the use of AJF by reducing the CO_2 offsetting requirements of airlines.

To date, the monetary impact of only some of these options have been studied for a limited set of feedstock-to-fuel production pathways (Bann et al. 2017, Bittner et al. 2015). However, the available evidence points to heterogeneity in the cost-effectiveness of these policy measures. Therefore, during AY 2017/2018 the MIT ASCENT Project 1 team (in collaboration with Purdue University and Hasselt University) plans to conduct a comprehensive analysis of a wide set of policy options and feedstock-to-fuel pathways using a consistent set of assumptions. This will be done using the harmonized stochastic TEA model developed at MIT (Bann et al. 2017). The model will be augmented to account for the policy measures identified by the Policy Task Group of AFTF, and will quantify the changes in net present value (i.e. financial performance of an AJF production facility) and AJF minimum selling prices resulting from these policies. We will also assess combinations of policy measures, for example, loan guarantees coupled with offtake agreements and a carbon offsetting system. The results of this task will provide insight into the absolute and relative effectiveness of different policy measures for enhancing the economic viability of alternative aviation fuels, both in isolation and in the form of bundles of different policy options. The results of these analysis will be used to inform the work of the Policy Task Group of AFTF. AFTF will use this work to provide guidance to ICAO CAEP on policies to encourage the use of AJF in international aviation.

Milestone(s)

The MIT ASCENT Project 1 team contributed to the identification of past and existing biofuels policies by the Policy Task Group of AFTF, and has volunteered to contribute to the quantitative stochastic TEA analysis of the group. The bulk of this work will be carried out in AY 2017/2018.

Major Accomplishments

This task falls under the work plan for AY 2017/2018. Therefore, the major accomplishments for this work will occur in the next period.

Publications

None.

Outreach Efforts

This work plan was discussed with the other technical experts of AFTF during the AFTF/4 meeting in June 2017, in Montreal.

Awards

None.

Student Involvement

The MIT graduate students involved in this task will be Paula do Vale Pereira and Juju Wang, both funded under ASCENT Project 1.

Plans for Next Period

This work will be discussed during the AFTF/5 meeting in October 2017 in Brasilia. Following AFTF/5, a list of case studies of particular interest to the Policy Task Group will be proposed by MIT and discussed with the Policy Task Group. The MIT team will then use the stochastic TEA model to quantify the impacts of the relevant policies on NPV and MSP of the selected AJF technologies.

This work will be summarized in an Information Paper and a Working Paper presented to AFTF/6 in April, 2018.

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Task #2 & Task #6: Additional Support of FAA in the Context of AFTF

Massachusetts Institute of Technology

Objective(s)

The objective of this task is to provide support to the FAA in the context of AFTF beyond the major LCA and policy analysis tasks outlined above. Specifically, this task will support the work of the induced land use change (ILUC) and sustainability task groups, and provide in-person support for FAA decision-making at meetings of AFTF and CAEP.

Research Approach

ILUC Task Group

The ILUC Task Group is responsible for the calculation of ILUC emissions factors, which are added to the core LCA values. Purdue University and the University of Toronto currently lead this task within AFTF. The MIT ASCENT Project 1 team will support the work of the ILUC Task Group by: providing relevant pathway and technology-specific data (e.g. expected fuel yields, fuel product slates) and scenario assumptions (e.g. anticipated global fuel production volumes) for ILUC analysis such that the work is consistent with the work of the LCA Task Group; identifying additional pathways for which ILUC values may be required (e.g. fuels derived from valuable by-product feedstocks, such as palm fatty-acid distillates or corn oil); and contributing to discussion on comparison of ILUC results from the GTAP and GLOBIOM models.

Sustainability Task Group

In order to qualify under CORSIA, AJFs have to satisfy sustainability criteria beyond the CO_2 reductions that are captured in the LCA and ILUC emissions analyses. These criteria encompass environmental, social and economic aspects. Over the previous year, the Sustainability Task Group of AFTF developed these criteria, which were finalized and presented to ICAO steering group in September 2017 in the SARPs appendix. However, no decision has been made yet on how fuel producers and airlines can prove that their AJF adheres to these criteria. In AY 2017/18, the MIT ASCENT Project 1 team will work with the Sustainability Task Group to contribute to proposing and evaluating different options for the recognition of existing sustainability certification schemes under CORSIA, as a means to meet the sustainability criteria defined by AFTF.

In-person Support
The MIT ASCENT Project 1 team will provide in-person support for FAA decision-making for purposes of the AFTF. The principal investigator from Hasselt University will continue serve as the co-lead of the task group on core LCA emission values, and a team member from the MIT ASCENT Project 1 team will lead the modeling work of the AFTF Task Group for Core LCA. Team members will lead and take part in ICAO CAEP AFTF in-person meetings in fall 2017 and spring and summer 2018, and will participate in other in-person meetings of AFTF or the U.S. delegation, such as the ICAO Alternative Fuels Conference in Mexico in fall 2017, as requested by FAA. Furthermore, team members will participate in teleconferences, virtual meetings, and the preparation of information and working papers.

Milestone(s)
This task falls under the work plan for AY 2017/2018. Therefore, the major milestones for this work will occur in the next period.

Major Accomplishments
This task falls under the work plan for AY 2017/2018. Therefore, the major accomplishments for this work will occur in the next period.

Publications
None.

Outreach Efforts
None.

Awards
None.

Student Involvement
The MIT graduate students involved in this task will be Paula do Vale Pereira and Juju Wang, both funded under ASCENT Project 1.

Plans for Next Period
Please see the task description above under “Research Approach”.

Task #4: Collaborate With ASCENT 21 to Capture Non-CO_2 Lifecycle Emissions in APMT-IC
Massachusetts Institute of Technology

Objective(s)
The objective of this task is to collaborate with Project A021 to incorporate non-CO_2 lifecycle GHG emissions into APMT-IC, and to evaluate the impact that the choice of climate metric has on results and conclusions from APMT-IC.

Research Approach
The MIT ASCENT Project 1 team will collaborate with the Project A021 team to properly represent AJF in the APMT-IC module. AMPT-IC was developed by MIT under the Partnership for AiR Transportation Noise and Emissions Reduction (PARTNER) to quantify the environmental impacts of policies influencing aircraft operations and the resulting changes in health and welfare outcomes for climate, air quality and noise. Currently, APMT-IC represents the differences between petroleum-derived jet fuels and AJF in terms of lifecycle CO_2-equivalent emissions, where the CO_2e value of CH_4 and N_2O emissions are calculated on the basis of 100-year global warming potential (GWP) equivalents. While this approach is useful as a first-order approximation to quantify the lifecycle climate impacts of different jet fuels, the use of 100-year GWP to capture non-CO_2 emissions misrepresents the climate impacts. For instance, the atmospheric background concentrations, radiative forcing, and atmospheric lifetime of CH_4 and N_2O are fundamentally different than those of CO_2. Using an equivalency metric that

depends on an arbitrarily defined time horizon, such as the GWP-100, masks these physical differences, and that could distort the results at each step of the analysis. In order to better reflect non-CO_2 lifecycle emissions in APMT-IC, it is proposed under ASCENT Project 21 to model lifecycle CH_4 and N_2O emissions to quantify their impacts on radiative forcing.

The MIT A001 team will contribute to this task by providing lifecycle emissions inventories for petroleum and AJF, disaggregated by emissions species, to the Project A021 team. This data will be used to verify and validate the modifications made to APMT-IC. The results will be used to evaluate the impact that the choice of climate metric has on results and conclusions from APMT-IC, and to enhance the ability to assess policies influencing the use of AJF.

Milestone(s)
This task falls under the work plan for AY 2017/2018. Therefore, the major milestones for this work will occur in the next period.

Major Accomplishments
This task falls under the work plan for AY 2017/2018. Therefore, the major accomplishments for this work will occur in the next period.

Publications
None.

Outreach Efforts
None.

Awards
None.

Student Involvement
This modifications to APMT-IC will be carried out by Carla Grobler, a graduate student at MIT, who is primarily funded by Project A021. Lifecycle emissions inventories for petroleum-derived jet fuel and AJF will be provided by Paula do Vale Pereira and Juju Wang, the MIT graduate students funded under ASCENT Project 1.

Plans for Next Period
Please see the task description above under “Research Approach”.

Task #5: Collaborate With WSU to Facilitate Development of Aspen HEFA Model
Massachusetts Institute of Technology

Objective(s)
The objective of this task is to collaborate with Washington State University (WSU) ASCENT Project 1 team to facilitate development of an Aspen model of the HEFA fuel production process.

Research Approach
Under this task, the MIT ASCENT Project 1 team will facilitate development of an Aspen model of the HEFA fuel production process by the ASCENT Project 1 research team at WSU. The HEFA model developed by WSU will leverage the model described in Pearlson et al. (2013), and will contain greater fidelity on the hydro-deoxygenation, isomerization and catalytic cracking unit processes than the original analysis. The purpose of this task is to build up a modeling tool suited for use in WSU’s lipid-focused advanced supply chain deployment support project, which is Task 3.1 of the ASCENT Project 1 Regional Project Planning numbering system.

Milestone(s)
This task falls under the work plan for AY 2017/2018. Therefore, the major milestones for this work will occur in the next period.

Major Accomplishments
This task falls under the work plan for AY 2017/2018. Therefore, the major accomplishments for this work will occur in the next period.

Publications
None.

Outreach Efforts
None.

Awards
None.

Student Involvement
None.

Plans for Next Period
Please see the task description above under “Research Approach”.